Unique Physics Probes Using e^-e^-, $e^-\gamma$ and $\gamma\gamma$ Colliders

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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 $e^- \rightarrow \mu^-$.**
- **Higgs studies related to above and to unification.**

We provide only a few examples.

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 $P_1=P_2=0.9\pm0.005$, $P_{\rm eff}=0.9945\pm0.0004$, i.e. $P_{\rm eff}$ is very large and has negligible error. It is $P_{\rm eff}$ that is important.

In the above,

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

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

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 $ys, (1-y)s \gg m_Z^2$

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

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

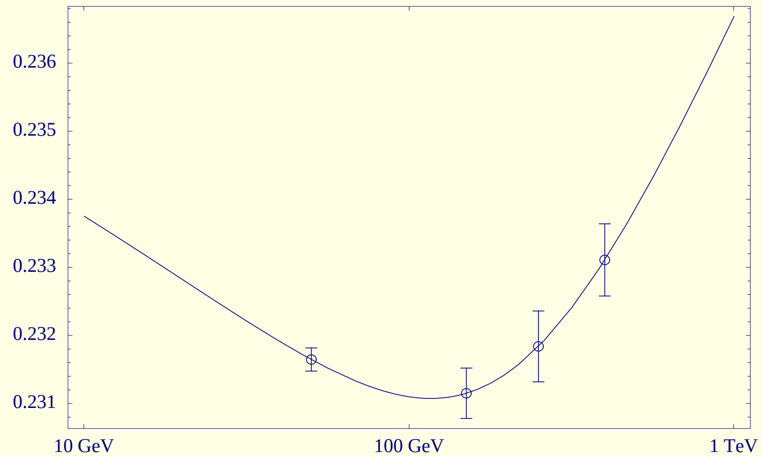
where factor of $(1-4s_W^2)$ means great sensitivity to s_W^2 since $s_W^2 \sim 1/4$. Note, that despite apparent y-independence of $A_{\rm LR}^{(2)}$, in fact s_W^2 depends on y, actually on the momentum transfer squared $Q^2 = ys$. This opens up the possibility of meauring Q dependence of s_W^2.

- 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 $\sqrt{s} = 1~\mathrm{TeV}$ 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

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

Need to assume you have a precise determination of P_1 and P_2 from above.

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.

$$\frac{\Lambda_{e^-e^-}}{\Lambda_{e^+e^-}} = 2^{-1/4} \langle \left(\frac{s}{u}\right)^{3/2} \rangle \,. \tag{9}$$

- Roughly, luminosity and $\sqrt{s}$ scaling dependence of maximum value of Λ probed is

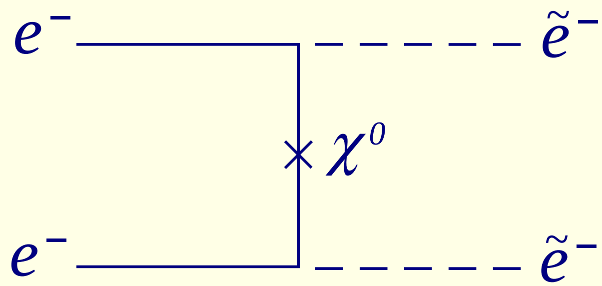
$$\Lambda^{\mathrm{limit}} \propto \mathcal{L}^{1/4}\sqrt{s}\,. \tag{10}$$

assuming that one does not encounter systematic error problems and such.

Note that weak $\mathcal{L}^{1/4}$ dependence of Λ^{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.

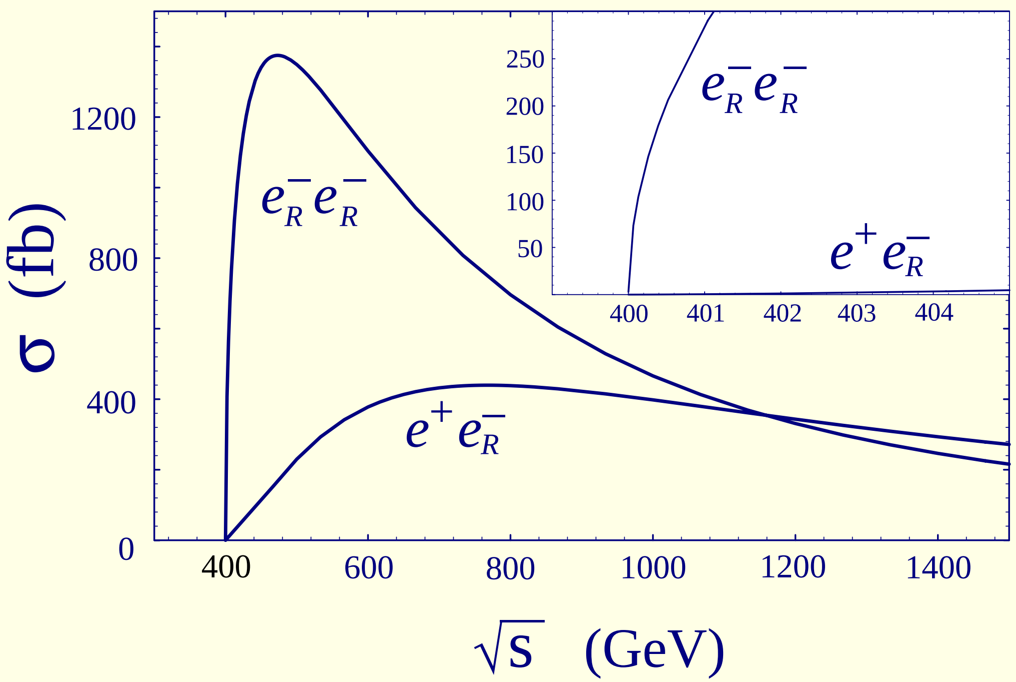
- The impact of reduced $\mathcal{L}$ due to beam disruption must be evaluated for each new physics case.

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 $e^- e^- \to \widetilde{e}_R^- \widetilde{e}_R^- \Rightarrow$ 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: $L = 1(10)\text{fb}^{-1} \Rightarrow \Delta m_{\widetilde{e}_R^-} = 70(20)$ 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 $\pm 5\ \mathrm{GeV}$ unlike e^+e^- where M_1 comes only from end-point game.**

- **Even if M_1 is very large, we get a 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. $\Rightarrow$, for example,

$$\mathcal{M}^2_{\rm slepton} = \left(\begin{array}{cc} m^2_{ee} & m^2_{e\mu} \\ m^2_{e\mu} & m^2_{\mu\mu} \end{array} \right) \tag{12}$$

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, especiallly if we have ability to turn off W^-W^-

production using e^-_R polarized beams.

1. $e^-e^- \to W^-W^-$ **forbidden by lepton number conservation.**
2. $e^-e^- \to \nu\nu W^-W^-$ **and** $e^-e^- \to e^-\nu W^-$ **are both turned off for double** e^-_R **polarization.**
3. $\gamma\gamma \to W^+W^-$ **is not a background since** $\Rightarrow$ **opposite (vs. same sign) dileptons.**

RPV SUSY

If there are R-parity violating interactions of the leptonic variety, an e^-e^- collider could provide some truly unique information. Consider, for example,

$$\lambda_{132} L_1 L_3 \mu^c + \lambda_{231} L_2 L_3 e^c \,.$$

Murayama (e-e-97) provides the following summary.

- These interactions do not $\Rightarrow$ $\mu \to e\gamma$ or μ-e conversion because they conserve $L_e + L_\mu$.

- Best bounds on the λ's come from muonium conversion, $\mu^+ e^- \leftrightarrow \mu^- e^+$, and e-μ-τ universality.
  Net bound: $\lambda < 0.1$ for $m_{\tilde L} \sim 200$ GeV.

- The above superpotential $\Rightarrow e^-_L e^-_R \to \mu^-_L \mu^-_R$ via $\widetilde{\nu}_\tau$ exchange.
  There is essentially no background. The event rate is given roughly by

$$\frac{\#(\text{event})}{20 \text{ fb}^{-1}} \simeq 10^6 \times \lambda^4 \times \left(\frac{200 \text{ GeV}}{m_{\tilde L}}\right)^4 \left(\frac{\sqrt{s}}{200 \text{ GeV}}\right)^2 .$$

$\Rightarrow \geq 5$ events if $\lambda \geq 0.05$, which is below the current limits.

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

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

- **Frampton will update bilepton gauge boson ideas. Briefly,**

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

  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. Usual notation is**

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} . \qquad (14)$$

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.

- Triplets are good for unification without SUSY, but at lower scale than usual (maybe desirable for large-scale extra dimensions, . . .).

  Use notation $N_{T,Y}$ for number of Higgs reps. of given T, Y. $T, Y = 1, 2$ and $T, Y = 1/2, 3$ both imply Δ^{--} state.

  $N_{\frac{1}{2},1} = 1$, $N_{1,2} = 2 \Rightarrow M_U \sim 1.5 \times 10^{13}$ GeV.

  $N_{\frac{1}{2},1} \geq 1$ and $N_{\frac{1}{2},3} \neq 0$ solutions $\Rightarrow M_U \lesssim 10^{13}$ GeV.

- Mass limits from LEP are model dependent, but certainly pair production pretty much excludes masses below 100 GeV.

- For $v_\Delta = 0$,
  - $W_L W_L$ couplings to Higgs bosons of triplet are absent.
  - Most $\Delta\Delta^{(\prime)}V$ couplings are non-zero.
  - Trilinear couplings of three Δ's are zero.

– $H\Delta\Delta$ couplings involving one doublet H and two triplet Δ's are non-zero if the doublet vev is non-zero.
– Δ couplings to $f^{(\prime)}\overline{f}$ are zero.

- 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:

$$\begin{aligned} e^-_R e^-_R &\to \Delta^{--}(T=0, T_3=0, Y=-4)\,, \\ e^-_L e^-_R &\to \Delta^{--}(T=\tfrac{1}{2}, T_3=-\tfrac{1}{2}, Y=-3)\,, \\ e^-_L e^-_L &\to \Delta^{--}(T=1, T_3=-1, Y=-2)\,. \end{aligned} \tag{15}$$

Note that the above cases do not include the $T=3, Y=-4$ representation that yields $\rho=1$, nor the $T=1, Y=-4$ triplet with no neutral member, but do include the $T=1/2, Y=-3$ doublet representation with no neutral member, and the $T=1, Y=-2$ triplet representation.

In the case of a $|Y|=2$ triplet representation the lepton-number-violating coupling to (left-handed) leptons is specified in the lepton-number violating Lagrangian form:

$$\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \text{h.c.}\,, \quad i,j = e,\mu,\tau\,. \qquad (16)$$

Limits on the h_{ij} by virtue of the $\Delta^{--} \to \ell^- \ell^-$ couplings: writing $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2(\text{ GeV})$, strongest limits (no limits on $c_{\tau\tau}$) are:

- $c_{ee} < 10^{-5}$ (Bhabha),
- $c_{\mu\mu} < 5 \times 10^{-7}$ ($(g-2)_\mu$ – predicted contribution has wrong sign)

and

- $\sqrt{c_{ee} c_{\mu\mu}} < 10^{-7}$ (muonium-antimuonium).

- If $v_\Delta = 0$, most decay channels are eliminated.

  If allowed, $\Delta \to \Delta' V$ might dominate, but since the Δ's of typical model are approximately degenerate, all these modes might be virtual.

  $\Rightarrow$ dominance of bi-lepton decay modes is possible if bi-lepton couplings are non-zero.

  Since there are currently no limits on $c_{\tau\tau}$, the $\tau^-\tau^-$ channel could easily have the largest partial width and be the dominant decay of the Δ^{--}.

  In any case, for $v_\Delta = 0$, $\Gamma_{\Delta^{--}}^T$ is likely to be small. $\Rightarrow$ possibly very large s-channel e^-e^- and $\mu^-\mu^-$ production rates.

- **Note:**

  For $v_\Delta = 0$, the Δ^0 (generally the lightest) will be stable unless it has bi-lepton couplings to $\nu_L \nu_L$.

  Such a Δ^0 would be a candidate for the dark matter.

Detection and Study:

- **Discover Δ^{--} in $p\overline{p} \to \Delta^{--}\Delta^{++}$ with $\Delta^{--} \to \ell^-\ell^-, \Delta^{++} \to \ell^+\ell^+$ ($\ell = e, \mu, \tau$) at TeV33 or LHC (J.G., Loomis, Pitts: hep-ph/9610237). LHC reach up to $m_{\Delta^{--}} \sim 1~\mathrm{TeV}$.**

  $\Rightarrow$ TeV33 + LHC will tell us if such a Δ^{--} exists in the mass range accessible to NLC and FMC and how it decays.

  - **If no W^-W^- decays are detected, it is very probable that $v_\Delta = 0$.**
  - **If Δ^{--} decays to $\ell^-\ell^-$ ($\ell = e, \mu, \tau$), then $\Rightarrow$ the $\ell^-\ell^-$ coupling clearly exists.**
  - **For any observed $\ell^-\ell^-$ mode(s), you know the $\Delta^{--} \to \ell^-\ell^-$ coupling(s) are non-zero, but you do not know that the others are zero — only that they are relatively smaller.**
  - **Even if only the Δ^-W^- mode is observed, that does not mean that the $c_{\ell\ell}$'s are zero, only that they are quite small.**

$\Rightarrow$ can still probe $c_{\ell\ell}$'s that are too small for $\ell^-\ell^-$ to appear in decays if total width of the Δ^{--} is small.

– If the $\Delta^- W^-$ mode is disallowed and the $c_{\ell\ell}$'s are all very small ($\lesssim 10^{-16}$), the Δ^{--} could be sufficiently long-lived to escape the detector.

  The hadron colliders would see the corresponding 'stable' particle highly ionizing tracks.

- Bottom line: from LHC will know if Δ^{--} exists and may know if some $c_{\ell\ell}$'s are non-zero, but will not have measured any $c_{\ell\ell}$.

- The $c_{\ell\ell}$'s are of fundamental importance. $\Rightarrow$ Look for (and study if found) in $e^-e^- \to \Delta^{--}$ s-channel collisions. (From Tevatron and/or LHC, we will know $m_{\Delta^{--}}$ quite precisely.)

  This should be done no matter how the Δ^{--} is seen to decay at the hadron colliders.

  Event rates can be enormous (see JFG, hep-ph/9803222 and hep-ph/9510350): equivalently can probe to very small $c_{\ell\ell}$.

  – Using the Gaussian approximation, the effective cross section for Δ^{--} production in the s-channel is obtained by convoluting the standard s-

channel pole form with the Gaussian distribution in $\sqrt{s}$ of rms width $\sigma_{\sqrt{s}}$.
A useful mnemonic for $\sigma_{\sqrt{s}}$ is

$$\sigma_{\sqrt{s}} \sim 0.2 \text{ GeV} \left(\frac{m_{\Delta^{--}}}{100 \text{ GeV}}\right)\left(\frac{R}{0.2\%}\right), \tag{17}$$

where R is the beam energy resolution in percent. The crucial issue is how $\sigma_{\sqrt{s}}$ compares to $\Gamma^T_{\Delta^{--}}$.
The resulting cross section is denoted by $\overline{\sigma}_{\Delta^{--}}$. For $\Gamma^T_{\Delta^{--}} \gg \sigma_{\sqrt{s}}$, $\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$, $\overline{\sigma}_{\Delta^{--}}$ at $\sqrt{s} = m_{\Delta^{--}}$ is given by:

$$\overline{\sigma}_{\Delta^{--}} = \begin{cases} \frac{4\pi BR(\Delta^{--}\to e^- e^-)}{m^2_{\Delta^{--}}}, & \Gamma^T_{\Delta^{--}} \gg \sigma_{\sqrt{s}}; \\ \frac{\sqrt{\pi}}{2\sqrt{2}} \frac{4\pi \frac{\Gamma(\Delta^{--}\to e^- e^-)}{\sigma_{\sqrt{s}}}}{m^2_{\Delta^{--}}}, & \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}. \end{cases} \tag{18}$$

We compute rates as $L\overline{\sigma}_{\Delta^{--}}$ with $L = 50\text{fb}^{-1}$ assumed under Gaussian peak (after accounting for losses in radiative tail).

In the following, we assume $\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$. As discussed above, this is likely if $v_\Delta = 0$.

– Taking $L = 50\mathrm{fb}^{-1}$, and using Eq. (17) for $\sigma_{\sqrt{s}}$ and the analytical form for $\Gamma(\Delta^{--} \to e^- e^-)$, we find from Eq. (18) an event rate of

$$N(\Delta^{--}) \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right) \left(\frac{0.2\%}{R}\right) . \tag{19}$$

An enormous event rate results if c_{ee} is within a few orders of magnitude of its upper bound.

– For 100 events, Eq. (19) $\Rightarrow$ we probe

$$c_{ee}|_{100 \text{ events}} \sim 3.3 \times 10^{-14} \left(\frac{R}{0.2\%}\right) \left(\frac{50\mathrm{fb}^{-1}}{L}\right) , \quad \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}} , \tag{20}$$

independent of $m_{\Delta^{--}}$.

– If $\Delta^{--} \to \mu^- \mu^-$ primarily, 10 events might $\to$ a viable signal.

– If $\Delta^{--} \to e^- e^-$ or $\Delta^- W^-$, 1000 events might be needed because of backgrounds. A better study is needed.

– $\Rightarrow$ dramatic sensitivity — at least factor of $10^8 - 10^9$ improvement over current limits.

– Observation ⇒ actual measurement of c_{ee} at level relevant to neutrino mass generation by a right-handed partner Δ_R representation (with $\langle \Delta_R^0 \rangle \neq 0$) of the left-handed Δ_L representation .

Other processes:

- $\Delta^{--} Z$ and $\Delta^{--}\gamma$ production in $e^- e^-$ collisions.

  This is essentially equivalent to using the bremsstrahlung tail in $\sqrt{s}$ at the $e^- e^-$ collider to self-scan for the Δ^{--}. Depending on c_{ee}, it can allow discovery and mass measurement, which in turn allows centering in $\sqrt{s}$ for direct resonance production as above.

  The total number of events is proportional to c_{ee} as in the $\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$ limit of on-resonance production, but observable rates are only possible if c_{ee} is not too far below current bounds.

- $e^- \gamma \to e^+ \Delta^{--} \to e^+ \mu^- \mu^-$ (Godfrey etal.)

  Can probe quite small h_{ee} if the energy is sufficient for the Δ^{--} to be resonantly produced.

  There is even some sensitivity if the Δ^{--} is massive and only appears as a virtually exchanged particle.

- $\Delta^- W^-$ production in $e^- e^-$ collisions.

  This process relies on a $\Delta^- \to e^- \nu_e$ coupling, and would be an interesting way of both observing any Δ^- with such a coupling and a way of determining the magnitude of the coupling.

  Observable rates require substantial coupling.

Heavy Majorana Neutrinos

- Minkowski and collaborators have shown that $e^- e^-$ colliders are uniquely able to probe for the existence of massive Majorana neutrinos.

  Their virtual exchange in the t-channel leads to $e^- e^- \to W^- W^-$.

- Masses as high as $\sim 12~\mathrm{TeV}$ can be probed (for mixing angle near its current upper bound) at $\sqrt{s} \sim 1~\mathrm{TeV}$ with $L = 100 \mathrm{fb}^{-1}$.

Strong W scattering

- If strong W scattering is nature's choices, we will have a situation very analogous to pion scattering in the early days of QCD.

- **We will wish to probe every possible channel.**

- **Only e^-e^- collisions provide access to the $W^-W^- \to W^-W^-$ channel required to complete the survey of all possible weak-isospin states in the WW system.**

- **Of course, very high energy $\sqrt{s} \gtrsim 3~\mathrm{TeV}$ is required to do a complete job. (Barger+Berger+Gunion+Han)**

- **But, even at low energy, $\sqrt{s} = 0.5 - 1~\mathrm{TeV}$, the e^-e^- channel would provide important information. (See, e.g. the summary by Murayama for e-e-97.)**

$\gamma\gamma$ Collider

By far the most important motivations are two:

- Ability to explore large scale extra dimension signals, for example in $\gamma\gamma \to \gamma\gamma, W^+W^-$ and $\gamma\gamma \to \gamma$+gravitons.

- Ability to study and/or make first discovery of Higgs bosons.

I will mainly focus on the latter. For more details, see later talk by D. Asner.
First a brief summary of the former.
Note: Although $\mathcal{L}$ for e^-e^- collisions can suffer from beam disruption, the laser photons are backscattered by the electrons prior to the e^-'s passing through one another.

- $\Rightarrow \gamma\gamma$ collisions get benefit of full geometric e^-e^- $\mathcal{L}$.

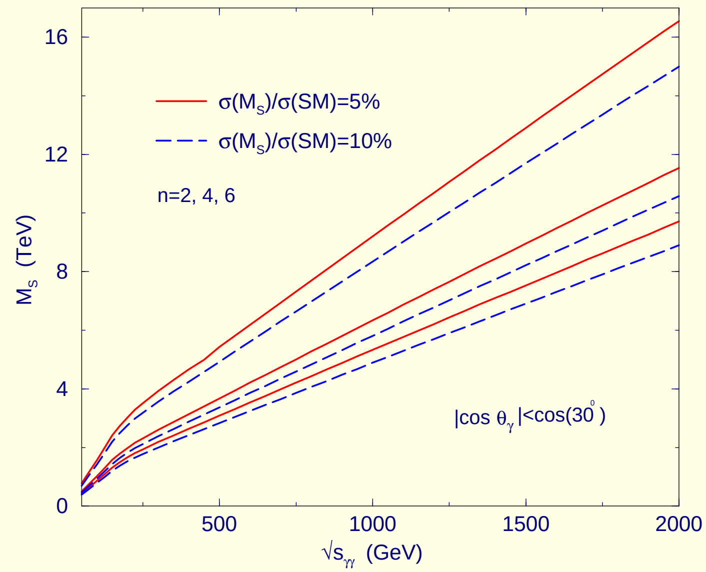
Extra Dimensions at a $\gamma\gamma$ collider (Cheung, Rizzo, ...)

- Of the Tevatron, e^+e^- and $\gamma\gamma$ colliders, the latter $\Rightarrow$ the best sensitivity reach on the cut-off scale M_S of the low scale gravity model.

- In particular, $\gamma\gamma \to \gamma\gamma$ can only occur via box diagrams in the SM while in e^+e^- and $p\bar{p}$ collisions the tree-level contributions from the SM dominates.

- The sensitivity reach in $\gamma\gamma \to \gamma\gamma$ collisions is about $5 - 8 \times \sqrt{s_{\gamma\gamma}}$ while it is only $3.5 - 5.5 \times \sqrt{s}$ in e^+e^- collisions. But, $\sqrt{s}_{\gamma\gamma} \sim 0.8\sqrt{s}_{ee}$.

- At the Run II of the Tevatron, the reach is only about 1.7 (1.4) TeV for $n = 2$ (4).



M_S reach versus $\sqrt{s_{\gamma\gamma}}$ using the process $\gamma\gamma \to \gamma\gamma$, by requiring the signal to be 5% or 10% of the SM prediction. A cut of $|\cos\theta_\gamma| < \cos 30^\circ$ is imposed. From K. Cheung.

Rizzo estimates the following:

Reaction	M_S Reach (TeV units) for $L = 100\mathrm{fb}^{-1}$
$e^+e^- \to f\overline{f}$	$6.5\sqrt{s}$
$e^+e^- \to e^+e^-$	$6.2\sqrt{s}$
$e^-e^- \to e^-e^-$	$6.0\sqrt{s}$
$pp \to \ell^+\ell^-$ (LHC)	5.3
$pp \to jj$ (LHC)	9.0
$pp \to \gamma\gamma$ (LHC)	5.4
$\gamma\gamma \to \ell^+\ell^-/t\bar{t}/jj$	$4\sqrt{s}$
$\gamma\gamma \to \gamma\gamma/ZZ$	$4-5\sqrt{s}$
$\gamma\gamma \to W^+W^-$	$11\sqrt{s}$

It seems that a $\gamma\gamma$ collider at a $\sqrt{s} \gtrsim 1~\mathrm{TeV}$ would better even the LHC using $\gamma\gamma$ and W^+W^- final states.

According to Davoudiasl etal., $e\gamma \to e\gamma$ can be competitive with $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to W^+W^-$.

Ghosh etal. claim that $e\gamma \to eG$ is also competitive.

Higgs bosons at a $\gamma\gamma$ collider

The three powerful results are:

- **Ability to determine very precisely the $\gamma\gamma$Higgs coupling.**
- **Ability to detect the MSSM Higgs bosons in the LHC/LC 'wedge' region of moderate $\tan\beta$ and $m_{A^0} \gtrsim 250~\mathrm{GeV}$.**
- **Ability to determine the CP nature of any Higgs boson detected.**

Still to be established but likely:

- **$\gamma\gamma$ collisions will provide best determination of Higgs self coupling.**

Ingredients

- **CAIN predictions for $\gamma\gamma$ luminosity, assuming fixed LLNL laser with $\lambda = 1.04~\mu$m. Assume electron polarization of $P_e = 80\%$ (i.e. $\lambda_e = 0.4$).**
- **For Higgs discovery use $P_c = \pm 1$ circular laser polarizations:**
  - **Broad $E_{\gamma\gamma}$ spectrum obtained for $P_e P_c = P'_e P'_c > 0$ (type-I).**

– Narrow spectrum (peaked at some $E_{\gamma\gamma} < \sqrt{s}_{ee}$) for $P_e P_c = P'_e P'_c < 0$ (type-II).

– For type-I, $\langle \lambda\lambda' \rangle \sim .5 - .6$ for the back-scattered photons.
For type-II, $\langle \lambda\lambda' \rangle \sim 0.85$ near $E_{\gamma\gamma}$ peak.
Want large $\langle \lambda\lambda' \rangle$ since supression of $J_z = \pm 2$ background in $b\bar{b}$ channel is $\propto 1 - \langle \lambda\lambda' \rangle$.
Note: even $\langle \lambda\lambda' \rangle \sim 0.85$ still leaves $J_z = \pm 2$ as the dominant background component.

– Use only type-II for Higgs of known mass, e.g. h^0 of SM or MSSM.
For light Higgs, can use LLNL laser frequency tripling technique to improve peaked spectrum shape.

– Use type-I plus type-II operation for Higgs of unknown mass, e.g. H^0, A^0 of MSSM.
For example, for $\sqrt{s}_{ee} = 630~\mathrm{GeV}$, the broad spectrum operation potentially allows H^0, A^0 discovery for $m_{A^0} \sim m_{H^0} \in [350, 450]~\mathrm{GeV}$ while the narrow spectrum operation covers $m_{A^0} \sim m_{H^0} \in [450, 500]~\mathrm{GeV}$.
Typically, for equivalent statistics in the two regions, would want to run about twice as long in the broad spectrum mode as in the narrow spectrum mode.

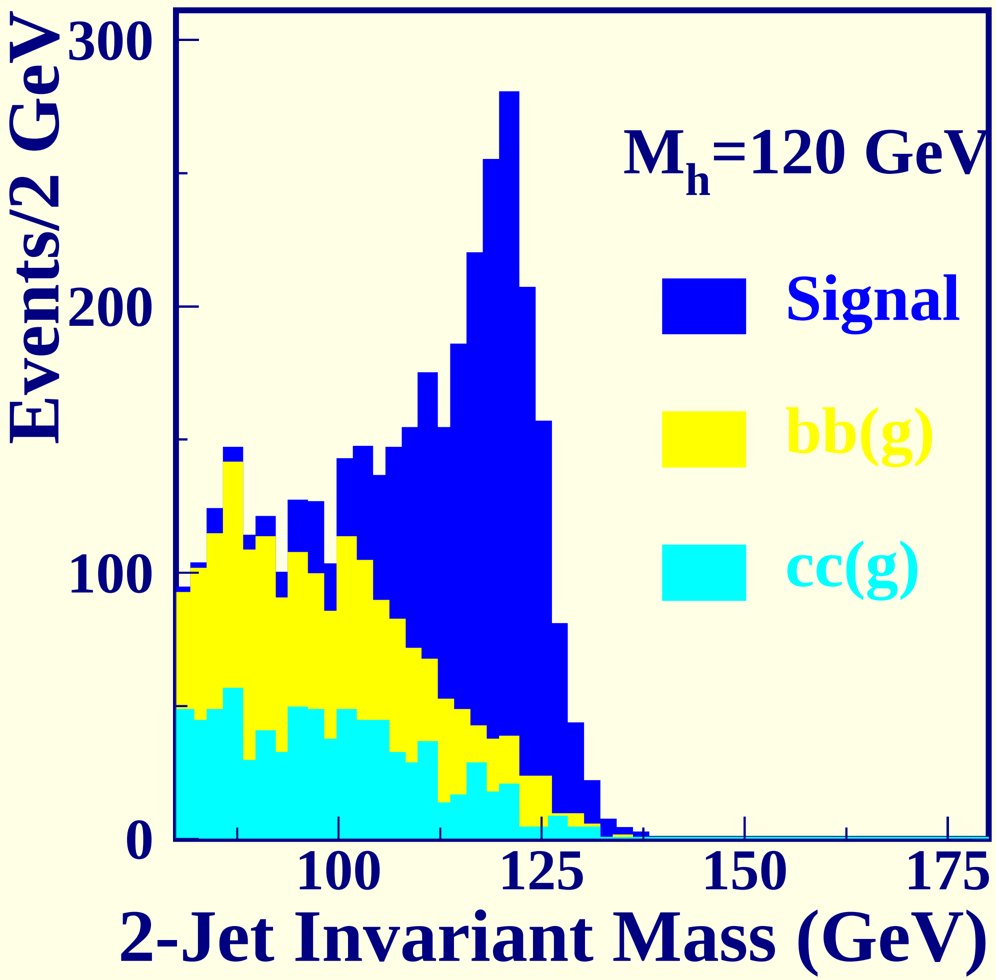
- For Higgs CP determination, use laser photons with 100% linear transverse

polarization.

For LLNL laser wavelength and lights Higgs of mass near 120 GeV, this leads to about 60% transverse and longitudinal polarization, which is nearly ideal.

Spectrum no longer peaked, but good CP determination still possible.

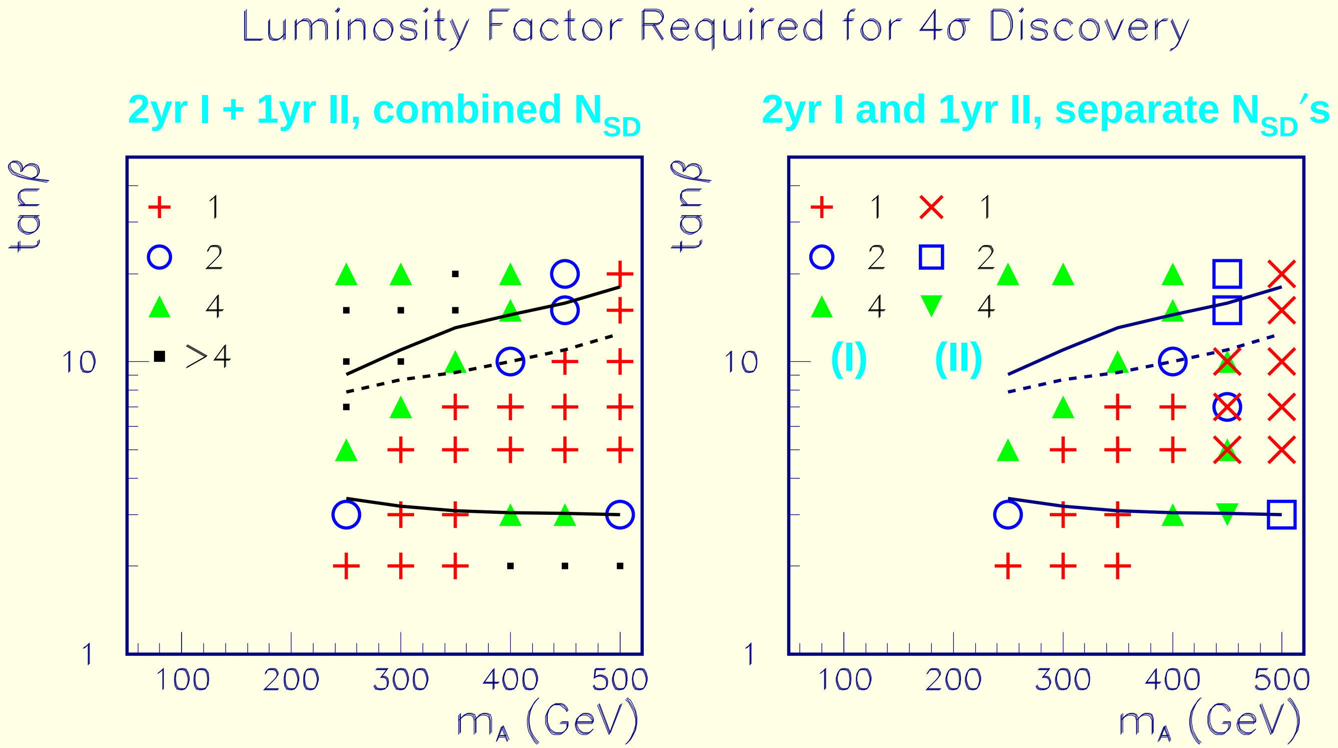
THE SM HIGGS BOSON (Gunion+Asner, Soldner-Rembold+Jikia)



Higgs signal and background, using tripler, $\sqrt{s} = 160$ GeV, $\epsilon_b = 0.7$, $\epsilon_c = 0.035$, $|\cos\theta^*| < 0.5$.

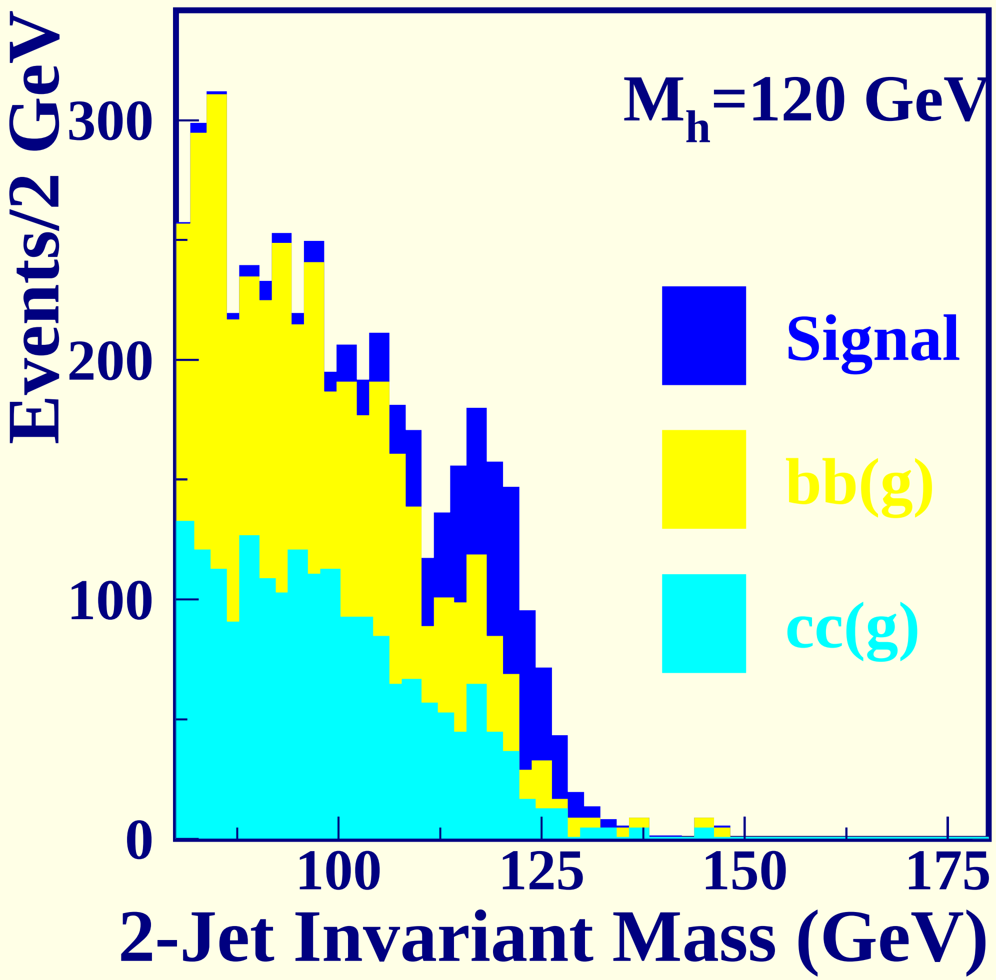
We find excellent signal; 1 10^7 sec year $\Rightarrow$ 2.9% measurement of $N(\gamma\gamma \to h_{\rm SM} \to b\overline{b})$.

THE H and A OF THE MSSM (Gunion+Asner, Muhlleitner etal)



Consider $\sqrt{s} = 630~\mathrm{GeV}$, broad (I) spectrum and narrow (II) spectrum.
LH window: $+$'s($\bigcirc$'s) = 3 yr 4σ NLC (TESLA) discovery after combining 2 yr type-I + 1 yr type-II operation.
Solid lines = LHC H^0, A^0 wedge.
Above dashed line, discover $H^\pm$ at LHC. $\Rightarrow$ preset $\sqrt{s}_{\gamma\gamma} = m_{H^\pm} \sim m_{A^0}$.
Pair production covers up to $m_{A^0} \gtrsim 300~\mathrm{GeV}$.
At lower $\tan\beta$, other channels ($A^0 \to Zh^0$, $H^0 \to h^0h^0$, $A^0, H^0 \to t\bar{t}$) $\Rightarrow$ additional sensitivity.

CP DETERMINATION (Gunion+Grzadkowski, Gunion+Kelly, Gunion+Asner)



Higgs signal and background for transversely polarized photons, $\sqrt{s} = 206$ GeV, $\epsilon_b = 0.7$, $\epsilon_c = 0.035$, $|\cos\theta^*| < 0.5$. 1/2 yr $\perp$ and 1/2 yr $\|$.

We find good signal; 1 10^7 sec year $\Rightarrow$ 7.9% measurement of $N(\gamma\gamma \to h_{\rm SM} \to b\overline{b})$ and $\delta\mathcal{CP}/\mathcal{CP} \sim 0.11$ check of $\mathcal{CP} = +1$.

HIGGS SELF COUPLINGS (Gunion+Asner in progress)

Theoretical studies (Jikia) suggest that $\gamma\gamma$ collisions may be ideal for studying Higgs self couplings.

CONCLUSIONS

- It is very hard to imagine that the physics possibilities provided by the combination of e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collisions will not play a very important role in unraveling the EWSB mechanism and related physics.

- It is really very likely that one or more of the completely unique capabilities of these colliders will, in fact, prove utterly essential to our understanding of EWSB.

- There are many new physics scenarios, such as SUSY and extra dimensions, for which these colliders again provide completely unique or exceptionally powerful probes.