Outstanding Problems

- **Electroweak Symmetry Breaking: Is it the SM, an effective 2HDM, technicolor, . . .**
- **Supersymmetry and Unification: Sparticle masses and properties, is there a desert, . . .**
- **Flavor Physics: Masses, mixings, CP violation, neutrino mass, . . .**
- **Space-time Structure: Large extra dimensions, branes, . . .**

In all cases, the e^-e^-, $e^-\gamma$ and $\gamma\gamma$ colliders provide unique and important probes.
Especially important: high luminosity, $L = 300 - 500\mathrm{fb}^{-1}$ per year, and high polarization, $P_e \sim 80 - 90\%$.

e^-e^- Collisions

Unique capabilities arise for

- **Contact interactions.**
- **SUSY studies, R-parity conserving.**
- **SUSY studies, R-Parity violating.**
- **Understanding or eliminating sources of neutrino masses and mixing.**
- **Looking for flavor violation via $e^- \to \mu^-$.**
- **Higgs studies related to above and to unification.**

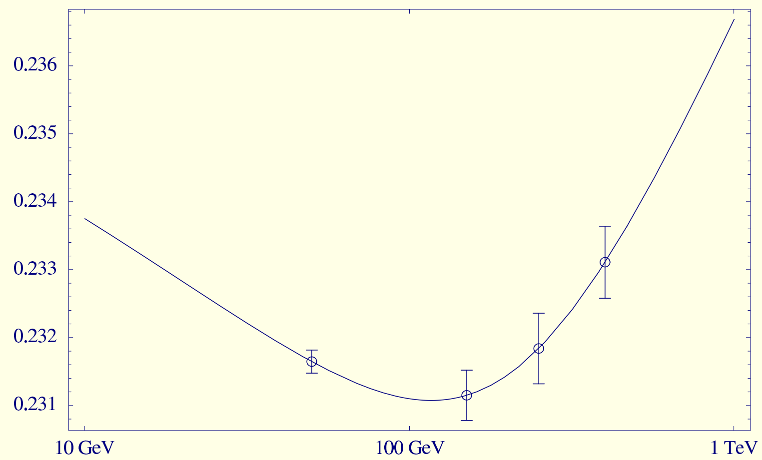
Moller Scattering Czarnecki+Marciano, Barklow

- Measure certain A_{LR} type asymmetries to determine $\sin^2\theta_W$ and/or expose new contact interactions.

- The accuracy achievable depends crucially on $P_{\rm eff} = \frac{P_1+P_2}{1+P_1P_2}$. Expect to have $P_1 = P_2 = 0.9 \pm 0.005$, $\Rightarrow P_{\rm eff} = 0.9945 \pm 0.0004$, i.e. $P_{\rm eff}$ is very large and has negligible error.

- Expect to achieve $\delta s_W^2 \sim \pm 0.0003$ at $\sqrt{s} = 1~{\rm TeV}$ and modest $\mathcal{L}$.

By adjusting angle of outgoing e^-e^- pair relative to beam direction, one probes Q^2 dependence of s_W^2 with great accuracy.



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

$$\mathcal{L}_{\rm eff} = \frac{2\pi}{\Lambda^2} \bar{e}_L \gamma^\mu e_L \bar{e}_L \gamma_\mu e_L \,. \tag{1}$$

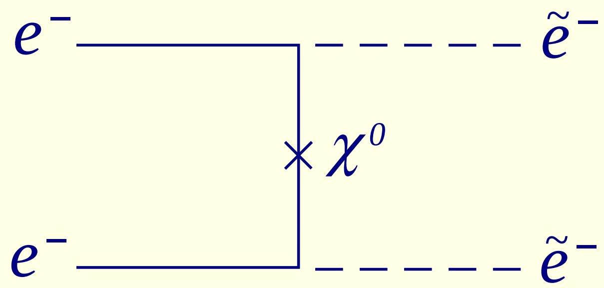
With $\sqrt{s} = 1~\mathrm{TeV}$ and $82 \mathrm{fb}^{-1}$ $\Rightarrow$ probe $\Lambda = 150~\mathrm{TeV}$.

- Bhabha scattering at e^+e^- with same L $\Rightarrow$ probes $\Lambda = 100~\mathrm{TeV}$. Moller is better because of u vs. s dependence of Moller vs. Bhabha.

$$\frac{\Lambda_{e^-e^-}}{\Lambda_{e^+e^-}} = 2^{-1/4} \langle \left(\frac{s}{u}\right)^{3/2} \rangle \,. \tag{2}$$

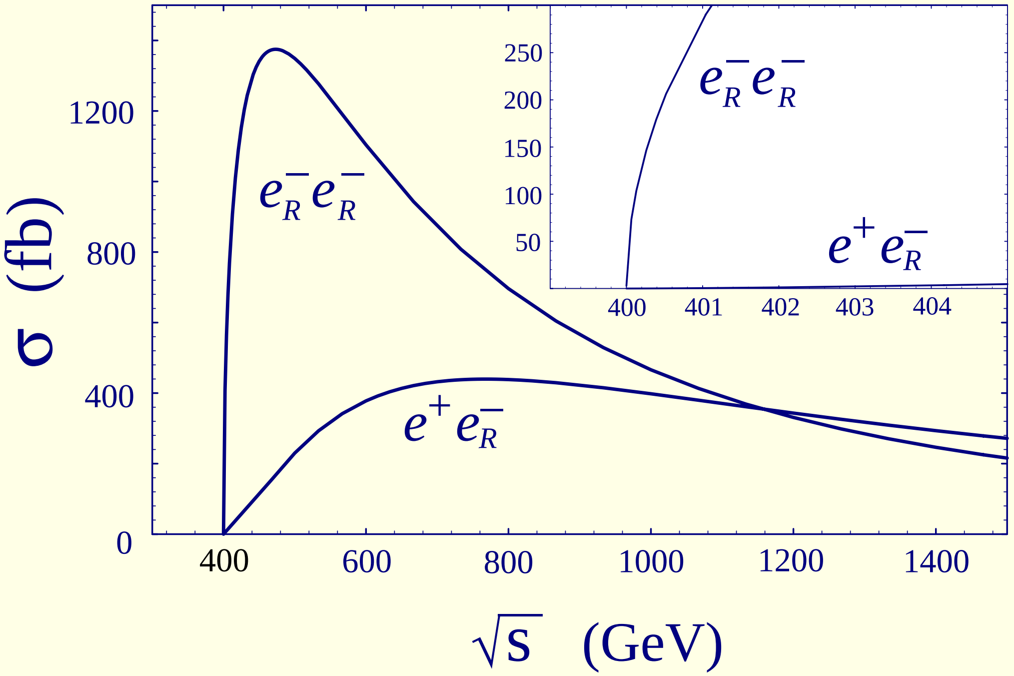
Weak $\mathcal{L}^{1/4}$ dependence of $\Lambda^{\rm limit}$ on $\mathcal{L}$ implies that if e^-e^- collisions have 1/3 as much luminosity as e^+e^- because of beam disruption, e^-e^- will still do better.

Standard SUSY **Peskin + Feng**



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 M_1^2}{2\cos^4\theta_W}\left(\frac{1}{t - M_1^2} + \frac{1}{u - M_1^2}\right)^2 \qquad (3)$$

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

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

  Such precision could be crucial for evolving up to GUT scale with adequate precision to really determine soft-SUSY-breaking boundary conditions.

- A 2-point scan determines M_1 to ± 5 GeV unlike e^+e^- where M_1 comes only from end-point game.

- Even if M_1 is very large, get determination of M_1 from cross section size.

- $e^+e^- \to \widetilde{e}_R^{\pm}\widetilde{e}_L^{\mp} \Rightarrow m_{\widetilde{e}_L^-}$ and then $m_{\widetilde{e}_L^-} - m_{\widetilde{e}_R^-} \Rightarrow$ model independent determination of $\tan\beta$ (at low to moderate $\tan\beta$).

- Check equality $\widetilde{g} = g$ of $\widetilde{g}e\widetilde{e}\widetilde{B}$ vs. $geeB_\mu$ couplings to much better than 1%.

  Non-decoupling of corrections to $\widetilde{g}/g = 1$ means that this ratio would be sensitive to sparticles of arbitrarily large mass.

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

- In general, the matrix that diagonalizes lepton flavor does not diagonalize slepton flavor.
- 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, followed by $\widetilde{e}^- \to e^-\widetilde{\chi}^0_1$ and $\widetilde{\mu}^- \to \mu^-\widetilde{\chi}^0_1$, yielding $e^-e^- \to e^-\mu^- + \not{E}_T$ events.
  2. Lepton number violating decay: $e^-e^- \to \widetilde{e}^-\widetilde{e}^-$ followed by $\widetilde{e}^- \to \mu^-\widetilde{\chi}^0_1$ decay.
- These events are much more background free in e^-e^- than corresponding events in e^+e^- collisions, especiallly if we have ability to turn off W^-W^- production using e^-_R polarized beams.

Bileptons and Doubly Charged Higgs Bosons Gunion, Frampton, . . .

- **Bileptons: extend SU(2)$_L$ to SU(3)$_L$:**

$$\mathcal{L} \sim \begin{pmatrix} \ell^+ & \nu & \ell^- \end{pmatrix}^*_L \begin{pmatrix} & & Y^{++} \\ & & Y^+ \\ Y^{--} & Y^- & \end{pmatrix} \begin{pmatrix} \ell^+ \\ \nu \\ \ell^- \end{pmatrix}_L , \qquad (4)$$

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 doublets with unusual Y, and/or triplets and/or higher reps. is possible and perhaps desirable, both within SM context and in attractive SM extensions:**

1. **If neutral vev $= 0$, then no EWSB impact and $\rho = 1$ is natural.**
2. **Such additions, esp. triplets, are good for unification without SUSY, but at lower scale than usual (maybe desirable for large-scale extra dimensions, . . .).**

3. Triplets are very desirable for neutrino mass game in L/R symmetric models. Usual notation for $Y = -2$ is

$$\Delta = \begin{pmatrix} \Delta^-/\sqrt{2} & \Delta^0 \\ \Delta^{--} & -\Delta^-/\sqrt{2} \end{pmatrix} . \qquad (5)$$

Introduce Δ_R triplet for see-saw with $\langle \Delta_R^0 \rangle =$large.
L/R symmetry requires Δ_L and $\langle \Delta_L^0 \rangle \equiv v_\Delta = 0$ is natural.

4. There is a possibility of non-zero bi-lepton couplings of Higgs bosons. For the standard SU(2)$_L$ case, with $Q = T_3 + \frac{Y}{2} = -2$, the allowed doubly-charged cases are:

$$\begin{aligned} e^-_R e^-_R &\to \Delta^{--}(T = 0, T_3 = 0, Y = -4)\,, \\ e^-_L e^-_R &\to \Delta^{--}(T = \tfrac{1}{2}, T_3 = -\tfrac{1}{2}, Y = -3)\,, \\ e^-_L e^-_L &\to \Delta^{--}(T = 1, T_3 = -1, Y = -2)\,. \end{aligned} \qquad (6)$$

5. If $v_\Delta = 0$, most decay channels are eliminated.
$\Rightarrow$ small $\Gamma_{\Delta^{--}}$, which, in turn, $\Rightarrow$ great sensitivity to small couplings of above type via s-channel $e^-e^- \to \Delta^{--}$ production.
also $\Rightarrow$ dominance of bi-lepton decay modes is possible.
The $\tau^-\tau^-$ channel could easily have the largest partial width and be the dominant decay of the Δ^{--}.