Summary Report for $e^+e^-$ Session

Got to finish in 8’ or you smile

LCWS 2004

Kingman Cheung
Participant talks

- **Heusch**: $e^-e^-$: Introduction and brief overview
- **Wood, Raubenheimer**: Luminosity studies: Comparison of $e^+e^-$ and $e^-e^-$ for NLC and TESLA
- **Markiewicz**: $e^-e^-$ IR Layout
- **Larsen**: $e^+e^-$ Switchover in the NLC Linac
- **Cannoni**: Loop-level lepton number and flavor violation in $e^-e^-$ collisions
- **Gunion**: Physics motivations for $e^-e^-$ collisions
M. Wood and T. Raubenheimer

Luminosity studies:
Comparison of $e^+e^-$ and $e^-e^-$ for NLC and TESLA
Luminosity studies:
Comparison of $e^+e^-$ and $e^-e^-$ for NLC and TESLA

Deflection Scans and Beam-based Feedback

Kink Instability

Effects from Crossing Angle and Solenoid

M. Woods and T. Raubenheimer (SLAC)
## Wakefields, Disruption and Kink instability

- (larger for NLC)
- (larger for TESLA)
- (comparable at NLC, TESLA)

Wakefields + Disruption \[\rightarrow\] Kink instability

Luminosity loss for nominally centered beams

### Luminosity \((x10^{33} \text{ cm}^{-2}\text{s}^{-1})\) for 6 NLC, TESLA simulations

<table>
<thead>
<tr>
<th>File</th>
<th>NLC (e^+e^-)</th>
<th>TESLA (e^+e^-)</th>
<th>NLC (e^e^-)</th>
<th>TESLA (e^e^-)</th>
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<tr>
<td>1</td>
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<td>6</td>
<td>17</td>
<td>33</td>
<td>2.6</td>
<td>2.4</td>
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</tbody>
</table>

Luminosity loss is much more variable for \(e^e^-\) mode, but is recoverable (to some extent) with use of beam-based feedbacks.
Tom Markiewics

$e^-e^-$ IR Layout
Conclusions

- In $e^+e^-$ both neutron and charged particle backgrounds are dominated by the beam-beam pairs.

- The factor of three decrease in luminosity in $e^-e^-$ reduces the number of pairs by the same factor.

- Charged particle background decreases by 3.

- Neutron background decreases by 2, neutrons from dump become significant.

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$e^-e^-$ backgrounds are fine.

Tom Markiewicz
R.S. Larsen

e\textsuperscript{+}e\textsuperscript{-} Switchover in the NLC Linac
System Goals and Requirements

• **Goal:** An optimum functional/cost model for achieving e⁻ e⁻ operation

• **Requirements Assumed in 1999 Presentation:**
  - Quick switchover from e⁺ e⁻
  - Switchover should cause minimum perturbation of running conditions for e⁺ e⁻
  - Automated means for switchover
  - Permanent magnet dipoles and sextupoles require mechanical switchover for e⁺ e⁻ beams travelling in same direction

• **Linac complexity < Injection**
  - Linac Quads do not require reversal
  - No. of kickers & correctors in Linac diagnostic areas is small

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* e⁺ e⁻ Switchover in the NLC Linac, 3rd International Workshop on Electron-Electron Interactions at TeV Energies University of California - Santa Cruz, December 10-12, 1999, R.S. Larsen, SLAC
Polarity Reversal Model

- 600MeV X-Band
- Q-Lattice Pi Shift
- e+ MAIN LINAC
- 6 GeV S or C Band Shared Tunnel
- Main e+ Damping Ring
- e+ Pre-Damping Ring
- Spin Rotator
- 2 GeV L Band
- Target
- Polarized e- Source
- e- Source

- e+
- e-
Direction Reversal Model

600MeV X-Band
Q-Lattice Pi Shift

6 GeV S or C Band Shared Tunnel
Main e+ Damping Ring
e+ Pre-Damping Ring

2 GeV L Band
Polarized e- Source

6 GeV S or C Band Shared Tunnel
Target

Polarized e- Source
e- Source

2 GeV L Band
Spin Rotator
e+ MAIN LINAC

Main e+ Damping Ring
e+ Pre-Damping Ring

e+

e-
Independent Systems Model

- 600MeV X-Band
- Q-Lattice Pi Shift
- 6 GeV S or C Band Shared Tunnel
- e+ MAIN LINAC
- Main e+ Damping Ring
- e+ Pre-Damping Ring
- Spin Rotator
- Polarized e- Source
- e- Source
- 2 GeV L Band
- 6 GeV S or C Band Shared Tunnel
- Target
- e+ Pre-Damping Ring
- e- Damping Ring
- e+ MAIN LINAC
- e- MAIN LINAC
Mirco Cannoni

Loop-level lepton number and flavor violation in $e^+e^-$ collisions
Outline

- OPAL search for $e^+e^- \rightarrow e\mu, e\tau$ at LEP
- See-Saw scenarios with Heavy Majorana Neutrinos (HMN) at the TeV scale

$$e^-e^- \rightarrow \ell^-\ell^- (\ell = \mu, \tau)$$


- If HMN too heavy SUSY can help us with sleptons mixing:
  SUSY seesaw radiative induced Lepton Flavour Violation (LFV)

$$e^-e^- \rightarrow \ell^-e^- (\ell = \mu, \tau)$$


- Conclusions
\( e^- e^- \rightarrow \ell^- \ell^- \) through virtual Neutrissimos

\[
\begin{array}{ccc}
\text{(a)} & \text{(b)} \\
\begin{array}{cc}
e^- & \phi \\
W & \phi \\
N_i & N_j \\
e^- & e^-
\end{array}
& & \\
\begin{array}{cc}
e^- & \phi \\
\phi & \phi \\
N_i & N_j \\
e^- & e^-
\end{array}
\end{array}
\]

Cutkoski rule: possibility to get an enhancement in proximity of the threshold for double gauge boson production, \( \sqrt{s} = 2M_W \)


External momenta in the propagators are considered much smaller than the masses: \( \sigma_0 \propto K_0 s \).

Depends on mixing and \( x_{i,j} = \frac{M_{i,j}}{M_W^2} \), not from energy.

- We calculate the exact energy dependence of \( K(s,t,u) \) with the package LOOPTOOLS.
MSSM + Neutrissimos: LFV from RGE (2)

- RGE from GUT to $M_R$ induce non diagonal elements in $(m^2_L)_{ij}$. 'Leading-log' approximation:

$$\left(\Delta m^2_L\right)_{ij} \propto (Y_\nu Y_\nu)_{ij} \ln \left(\frac{M_{GUT}}{M_R}\right)$$

- RGE for right-sleptons $(m^2_R)_{ij}$ do not contain terms $\propto Y_\nu Y_\nu$

- The mixing matrices generate LFV coupling in the lepton-slepton-gaugino vertex $\tilde{\ell}^\dagger_L U_{Li} \tilde{\ell}_L \chi$.

- We consider two generations: mass matrices for left-slepton and sneutrinos:

$$\tilde{m}^2_L = \begin{pmatrix} \tilde{m}^2 & \Delta m^2 \\ \Delta m^2 & \tilde{m}^2 \end{pmatrix} , \quad U_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

with eigenvalues: $\tilde{m}^2_{\pm} = \tilde{m}^2 \pm \Delta m^2$ and 'maximal mixing'

- We quantify the amount of LFV with $\delta_{LL} = \frac{\Delta m^2}{\tilde{m}^2}$
$e^- e^- \rightarrow \ell^- e^- (\ell = \mu, \tau)$ in SUSY

- (a) $\langle \tilde{\ell}_i \tilde{\ell}_j \rangle_0 = i \frac{\Delta m^2}{(p^2 - \tilde{m}^2_\pm)(p^2 - \tilde{m}^2_-)}$

- Neutralinos: Bino $\simeq M_1$ and Wino $\simeq M_2$

- Chargino: $\simeq M_2$, mSUGRA relation $M_1 \simeq 0.5 M_2$

- Loop-level lepton number and flavor violation in $e^- e^- \rightarrow \ell^- e^-$ collisions

\[ \sigma_h = \frac{1}{32\pi s} \int d(\cos \theta) |\mathcal{M}_h|^2 \]

\[ \sigma = (1/4) \sum_h \sigma_h \]
Conclusions

- If there are Neutrissimos with $M \leq 3$ TeV and substantial mixing we can find $e^-e^- \rightarrow \tau\tau$ with $\sqrt{s} \simeq 500 - 800$ GeV.

- $e^-e^- \rightarrow \ell^-e^- \ (\ell = \mu, \tau)$ induced by sleptons mixing: the LFV cross section reaches its maximum value at the energy corresponding to the threshold for sleptons pair production.

- An observable ($e^-e^- \rightarrow \tau^-e^-$) signal is compatible with the non-observation of the decay $\tau \rightarrow e\gamma$ giving some tens of events with $L_0 = 100$ fb$^{-1}$ for SUSY masses up 200 GeV.

- The more restrictive constraints from the non-observation of $\mu \rightarrow e\gamma$ make the search of $e^-e^- \rightarrow \mu^-e^-$ unrealistic.

- The SM background is low and can be easily suppressed.

- The $e^-e^-$ option of LC with left-polarized beams is a nice instrument to look for LNV and LFV.
Jack Gunion

Unique Physics Probes Using an $e^+e^-$ Collider
\[
\frac{N_{LL} + N_{LR} - N_{RL} - N_{RR}}{N_{LL} + N_{LR} + N_{RL} + N_{RR}} = P_1 A_{LR}^{(1)}(y), \quad (1)
\]
\[
\frac{N_{RR} + N_{LR} - N_{RL} - N_{LL}}{N_{RR} + N_{LR} + N_{RL} + N_{LL}} = -P_2 A_{LR}^{(1)}(y), \quad (2)
\]
\[
\frac{N_{LL} - N_{RR}}{N_{LL} + N_{RR}} = P_{\text{eff}} A_{LR}^{(2)}(y) \left( \frac{1}{1 + \frac{1 - P_1 P_2 \sigma_{LR} + \sigma_{RL}}{1 + P_1 P_2 \sigma_{LL} + \sigma_{RR}}} \right), \quad (3)
\]
\[
y = \frac{1 - \cos \theta}{2}
\]
\[
P_{\text{eff}} = \frac{P_1 + P_2}{1 + P_1 P_2}.
\]

For \( P_1 = P_2 = 0.9 \pm 0.005 \), \( P_{\text{eff}} = 0.9945 \pm 0.0004 \), i.e. \( P_{\text{eff}} \) is very large and has negligible error. It is \( P_{\text{eff}} \) that is important.

In the above,

\[
A_{LR}^{(1)} \equiv \frac{d\sigma_{LL} + d\sigma_{LR} - d\sigma_{RL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{LR} + d\sigma_{RL} + d\sigma_{RR}} \quad (4)
\]
\[
A_{LR}^{(2)} \equiv \frac{d\sigma_{LL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{RR}},
\]
(5)

where \(d\sigma\)'s are for \(e_i^- e_j^- \to e^- e^-\). Since \(d\sigma_{RL} = d\sigma_{LR}\), \(A_{LR}^{(2)}\) differs from \(A_{LR}^{(1)}\) only in the denominator. \(A_{LR}^{(2)}\) requires double polarization. Assuming dominance by \(\gamma, Z\) exchange, we find for \(y s, (1 - y) s \gg m_Z^2\)

\[
A_{LR}^{(1)}(y) = \frac{(1 - 4s_W^2)(1 + 4s_W^2)}{1 + 16s_W^4 + 8[y^4 + (1 - y)^4]s_W^4},
\]
(6)

\[
A_{LR}^{(2)}(y) = \frac{(1 - 4s_W^2)(1 + 4s_W^2)}{1 + 16s_W^4}.
\]
(7)

where factor of \((1 - 4s_W^2)\) means great sensitivity to \(s_W^2\) since \(s_W^2 \sim 1/4\).

Note, that despite apparent \(y\)-independence of \(A_{LR}^{(2)}\), in fact \(s_W^2\) depends on \(y\), actually on the momentum transfer squared \(Q^2 = y s\). This opens up the possibility of measuring \(Q\) dependence of \(s_W^2\).

- Use the above and ‘sufficiently’ (e.g. from \(Z\) pole data) known value of \(A_{LR}^{(1)}\) to simultaneously determine \(P_1, P_2\) and \(A_{LR}^{(2)}\).
For $P_1 = P_2 = 0.9$, the correction term in parentheses of Eq. (3) is small but must be accounted for.

- **Expected accuracy:** $\delta s_W^2 \sim \pm 0.0003$ at $\sqrt{s} = 1$ TeV and modest $\mathcal{L}$.

- $A_{LR}^{(2)}$ can probe running of $\sin^2 \theta_W$ with unprecedented accuracy.

- A deviation in Moller scattering from expectations would signal “new physics.” For example, deviations in angular dependence of cross section would probe

$$\mathcal{L}_{\text{eff}} = \frac{2\pi}{\Lambda^2} \bar{e}_L \gamma_\mu e_L \bar{e}_L \gamma_\mu e_L.$$  (8)
\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2 M_1^2}{2 \cos^4 \theta_W} \left( \frac{1}{t - M_1^2} + \frac{1}{u - M_1^2} \right)^2 \] (11)

Very sensitive to $M_1$ as well as to $m_{\tilde{e}^-}$ (through threshold turn on in $S$-wave).
• $S$-wave $\beta$ turn on of $e^-e^- \rightarrow \bar{e}_R \bar{e}_R \Rightarrow$ uniquely precise measurement of $m_{e_R}$. About 100x as much $L$ required for same precision in $e^+e^-$ where turn on is $\beta^3$.

• $m_{e_R}^{-}$-optimized mode: $L = 1(10) \text{fb}^{-1} \Rightarrow \Delta m_{e_R}^{-} = 70(20)$ MeV assuming $m_{\tilde{\chi}_1^0}$ is well-determined from kinematic end-point measurements elsewhere (e.g. $e^+e^-$). Backgrounds very small, unlike $e^+e^-$. 

J. Gunion
Looking for slepton flavor oscillations (J. Feng, S. Thomas, G. Kribs, ...)

- In general, the matrix that diagonalizes lepton flavor does not diagonalize slepton flavor. \( \Rightarrow \), for example,

\[
M_{\text{slepton}}^2 = \begin{pmatrix}
m_{ee}^2 & m_{e\mu}^2 \\
m_{e\mu}^2 & m_{\mu\mu}^2
\end{pmatrix}
\]

where it is very possible that \( m_{e\mu}^2 \) is comparable to \( m_{ee}^2 - m_{\mu\mu}^2 \).

- This \( \Rightarrow \) \( e^-e^- \rightarrow e^-\mu^- + \not{E}_T \) final states in 2 ways.

1. Direct \( \tilde{\mu}^- \) production: \( e^-e^- \rightarrow \tilde{e}^-\tilde{\mu}^- \) via \( \tilde{\chi}_1^0 \) exchange.
   The sleptons then decay \( (\tilde{e}^- \rightarrow e^-\tilde{\chi}_1^0, \tilde{\mu}^- \rightarrow \mu^-\tilde{\chi}_1^0) \), yielding \( e^-e^- \rightarrow e^-\mu^- + \not{E}_T \) events.
   The cross section could be small if \( m_{\tilde{\chi}_1^0} \) is large.

2. Lepton number violating decay: \( e^-e^- \rightarrow \tilde{e}^-\tilde{e}^- \) followed by \( \tilde{e}^- \rightarrow \mu^-\tilde{\chi}_1^0 \) decay.
   This mechanism might have little phase space.

- These events are much more background free in \( e^-e^- \) than corresponding events in \( e^+e^- \) collisions, especially if we have ability to turn off \( W^-W^- \)
Even within SM context, should consider extended Higgs sector possibilities.

- Frampton considered bilepton gauge bosons. Briefly,

\[
\mathcal{L} \sim (\ell^- \nu \ell^+) L^* \begin{pmatrix} Y^{--} \\ Y^{++} \end{pmatrix} \begin{pmatrix} \ell^- \\ Y^- \nu \ell^+ \end{pmatrix}_L, \tag{13}
\]

where \( Y \) are new gauge bosons. \( Y^{--} \) are produced as an \( s \)-channel resonance at \( e^-e^- \) colliders, and \( \Rightarrow \) background-free events like \( e^-e^- \rightarrow Y^{--} \rightarrow \mu^-\mu^- \).

- For Higgs, adding triplets or higher reps. is a possibility.

  If neutral vev = 0, then no EWSB impact and \( \rho = 1 \) is natural.

- Triplets very desirable for neutrino mass game in L/R symmetric models.
Littlest Higgs Model

- This model has a triplet Higgs of the classic $T = 1, Y = 2$ type, called $\Phi$ in the model.

- The interesting point from the $e^{-}e^{-}$ point of view is that $v' \equiv \langle \Phi^0 \rangle \neq 0$ does not present any particular problems below the ultraviolet completion scale of $4\pi f$.

In fact, it is very awkward to have $v' = 0$ in the littlest Higgs model since this would imply very large non-oblique radiative corrections to precision EW observables. (The limit in which $v' = 0$ corresponds to the case where the gauge coupling constants for the two SU(3)'s are equal: $g_1 = g_2$, whereas small non-oblique requires $g_2 \gg g_1$.)

It is conventional to define
\[ v' \equiv x \frac{v^2}{4f}. \]  
(21)

$x \sim 1$ is expected if $g_2 \gg g_1$.

- Consistency requires $v'/v \lesssim v/4f$, i.e. $x \lesssim O(1)$. 
- Precision electroweak at 5\% level requires \( f \gtrsim \frac{1}{2}v/\sqrt{0.05} \sim 2.3v \) and \( v' \lesssim \frac{1}{2}\sqrt{0.05}v \sim 0.1v \). The latter is completely consistent with \( x \lesssim \mathcal{O}(1) \) for \( f \gtrsim 2.3v \). \( x \sim 1 \) would imply \( v' \sim 10 \text{ GeV} \).

- There is nothing to prevent \( \ell^-\ell^- \rightarrow \Phi^-\Phi^- \) couplings for example from \( h_{\ell\ell}^{\Phi^-\Phi^-} L\Phi L \) lepton-number violating coupling.

- However, there are some strong constraints on the model.

  1. The magnitude of \( h_{\ell\ell}^{\Phi^-\Phi^-} \) cannot be very large if it is related by SU(2) invariance to the \( h_{\nu\nu}^{\Phi^0} \) coupling since the latter will give a Majorana mass contribution to the left-handed neutrinos. We require

\[
    h_{\nu\nu}^{\Phi^0} v' \lesssim 1 \text{ eV}, \quad (22)
\]

which converts to

\[
    h_{\nu\nu}^{\Phi^0} \lesssim 10^{-9} x. \quad (23)
\]

This could be regarded as an unnaturally small coupling. Maybe we should not allow it, but for purposes of discussion, let us suppose that it is there.
2. Another important relation implied by the model is

\[ m_\Phi \gtrsim \sqrt{2m_h f \over v} \gtrsim 4m_h. \tag{24} \]

Thus, the \( \Phi^{--} \) would not be very light.

3. The large mass means that very high energy would be required to produce the \( \Phi^{--} \) on-shell either in \( e^-e^- \) collisions through the lepton-number violating coupling or through \( e^-e^- \to \nu \nu W^* W^- \to \nu \nu \Phi^{--} \) via the coupling proportional to \( gv' \).

The first possibility does not look very promising. Taking \( m_\Phi \sim 1 \) TeV would give a corresponding \( c_{\ell \ell} = h^2_{\ell \ell}/m^2_\Phi (\text{GeV}) \sim 10^{-24} \), well below the maximum sensitivity estimated for an \( e^-e^- \) collider for direct \( s \)-channel production.

As regards the latter possibility, Wacker estimates that this will be difficult to see in the presence of backgrounds.

4. At a low energy \( e^-e^- \) collider, one could only look for virtual effects in \( e^-e^- \to \Phi^{--*} \to e^-e^-, \mu^-\mu^-, \tau^-\tau^- \) for the \( L \) violating coupling or \( e^-e^- \to \nu \nu W^* W^- \to \nu \nu \Phi^{--*} \to \nu \nu W^-W^- \) for the \( gv' \)-induced coupling.

Our preliminary estimates are that the backgrounds are too large for such
**Other interesting physics**

- **Strong WW scattering:** $e^- e^- \rightarrow \nu_e \nu_e W^- W^-$ provides a unique setting for $W^- W^- \rightarrow W^- W^- \ (\text{isospin}=2)$.

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

Cross sections (fb) at $\sqrt{s} = 2 \ \text{TeV}$ with optimized cuts. Those in parentheses correspond to the # of events with hadronic $W, Z$ decays for an integrated luminosity of 300 fb$^{-1}$. (Barger, Beacom, Cheung, Han 94')
• Majorana neutrino mass:

\[ e^- \rightarrow W^- \]

Rate is \( \sim M_N^2 \).

The question is how small the mass it can probe.
• KK electron in universal extra dimension model:

\[ e^{-} \rightarrow e^{-}(1) \]

\[ e^{-}(1) e^{-}(1) \rightarrow e^{-} e^{-} \gamma^{(1)} \gamma^{(1)} \]

Two soft electrons plus missing energy

Unique, free from 2\(\gamma\) bkgd (H. Cheng)
Conclusions

We have seen a number of new physics that are unique to \( e^- e^- \) collisions.

But the questions are: is the extra new physics worth the extra cost? Technology?

We may want to invent some quantities such as

\[
\text{Credits/Merits of New Physics} \\
\text{Cost}
\]

...to evaluate different possible options in the future.