Physics Motivations for a Photon-Photon Collider

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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.

Photon-Collider Meeting, SLAC, Nov. 21, 2002

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.

- 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.

  In particular, the source and nature of EWSB will only be completely revealed if a $\gamma\mathrm{C}$ is available.

  Some examples:

  – If the SM or MSSM or similar applies, detailed (and critical) studies of the Higgs boson(s), produced through the $\gamma\gamma \to$Higgs loop graphs, are possible.

- 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.
  Also $\gamma\gamma \to W^+W^-$ and $t\bar{t}$ will be important if strong interactions are present, as they will influence these channels, for example via anomalous couplings.
- If extra dimensions are present, important characteristics will be probed through $\gamma\gamma \to$Higgs, $\gamma\gamma \to$Radion, $\gamma\gamma \to \gamma\gamma$ and $\gamma\gamma \to W^+W^-$ 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.

- 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 .

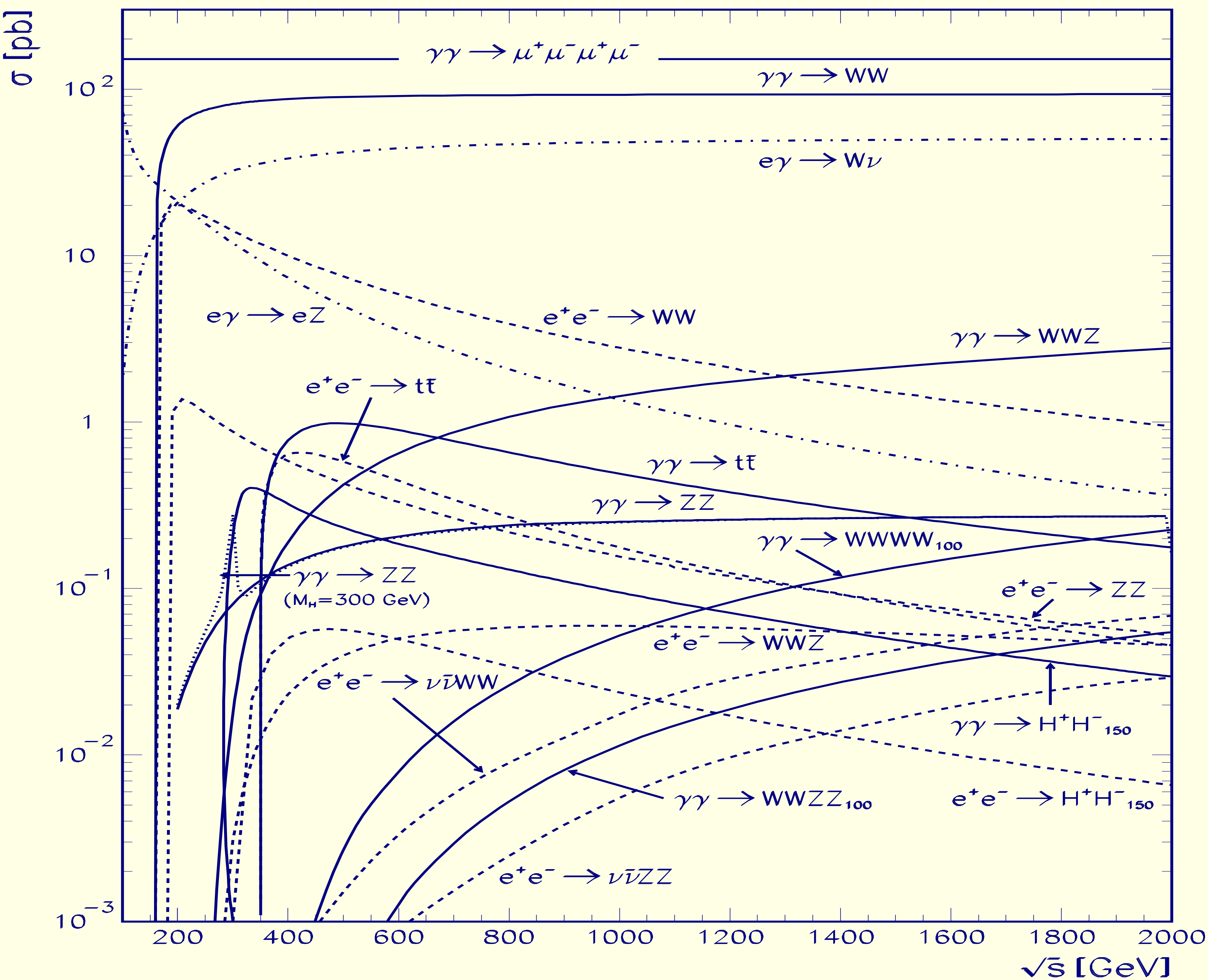


Figure 1: Typical cross sections: solid=$\gamma\gamma$; dot-dash=$e\gamma$; dashed=e^+e^-. $m_h = 100$ GeV; $m_{H^\pm} = 150$ GeV. Zero polarization.

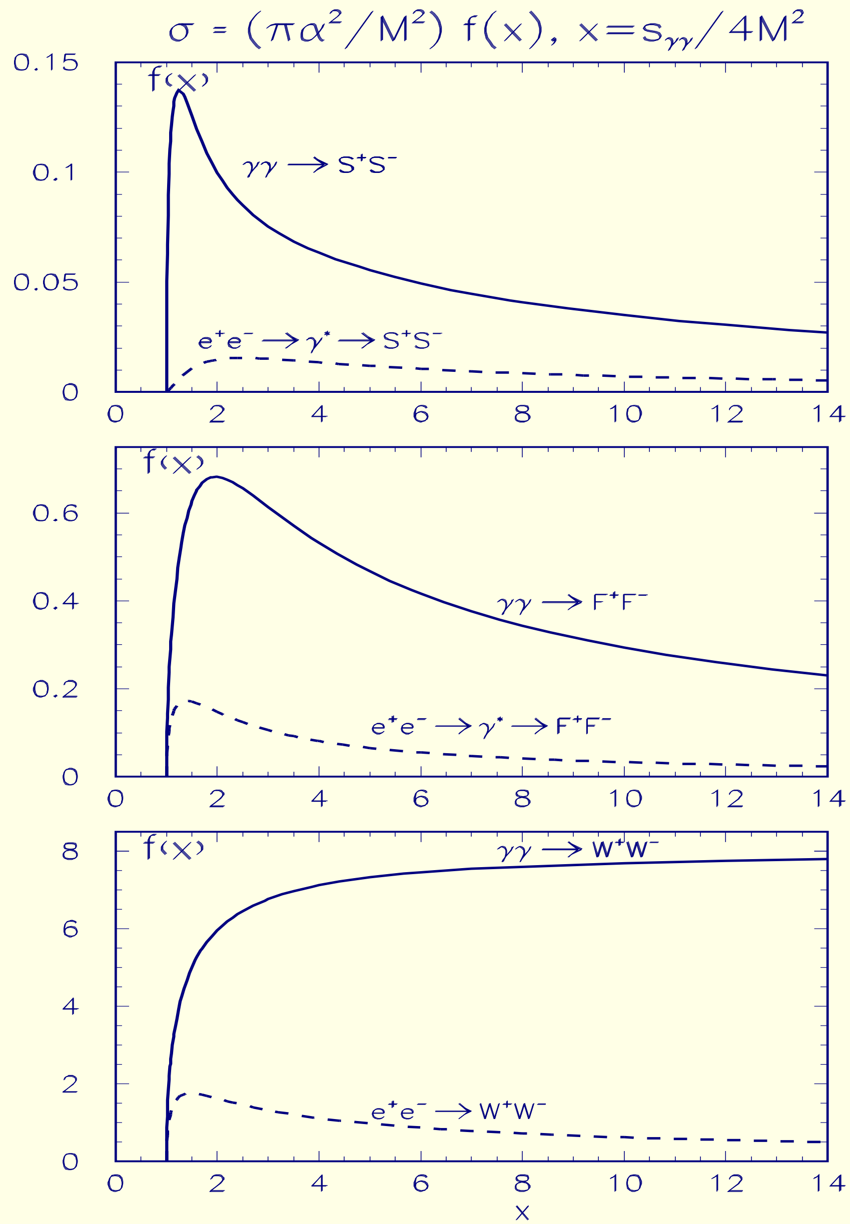


Figure 2: Charged pair production cross sections – no Z exchange in e^+e^- case. Threshold: β^3 in e^+e^- vs. β in $\gamma\gamma$.

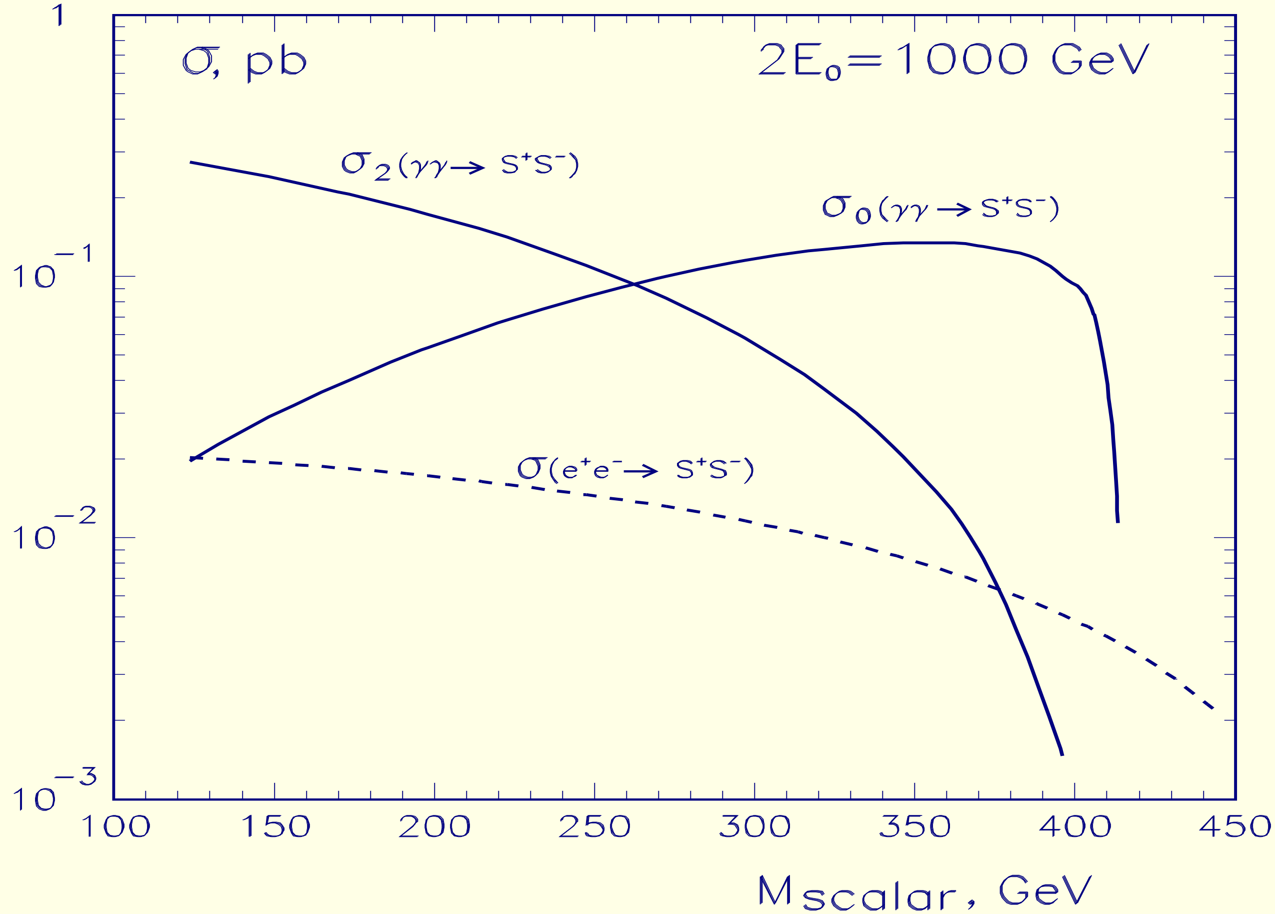


Figure 3: Charged Higgs $\boldsymbol{\sigma}$'s: e^+e^- vs. $\gamma\gamma$ for $\sqrt{s}_{e^+e^-} = 1$ TeV and $E_{\gamma\gamma}^{\rm max} \approx 0.82$ TeV ($x = 4.6$); σ_0 and σ_2 correspond to the total $\gamma\gamma$ helicity 0 and 2, respectively. $\Rightarrow$ polarization increases advantage of $\gamma\gamma$.

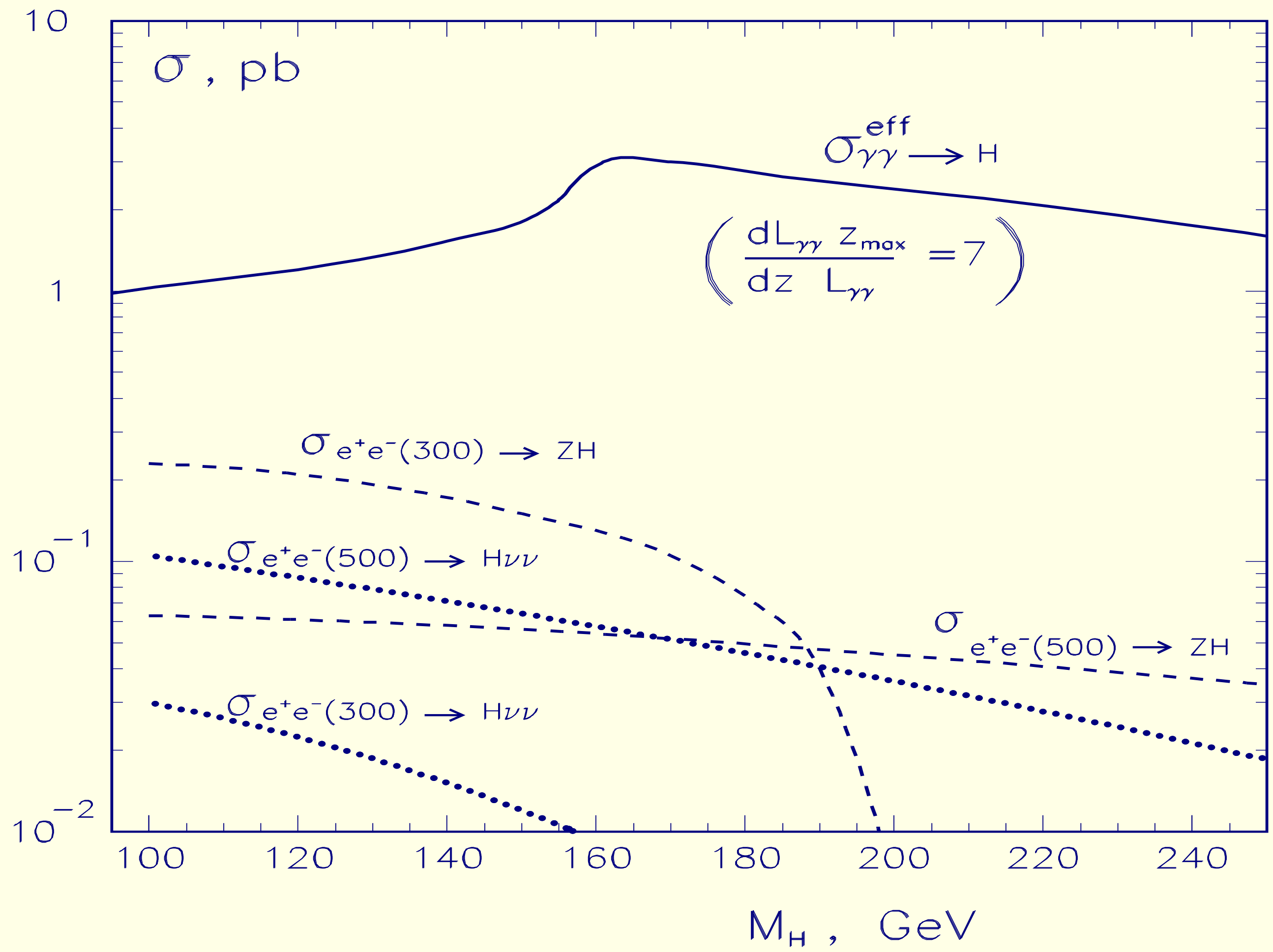


Figure 4: σ for Higgs production in $\gamma\gamma$ and e^+e^- collisions. $\gamma\gamma$ rate=$\sigma \times L^{\gamma\gamma}(z > .64)$ is $1 - 5$ times higher than e^+e^- rate.

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

  Indeed, photon colliders can have distinct advantages for discovering and studying certain kinds of new physics.

  Examples include:

  - **Scalars (Higgs) with no or small WW, ZZ coupling can be produced singly.**
  - **Same of PNGB P's.**
  - **In $e\gamma$, a heavy charged particle and light neutral particle (or vice versa) can be made 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.**

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 very heavy charged particles (both weakly and strongly interacting) that acquire mass via the Higgs mechanism (vs. e.g. soft-SUSY-breaking).**

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 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 $\gamma\gamma \to h \to b\bar{b}$ and rough measurement of $\gamma\gamma \to h \to \gamma\gamma$.**

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

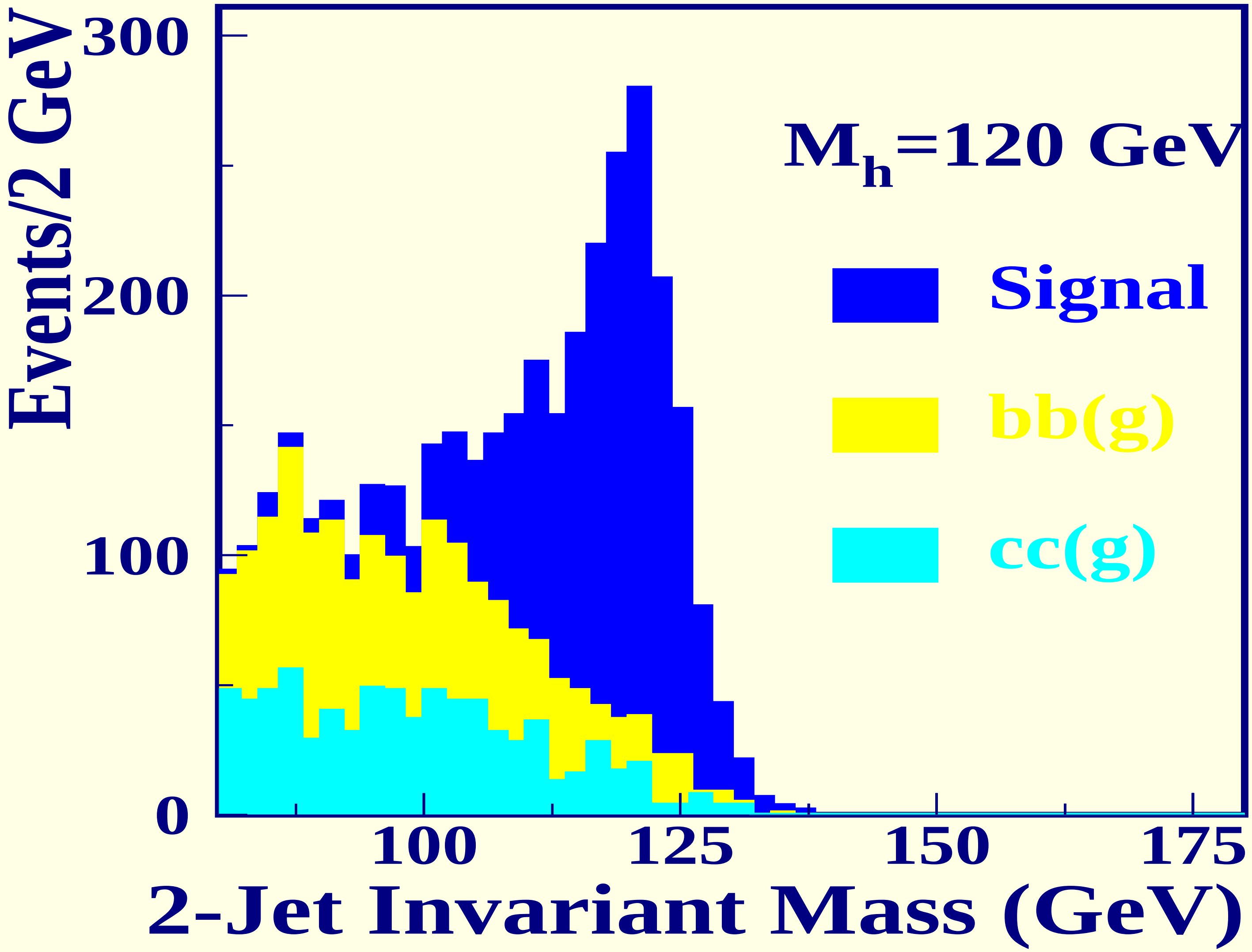


Figure 5: Signal and background rates in the $b\bar{b}$ channel for $h_{\rm SM} = 120~{\rm GeV}$. Precision of rate measurement $\sim 2.9\%$ $\Rightarrow$ relatively small deviations from SM couplings (e.g. as for h^0 of SUSY or due to new particles, even SUSY particles) can be detected.

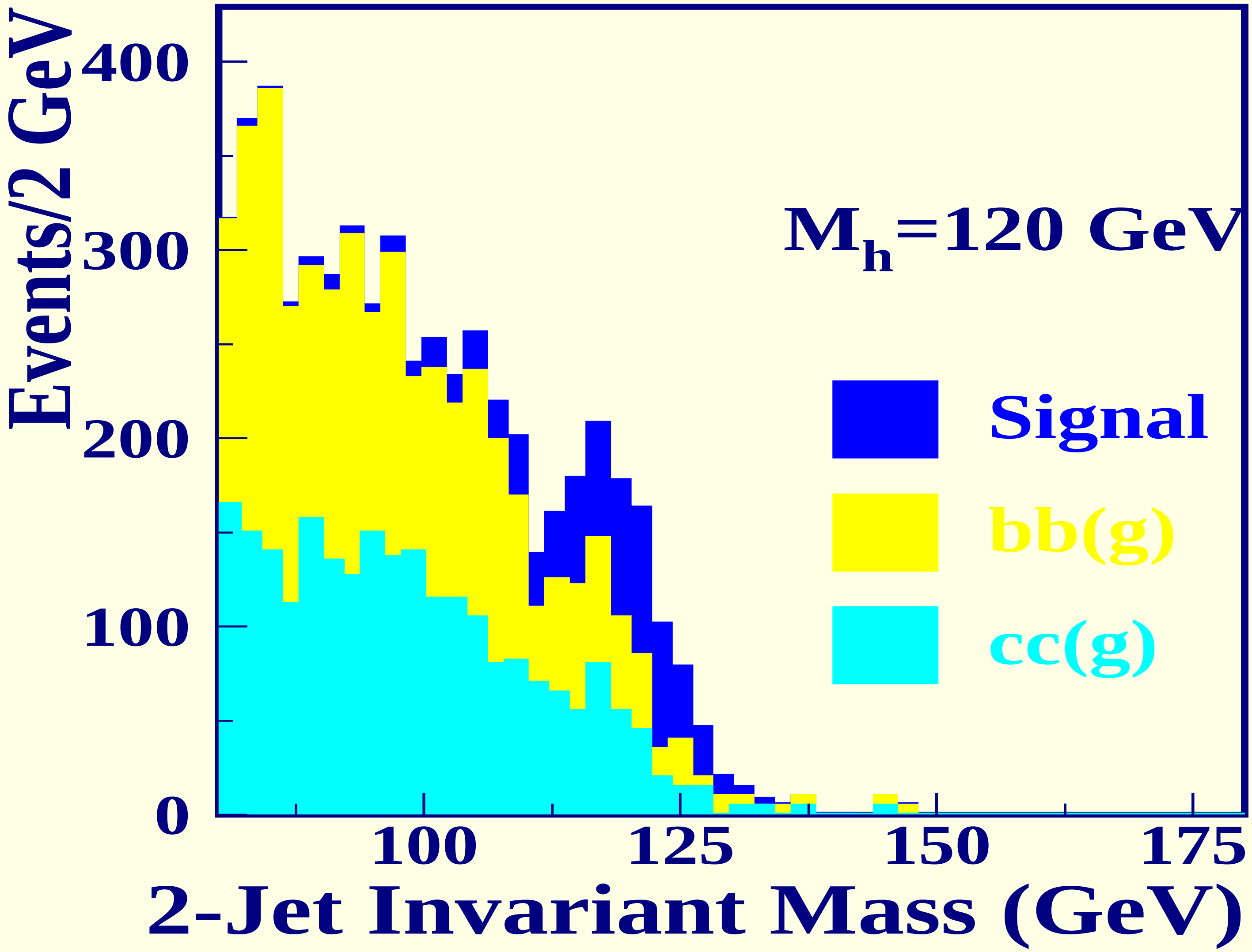


Figure 6: Signal and background rates in the $b\bar{b}$ channel for $h_{\rm SM} = 120~{\rm GeV}$ for the transversely polarized γC configuration needed for the CP determination ($\sqrt{s} = 206~{\rm GeV}$ and $x = 1.86$). $\Rightarrow$ $\frac{\delta\mathcal{CP}}{\mathcal{CP}} \sim 0.11$

- 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.

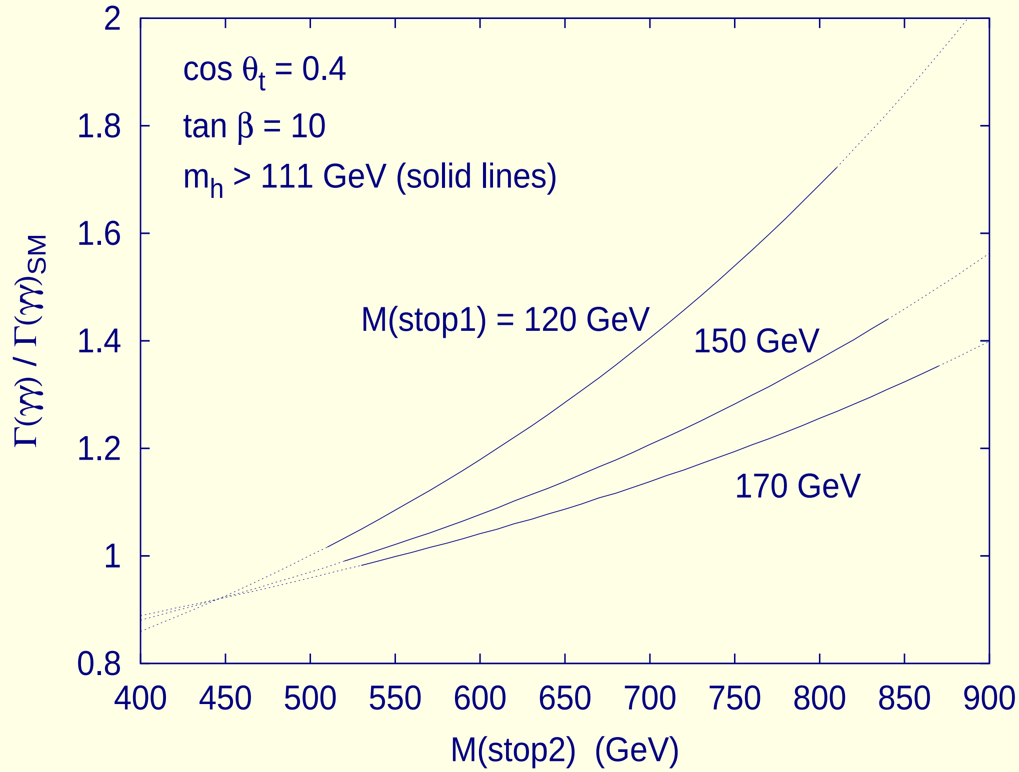


Figure 7: Dependence of the partial width $\Gamma(h^0 \to \gamma\gamma)$ on $m_{\tilde{t}_2}$ for various values of $m_{\tilde{t}_1}$ and $\cos\theta_{\tilde{t}}$. Here $m_A = 1$ TeV, $\tan\beta = 10$, $M_2 = -\mu = 200$ GeV, and the remaining SUSY mass parameters are set to 1 TeV.

- **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 $\Gamma(h \to \gamma\gamma)$.**

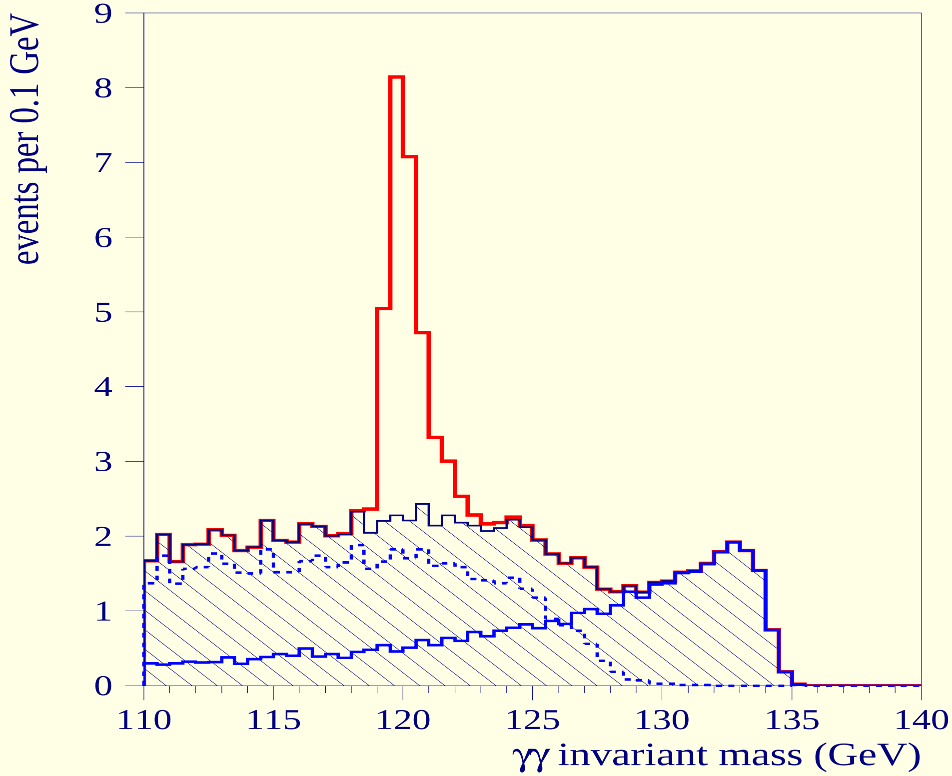


Figure 8: The mass distribution, including backgrounds from $\gamma\gamma \to \gamma\gamma$ (dashed line extending to ~ 130 GeV) and $e\gamma \to e\gamma$ (heavy solid line extending to ~ 135 GeV) as well as the signal (peak at 120 GeV). The hatched histogram shows the sum of background contributions.

- $\gamma\gamma \to hh$ **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:**

$$\delta\mathcal{L}_{\rm Higgs} = -\frac{\delta\kappa}{2}\frac{m_H^2}{v}\left[H^3 + \frac{3}{v}G^+G^-H^2\right] + \cdots, \quad (1)$$

    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		
	$\int \mathcal{L}_{th}$ (fb$^{-1}/10^7$ s)	σ (fb)	Event yield	$\int \mathcal{L}_{th}$ (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.

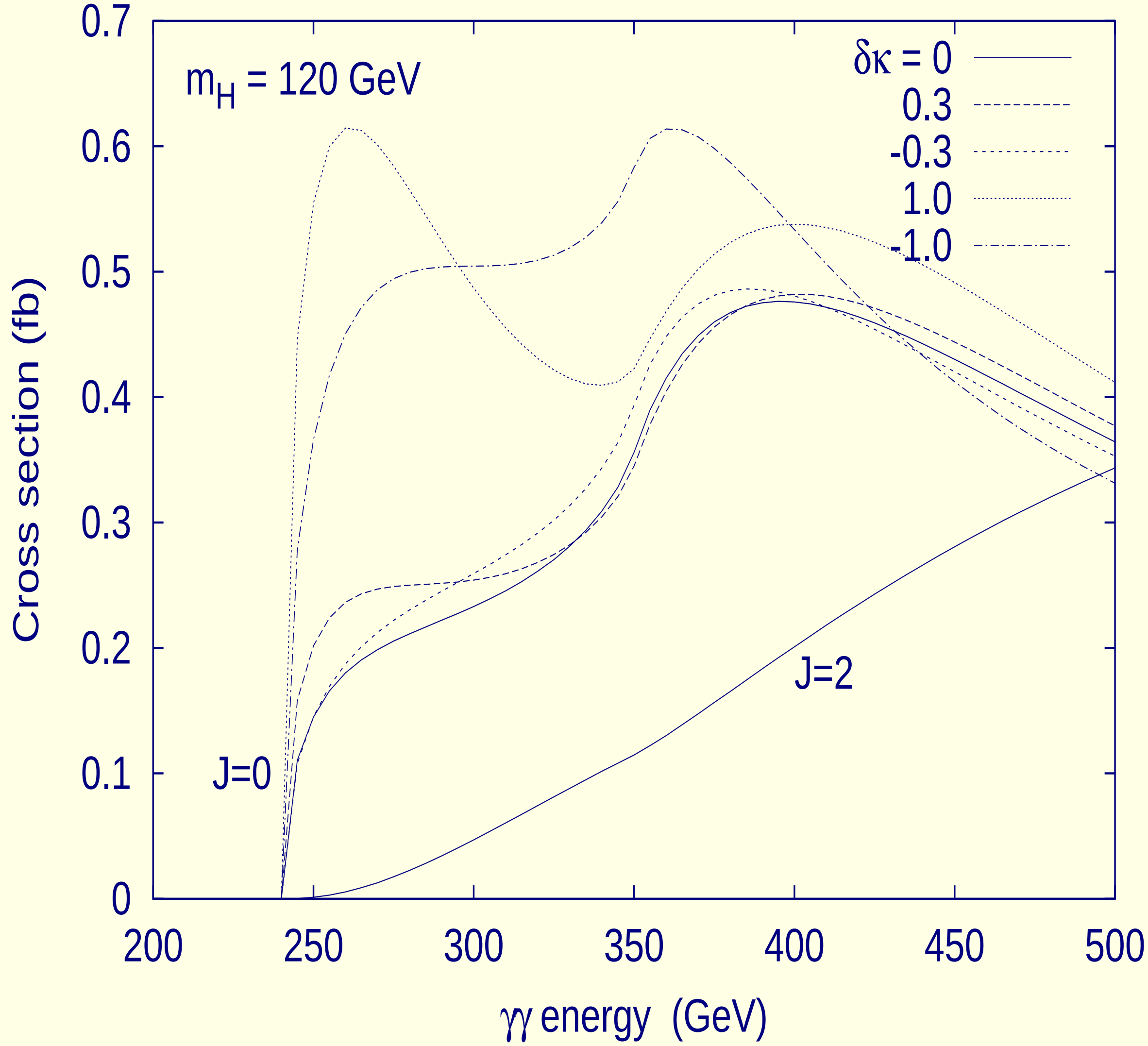


Figure 9: Parton-level cross section for $\gamma\gamma \to hh$ as a function of the $\gamma\gamma$ center-of-mass energy, for $J = 0$ and $J = 2$. The effects of varying the trilinear coupling are shown.

The heavy MSSM H^0 and A^0

- For heavy MSSM Higgs, we will assume operation at $\sqrt{s} = 630\ \mathrm{GeV}$ ($\rightarrow x = 5.69$ 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 $500\ \mathrm{GeV}$ with good $\langle\lambda\lambda'\rangle$ and $\mathcal{L}$ down to $450\ \mathrm{GeV}$.
    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 $m_{A^0} \sim 250 - 400\ \mathrm{GeV}$.
    Note: p_z cut to 'clean up' low-$E_{\gamma\gamma}$ tail in broad spectrum case = BAD.

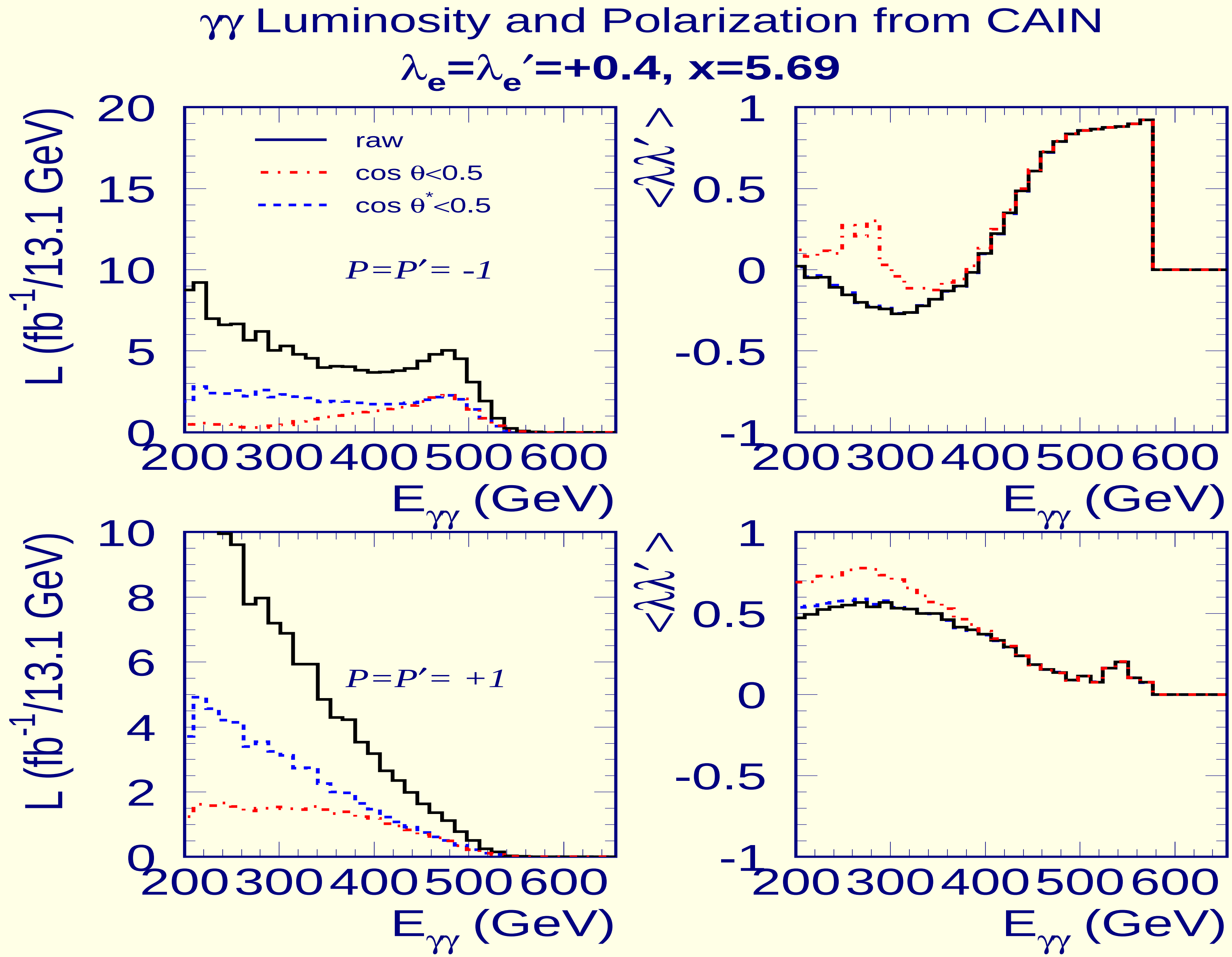


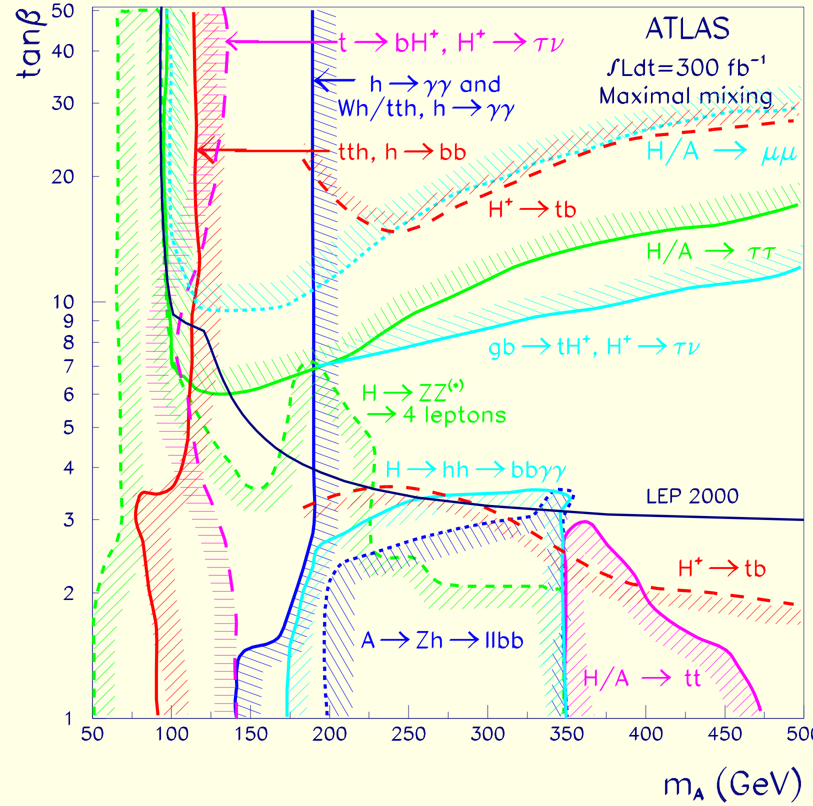
Figure 10: Luminosity (for 1 10^7 sec year) and $\langle\lambda\lambda'\rangle$ expectations for $\lambda_e = \lambda'_e = 0.4$ vs. $E_{\gamma\gamma}$ for $P = P' = -1$ (type-II) and $P = P' = +1$ (type-I)

- **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 $m_{A^0} \sim 200$ GeV at $\tan\beta \sim 6$, widening to $2.5 < \tan\beta < 15$ at $m_{A^0} = 500$ 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 $\sqrt{s}_{e^+e^-} \lesssim 0.8 - 1$ 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.

Basic Signal Cross Sections

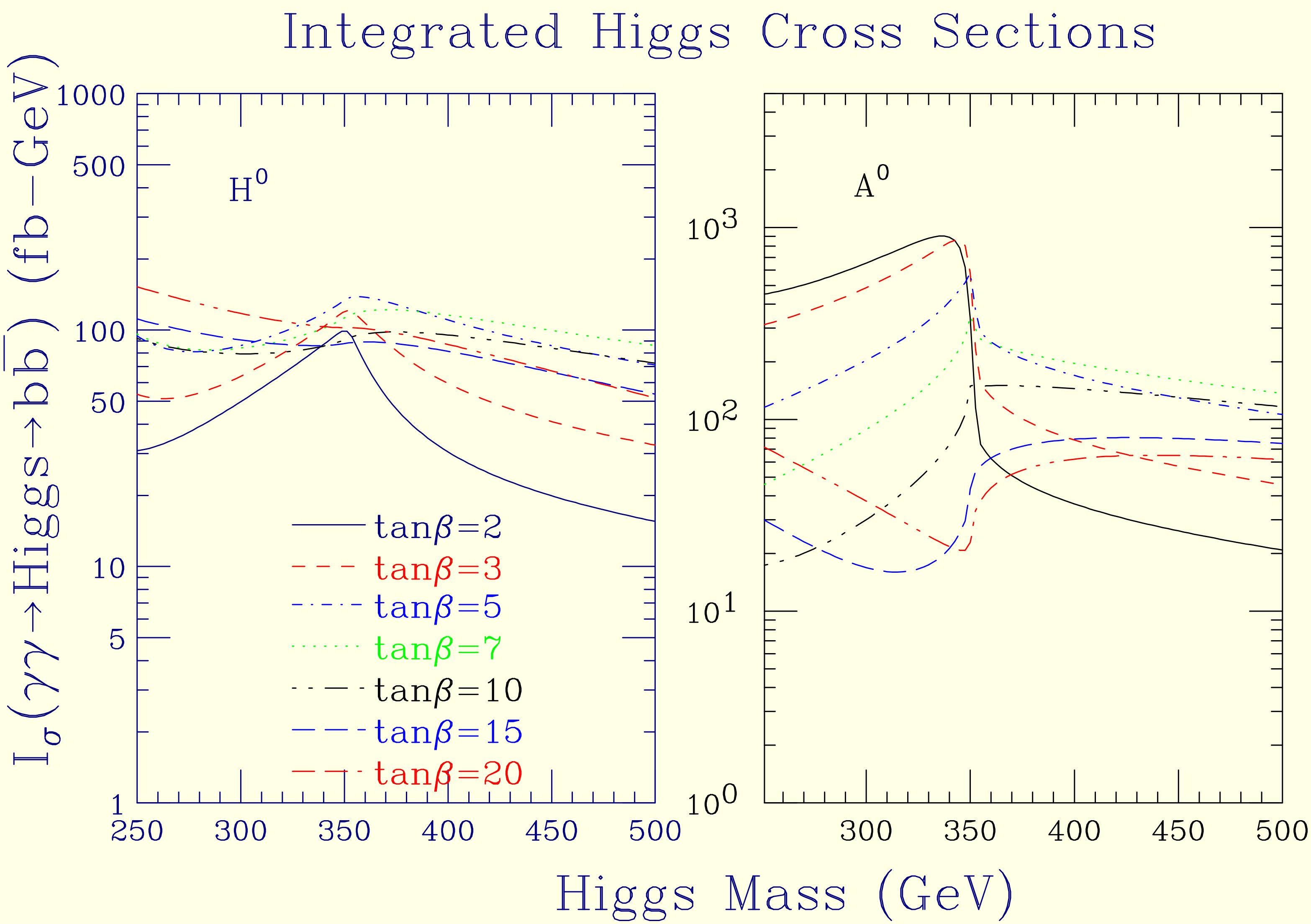
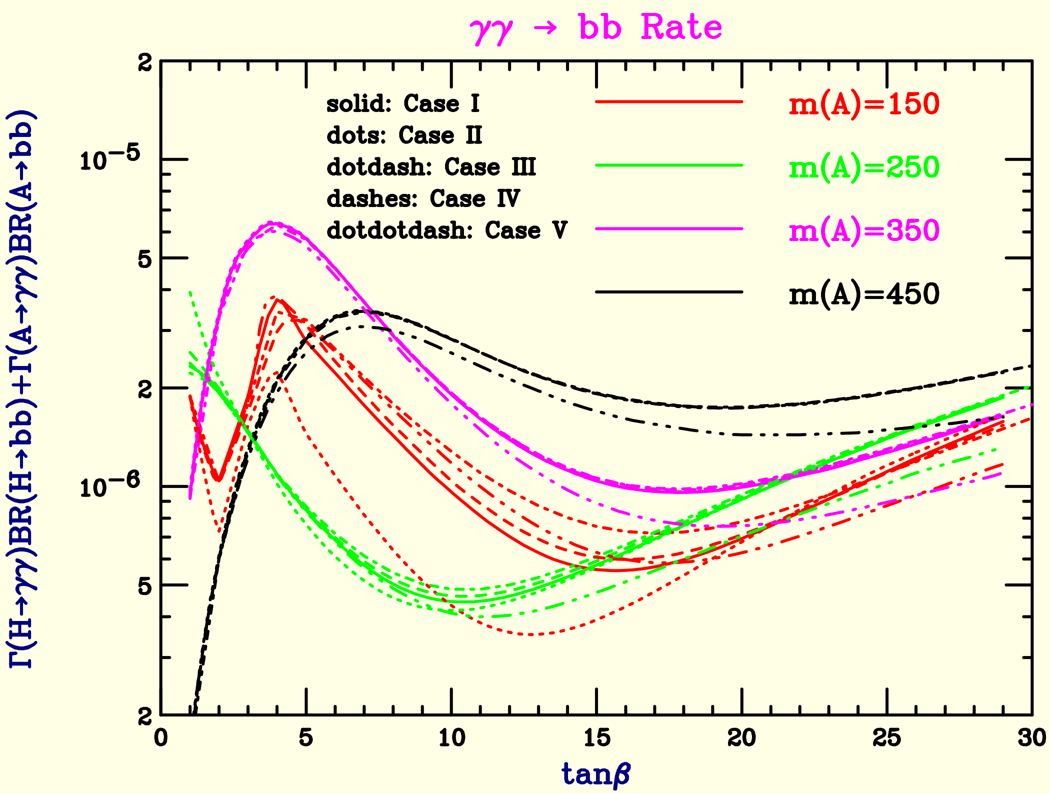


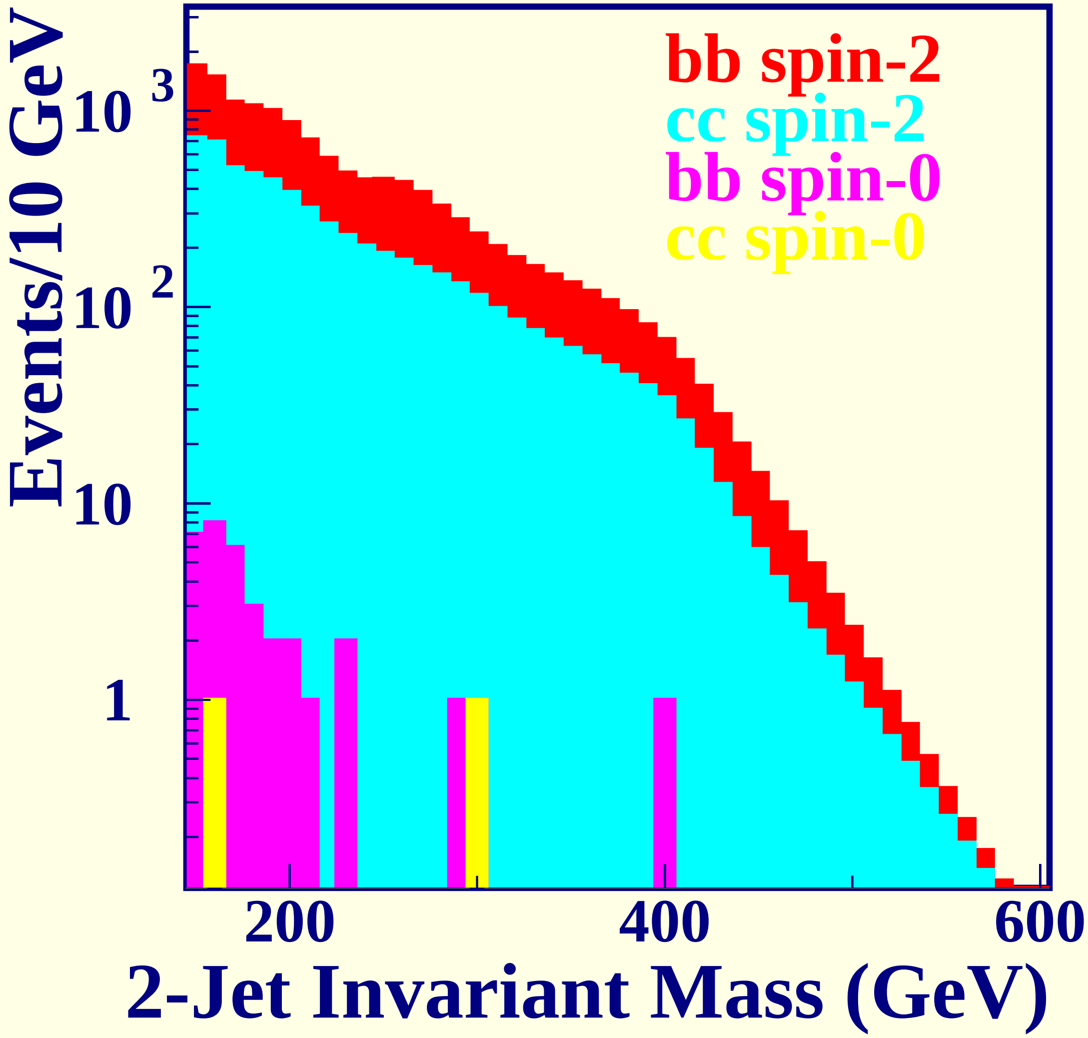
Figure 11: Cross section ($\mathrm{fb}-\ \mathrm{GeV}$ units) to be multiplied by efficiencies, $\mathbf{1+\langle\lambda\lambda'\rangle}$ and $\left[\frac{dL}{dE_{\gamma\gamma}}\right]_{E_{\gamma\gamma}=m_{A^0}}$.

Model Dependence of Cross Sections



I: max-mix, $m_{\rm SUSY} = \mu = 1$ TeV, no Δ_b.
II: max-mix, $m_{\rm SUSY} = -\mu = 1$ TeV, no Δ_b.
III: no-mix, $m_{\rm SUSY} = \mu = 1$ TeV, no Δ_b.
IV: max-mix, $m_{\rm SUSY} = 1$ TeV, $\mu = 0$, no Δ_b
V: max-mix, $m_{\rm SUSY} = \mu = 1$ TeV, w. Δ_b

Cross section sum is model independent except for large-μ, large-$\tan\beta$ SUSY loop corrections to $b\overline{b}$ coupling.
Even these corrections mainly affect the h^0 and not the H^0, A^0.
Note: Dip in $\sum \Gamma(\gamma\gamma)B(b\overline{b})$ at $\tan\beta \sim 15-20 \Rightarrow$ signals will be weak in that region, but then improve again at very high $\tan\beta$ somewhat above the LHC wedge region.



Note: Since our $\langle\lambda\lambda'\rangle$ is never really close to 1, $\sigma_{J_z=2}$ background is always dominant.

$\Rightarrow$ detailed radiative corrections for $J_z = 0$ bkgnd not needed.

Better: use PYTHIA with full Initial and final state radiation (which in any case $\Rightarrow$ leading-log approx. to loss of $1-\langle\lambda\lambda'\rangle$ suppression for $J_z = 0$).

Note: Same cuts as for SM Higgs. Typical: $\epsilon_{\rm cuts} \sim 0.35 - 0.4$.

Type-II case background

For type-I, $J_z = 2$ background is even more dominant.

The total number of Higgs events is given by (with $I_\sigma(H^0, A^0)$ as plotted):

$$N_{Higgs} = [I_\sigma(H^0) + I_\sigma(A^0)](1 + \langle\lambda\lambda'\rangle)\left(\frac{dL}{dE_{\gamma\gamma}}\right)_{E_{\gamma\gamma}=m_{A^0}} \epsilon_{\rm cuts}\epsilon_b \quad (2)$$

The mass resolution for pure jet states is being studied. We estimate 1σ width ranging from about 3 GeV at $m_{b\bar b} \sim 250~\mathrm{GeV}$ to about 6 GeV at $m_{b\bar b} \sim 500~\mathrm{GeV}$. This is similar to TESLA estimates of $30\%\sqrt{m_{b\bar b}}$.

Need to increase this effective width to account for b decays containing neutrinos and to account for intrinsic Higgs widths.

Note: Neither analysis includes underlying overlap events, in particular those related to resolved photon processes, but overlapping events should not be a problem at TESLA; NLC?

Results including estimated smearing and Higgs width effects

- At large $\tan\beta$, need to include Higgs intrinsic widths.

- Also need to smear the pure jet final state mass distribution.

  We assume the standard $30\% \times \sqrt{m_{b\bar{b}}}$ Gaussian width corresponding to individual jet resolution of $\sim 30\%/\sqrt{E}$.

- Assume that effectively 50% of the time the neutrinos have a large impact and use the low Higgs mass ($120~\mathrm{GeV}$) result that that the Gaussian width for such final states is twice as large, i.e. $60\% \times \sqrt{m_{b\bar{b}}}$.

- Plot distributions in which 50% of the signal is smeared with $30\%\sqrt{m_{b\bar{b}}}$ and 50% of the signal is smeared with twice this width.

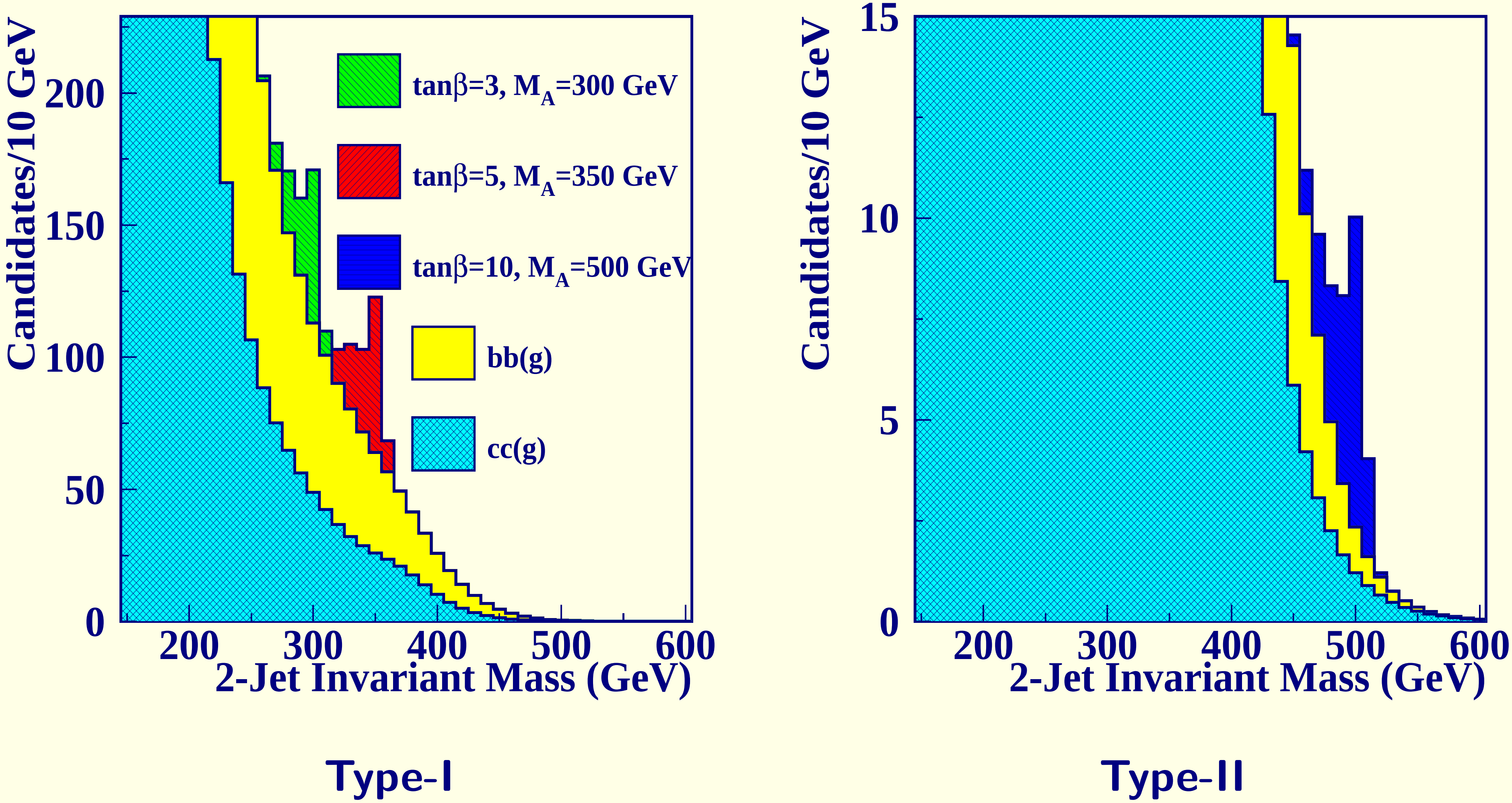


Figure 12: Typical one-year peaks after smearing and width effects for type-I and type-II luminosity spectra

- **In fact, we don't expect the neutrino smearing to be quite this bad.**

  We have provisionally adopted the following.

  - **50% of the events have Gaussian width $0.3\sqrt{m_{A^0}}$.**
  - **50% of the events have Gaussian width $1.6 \times 0.3\sqrt{m_{A^0}}$.**

- **We then determine an acceptance interval for which 67% of the signal events would be accepted when the Higgs bosons are narrow compared to the smearing widths. (This is the relevant situation within the LHC wedge and below.)**

  The result is an interval of $\pm\sqrt{1.5} \times 0.3\sqrt{m_{A^0}}$ centered about m_{A^0}, for which 78% of the $0.3\sqrt{m_{A^0}}$ events are accepted and 56% of the $1.6 \times 0.3\sqrt{m_{A^0}}$ events are accepted.

  Were we to use $2 \times 0.3\sqrt{m_{A^0}}$ for the 2nd 50% of the events, our signal-acceptance fraction (for small Higgs width) would be 62%, i.e. not enormously different.

- **We have temporarily (we will do a full job when we have more time) incorporated the Higgs widths by using an effective overall acceptance** interval of:

$$\Delta = 2 \times \sqrt{\left[\frac{1}{2}\langle\Gamma^{\rm tot}_{H,A}\rangle\right]^2 + 1.5[0.3\sqrt{m_{A^0}}]^2} \tag{3}$$

According to our input assumptions 67% of the signal events are accepted in both the limit of large intrinsic Higgs widths compared to detector/smearing effects and in the limit of small intrinsic Higgs widths.

- We continue to use $\epsilon_{b-tag} = 0.7$ and $\epsilon_{\rm acceptance} = 0.35$ as before.
- The background is then computed by accepting background events in the same interval, Δ, centered on m_{A^0}.
- We then contour various levels of statistical significance for the $H^0 + A^0$ signal in the $(m_{A^0}, \tan\beta)$ parameter plane.
- The contours shown assume maximal mixing, $m_{\rm SUSY} = 1~{\rm TeV}$, and no light stops, charginos, ... that would modify the one-loop $\gamma\gamma$ couplings of the H^0 and A^0.

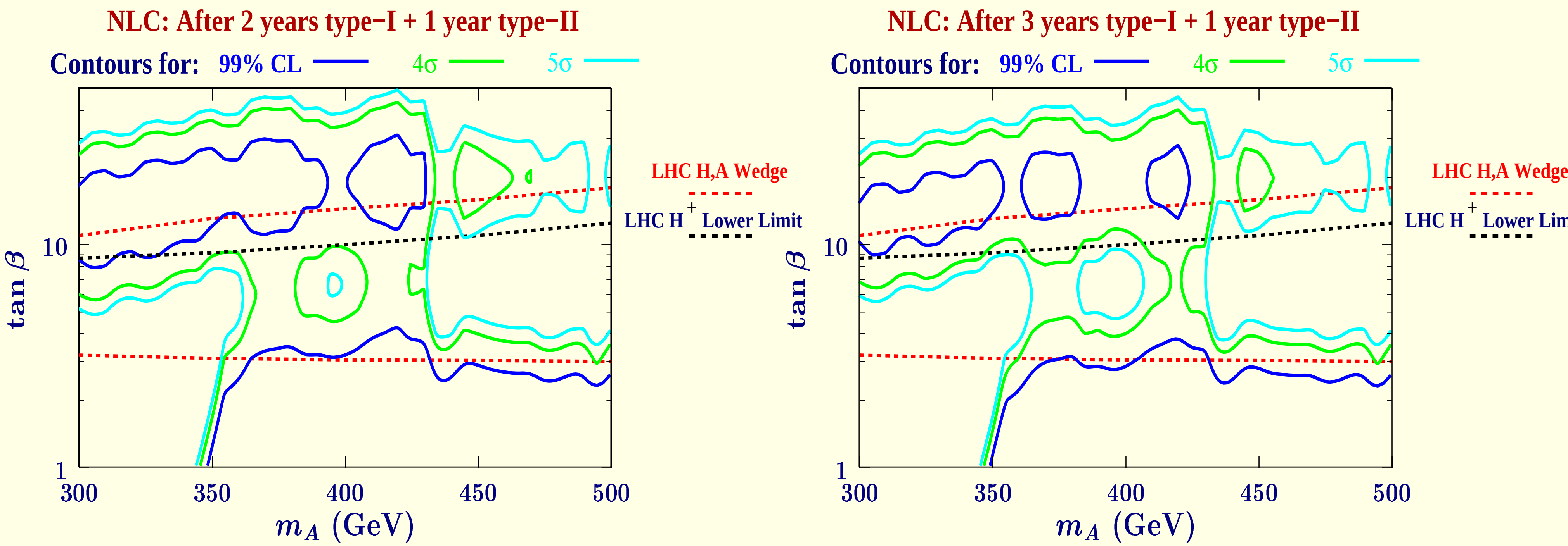


Figure 13: Contours for discovery and 99% CL exclusion after 3 or 4 years of NLC $\gamma\gamma$ running.

- Note the holes at $m_{A^0} \sim 375~\mathrm{GeV}$ and $\sim 425~\mathrm{GeV}$ 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.

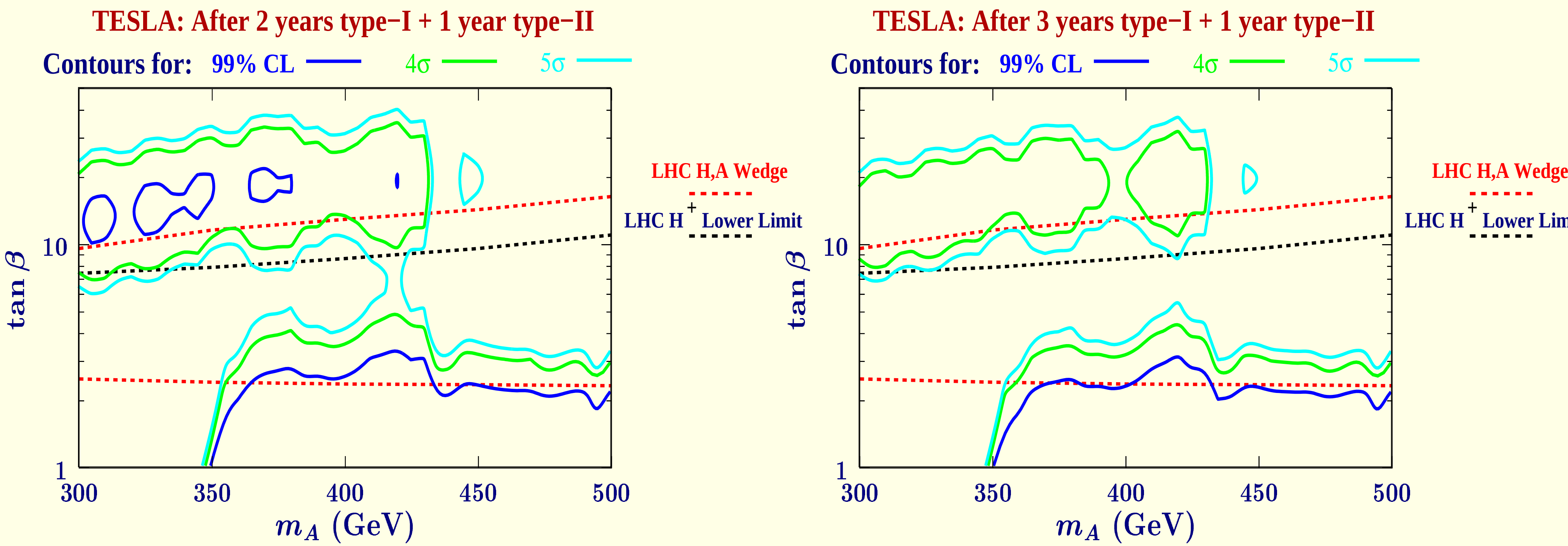


Figure 14: Contours for discovery and 99% CL exclusion after 3 or 4 years of TESLA $\gamma\gamma$ running.

- **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.

- 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 well way 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.

$m_{A^0}(\text{ GeV})$	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 $\gamma\gamma \to H^0, A^0 \to b\overline{b}$ 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 $\sqrt{s} = 630\text{ GeV}$. 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 by a factor of 2 with 4 years of operation. Ultimately, this would prove absolutely critical in the wedge region, unless the machine $\sqrt{s}$ can be increased to the point where H^0A^0 and H^+H^- pair production becomes possible.

Determination of CP

- Let us recall that the $\sigma(\gamma\gamma \to H^0) \propto \vec{\epsilon}_1 \cdot \vec{\epsilon}_2$ while $\sigma(\gamma\gamma \to A^0) \propto \vec{\epsilon}_1 \times \vec{\epsilon}_2$.

  For perpendicular polarizations of colliding photons you get A^0 while for parallel polarizations you get the H^0.

- In practice you can only linearly polarize the laser photons, so the even number asymmetry

$$\mathcal{A} = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \tag{4}$$

  is diluted (Stokes parameters) at the colliding photon level, but still very observable.

- $\Rightarrow$ allows separation, i.e. verification that both types of Higgs bosons actually present and checking predicted relative level of the two signals.

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.

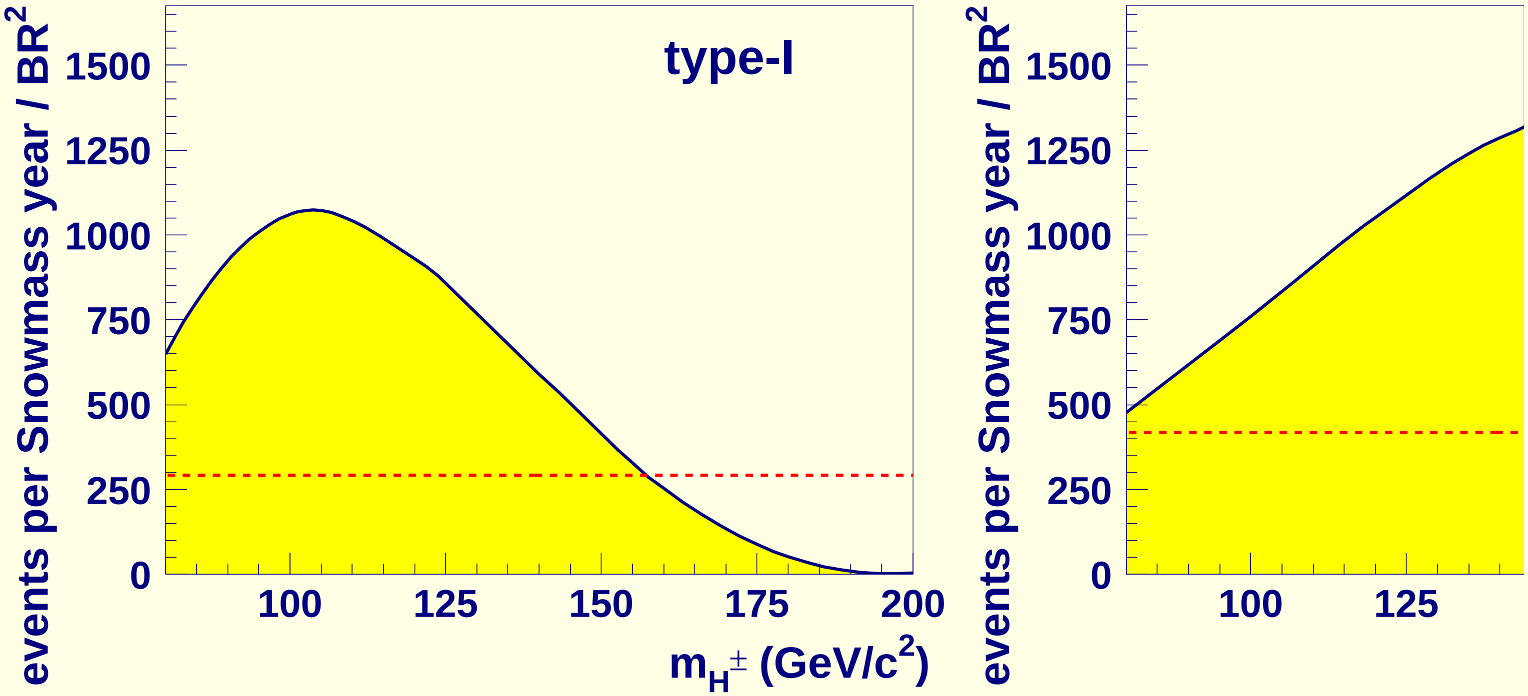


Figure 15: The plots show the number of accepted events per $\mathrm{BR}(h \to \tau^+\tau^-)^2$ per Snowmass year, as a function of $m_{H^\pm}$. The dashed horizontal line shows the number of accepted background $\gamma\gamma \to W^+W^-$ events. Sorry: could not get the 2nd guy to come out. It peaks at $m_{H^\pm} \sim 160~\mathrm{GeV}$ and falls below WW at $m_{H^\pm} \sim 185~\mathrm{GeV}$.

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.**

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

Luminosity Factor Required for 4σ Discovery of 2HDM A

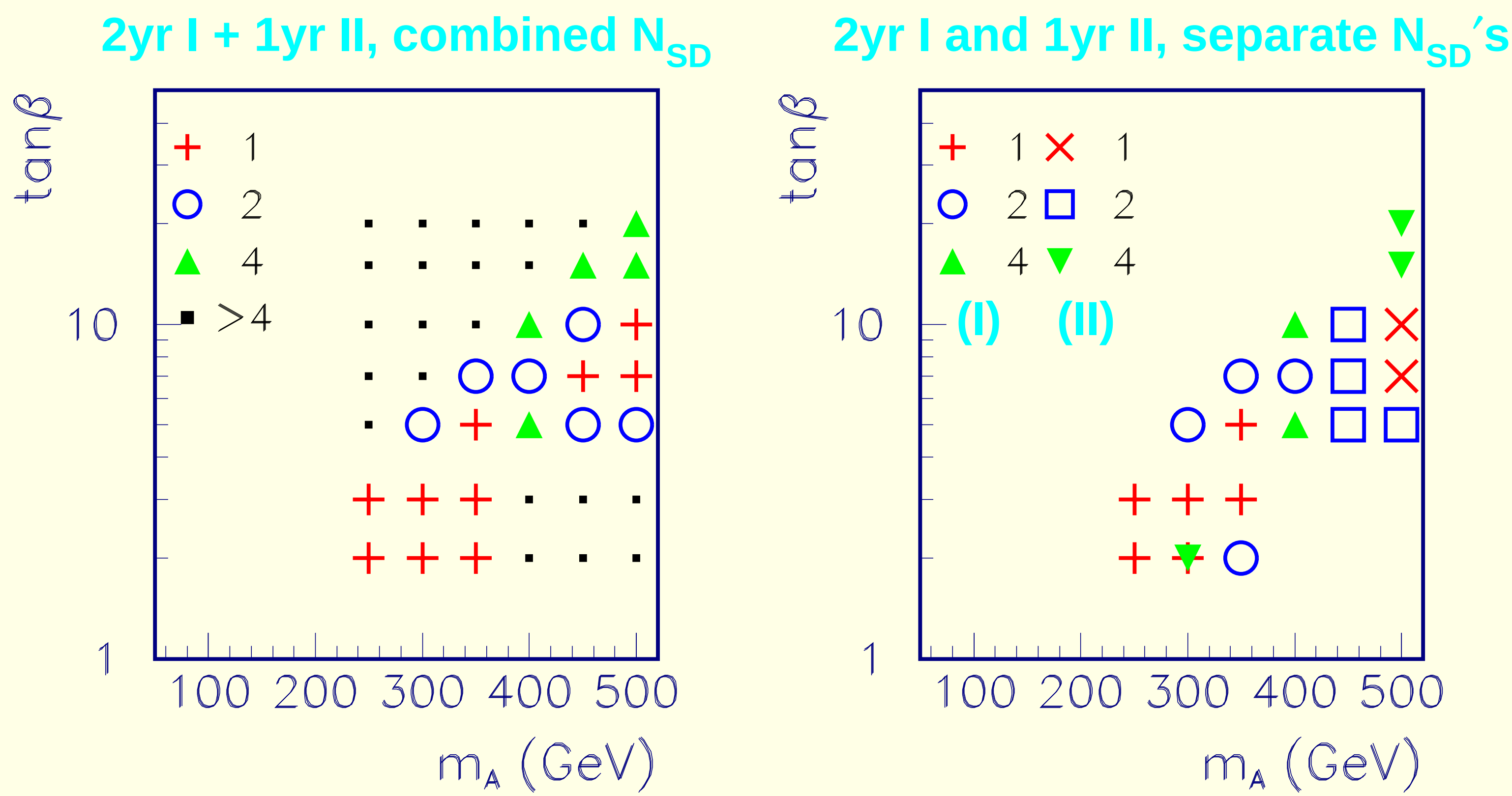


Figure 16: Assuming a machine energy of $\sqrt{s} = 630~\mathrm{GeV}$, we show the $[m_{A^0}, \tan\beta]$ points for which two 10^7 sec years of operation using the type-I $P\lambda_e, P'\lambda'_e > 0$ polarization configuration and one 10^7 sec year of operation using the type-II $P\lambda_e, P'\lambda'_e < 0$ 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 $1~\mathrm{TeV}$.

- **In the general 2HDM, there is a possibility for either spontaneous or explicit CP violation in the Higgs sector.**
  - **Use certain helicity asymmetries to probe the CP nature of an observed Higgs boson.**

$$\mathcal{A}_1 = \frac{|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2}{|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2}, \quad \mathcal{A}_2 = \frac{2\mathrm{Im}\left(\mathcal{M}_{++}\mathcal{M}^*_{--}\right)}{|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2} \tag{5}$$

  - **In terms of the Stokes polarization parameters**

$$\begin{aligned} dN &= dL_{\gamma\gamma} dPS \tfrac{1}{4}\left(|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2\right) \times \\ & \left[(1 + \langle\xi_2\xi_2'\rangle) + (\langle\xi_2\rangle + \langle\xi_2'\rangle)\mathcal{A}_1 + \left(\langle\xi_3\xi_1'\rangle + \langle\xi_1\xi_3'\rangle\right)\mathcal{A}_2\right]. \end{aligned} \tag{6}$$

  - **The asymmetry measured with circularly polarized photons is given by**

$$T_- = \frac{N_{++} - N_{--}}{N_{++} + N_{--}} = \frac{\langle\xi_2\rangle + \langle\xi_2'\rangle}{1 + \langle\xi_2\xi_2'\rangle}\mathcal{A}_1 \,. \tag{7}$$

where subscripts indicate the laser polarizations, which are simultaneously flipped.

– The asymmetry measured with linearly polarized photons is

$$T_\psi = \frac{N(\phi = \frac{\pi}{4}) - N(\phi = -\frac{\pi}{4})}{N(\phi = \frac{\pi}{4}) + N(\phi = -\frac{\pi}{4})} = \frac{\langle \xi_3 \xi_1' \rangle + \langle \xi_1 \xi_3' \rangle}{1 + \langle \xi_2 \xi_2' \rangle} \mathcal{A}_2 \,, \tag{8}$$

where ϕ is the angle between the linear polarizations of the laser photons. This one is a bit harder because the Stoke's parameters in the numerator above are not as large as for the circularly polarized numerator.

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

- 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 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.

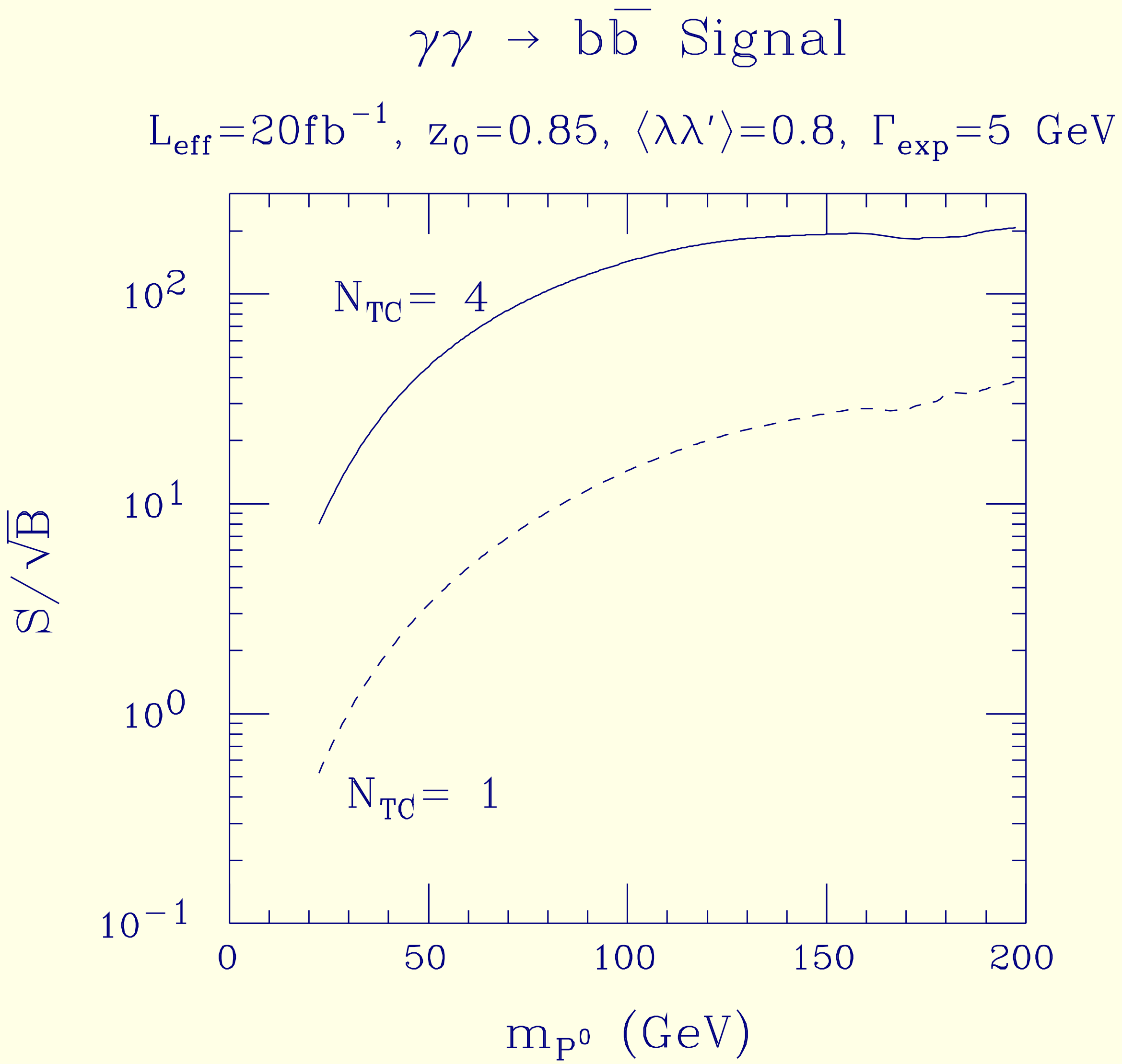


Figure 17: **For $L_{\rm eff} = 20{\rm fb}^{-1}$ (assumed independent of m_{P^0}), $|\cos\theta| < 0.85$, and $\Gamma_{\rm exp} = 5~{\rm GeV}$, we plot $S/\sqrt{B}$ for $N_{TC} = 4$ and $N_{TC} = 1$. Modern results would be better.**

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).
- It is natural for there to be Lagrangian terms that mix the radion and Higgs degrees of freedom (they have the same quantum numbers).
- In this case, there can be great difficulty in fully exploring the Higgs-radion system.
- 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 $gg \rightarrow h \rightarrow \gamma\gamma$ data from LHC.
- $\gamma\gamma \rightarrow h \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow \phi \rightarrow \gamma\gamma$ are also very interesting in this context.

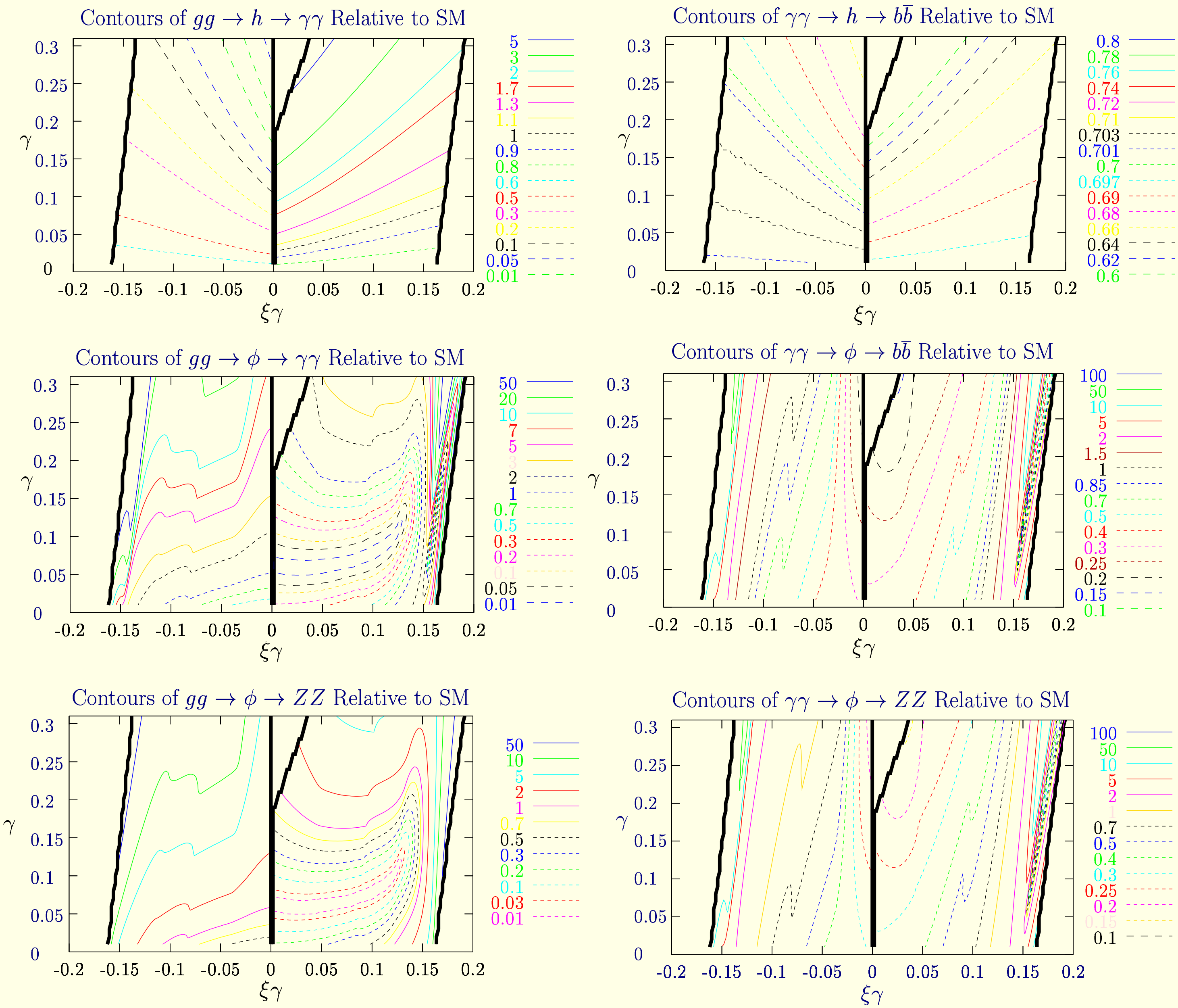
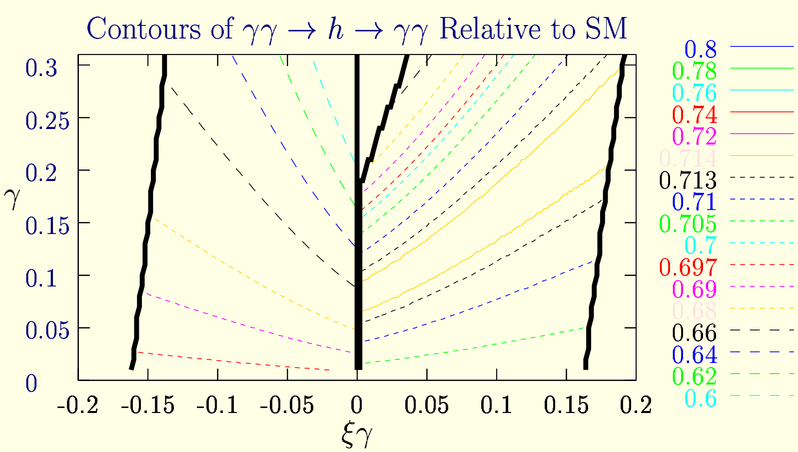


Figure 18: Contours of rates (relative to a SM Higgs of the same mass) in the $(\xi\gamma, \gamma)$ parameter space for fixed $m_h = 120$ GeV and $g^2_{Vfh} = 0.7$ (relative to SM).



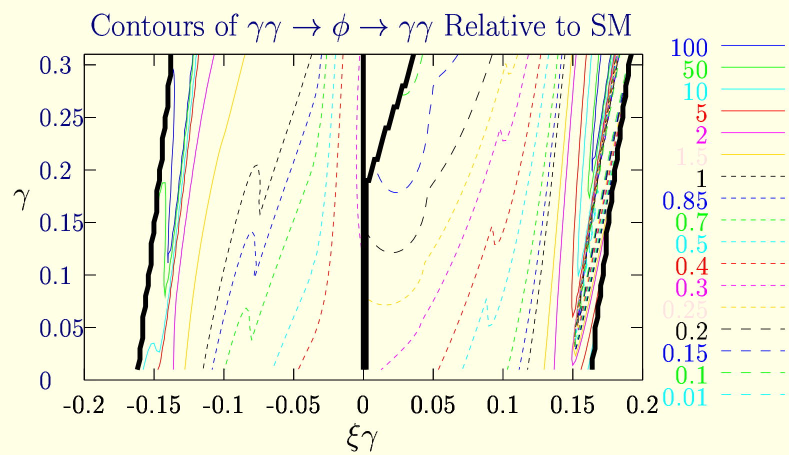


Figure 19: Contours of $\gamma\gamma \to h, \phi \to \gamma\gamma$ rates (relative to a SM Higgs of the same mass) in the $(\xi\gamma, \gamma)$ parameter space for fixed $m_h = 120$ GeV and $g^2_{Vfh} = 0.7$ (relative to SM).

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 $n = 2\ (4)$.**

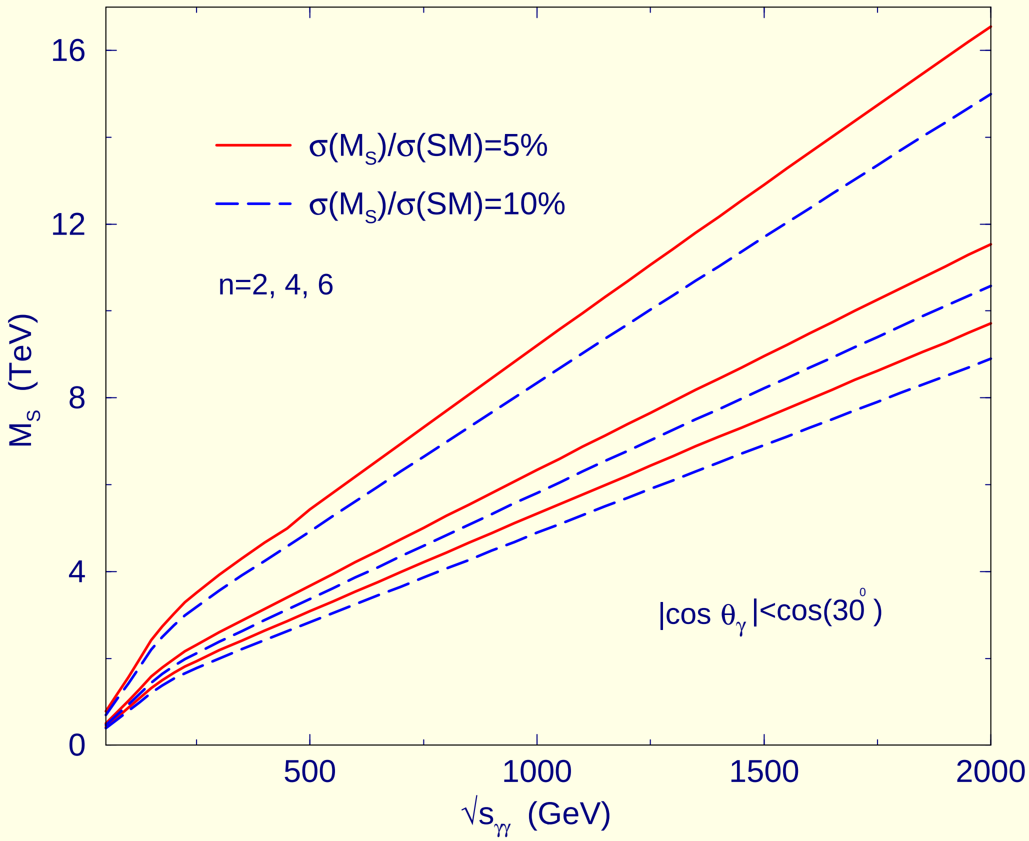


Figure 20: M_S reach versus $\sqrt{s_{\gamma\gamma}}$ using the process $\gamma\gamma \rightarrow \gamma\gamma$, by requiring the signal to be 5% or 10% of the SM prediction. A cut of $|\cos\theta_\gamma| < \cos 30°$ is imposed. From K. Cheung.

Rizzo estimates the following:

Reaction	M_S Reach (TeV units) for $L = 100\mathrm{fb}^{-1}$
$e^+e^- \to f\bar{f}$	$6.5\sqrt{s}$
$e^+e^- \to e^+e^-$	$6.2\sqrt{s}$
$e^-e^- \to e^-e^-$	$6.0\sqrt{s}$
$pp \to \ell^+\ell^-$ (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 $e^-\gamma \to \widetilde{e}^-\widetilde{\chi}_1^0$.

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

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

- 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 $M_S = 200~\mathrm{GeV}$ 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 ($\Delta_{\text{sys.}} \sim 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{\text{sys.}} \sim 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
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 $\gamma\gamma$ and $e\gamma$ probes of Higgs physics and related will probably be absolutely critical to a full exploration of a Higgs or Higgs-like sector**
- **It is hard to imagine that we would not want to plan on a $\gamma\mathrm{C}$ facility at the LC.**
- **. . .**