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PERSPECTIVES IN e^+e^- PHYSICS

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INTRODUCTION

Forty years ago this month, September 1946, there was a panel discussion at an APS meeting in New York with Alvarez, Lawrence, McMillan, and R.R. Wilson discussing "The Relative Advantages of Proton and Electron Accelerators."[1)] It is amusing to speculate whether there will be another meeting 40 years from now at which this question will be discussed again and, if so, whether that discussion will be as incomprehensible to us now as our discussion today would have been in 1946.

It is neither my assignment nor my intention today to discuss the relative advantages of proton and electron accelerators. However, I want to take a minute or two to point out the source of the strength of e^+e^- collisions. Today we tend to view all high energy collisions as one packet of particles colliding with another packet of particles as shown in Fig. 1a. Two of the particles, or partons, one from each bunch, either annihilate or scatter. The scattering process generally occurs at much lower momentum transfer than the annihilation process and thus generally has a much higher rate. In the case of e^+e^- collisions the picture simplifies to that shown in Fig 1b. There are basically three advantages to e^+e^- collisions:

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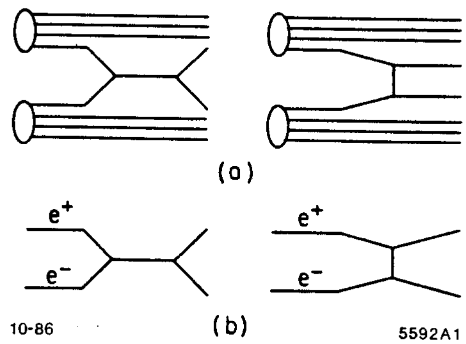

Figure 1. a) General form of high energy collisions. b) The case for electron-positron collisions.

1. Each packet consists of only one particle. Thus the nature of the interaction is well understood. (Two-photon interactions are exceptions, but in practice they have been easily separated from one photon annihilation.)
2. The center-of-mass energy is known. This allows the detailed study of s-channel resonances. (At very high energy future colliders it may be necessary to give up this advantage. We will come back to this issue in a few minutes.)
3. The incident particles are leptons, so the t-channel scattering (Bhabha scattering) is not bothersome because it cannot be confused with any other process.

In the remainder of this talk, I will briefly review the present and future e^+e^- facilities and then discuss the perspectives for future physics with e^+e^- collisions.

PRESENT AND FUTURE FACILITIES

Table 1 lists the existing e^+e^- colliding beam facilities. The "typical luminosity per day" are taken from a HEPAP report[2] and should be used only as a general guide as some days are more typical than others. The PETRA ring is now collecting its final data and will shut down in a couple of months. The VEPP-4M ring has not achieved sufficiently high luminosity to study Υ or B physics, except for a precision measurement of the Υ mass.[3] The other storage rings in Table 1 have several years of productive work ahead of them.

Table 1. Existing e^+e^- Colliders

Name	Laboratory	$E_{c.m.}$	Typical Luminosity per Day (pb^{-1})
SPEAR	SLAC	ψ	0.1
DORIS	DESY	Υ	1.0
VEPP-4M	Novosibirsk	Υ	–
CESR	Cornell	Υ	0.6
PEP	SLAC	29 GeV	1.0
PETRA	DESY	44 GeV	0.2

Table 2 lists the two e^+e^- storage rings now under construction which will operate below the Z mass. The luminosity per day is the design luminosity derated for normal beam lifetime and beam filling times.

Table 2. Future e^+e^- Colliders Operating below the Z Mass

Name	Laboratory	$E_{c.m.}$	Luminosity per Day (pb^{-1})	Starting Date
BEPC	IHEP (Beijing)	ψ	0.7	1988
TRISTAN	KEK	60 GeV	3.5	1986

Finally, Table 3 lists the future e^+e^- colliders which will operate at the Z mass or higher energies. The 27 km circumference LEP ring is probably the last of the e^+e^- storage rings. It will start physics operation in 1989 with four very sophisticated detectors. LEP has been optimized for 200 GeV operation with superconducting rf. Present plans call for it to reach this energy in the early to mid 1990s.

The SLC is the first linear e^+e^- collider. We believe that all future e^+e^- colliders will be linear. The reason for this belief comes from the scaling law for

Table 3. Future e^+e^- Colliders Operating at or above the Z Mass

Name	Laboratory	Type	$E_{c.m.}$	Luminosity ($cm^{-2}sec^{-2}$)	Date of 1st Physics
LEP	CERN	storage ring	Z	1.6×10^{31}	1989
			200 GeV	$10\ \times10^{31}$	1992?
SLC	SLAC	(quasi-) linear	Z	0.6×10^{31}	1987
?	?	linear collider	$\frac{1}{2}$-few TeV	$\geq10^{33}$	?

the cost of e^+e^- storage rings,[4)]

$$C = \alpha R + \beta \frac{E^4}{R}, \tag{1}$$

where C is the cost of the ring, R is the radius, and E is the energy. The first term, which is linear in R, represents the cost of tunnels, magnets, vacuum systems, etc., and the second term, which is inversely proportional to R, represents the cost of the rf system needed to replenish the energy lost to synchrotron radiation. Minimizing this equation with respect to cost gives that both the cost and radius of an e^+e^- storage ring scale with E^2. The cost of linear colliders, on the other hand, clearly scale linearly with E. At some point, then, they have to become more economical than storage rings. Although the technology of higher-energy linear colliders is not yet completely understood, we believe that the crossover point is passed with the next e^+e^- collider.

Table 4 gives some possible parameters for a very high-energy linear collider compared with the SLC.[5)] These parameters have not been optimized. The relatively small number of electrons per bunch is dictated by the desire to keep the beam energy spread down to 10%. If we were to allow a larger beam spread, then one could either achieve more luminosity for the same power or relax the requirement on the emittance. It is SLAC's goal to be ready to propose an "intermediate energy" linear collider (0.5 to 1.5 TeV) by the early 1990s.[5)]

As an aside, we can ask whether a B factory would make sense as a testing ground for linear colliders. The most stringent (and most interesting) test of a B

Table 4. Possible parameters for a 10 TeV c.m. linear collider compared to the parameters of the SLC. (from Ref. 5)

Collider	LLC			SLC
$E^\star$ (TeV)	10			0.1
$\mathcal{L}$ (cm^{-2}s^{-1})	10^{34}			6×10^{30}
$\sigma_{E^\star}/E^\star$ (%)	10			0.04
$\beta^\star$ (cm)	0.1			0.5
D	0.1			1.0
P (MW)	1	3	10	0.16
f (Hz)	3000	9000	30,000	180
N (e^+ or e^-)	4.1×10^8	4.1×10^8	4.1×10^8	5×10^{10}
ϵ_N (m)	4×10^{-9}	1.2×10^{-8}	4×10^{-8}	3×10^{-5}
σ_{r_o} (μm)	6.4×10^{-4}	1.1×10^{-3}	2×10^{-3}	1.5
σ_z (mm)	3.4×10^{-4}	1×10^{-3}	3.4×10^{-3}	1.5

factory would be its ability to measure CP violation in the $B\bar{B}$ system. According to present models, this measurement would require 10^7 to 10^8 $B\bar{B}$ events per year. At the $\Upsilon(4S)$ this translates into a luminosity of 10^{33} to 10^{34} cm^{-2}sec^{-1}. Amaldi and Coignet have suggested an e^+e^- linear collider for B physics that does not require any large advances in present technology and which would have a luminosity of 5×10^{32} cm^{-2}sec^{-1}.[6] By pushing on technology some, it might be possible to reach the luminosity level needed for studying CP violation. These ideas are being explored actively at the present time.[7]

PHYSICS PERSPECTIVES

The basic question that we seem to ask in e^+e^- physics is "What are the particles of nature?" This question can take several forms:

How many generations are there?

To try to answer this question we can search for new quarks and leptons and count the number of neutrinos.

What is the unifying group?

To try to answer this question we can again search for new quarks and leptons as well as new gauge bosons, supersymmetric particles, etc.

What spontaneously breaks gauge symmetry?

To try to answer this question we can search for Higgs bosons, technicolored particles, compositeness, etc. In the remainder of this talk, I will try to outline the perspectives for answering some of these questions.

WHERE TO LOOK

Figure 2 shows our present projection for the total e^+e^- cross section to hadronic states as a function of center-of-mass energy. It does not take any sophistication to figure out where a good place would be to start studying higher energy e^+e^- annihilations. Even if it were not for the advantage of studying the weak couplings of the Z, the factor of 1000 gain in cross section make the Z extraordinarily attractive. We will start here, but eventually be drawn to higher energies with LEP II and future linear colliders.

NEW PARTICLE PAIR PRODUCTION

The power of e^+e^- annihilation is that all fundamental particles which couple to the exchange gauge boson (photon or Z) and have a mass less than half the center-of-mass energy can be produced copiously, that is, typically with a few percent of the total cross section. What is new and exciting about the Z is that for the first time neutral particles will be pair produced.

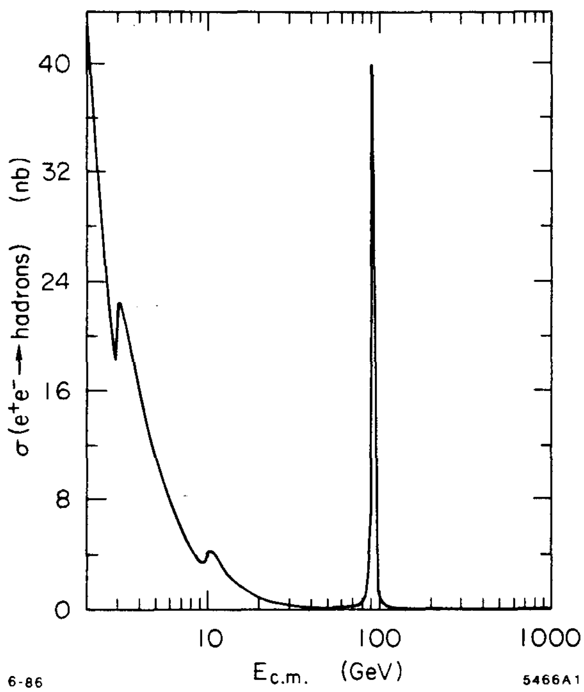

Figure 2. The expected total cross section for $e^+e^- \rightarrow$ hadrons.

There are a few exceptions to this general rule. One to be noted is that pairs of identical neutral scalars cannot be pair produced by Bose-Einstein statistics. Thus $e^+e^- \not\rightarrow H^0H^0$, but $e^+e^- \rightarrow H_1{}^0H_2{}^0$, two different Higgs scalars. We will return to this shortly.

A good example of new particle production is given by $Z \rightarrow t\bar{t}$. For a 40 GeV/c^2 mass top quark, the branching fraction for $Z \rightarrow t\bar{t}$ is 2.6%. At first thought, one might think that these events would be entirely background free in the absence of other new particle production. However, this is not the case due to backgrounds from the production of lighter quarks accompanied by multi-gluon emission. The uncertainties in this background from different Monte Carlo models is sufficient to make the identification of top by event shape parameters alone questionable.[8)]

A more reliable way of detecting top is to take advantage of the large number of leptons produced at high transverse momentum in the quark cascade decays from the top. Figure 3 shows the spectrum of lepton transverse momentum expected from Z decays with a 40 GeV/c^2 top mass.[9)] For 10,000 hadronic Z decays, there would be approximately 160 $t\bar{t}$ events with a lepton having greater than 3

GeV/c transverse momentum on top of a background of about 80 events from other hadronic Z decays. An mild aplanarity cut (A >0.02) reduces the background by about a factor of 2 while reducing the signal between 15 and 20%.

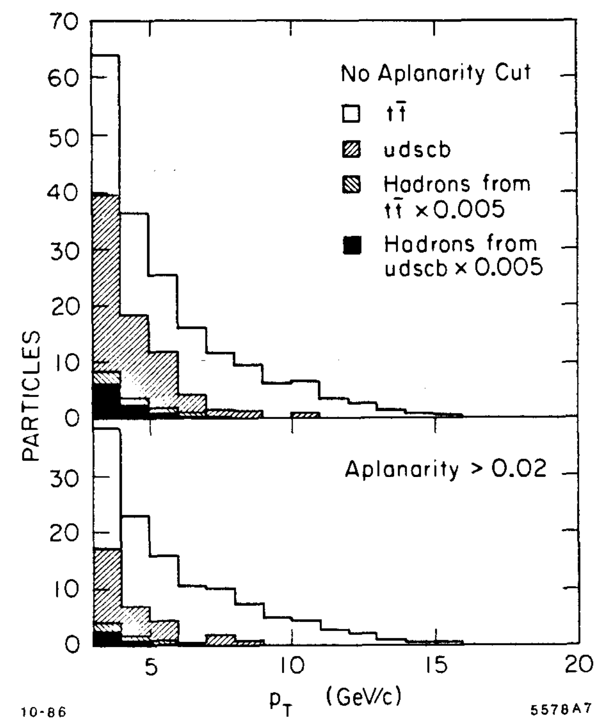

Figure 3. Lepton transverse momentum spectra from Z decays with a 40 GeV/c^2 top quark mass.

The top quark example sets the scale for the difficulty of finding new particles which are pair produced in Z decays. Other examples would be comparable or somewhat more difficult. Of course, if more than one new heavy particle is being produced, it will be considerably more difficult to tell them apart.

The Number of Light Neutrinos

One of the most interesting aspects of studying Z decay is that for the first time we will be able to count the number of generations which have light neutrinos ("light" meaning less than half the Z mass).

There are three independent ways that we will be able to do this measurement:

1. Each species of neutrino contributes about 6% to the Z width. More precisely,

$$\Delta\Gamma_Z = 176\beta(\frac{3+\beta^2}{4})\ \mathrm{MeV/c^2}. \tag{2}$$

We can directly measure the Z width by scanning in beam energy. A data sample of 40,000 Z decays allows a statistical accuracy of about 40 GeV/c^2. Systematic errors will be comparable. If an excess over the expected width is found, a measurement of the partial width to visible particles will allow a determination whether the excess width is due to neutrinos or visible decays.

2. A check on the direct width measurement is a measurement of the cross section for muon pairs on the Z peak,

$$\sigma_{\mu\mu} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_Z^2}. \tag{3}$$

Both Γ_{ee} and $\Gamma_{\mu\mu}$ are completely determined in the standard model,

$$\Gamma_{ee} = \Gamma_{\mu\mu} = \frac{G_F m_Z^3 (v^2 + a^2)}{24\sqrt{2}\pi}, \tag{4}$$

leaving only Γ_Z to be determined from the measurement. A 40 MeV/c^2 measurement requires a 3% measurement of $\sigma_{\mu\mu}$, close to the systematic limit from uncertainties in luminosity measurements and radiative corrections. Statistically, this measurement also requires about 40,000 Z decays.

3. The final technique is to run at a center-of-mass energy above the Z and observe $e^+e^- \to \gamma Z \to \gamma\nu\bar{\nu}$.[10] The signal is a photon with transverse momentum above some minimum and no other visible particles. The ASP and MAC experiments at PEP have already shown that this type of experiment can be done cleanly.[11] The optimum center-of-mass energy to run this experiment and to optimize both rate and control of systematic errors appears to be about 4 GeV above the Z peak.[12] (See Fig. 4.) At this energy, requiring the photon to have an energy greater than 1 GeV and to be emitted at an angle greater than 30° from the beam, the cross section is 0.15 nb. For the same precision as in the other two techniques, $\Delta N_\nu = \frac{1}{4}$, we also require the equivalent luminosity corresponding to 40,000 produced Z decays (on the Z peak).

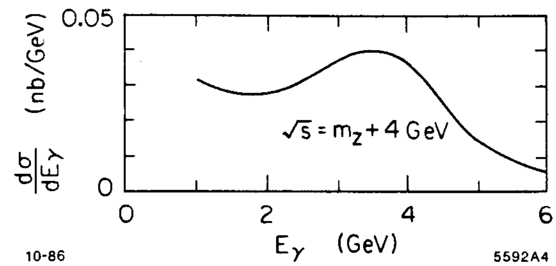

Figure 4. The photon energy spectrum for $e^+e^- \to \gamma\nu\bar{\nu}$ for conditions described in the text.

POLARIZATION

The SLC has the capability of producing and accelerating longitudinally polarized electron beams. This facility is scheduled to be installed in the summer of 1988. The power of having longitudinally polarized beams can be seen by a few simple observations:

1. Since the weak interactions are spin 1, the Z spin must be in the same direction as the electron spin.

2. The Z coupling to left and right handed electrons is slightly different, leading to a net Z polarization, even in the absence of polarized electrons:

$$\begin{aligned} v_e &= -1 + 4\sin^2\theta_w \approx -0.10, \\ a_e &= -1, \\ g_L &\equiv (v_e + a_e) \approx -1.10, \\ g_R &\equiv (v_e - a_e) \approx \ 0.90, \end{aligned} \tag{5}$$

which implies that the natural Z polarization, $\mathcal{P}_e$ is

$$\mathcal{P}_e = \frac{2v_e a_e}{v_e^2 + a_e^2} \approx 0.20. \tag{6}$$

3. In Z decay, say to muon pairs, this process is reversed. Muons are emitted with their spins aligned along the Z spin direction. Since the Z is naturally

polarized and there is a difference in the right and left handed couplings to muons, a front-back asymmetry appears:

$$A_{FB} = \frac{3}{4}\mathcal{P}_e\mathcal{P}_\mu = \frac{3v_e a_e v_\mu a_\mu}{(v_e^2 + a_e^2)(v_\mu^2 + a_\mu^2)} \approx 0.03. \tag{7}$$

A_{FB} is sensitive to $\sin^2\theta_W$, but it is small and a precision measurement requires enormous statistics. With longitudinally polarized beams, we can increase and control the Z polarization, $\mathcal{P}_e$. More important, we can also look for a cross section asymmetry for left and right handed electrons:

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{P}_e = \frac{2v_e a_e}{v_e^2 + a_e^2} \approx 0.20. \tag{8}$$

A_{LR} is more sensitive to $\sin^2\theta_W$ than A_{FB} and all Z decays can be used to measure it, not just $Z \to \mu\mu$ decays. With 45% polarization and the experimental acceptance appropriate for the Mark II detector, the statistical gain in using polarization is almost two orders of magnitude. Figure 5 shows the precision which can be obtained.

As an application of how this type of measurement could have a bearing on particle content, consider the case of additional Z mesons. Many GUT models allow or require extra Z bosons. One popular example from superstrings is that

$$E_8 \times E_8 \to E_6 \to SU(3) \times SU(2) \times [U(1)]^{2 \text{ or } 3}, \tag{9}$$

yielding one or two extra Z bosons.[13,14] For example, consider the extra Z boson "Z_η" discussed in Ref. 13. It will mix with the normal Z and change the normal Z properties, including A_{LR}. Figure 6 shows the currently allowed region for a new Z boson as a function of its mass and mixing angle. Figure 7 shows the sensitivity of the mixing angle to a measurement of A_{LR}. It is clear that there is a sizable region in which indications for a new Z could be found by this measurement.

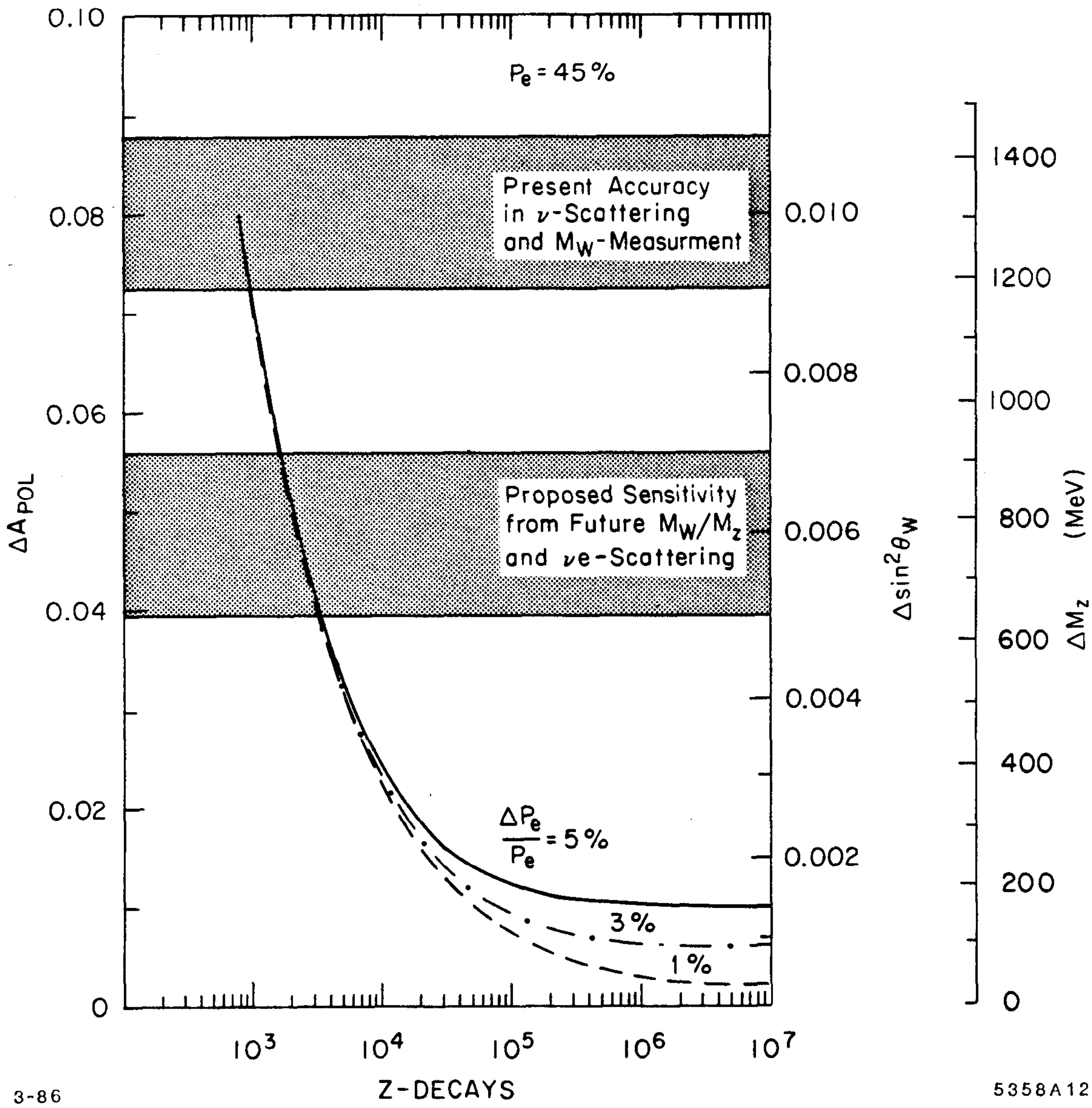

Figure 5. Level of precision which can be obtained in A_{LR} and, equivalently, in $\sin^2\theta_W$ or m_Z as a function of the number of Z decays and the error with which the polarization is measured.

Higgs Bosons

The standard model is incomplete without some mechanism for spontaneously breaking gauge symmetry and giving mass to the W, Z, and fermions. In the standard model this is done by inserting a complex doublet of Higgs fields into the Lagrangian by hand. This is the minimal scheme, but it is arbitrary and without any experimental basis. Other models will also work. It is clearly imperative to study this sector experimentally.[15)]

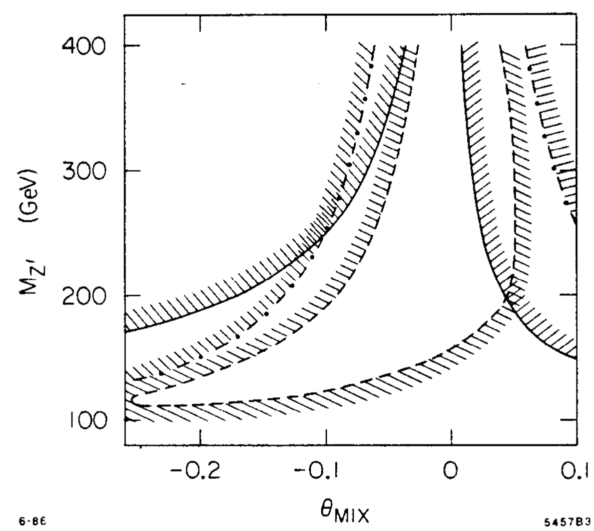

Figure 6. Allowed region for a new Z boson. See Ref. 13 for a discussion of the different limits.

The non-minimal case is the easier to find in e^+e^- annihilations. Many models, including supersymmetry, require a more complex Higgs sector. In all of these cases, pairs of Higgs bosons are produced copiously.[16)] For example, two Higgs doublets will give five physical Higgs particles: $H^0{}_1$, $H^0{}_2$, $H^0{}_3$, H^+, and H^-, where $H^0{}_3$ is a pseudoscalar and the others are scalars. In this case, the branching fractions for the Z to decay into pairs of Higgs bosons are

$$\begin{aligned} B(Z \to H^+H^-) &= 0.01\beta^3, \\ B(Z \to H_1^0 H_3^0) &= 0.033\beta^3 \sin^2\chi, \\ B(Z \to H_2^0 H_3^0) &= 0.033\beta^3 \cos^2\chi, \end{aligned} \tag{10}$$

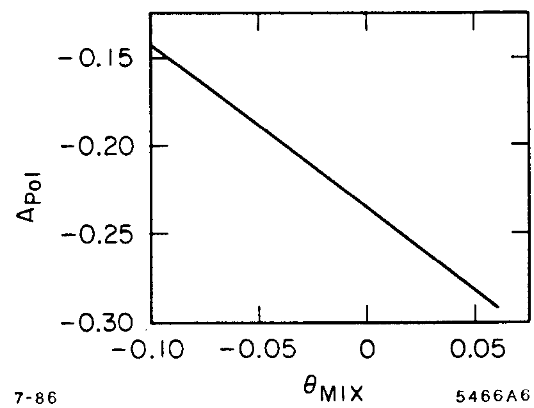

Figure 7. The change in A_{LR} due to a new Z boson with mixing angle Θ_{mix}.

where χ is a mixing angle. Similar fractions of events are produced at higher energies. These are sizeable branching fractions, comparable to the $Z \rightarrow t\bar{t}$ case discussed previously.

The case of the minimal Higgs boson is harder because it cannot be pair produced. The basic reaction for producing this Higgs boson in e^+e^- annihilation is

$$e^+e^- \rightarrow Z \rightarrow ZH^0 \rightarrow \ell^+\ell^- H^0. \qquad (11)$$

In general the H^0 is identified by a peak in the recoil mass spectrum to the two leptons. In order to obtain a reasonable cross section for reaction (11), one of the two Z's should be real.

For low-mass Higgs bosons, the first Z will be real — that is, the measurement will be done on the Z peak. Figure 8 shows the branching fraction for this process. To identify a 10 GeV/c^2 Higgs boson, about 100,000 Z decays will be needed; for a 30 GeV/c^2 Higgs boson, about an order of magnitude more are required.

For higher mass Higgs bosons, it is necessary to go to higher center-of-mass energies. Figure 9 shows the cross section for reaction (11) as a function of energy.[17] The 50 GeV/c^2 curve illustrates the statement that one of Z's should be real. There is peak at the Z pole, then a deep dip in the region in which both Z's are virtual, and finally a sharp rise at around 150 GeV, where the second Z becomes real. The cross section in this last region is small, but not impossible at LEP II. With a

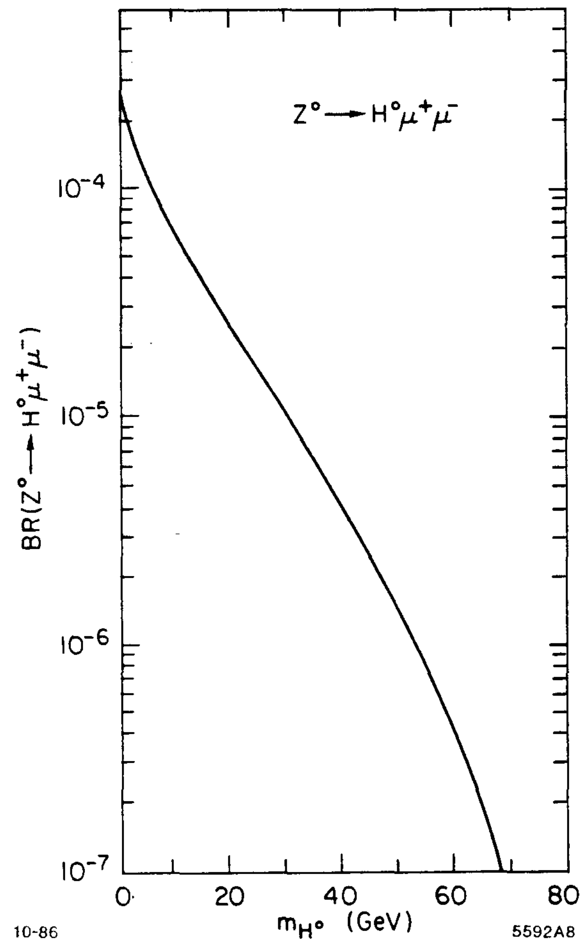

Figure 8. The branching fraction for $Z \rightarrow H^0\mu^+\mu^-$ as a function of the Higgs boson mass.

reasonable derating factor, it corresponds to about 3 events per month at LEP II design luminosity.

Finally, for very high Higgs boson masses, the optimum process becomes Higgs boson production by WW fusion, $Z \rightarrow H^0\nu\bar{\nu}$.[18–20] The Higgs boson will decay to W pairs, and thus $e^+e^- \rightarrow W^+W^-$ is the major background. Dawson and Rosner[19] conclude that the backgrounds are manageable if $m_H \leq 0.4\sqrt{s}$. The cross sections and background limits are shown in Fig. 10.

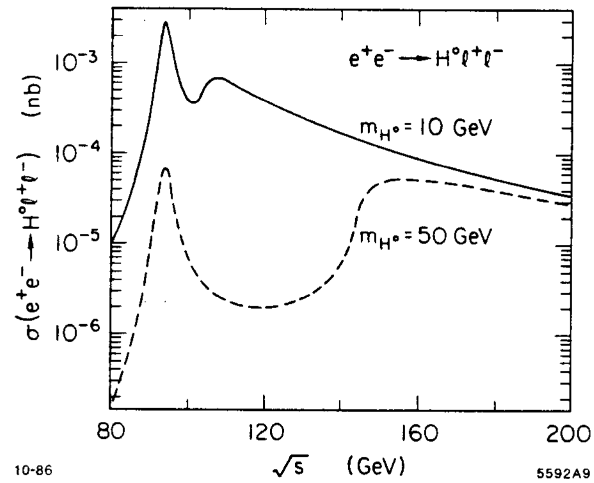

Figure 9. Cross sections for $e^+e^- \rightarrow H\ell^+\ell^-$ as a function of center-of-mass energy for two Higgs boson masses. (From Ref. 17.)

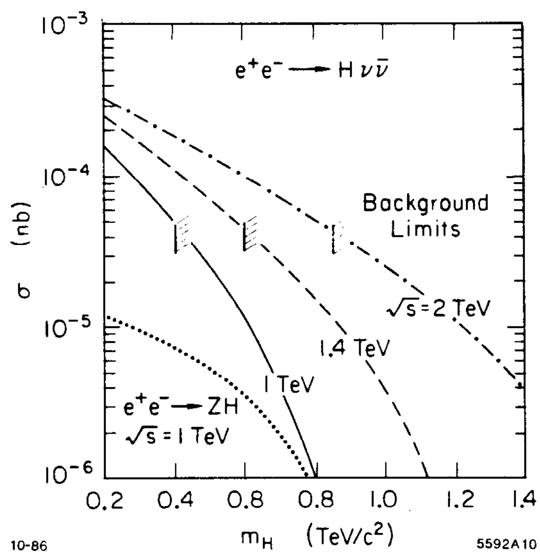

Figure 10. Cross sections and background limits for $e^+e^- \rightarrow H\nu\bar{\nu}$ from Ref. 19.

Conclusions

It is clear that the study of e^+e^- collisions has the power to probe what lies beyond the standard model. We are now designing and building the colliders which will take us into new energy regions. If nature cooperates, we will learn a great deal.

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