Summary Report for the $e^-e^-$ session in LCWS 2004 *

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In this talk, I summarize the activities in the $e^-e^-$ session. The consensus is that if the next generation $e^+e^-$ linear collider wants to include an $e^-e^-$ option, the planning has to include it as early as possible. By doing so the extra cost would be only a small fraction of the total, and of course the physics potential would be very rewarding.

I. INTRODUCTION

An electron-electron collider would be an ideal place to search for lepton-number and lepton-flavor violation. In fact, it is so unique that most of its physics cannot be easily tested at other colliders, including $pp$ and $e^+e^-$ colliders. That is why a session in the Linear Collider Workshop was devoted to $e^-e^-$ physics, including both accelerator technology talks and physics talks. In this report, I summarize the talks on both aspects.

II. ACCELERATOR TECHNOLOGY

The first major concern is the luminosity of the $e^-e^-$ option compared to the $e^+e^-$ mode. Wood and Raubenheimer performed luminosity comparison for both NLC and TESLA designs due to the effects of wakefields, disruption, and kink instability. They found that the $e^-e^-$ option for both designs suffers more serious luminosity loss than the $e^+e^-$ by a factor of about 10, but is recoverable to some extent with the use of beam-based feedbacks. Markiewicz studied the IR layout, in particular the pair-induced backgrounds. In $e^+e^-$ collisions, both neutron and charged particle backgrounds are dominated by beam-beam pairs. The factor of a few decrease in luminosity in $e^-e^-$ option also reduces the number of beam-beam pairs by the same factor. Therefore, although the $e^-e^-$ option suffers luminosity loss, the beam-beam pair backgrounds however is less than the $e^+e^-$ mode.

Another important issue of the $e^-e^-$ option is the switchover in the linac, i.e., how easy or how automatic should one expect for switching from $e^+e^-$ to $e^-e^-$ and vice versa. The goal is to obtain an optimally functional and cost effective model for achieving the $e^-e^-$ mode. The requirements include: (i) quick switch, (ii) the switchover should cause a minimal perturbation to the running condition for $e^+e^-$ mode, (iii) automated means to do the switchover job. Larsen proposed three models for switchover. The first one is polarity reversal model. Just by the name it reverses the polarity of the magnets so that the electron and the positron can be accelerated in the same path. The second is direction reversal model, which makes the electron to accelerate in the opposite direction as the positron. The third is independent system model, i.e., separate beam path for positron and electron, which is of course the most expensive.

Overall, there are quite a few issues involving in the $e^-e^-$ option. However, if one plans ahead and includes the consideration for $e^-e^-$ when they design the whole linear collider, the extra cost should only be a small fraction of the total. The physics paid-off would be far more than the cost if we plan well in advance.

III. PHYSICS POTENTIAL

There were talks given by Heusch, Gunion, and Cannoni. I briefly summarize their presentations. Readers can find some nice reviews on the physics potential of $e^-e^-$ colliders in Refs. 4, 5.

A. Möller Scattering

Since both electron beams can be polarized to very high purity, one can measure the polarized cross sections, and then determine the left-right cross section asymmetries and the Weinberg angle to very high accuracy. One can

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define the following asymmetries

\[ A^{(1)}_{LR} = \frac{d\sigma_{LL} + d\sigma_{LR} - d\sigma_{RL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{RL} + d\sigma_{RL} + d\sigma_{RR}}, \quad A^{(2)}_{LR} = \frac{d\sigma_{LL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{RR}}, \]

(1)

where \(d\sigma_{\alpha\beta}\) denotes the cross section for \(e^+e^- \to e^+e^-\). Assuming dominance by \(\gamma\) and \(Z\) exchanges, in the limit \(ys, (1-y)s \gg M_{\Phi}^2\), the above asymmetries can be written as

\[ A^{(1)}_{LR} = \frac{(1 - 4s_W^2)(1 + 4s_W^2)}{1 + 16s_W^4 + 8(y^4 + (1 - y)^4)s_W^4}, \quad A^{(2)}_{LR} = \frac{(1 - 4s_W^2)(1 + 4s_W^2)}{1 + 16s_W^4}. \]

(2)

By measuring the polarized cross sections the asymmetries \(A^{(1,2)}_{LR}\) can be determined and so can \(s_W^2\) to high accuracy: \(\delta s_W^2 \sim 0.0003\) at \(\sqrt{s} = 1\) TeV and \(O(100)\) fb\(^{-1}\) luminosity. One can also make use of the \(y\) dependence on \(A^{(2)}_{LR}\) to determine the \(y\) dependence of \(s_W^2\).

B. Lepton Flavor or Number Violation

Certain types of new physics can be directly tested at \(e^+e^-\) colliders, in particular those involving lepton-number violating interactions.

One unique new physics of \(e^+e^-\) colliders is to search for any doubly charged particle that has at least a weak coupling to electrons. Typical examples include doubly-charged Higgs bosons of some triplet Higgs or more complicated representations, bilepton gauge bosons that exist in some 3-3-1 models, and little Higgs models. In Frampton’s 3-3-1 model, the bilepton gauge boson couples to the lepton triplet

\[ \mathcal{L} = (\ell^- \nu \ell^+)_L Y_{

(3)

Y^{--} \quad Y^{+-} \quad Y^{+} \quad Y^{-} \quad Y^{--} \quad Y^{+-} \quad Y^{+} \quad Y^{-} \quad Y^{--} \quad Y^{+-} \quad Y^{+} \quad Y^{-} \]

where \(Y\) is the new gauge boson. \(Y^{--}\) can be produced as an \(s\)-channel resonance at \(e^+e^-\) collisions, and then decay into \(\mu^+\mu^-\). It is background free and \(Y^{--}\) appears as a clean resonance. In the case of Higgs-triplet or higher Higgs representations, as long as the VEV of the neutral component is small enough, it will not affect the electroweak symmetry breaking and \(\rho = 1\) is preserved. In fact, triplets are desirable in a number of neutrino mass models.

Recently, a new class of models, called little Higgs, were advocated to delay the gauge hierarchy problem to \(10^{10}\) TeV scale. In these models, e.g., the littlest Higgs model, there often exists a Higgs triplet field \(\Phi\), which is needed to cancel the divergence associated with the scalar-boson loop of the Higgs boson mass. The Higgs triplet has \(T = 1, Y = 2\), which couples to \(e^+e^-\) with a lepton-number violating coupling \(H_{\Phi}^3 L\Phi L\). One would expect \(e^+e^- \to \Phi^{--} \to \mu^+\mu^-\), for lepton flavor violation. However, this coupling is related by SU(2) invariance to \(H_{\Phi}^3\), which gives a Majorana mass to left-handed neutrinos. Therefore, \(H_{\Phi}^3\) is constrained to be very small. Another possibility is that \(\Phi^0\) develops a VEV \(v'\) such that it couples to \(WW\) and \(ZZ\). Through this VEV, \(\Phi^{--}\) can be produced via \(e^+e^- \to \nu\nu W^+W^-\rightarrow \nu\nu\Phi^{--}\rightarrow \nu\nu W^-W^-\). However, it is well known that precision electroweak measurements require \(v'\) to be small. Preliminary estimates showed that backgrounds are too large to observe such a resonance.

One of the lepton-number violating reactions is the inverse of neutrinoless double beta decay, via a \(t\)-channel exchange of a Majorana neutrino, shown in Fig. 11. The rate of the process is proportional to the square of the Majorana neutrino mass \(M^2_N\). The question is how low the mass the collider can probe.

Another interesting process is the \(e^-e^- \to \bar{\nu}\bar{\nu}\), via a \(t\)-channel neutralino exchange. The differential cross section of the process is given by

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2 M_N^2}{2\cos^2 \theta_w} \left( \frac{1}{t - M_N^2} + \frac{1}{u - M_N^2} \right) \]

(4)

FIG. 1: Feynman diagram for the inverse neutrinoless double beta decay via a Majorana neutrino \(N\).
where $\theta_w$ is the Weinberg angle and $M_1$ is the bino mass. The cross section scales as $M_1^2$, the measurement of which can determine the soft parameter $M_1$ quite precisely. In addition, the cross section versus $\sqrt{s}$ is a sensitive function of $m_\nu$; in particular $e^-e^- \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^-$ has a $S$-wave turn-on such that it provides an excellent measure of the mass of $\tilde{\ell}_R^+$ at the threshold \[1\].

Another related process is the slepton flavor oscillation \[12\]. The word “oscillation” might be a little bit misleading. It is essentially a slepton flavor mixing that will give rise to observable lepton flavor violation. In general, the matrix that diagonalizes the lepton flavors may not diagonalize the slepton flavors, and so we could have the following slepton mass matrix, supposed we only care the first and second generations,

\[
M^2_{\ell} = \begin{pmatrix}
m^2_{e\mu} & m^2_{e\mu} \\
m^2_{e\mu} & m^2_{\mu\mu}
\end{pmatrix}
\]

in which the off-diagonal entry $m^2_{e\mu}$ could be of the same order as the diagonal elements. In this case, there will be near-maximal mixing between selectron and smuon. Then the following process becomes possible

\[
e^-e^- \rightarrow \tilde{e}^- \tilde{\mu}^- \rightarrow e^-\tilde{\chi}^0_1 \mu^-\tilde{\chi}^0_1
\]

which has one electron and one muon plus missing energies in the final state. The same final state could also go through $e^-e^- \rightarrow \tilde{e}^- \tilde{e}^-$, followed by $\tilde{e}^- \rightarrow \mu^-\tilde{\chi}^0_1$ decay.

Yet, another related process, though in an entirely different framework, is production of a pair of Kaluza-Klein electrons. It is in the framework of universal extra dimensions, in which all SM particles are allowed to propagate in extra dimensions. In this model, there exists a KK parity assigned for each SM particle and KK particle such that the parity is odd for odd $n$ and even otherwise (SM particles are even). The lightest KK state $\gamma^{(1)}$ with a negative KK parity is therefore stable. In fact, it could be a potential dark matter candidate. The relevant process at $e^-e^-$ colliders is $e^-e^- \rightarrow e^-\gamma^{(1)}$ via a $t$-channel $\gamma^{(1)}$ \[12\]. The KK electron pair will then decay into a pair of electrons and KK photons. Thus, the signature is two soft electrons plus a large missing energy. It is unique and free from $2\gamma$ background.

So far we have only discussed tree-level lepton-flavor violation, Cannoni reported a work on loop-level lepton number and flavor violation \[4\] in models of TeV Majorana neutrino and in the supersymmetric extension of the SM. The heavy Majorana neutrino contributes to the lepton flavor violating process $e^-e^- \rightarrow \mu^-\mu^-$, $\tau^-\tau^-$ through box diagrams \[4\]. For Majorana neutrino masses $M_{N_2} = M_{N_1} = 3$ TeV the signal cross section can reach the level of $10^{-1}$ and $10^{-2}$ fb for $\tau^-\tau^-$ and $\mu^-\mu^-$ channels, respectively. The cross section may be too small for discovery unless the luminosity is of order 1000 fb$^{-1}$.

In the general supersymmetric standard model (SSM), the squark and slepton mass matrices are in general non-diagonal. The off-diagonal matrix elements have to be under control in order to satisfy the flavor constraints. One usually has to adopt universal boundary conditions. However, when the seesaw mechanism is embedded in the SSM, a new source of lepton-flavor violation arises. The seesaw requires three singlet neutrinos at the seesaw scale usually has to adopt universal boundary conditions. However, when the seesaw mechanism is embedded in the SSM, diagonal. The off-diagonal matrix elements have to be under control in order to satisfy the flavor constraints. One can determine the soft parameter $M_1$, in particular $e^-e^- \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^-$, has a $S$-wave turn-on such that it provides an excellent measure of the mass of $\tilde{\ell}_R^+$ at the threshold \[1\].

C. Strong $WW$ Scattering

We can also study the strong $WW$ scattering at $e^-e^-$ colliders, in particular the $W^-W^- \rightarrow W^-W^-$ mode, which has an isospin $I = 2$. $e^-e^-$ collisions provide a unique setting for testing the isospin $I = 2$ channel. A study was performed about 10 years ago before the precision measurements prefer a light Higgs boson. At any rates one should always bear in mind that we always prepare for the surprise. So here I quote the table showing the event numbers \[14\].

Finally, the $e^-e^-$ option has unique physics potential, and the cost for it is minimal if the linear collider project includes it as early as possible.
TABLE I: Cross sections (fb) for various strong $W W$ scattering models in $e^- e^- \rightarrow \nu_e \bar{\nu}_e W^- W^-$ at $\sqrt{s} = 2$ TeV with optimized cuts. Those in parentheses correspond to the # of events with hadronic $W, Z$ decays for an integrated luminosity of $300 \text{ fb}^{-1}$.

| $M_{WW}^{\text{min}}$ | SM $m_H = 1$ TeV | Scalar $m_S = 1$ TeV | Vector $m_V = 1$ TeV | LET | Bkgd |
|----------------------|-----------------|---------------------|---------------------|-----|------|
| 0.5 TeV              | 0.88 (130)      | 1.2 (175)           | 1.1 (167)           | 1.7 (245) | 10 (1470) |
| 0.75 TeV             | 0.44 (65)       | 0.72 (106)          | 0.63 (93)           | 1.0 (150) | 3.5 (515)  |
| 1 TeV                | 0.15 (22)       | 0.31 (46)           | 0.26 (38)           | 0.48 (71)  | 1.0 (147)  |

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