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

Subtitle: Battle of the Wedge

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Collaborators: D. Asner, J. Gronberg
Reference: hep-ph/0110320
Brief summary of updates on this and other topics:
New results for a photon-photon collider
D. Asner, B. Grzadkowski, J.F. Gunion
H.E. Logan, V. Martin, M. Schmitt, M.M. Velasco, hep-ph/0208219.
Other papers on topic:
M.M. Muhlleitner, M. Kramer, M. Spira, P.M. Zerwas: hep-ph/0101083

LCWS, Jeju, Korea, August 27, 2002

Inputs

- **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.**

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

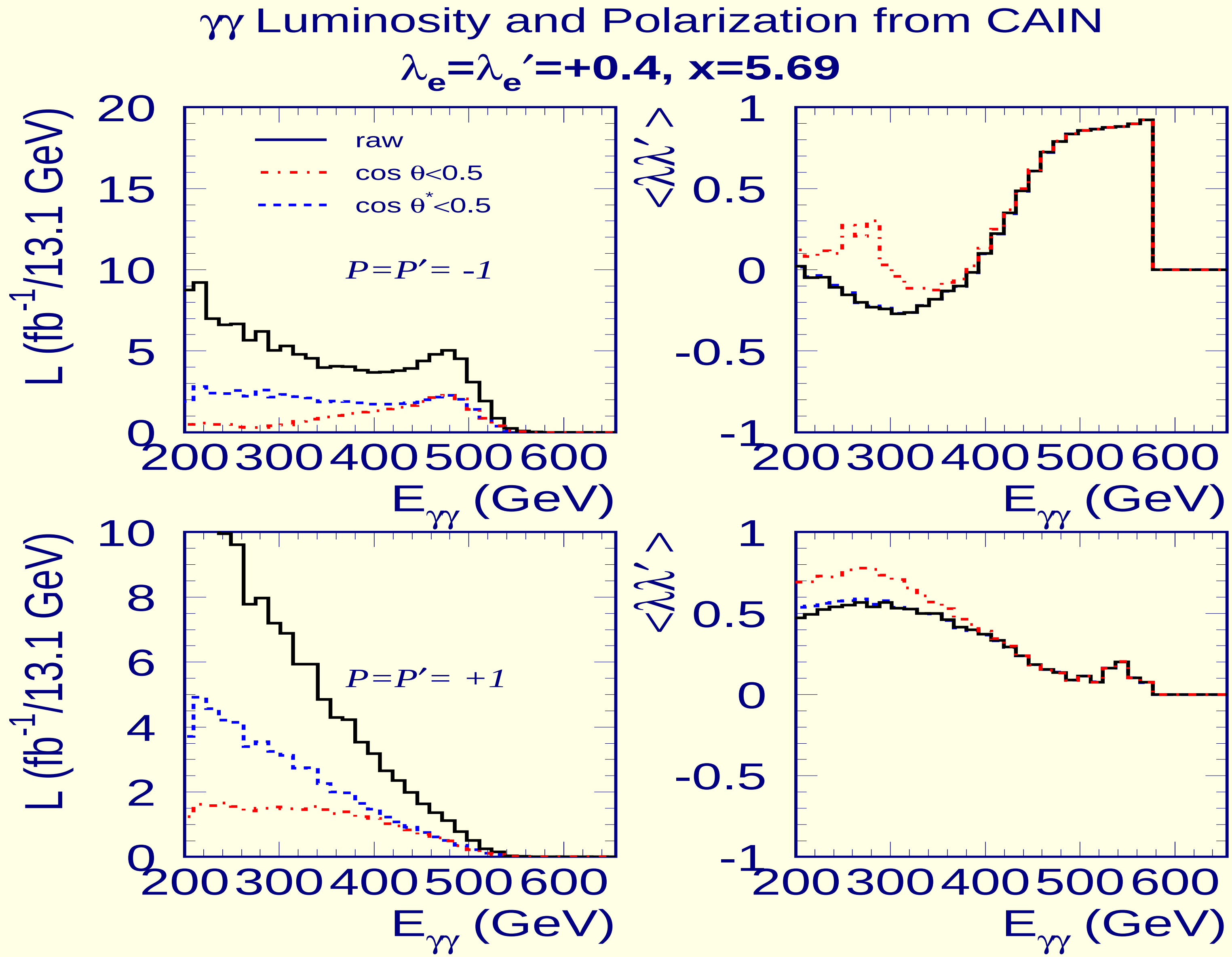


Figure 1: Luminosity (for 1 10^7 sec year) and $\langle\lambda\lambda'\rangle$ expectations for $\lambda_e = \lambda'_e = 0.4$ vs. $E_{\gamma\gamma}$ for $P = P' = -1$ (type-II) and $P = P' = +1$ (type-I)

- **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.**

- **If the laser power were increased from 1J to 2J (laser would be much more expensive) the conversion efficiency for an electron to Compton backscattered photon increases from 65% to about 95%. Since the luminosity goes as N^2, this would double the luminosity, but increase the non-linear and multiple scatter effects $\Rightarrow$**
  - **reduced peak luminosity and γ polarization (relative to overall spectrum);**
  - **less sharp $E_{\gamma\gamma}$ end point.**

- **If the flat beams were changed to round beams for e^-e^- collisions (how hard would this be?) we could get another factor of 2 in luminosity.**

- **Current design uses two-pass optics (i.e. one reflection to make use of the mostly unused laser photons).**

  If a four-pass optics system could be designed, then need only 1/2 as many lasers $\Rightarrow$ cost reduction.

- **If TESLA implements the NLC design, but takes advantage of their pulse/bunch structure, they can get twice the luminosity using 1J lasers, but they need nearly twice as many $\Rightarrow \mathbf{2}$ times the laser cost.**

- **It may be that TESLA could implement a rather different design (optical cavity, ...).**

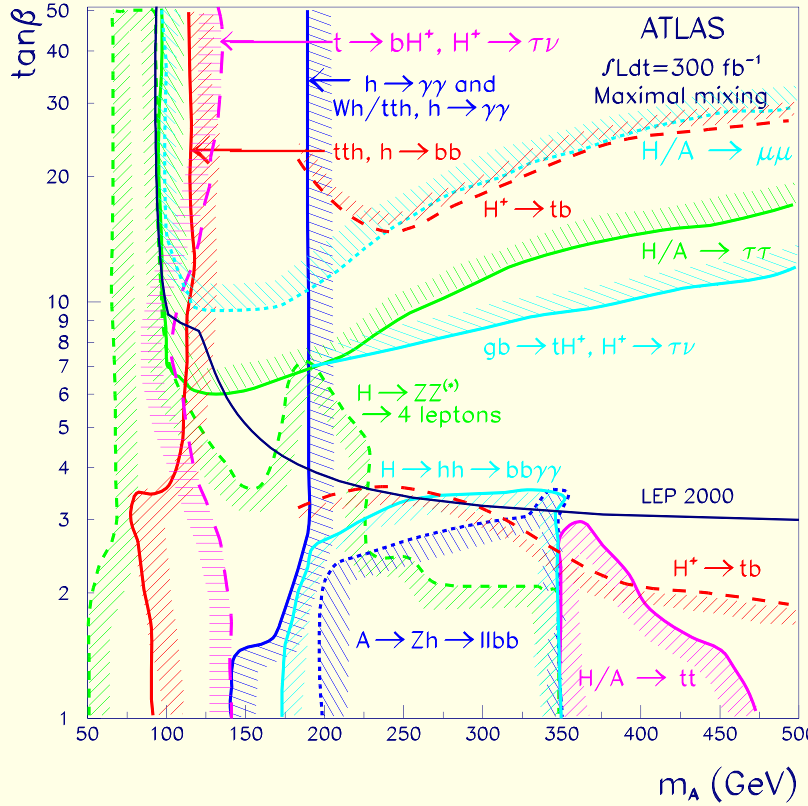
THE HEAVY MSSM H^0 and A^0

- **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. 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 $\Gamma(h^0 \rightarrow b\bar{b})$) 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 polarizaton 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

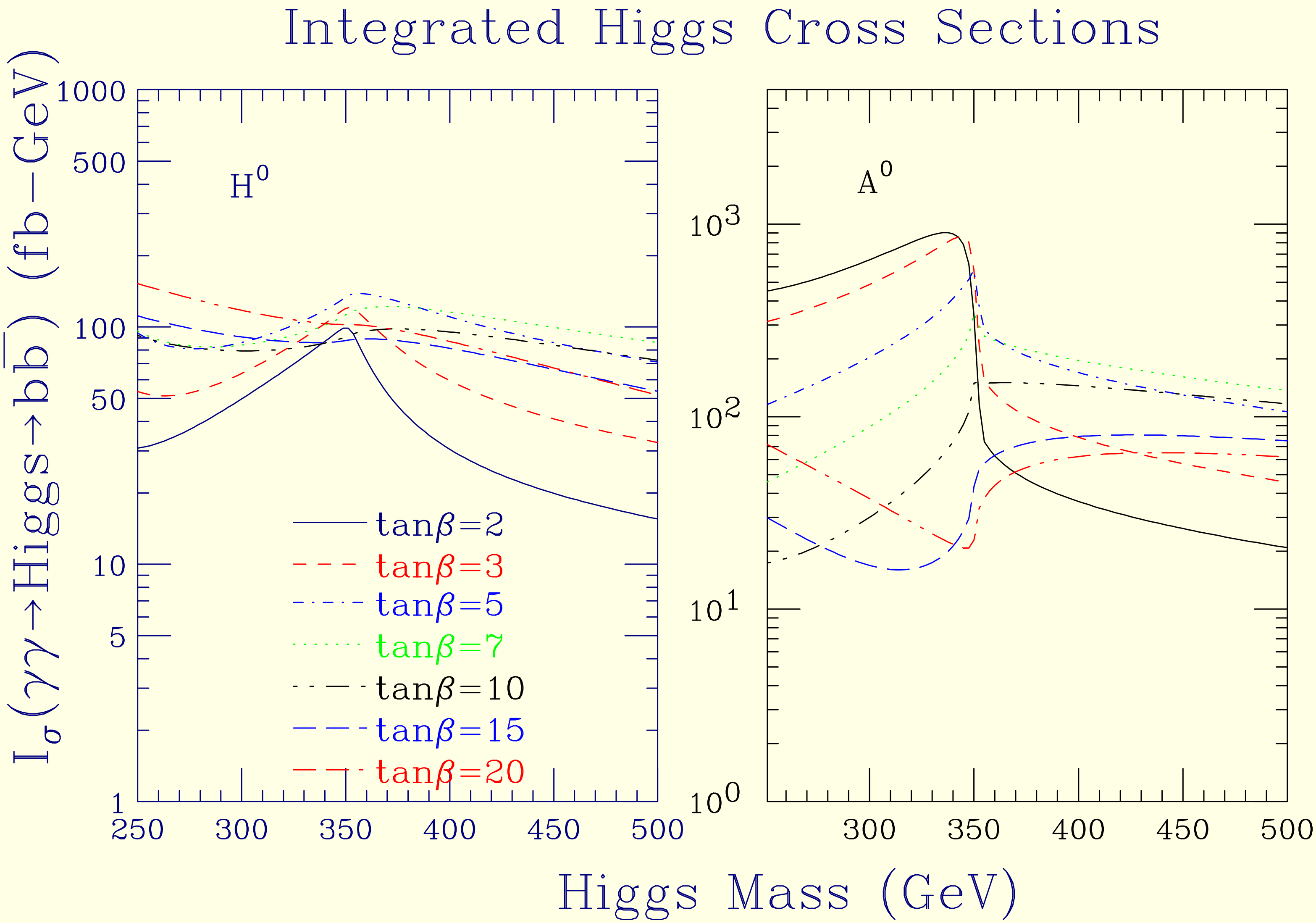
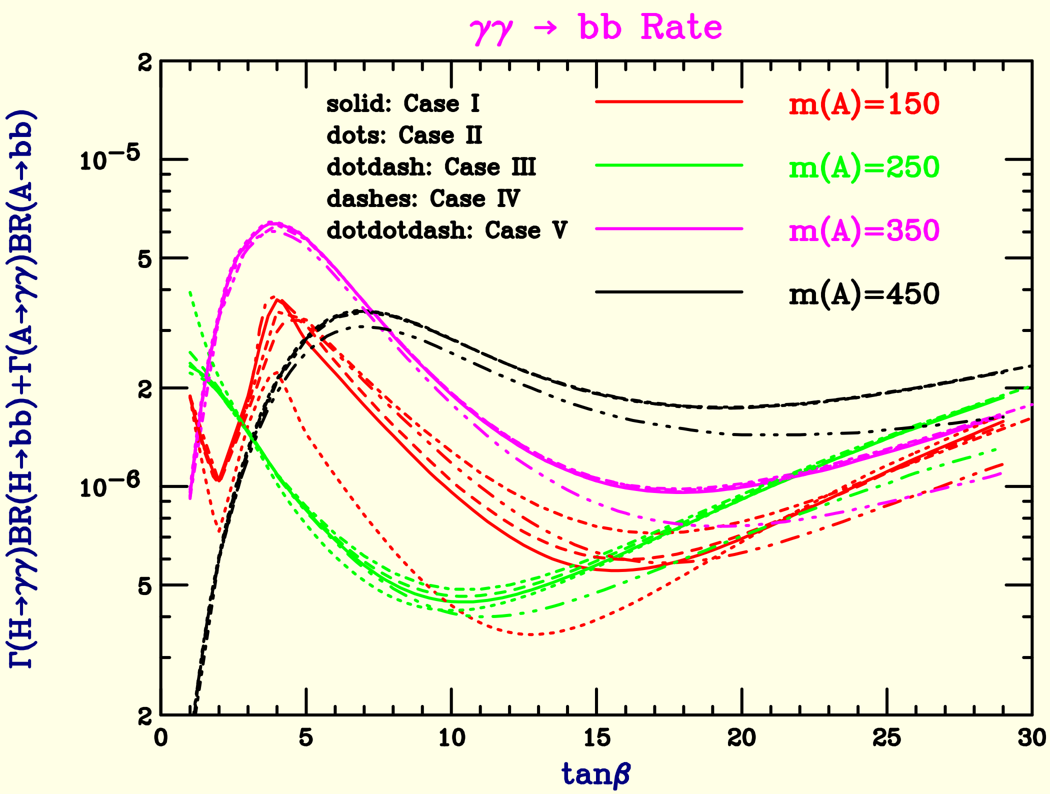


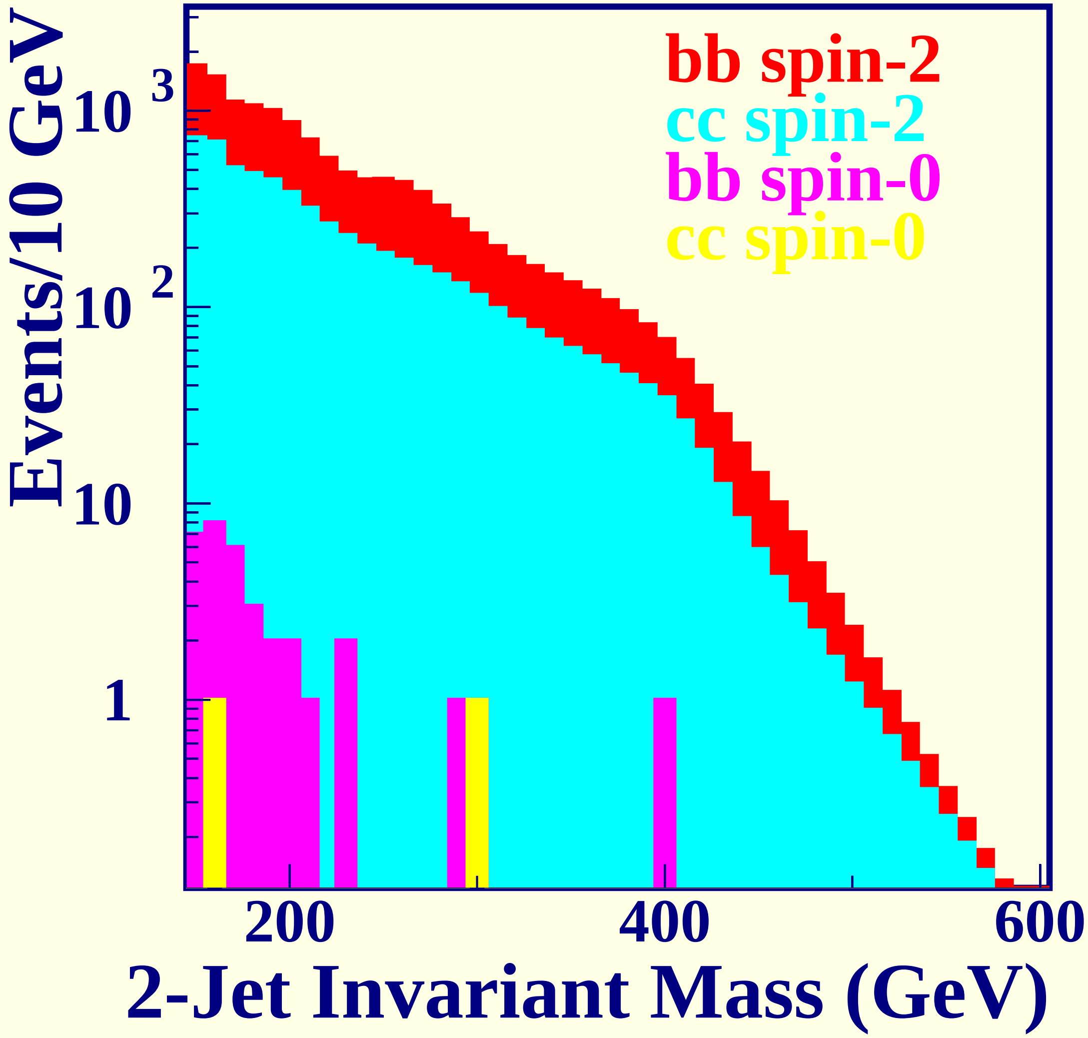
Figure 2: Cross section ($\text{fb}-\ \text{GeV}$ units) to be multiplied by efficiencies, $1+\langle\lambda\lambda'\rangle$ and $\left[\frac{dL}{dE_{\gamma\gamma}}\right]_{E_{\gamma\gamma}=m_{A^0}}$.

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

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.



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. Typical: $\epsilon_{\rm cuts} \sim 0.35 - 0.4$.

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):

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

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

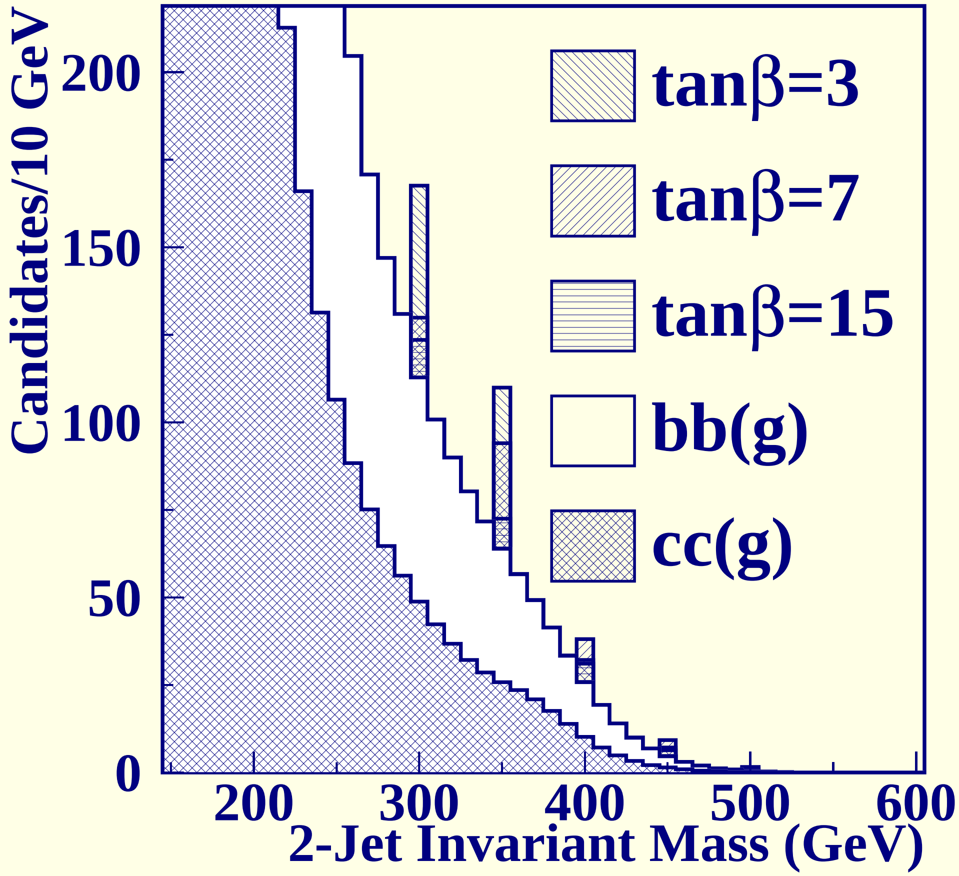
Need to increase this effective width to account for b decays containing neutrinos and to account for intrinsic Higgs widths.

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?

In our paper, we assumed that 50% of Higgs events fall into 10 GeV bin, and computed $N_{SD} = S/\sqrt{B}$ for the best bin.

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

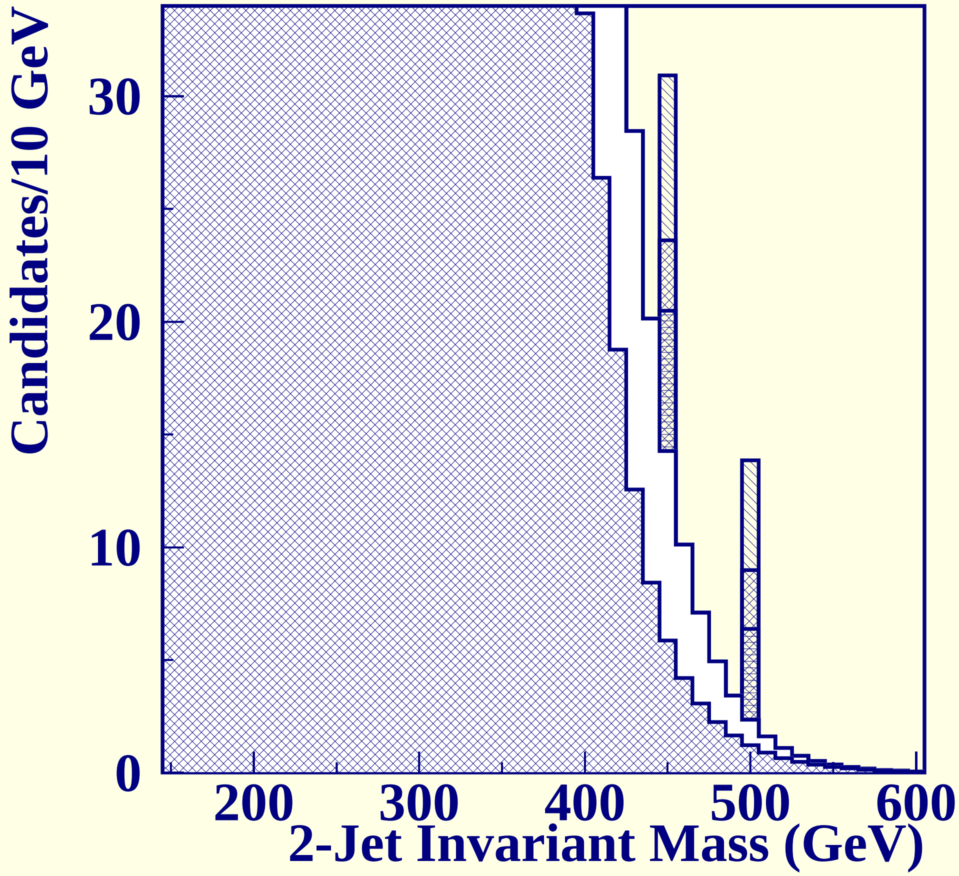
The Results for 1 year of operation in $P = P' = +1$ (type-I) mode



Assume all signal events fall into single $10\ \mathrm{GeV}\ m_{b\bar{b}}$ bin.

Type-I yields broad luminosity spectrum peaking at $E_{\gamma\gamma} = 250 - 400\ \mathrm{GeV}$ and substantial $\langle\lambda\lambda'\rangle$ there.

The Results for 1 year of operation in $P = P' = -1$ (type-II) mode

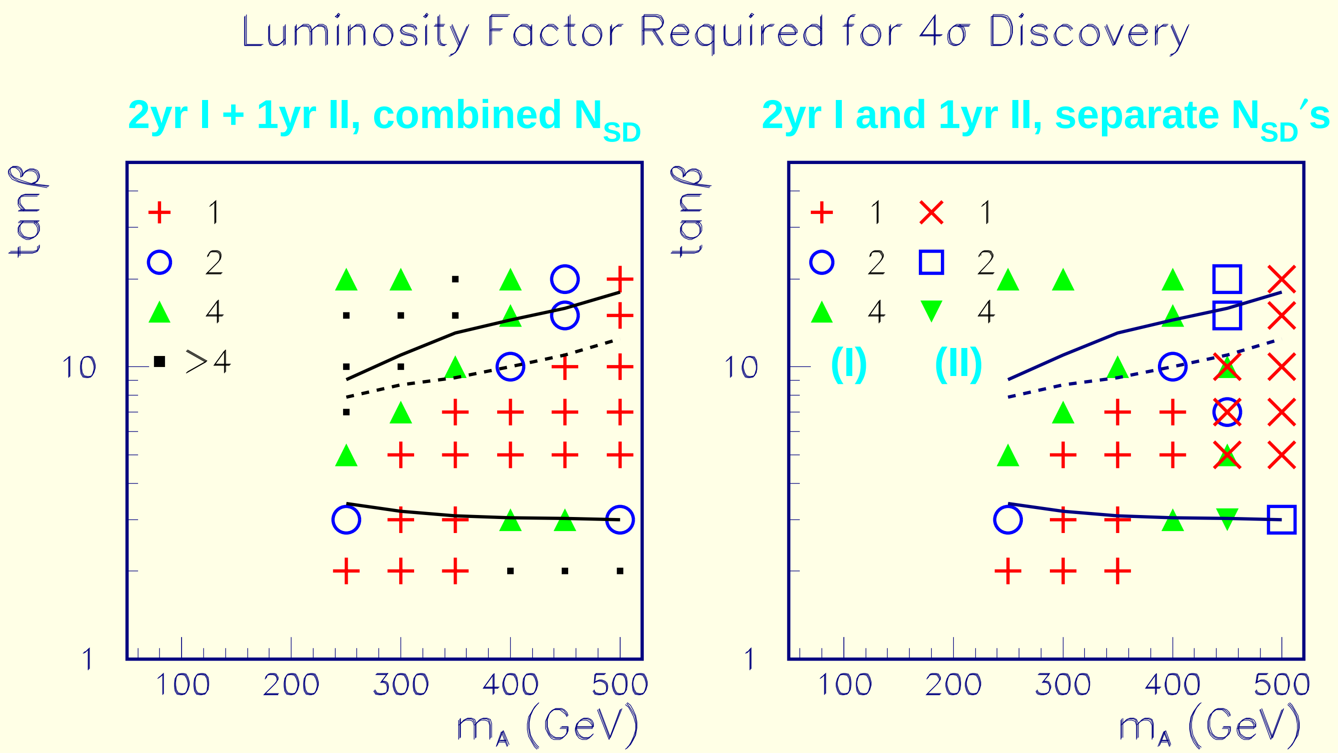


Assume all signal events fall into single $10\ \mathrm{GeV}$ $m_{b\bar{b}}$ bin.
Type-II yields luminosity peak at $E_{\gamma\gamma} = 500\ \mathrm{GeV}$ and large $\langle \lambda\lambda' \rangle$ there.

First estimates of statistical significance

- **Assume 2 year of NLC operation in $P = P' = +1$ mode (type-I) and 1 year in $P = P' = -1$ (type-II) 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 $P = P' = +1$ (type-I).**
- **$\Rightarrow$ some reasonable signals at highest mass for $P = P' = -1$ (type-II).**

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.

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 $18\%/\sqrt{E}$.

- **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.**

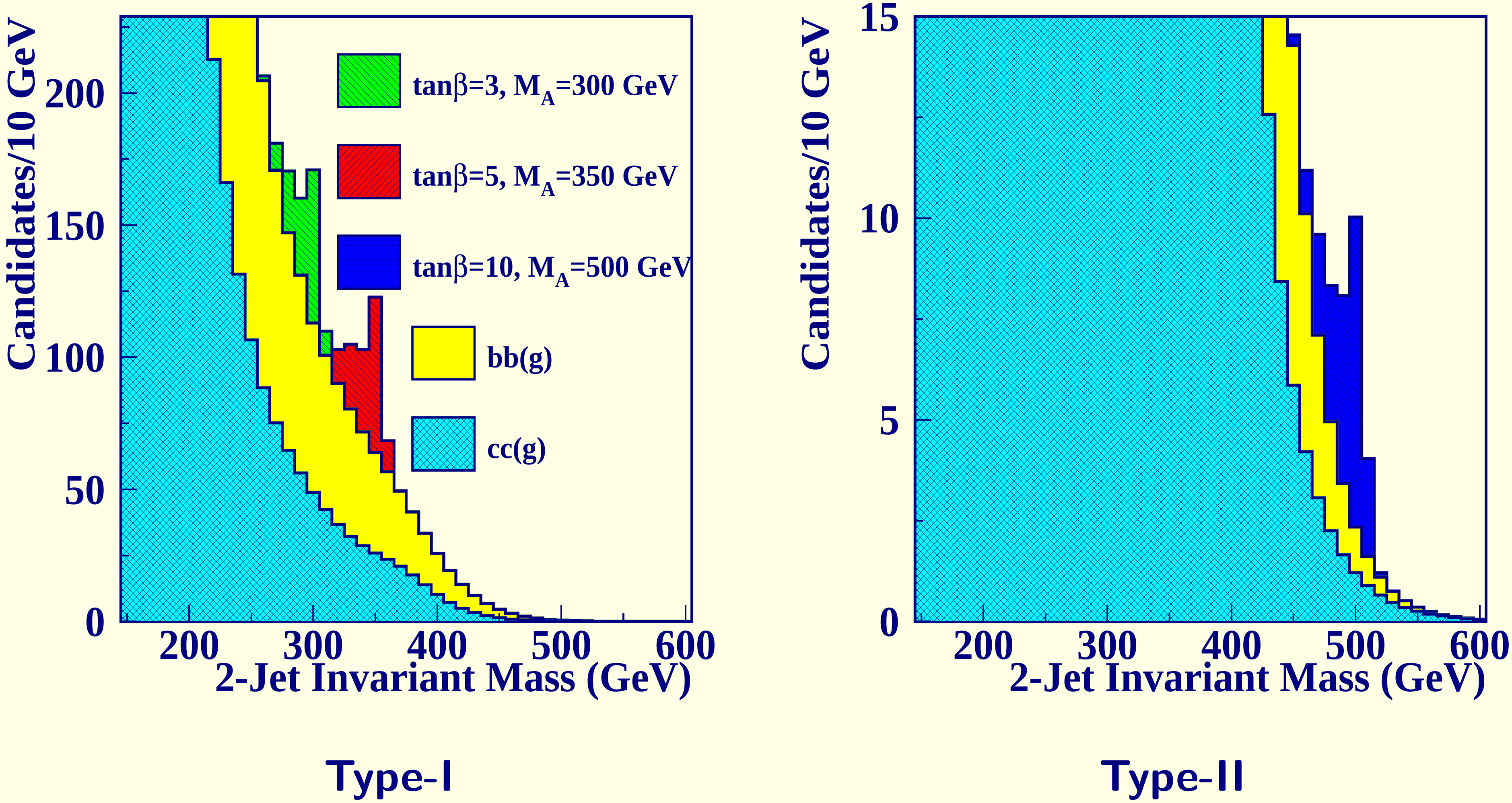


Figure 3: Typical peaks after smearing and width effects for type-I and type-II luminosity spectra

- **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:

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

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.

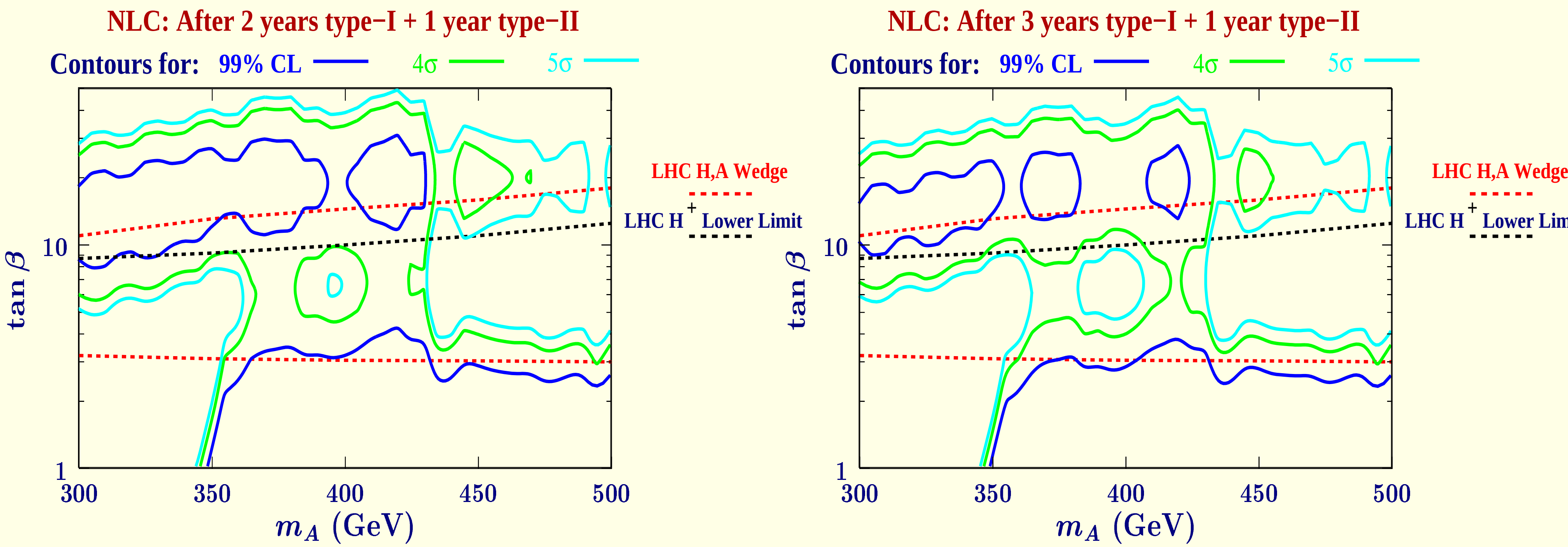


Figure 4: Contours for discovery and 99% CL exclusion after 3 or 4 years of NLC $\gamma\gamma$ running.

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

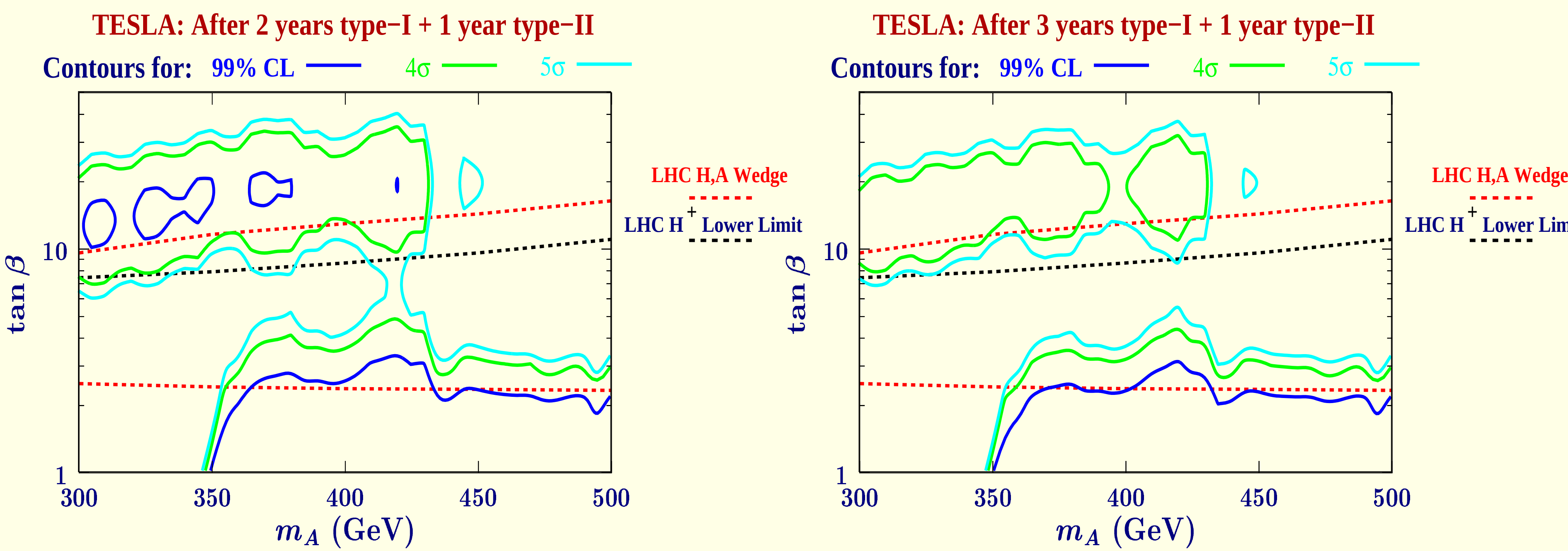


Figure 5: Contours for discovery and 99% CL exclusion after 3 or 4 years of TESLA $\gamma\gamma$ running.

- Assume TESLA gives factor of 2 luminosity increase, without necessitating IR or detector setup changes that impact acceptance, ...
- $\Rightarrow$ no holes at $m_{A^0} \sim 375~\mathrm{GeV}$ and $\sim 425~\mathrm{GeV}$ 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 $m_{A^0} > 350~\mathrm{GeV}$.

CONCLUSIONS

The MSSM

1. Very important to verify H^0, A^0 mass resolutions assumed, including impact of neutrino decays; more work on this is in progress.

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 $A^0 \to Z h^0$ final states.

6. Once the A^0, H^0 are located, one will shift the $e^- e^-$ energy to center the type-II $W_{\gamma\gamma}$ peak at $\sim m_{A^0}$.

   $\Rightarrow$ large $N_{\rm SD}$ for signal, such that 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 $800\ \mathrm{GeV} - 1\ \mathrm{TeV}$).
  - 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.