Detecting Heavy SUSY Higgs Bosons in Two-Photon Collisions at a Linear Collider

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Collaborators: D. Asner, J. Gronberg
Reference: hep-ph/0110320

Other recent papers on topic:
M.M. Muhlleitner, M. Kramer, M. Spira, P.M. Zerwas: hep-ph/0101083

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GENERALITIES

The rate for $\gamma\gamma$ production of any final state X consisting of two jets is given by

$$N(\gamma\gamma \to \widehat{h} \to X) =$$

$$\sum_{\lambda=\pm1,\lambda'=\pm1} \int dz dz' dz_{\theta^*} \frac{d\mathcal{L}_\gamma^\lambda(\lambda_e, P, z)}{dz} \frac{d\mathcal{L}_\gamma^{\lambda'}(\lambda'_e, P', z')}{dz'} A(z, z', z_{\theta^*}) \times$$

$$\left\{ \frac{1+\lambda\lambda'}{2} \frac{d\sigma_{J_z=0}}{dz_{\theta^*}}(zz's, z_{\theta^*}) + \frac{1-\lambda\lambda'}{2} \frac{d\sigma_{J_z=\pm2}}{dz_{\theta^*}}(zz's, z_{\theta^*}) \right\}. \quad (1)$$

Higgs Signal:

$$\frac{d\sigma_{J_z=0}}{dz_{\theta^*}}(s', z_{\theta^*}) = \frac{8\pi\Gamma(h \to \gamma\gamma)\Gamma(h \to X)}{(s' - m_h^2)^2 + [\Gamma_h^{\rm tot}]^2 m_h^2}, \quad (2)$$

Background:

$$\frac{d\sigma_{J_z=0}}{dt'}(s',t',u') = \frac{12\pi\alpha^2 Q_q^4}{s'^{\,2}}\frac{m_q^2(s'-2m_q^2)}{\widehat{t}^2\widehat{u}^2} \ll \tag{3}$$

$$\frac{d\sigma_{J_z=\pm 2}}{dt'}(s',t',u') = \frac{12\pi\alpha^2 Q_q^4}{\widehat{s}'^{\,2}}\frac{(\widehat{t}\widehat{u}-m_q^2 s')(\widehat{t}^2+\widehat{u}^2-2m_q^2 s')}{\widehat{t}^2\widehat{u}^2} \tag{4}$$

In a common approximation, the dependence of the acceptance and cuts on z and z' is ignored and one writes

$$\sum_{\lambda,\lambda'}\int dz dz' \frac{d\mathcal{L}_\gamma^{\lambda}(\lambda_e,P,z)}{dz}\frac{d\mathcal{L}_\gamma^{\lambda'}(\lambda'_e,P',z')}{dz'}[1,\lambda\lambda']$$
$$= \int dy \frac{d\mathcal{L}_{\gamma\gamma}(\lambda_e,\lambda'_e,P,P',y)}{dy}[1,\langle\lambda\lambda'\rangle(y)]\,, \tag{5}$$

where $y = E_{\gamma\gamma}/\sqrt{s} = \sqrt{s'}/\sqrt{s} = zz'$. In this approximation, one obtains

$$N(\gamma\gamma\to h\to X) = \frac{4\pi^2\Gamma(h\to\gamma\gamma)B(h\to X)(1+\langle\lambda\lambda'\rangle(y))}{\sqrt{s}m_h^2}\left.\frac{d\mathcal{L}_{\gamma\gamma}}{dy}\right|_{y=m}$$

$$\equiv I_\sigma(\gamma\gamma \to h \to X) \qquad \left[(1+\langle\lambda\lambda'\rangle)\frac{d\mathcal{L}_{\gamma\gamma}}{dE_{\gamma\gamma}}\right]_{E_{\gamma\gamma}=m_h} \frac{\int_{-1}^{1} dz_{\theta^*} A(z_{\theta^*})}{2},$$

where we have assumed that the resolution, $\Gamma_{\rm res}$, in the final state invariant mass m_X is such that $\Gamma_{\rm res} \gg \Gamma_h^{\rm tot}$ and that $\frac{d\mathcal{L}}{dE_{\gamma\gamma}}$ does not change significantly over an interval of size $\Gamma_h^{\rm tot}$.

Inputs

- Recall naive expectations for back-scattered photons:

  $P\lambda_e = P'\lambda'_e < 0$ yields $E_{\gamma\gamma}$ spectrum with peak and for $|\lambda_e| = |\lambda'_e| \geq 0.5$ (100% polarization) one finds $\langle\lambda\lambda'\rangle \geq 0.9$ for colliding photons at peak.

  $P\lambda_e = P'\lambda'_e > 0$ yields broad hump-shaped $E_{\gamma\gamma}$ spectrum with substantial $\langle\lambda\lambda'\rangle \sim 0.5 - 0.6$ over broad spectrum hump.

- More realistic is to employ CAIN Monte Carlo for luminosity, realistic polarization expectations and LLNL laser expectations (1 micron wavelength, . . .)

  In particular,

  – $\sqrt{s} = 630~\mathrm{GeV}$, $x \simeq 5.69 \Rightarrow$ peak at $500~\mathrm{GeV}$.
  – Current advice on electron polarization: use $\lambda_e = 0.4$ (80% pol.).
  $\Rightarrow$, $\langle\lambda\lambda'\rangle \sim 0.8$ at the peak in the peaked spectrum case.
  $\Rightarrow$ dominant background is $J_z = \pm 2$!

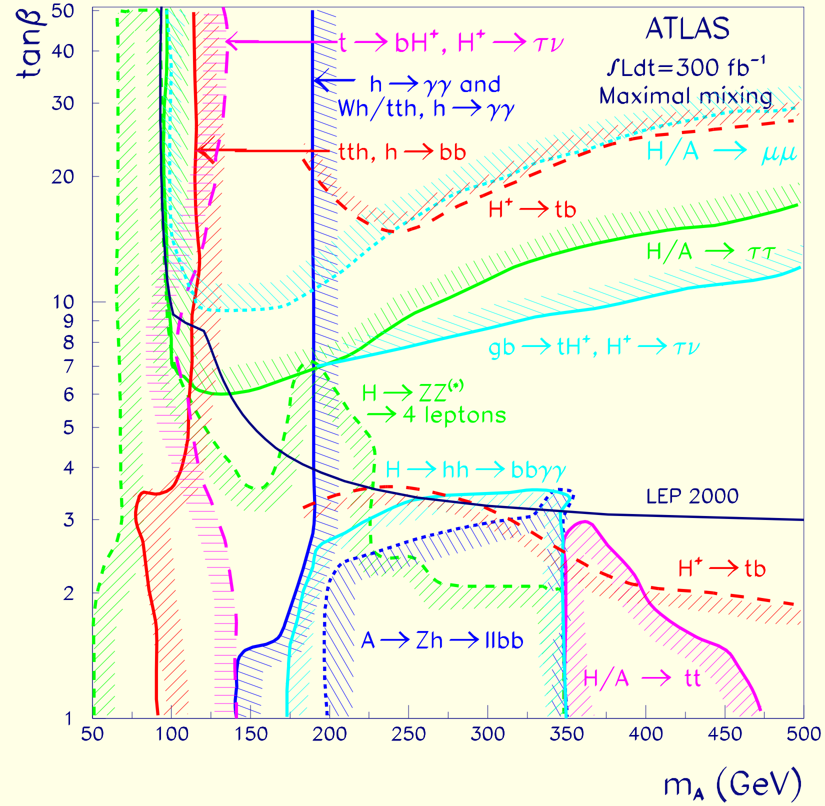
THE HEAVY MSSM H^0 and A^0

- 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

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

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 LHC cannot directly observe any of the heavy MSSM Higgs bosons.



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.

There are two scenarios:

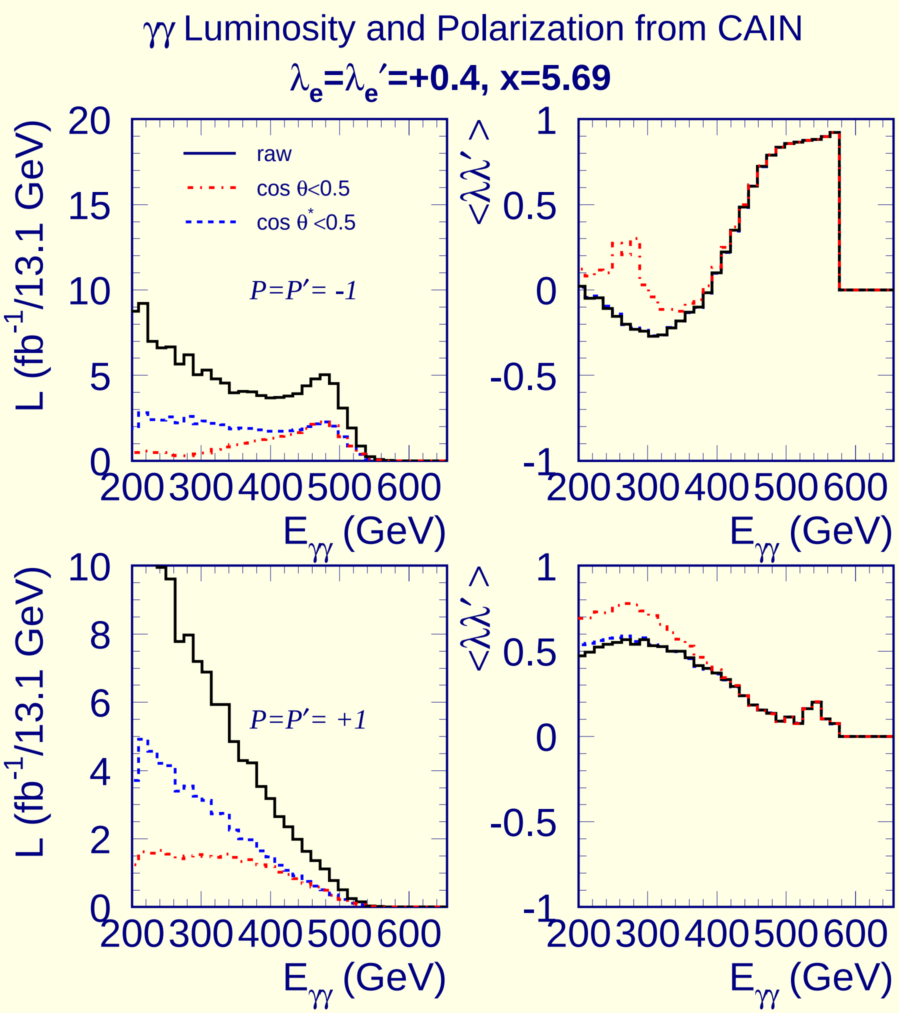
- We have some constraints from precision h^0 measurements ($e.g.$ from $\Gamma(h^0 \to b\bar{b})$) that determine $m_{H^0} \sim m_{A^0}$ within $50~\mathrm{GeV}$.
  $\Rightarrow$ choose $\sqrt{s}$ and peaked luminosity spectrum with peak near this mass.
- We do not have such constraints. In particular: are there reasonable scenarios for which decoupling ($\cos^2(\beta - \alpha) = 0$) happens essentially independent of m_{A^0} (Yes!).
  No deviation seen $\Rightarrow$ (a) scan or (b) run at high energy and run part of time with broad spectrum and part of time with peaked spectrum. To cover all of wedge region, (b) turns out to be best.

We shall examine what happens if we operate at $\sqrt{s} = 630~\mathrm{GeV}$ ($\to x = 5.69$ for 1 micron laser wavelength).

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 $450~\mathrm{GeV}$.

For $P = P' = +1$, get broad spectrum sensitivity in region of $m_{A^0} \sim 350 - 400~\mathrm{GeV}$.

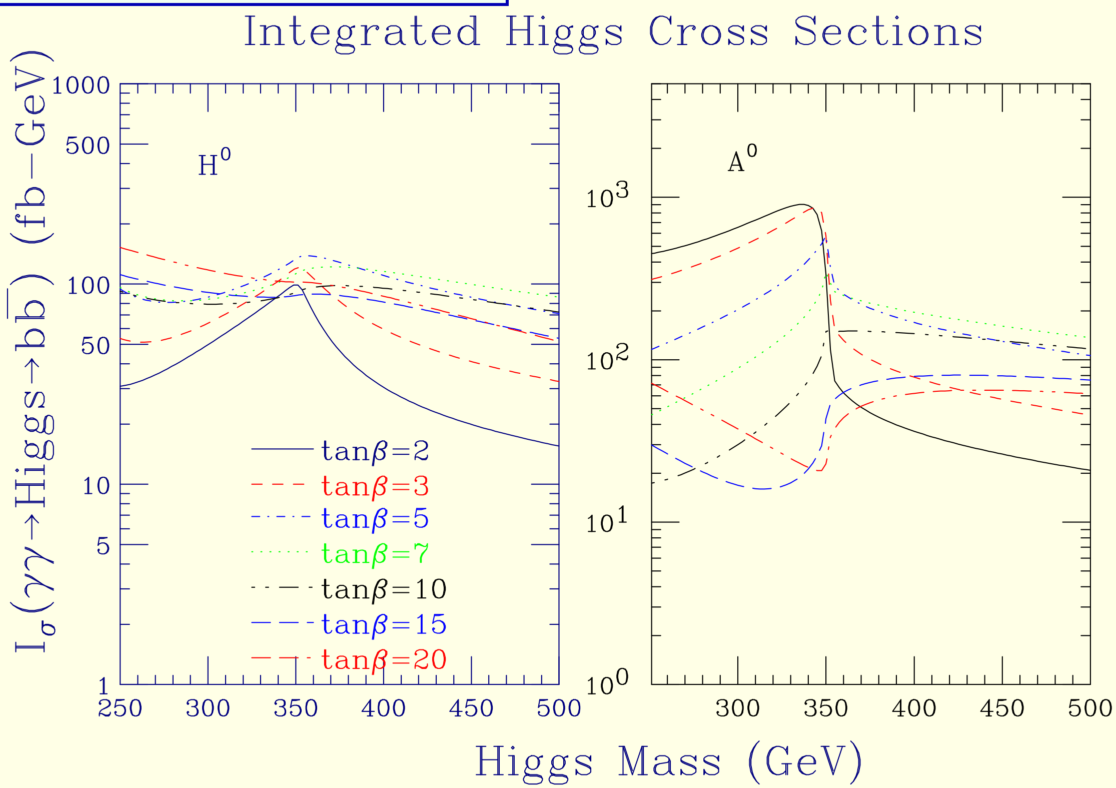
The Luminosity Spectra



Luminosity and $\langle\lambda\lambda'\rangle$ expectations for $\lambda_e = \lambda'_e = 0.4$ vs. $E_{\gamma\gamma}$ for $P = P' = -1$ and $P = P' = +1$.

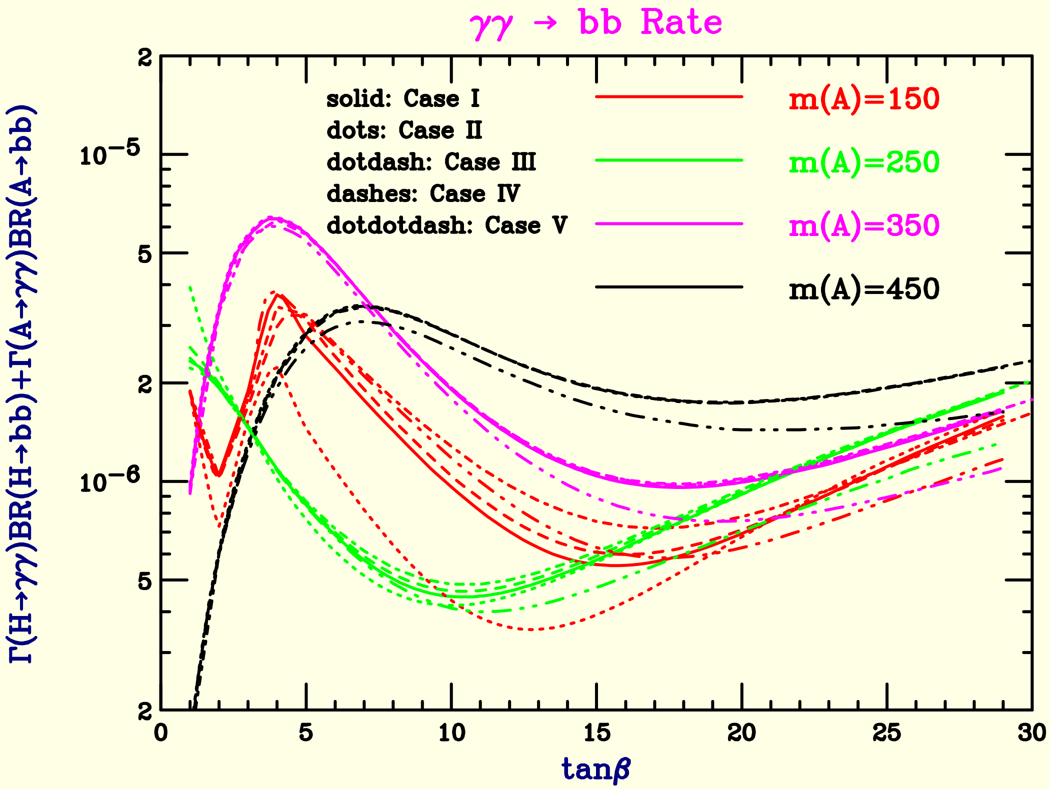
Note: p_z cut to 'clean up' low-$E_{\gamma\gamma}$ tail in broad spectrum case = BAD.

Basic Signal Cross Sections



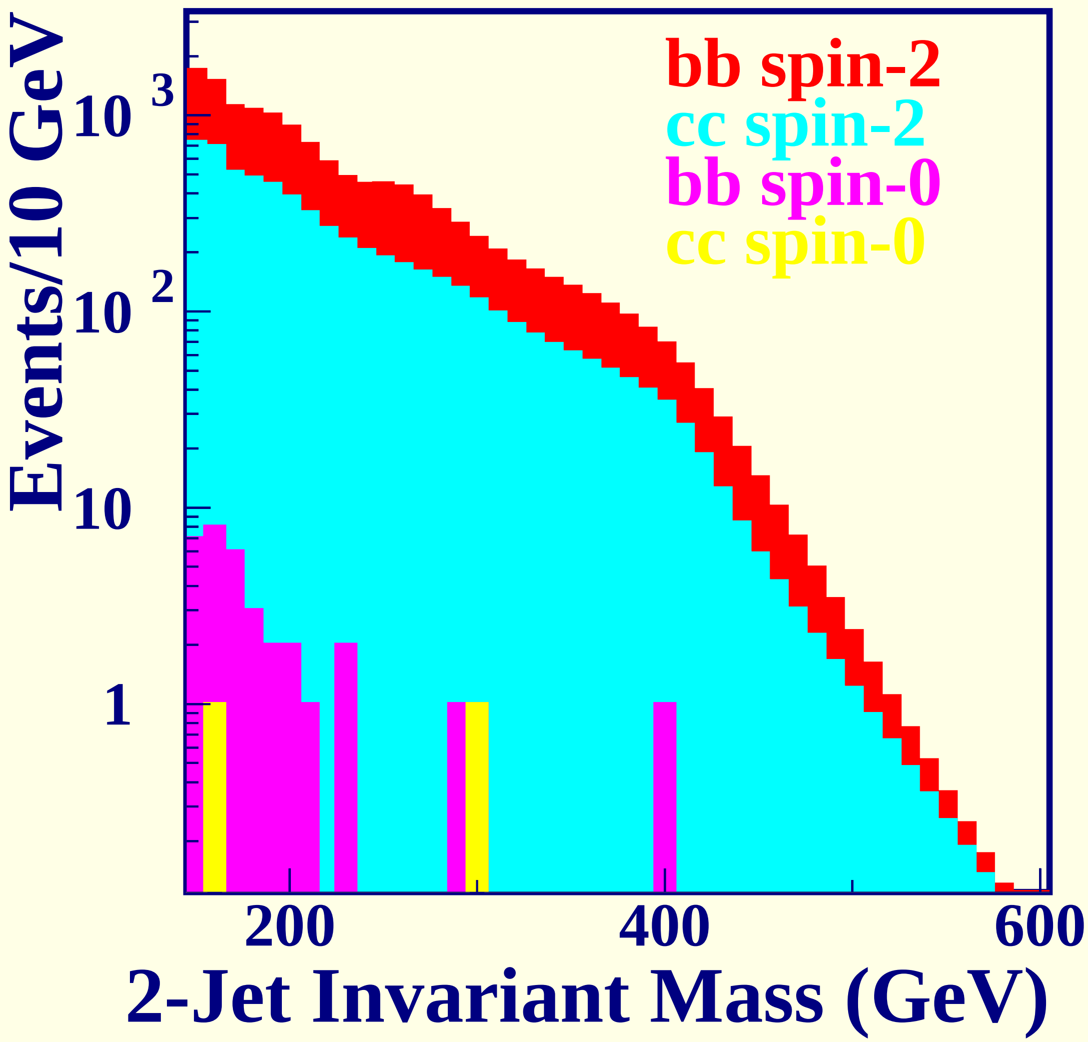
Cross section ($\mathrm{fb} - \mathrm{GeV}$ units) to be multiplied by efficiencies, $1 + \langle \lambda\lambda' \rangle$ and $\left[\frac{dL}{dE_{\gamma\gamma}}\right]_{E_{\gamma\gamma}=m_{A^0}}$.

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

Model indep. 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 improve above the LHC wedge region.



Type-II case background

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 (see talk by Asner). Typical: $\epsilon_{\rm cuts} \sim 0.35 - 0.4$.

The total number of Higgs events is given by (with σ_{H^0,A^0} as plotted):

$$N_{Higgs} = [I_\sigma(H^0) + I_\sigma(A^0)](1 + \langle\lambda\lambda'\rangle) \left(\frac{dL}{dE_{\gamma\gamma}}\right)_{E_{\gamma\gamma}=m_{A^0}} \epsilon_{\rm cuts}\epsilon_b \qquad (7)$$

The mass resolution is being studied, but we estimate 1σ width ranging from about 3 GeV at $m_{b\bar b} \sim 250~\mathrm{GeV}$ to about 6 GeV at $m_{b\bar b} \sim 500~\mathrm{GeV}$

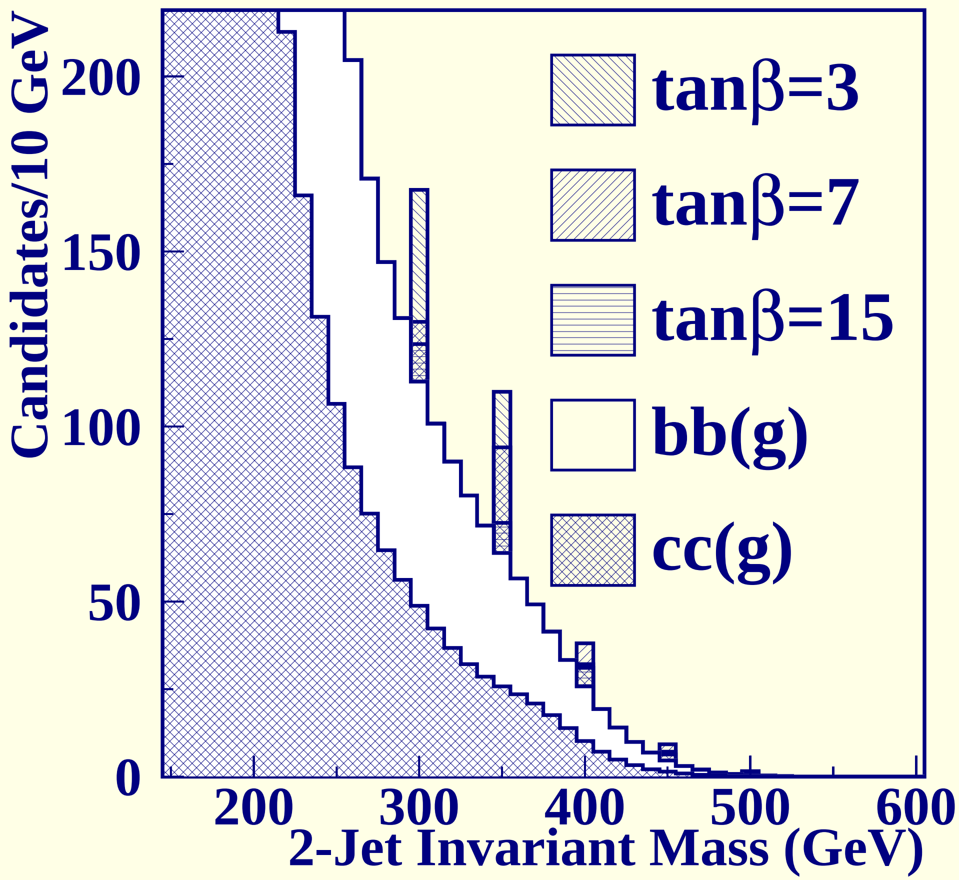
This is similar to TESLA estimates of $30\%\sqrt{m_{b\bar b}}$.

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?

We will assume that 50% of Higgs events fall into 10 GeV bin, and compute $N_{SD} = S/\sqrt{B}$ for the best bin.

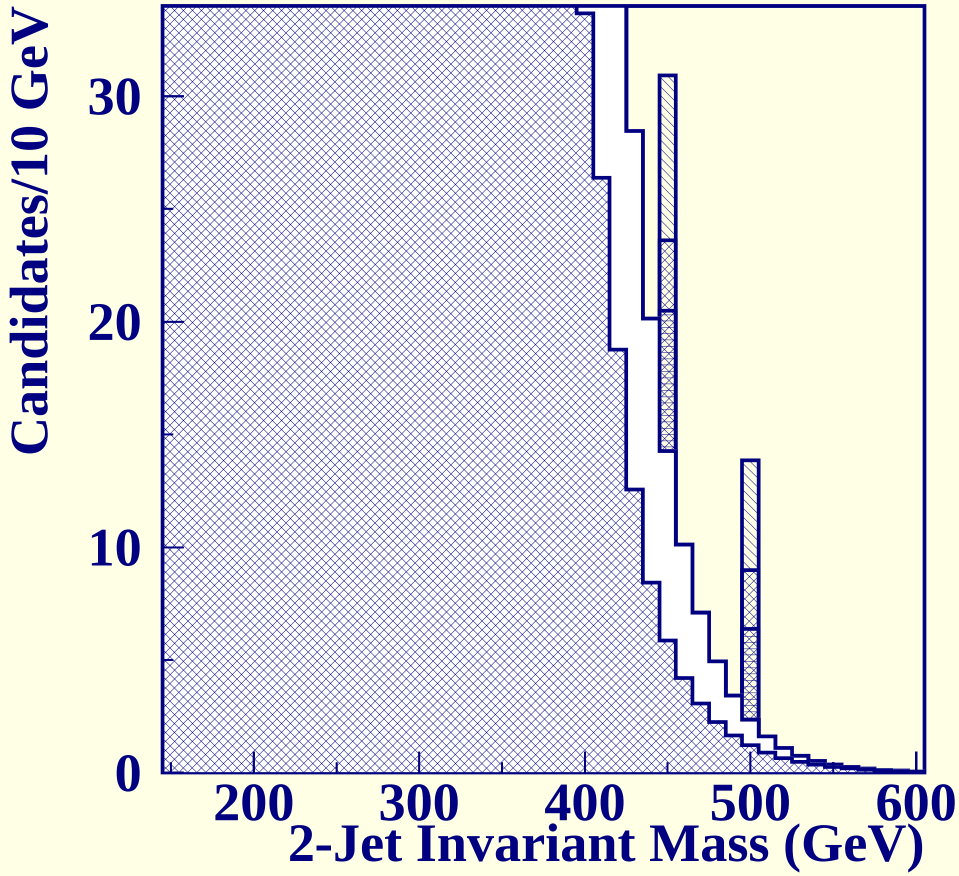
This bin size is meant to roughly account for resolution, (small) mass difference $m_{H^0} - m_{A^0}$, and Higgs widths that start to be of order a few GeV at the higher $\tan\beta$ values in the wedge region.

Results for 1 year of operation in $P = P' = +1$ mode.



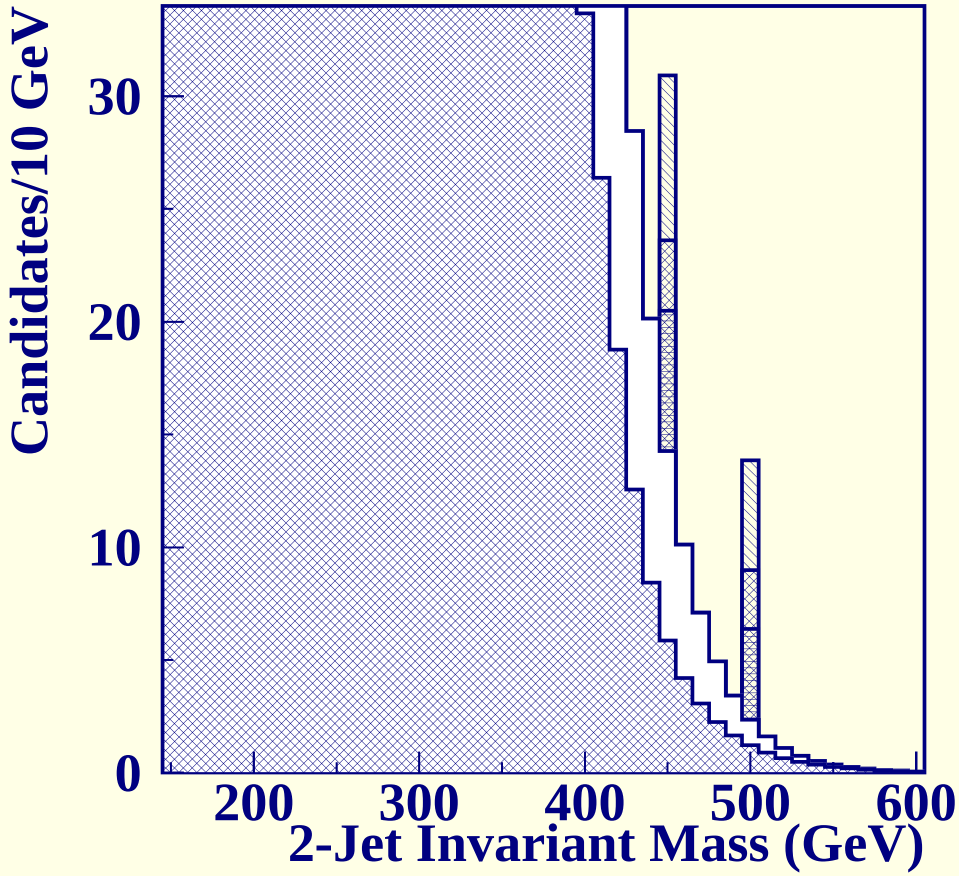
Assume all signal events fall into single 10 GeV $m_{b\bar{b}}$ bin.
$P = P' = +1$ **yields reasonably large** $\lambda\lambda'$ **at** $E_{\gamma\gamma} \sim 250 - 400\ \mathrm{GeV}$.

The Results for 1 year of operation in $P = P' = -1$ mode



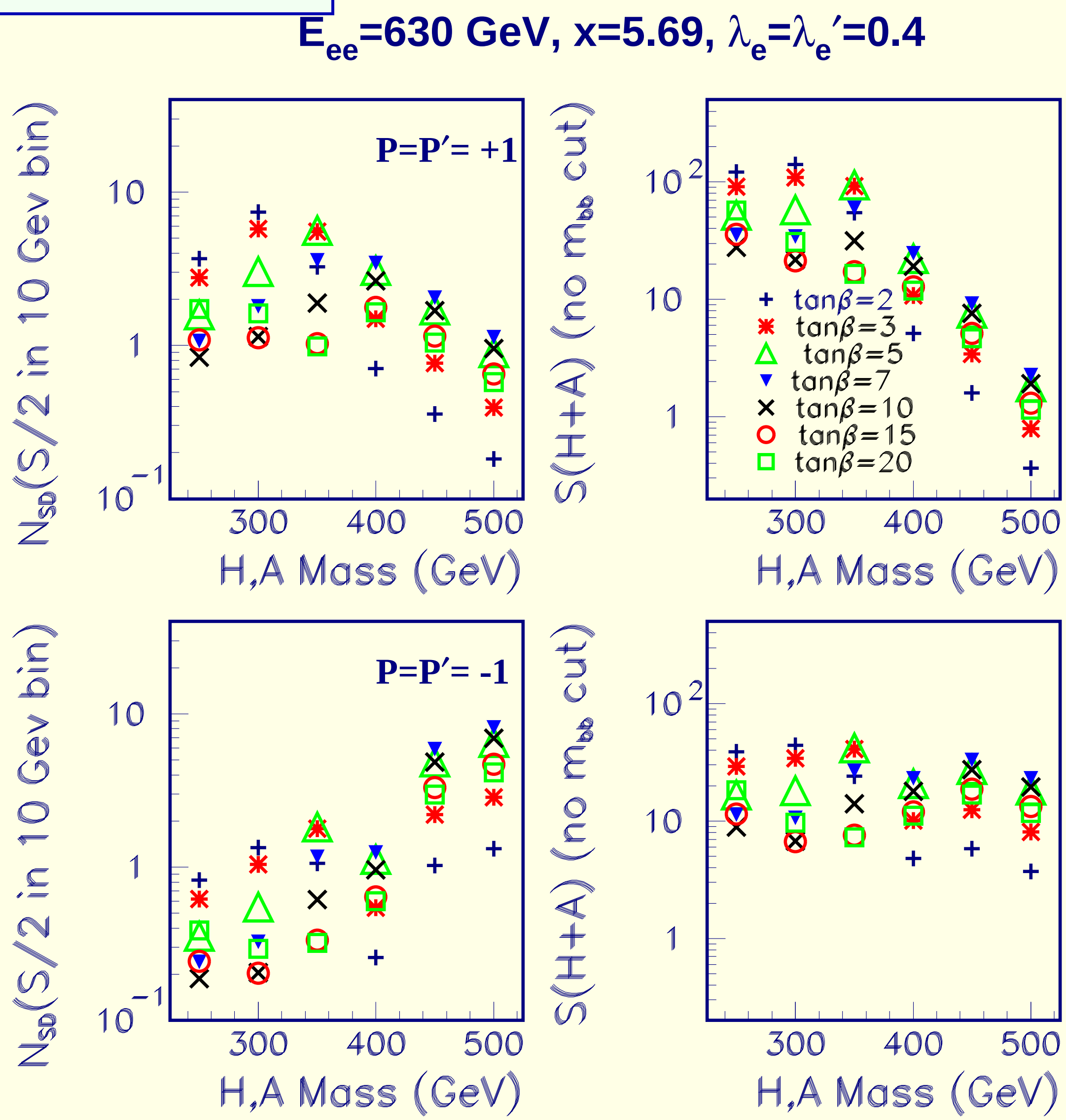
Assume all signal events fall into single $10\ \mathrm{GeV}\ m_{b\bar{b}}$ bin.
$P = P' = -1$ yields luminosity peak at $E_{\gamma\gamma} = 500\ \mathrm{GeV}$ and large $\lambda\lambda'$ there.

The Results for 1 year of operation in $P = P' = -1$ mode



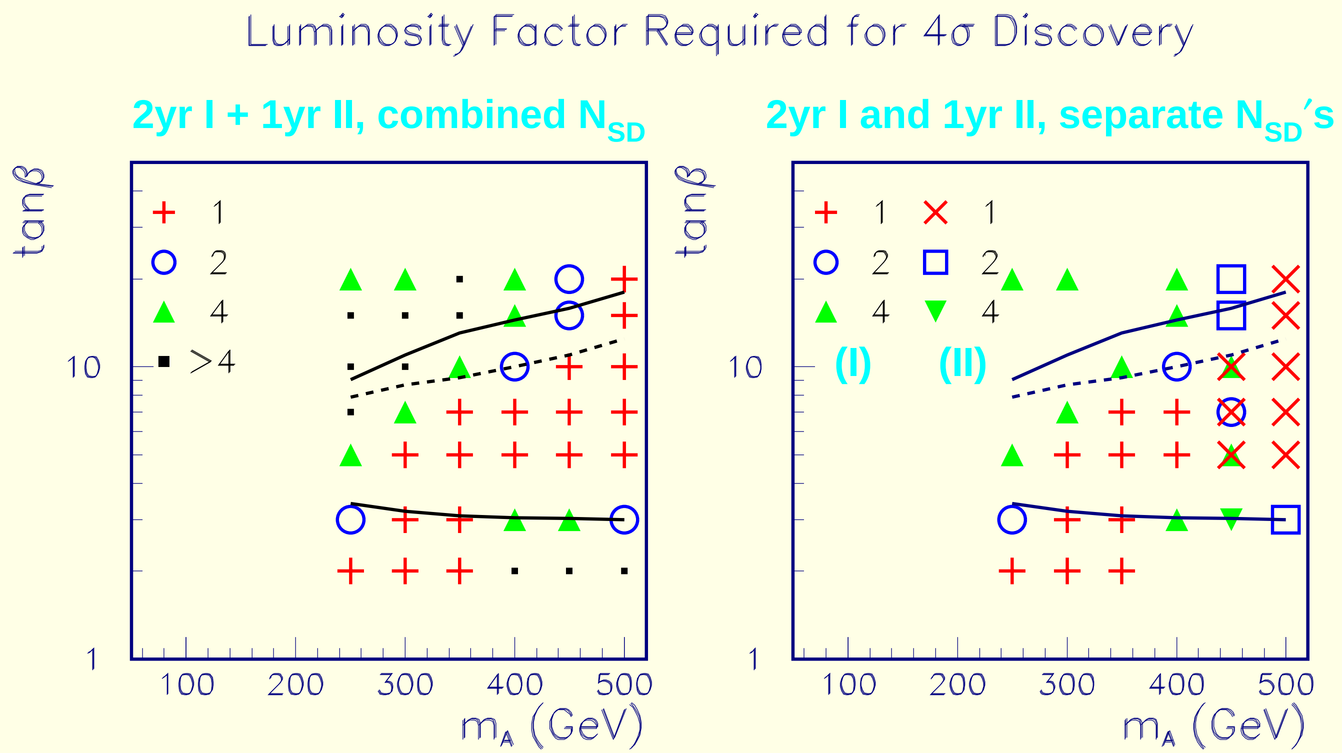
Assume all signal events fall into single $10\ \mathrm{GeV}\ m_{b\bar{b}}$ bin.
$P = P' = -1$ yields luminosity peak at $E_{\gamma\gamma} = 500\ \mathrm{GeV}$ and large $\lambda\lambda'$ there.

$\sqrt{s} = 630$ GeV fixed energy approach



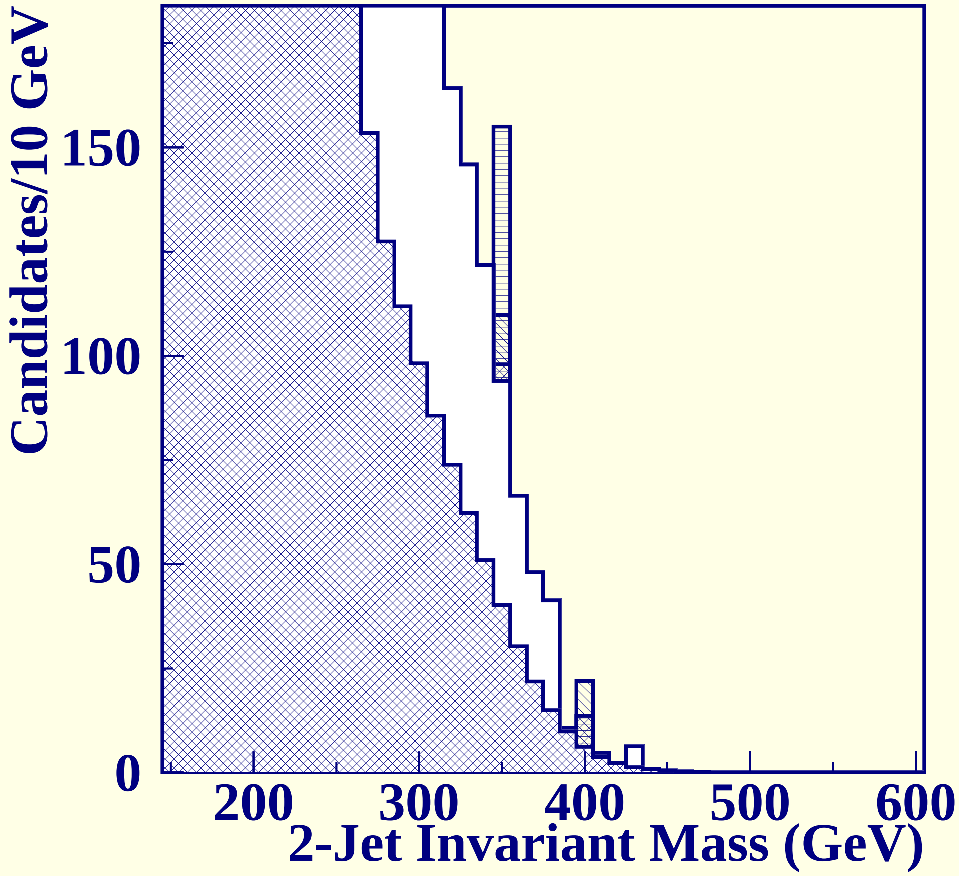
Assume 2 year of NLC operation in $P = P' = +1$ mode and 1 year in $P = P' = -1$ mode.
Assume that 1/2 of signal events fall into a single 10 GeV bin centered on $m_{A^0} \sim m_{H^0}$.
$\Rightarrow$ **some reasonable signals at intermediate masses for $P = P' = +1$.**
$\Rightarrow$ **some reasonable signals at highest mass for $P = P' = -1$.**

The Wedge Results: peaked + broad spectrum running.



RH window: separate N_{SD}'s for 2 yr type-I and 1 yr type-II operation.
LH window: combined N_{SD}'s.
Solid lines = LHC H^0, A^0 wedge.
Above dashed line = LHC $H^\pm$ discovery (then know $\sqrt{s}$ for $m_{A^0} \sim m_{H^\pm}$).
Pair production covers up to $m_{A^0} \gtrsim 300$ GeV.

The Results for 1 year $P = P' = -1$ (peaked) mode, $\sqrt{s} = 535$ GeV.



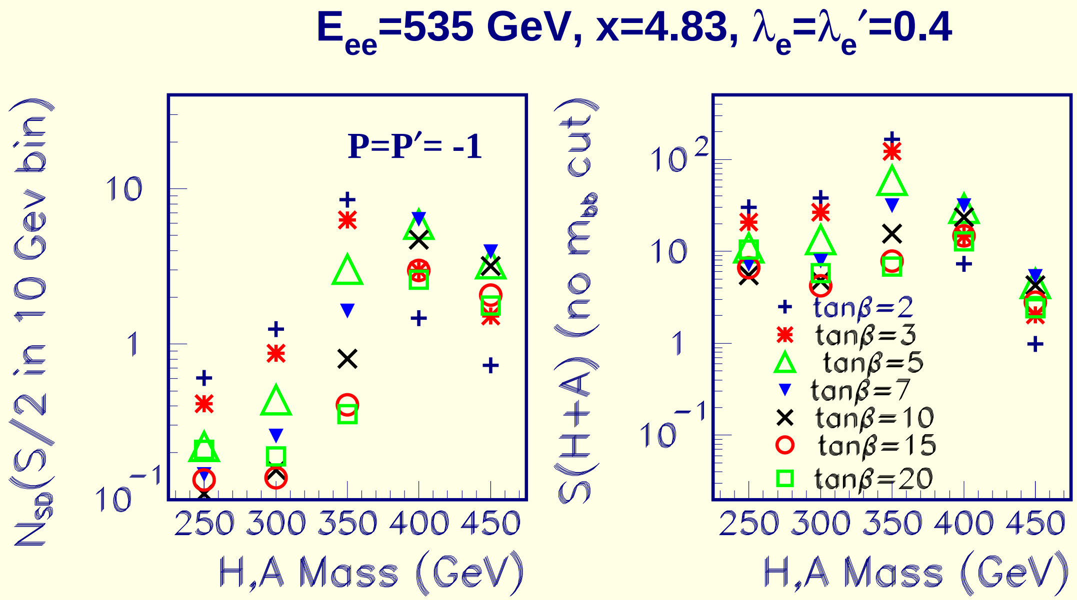
Assume all signal events fall into single 10 GeV $m_{b\bar{b}}$ bin.
$P = P' = -1$ yields luminosity peak at $E_{\gamma\gamma} = 400$ GeV for $\sqrt{s} = 535$ GeV and large $\lambda\lambda'$ there.

$\sqrt{s} = 535$ GeV peaked spectrum results

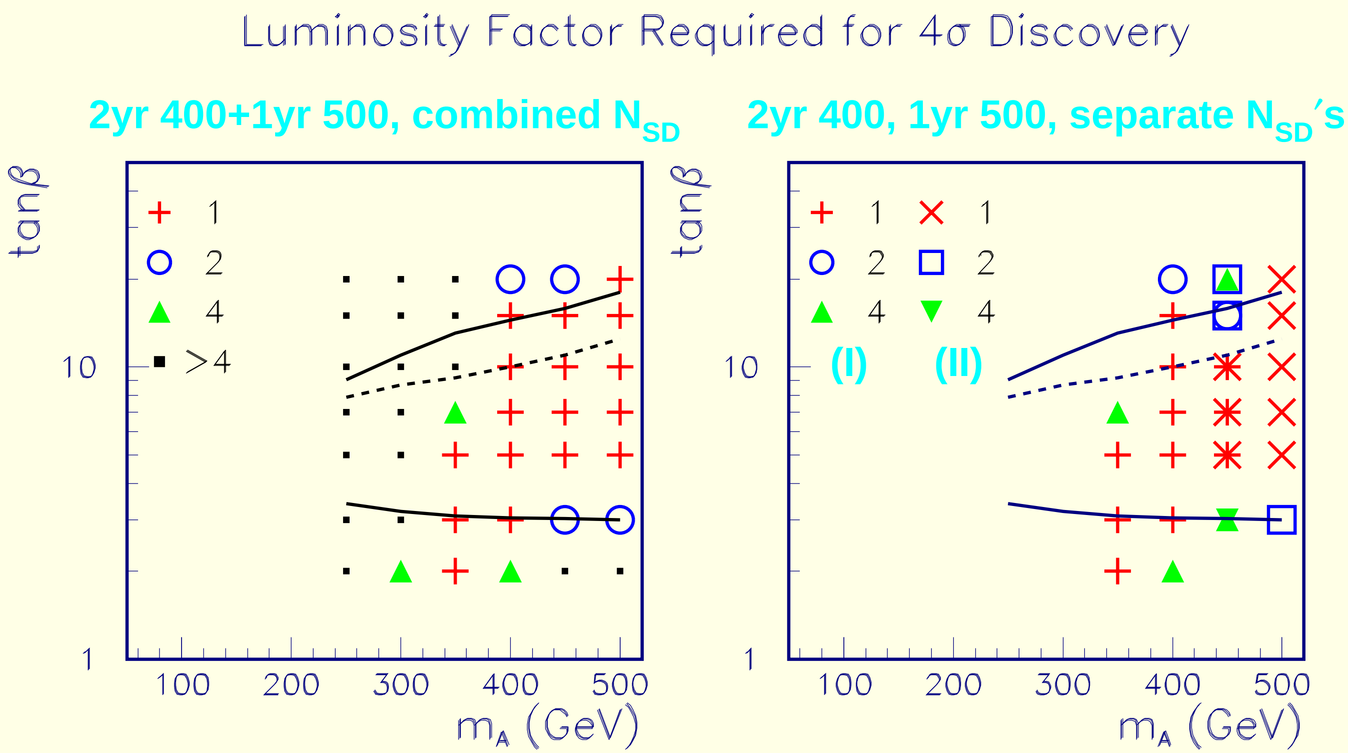
For 1 year of NLC operation in $P = P' = -1$ mode at $\sqrt{s} = 535$ GeV (i.e. peak at $E_{\gamma\gamma} = 400$ GeV). Assume that 1/2 of signal events fall into a single 10 GeV bin centered on $m_{A^0} \sim m_{H^0}$.

$\Rightarrow$ some reasonable signals for $m_{A^0} \sim 350$ GeV $- 400$ GeV.

Below 350 GeV is covered by pair production at $\sqrt{s} = 630$ GeV.



The Wedge Results: two $\sqrt{s}$ values with peaked spectrum



RH window: separate N_{SD}'s for 2 yr $\sqrt{s} = 535$ GeV and 1 yr $\sqrt{s} = 630$ GeV type-II operation.
LH window: combined N_{SD}'s.

CONCLUSIONS

The MSSM

1. Very important to verify H^0, A^0 mass resolutions assumed; work on this is in progress, but there is general agreement that earlier assumptions are not unreasonable.

2. Resolved photon process backgrounds still need study for NLC. TESLA bunch spacing $\Rightarrow$ no problem there.

3. NLC yearly luminosities assumed above are about a factor of 2 smaller at the peak than TESLA values.

   Also get a factor of 2 increase using round beams at NLC.

   $\Rightarrow$ good wedge coverage.

4. Going to TESLA assumption of higher λ_e would reduce background by perhaps as much as a factor of 2.

   $\Rightarrow$ another 40% improvement in $S/\sqrt{B}$.

5. Some of the weaker low-$\tan\beta$ signals could be enhanced by using the $A^0, H^0 \to t\bar{t}$, $H^0 \to h^0 h^0$ and $A^0 \to Zh^0$ final states.

6. With large $N_{\rm SD}$ for signal, CP studies/separation of the heavy Higgs bosons become possible.

CLEARLY, $\gamma\gamma$ COLLISIONS WILL BE A VERY POWERFUL PROBE OF HEAVY MSSM HIGGS BOSONS.

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 $800~{\rm GeV} - 1~{\rm TeV}$).
  - 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.