Essential Motivations for a Photon-Photon Collider and Complementarity to LHC and LC

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Based in part on work by members of the photon-collider working group:
D. Asner, B. Grzadkowski, J. Gunion, H. Logan, V. Martin, M. Schmitt, M. Velasco.
References: hep-ph/0110320, hep-ex/0111055, hep-ph/0208219.
For general overview, see also: E. Boos *et al.*, hep-ph/0103090.
On Higgs topics, see also:
S. Soldner-Rembold, G. Jikia: hep-ex/0101056;
M.M. Muhlleitner, M. Kramer, M. Spira, P.M. Zerwas: hep-ph/0101083;
P. Niezurawski, A. F. Zarnecki and M. Krawczyk, hep-ph/0208234.

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The General Physics Case

- The photon collider designs now make it clear that high luminosity can be achieved.

  Very roughly, for $L_{ee\, geometrical} \sim\sim 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, as typical at $\sqrt{s} = 500~\mathrm{GeV}$ machine, $L_{\gamma\gamma}(z > 0.8 z_{\max}(\gamma\gamma)) \sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $L_{e\gamma}(z > 0.8 z_{\max}(e\gamma)) \sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

  This is fully competitive with e^+e^- collisions.

- I will try to support two basic claims regarding the γC.

1. If the Higgs sector goes beyond the simple SM Higgs sector (as is highly probable) then some of the Higgs bosons may only be detectable at a γC, and it is very certain that the Higgs bosons can only be fully studied by including γC measurements.
   Thus, it seems highly possible that the source and nature of EWSB will only be completely revealed if a $\gamma\mathrm{C}$ is available.
2. A photon collider can contribute important new measurements of the detailed properties of new particles, new interactions, and new (large

scale) dimensions discovered earlier at the LHC or at an already operating LC.

A little bit of model discussion is needed in order to justify my first claim and lead in to later specific cases I will summarize.

- **The SM Higgs sector is unnatural and requires fine-tuning. The quadratic divergence for the Higgs mass should be stabilized.**

- **This implies an extension of the SM of some sort, some possibilities being:**
  - supersymmetry (extra Higgs bosons);
  - left-right symmetric theories, which give see-saw neutrino masses and (if supersymmetric) solve the strong CP and SUSY CP problems (even more extra Higgs bosons);
  - various types of effective theories, valid below some $\Lambda > 1$ TeV (typically containing an extended Higgs sector);
  - extra dimensions (radion detection, possible radion-Higgs mixing);
  - technicolor (possibly light pseudo-Nambu-Goldstone bosons, PNGB's);
  - ....

- **In all these cases, a $\gamma\gamma$ collider is fairly certain to be absolutely critical to a full exploration of the bosonic sector.**

- **Even if the SM is correct, we will want to:**
  - *directly* **verify that the Higgs boson is CP-even;**
  - **check for new charged particles beyond our kinematic reach that contribute to the $\gamma\gamma \to h_{\rm SM}$ one-loop coupling.**

Some more detailed ideas along this line:

- **In the MSSM, $\gamma\gamma \to H^0, A^0$ may be the only way to see the heavy MSSM Higgs bosons. This happens if $(m_{A^0}, \tan\beta)$ is in the "wedge" region at moderate $\tan\beta$ and $m_{A^0} \gtrsim 250 - 300~{\rm GeV}$.**

- **More generally, if CP-odd scalars or CP-even scalars with small VV coupling are present, $\gamma\gamma \to A^0$ may be the only way to detect them if (1) they don't have enhanced Yukawa couplings and (2) there is no CP-even or CP-odd scalar of low enough mass for pair production.**

- **For any Higgs boson, but especially for ones with small VV coupling, the $\gamma\gamma$ collider is definitively the best way to directly determine the CP properties.**

  I believe that ultimately, a $\gamma\gamma$ collider will be a necessity if only for this purpose.

- If there is CP-violation in the Higgs sector, as is possible in the MSSM for complex soft-SUSY-breaking phases as well as in the general 2HDM, both CP determination and detection of almost decoupled Higgs bosons could be critical.

- In the CP-conserving NMSSM, there are parts of parameter space in which the CP-odd a_1 and a_2 dominate CP-even $h_{1,2,3}$ decays.

  If this is the case, the LHC will probably not see any Higgs bosons (current analysis).

  At the LC, the signals for $Zh_{1,2,3}$ could overlap by virtue of experimental resolution ($10~\mathrm{GeV}$ or so). The missing mass enhancement would be detectable at the LC, but sorting out what was going on would require CP analysis of all the Higgs bosons, and this would absolutely require the γC.

- In a kind of worst case scenario, we could combine all the worst possibilities.

  1. We could have a CP-violating MSSM Higgs sector or general CP-violating 2HDM or more complicated Higgs sector.
  2. We could have overlapping signals within experimental resolution.
  3. The CP-mixed Higgs bosons could (and generally will!) share the VV coupling-strength-squared: $\sum_i g^2_{VVh_i} = 1$.

4. Higgs pair cross sections could all be below maximal strength (again there is a sum rule that requires sharing of the relevant coupling-squared) and/or some could be kinematically forbidden.

$\Rightarrow$ LHC/Tevatron discovery very problematical.

$\Rightarrow$ LC signals will require a lot of sorting out and CP analysis will be absolutely critical.

- If something like technicolor is correct, then studies of pseudo-Nambu-Goldstone production etc. via the very characteristic anomalous $\gamma\gamma \to P$ couplings will be very revealing.

  Note: $gg \to P^0 \to \gamma\gamma$ will probabaly be detectable at the LHC, but $e^+e^- \to ZP^0$ would be very weak. We would want to check that the observed P^0 is really CP-odd.

- $\gamma\gamma \to W^+W^-$ and $t\bar{t}$, and related $e\gamma$ processes, will be important if strong interactions and/or anomalous couplings are present, as they will influence these channels, very possibly more strongly than other processes.

- If extra dimensions are present, important characteristics will be probed through $\gamma\gamma \rightarrow$Higgs, $\gamma\gamma \rightarrow$Radion, $\gamma\gamma \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow W^+W^-$ production.

- Even if minimal new physics is seen, a $\gamma\mathrm{C}$ can perform unique precision studies of the electroweak gauge bosons and the top quark, where deviations from SM predictions could provide clues to hidden new physics.

- A $e\gamma$ collider might also prove very useful.

  The most important example I know of is the production of a heavy charged particle and light neutral particle (or vice versa). In $e\gamma$ this can be possible whereas two of the heavy particles would need to be made in e^+e^- collisions.

  Examples include: $\widetilde\chi_2^+\widetilde\chi_1^0$ in SUSY; $W'\nu$ new gauge boson.

To Summarize

- At a minimum, a $\gamma\mathrm{C}$ will provide complementary information to that obtained in pp collisions and e^+e^- collisions.
  - $\gamma\gamma$ collisions do not have possible confusion of Z exchange (and in some cases t channel exchange) contributions present in e^+e^- collisions.

- Some important cross sections and rates are actually larger at the $\gamma\mathrm{C}$ than at the LC .

- However, it is also very possible that certain discoveries will only be possible at a $\gamma\mathrm{C}$.

  Indeed, photon colliders have distinct advantages for discovering and studying certain kinds of new physics, but most especially non-SM Higgs physics.

e^+e^-, $\gamma\gamma$ to W^+W^-

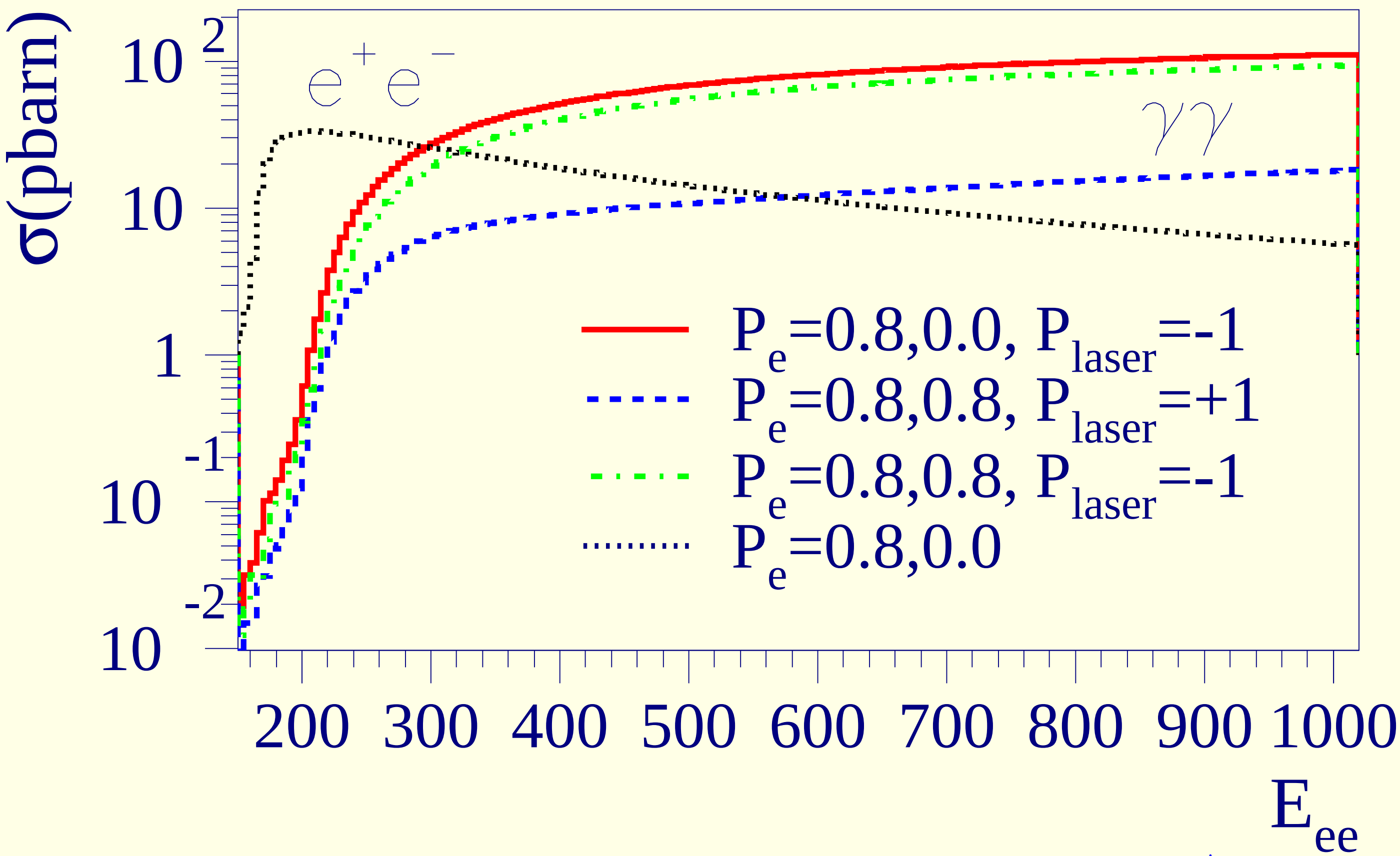


Figure 1: Comparison of WW cross sections in e^+e^- collisions vs. $\gamma\gamma$ collisions (after luminosity folding in latter case).

$\gamma\gamma$ to H^+H^-

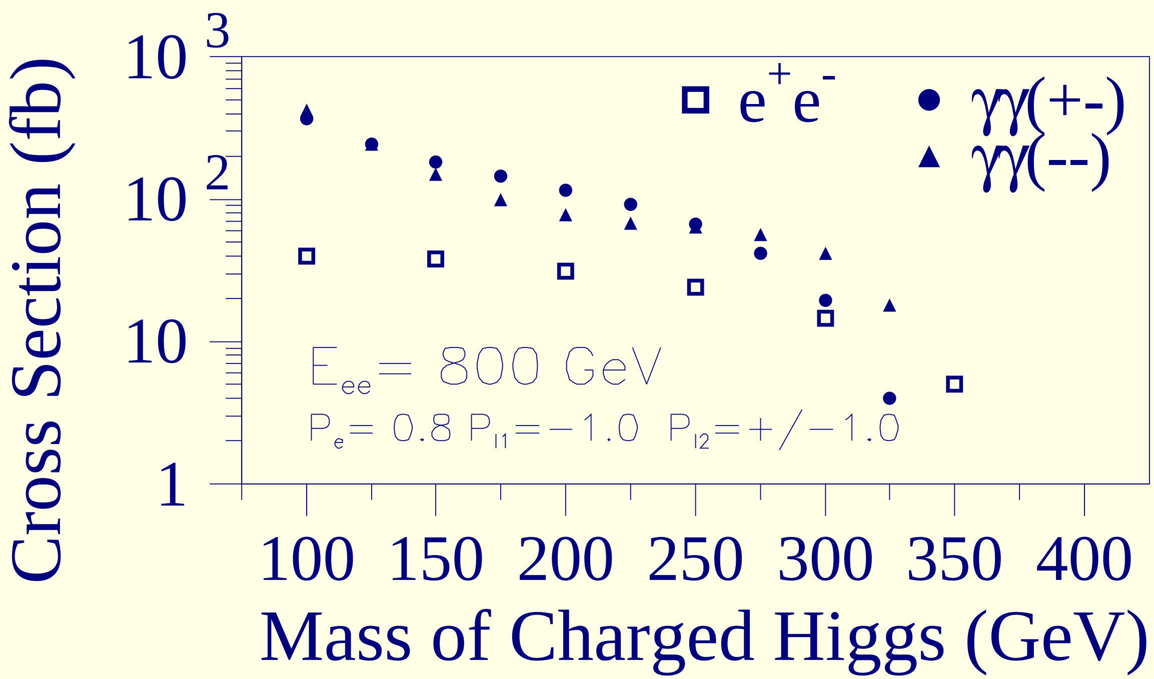


Figure 2: Comparison of $e^+e^- \to H^+H^-$ and $\gamma\gamma \to H^+H^-$ (after luminosity folding) pair production cross sections – no Z exchange in e^+e^- case. Threshold: β^3 in e^+e^- vs. β in $\gamma\gamma$.

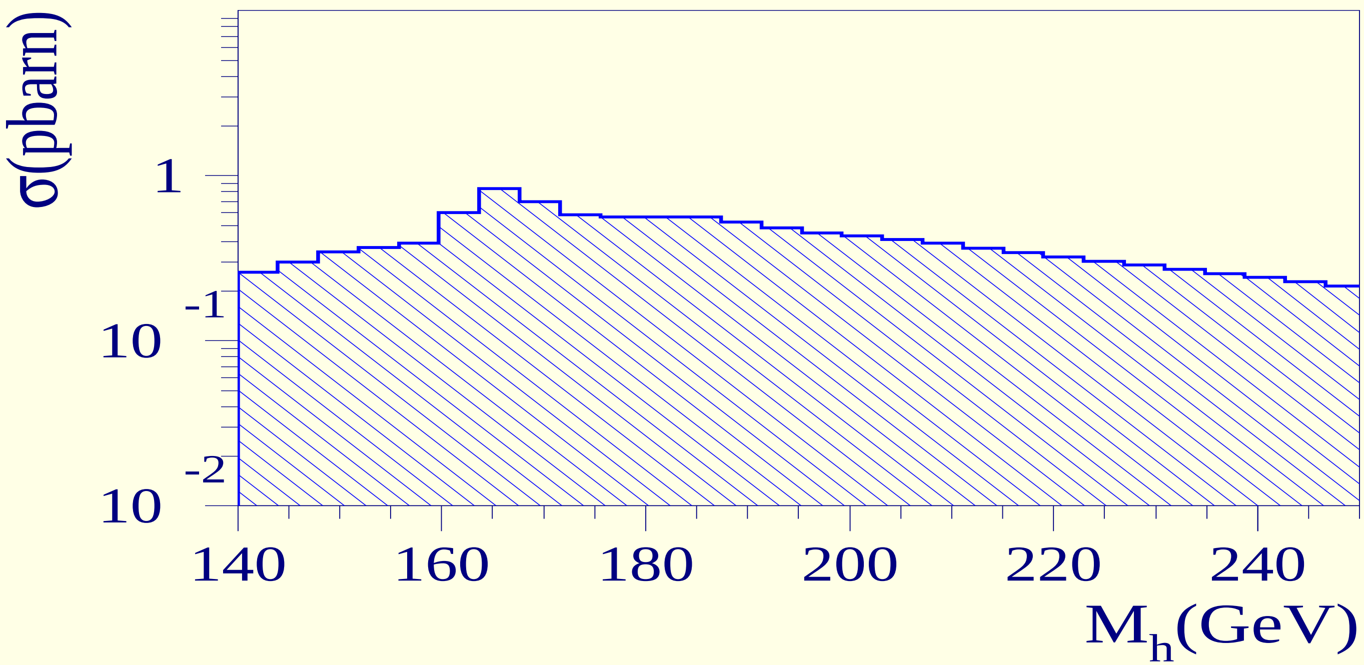


Figure 3: σ **for Higgs production in** $\gamma\gamma$ **collisions at** $\sqrt{s} = 500$ GeV. **Resulting** $\gamma\gamma$ **rate is** $1 - 5$ **times higher than** e^+e^- **rate.**

Resonance CP-determination at a γC

Just a brief reminder of what one does. (JFG+Grzadkowski, JFG+Kelly, Zerwas etal)

- Perfect laser polarization is possible at the γC: either 100% circular or 100% transverse will typically be used.

- This polarization is not entirely transferred to the back-scattered photons.

  The dilution is characterized by the "Stoke's parameters" $\xi_{1,2,3}$ for each of the back scattered photons.

  Computing these accurately requires something like the CAIN Monte Carlo which incorporates multiple interactions and so forth.

- To fully explore the CP nature of a Higgs boson or other resonance, measurements of three asymmetries, $\mathcal{A}_{1,2,3}$ would be ideal.

$$\mathcal{A}_1 = \frac{|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2}{|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2}, \quad \mathcal{A}_2 = \frac{2\mathrm{Im}\left(\mathcal{M}_{++}\mathcal{M}^*_{--}\right)}{|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2},$$

$$\mathcal{A}_3 = \frac{2\mathrm{Re}\left(\mathcal{M}_{++}\mathcal{M}^*_{--}\right)}{|\mathcal{M}_{++}|^2+|\mathcal{M}_{--}|^2} = \frac{|\mathcal{M}_{\|}|^2-|\mathcal{M}_{\perp}|^2}{|\mathcal{M}_{\|}|^2+|\mathcal{M}_{\perp}|^2} \, . \quad (1)$$

The first two asymmetries are typically quite substantial for a large range of 2HDM parameter space for which CP violation occurs.

$\mathcal{A}_3 = +1$ (-1) **for a purely CP-even (CP-odd) Higgs boson or resonance.**

- **In terms of the Stokes parameters specifying the polarizations of the back-scattered photons**

$$dN = dL_{\gamma\gamma} dPS \frac{1}{4} \left(|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2\right) \times$$
$$\Big[(1 + \langle\xi_2\xi_2'\rangle) + (\langle\xi_2\rangle + \langle\xi_2'\rangle)\mathcal{A}_1 + \left(\langle\xi_3\xi_1'\rangle + \langle\xi_1\xi_3'\rangle\right)\mathcal{A}_2$$
$$+ \left(\langle\xi_3\xi_3'\rangle - \langle\xi_1\xi_1'\rangle\right)\mathcal{A}_3\Big] \, . \quad (2)$$

- **The actually measured asymmetries are then**

$$T_1 = \frac{N_{++}-N_{--}}{N_{++}+N_{--}} = \frac{\langle\xi_2\rangle+\langle\xi_2'\rangle}{1+\langle\xi_2\xi_2'\rangle}\mathcal{A}_1 \, , \quad (3)$$

$$T_2 = \frac{N(\phi=\frac{\pi}{4})-N(\phi=-\frac{\pi}{4})}{N(\phi=\frac{\pi}{4})+N(\phi=-\frac{\pi}{4})} = \frac{\langle\xi_3\xi_1'\rangle+\langle\xi_1\xi_3'\rangle}{1+\langle\xi_2\xi_2'\rangle}\mathcal{A}_2\,, \quad (4)$$

$$T_3 = \frac{N(\phi=\frac{\pi}{2})-N(\phi=0)}{N(\phi=\frac{\pi}{2})+N(\phi=0)} = \frac{\langle\xi_3\xi_3'\rangle-\langle\xi_1\xi_1'\rangle}{1+\langle\xi_2\xi_2'\rangle}\mathcal{A}_3\,, \quad (5)$$

For T_1, we 100% polarize the laser photons both with $+$ helicity and then flip both to negative helicities.

For $T_{2,3}$, ϕ is the angle between the 100% linear polarizations of the laser photons.

T_2 and T_3 are harder to measure than T_1 because the Stoke's parameters in the numerators are smaller for the former two. Nonetheless, excellent accuracy can be achieved.

CP Determination at LHC and LC

A brief comparison:

- At the LHC, the only techniques possible are:

1. Observe large number of Higgs bosons and look at self-analyzing $\tau^+\tau^-$ decays. (Gunion, Grzadkowski; Zerwas etal)
   But, to be effective you need to know $\tau^+\tau^-$ (i.e. Higgs) rest frame. Smearing is probably a killer — no detailed study available.
   If Higgs decays to other Higgs, then $BR(\to \tau^+\tau^-)$ is reduced — $\Rightarrow$ poor results.
2. Observe distributions of h with respect to t and $\bar{t}$ in $t\bar{t}h$ final state. Some early theory studies (Pliszka and Gunion) suggest some hope for $h = h_{\rm SM}$ — experimental study with Sapinski is in progress, but looks less hopeful.
   If $\tan\beta \gtrsim 2$, forget it — rate is too small.
   Note: Analogue in $b\bar{b}h$ final state does not work, since the CP-distinguishing features are proportional to the quark mass. $\Rightarrow$ no high-$\tan\beta$ substitute.

- At the LC, the possibilities are:

1. $\tau^+\tau^-$ self-analyzing decays (JFG + Grzadkowski, Zerwas etal, Brower etal). With $h = h_{\rm SM}$, looks ok but not wonderful.
   For general CP-even guy with reduced ZZ coupling, accuracy detiorates rapidly.

Similar rate problem if $h \to aa$ or similar decays are substantial, as possible in a general model.

2. $t\bar{t}h$ final state distributions (JFG + He); looks good for $h = h_{\rm SM}$ if $\sqrt{s} \gtrsim 800~{\rm GeV}$ and $m_{h_{\rm SM}} \sim 120~{\rm GeV}$.

   But, if $\tan\beta \gtrsim 2$ the rate falls very rapidly.

   And, as m_h increases, the threshold kills the rate very rapidly.

3. Warning: the distribution of the Higgs relative to the Z in the $e^+e^- \to Zh_M$ final state ($h_M = \cos\phi_M h + \sin\phi_M a$) is insensitive to the a component since the hZZ coupling is tree-level, while the aZZ coupling is 1-loop.

$$\frac{d\sigma}{d\cos\theta} \propto E(\cos\theta)\cos^2\phi_M + O(\cos\theta)\sin\phi_M\cos\phi_M L + E'(\cos\theta)\sin^2\phi_M L^2\,, \quad (6)$$

   where E, E' are even functions of $\cos\theta$ and O is odd in $\cos\theta$. L is a typical one-loop factor (small).

   The rate does not distinguish between mixing with another CP-even Higgs boson or with a CP-odd Higgs boson.

   Since L is small, the $O(\cos\theta)$ term would be very hard to detect relative to the $E(\cos\theta)$ term unless $\cos\phi_M \sim L\sin\phi_M$, in which case the rate would be quite small ($\propto L^2$) and errors would be large for that reason.

Special Capabilities for Higgs bosons

1. **Precision studies of a SM-like Higgs boson, esp. light h^0 of SUSY,** *that are directly sensitive to the $\gamma\gamma$ coupling* **and hence to heavy charged particles (both weakly and strongly interacting) that acquire mass via the Higgs mechanism (vs. e.g. soft-SUSY-breaking — but there is some sensitivity to SUSY loops as well).**

2. **Discovery of the H^0, A^0 of the MSSM in the "wedge" region.**

3. **Determination of the CP nature of any Higgs boson that can be observed.**

4. **Discovery of a CP-odd A^0 that is undetectable at any other collider.**

5. **Charged Higgs bosons.**

- Employ CAIN Monte Carlo for luminosity, using realistic polarization expectations (80%) for e^- beam, e^-e^- collisions ($i.e.$ predictions based on both beams being polarized), NLC parameters and IR, including LLNL laser expectations (1 micron wavelength, . . .) and IP design.

- The results shown will assume full devotion of e^-e^- collisions to $\gamma\gamma$ collider for a certain number of Snowmass 10^7 sec years.

- We will show NLC expectations for the LLNL laser design.

- Some possibility of a factor of 2 higher luminosity (TESLA, round beams, more laser power, ...)

A light SM-like Higgs

The two items on the agenda will be:

- precision measurements of $\gamma\gamma \to h \to b\overline{b}$ and rough measurement of $\gamma\gamma \to h \to \gamma\gamma$.

- direct verification that the h has CP=$+$.

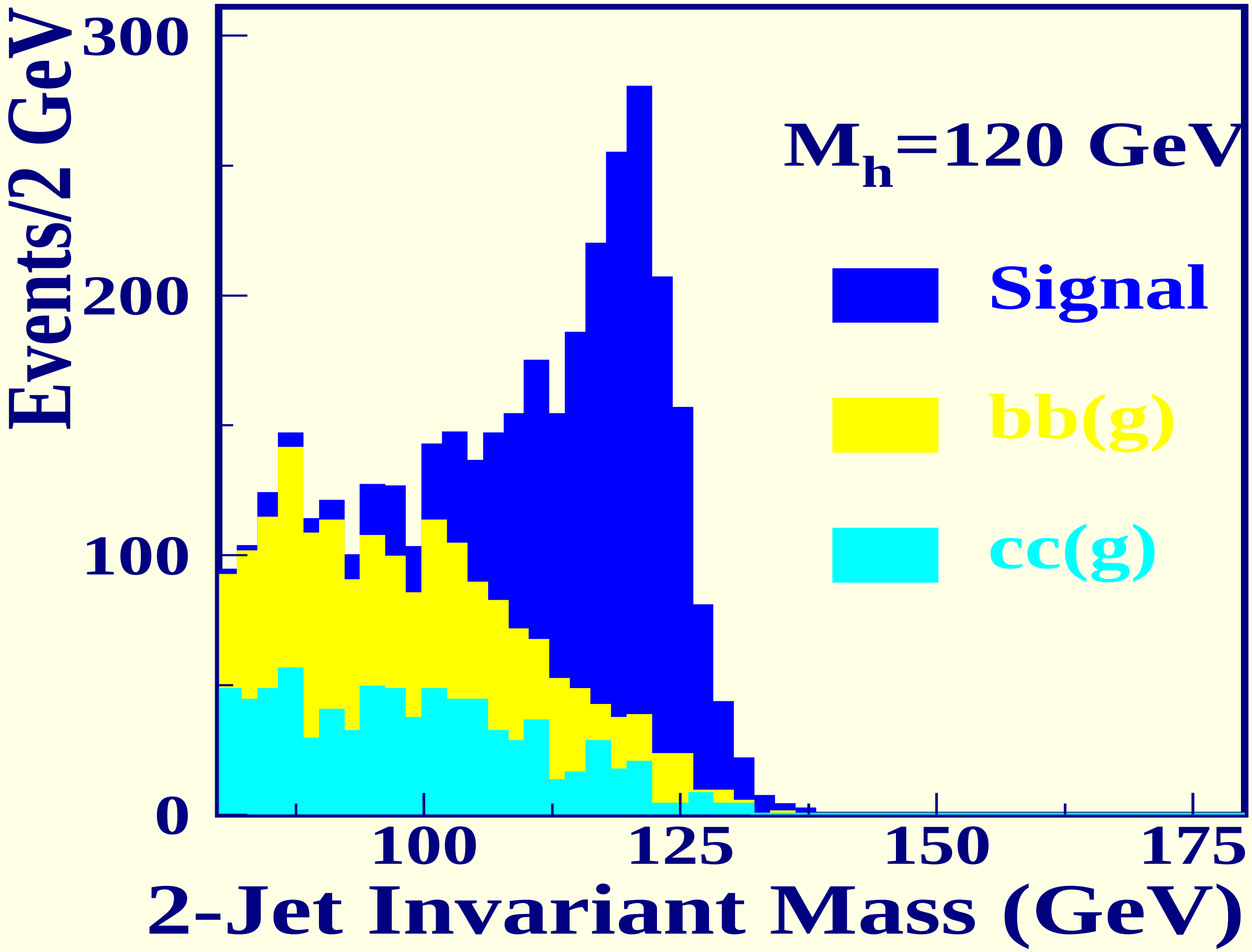


Figure 4: Signal and background rates in the $b\bar{b}$ channel for $h_{\rm SM} = 120~{\rm GeV}$. Precision of rate measurement $\sim 2.9\%$ $\Rightarrow$ relatively small deviations from SM couplings (e.g. as for h^0 of SUSY or due to new particles, even SUSY particles) can be detected.

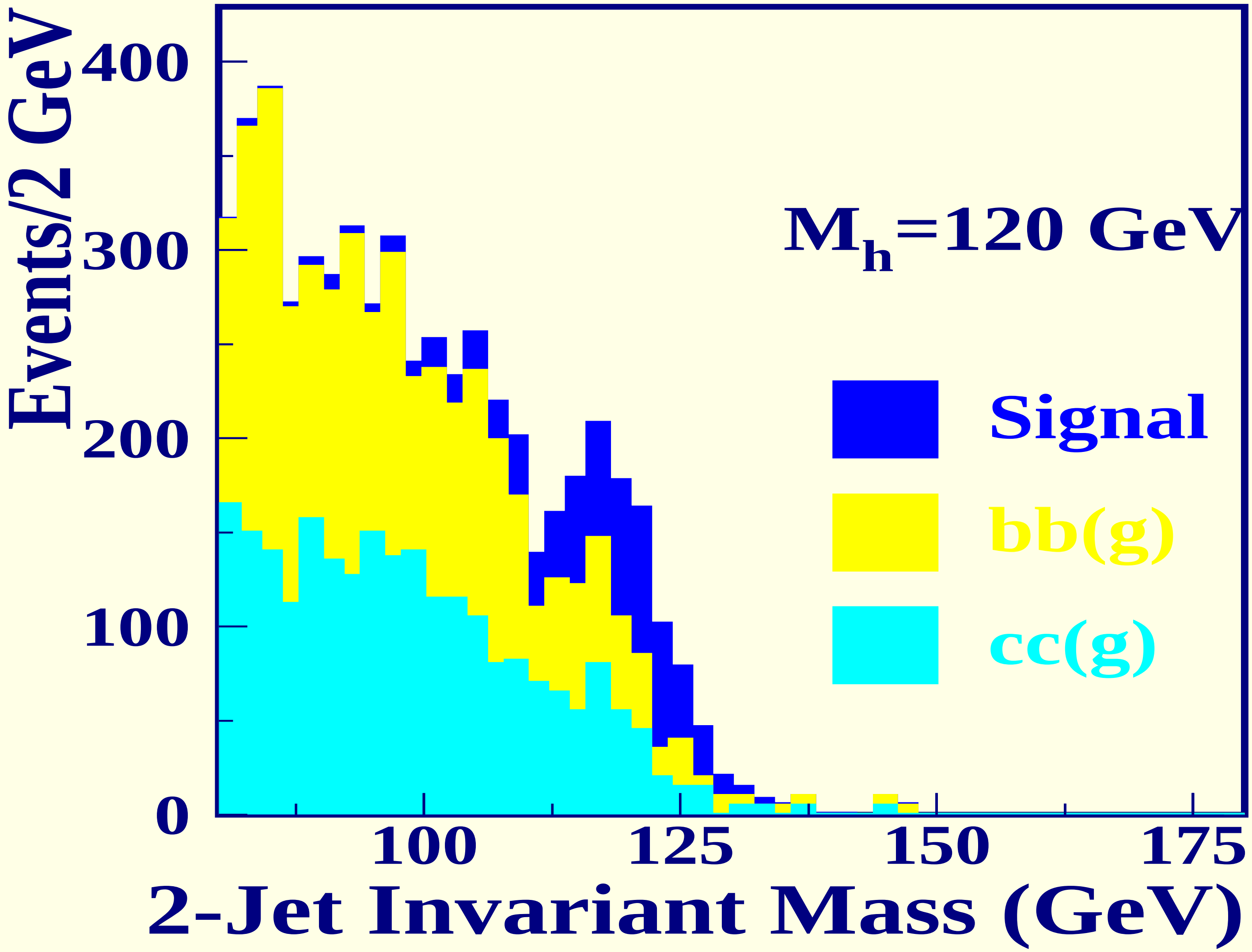


Figure 5: Signal and background rates in the $b\bar{b}$ channel for $h_{\rm SM} = 120~{\rm GeV}$ for the transversely polarized γC configuration needed for the CP determination ($\sqrt{s} = 206~{\rm GeV}$ and $x = 1.86$). $\Rightarrow$ $\frac{\delta\mathcal{CP}}{\mathcal{CP}} \sim 0.11$

- **To show what precision measurements of $\gamma\gamma \to h^0 \to b\bar{b}$ might accomplish consider case where there is a light stop, $\widetilde{t}_1$ that has been observed and that the stop-section mixing angle $\theta_{\widetilde{t}}$ has been approximately measured. We can then determine $m_{\widetilde{t}_2}$ via $\widetilde{t}_2$-loop contributions to the $\gamma\gamma \to h^0$ coupling.**

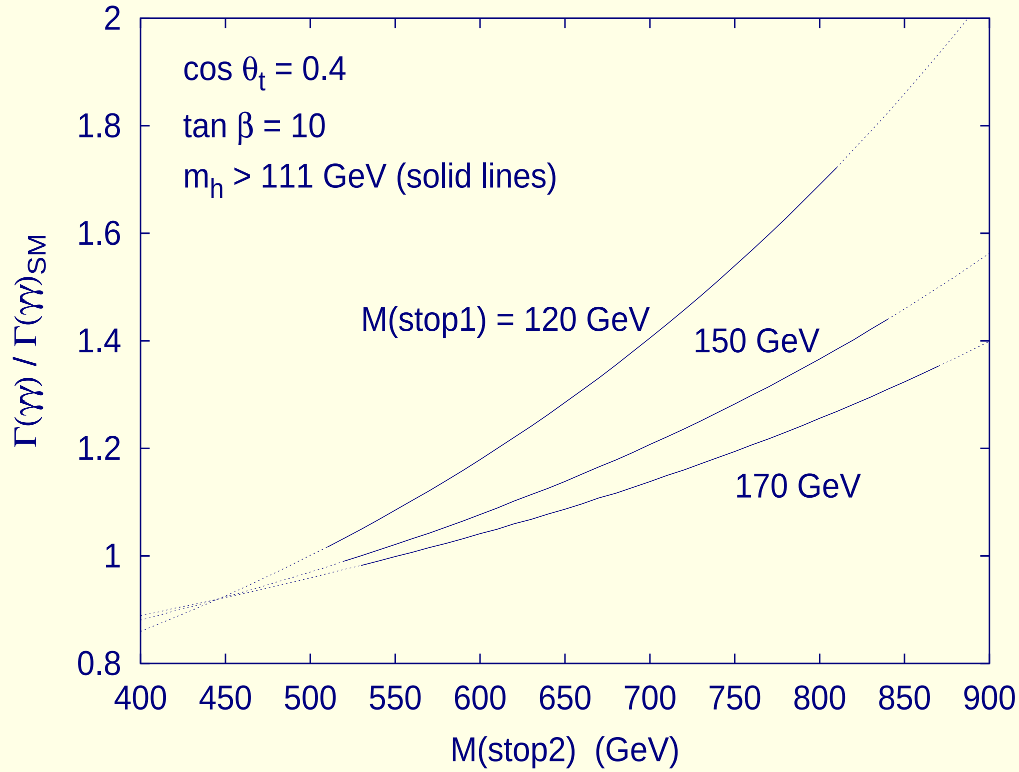


Figure 6: Dependence of the partial width $\Gamma(h^0 \to \gamma\gamma)$ on $m_{\tilde{t}_2}$ for various values of $m_{\tilde{t}_1}$ and $\cos\theta_{\tilde{t}}$. Here $m_A = 1$ TeV, $\tan\beta = 10$, $M_2 = -\mu = 200$ GeV, and the remaining SUSY mass parameters are set to 1 TeV.

- **The large h production rate ($11K$ per year roughly at $m_h = 120$ GeV) means that we can even look for $\gamma\gamma \to h \to \gamma\gamma$, which is doubly sensitive to $\Gamma(h \to \gamma\gamma)$.**

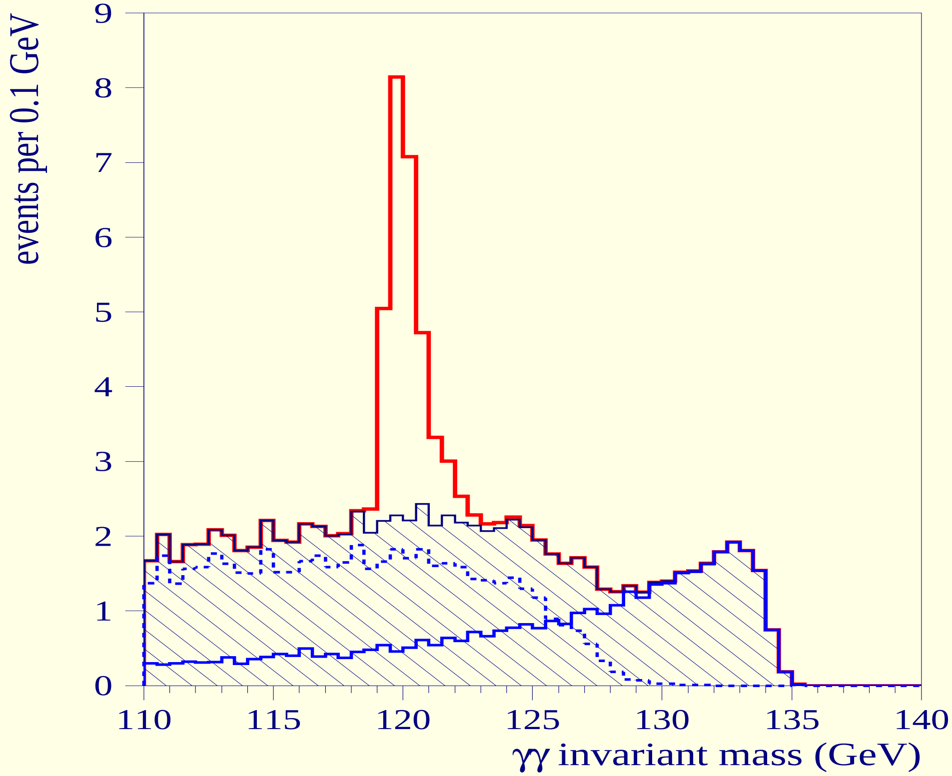


Figure 7: The mass distribution, including backgrounds from $\gamma\gamma \to \gamma\gamma$ (dashed line extending to ~ 130 GeV) and $e\gamma \to e\gamma$ (heavy solid line extending to ~ 135 GeV) as well as the signal (peak at 120 GeV). The hatched histogram shows the sum of background contributions.

- $\gamma\gamma \to hh$ production is also interesting as a complementary probe of the hhh self coupling.

  - To evaluate the sensitivity of the cross section to the trilinear Higgs coupling, we introduce an anomalous trilinear Higgs coupling in a gauge-invariant way:

$$\delta\mathcal{L}_{\rm Higgs} = -\frac{\delta\kappa}{2}\frac{m_H^2}{v}\left[H^3 + \frac{3}{v}G^+G^-H^2\right] + \cdots, \qquad (7)$$

    where $v = 246$ GeV is the Higgs vacuum expectation value, H is the SM Higgs field, $G^\pm$ are the charged Goldstone bosons, and $\delta\kappa$ is the dimensionless anomalous trilinear Higgs coupling normalized so that for $\delta\kappa = 1$, the anomalous term will cancel the SM H^3 coupling.
  - A comparison of hh event yields in e^+e^- and $\gamma\gamma$ collisions indicates similar sensitivity. (NLC designs assumed.)

	$\sqrt{s_{ee}} = 500$ GeV			$\sqrt{s_{ee}} = 800$ GeV		
	$\int \mathcal{L}_{th}$ ($\mathrm{fb}^{-1}/10^7$ s)	σ (fb)	Event yield	$\int \mathcal{L}_{th}$ ($\mathrm{fb}^{-1}/10^7$ s)	σ (fb)	Event yield
Spin-0	40	0.3	13	120	0.3	39
Spin-2	20	0.1	1-2	60	0.2	1-2
e^+e^-	160	0.2	32	250	0.15	38

Table 1: Comparison of the integrated luminosity above threshold ($\int \mathcal{L}_{th}$), the "average" cross section (σ), and the event yield per Snowmass year of 10^7 sec for double-Higgs production in $\gamma\gamma$ and e^+e^- collisions. We assume $m_H = 120$ GeV.

– In e^+e^- collisions, the reconstruction efficiency of the ZHH final state is 43%.
  We expect it to be better than this in $\gamma\gamma$ collisions, because of the simpler HH final state.
  The dominant background in both analyzes is $e^+e^-/\gamma\gamma \to WW$.
– We estimate comparable sensitivity to the cross section per running time in $\gamma\gamma$ or e^+e^- collisions at $\sqrt{s}_{ee} = 800$ GeV.

- Overall, it is clear that the $\gamma\gamma \to hh$ measurement of the trilinear self-coupling could prove very valuable.

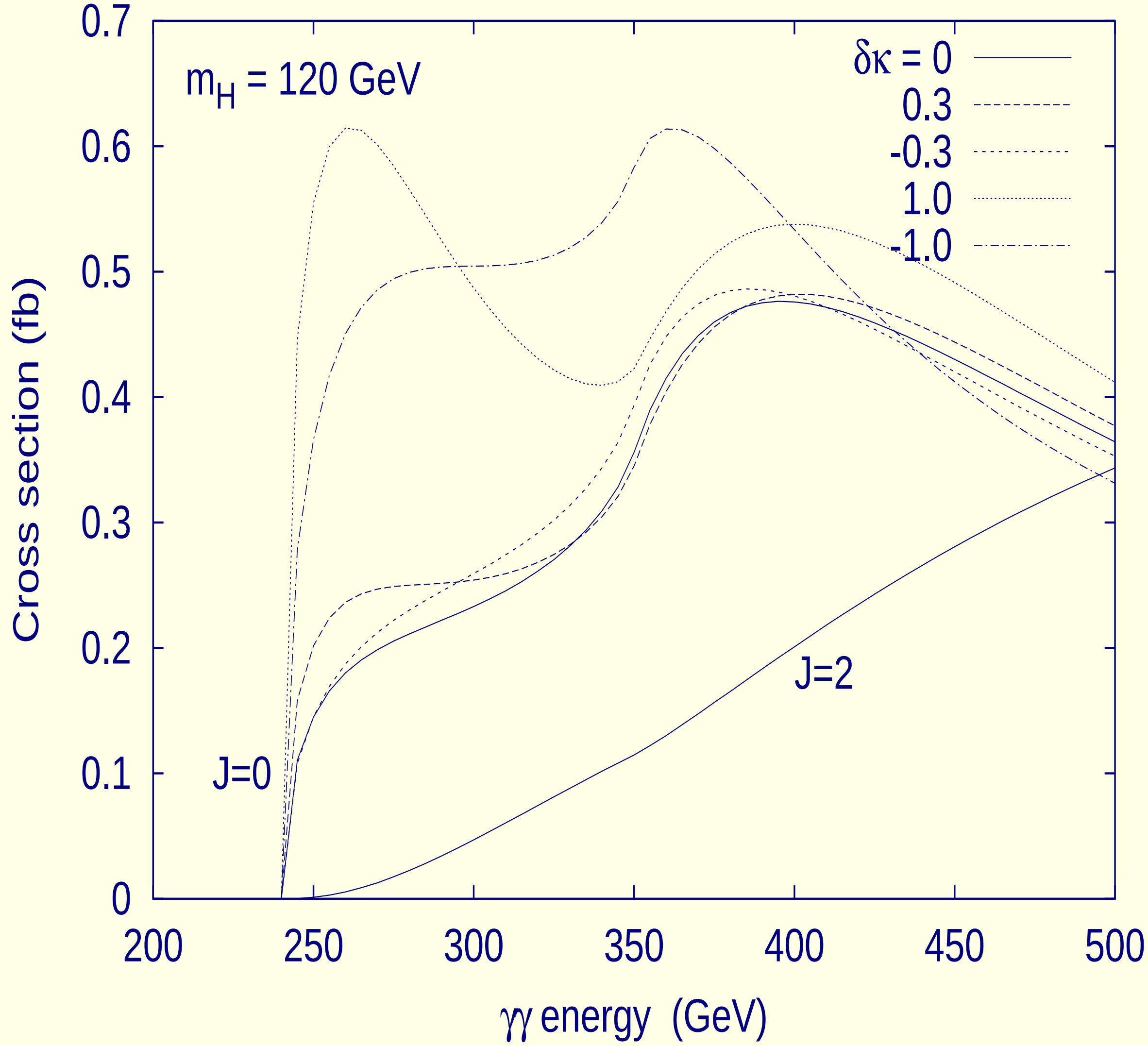


Figure 8: Parton-level cross section for $\gamma\gamma \to hh$ as a function of the $\gamma\gamma$ center-of-mass energy, for $J = 0$ and $J = 2$. The effects on the $J = 0$ cross section from varying the trilinear coupling are shown.

The heavy MSSM H^0 and A^0

- For heavy MSSM Higgs, we will assume operation at $\sqrt{s} = 630$ GeV ($\rightarrow x = 5.69$ for 1 micron laser wavelength).
  - Type-II Configuration:
    The luminosity peak for $\lambda_e = \lambda'_e = 0.4$ and $P = P' = -1$ is at about 500 GeV with good $\langle \lambda\lambda' \rangle$ and $\mathcal{L}$ down to 450 GeV.
    Since $\langle \lambda\lambda' \rangle \sim 0.8$ at the peak, $\Rightarrow$ dominant background is $J_z = \pm 2$!
  - Type-I Configuration:
    For $P = P' = +1$, get broad spectrum sensitivity in region of $m_{A^0} \sim 250 - 400$ GeV.

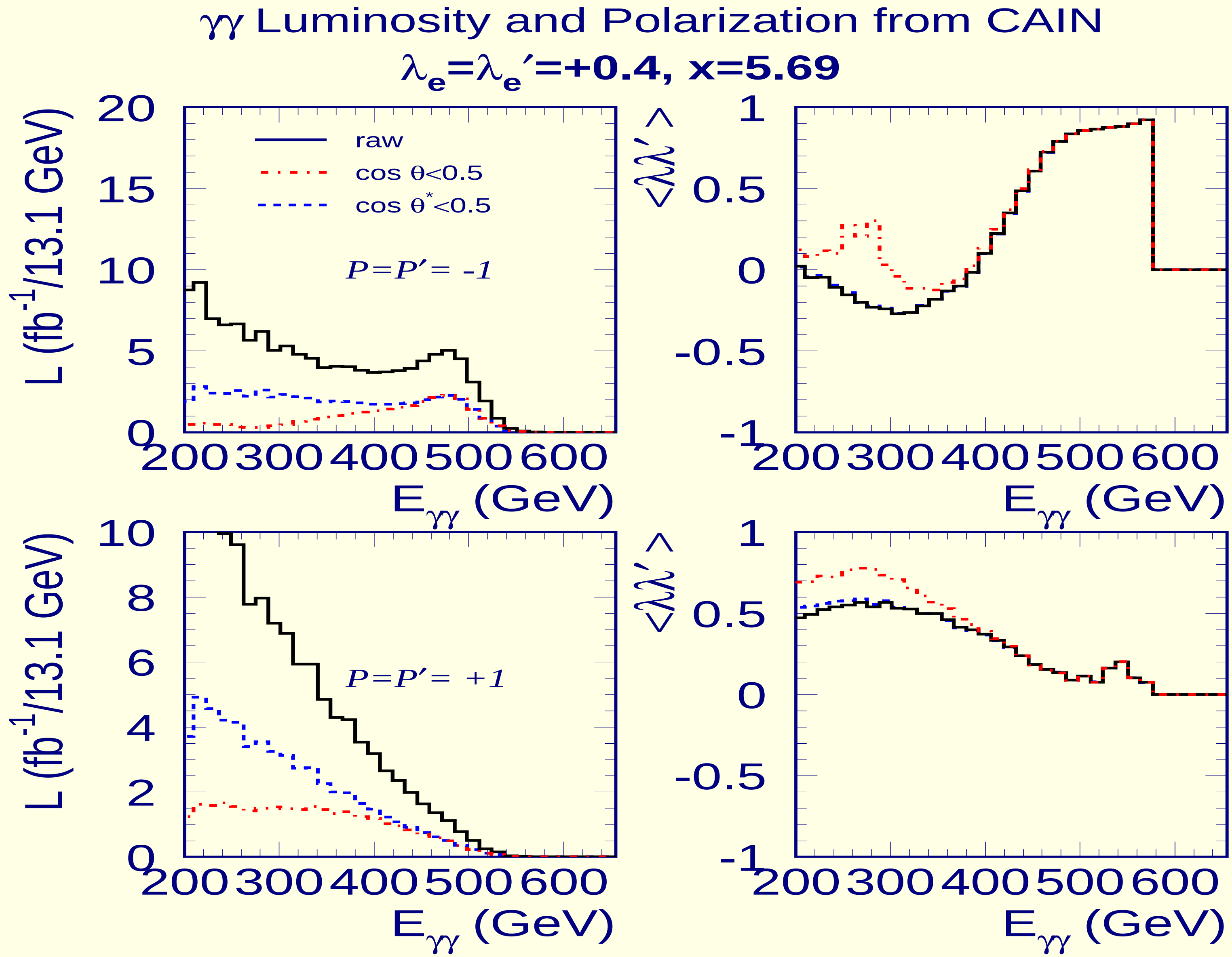


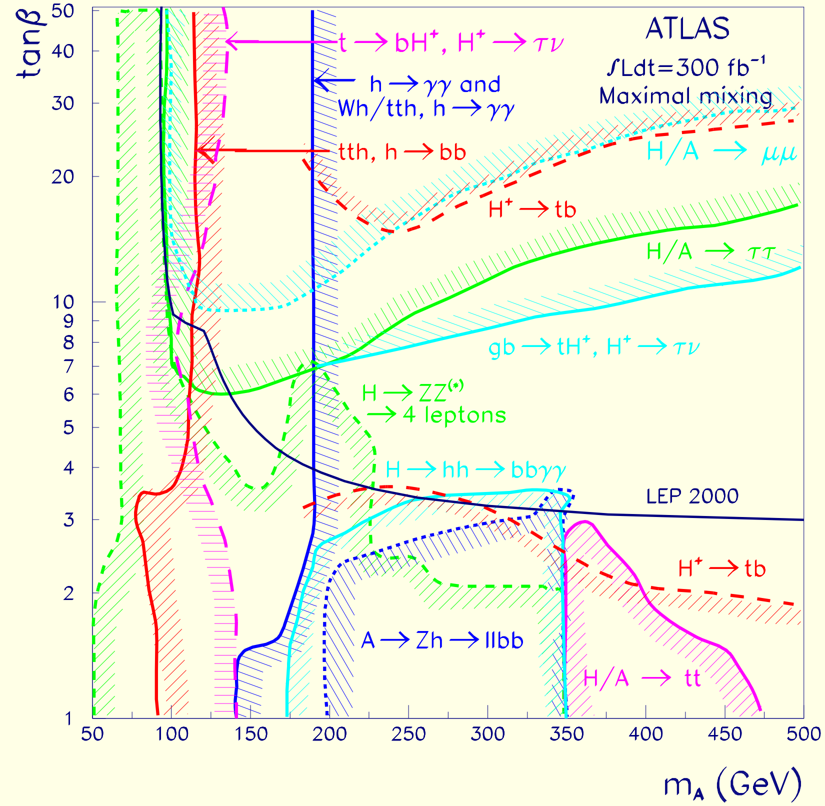
Figure 9: Luminosity (for 1 10^7 sec year) and $\langle\lambda\lambda'\rangle$ expectations for $\lambda_e = \lambda'_e = 0.4$ vs. $E_{\gamma\gamma}$ for $P = P' = -1$ (type-II) and $P = P' = +1$ (type-I)

- Imagine SUSY has been discovered so we would expect that the two doublet MSSM Higgs sector must be present (or some extension thereof).

- It is very possible that only the h^0 of the MSSM will be discovered in normal LC e^+e^- collisions and LHC operation. This happens if:
  - The $[m_{A^0}, \tan\beta]$ values are in the 'wedge' where the LHC can detect only the h^0 and cannot find the $H^0, A^0, H^\pm$.
  - $\sqrt{s}$ at the LC is $< m_{A^0} + m_{H^0} \sim 2m_{A^0}$ and $< 2m_{H^\pm} \sim 2m_{A^0}$, so the pair processes (i.e. H^0A^0, H^+H^-, $WW \to A^0A^0$, $WW \to H^0H^0$, ...) are all kinematically forbidden.
  - In the 'wedge', the $e^+e^- \to t\bar{t}H^0$, $t\bar{t}A^0$, $b\bar{b}H^0$ and $b\bar{b}A^0$ production processes are also highly suppressed. In fact, the LC wedge (for $\sqrt{s} < 800~\mathrm{GeV}$) is larger than the LHC wedge.
  - Other single production processes, the best being $e^+e^- \to \gamma H^0$ and γA^0, are basically one-loop and highly suppressed.

- $\Rightarrow \gamma\gamma$ collisions would give the best chance for H^0, A^0 detection.

At the LHC, there is a region starting at $m_{A^0} \sim 200~\mathrm{GeV}$ at $\tan\beta \sim 6$, widening to $2.5 < \tan\beta < 15$ at $m_{A^0} = 500~\mathrm{GeV}$ for which the the heavy MSSM Higgs bosons cannot be seen.



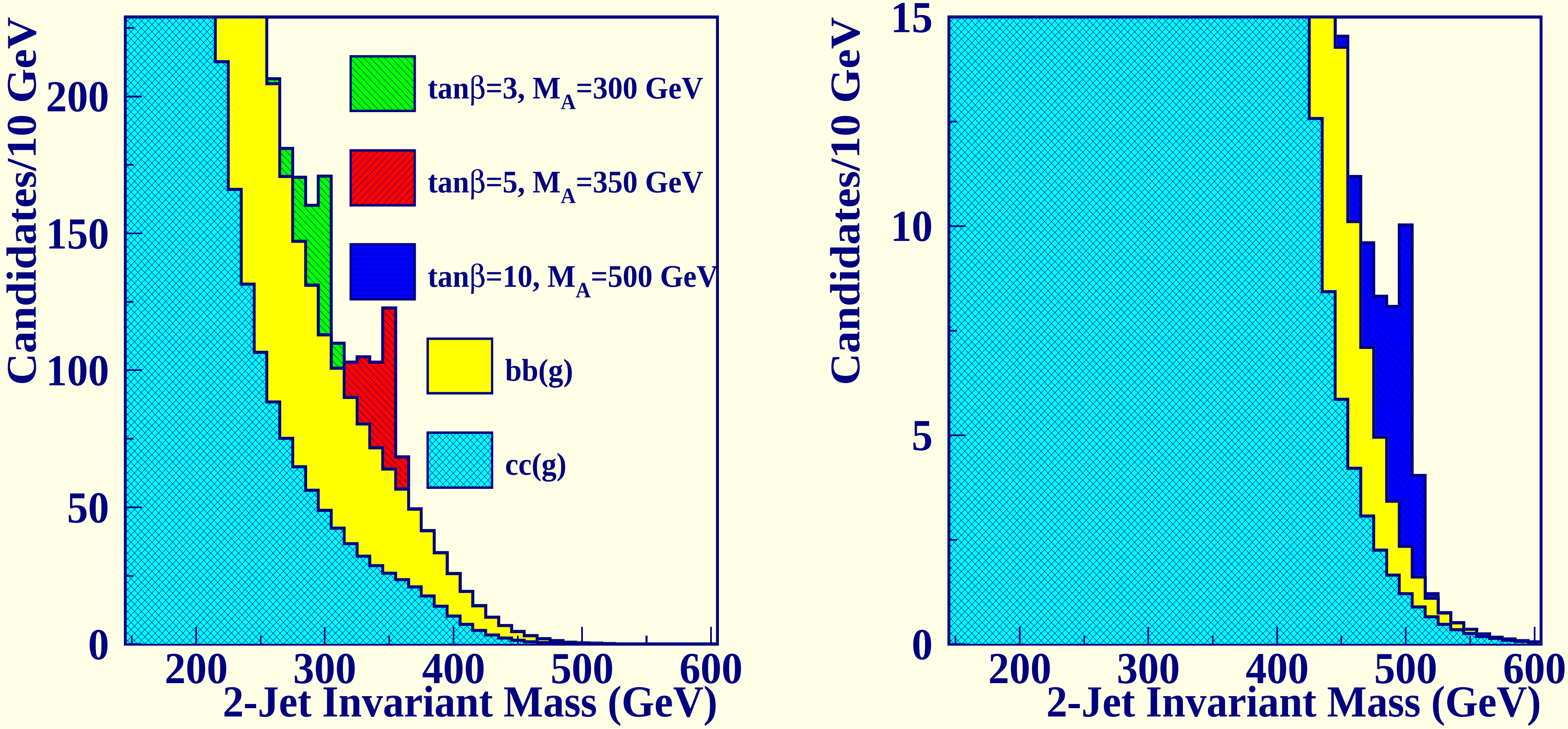
5σ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A^0}, \tan\beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\mathrm{fb}^{-1}$ for the ATLAS detector. This figure is preliminary.

At the LC, the upper $\tan\beta$ edge of the wedge is even higher for $\sqrt{s}_{e^+e^-} \lesssim 0.8 - 1~\mathrm{TeV}$, and processes allowing single production of H^0 or A^0 using one (t) loop couplings ($e.g.$ $e^+e^- \to \gamma A^0$) only really become visible when $\tan\beta \lesssim 1$.

There are two scenarios:

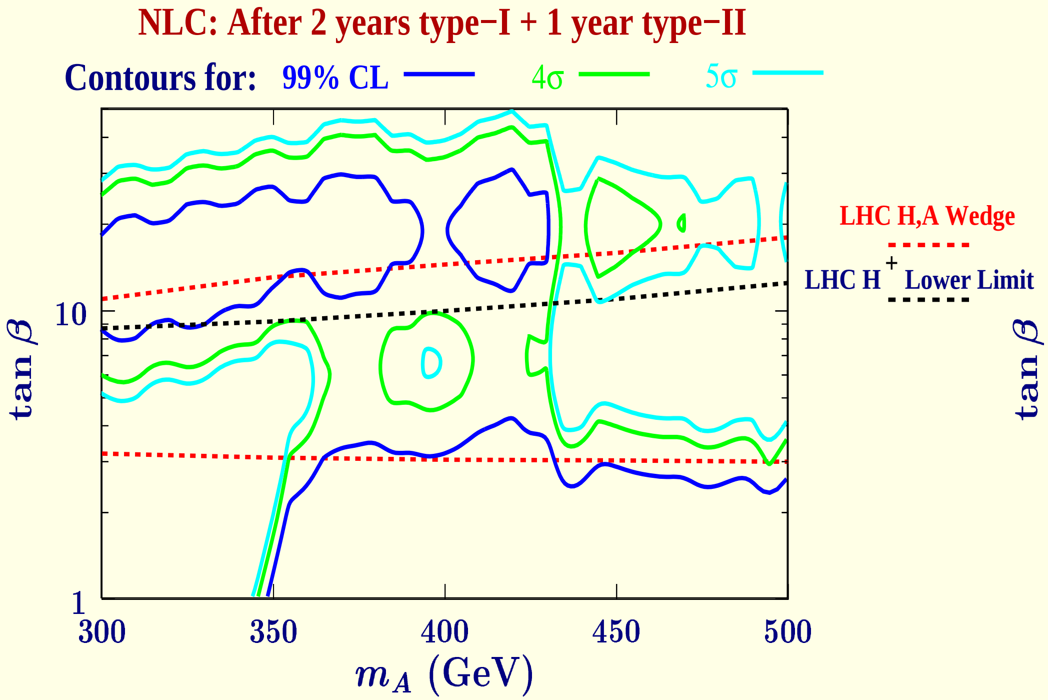
- **We have some constraints from precision h^0 measurements ($e.g.$ from $\Gamma(h^0 \to b\bar{b})$) that determine $m_{H^0} \sim m_{A^0}$ within 50 GeV.**
  $\Rightarrow$ choose $\sqrt{s}$ and peaked luminosity spectrum with peak near this mass.
- **We do not have such constraints.**
  In particular: there are reasonable MSSM scenarios for which decoupling ($\cos^2(\beta - \alpha) = 0$) happens essentially independent of m_{A^0}.
  $\Rightarrow$ No deviations are seen.
  Also: there are cases where large radiative corrections can make interpretation of precision h^0 measurements uncertain.
  $\Rightarrow$ uncertain knowledge about m_{A^0}. (How will we know ahead of time?)
  Either way we must
  - **(a) scan with many $\sqrt{s}$ settings and peaked luminosity type-II polarization choices or**
  - **(b) run at high energy and run part of time with broad spectrum (type-I) and part of time with peaked spectrum (type-II).**

To cover all of wedge region up to $m_{A^0}, m_{H^0} \sim 500$ GeV, (b) is slightly superior to (a) and is, of course, compatible with continually running at maximum machine energy for other possible new physics processes.



Type-I **Type-II**

Figure 10: Typical one-year peaks after smearing and width effects for type-I and type-II luminosity spectra



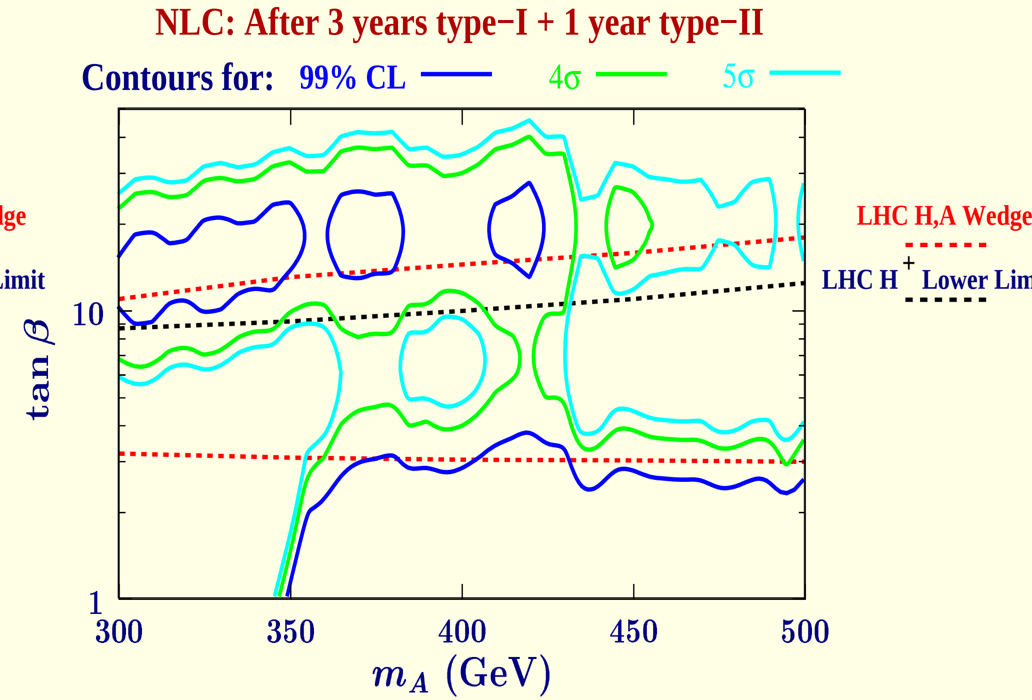


Figure 11: Contours for discovery and 99% CL exclusion after 3 or 4 years of NLC $\gamma\gamma$ running.

- **Note the holes at $m_{A^0} \sim \mathbf{375}$ GeV and $\sim \mathbf{425}$ GeV for 2+1 years. (These were present in our earlier analysis, but grid employed did not spot them.)**
- **These holes are largely covered at 4σ by 3+1 year operation.**
- **At the lower $\tan\beta$ values in wedge, $H^0, A^0 \to t\bar{t}$ final state would probably allow discovery for just 2+1 years.**

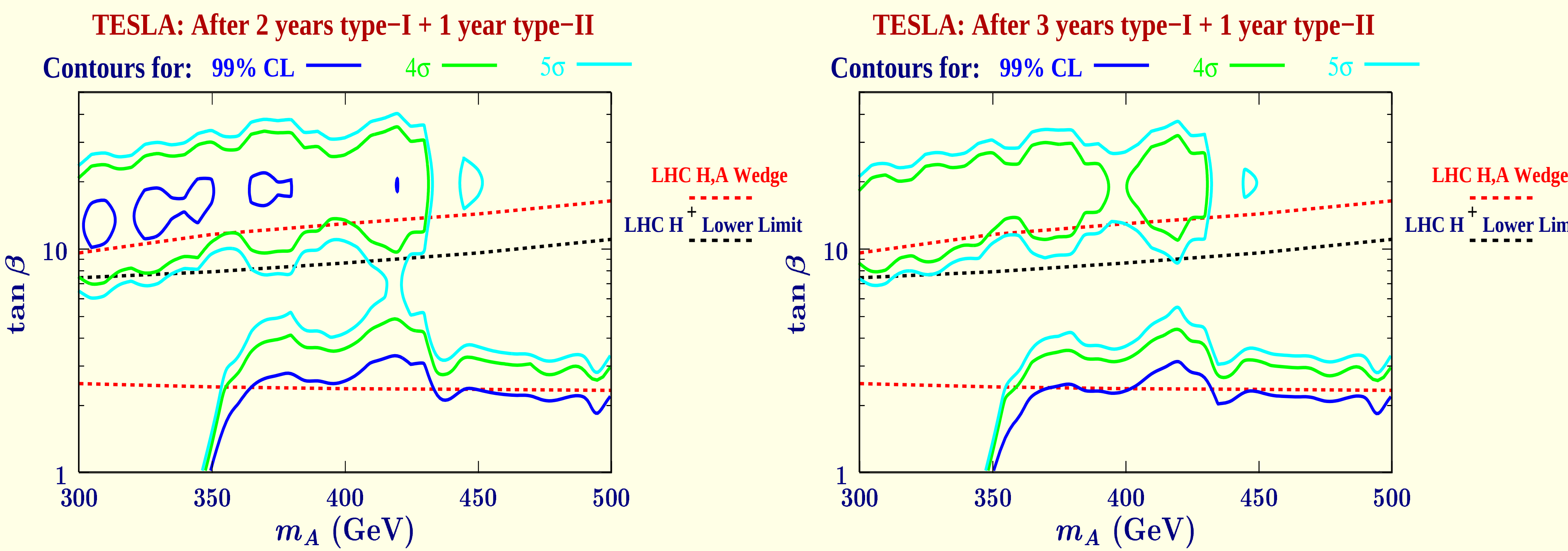


Figure 12: Contours for discovery and 99% CL exclusion after 3 or 4 years of TESLA $\gamma\gamma$ running.

- Assume TESLA gives factor of 2 luminosity increase, without necessitating IR or detector setup changes that impact acceptance, ...
- $\Rightarrow$ no holes at $m_{A^0} \sim 375$ GeV and ~ 425 GeV for 2+1 years at 4σ level.
- $\Rightarrow$ no holes at 5σ level after 3+1 years.
- $t\bar{t}$ still needed in lower part of wedge for $m_{A^0} > 350$ GeV.

Bottom Line

For discovery, the $\gamma\mathrm{C}$ is almost perfectly complementary to the LHC "wedge" region.

Determination of $\tan\beta$

- **An important question, if SUSY is detected and the H^0, A^0 can be detected, is whether the Yukawa couplings of the H^0, A^0 are indeed determined by $\tan\beta$ in the predicted way: $b\overline{b} \propto \tan\beta$; $t\overline{t} \propto \cot\beta$.**
- **One loop corrections will be necessary for a precision comparison.**
- **Only the $\gamma\mathrm{C}$ will be able to do this in the wedge region.**
- **Our rough estimates of how well we can do are given in the table below assuming that we have only the discovery data.**
- **Once we have seen the H^0, A^0, we can really center the $E_{\gamma\gamma}$ peak on m_{A^0} and do much better.**

  Of course, at $m_{A^0} \sim 500~\mathrm{GeV}$ where our peak is located, the results given are the correct *one year* results.

m_{A^0}(GeV)	250	300	350	400	450	500
$\tan\beta = 2$	0.51	0.34	0.20	0.66	0.46	0.48
$\tan\beta = 3$	0.51	0.27	–	0.45	0.30	0.32
$\tan\beta = 5$	0.71	0.34	0.19	–	0.56	0.55
$\tan\beta = 7$	–	0.66	0.23	0.62	0.67	0.87
$\tan\beta = 10$	–	–	0.50	0.64	0.46	0.53
$\tan\beta = 15$	0.46	0.67	–	–	–	–

Table 2: We give the rough error for $\tan\beta$ based on measuring a certain $\gamma\gamma \to H^0, A^0 \to b\bar{b}$ rate associated with Higgs discovery in the wedge region. These errors assume two years of operation in broad spectrum mode and one year of operation in peaked spectrum mode at $\sqrt{s} = 630$ GeV. The –'s indicate $[m_{A^0}, \tan\beta]$ cases for which the error exceeds 100%. The errors are computed as described in the text. Because of the finite difference approach, results are not presented for $\tan\beta = 20$, but errors there would be large.

Results are not wonderful, but would improve greatly once we used a peaked spectrum at a known Higgs mass and ran for a few years.

At high $\tan\beta$, not only does the rate give a $\tan\beta$ measurement, but also can directly measure H^0, A^0 average width: $\Rightarrow$ good $\tan\beta$ determination.

Ultimately, this $\tan\beta$/Yukawa coupling measurement would prove absolutely critical in the wedge region, unless the machine $\sqrt{s}$ can be increased to the point where $H^0 A^0$ and $H^+ H^-$ pair production becomes possible.

Determination of CP

- Recall our asymmetries that probe $\sigma(\gamma\gamma \to H^0) \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2$ vs. $\sigma(\gamma\gamma \to A^0) \propto \vec{\epsilon}_1 \times \vec{\epsilon}_2$.

- These could be used to check (assuming CP-conserving Higgs sector) that A^0 and H^0 are both present and that they have the expected relative weights (which are not the same for most choices of m_{A^0} and $\tan\beta$).

Charged Higgs pair production

- We have already emphasized that the $H^{\pm}$ will not be detected in the LHC wedge, which begins at $m_{H^{\pm}} \sim 125~\mathrm{GeV}$.

  Thus, it is important to assess H^+H^- pair production in $\gamma\gamma$ and e^+e^- collisions.

  The kinematic reach of the former is a bit less than the latter (the 0.8 rule), but the cross section is much bigger.

- A somewhat detailed study was performed for $\sqrt{s}_{ee} = 500~\mathrm{GeV}$.

  The best results are for Type-II luminosity spectrum.

- The study focused on the $H^{\pm} \to \tau^{\pm}\nu$ decay modes and pulling such events out of the background from $\gamma\gamma \to W^+W^-$.

- A good strong signal is seen above background (after selection cuts) over the expected mass range.

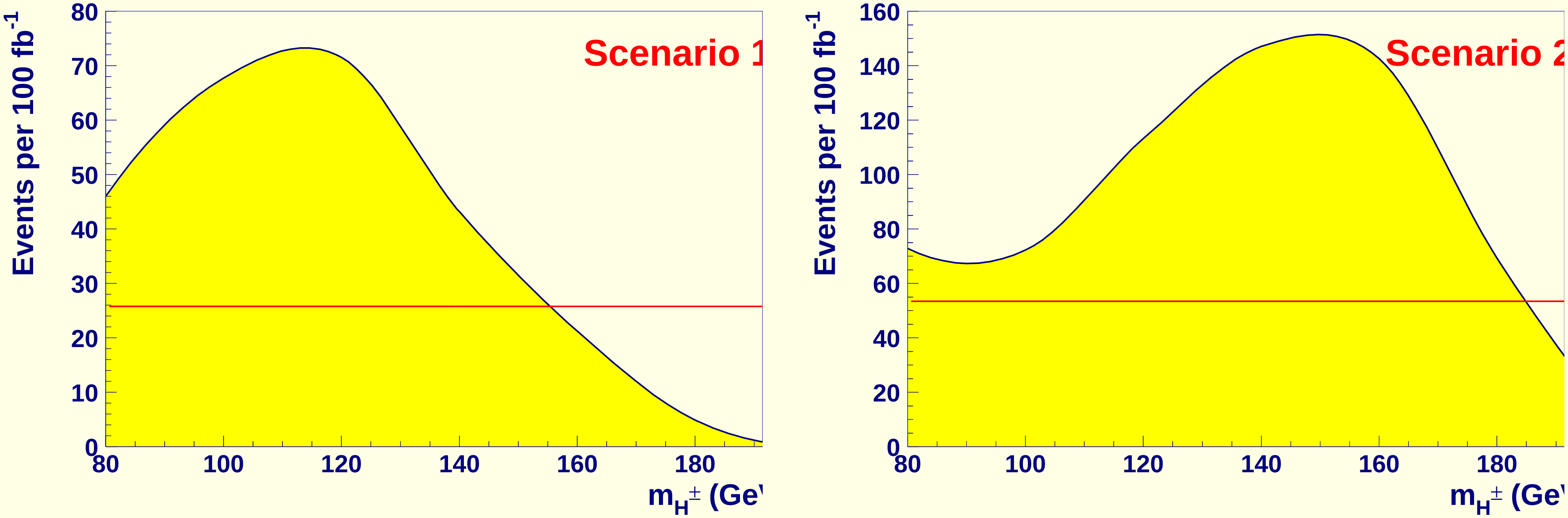


Figure 13: The plots show the number of accepted events per $\mathrm{BR}(h \to \tau^+\tau^-)^2$ per Snowmass year, as a function of $m_{H^\pm}$. The dashed horizontal line shows the number of accepted background $\gamma\gamma \to W^+W^-$ events.

Beyond the MSSM

- **There are general 2HDM models in which the only light Higgs boson is a A^0 (all other Higgs bosons can be heavier than $800~\mathrm{GeV} - 1~\mathrm{TeV}$).**
  - **Such models can be consistent with precision electroweak data.**
  - **A light A^0 can explain (part of) a_μ.**
  - **$\gamma\gamma$ collisions (using peaked + broad approach) can discover such an A^0 in about 40% of the wedge region for which it cannot be discovered at the LC or LHC.**

- **In the NMSSM, the LHC could fail to see any Higgs boson if there is a light A^0 into which the CP-even Higgs bosons decayed.**

  The LC would see one or more CP-even Higgs bosons, but ability to detect and study the light A^0 would be crucial.

- **If we go beyond 2 doublets and one singlet, it is probable that a larger and larger fraction of the Higgs bosons would not be detectable except at a γC.**

Luminosity Factor Required for 4σ Discovery of 2HDM A

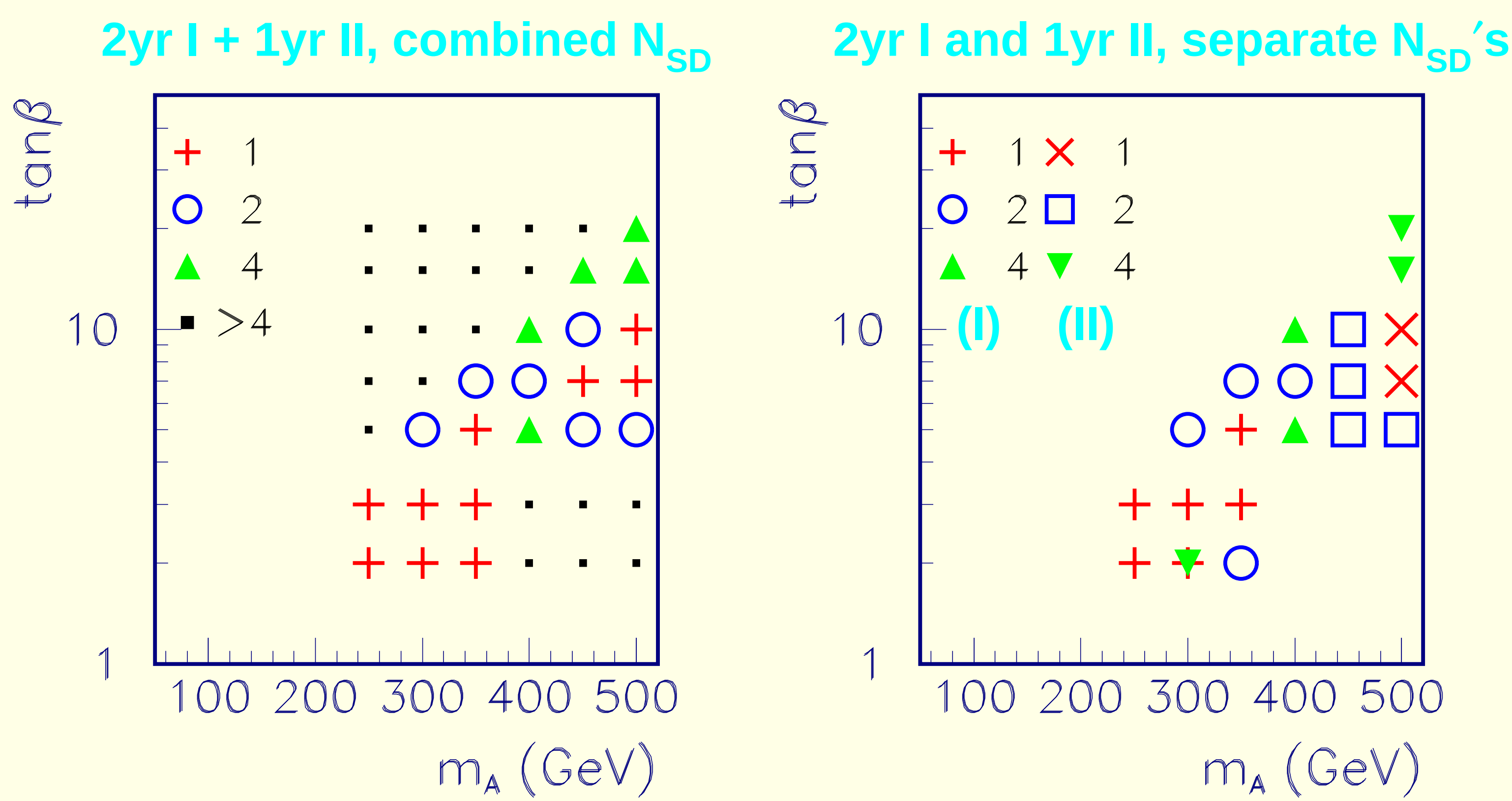


Figure 14: **Assuming a machine energy of $\sqrt{s} = 630$ GeV, we show the $[m_{A^0}, \tan\beta]$ points for which two 10^7 sec years of operation using the type-I $P\lambda_e, P'\lambda'_e > 0$ polarization configuration and one 10^7 sec year of operation using the type-II $P\lambda_e, P'\lambda'_e < 0$ configuration will yield $S/\sqrt{B} \geq 4$ for the A^0 of a general 2HDM, assuming all other 2HDM Higgs bosons have mass of 1 TeV. This assumes no knowledge of m_{A^0}, other than $m_{A^0} > \sqrt{s}/2$. If we know m_{A^0}, observation and study is a cinch in the wedge region.**

- **In the general 2HDM, there is a possibility for either spontaneous or explicit CP violation in the Higgs sector.**

- **In the MSSM, if soft-SUSY-breaking parameters have phases, the Higgs sector will be CP-violating.**

- **The γC is very possibly the only collider that can detect some of the Higgs bosons.**

- **For any Higgs boson that can be observed, its CP nature can be probed at a γC and the nature of the Higgs sector unraveled. This is not** *generally* **possible even in e^+e^- collisions (see earlier discussion and below).**

- **The asymmetries defined earlier are typically larger than 10% and are observable for a large range of 2HDM parameter space for which CP violation occurs.**

- **For Higgs bosons that are largely CP-odd, only the γC will be able to study their CP nature unless the Higgs has large production rate and $\tau^+\tau^-$ self-analyzing decay mode can be used.**

Large rate requires either a highly enhanced Yukawa coupling to $t\bar{t}$ or $b\bar{b}$ or a fairly full strength Higgs pair cross section with a CP-even Higgs boson *and no significant extra decays*.

- For a light Higgs boson that is largely CP-even, the γC and the $\tau^+\tau^-$ options are both a possibility.

  The $\tau^+\tau^-$ option is present in this case since $e^+e^- \to Z+$Higgs will have a substantial rate.

- The $t\bar{t}+$Higgs distribution techniques will work if coupling is $\geq$ SM strength (e.g. $\tan\beta \lesssim 1$ for A^0) and Higgs mass is not too large.

- If the Higgs is heavy and produced at a high rate, the $t\bar{t}$ final state is also self-analyzing, but more difficult to reconstruct. Lepton distributions may retain enough info.

Technicolor models and related

- In technicolor models, there can be a light PNGB P^0 with anomalous $\gamma\gamma$ coupling being characteristic of the model.

- The ability to detect the P^0 and precisely measure its $\gamma\gamma$ coupling could be quite crucial.

- The $\gamma\gamma P^0$ coupling required arises from an anomalous vertex graph and is proportional to N_{TC}, yielding production rates proportional to N_{TC}^2.

- For $N_{TC} = 4$, we find that discovery of the P^0 in $e^+e^- \to \gamma P^0$ will be possible for at least a limited range of masses.

- The $\gamma\gamma$ collider will provide very robust P^0 signals allowing for fairly precise measurements of rates in a variety of channels.

  However, prospects decline at smaller N_{TC}.

  The figure assumes we have centered on $E_{\gamma\gamma} \sim m_{P^0}$. If the P^0 has not been detected elsewhere, this might require some luminosity to do.

- A direct check of the CP-odd nature of the P^0 would only be possible via γC collisions.

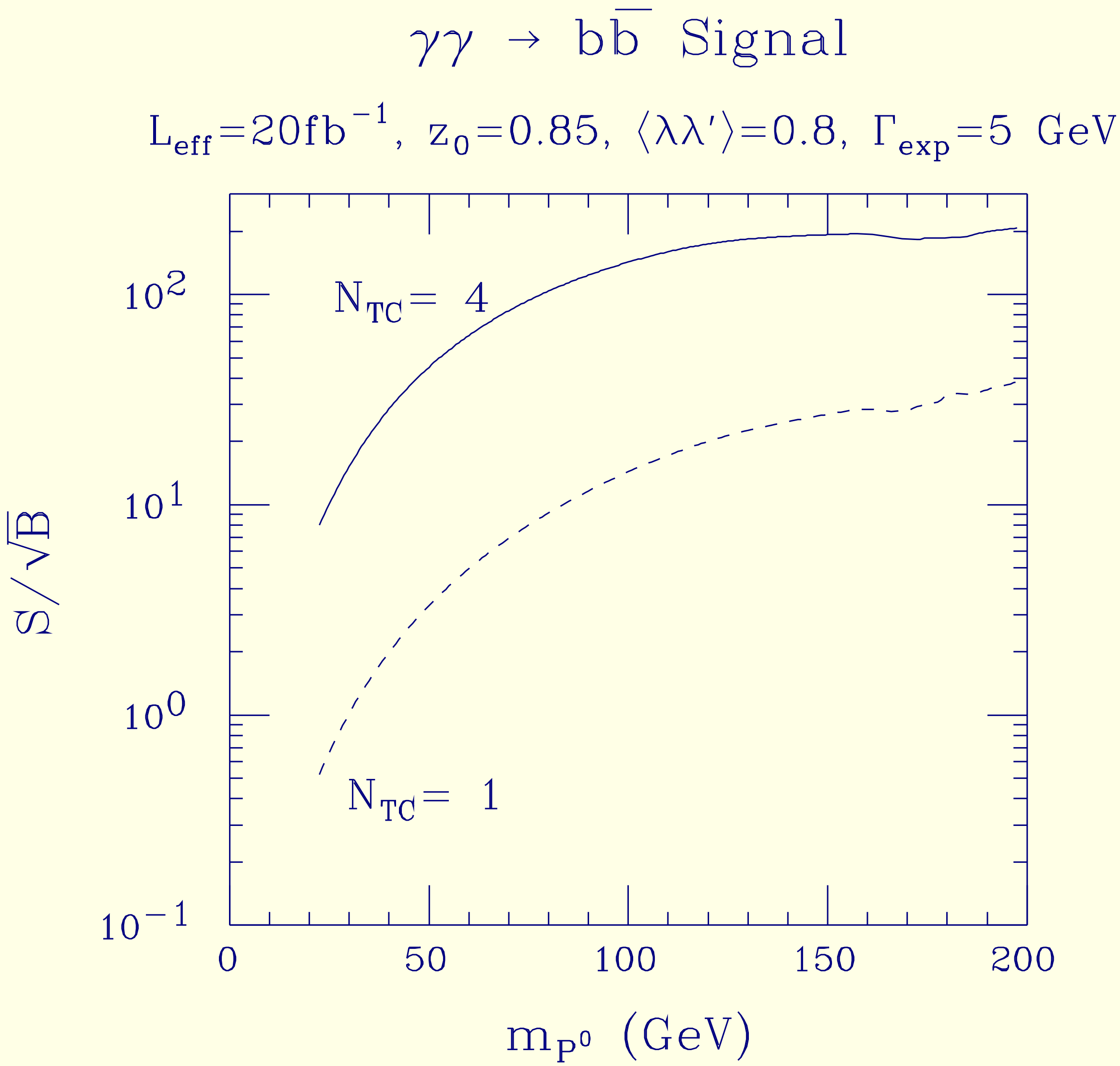


Figure 15: For $L_{\rm eff} = 20{\rm fb}^{-1}$ (assumed independent of m_{P^0}), $|\cos\theta| < 0.85$, and $\Gamma_{\rm exp} = 5~{\rm GeV}$, we plot $S/\sqrt{B}$ for $N_{TC} = 4$ and $N_{TC} = 1$. Modern results would be better.

Radion-Higgs mixing scenario in Randall Sundrum Model

- **If there is a warped 5th dimension that naturally explains the TeV $\rightarrow$ Planck scale hierarchy, the fluctuations of the distance between the TeV and Planck branes is a quantum degree of freedom called the radion (ϕ_0).**

- **It is natural for there to be Lagrangian terms that mix the radion and Higgs (h_0) degrees of freedom (they have the same quantum numbers).**

  The mass eigenstates will be called h and ϕ.

- **In this case, there can be great difficulty in fully fixing the Higgs-radion system, since one must determine at least 4 parameters:**

$$m_h, \quad m_\phi, \quad \gamma \equiv \frac{v}{\Lambda_\phi}, \quad \xi \tag{8}$$

  where ξ specifies the amount of mixing and Λ_ϕ is the vev of the radion field, a new physics parameter of order a TeV.

- Further, the most unique couplings of this model are the anomalous $\gamma\gamma$ and gg couplings to the radion and Higgs.

- Only a $\gamma\gamma$ collider can fully unravel what is going on and check with precision the predictions of the model.

  Especially powerful when combined with $gg \to h \to \gamma\gamma$ data from LHC.

- $\gamma\gamma \to h \to \gamma\gamma$ and $\gamma\gamma \to \phi \to \gamma\gamma$ are also very interesting in this context.

- To illustrate, suppose that we have seen at the LC (and possibly LHC) a boson that looks Higgs-like with mass of $120~\mathrm{GeV}$ and ZZ-coupling-squared $= 0.7\times$ SM value. What would be required to realize that a radion was present and that the observed boson was really a Higgs boson mixed with a radion (or vice versa!)?

  A $\gamma\gamma$ collider might be completely crucial.

- To sort out what is what, first note that, for the scenario considered, $e^+e^- \to Z\phi$ would be detectable and $g^2_{ZZ\phi} \gtrsim 0.3$ would be measured with reasonable accuracy.

One might suppose that measuring m_ϕ and $g^2_{ZZ\phi}$ would completely fix the parameters. But the similar nature of m_ϕ contours and $g^2_{ZZ\phi}$ contours implies parameters might not be well fixed.

Also, very possibly we could not say which boson was the relative of the h_0 and which was the relative of the ϕ_0.

- The $gg \to h, \phi \to \gamma\gamma$ and $\gamma\gamma \to h, \phi \to b\bar{b}$ rates, not to mention the $\gamma\gamma \to h, \phi \to \gamma\gamma$ rates, would allow precise parameter determinations and wonderful cross checks on the model (which might be needed to determine whether or not the Higgs lives partly in the bulk or the Higgs sector is a 2HDM rather than 1HDM,....).

- Especially important would be a model-independent measurement of the anomalous ggh, $gg\phi$, $\gamma\gamma h$ and $\gamma\gamma\phi$ couplings.

  Their precise values are very much related to and determined by the presence of a 5th dimension.

  Their model-independent determination is only possible if γC measurements are available. (No time to discuss procedure here – trust me.)

- **Also, let me stress that the particular Higgs-radion mixing model I am discussing is the very simplest.**

  For example, supersymmetrize, add doublets, add singlets, allow CP-violation in Higgs sector, . . .

  $\Rightarrow$ **hopeless without γC information.**

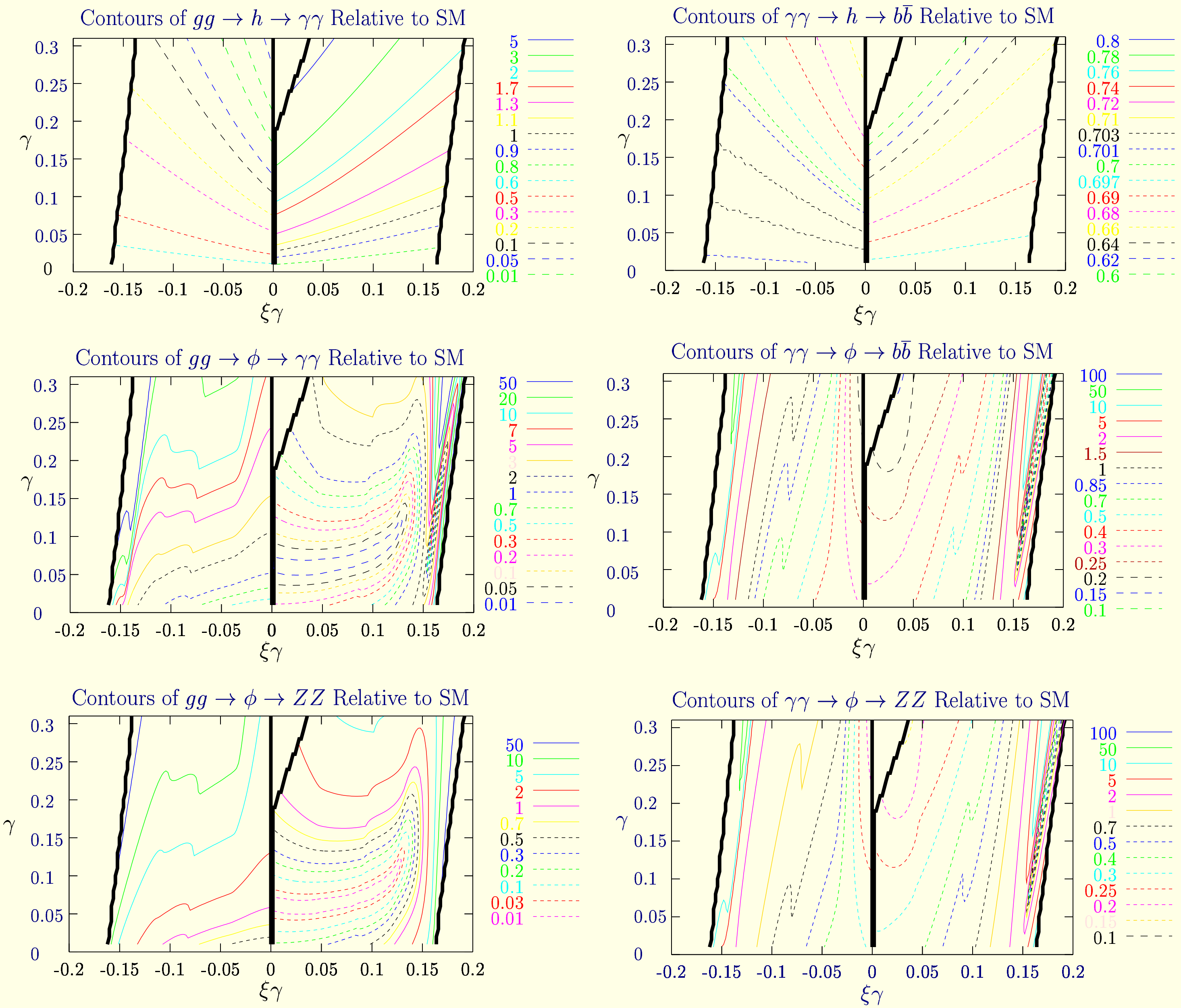


Figure 16: Contours of rates (relative to a SM Higgs of the same mass) in the $(\xi\gamma, \gamma)$ parameter space for fixed $m_h = 120$ GeV and $g^2_{Vfh} = 0.7$ (relative to SM).

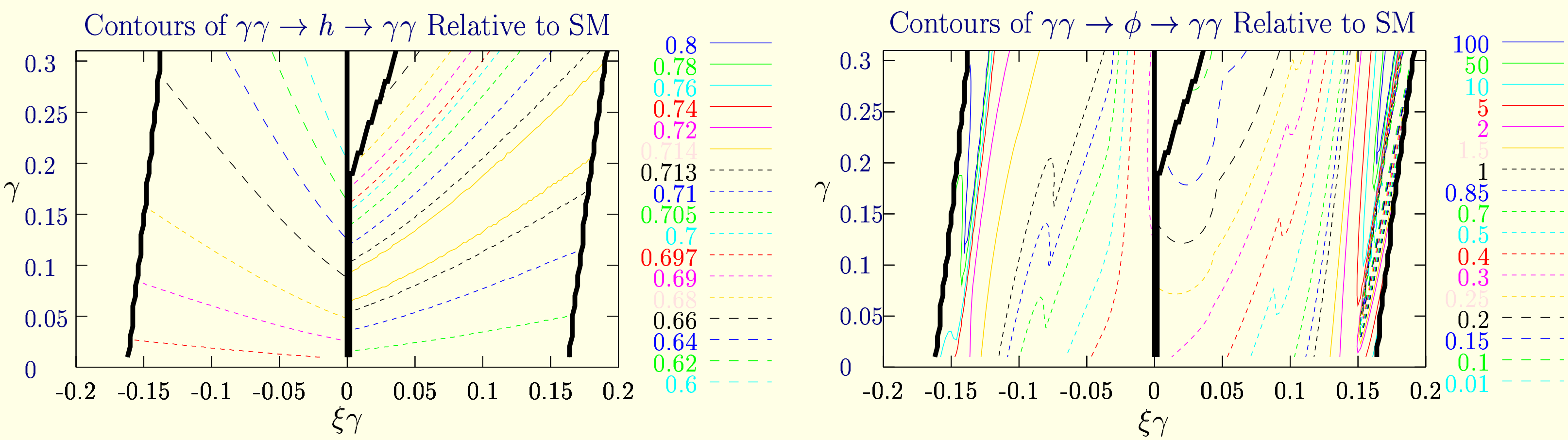


Figure 17: Contours of $\gamma\gamma \to h, \phi \to \gamma\gamma$ rates (relative to a SM Higgs of the same mass) in the $(\xi\gamma, \gamma)$ parameter space for fixed $m_h = 120$ GeV and $g^2_{Vfh} = 0.7$ (relative to SM).

The important points to note from all these curves are:

- **some tell you the h *is, in fact* the h because predictions are close to $g^2_{ZZh} = 0.7$ expectation;**
- **and others differ from one another so dramatically that you can really pin down parameters and test the model.**

Beyond Higgs bosons and the SM

Large scale extra dimensions (Cheung, Rizzo, ...)

- The $\gamma\gamma$ collider has superb ability to explore large scale extra dimension signals, for example in $\gamma\gamma \to \gamma\gamma, W^+W^-$ and $\gamma\gamma \to \gamma$+gravitons.

- 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.

  And, the $\gamma\gamma \to W^+W^-$ cross section is very sensitive because the extra dimension contribution is big just like the SM piece.

- 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.

  Of course, $\sqrt{s}_{\gamma\gamma} \sim 0.8\sqrt{s}_{ee}$.

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

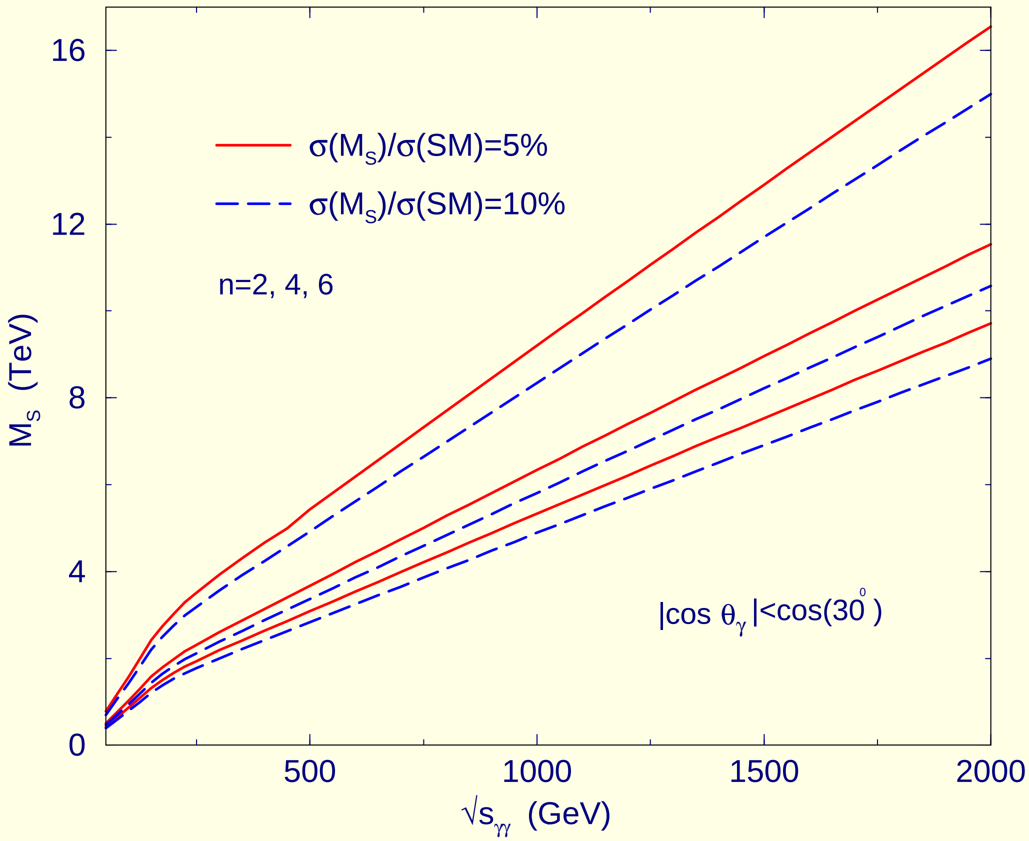


Figure 18: M_S reach versus $\sqrt{s_{\gamma\gamma}}$ using the process $\gamma\gamma \to \gamma\gamma$, by requiring the signal to be 5% or 10% of the SM prediction. A cut of $|\cos\theta_\gamma| < \cos 30°$ is imposed. From K. Cheung.

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 even be better than 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.

Supersymmetry

- Probably the most interesting case is $e^-\gamma \to \widetilde{e}^-\widetilde{\chi}^0_1$.

  Detection is possible for $m_{\widetilde{e}} + m_{\widetilde{\chi}^0_1} \lesssim 0.9\sqrt{s}_{ee}$.

  This would exceed the reach in $m_{\widetilde{e}}$ of the e^+e^- collider if $m_{\widetilde{\chi}^0_1} < 0.4\sqrt{s}_{ee}$.

- Stoponium resonances are a possibility.

  A photon collider would be an ideal place to look for and study such resonances.

  About 10000 S resonances are produced for $M_S = 200$ GeV for peaked luminosity distribution.

  Precise measurements of the S effective couplings, mass and width would be possible.

  At e^+e^- colliders, the counting rate is much lower and in some scenarios backgrounds are even too large for detection in e^+e^- collisions.

W boson interactions

- Due to the huge cross sections, of order 10^2 pb (well above thresholds), the $\gamma\gamma \to W^+W^-$ and $e^-\gamma \to \nu W^-$ processes seem to be ideal reactions to study the anomalous gauge interactions.

  The σ's are about 80 pb and 40 pb, respectively, at 200 GeV and do not decrease with increasing energy.

- The $e^+e^- \to W^+W^-$ reaction is dominated by the large t-channel neutrino exchange diagram, which would be mostly removed using e^- beam polarization yielding $\sigma \sim 2$ pb at LEP2 energies and decreases for higher energies.

- Anomalous gauge boson couplings

  – The $\gamma\gamma \to W^+W^-$ and $e^-\gamma \to W^-\nu$ processes isolate the anomalous photon couplings to the W, while $e^+e^- \to W^+W^-$ involves the potentially anomalous Z couplings.
  $\Rightarrow$ complementarity of e^+e^- and $e\gamma, \gamma\gamma$.

- Resulting accuracy on λ_γ is comparable to e^+e^-, while accuracy for $\delta\kappa_\gamma$ comparable to e^+e^- can be achieved with $1/20$ of the e^+e^- luminosity.
- The $e^-\gamma \to W^-\nu$ processes is very sensitive to the admixture of right-handed currents in the W couplings with fermions: $\propto (1 - 2\lambda_e)$.
- 3rd and 4th order couplings can be probed:

$$e\gamma \to eW^+W^-\,, \quad e\gamma \to \nu W^- Z\,. \tag{9}$$

$$\gamma\gamma \to ZW^+W^-\,, \quad \gamma\gamma \to W^+W^-W^+W^-\,, \quad \gamma\gamma \to W^+W^-ZZ\,. \tag{10}$$

All have substantial rates, but if EWSB mainly affects W_L (longitudinal W's) then the dominant $\gamma\gamma \to W_T W_T$ process would have to be cut against $\Rightarrow$ still competitive with e^+e^-.

Large extra dimension theories affect the $W_T W_T$ cross section and the $\gamma\gamma$ collider would then be a superb probe.

- Strong $WW \to WW$ and $WW \to ZZ$ scattering might emerge as natures choice.
  - For high enough $\gamma\gamma$ energy, the effective WW luminosity in $\gamma\gamma$ collisions becomes large enough to allow for the study of $W^+W^- \to W^+W^-, ZZ$

via the reactions

$$\gamma\gamma \to W^+W^-W^+W^-, W^+W^-ZZ\,. \tag{11}$$

Here, each incoming photon turns into a virtual W^+W^- pair, followed by scattering of one W from each γ.

– The same reactions can be used to study anomalous quartic $WWWW$ and $WWZZ$ couplings.
– A potential advantage of the $\gamma\gamma$ colliders is the W_L spectrum inside the photon.
  It is logarithmically enhanced, being bigger for large W momentum fraction than the electron equivalent at very high energies. (But, this requires $\sqrt{s} \gtrsim 2~\mathrm{TeV}$.)

Studies of the top quark

- **Anomalous couplings**
  - in $\gamma\gamma$ collisions the $\gamma t\bar{t}$ coupling enters with the 4th power in the cross section.
  - the $\gamma t\bar{t}$ coupling is isolated in $\gamma\gamma$ collisions while in e^+e^- collisions both $\gamma t\bar{t}$ and $Zt\bar{t}$ couplings contribute.
  - new physics scales Λ up to $10~\mathrm{TeV}$ can be probed at $\sqrt{s}_{ee} = 500~\mathrm{GeV}$.

- **Single top production in $\gamma\gamma$ and $e\gamma$.**
  - The idea is to probe for anomalous Wtb couplings.
    Obviously, $e\gamma$ collisions are perfect.
  - Excellent limits/probes of new physics scale Λ are possible at very high energy γe colliders.
    Assume $\sqrt{s} = 500~\mathrm{GeV}$ and $L_{e\gamma} = 250\mathrm{fb}^{-1}$ or $\sqrt{s} = 2~\mathrm{TeV}$ and $L_{e\gamma} = 500\mathrm{fb}^{-1}$. The table gives the $e\gamma$ results compared to other machines.

Table 3: Expected sensitivity for some anomalous couplings

	f_2^L	f_2^R
Tevatron ($\Delta_{\rm sys.} \sim 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{\rm sys.} \sim 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
e^+e^- ($\sqrt{s}_{ee} = 0.5$ TeV)	$-0.025 \div +0.025$	$-0.2 \div +0.2$
γe ($\sqrt{s}_{ee} = 0.5$ TeV)	$-0.045 \div +0.045$	$-0.045 \div +0.045$
γe ($\sqrt{s}_{ee} = 2$ TeV)	$-0.008 \div +0.008$	$-0.016 \div +0.016$

The γe collider is more than competitive!

Conclusions

- **There is a huge physics program for the $\gamma\gamma$ collider.**
- **The γC will probably be absolutely critical to a full exploration of a Higgs or Higgs-like sector.**
  - **It can discover Higgs bosons, PNGB's, radion, . . . that are not detectable at any other collider.**
  - **It is very likely that a γC will be absolutely necessary to a full unraveling of the CP nature of any multi-boson Higgs, radion, PNGB, ... sector.**
- **It can probe extra dimensions to higher scales than any other collider.**
- **It, and the related $e\gamma$ collider, can do a superb job on anomalous triple-gauge couplings, anomalous $\gamma t\bar{t}$ coupling, strong WW scattering, and the like.**
- **. . . .**

IT IS HARD TO IMAGINE THAT WE WOULD NOT WANT TO PLAN ON A

γC

FACILITY AT THE LC.