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NEW PARTICLE SEARCHES IN e^+e^- COLLISIONS*

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1. INTRODUCTION

This report summarizes the results of the Study Group on New Particle Searches at e^+e^- Colliders. The work of this Group was organized by U. Nauenberg. The Group was divided into two subgroups: Low Energy Colliders ($E_{cm} \leq 200$ GeV) led by R. Schindler and M. Chen, and High Energy Colliders ($E_{cm} \geq 200$ GeV) led by D. Burke.

A variety of e^+e^- colliders, from 100 GeV to 2 TeV in the center-of-mass, were considered. These facilities, with the assumed luminosities for each, are listed in Table I. Some of these facilities (SLC and LEP) are now under construction and will start operating in the next year or so, while the high energy colliders are quite hypothetical with no credible detailed designs existing at this time.

Table I. e^+e^- colliders considered in the study.

E_{cm}	Facilities	Assumed Luminosity ($\mathrm{cm}^{-2}\mathrm{sec}^{-1}$)
100 GeV	SLC/LEP	$(0.6 \text{ to } 2) \cdot 10^{31}$
200 GeV	LEP II	$(1\text{–}2) \cdot 10^{31}$
100 GeV	Super Z^0 Factory	10^{33}
1/2 to 2 TeV	ILC/TLC/CLIC	$(0.2 \text{ to } 4) \cdot 10^{33}$

This report, as well as the deliberations of the Study Group, have drawn heavily on previous studies. Particularly helpful were the Proceedings of the La Thuile Workshop (CERN Report 87–07) 1987 and the SLAC Study Group Report (SLAC–PUB–329) 1988.

The general motivation for studying new particle searches, and in particular e^+e^- collisions, in the context of Particle Physics for the 1990's, is given in the preceding article, New Particle Production — An Overview. As mentioned in the Overview, investigations of the Higgs sector were made and reported in the Gauge Symmetry Breaking working group section of the Workshop.

Members of the study group were: Low Energy Colliders: D. Atwood, H. Baer, G. Bélanger, A. Blondel, M. Chen, G. Couture, J. Grifols, P. Grosse-Wiesemann, C. Heusch, B. Irwin, D. London, P. McBride, A. Mendez, U. Nauenberg, J. Robinson, R. Schindler, S. Sugimoto, X. Tata, R. Zhu; High Energy Colliders: J. Alexander, H. Baer, C. Baltay, T. Barklow, P. Burchat, D. Burke, C. Dib, K. Gan, J. Gomez-Cadenas, J. Grifolo, H. Haber, J. Hewett, S. Komamiya, W. Kozanecki, P. Rankin, T. Rizzo, S. Selipsky, A. Sill, C. Simopoulos, R. Stroynowski, W. Tuung, R. Van Kooten, B. Ward, E. Yehudai, D. Zeppenfeld.

2. LUMINOSITY REQUIREMENT OF e^+e^- COLLIDERS

The e^+e^- cross sections at high energies are rather small; thus high luminosities are needed to achieve useful event rates at high energy e^+e^- colliders. It is customary to discuss cross sections in units of R, where one unit of R is the cross section for the process:

$$\begin{aligned}\sigma(R=1) &= \sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) \\ &= 87 \times 10^{-39} cm^{-2}/s(\mathrm{TeV}^2) \quad ,\end{aligned}$$

where s is the square of the total center-of-mass energy, $s = E_{cm}^2$.

Cross sections in the vicinity of one unit of R are typical of many new particle production processes. A minimum useful event rate seems to be 1000 events/year/unit of R. For example at 1 TeV, using 10^7 second/year (one "Snowmass year") we need $\mathcal{L} = 10^{33}$ cm^2 sec^{-1}. Because of the s^{-1} dependence of $\sigma(R=1)$, the minimum useful luminosities for the high-energy machines that we consider are:

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E_{cm}	$\mathcal{L}_{min}$ (cm^{-2} sec^{-1})
400 GeV	2×10^{32}
1 TeV	10^{33}
2 TeV	4×10^{33}

It should also be noted that these minimum luminosities might be just enough to discover possible new effects. Higher luminosities (by an order of magnitude?) could be needed to carry out detailed studies of such effects.

3. GENERAL FEATURES OF e^+e^- COLLISIONS

In the past it has generally been true that electron accelerators and colliders had lower center-of-mass energies than the corresponding hadron facilities in existence at any given time. This has limited the energy reach of the electron facilities. However, in reality, the effective physics reach of the various colliders have been rather similar, since in e^+e^- collisions the entire energy goes into the point interactions of interest, while in hadron collisions the larger total energy is divided among many constituent quarks and only a small fraction of it goes into any particular quark-quark collision of interest. Similar comments can be made about cross sections. Total cross sections are much larger at hadron colliders, but the cross sections for the subprocesses of interest are not so different from the corresponding cross sections at e^+e^- colliders. In fact, the absence of the large background cross sections, and the simplicity of the e^+e^- collisions, have made the results of e^+e^- colliders much clearer and easier to interpret. Another nice feature of e^+e^- collisions is that because of the well known electromagnetic couplings, negative results can be more easily converted into reliable limits on the relevant physics parameters.

The general characteristics outlined above are expected to be similar in the next generation of TeV Colliders. However, the nature of e^+e^- collisions will change in many ways, which we discuss in a little more detail in the remainder of this section.

3.1 Features of Low Energy e^+e^- Collisions (i.e., $E_{cm} \leq 200$ GeV or so)

(a) The particles of interest decay into light quarks and leptons. In fact most of the important discoveries were made by observing leptonic decays such as $\psi \to e^+e^-$ or $\tau \to \mu\nu\bar{\nu}$. For this reason, good lepton detection and measurement was emphasized in the design of detectors.

(b) The backgrounds to the processes of interest were very small. The cross sections for light quark pair production are similar to those of the interesting lepton pair or heavy quark pair production processes. The only known annihilation background was the two-gamma process which could easily be separated by a visible energy cut. In the colliders at the Z^0 mass, the collisions are dominated by the signal, Z^0 production, with a cross section of ~ 5000 units of R, while the known Z^0 background has a cross section of the order of 10 units of R.

(c) In the low-energy colliders the energies of the incident $e^\pm$ beams at the collision point were known to a precision of typically 10^{-3} or 10^{-4}. This provided two very powerful constraints, *i.e.*, precise knowledge of the total center-of-mass energy, $E_{cm} = 2E_{beam}$, and the total momentum, $\bar{P} = 0$, *i.e.*, the center-of-mass of the collision was stationary in the lab. These constraints were very important in understanding the details of the processes of interest.

3.2 Features of High Energy e^+e^- Collisions ($E_{cm} \geq 200$ GeV or so)

(a) At the high energy colliders we anticipate that the new particles we are interested in will have prominent decay modes into Z's and W's, such as the Higgs boson, $H^0 \to W^+W^-$, or new heavy quarks $Q \to q + W$. Detailed studies (see following sections) indicate that in e^+e^- collisions the backgrounds will be sufficiently small so that the dominant hadronic decays $W, Z \to q + \bar{q} \to 2$ jets will be useful signatures in addition to the leptonic W and Z decay modes. This possibility has a number of significant advantages:

(1) The branching fractions for the hadronic decays is of the order of 70%, compared to a few percent for any particular leptonic decay. Since often there are two or more W's or Z's involved in a signature for a new process, the feasibility of using the hadronic modes can enhance the detection efficiencies by orders of magnitude.

(2) In the leptonic decay $W^\pm \to \ell^\pm\nu$ there is a neutrino which is undetected, so that generally the mass of the new particle in question cannot be reconstructed in a straightforward way. With the hadronic decay modes most of the energy is measurable and the masses of the new particle can be reconstructed. (See Fig. 1.) This allows the measurement of the mass, as well as a much more convincing signature for the discovery of some new particle, *i.e.*, a peak in some effective mass distribution (see the detailed discussions in the following sections).

(3) The precision of hadron calorimetry improves as the energies increase. Thus the energies and angles of the jets in W, $Z \to q\bar{q} \to 2$ jets can be measured well enough that the W or Z mass can be reconstructed using this technique.

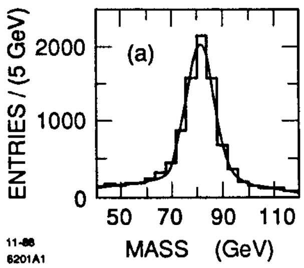


Fig. 1. Reconstructed W and Z mass distributions for machine and detector parameters used in this report.

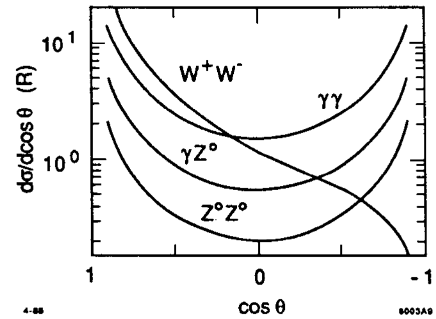


Fig. 2. Differential cross sections for the production of gauge bosons by e^+e^- annihilation at $\sqrt{s}$ = 1 TeV.

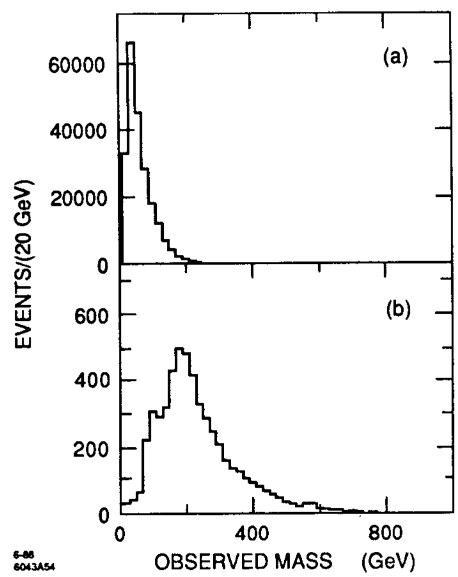


Fig. 3. Distribution of observed masses for two-photon process, (a) $\gamma\gamma \to q\bar{q}$ and (b) $\gamma\gamma \to W^+W^-$. The distributions are normalized to e^+e^- integrated luminosity of 10 fb^{-1}.

Table II. Cross sections and event rates at a 1 TeV e^+e^- collider.

Process	σ (units of R)	Events/year[†]
1. Annihilation		
$e^+e^- \to \nu_\mu\bar{\nu}_\mu$	0.25	250
$\mu^+\mu^-$	1.3	1300
$d\bar{d}$	1.1	1100
$u\bar{u}$	2.1	2100
total $\ell^+\ell^-$	4	4000
total $q\bar{q}$	9	9000
$e^+e^- \to W^+W^-$	27	27000
Z^0Z^0	1.5	1500
$\gamma\gamma$	10	10000
γZ^0	31	31000
$W^+W^-Z^0$	0.4	400
$Z^0Z^0Z^0$	0.03	30
2. Two-γ, $\gamma - W$, $\gamma - Z$ fusion		
$e^+e^- \to e^+e^-q\bar{q}$	~1	1000[‡]
$e^+e^-W^+W^-$	9.3	9300
$e\nu W^\pm Z^0$	3.4	3400
3. $e^+e^- \to e\nu W^\pm$	140	140000
$e^+e^-Z^0$	70	70000

[†]With $\int \mathcal{L}dt = 10^{40}$ cm^{-2} = 10 fb^{-1}, neglecting beamstrahlung.

[‡]$m\ (q\bar{q}) \geq 200$ GeV.

(b) New background processes, such as W^+W^- pair production and $\gamma\gamma$, $\gamma - W$, and $\gamma - Z$ fusion processes, become important, with relatively large cross sections at high energies. The cross sections and event rates for the relevant processes of 1 TeV are summarized in Table II. While some of these reactions, like $e^+e^- \to W^+W^-$, are of great interest on their own, they nevertheless represent a background in searches for new particle production. Detailed studies, however, indicate that these processes have some very distinctive features that allow various selection criteria to eliminate them as serious backgrounds to new particle production. Examples of these are an angle cut to eliminate the bulk of the $e^+e^- \to W^+W^-$ process (see Fig. 2) and a total visible energy cut to eliminate the $\gamma\gamma$, γW, or γZ fusion processes (see Fig. 3). As will become apparent from the detailed discussion of various particle searches, these backgrounds will have to be worried about but should turn out to be manageable.

(c) The very high energy e^+e^- colliders will most likely be colliding linear accelerators. To obtain the required high luminosities the beams will have to be focused very hard to produce sub-micron size spots at the collision point. As the $e^{\pm}$ beams pass through each other at the intersection region they can radiate a non-negligible fraction of their energy (called beamstrahlung) before the e^+e^- collision takes place. Thus, the total center-of-mass energy and the total momentum of the collision (*i.e.,* the motion of the center-of-mass in the lab) are no longer precisely defined, and the constraints $E_{cm} = 2\,E_{beam}$ and $\vec{P}_{cm} = 0$, which were so useful at low energy colliders, might be lost. There is some flexibility in the design of the colliders to minimize these effects, and it is therefore not clear at this time how seriously these constraints will be compromised. The size of this effect can be characterized by the parameter δ, which is the mean energy loss of one beam as it passes through the other beam. The spread in E_{cm} for the actual e^+e^- collisions are shown for various existing preliminary collider designs in Fig. 4 (TLC design at SLAC with $\delta = 0.26$) and in Fig. 5 (CLIC design at CERN with $\delta \approx 0.1$).

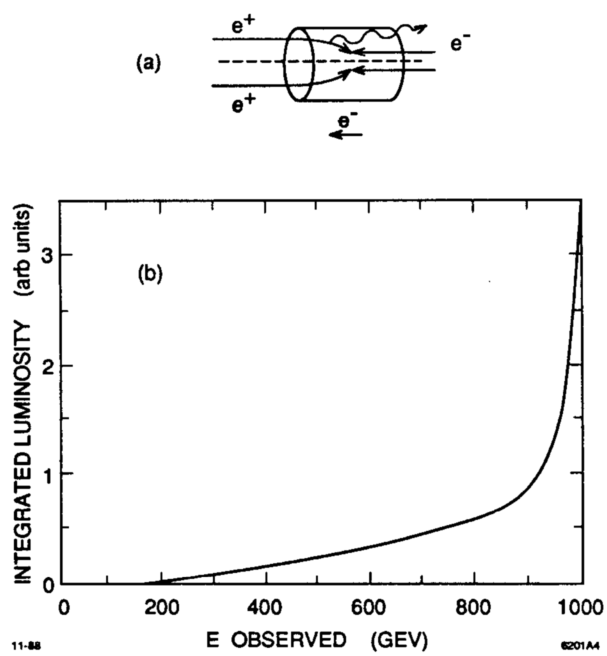


Fig. 4. (a) Beamstrahlung induced by the deflection of particles in one bunch by the collective fields of the opposing bunch. (b) A typical spectrum of center of mass energy in e^+e^- *collisions in the presence of beamstrahlung. The curve is computed for one particular design of colliding beams each with initial energy of 500* GeV.

The deterioration of the E_{cm} and P_{cm} constraints were taken into account in the detailed studies of new particle searches presented in the remainder of this report. These studies indicate that the deterioration of these constraints makes the analyses more difficult, but the problems are manageable and all of the searches are feasible.

A useful feature of the smearing of the collision energy is that the high energy colliders become self-scanning, *i.e.,* a collider sitting at its peak energy can see resonances at lower masses without doing an energy scan. This sensitivity is illustrated in Fig. 6 for the TLC design with $\delta = 0.26$.

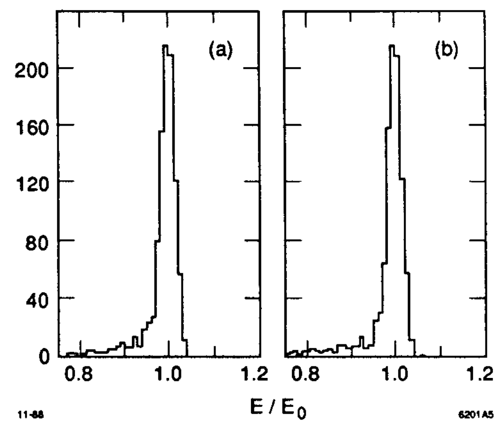


Fig. 5. Spectra similar to that shown in Fig. 4(b) for alternative machine designs at (a) 1 TeV, *and (b) 2* TeV.

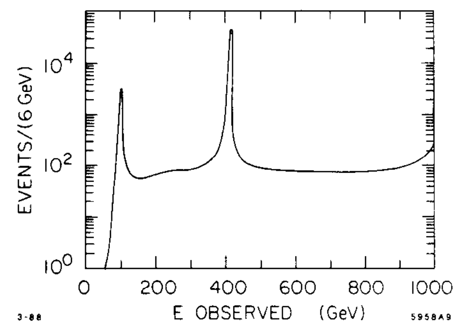


Fig. 6. Distribution of observed hadronic invariant masses resulting from e^+e^- *annihilation to hadrons. The effect of a new* Z' *boson of mass 400* GeV *is also shown. The distribution is computed with the beamstrahlung spectrum shown in Fig. 4(b).*

4. COMMENT ON DETECTORS

There was not much discussion of detailed detector design at this Summer Study. However, the SLAC study (SLAC–PUB–329) did consider the detector parameters needed to do the physics at a TeV collider. The following detector parameters were adopted for that study:

4.1 Tracking

A momentum resolution of $\delta p/p = 3 \times 10^{-4}$ p(GeV) was assumed (*i.e.,* $\sim 15\%$ at 500 GeV). This can be achieved in a relatively straightforward way with a drift chamber of 1.8 m radius in a magnetic field of 0.6 Tesla with 80 layers of wires with a resolution of 120 μm on each wire. Precision vertex detectors of the kind being built for the SLC and LEP detectors will be desirable.

4.2 Calorimetry

The following parameters were assumed:

Energy Resolution:

Electromagnetic: $\frac{\delta E}{E} = \frac{8\%}{\sqrt{E}} + 2\%$

Hadronic: $\delta E = \frac{50\%}{\sqrt{E}} + 2\%$

Segmentation: — $4° \times 4°$ Projective Towers

The segmentation requirement was arrived at by studying the mass resolution and detection efficiency of reconstructing a $W \to q\bar{q} \to 2$ jets as a function of segmentation. As can be seen from Fig. 7, $4° \times 4°$ towers seem quite adequate.

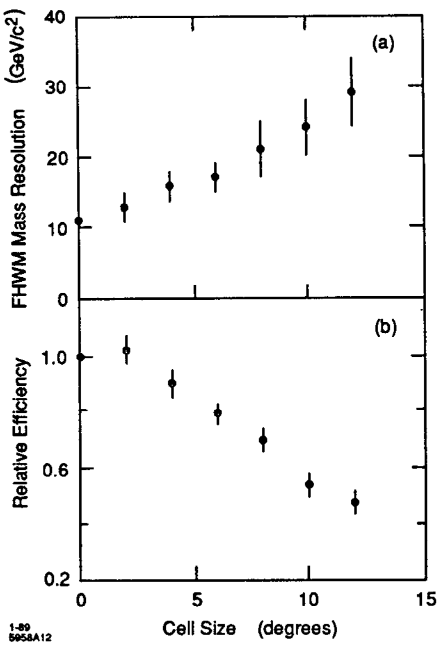


Fig. 7. (a) Mass resolution for gauge bosons obtained from $e^+e^- \to W^+W^-$ events reconstructed with calorimeters with differing granularity. (b) Acceptance for $e^+e^- \to W^+W^-$ events as a function of calorimeter cell size after demanding each W be properly reconstructed.

The event rates at a 1 TeV collider with a luminosity of 10^{33} cm^{-2} sec^{-1} are less than the event rates expected at SLC and LEP, thus no new problems associated with triggering or radiation damage are expected.

The conclusion thus seems to be that the parameter of the detectors required for a TeV e^+e^- collider are not far from those at SLC and LEP. Therefore, the detectors for the new high energy e^+e^- colliders are a straightforward extrapolation of the detectors now under construction at SLC and LEP, and no real problems are expected.

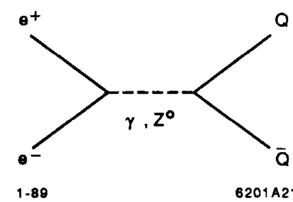
5. DISCUSSION OF SELECTED SEARCH TOPICS

5.1 Search For New Heavy Quarks

The possibility of a fourth generation of quarks was considered:

$$\begin{pmatrix} d \\ u \end{pmatrix} \begin{pmatrix} s \\ c \end{pmatrix} \begin{pmatrix} b \\ t \end{pmatrix} \begin{pmatrix} b' \\ t' \end{pmatrix} ,$$

where b', t' are new heavy quarks with charges of $-1/3$ and $+2/3$, respectively. The dominant production process in e^+e^- collisions is expected to be via a γ or Z^0 exchange in the s channel:



The cross sections for these processes are essentially independent of M_Q, the quark mass, almost up to the kinematic limits:

$$\sigma(e^+e^- \to b'\bar{b}') \sim 1 \text{ unit of } R$$
$$\sigma(e^+e^- \to t'\bar{t}') \sim 2 \text{ units of } R$$

The expected numbers of events produced at a 2 TeV collider in a sample of 1000 events per unit of R (an integrated luminosity of $\sim 4 \times 10^{40}$ cm^{-2}) are shown in the first column of Table III for various b' and t' masses.

The backgrounds are expected to be sufficiently small so that the dominant hadronic decay modes can be used in the search:

$$b' \to W^- + q \quad , \quad W^- \to q + \bar{q} \quad ;$$
$$t' \to W^+ + b' \quad , \quad b' \to W^- + q \quad , \quad W^\pm \to q + \bar{q} \quad .$$

The signature, for example for a $b'\bar{b}'$ pair, are events with six jets, divided into two hemispheres with three jets each. The main backgrounds are annihilation processes like $e^+e^- \to q\bar{q}$ or W^+W^-, and the $\gamma\gamma$ or γW fusion processes $e^+e^- \to e^+e^-q\bar{q}$, $e^+e^-W^+W^-$, or $e\nu WZ$ with the e^+e^- going down the beam pipe. The total numbers of these events are also shown in the first column of Table III.

Table III. Heavy quark event rates in 2 TeV e^+e^- collisions.

Use sample of 1000 events/unit of R		
Process	Events Produced	Events after Selection
• $e^+e^- \to b'\bar{b}'$		
$m_{b'} = 300$ GeV	1000	330
500	900	250
700	700	150
900	450	100
• $e^+e^- \to t'\bar{t}'$		
$m_{t'} = 300$ GeV	2000	850
500	1800	700
700	1400	450
900	900	300
• Backgrounds		
$e^+e^- \to q\bar{q}$	9000	200
W^+W^-	36000	900
$e^+e^-W^+W^-$	250000	300

Some fraction of these events will have a 6-jet topology due to jets from hard gluon Bremsstrahlung, and thus be a background to heavy quark production.

Several detailed Monte Carlo calculations were carried out to simulate the effects of realisitic detector parameters and the necessary selection criteria on the signal and the backgrounds. Figure 8 shows the results of an analysis by P. Igo-Kemenes from the La Thuile study.[1] The LUND Monte Carlo generation with JETSET 6.3 and LUCLUS were used. A 2 TeV Collider with an integrated luminosity of 1000 events/unit of R were assumed. The following selection criteria were applied.

1. Select multijet events with at least five or more jets.
2. Total visible energy larger than 50% of the nominal collider E_{cm}, *i.e.*, $Evis \geq 1$ TeV.
3. The event was separated into two hemispheres along the thrust axis. The effective mass of each hemisphere was calculated, and the two masses were required to be equal to within 30%.
4. The sphericity of the events were required to be larger than 0.04.

   The number of signal and background events passing these cuts are shown in the last column of Table III. The efficiency for the signal events is quite good, while the backgrounds have been reduced by large factors to a manageable level. The distribution of the effective mass of each hemisphere for the events surviving the cuts is shown in Fig. 8. It can be seen that the remaining background peaks at low masses, and the signal corresponding to heavy quark production stands out quite clearly.

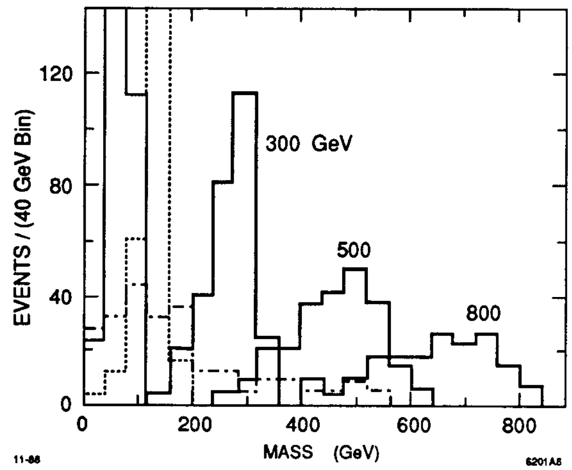


Fig. 8. Reconstructed invariant mass per hemisphere for $e^+e^- \to b'\bar{b}'$ events with various b' masses. Backgrounds are also shown and described in the text.

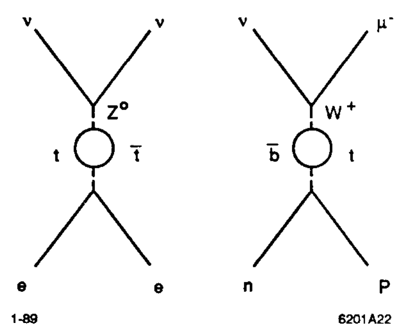
This analysis indicates that heavy quarks can be found cleanly up to almost the kinematic limits with high energy e^+e^- colliders.

5.2 Search for the *t* Quark

The expected sixth quark, the t quark, has so far eluded detection. The current limits on the mass of the t quark are:

$$41 \leq m_t \leq 200 \text{ MeV} \quad ;$$

the lower limit comes from the UA1 experiment at CERN. The upper limit comes from theoretical considerations of loop corrections of the general kind:



The size of such corrections typically depends on m_t^2; $m_t \geq 200$ GeV would lead to corrections which would be large and different for neutral current and charged current processes, in direct disagreement with the experimentally measured consistency of the W and Z masses and $\sin\theta_W$.

The SLC, LEP, and the Tevatron can probe some, but probably not all, of the allowed range of m_t in the near future. If the t is not found at these facilities in the near future an e^+e^- collider with an E_{cm} of 400 to 500 GeV would be sufficient to probe the whole mass range to either find the t or to show that something unexpected is going on.

A detailed Monte Carlo analysis of the feasibility of a t quark search at a 400 GeV e^+e^- collide was carried out at this Summer Study by R. Van Kooten. The dominant production process is via γ and Z^0 exchange in the s channel.

The cross sections for various values of m_t and the numbers of events produced in a 10 fb^{-1} sample are given in Table IV. The backgrounds are similar to those discussed in the previous section and listed in Table III.

Table IV. Cross sections and event rates for top quark production at a 400 GeV e^+e^- collider.

m_t (GeV)	σ (units of R)	Events in 10 fb^{-1}
50	2.1	11000
100	1.8	9000
150	1.4	7600
170	1.1	6000
190	0.7	3800

The decay modes used in the analysis were:

$$e^+e^- \to t + t'$$
$$t \to b + W^+, W^+ \to e^+ \text{or } \mu^+ + \nu$$
$$\bar{t} \to b + W^-, W^- \to q\bar{q} \to 2 \text{ jets} \quad ;$$

thus the signature looked for is a jet and an isolated fast-charged lepton with two or three jets in the opposite hemisphere. Signal and background events were generated using the LUND 6.3 generator with LULEPT. The following selection criteria were applied:

1. Select multijet events with one energetic ($p \geq 2$ GeV/c) e or μ that is isolated from the rest of the particles in the event (less than 2 GeV of energy within a 20° cone around the e or μ).
2. Find the thrust axis, and require $\cos\theta_{thrust} \leq 0.8$.
3. Separate the event into two hemispheres along the thrust axis and calculate the effective mass of each hemisphere. Require that both masses are larger than 104 GeV.

The distribution of the mass in the hemisphere opposite to the isolated e or μ is shown in Fig. 9. A top mass of 150 GeV was used to generate this distribution. A clear peak near the t mass is visible. The backgrounds, shaded in Fig. 9, are quite small.

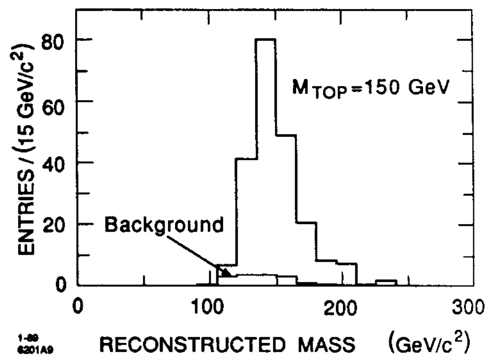


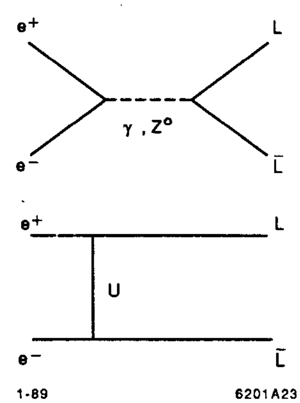
Fig. 9. Observed signal from a top quark search with integrated luminosity of 10 fb^{-1} at an e^+e^- collider with $\sqrt{s}$ = 400 GeV if the top mass is 150 GeV. The shaded region shows the backgrounds from all known processes.

5.3 Leptoquark Search

Leptoquarks are hypothetical new particles with both lepton (L=±1) and quark (B = ± 1/3 or 2/3) quantum numbers. They are predicted in all technicolor and extended technicolor models. Recent interest has been added by predictions of leptoquarks by superstring-inspired E6 models. As an example we considered the scalar lepto quarks with charge −1/3 and the following expected decay modes:

$$L_0^e \to u + e-$$
$$L_0^\mu \to c + \mu^- \quad ,$$

where u and c are the up and charmed quarks, respectively. The main production processes in e^+e^- collisions are expected to be via the diagrams.



The cross section is predicted to be:

$$\sigma(e^+e^- \to L_0 + \bar{L}_0) \cong 0.4B^3 \text{ in units of } R \quad .$$

The cross sections for various values of the leptoquark mass are given in the first column of Table V. The expected numbers of events produced by a 2 TeV collider with an integrated luminosity of 1000 events/units of R are given in the second column of Table IV.

Table V. Cross sections and event rates for leptoquark search in 2 TeV e^+e^- collisions.

Use sample of 1000 events/units of R			
Process	Cross Section Units of R	Events Produced	Events after Selection
1. $e^+e^- \to L_0\bar{L}_0$			
$m_L = 200$ GeV	0.4	400	375
400	0.3	300	280
600	0.2	200	150
800	0.08	80	65
900	0.03	30	20
2. Backgrounds			
$e^+e^- \to q\bar{q}$	9	9000	45
W^+W^-	36	36000	4
e^+e^-WW	250	250000	$\leq$ 1

These leptoquark events should have a very simple signature: an isolated energetic e^- or μ^- with a jet on one side, with an e^+ or μ^+ and a jet on the other. The potential backgrounds to this process are also shown in Table V.

A detailed Monte Carlo calculation for a leptoquark ($L \to u + e^-$) search was carried out by Shaile and Zerwas at the La Thuile Study.[2] They used the latest version of the LUND Monte Carlo generator with JETSET 6.3 and LUCLUS to simulate both the signal and the background events at a 2 TeV Collider. They applied the following selection criteria to the events.

1. Select events with an energetic e^+ and an energetic $e^-(P_{e^\pm} \geq 20$ GeV) and two or more hadronic jets.
2. Total visible energy $E_{vis} \geq 1.6$ TeV.
3. $\sum P_Z \leq 0.15 E_{vis}$.
4. $\sum P_\perp \leq 150$ GeV/c.

The numbers of events passing these cuts are shown in the third column of Table V. For the events passing these cuts the effective masses for the $e^\pm$-jet combinations were calculated. Figure 10 shows the distribution in the e-jet mass for the events passing the cuts. The solid curve is for the $L \to u + e$ signal for a L mass of 600 GeV. The shaded curve is the background passing the cuts, mostly due to $e^+e^- \to q\bar{q}$ with an energetic $e^\pm$ in each jet. The signal is quite clearly distinguished from the background.

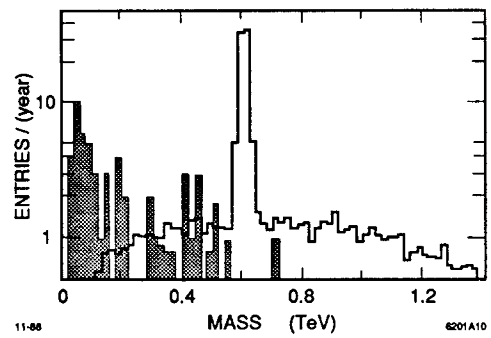


Fig. 10. Reconstructed signal from a search for leptoquarks with a data sample of 10 fb^{-1} at $\sqrt{s}$ = 2 TeV. *The solid line is the invariant mass of all e-jet combinations in accepted signal events and the shaded region gives the background.*

5.4 New Neutral Gauge Boson Z′

There are a variety of theoretical reasons for expecting additional heavy Z^0 type gauge bosons. We will call these Z' in this report. Left-right symmetric models predict additional Z' as well as right-handed charged bosons $W_R^\pm$. Superstring-inspired E_6 Models, which are very fashionable with theorists this year, predict several new neutral bosons. In this model the E_6 group breaks down into several U(1) groups [the new U(1) groups have new Z bosons associated with them];

$$E_6 \to SO(10) + U(1)_\psi$$
$$SO(10) \to SU(5) + U(1)_\chi \quad ,$$

thus predicting the existence of two new Z' bosons Z_ψ and Z_χ. In general, these can mix to produce mass eigenstates:

$$Z'_\eta = \cos\theta Z_\psi + \sin\theta Z_\chi \quad .$$

The value of this E_6 mixing angle θ is of some interest theoretically. One value of particular interest is $\cos\theta = -\sqrt{5/8}$ which yields:

$$Z'_\eta = -\sqrt{5/8} Z_\psi + \sqrt{3/8} Z_\chi \quad .$$

The search for such Z' bosons and their detailed study, shedding light on their origin and mixing angles like θ, is obviously of great interest.

5.4.1. Search for Z′ bosons in e⁺e⁻ collisions

(a) If a Z' boson exists in the kinematic range of an e^+e^- collider, *i.e.*, with mass less than the total center-of-mass energy, $m_{Z'} \leq E_{cm}$, the Z' will manifest itself as a resonance in the total cross section at an energy equal to the mass of the Z'. The total cross section at resonance is expected to be in the range of 1,000 to 10,000 units of R. Compared to the expected cross sections without a Z' (see Table II), a collider with any appreciable luminosity cannot fail to find such a Z' within its kinematic range.

(b) An e^+e^- collider is sensitive to a new Z' even if the mass of the Z' is several times larger than E_{cm} of the collider. This is because the tail of a Z' will affect the cross sections, the forward-backward asymmetries, A_{FB}, and the polarization asymmetries A_{LR} of various processes such as $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to q\bar{q}$. These effects can be quite large, but are generally dependent on the details of the model predicting the Z'. At this study, J. Hewett and T. Rizzo carried out extensive calculations of such effects in the context of a superstring-inspired E_6 model. In these models the effects, like the deviation of the polarization asymmetry A_{LR}, depend sensitively on the E_6 mixing angle θ. Figure 11 shows their result of the sensitivity to the mass of a new Z' (M_2 in the Figure) for a 1 standard deviation change in A_{LR} for various channels as a function of the mixing angle θ for a 400 GeV collider. The curves indicate a sensitivity up to 1.2 to 2.0 TeV. Figure 12 shows the same thing for a 1 TeV collider, again showing sensitivity to a Z' mass up to several times the center-of-mass energy of the collider.

5.4.2 Detailed study of a new Z′ boson.

It is quite possible that if a new Z' boson exists it will be discovered at a hadron collider like the Tevatron or the SSC. The detailed study of such a new Z' will be best carried out at an e^+e^- collider with a center-of-mass energy at or just above the mass of the Z'. The situation would be quite analogous to the standard model Z^0, which was discovered at a hadron collider but whose detailed study has to wait for the e^+e^- colliders SLC and LEP.

The total e^+e^- cross section on a Z' resonance is expected to be in the range of 1,000 to 10,000 units of R. Thus a collider with the minimum luminosity of 1,000 events/year/unit of R discussed in Section II above should produce 10^6 to 10^7 Z' bosons/year. The non-Z' background should be of the order of 1% or less of the Z' production (see Table II). Thus clean, detailed studies should be possible. The analogy with the Z^0 at SLC and LEP is quite close. The physics potential of SLC and LEP should be an indication of the richness of an e^+e^- collider should a new Z' boson exist.

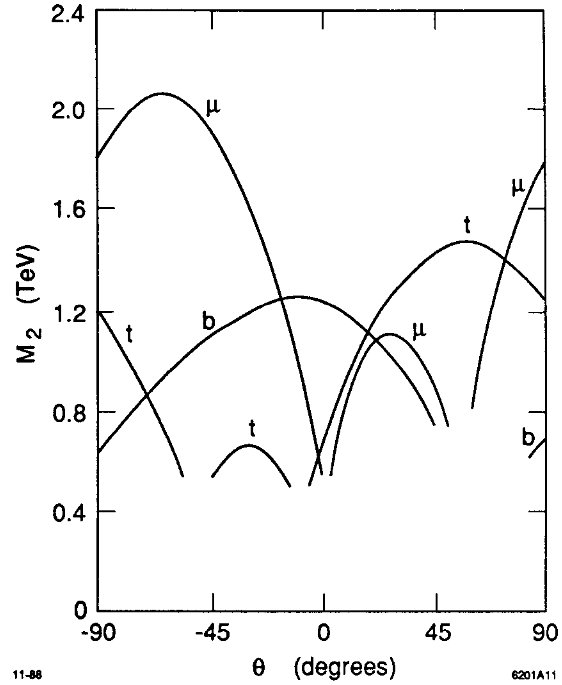


Fig. 11. Mass limits on new gauge bosons that would generate one standard deviation changes in polarization asymmetry measurements in various channels at an e⁺e⁻ *collider with* $\sqrt{s}$ = *400* GeV. *The angle* θ *is a mixing angle needed to define the gauge structure in the theory.*

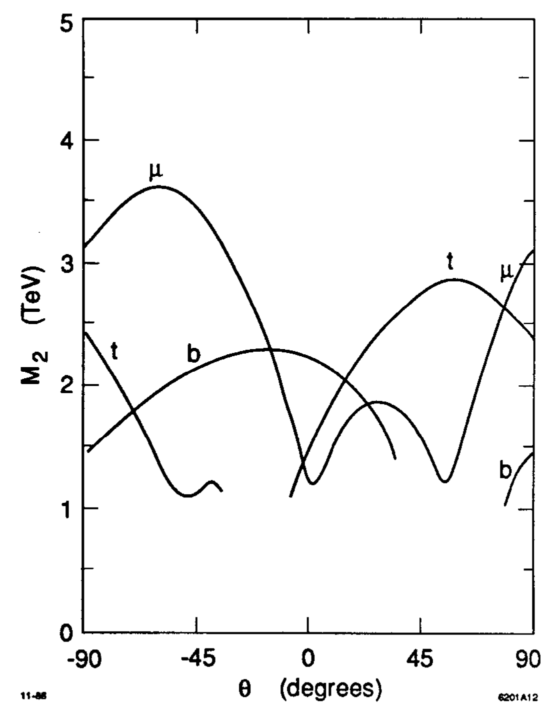


Fig. 12. Limits similar to those shown in Fig. 11 for a collider with $\sqrt{s}$ = *1* TeV.

5.5 Neutrino Counting

Our present view of particle physics is based on three generations of quarks and leptons. It is obviously of fundamental importance to determine experimentally whether there are additional generations of quarks and leptons, and if so, how many. One way to do this is to look for new heavy quarks and leptons; these could be quite heavy and beyond the reach of our facilities. However, the neutrinos associated with the existing three families are very light, probably massless. Assuming this trend to continue, counting the number of neutrino types that occur in Z^0 decay would give a good indication of the number of generations.

The total width of the Z^0 is sensitive to the number of neutrino types. With the three known generations the total width of the Z^0 should be around 2.7 GeV. Each additional neutrino type will increase this by 170 MeV. Thus, a fairly accurate measurement of the width is required. Radiative corrections and other systematic errors will make this a difficult measurement.

A better way to measure the number of neutrinos is to run the collider 5 to 10 GeV above the Z^0 mass and look at the reaction $e^+e^- \to Z^0 + \gamma$. The reaction is identified by a monochromatic γ. One then measures the branching ratio of the Z^0 into ν's, normalized to say the branching ratio into $\mu^+\mu^-$ — *i.e.*,

$$r = \frac{e^+e^- \to \gamma + Z^0 \to \gamma + \nu\bar{\nu}}{e^+e^- \to \gamma + Z^0 \to \gamma + \mu^+ + \mu^-} \quad .$$

This ratio is expected to be:

$$\begin{aligned} r = 2\cdot(\text{number of } \nu \text{ types}) &= 6 \text{ for } 3\ \nu \text{ types} \\ & 8 \text{ for } 4\ \nu \text{ types} \\ & 10 \text{ for } 5\ \nu \text{ types} \end{aligned}$$

The factor of two comes from the relative neutral current couplings of neutrinos and muons to the Z^0. Thus the difference between three or four neutrinos is 33%. However, it is important to measure this branching ratio as well as possible since it is sensitive to the existence of any other weakly interacting neutrals that couple to the Z^0. For example, a supersymmetric neutrino would change the ratio from six to seven.

Neutrino counting using this technique was looked at in this study to answer the question of how much better than SLC or LEP could a super Z^0 factory (100 GeV e^+e^- collider with 10^{33} luminosity) do? The cross section for $e^+e^- \to Z^0 + \gamma$ around E_{cm} = 97 GeV is around 2×10^{-35} cm^2. Figure 13 shows the expected precision that can be obtained for a measurement of r. At integrated luminosities of 10^{37} cm^{-2} or less the precision is statistics

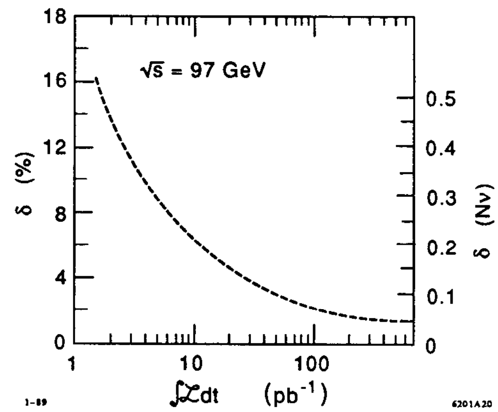


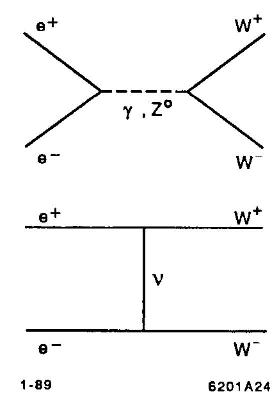
Fig. 13. Limits obtainable on the coupling of the Z^0 to neutral weakly-interacting particles by a dedicated experiment as a function of intergrated luminosity.

limited. At higher integrated luminosities systematic uncertainties become important, which eventually limit the precision in r to about 1% or so.

From Fig. 13 we see that a long dedicated run at SLC or LEP could get a precision in r of around 2%, which is about 1/10 of a neutrino family. A super Z^0 factory with two orders of magnitude more luminosity can improve the measurement precision only by a factor of two, to 1% in r, since at that level of precision systematic effects dominate.

5.6 Study of the Reaction $e^+e^- \to W^+W^-$.

This reaction proceeds by the following three diagrams:



A study of this reaction probes the γWW and the Z^0WW couplings, and is very sensitive to new physics beyond the Standard Model. Some examples are:

1. Sensitivity to an anomalous magnetic moment of the W (*i.e.*, evidence for internal structure of the W). An anomalous magnetic moment would change the differential cross section for this reaction from the Standard Model prediction. The size of the effect expected is shown in Fig. 14 for a 1 TeV collider.

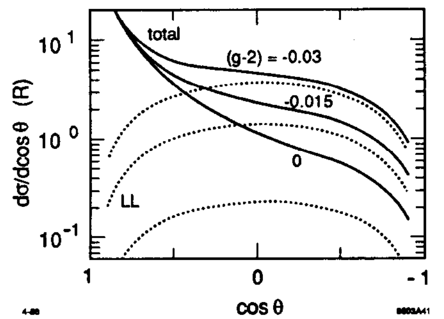


Fig. 14. Sensitivity of the $e^+e^- \to W^+W^-$ differential cross section to an anomalous magnetic moment of the W. The solid lines give the total cross section and the dashed curves show the cross section for production of longitudinal W's only.

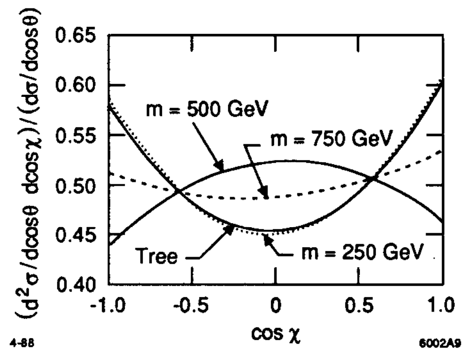


Fig. 15. Effect of a new generation of heavy fermions on the distribution of lepton angles χ from W decay, at $\sqrt{s}$ = 1 TeV *and $\cos\theta$ = 0. The heavy fermions are assumed to be degenerate.*

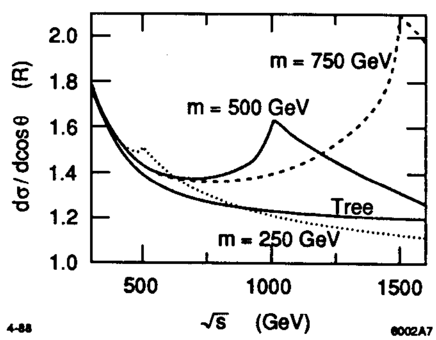


Fig. 16. Effect on the differential cross section for $e^+e^- \to W^+W^-$, at $\cos\theta = 0$, of an additional generation of heavy quarks and leptons.

2. Sensitivity to a 4th generation of quarks too heavy to be pair-produced (*i.e.*, $m_Q \geq 1/2E_{cm}$) comes from quark loop corrections to the above diagrams. The measurable effects are a distortion of the expected distribution in the lepton decay angles χ at a fixed energy, as shown for a 1 TeV collider in Fig. 15, or a change in the cross section at a fixed angle as a function of E_{cm}, as shown in Fig. 16.

3. Sensitivity to the existence of a heavy techni-ρ, ρ_T, beyond the mass reach of the collider. Such a particle would manifest itself as a very broad resonance in the $e^+e^- \to W^+W^-$ cross section, as shown in Fig. 17. The resonance is so broad that a measurable deviation occurs even if the mass of the resonance is considerably larger than the E_{cm} of the collider. Thus, a 1 TeV collider is sensitive to a ρ_T of mass up to 1-1/2 or 2 TeV.

The main motivation behind LEP II is to study this important reaction. The energy of 200 GeV was chosen to be just above threshold. However, the sensitivity to all of the new effects discussed above increases as $\beta \cdot (s/m_W^2)$ as the energy of the collider is increased ($s = E_{cm}^2$). This rapidly increasing sensitivity is shown in Fig. 18. An intermediate energy collider with 500 GeV in center-of-mass energy has 10 times the sensitivity of LEP II to deviations from the Standard Model.

Much of the discussion of this reaction both at this study as well as the SLAC study were concerned with the question of how well an actual detector would be able to reconstruct this reaction and how well the angular distribution could be measured. Backgrounds are not a big issue since this process is the dominant annihilation process with a large cross section. The $\gamma\gamma$ fusion processes can easily be separated. Since measurement of the angular distributions and asymmetries is important one must know the sign of the W's. The analysis therefore should look at one W decaying leptonically, $W \to e$ or $\mu + \nu$, with the other W decaying hadronically, $W \to q\bar{q} \to$ jets. A detailed Monte Carlo study of this process at 1 TeV was carried out in the SLAC study.[3] The following selection criteria were applied:

1. Select events with an isolated lepton (less than 2 GeV of energy in a 30° cone around an $e^\pm$ or $\mu^\pm$) opposite two hadronic jets.

2. Require that the effective mass of the two jets agree with the W mass to ± 10 GeV.

3. Reconstruct the missing ν using the constraints $m(\ell, \nu) = m(W)$ and $P_x = P_y = 0$ for the event. Resolve the quadratic ambiguity by choosing the smaller ν momentum.

4. Do a Lorentz transformation to $P_z = 0$ frame (where the Z axis is along the beam direction).

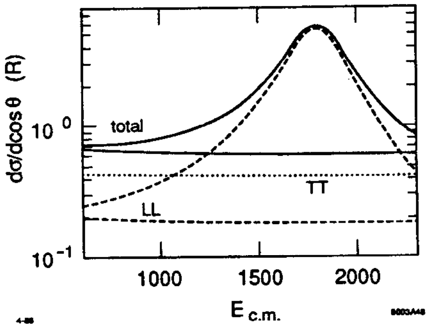


Fig. 17. Effect of a techni-rho resonance, in the minimal scheme of technicolor, on the differential W-pair cross sections at cosθ = −0.5. The dashed lines indicate the contributions of longitudinally polarized W bosons alone.

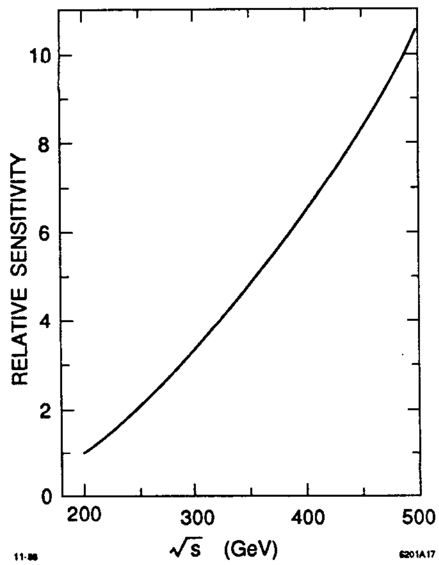


Fig. 18. Relative sensitivity to anomalies in $e^+e^- \to W^+W^-$ *cross sections as a function of the center-of-mass energy of the machine.*

These criteria yield a clean sample of $e^+e^- \to W^+W^-$ events. The effective mass distribution of the two hadron jets is shown in Fig. 19. The peak of the W mass is prominent with very little background. The angular distribution for the events passing these selection criteria are shown in Fig. 20. The Monte Carlo events were generated with the angular distribution given by the Standard Model, which is the solid curve on Fig. 20. The distribution of the reconstructed events, shown by the points with error bars, agrees well with the solid curve, indicating that the selection criteria and the reconstruction of the events do not significantly distort the angular distribution. The sensitivity to anomalous values of $g-2$ are also shown on the figure.

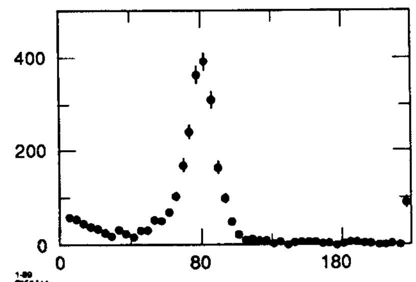


Fig. 19. Reconstructed W boson mass in $e^+e^- \to W^+W^-$ *events at* $\sqrt{s} = 1$ TeV.

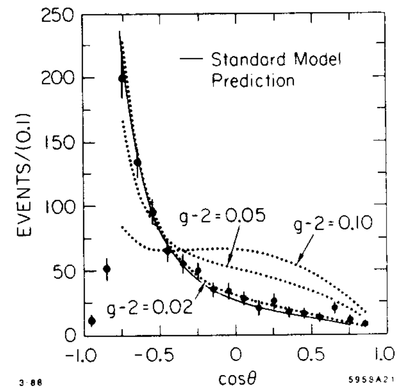


Fig. 20. Precision with which the production angle distribution can be measured for the W-pair process with integrated luminosity of 30 fb^{-1} *at* $\sqrt{s}$ = *1* TeV. *The effect of an anomalous magnetic moment of the W is also shown.*

6. SUMMARY AND CONCLUSIONS

The physics reach of the various energy e^+e^- colliders considered are summarized in Table VI. The luminosities for the high energy colliders have been assumed to be the minimum useful luminosities discussed in Section II. The numbers in Table VI are the masses up to which new particles of the various categories could be discovered if they existed, or the mass limits that could be set if they did not exist. It can be seen from this table that most of the new particles discussed can be discovered up to masses close to the kinematic limits of the colliders considered.

The study has led to the following general conclusions about new particle production at e^+e^- colliders:

1. The minimum desirable luminosity for high energy e^+e^- colliders is:

$$\mathcal{L} \cong 10^{33} \times E_{\rm cm}^2 \ {\rm TeV}^2 \ {\rm cm}^{-2} \ {\rm sec}^{-1} \quad .$$

2. Low energy e^+e^- colliders have given clear and unambiguous results on new particle searches. Life

Table VI. Physics reach of e^+e^- colliders.

E_{cm}(GeV) New $\mathcal{L}$ Particle	100 $\sim 10^{31}$ SLC, LEP	200 $\sim 10^{31}$ LEP II	100 10^{33}	500 2×10^{32} NEXT LINEAR COLLIDER	1 TeV 10^{33}	2 TeV 4×10^{33}
New Quarks	45	90	45	225	450	900
New Leptons	45	90	45	200	400	800
$Z^{0\prime}$	*	200	*	500^a	1000^a	2000^a
$W^{\pm\prime}$				250	500	1000
H^0	40	80	50	250	500	1000
$H^\pm$	45	90	45	200	400	800
Supersymmetry						
$\tilde{q}, \tilde{\ell}$	45	80	45	200	400	800
$\tilde{W}, \tilde{Z}(\tilde{\chi}^\pm,\ \tilde{\chi}^0)$	45	80	45	200	400	800
Technicolor						
$P_8^\pm$	45	80	45	200	400	800
Leptoquarks	45	80	45	200	400	800
ρ_T				500	1500	3000
Composite e^*, μ^*, q^*	100	200	100	500	1000	2000
Number of ν Generations	± 0.1		± 0.05			

(a) These limits refer only to direct observation of the excitation of a new resonance. See text.

gets harder at high energies due to new background processes and loss of precise knowledge of the total center-of-mass energy because of beamstrahlung. However, the detailed studies indicate that these problems are manageable.

3. The detectors for TeV e^+e^- colliders are a reasonable and buildable extrapolation of the present generation of SLC and LEP detectors now under construction.

4. Detailed Monte Carlo studies indicate that we can get clean signals, and in many cases do detailed studies, for the new particles that have been considered, up to masses close to the kinematic limits of the colliders.

5. From the point of view of new particle searches, a collider with $E_{cm} \sim 400$ to 500 GeV seems like a sensible and productive first step toward the eventual multi TeV e^+e^- collider.

6. Proof of feasibility and credible estimates of costs and time scales do not exist at this time for the TeV e^+e^- colliders. Therefore they are of a different level of reality from hadron colliders like the SSC, for which a detailed design with cost estimates and schedules exist.

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2. D. Shaile and P. M. Zerwas, *Proceedings of the La Thuile Study,* Volume II, p. 251.
3. C. Ahn *et al.,* SLAC–PUB–329, 1988, p. 138.