Summary Report for e^-e^- Session

Got to finish in $8'$ or you smile

LCWS 2004

Kingman Cheung

Participanting 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

Colloque international sur les collisionneurs linéaires
LCWS04 19-23 Avril, 2004 Paris, France

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) **Wakefields** + (larger for TESLA) **Disruption** → (comparable at NLC, TESLA) **Kink instability**

Luminosity loss for nominally centered beams

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

File	NLC e^+e^-	TESLA e^+e^-	NLC e^-e^-	TESLA e^-e^-
1	20	33	5.7	3.7
2	20	32	3.3	3.2
3	18	33	2.1	4.0
4	20	36	5.3	4.0
5	17	32	5.3	4.3
6	17	33	2.6	2.4

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 on Pair Induced Backgrounds

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 signifigant.

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e^-e^- backgrounds are fine.

R.S. Larsen

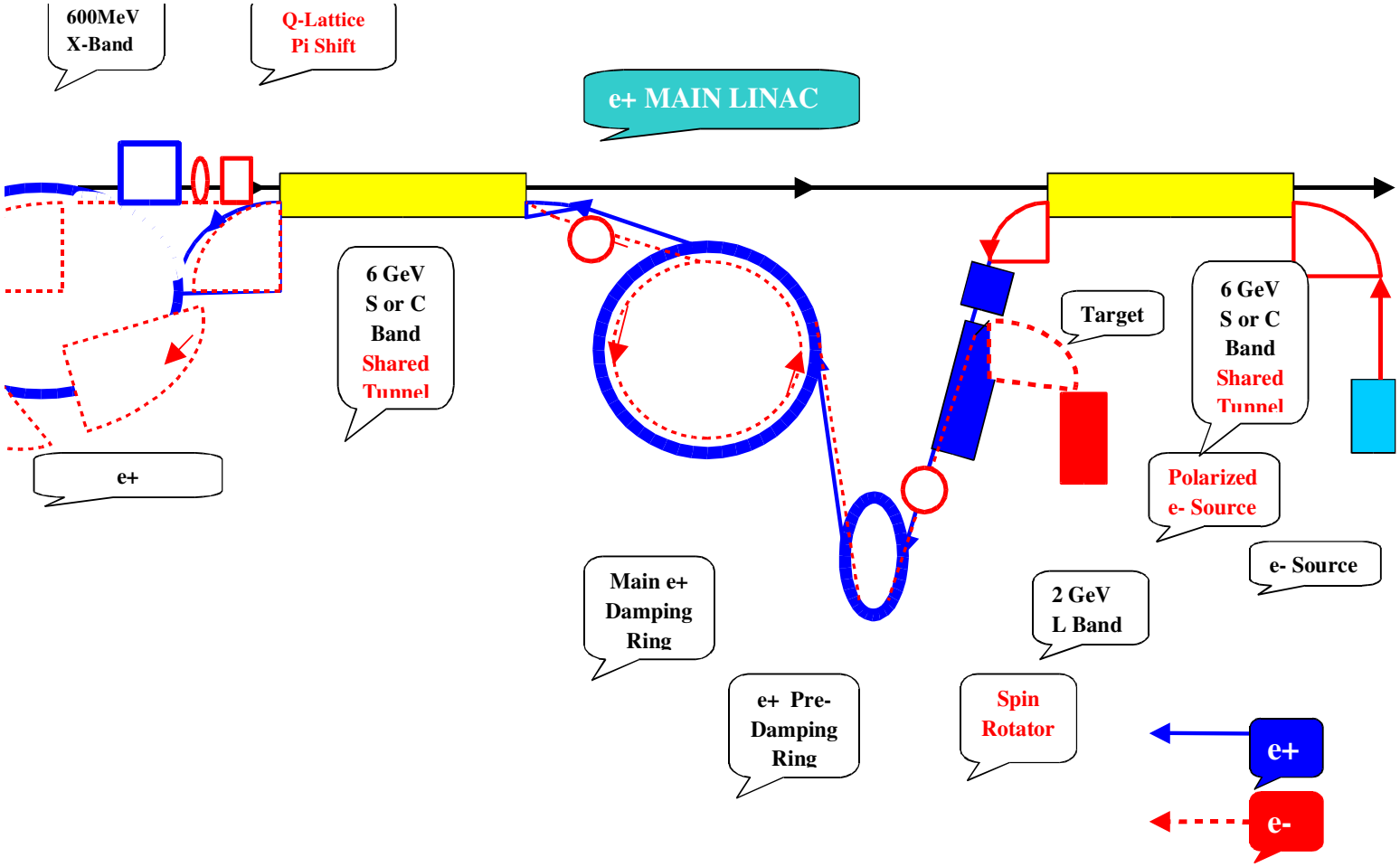
e^+e^- Switchover in the NLC Linac

System Goals and Requirements

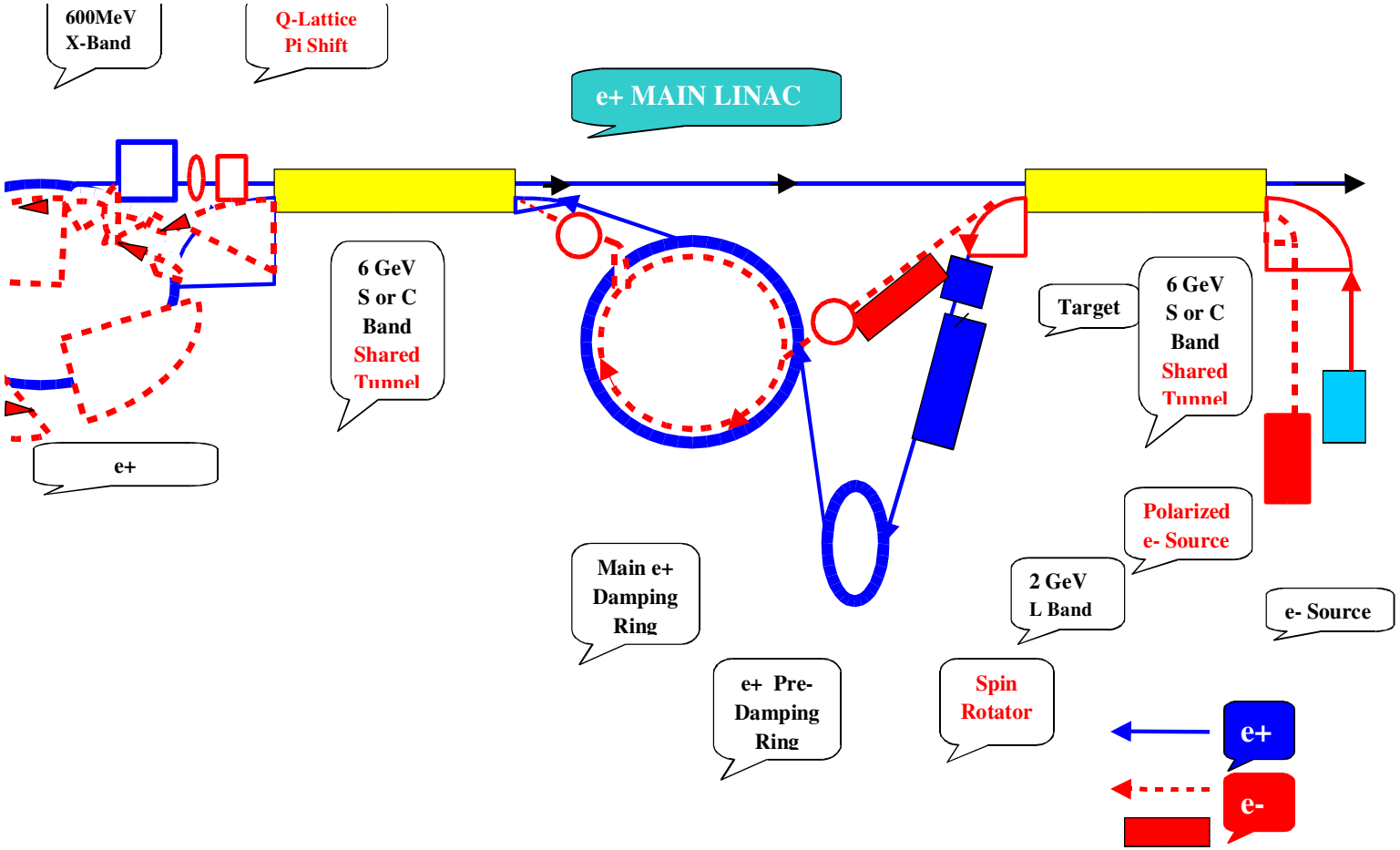
- Goal: An optimum functional/cost model for achieving e^- e^- operation
- Requirements Assumed in 1999 Presentation:*
  - Quick switchover from e^+ e^-
  - Switchover should cause minimum perturbation of running conditions for e^+ e^-
  - Automated means for switchover
  - Permanent magnet dipoles and 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

* 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

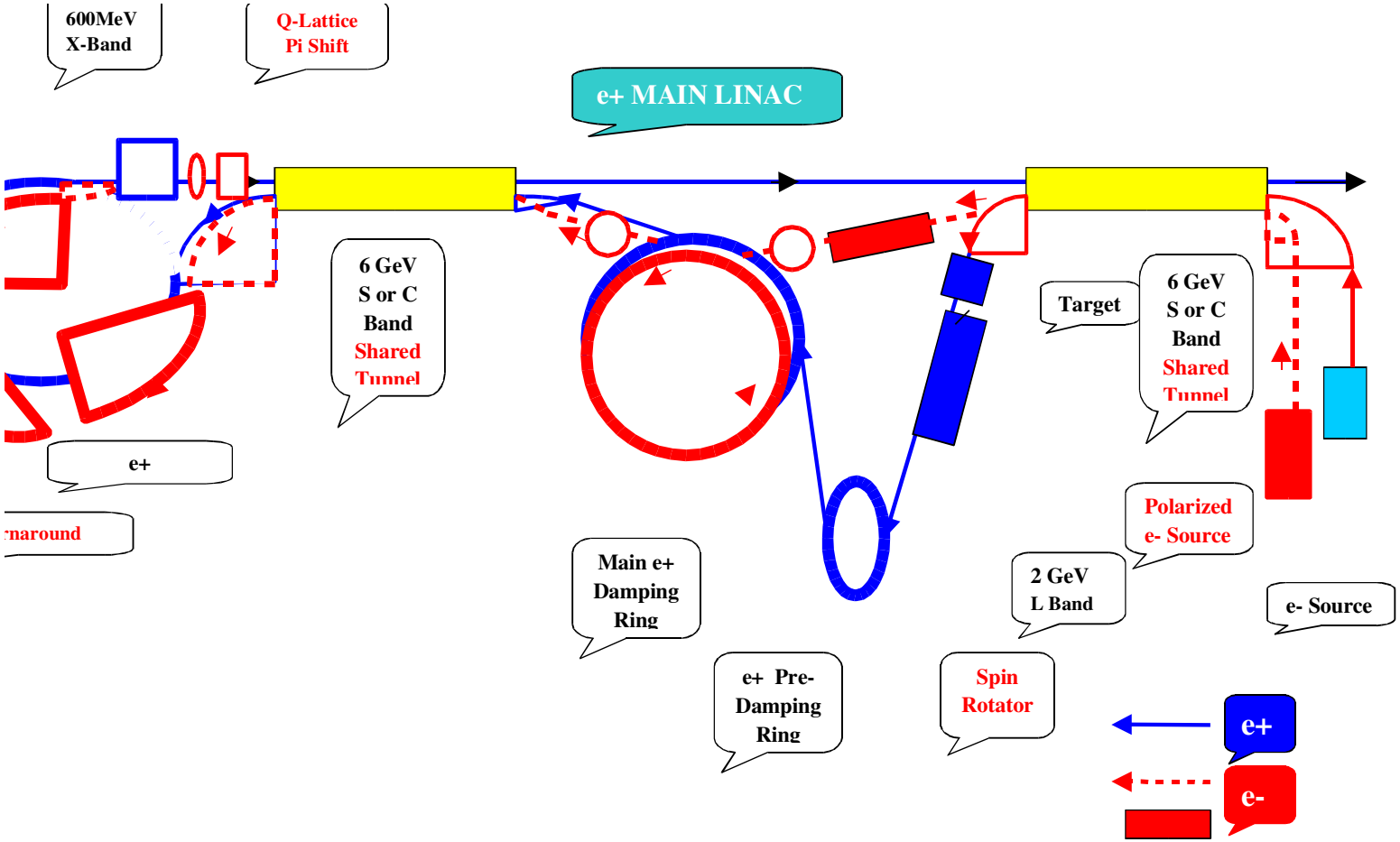
Polarity Reversal Model



Direction Reversal Model



Independent Systems Model



Mirco Cannoni

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

Outline

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

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

M. C., St. Kolb and O. Panella, Eur. Phys. J. C **28** (2003) 375, hep-ph/0209120

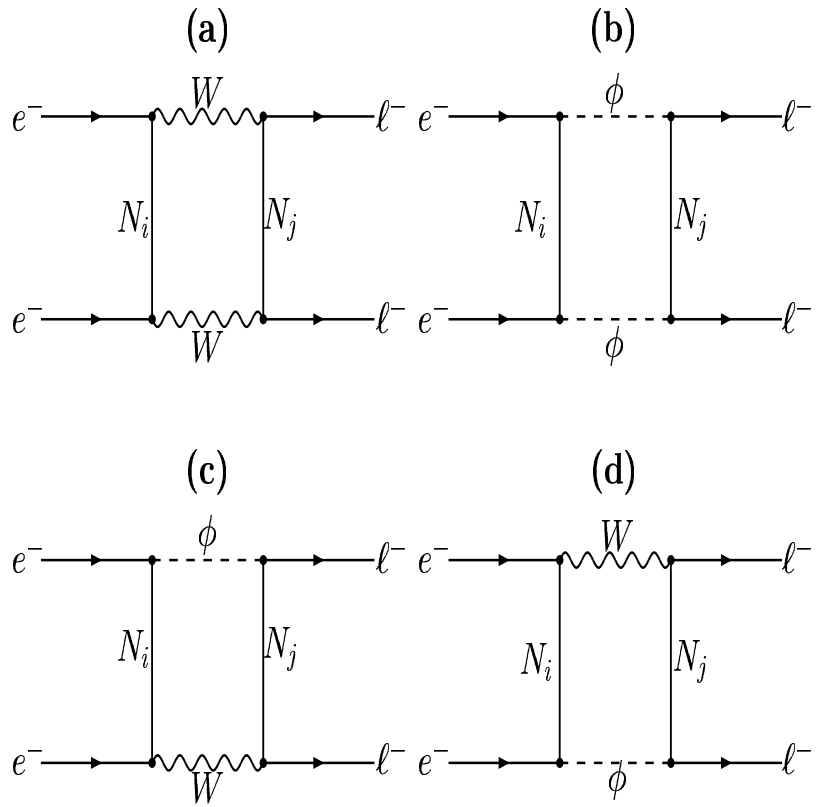
- If HMN too heavy SUSY can help us with sleptons mixing: SUSY seesaw radiative induced Lepton Flavour Violation (LFV)

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

M. C., St. Kolb and O. Panella, Phys. Rev. D **68** (2003) 096002, hep-ph/0306170

- Conclusions

$e^-e^- \to \ell^-\ell^-$ $(\ell = \mu\tau)$ through virtual Neutrissimos



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

- X. Y. Pham, Phys. Lett. B **495** (2000) 131

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

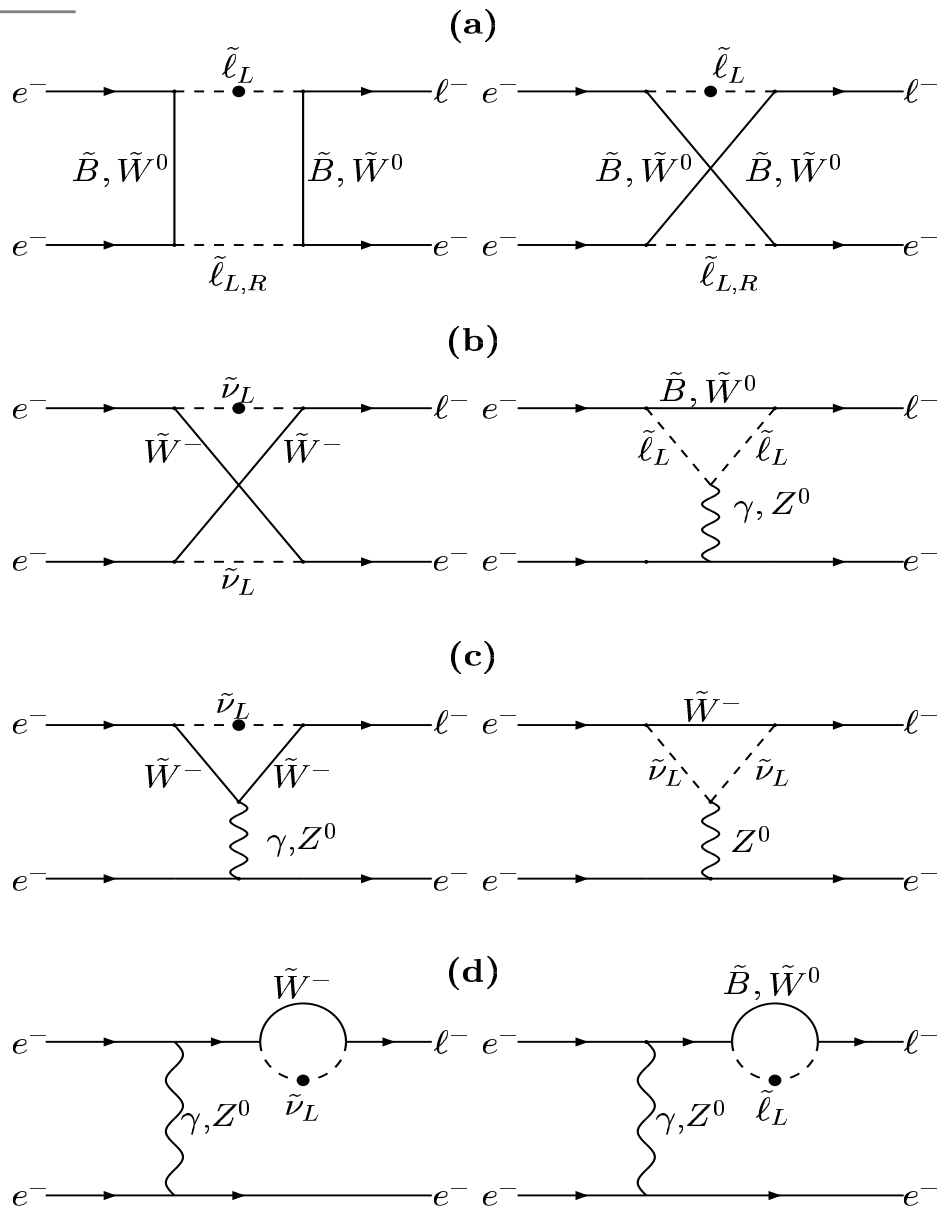
  Depends on mixing and $x_{i,j} = \frac{M_{i,j}}{M_W^2}$, not from energy

- 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 $(m^2_{\tilde{L}})_{ij}$. 'Leading-log' approximation:
$$(\Delta m^2_{\tilde{L}})_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij} \ln\left(\frac{M_{GUT}}{M_R}\right)$$
RGE for right-sleptons $(m^2_{\tilde{R}})_{ij}$ do not contain terms $\propto Y_\nu^\dagger Y_\nu$
- The mixing matrices generate LFV coupling in the lepton-slepton-gaugino vertex $\tilde{\ell}^\dagger_{L_i} U_{Lij} \tilde{\ell}_{L_j} \chi$.
- We consider two generations: mass matrices for left-slepton and sneutrinos:
$$\tilde{m}^2_L = \begin{pmatrix} \tilde{m}^2 & \Delta m^2 \\ \Delta m^2 & \tilde{m}^2 \end{pmatrix}, U_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$
with eigenvalues: $\tilde{m}^2_\pm = \tilde{m}^2 \pm \Delta m^2$ and 'maximal mixing'
- We quantify the umount of LFV with $\delta_{LL} = \frac{\Delta m^2}{\tilde{m}^2}$

$e^-e^- \to \ell^-e^- \, (\ell = \mu, \tau)$ in SUSY



- $\langle \tilde{\ell}_i \tilde{\ell}_j^\dagger \rangle_0 = i \frac{\Delta m^2}{(p^2 - \tilde{m}_+^2)(p^2 - \tilde{m}_-^2)}$
- Neutralinos: Bino $\simeq M_1$ and Wino$\simeq M_2$
- Chargino: $\simeq M_2$, mSUGRA relation $M_1 \simeq 0.5 M_2$
- $\sigma_h = \frac{1}{32\pi s} \int d(\cos\theta) \, |\mathcal{M}_h|^2$
- $\sigma = (1/4) \sum_h \sigma_h$

Conclusions

- If there are Neutrissimos with $M \leq 3$ TeV and substantial mixing we can find $e^-e^- \to \tau\tau$ with $\sqrt{s} \simeq 500 - 800$ GeV
- $e^-e^- \to \ell^-e^-$ $(\ell = \mu, \tau)$ 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 ($e^-e^- \to \tau^-e^-$) signal is compatible with the non observation of the decay $\tau \to e\gamma$ 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 $\mu \to e\gamma$ make the search of $e^-e^- \to \mu^-e^-$ 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

Moller Scattering | Czarnecki+Marciano, Barklow

$$\frac{N_{\rm LL}+N_{\rm LR}-N_{\rm RL}-N_{\rm RR}}{N_{\rm LL}+N_{\rm LR}+N_{\rm RL}+N_{\rm RR}} = P_1 A^{(1)}_{\rm LR}(y), \quad (1)$$

$$\frac{N_{\rm RR}+N_{\rm LR}-N_{\rm RL}-N_{\rm LL}}{N_{\rm RR}+N_{\rm LR}+N_{\rm RL}+N_{\rm LL}} = -P_2 A^{(1)}_{\rm LR}(y), \quad (2)$$

$$\frac{N_{\rm LL}-N_{\rm RR}}{N_{\rm LL}+N_{\rm RR}} = P_{\rm eff} A^{(2)}_{\rm LR}(y)\left(\frac{1}{1+\frac{1-P_1P_2}{1+P_1P_2}\frac{\sigma_{\rm LR}+\sigma_{\rm RL}}{\sigma_{\rm LL}+\sigma_{\rm RR}}}\right), \quad (3)$$

$$y=\frac{1-\cos\theta}{2} \qquad P_{\rm eff}=\frac{P_1+P_2}{1+P_1P_2}.$$

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

In the above,

$$A^{(1)}_{LR} \equiv \frac{d\sigma_{LL}+d\sigma_{LR}-d\sigma_{RL}-d\sigma_{RR}}{d\sigma_{LL}+d\sigma_{LR}+d\sigma_{RL}+d\sigma_{RR}} \quad (4)$$

$$A_{LR}^{(2)} \equiv \frac{d\sigma_{LL} - d\sigma_{RR}}{d\sigma_{LL} + d\sigma_{RR}}, \tag{5}$$

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 γ, Z exchange, we find for $ys, (1-y)s \gg m_Z^2$

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

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

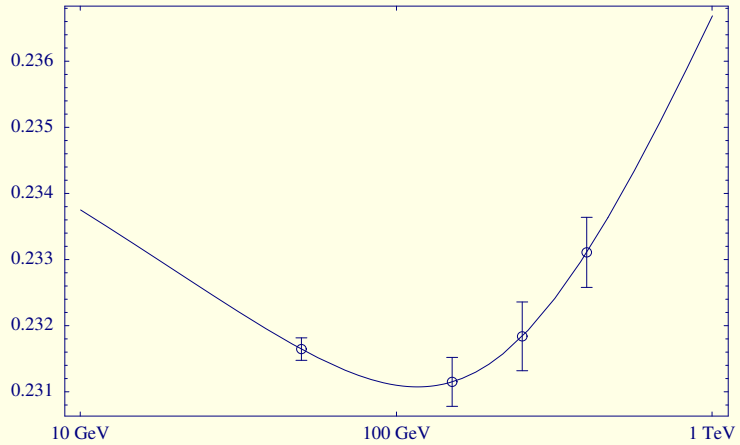
where factor of $(1-4s_W^2)$ means great sensitivity to s_W^2 since $s_W^2 \sim 1/4$. Note, that despite apparent y-independence of $A_{\rm LR}^{(2)}$, in fact s_W^2 depends on y, actually on the momentum transfer squared $Q^2 = ys$. This opens up the possibility of measuring Q dependence of s_W^2.

- 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 $\mathcal{L}$.

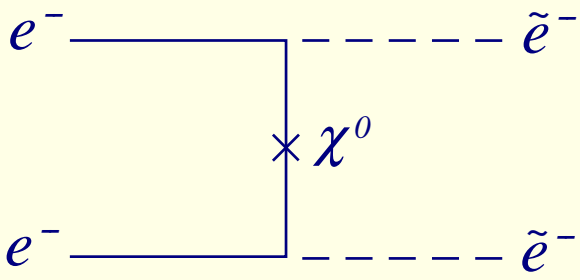
- $A_{LR}^{(2)}$ can probe running of $\sin^2\theta_W$ with unprecedented accuracy.



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

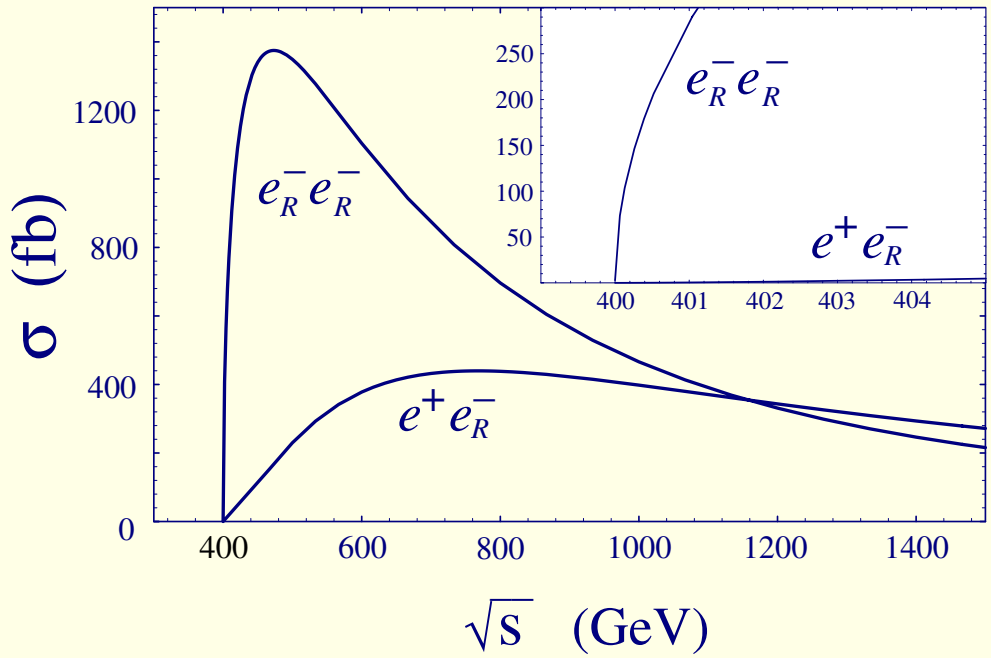
$$\mathcal{L}_{\rm eff} = \frac{2\pi}{\Lambda^2}\bar{e}_L\gamma^\mu e_L \bar{e}_L\gamma_\mu e_L \,. \tag{8}$$

RPC SUSY | Peskin + Feng



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 M_1^2}{2\cos^4\theta_W}\left(\frac{1}{t - M_1^2} + \frac{1}{u - M_1^2}\right)^2 \tag{11}$$

Very sensitive to M_1 as well as to $m_{\tilde{e}^-}$ (through threshold turn on in S-wave).



- S-wave β turn on of $e^-e^- \to \tilde{e}_R^- \tilde{e}_R^-$ $\Rightarrow$ uniquely precise measurement of $m_{\tilde{e}_R^-}$. About $100\times$ as much L required for same precision in e^+e^- where turn on is β^3.

- $m_{\tilde{e}_R^-}$-optimized mode: $L = 1(10)\mathrm{fb}^{-1} \Rightarrow \Delta m_{\tilde{e}_R^-} = 70(20)$ 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^-.

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,

$$\mathcal{M}^2_{\rm slepton} = \begin{pmatrix} m^2_{ee} & m^2_{e\mu} \\ m^2_{e\mu} & m^2_{\mu\mu} \end{pmatrix} \tag{12}$$

  where it is very possible that $m^2_{e\mu}$ is comparable to $m^2_{ee} - m^2_{\mu\mu}$.

- This $\Rightarrow$ $e^-e^- \to e^-\mu^- + \not{E}_T$ final states in 2 ways.

  1. Direct $\widetilde{\mu}^-$ production: $e^-e^- \to \widetilde{e}^-\widetilde{\mu}^-$ via $\widetilde{\chi}^0_1$ exchange.
     The sleptons then decay ($\widetilde{e}^- \to e^-\widetilde{\chi}^0_1$, $\widetilde{\mu}^- \to \mu^-\widetilde{\chi}^0_1$), yielding $e^-e^- \to e^-\mu^- + \not{E}_T$ events.
     The cross section could be small if $m_{\widetilde{\chi}^0_1}$ is large.
  2. Lepton number violating decay: $e^-e^- \to \widetilde{e}^-\widetilde{e}^-$ followed by $\widetilde{e}^- \to \mu^-\widetilde{\chi}^0_1$ 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^-

Bileptons and Doubly Charged Higgs Bosons

Gunion, Frampton, Littlest Higgs Model . . .

Even within SM context, should consider extended Higgs sector possibilities.

- Frampton considered bilepton gauge bosons. Briefly,

$$\mathcal{L} \sim \begin{pmatrix} \ell^- & \nu & \ell^+ \end{pmatrix}^*_L \begin{pmatrix} & & Y^{--} \\ & & Y^- \\ Y^{++} & Y^+ & \end{pmatrix} \begin{pmatrix} \ell^- \\ \nu \\ \ell^+ \end{pmatrix}_L , \qquad (13)$$

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

- 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 Φ 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 ultraviolate 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

$$v' \equiv x \frac{v^2}{4f} \,. \tag{21}$$

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

- Consistency requires $v'/v \lesssim v/4f$, i.e. $x \lesssim \mathcal{O}(1)$.

- 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 $v' \sim 10$ GeV.

- There is nothing to prevent $\ell^-\ell^- \to \Phi^{--}$ couplings for example from $h^{\Phi^{--}}_{\ell\ell} L\Phi L$ lepton-number violating coupling.

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

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

$$h^{\Phi^0}_{\nu\nu} v' \lesssim 1 \text{ eV}\,, \tag{22}$$

which converts to

$$h^{\Phi^0}_{\nu\nu} \lesssim 10^{-9} x\,. \tag{23}$$

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

$$m_\Phi \gtrsim \sqrt{2}\frac{m_h f}{v} \gtrsim 4m_h\,. \tag{24}$$

   Thus, the Φ^{--} would not be very light.
3. The large mass means that very high energy would be required to to produce the Φ^{--} 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 $c_{\ell\ell} = h^2_{\ell\ell}/m^2_\Phi(GeV) \sim 10^{-24}$, 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

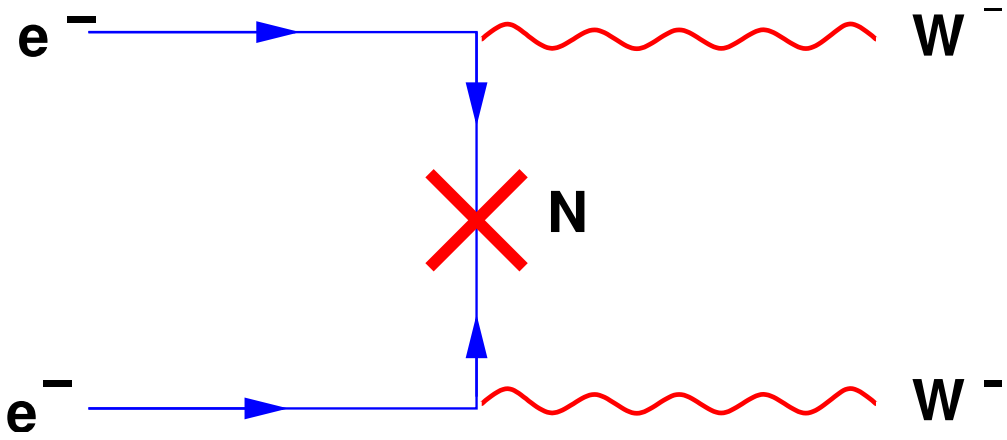
Other interesting physics

• Strong WW scattering: $e^-e^- \to \nu_e\nu_e W^-W^-$ provides a unique setting for $W^-W^- \to W^-W^-$ (isospin=2).

M_{WW}^{min}	SM $m_H = 1$ TeV	Scalar $m_S = 1$ TeV	Vector $m_V = 1$ TeV	LET	Backgrounds
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)

Cross sections (fb) 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 fb^{-1}. (Barger, Beacom, Cheung, Han 94')

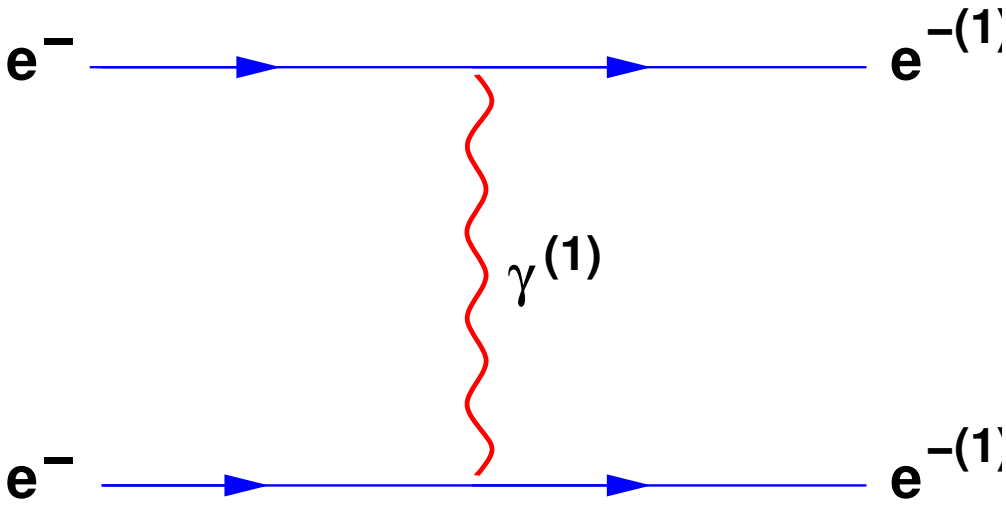
- Majorana neutrino mass:



Rate is $\sim M_N^2$.

The question is how small the mass it can probe.

- KK electron in universal extra dimension model:



$$e^{-(1)}e^{-(1)} \to e^- e^- \gamma^{(1)}\gamma^{(1)}$$

Two soft electrons plus missing energy

Unique, free from 2γ 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

$$\frac{\text{Credits/Merits of New Physics}}{\text{Cost}}$$

to evaluate different possible options in the future.