NEW PARTICLES NEAR THE Z^o

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We review the feasibility of observing new particles in e^+e^- annihilation at energies near the Z^o. In particular, we consider the signature, rates, and backgrounds in the production of technipions, scalar leptons, and heavy leptons. We also discuss the possibility of observing composite substructure in leptons. Most of what follows arose out of discussions within the lepton-lepton collider group and from the contributed review papers of K. D. Lane[1] and I. Hinchliffe.[2]

In order to evaluate the physics possibilities, we have assumed the existence of an e^+e^- collider with an average luminosity of 2×10^{31} cm^{-2} sec^{-1} and a maximum energy of $(s)^{1/2} = 120$ GeV which operates for 2×10^7 sec/year. Further we use $\sin^2\theta_W = 0.22$ yielding $M_Z = 93$ GeV, $\Gamma_Z = 2.92$ GeV, and $M_W = 86$ GeV.

Technicolor Particles

Technicolor[1,3,4] represents a non-abelian symmetry, analogous to the SU(3) of color which gives rise to a new strong interaction on the scale $\Lambda_{TC} \sim 1$ TeV. Within technicolor models the electroweak SU(2) X U(1) group is spontaneously broken to the electromagnetic U(1) via the strong interaction,[4,5] thus replacing the standard Higgs mechanism. In fact, the standard Higgs H^o is replaced by (a minimum of) four observable 0^- Goldstone bosons p^+, p^-, p^o and $\bar{p}^o$. These are the technipions (hyperpions) and are expected to have masses in the range 5-40 GeV.[6] The p^+, p^-, p^o and $\bar{p}^o$ couple weakly to matter and are expected to decay predominantly into heavy quarks and leptons. Within the model discussed by K. D. Lane[4] the branching fractions for hyperpion decays are given in Table I as a function of hyperpion mass.[7]

	Branching Ratio (%)			
Decay Mode	M = 10 GeV	20 GeV	30 GeV	40 GeV
$p^+ \rightarrow t\bar{b}$			55 (82)	86
$c\bar{b}$	84	87	36 (13)	9
$t\bar{s}$			2 (3)	3
$c\bar{s}$	5	4	2 (3)	.3
$\tau^+ \nu$	11	8	4 (1)	1

Table I. Expected branching ratios for $p^\pm$ decays from Ref. 4 with $M_t = 25$ GeV. The numbers in parentheses are for $M_t = 20$ GeV.

The most useful signature of $p^\pm$ decay in e^+e^- annihilation is $p \rightarrow \tau\nu$ together with $p \rightarrow q\bar{q}' \rightarrow 2$ jets. Here one looks for a single lepton from $\tau \rightarrow \mu$ or e roughly back-to-back with a hadron jet. From Table I we expect this to occur ~ 14-25% of the time when $M_p\pm < M_t$ and ~ 2-7% of the time when $M_p\pm > M_t$. Further, the $p^\pm$ angular distribution ~ $\sin^2\theta$ and peaks at 90°.

Several PEP and PETRA experiments have searched for charged technipions with this signature.[8] In the continuum the $p^\pm$ production cross section is given by:

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow p^+p^-) = 0.25 \cdot \sigma(e^+e^- \rightarrow \mu^+\mu^-) \cdot \beta^3$$
$$= \frac{21.9 \text{ nb}}{s} \beta^3,$$

where $\beta = (1 - 4M_p^2/E^2_{cm})^{1/2}$ is the $p^\pm$ velocity. The results of these experiments are shown in Fig. 1. They are only sensitive to small $p^\pm$ masses and relatively large $p^\pm \rightarrow \tau\nu$ branching fractions. For the range $6\% < Br(p \rightarrow \tau\nu) < 90\%$ these experiments exclude, at the 90% confidence level, $p^\pm$ masses from 4-11 GeV/c^2.

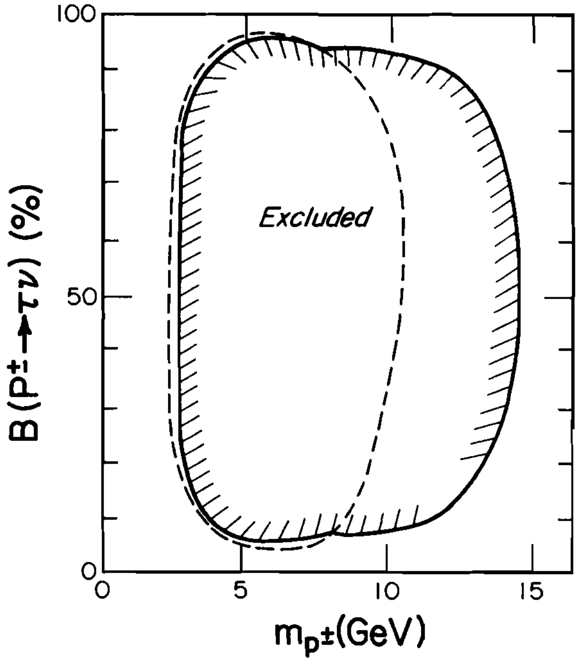


Figure 1. 90% Confidence Limits on Charged Technipion Production from Jade (-) and Mark II (--)

The crucial test for technicolor will occur at Z^o energies. Here, if the technipions exist (and $M_p\pm < 1/2\ M_Z o$) they will be produced with the cross section

$$\sigma(e^+e^- \rightarrow Z^o \rightarrow p^+p^-) = 0.31 \cdot \beta^3 \cdot \sigma(e^+e^- \rightarrow Z^o \rightarrow \mu^+\mu^-)$$
$$= 428 \text{ pb} \cdot \beta^3 \text{ at the } Z^o \text{ peak.}$$

This can be compared with the continuum production

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow p^+p^-) = \frac{21.9 \text{ nb}}{s} \cdot \beta^3$$
$$= 2.5 \text{ pb } \beta^3 \quad \text{at the } Z^o \text{ peak.}$$

The expected rates are shown below

		Events/Year			
$M_{p^\pm}$	$\sigma(p^+p^-)$	p^+p^-	$\tau\nu$ + hadrons	(e or μ + hadrons) * eff	$\sigma \cdot B$
10 GeV	400 pb	160 K	31.0 K	5480	27.4 pb
20 GeV	315 pb	126 K	18.5 K	3250	16.2 pb
30 GeV	191 pb	76 K	5.9 K (1.5 K)	1030 (260)	5.1 pb (.7 pb)
40 GeV	57 pb	23 K	450	75	.4 pb

where $\sigma \cdot B$ is the cross section times the branching fraction. Note that the rate in the next to last column includes a 50% efficiency factor for detecting leptons. The numbers in parentheses are for M_t = 20 GeV instead of M_t = 25 GeV.

The branching fractions given in Table I are both model dependent and sensitive to phase space i.e. quark masses. Thus the predictions above only set the scale of the effect in relation to the various background processes. The predominant backgrounds come from $\tau\tau$ production, 2γ production and heavy quark ($t\bar{t}$) production.

The $\tau\tau$ background consists of $\tau \rightarrow e$ or μ plus $\tau \rightarrow$ hadrons. However the multiplicity of $\tau \rightarrow$ hadrons is always less than 5. If we require at least 6 charged tracks from the hadronic decay then $\sigma \cdot B$ for this process is at most $\sigma \cdot B = 45.5$ nb x .03 x .0001 x 2 $\underline{=}$ .05 pb. Further, since the p^+ decays primarily to $t\bar{b}$ and $c\bar{b}$, the signal has high multiplicity and many kaons in the hadronic final state. The average charged multiplicity is ~6 in B decays and ~3 in D decays. Thus we estimate that a multiplicity cut of 6 loses at most 10% of the signal. Notice that new heavy leptons will contribute a background, depending on their mass, but will have a different angular distribution. We also note that an invariant mass cut on the hadronic decays distinguishes τ decays from p^+ decays. Thus the $\tau\bar{\tau}$ background can be handled quite easily.

In order to remove the 2γ background we require that the missing momentum vector point into our detector, that the hadrons contain at least 30% of the CM energy, and that the lepton be at a large angle with respect to the beam pipe. These cuts should reduce the 2γ cross section to < .1 pb while not losing more than 20% of the signal.

The ($t\bar{t}$) background can be handled with kinematic cuts. We require that the lepton not be within 60° of another particle. This is being studied by Monte Carlo. We expect this source of background to be <.1 pb.

Thus it appears that this experiment is feasible up to hyperpion masses of 40 GeV/c^2.

We also note that these events will have a striking feature with many kaons and leptons due to the heavy quark couplings of the $p^\pm$. Further, with a reasonable detector with 1° - 2° angular resolution on jets and a hadron calorimeter with $\delta E/E = .4/\sqrt{E}$ it should be possible to find the mass of the $p^\pm$ to 10%.

Finally we note that if the standard Higgs H^o is found by the methods described by M. Goldberg[9] and S. Olsen[10] then technicolor is ruled out.[4]

Supersymmetric Particles

Supersymmetry[2,11] is a conjectured fundamental correspondence between fermions and bosons. In this framework each spin J particle has a spin J ± 1/2 partner. The partners of the electron and muon are the spin 0 selectron $\tilde{e}$ and smuon $\tilde{\mu}$. These are the lightest scalars in the theory. The production and decay mechanisms are shown in Fig. 2 where the photino($\tilde{\gamma}$), the spin 1/2 partner of the photon, is a neutrino-like carrier of some conserved quantum number associated with supersymmetry. For each model the couplings of the supersymmetric particles are defined but, unfortunately, the mass scale is not.

After being pair produced in e^+e^- interactions the sleptons decay quickly to a photino and a lepton. Thus the observable final states consist of only a lepton pair or its decay products (since the $\tilde{\gamma}$ escapes undetected). The event signature is

$$e^+e^- \rightarrow 2 \text{ Acoplanar leptons + missing energy}$$

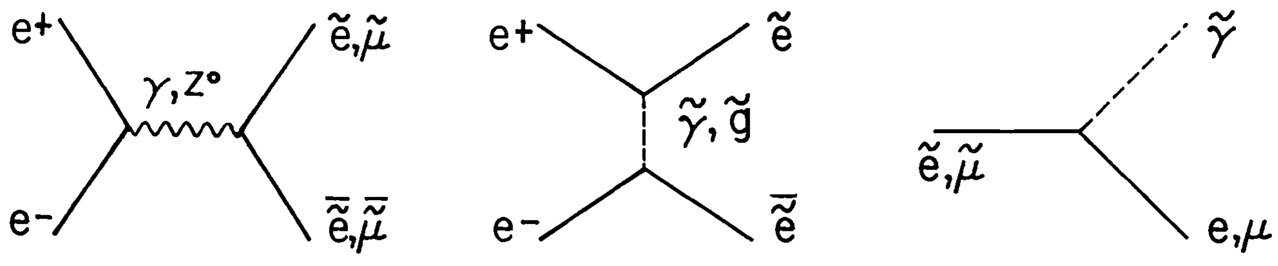
with an angular distribution $d\sigma/d\Omega \sim \sin^2\theta$.

Various PETRA experiments have searched for scalar leptons with this signature. In the continuum the slepton production cross section is

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow \tilde{\ell}\,\bar{\tilde{\ell}}) = (\tfrac{1}{4}-\tfrac{1}{2})\cdot\beta^3\cdot\sigma\,(e^+e^- \rightarrow \mu^+\mu^-)$$

The results of these searches[12] are shown below

Experiment	Mass $\tilde{e}$	Mass $\tilde{\mu}$
Jade	> 16 GeV	-
Mark J	-	> 15 GeV
Pluto	> 13 GeV	-
Cello	> 16.8 GeV	> 16 GeV
Tasso	> 16.6 GeV	> 16.4 GeV



Production

Decay

Figure 2. Production and decay diagrams of scalar leptons. $\tilde{\gamma}$ is the photino, the spin 1/2 partner of the photon; $\tilde{g}$ is the gluino, the spin 1/2 partner of the gluon.

The next interesting place to search for scalar leptons is at the Z^o. At the Z^o

$$\sigma(e^+e^- \rightarrow Z^o \rightarrow \tilde{\ell}\bar{\tilde{\ell}}) = .5\beta^3 \cdot \sigma(e^+e^- \rightarrow Z^o \rightarrow \mu^+\mu^-)$$

or

$$\sigma(e^+e^- \rightarrow Z^o \rightarrow \tilde{\ell}\bar{\tilde{\ell}}) = 750 \text{ pb} \cdot \beta^3 \text{ at the } Z^o \text{ peak.}$$

The estimated rates are

$M_{\tilde{\ell}}$	$\sigma(e^+e^- \rightarrow Z^o \rightarrow \tilde{\ell}\bar{\tilde{\ell}})$	$\tilde{\ell}\bar{\tilde{\ell}}$
10 GeV	700 pb	280 K
20 GeV	670 pb	270 K
30 GeV	350 pb	140 K
40 GeV	100 pb	40 K

The possible background sources include the QED reaction $e^+e^- \rightarrow e^+e^-\gamma$ with one undetected photon, the 2γ process $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ where the scattered electrons are in the beam pipe and $\tau\tau$ production with both τ's decaying leptonically.

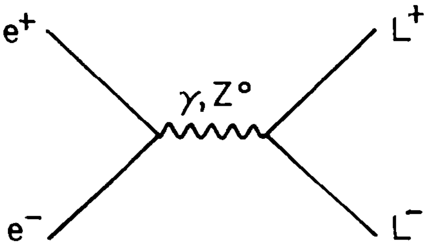
The radiative bhabha process $e^+e^- \rightarrow e^+e^-\gamma$ is clearly only a background to the e^+e^- final state. It can be reduced, as can the 2γ process, by requiring that the missing momentum vector lie in the acceptance of the detector. The 2γ background can be further reduced by requiring a minimum angle between observed leptons. In both these cases the detector should have large solid angle coverage for e's and γ's.

The $\gamma\gamma$ background arises when $\tau\tau \rightarrow \ell\bar{\ell}X$ where ℓ = e or μ. The production cross-section for this process is $\sigma(e^+e^- \rightarrow Z^o \rightarrow \tau\tau) = 1.4$ nb. We find this background contributes $\sigma \cdot B \simeq 50$ pb. However at Z^o energies these leptons are almost back-to-back. Thus, if the slepton mass is greater than 10 GeV, as indicated by the PETRA experiments, a collinearity cut should reduce this background to the acceptable level of < 1-10 pb. We have a further handle on this background by comparing $\tau\tau \rightarrow \ell 3\pi$ and $\tau\tau \rightarrow e\mu$ with the $\ell\bar{\ell}$ signal.

Overall, if scalar leptons exist with mass between 10 GeV $< M_{\tilde{\ell}} < 1/2\, M_{Z^o}$ they will be discovered at the Z^o.

Heavy Lepton Production

In e^+e^- interactions heavy leptons should be produced in pairs like the muon and τ lepton. The rates are calculable from the annihilation diagram:



The leptonic branching fraction of the heavy lepton, neglecting phase space, is given by

$$Br(L \rightarrow e\nu\nu) = \frac{1}{N_L + 3N_q}$$

where N_L is the number of lepton doublets and N_q is the number of quark doublets open for heavy lepton decay.

The clearest indication of heavy lepton production comes from observing their leptonic decays. In particular

$$e^+e^- \to L^+L^- \to \mu^\pm e^\mp + \text{missing energy.}$$

The signature is then an opposite sign μe pair plus missing energy. This was the signature used by Perl et al.[13] to discover the τ lepton.

Various experiments at PEP and PETRA have searched for heavy leptons beyond the τ.[14] However, due to the small cross-section in the continuum, these experiments have relied on distinctive decay modes involving at least one lepton. No evidence was found and the resulting mass limits are listed below:

Experiment	Mass L	Signature
Mark J	> 16.0 GeV	μ vs hadrons
Pluto	> 14.5 GeV	μ vs hadrons
Tasso	> 15.5 GeV	single charged track vs hadrons
Mac	> 14.0 GeV	acollinear μe
Mark II	> 13.8 GeV	acollinear μe

If the mass of the next lepton is less than half the mass of the Z^o then heavy leptons will be pair produced at the Z^o. The branching fraction from the Z^o is given by:

$$Br(Z^o \to L^+L^-) = \beta \cdot Br(Z^o \to \mu^+\mu^-) = 0.03\beta$$

Thus with $Br(L \to \ell\nu\nu) \approx .08$ the estimated rates are:

M_L	$\sigma(e^+e^- \to Z^o \to L^+L^-)$	L^+L^-/yr	μe/yr	σ·B
20 GeV	1.2 nb	480K	3.1K	7.9 pb
30 GeV	1.0 nb	400K	2.6K	6.7 pb
40 GeV	0.7 nb	289K	1.8K	4.5 pb

The main background to the μe signature comes from ττ production at the Z^o and the 2γ processes $e^+e^- \to ee\mu\mu$ and $e^+e^- \to ee\tau\tau$. The ττ background is large since $Br(\tau \to \ell\nu\nu) \approx .18$. Thus the ττ contribution to μe is ~5 times larger than the L^+L^- contribution or 18K events/year. However, if the heavy lepton mass, M_L, is greater than 10 GeV the collinearity angle between the μ and e can be used to separate different masses. In addition, Vermaseren[15] suggests using the variable $p_t^\mp$ where $p_t^\mp$ is the minimum of the transverse momentum of the e(μ) with respect to the μ(e) direction. This quantity measures the transverse momentum of the heavy lepton decay and has a kinematic limit determined by M_L. Thus if the number of heavy leptons between the τ mass and the $M_{Z^o}/2$ is not too large, with several thousand events, one can obtain an approximate measure of the heavy lepton mass.

To eliminate the QED 2γ process we require that the missing momentum vector point into the acceptance of the detector. This should suppress the 2γ background to < .5 pb. Further the background can be estimated by comparing $e^+\mu^+$, $e^-\mu^-$ with $e^\pm\mu^\mp$ events.

Composite Structure of Leptons

The standard SU(2) x U(1) theory of weak interactions yields unambiguous predictions for purely electromagnetic processes. These predictions are based on the premise that leptons are elementary point-like objects. Deviations from these predictions, at small distances, could occur due to strong interaction contributions to the photon propagator or due to a composite structure of leptons.

The contributions to the photon propagator, in bhabha scattering, only depend on the mass of the virtual photon and are usually parametrized by a form factor[16]

$$F_\pm(q^2) = 1 \mp \frac{q^2}{q^2 - \Lambda_\pm^2}$$

where $\Lambda_\pm$ is a parameter which characterizes the mass of the exchanged system i.e.:

$$\frac{1}{q^2} \to \frac{1}{q^2} \mp \frac{1}{q^2 - \Lambda_\pm^2}$$

Experimentally one looks for deviations from the electro-weak predictions to place limits on $\Lambda_\pm$.

Various PETRA experiments have searched for such deviations.[17] The 95% confidence level lower limits for $\Lambda_\pm$ in bhabha scattering are listed below

Experiment	√s	Λ_+	Λ_-
Cello	36 GeV	83 GeV	155 GeV
Jade	36 GeV	112 GeV	106 GeV
Mark J	36 GeV	128 GeV	161 GeV
Pluto	31 GeV	80 GeV	234 GeV
Tasso	36 GeV	140 GeV	296 GeV

These data show that the standard model is valid down to distances ~ 10^{-16} cm.

At Z^o energies one expects to probe down to distances ~ 10^{-17} cm, and hence place limits of $\Lambda_\pm \gtrsim .5$ TeV.

The idea that quarks and leptons are composite has received considerable attention.[18] Specific models expect such effects to occur at the scale of 1-100 TeV[18,19]. Experimentally the lower limit to the scale is ~ 30 GeV from electron (g-2) measurements.

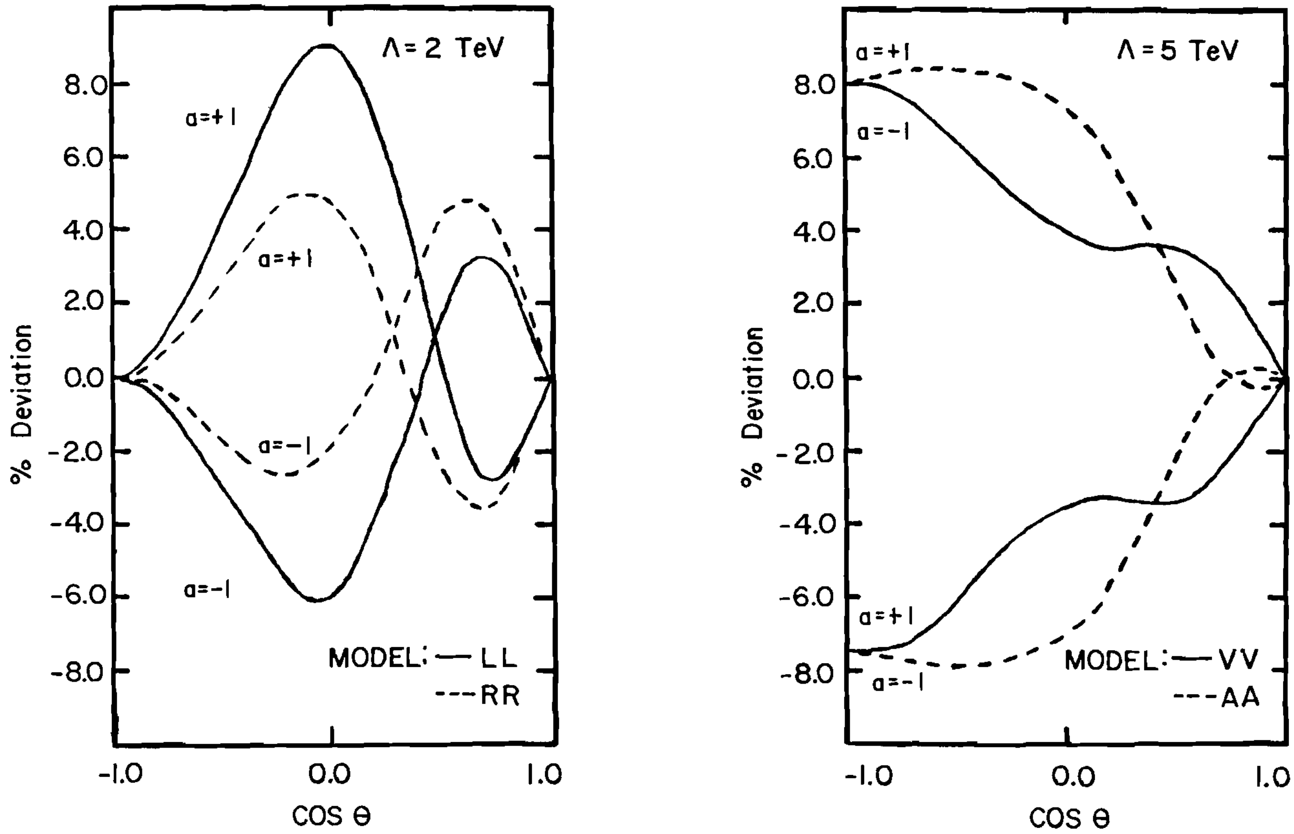


Figure 3. Deviation from the bhabha cross section at $\sqrt{s}$ = 100 GeV due to the composite structure of the electron. The models shown include left-left (LL), right-right (RR), vector-vector (VV) and axial vector-axial vector (AA) couplings.[20] a is the overall sign of the coupling (a = ±1); Λ sets the scale.

In a composite model for the electron an extra term contributes to the bhabha amplitude. This term comes from an effective 4-fermi interaction and contributes to the cross-section interference terms of order $s/\alpha\Lambda^2$ and $t/\alpha\Lambda^2$,[20,21] where Λ sets the scale of composite electron structure. Effects due to this structure will become observable when

$$\frac{s}{\alpha\Lambda^2} \sim 1.$$

Thus at $\sqrt{s}$ = 100 GeV it becomes possible to test compositeness down to distances ~ 10^{-18} cm.

Figure 3 shows the deviation from the electroweak theory in bhabha scattering at $\sqrt{s}$ = 100 GeV due to composite structure of electrons.[20] Here LL denotes a model with left-left coupling, VV denotes vector-vector coupling, etc. Notice that for Λ = 2-5 TeV the expected deviations from the electroweak theory peak at 5-8%. Also notice large effects near 90°.

The differential cross section for bhabha scattering, including effects from compositeness, is $d\sigma/d(\cos\theta) \simeq 20$ pb when $\cos\theta < .2$ i.e., away from the forward peak. Thus, within the angular range $\delta(\cos\theta) = .3$ (when $\cos\theta < .2$) the cross section is ~ 6 pb. An experiment which runs for 8×10^6 sec (4-5 months of data taking) would obtain ~ 950 events per $\delta(\cos\theta)$ bin. This would result in a 3% measurement per point, roughly comparable to the expected systematic error. Thus, composite effects in the Λ = 2-5 TeV region should be easily observable at $\sqrt{s}$ = 100 GeV.

Conclusion

We have investigated the feasibility of observing new particles in e^+e^- interactions at energies near the the Z^0. With a storage ring capable of producing a luminosity of 2×10^{31} cm^{-2} sec^{-1}, large event rates and relatively low backgrounds make e^+e^- interactions an ideal place to search for technipions, scalar leptons and sequential heavy leptons. In addition, experiments at these energies will probe the structure of the electron down to distances ~10^{-18} cm.

The work described in this report owes much to discussions with and contributions from the other members of the lepton-lepton collider subgroup. This document would not have been possible without the skills of D. Fisher, J. Fitch, D. Kagan, and L. Mabo.

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