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

Subtitle: Battle of the Wedge

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Brief summary of updates on this and other topics:
New results for a photon-photon collider
D. Asner, B. Grzadkowski, J.F. Gunion

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

LCWS, Jeju, Korea, August 27, 2002
• 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 $1 \times 10^7$ 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 $\gamma$ 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 $\Rightarrow$ 2 times the laser cost.

• It may be that TESLA could implement a rather different design (optical cavity, ...).
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. $H^0A^0$, $H^+H^-$, $WW \rightarrow A^0A^0$, $WW \rightarrow H^0H^0$, ...) are all kinematically forbidden.
- In the ‘wedge’, the $e^+e^- \rightarrow t\bar{t}H^0$, $t\bar{t}A^0$, $b\bar{b}H^0$ and $b\bar{b}A^0$ production processes are also highly suppressed. In fact, the LC wedge (for $\sqrt{s} < 800 \text{ GeV}$) is larger than the LHC wedge.
- Other single production processes, the best being $e^+e^- \rightarrow \gamma H^0$ and $\gamma A^0$, 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.

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 ($e.g.$ $e^+e^- \rightarrow \gamma A^0$) only really become visible when $\tan\beta \lesssim 1$. 

$5\sigma$ 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 $L = 300 fb^{-1}$ for the ATLAS detector. This figure is preliminary.
There are two scenarios:

- We have some constraints from precision $h^0$ measurements (e.g. from $\Gamma(h^0 \rightarrow b\bar{b})$) 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.
Figure 2: Cross section (fb − GeV units) to be multiplied by efficiencies, $1 + \langle \lambda \lambda' \rangle$ and $\left[ \frac{dL}{dE_{\gamma\gamma}} \right]_{E_{\gamma\gamma}=m_{A^0}}$. 

Basic Signal Cross Sections

Integrated Higgs Cross Sections
Cross section sum is model independent except for large-μ, large-tan β SUSY loop corrections to $b\bar{b}$ coupling. Even these corrections mainly affect the $h^0$ and not the $H^0, A^0$.

**Note:** Dip in $\sum \Gamma(\gamma\gamma) B(b\bar{b})$ 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: $\epsilon_{\text{cuts}} \sim 0.35 - 0.4$.

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):

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

The mass resolution for pure jet states is being studied. We estimate $1\sigma$ 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 GeV $m_{bb}$ bin. Type-I yields broad luminosity spectrum peaking at $E_{\gamma\gamma} = 250 - 400$ 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 GeV $m_{b\bar{b}}$ bin. Type-II yields luminosity peak at $E_{\gamma\gamma} = 500$ 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.**

**Luminosity Factor Required for 4σ Discovery**

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 $30\% \times \sqrt{m_{bb}}$ 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 GeV) result that that the Gaussian width for such final states is twice as large, i.e. $60\% \times \sqrt{m_{bb}}$.

- Plot distributions in which 50% of the signal is smeared with $30\% \sqrt{m_{bb}}$ 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:

$$\Delta = 2 \times \sqrt{\left[\frac{1}{2}\langle \Gamma_{H,A}^{\text{tot}} \rangle \right]^2 + 1.5[0.3 \sqrt{m_{A^0}}]^2}$$  \hspace{1cm} (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 $\epsilon_{\text{acceptance}} = 0.35$ as before.

- The background is then computed by accepting background events in the same interval, $\Delta$, 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, $m_{\text{SUSY}} = 1$ 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 $\sim 425$ 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 $4\sigma$ by 3+1 year operation.
- At the lower $\tan \beta$ values in wedge, $H^0, A^0 \rightarrow t\bar{t}$ final state would probably allow discovery for just 2+1 years.
Contours for:
- LHC H    Lower Limit
- LHC H,A Wedge

TESLA: After 2 years type–I + 1 year type–II

- $4\sigma$
- 99% CL
- $5\sigma$

**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 $m_{A^0} \sim 375 \text{ GeV}$ and $\sim 425 \text{ GeV}$ for 2+1 years at $4\sigma$ level.

  - $\Rightarrow$ no holes at $5\sigma$ level after 3+1 years.

  - $t\bar{t}$ still needed in lower part of wedge for $m_{A^0} > 350 \text{ GeV}$. 
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 $\lambda_e$ 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 $A^0, H^0 \rightarrow t\bar{t}, H^0 \rightarrow h^0h^0$ and $A^0 \rightarrow Zh^0$ 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 $N_{SD}$ 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 $800 \text{ GeV} - 1 \text{ TeV}$).
  - Such models can be consistent with precision electroweak data.
  - A light $A^0$ can explain (part of) $a_\mu$.
  - $\gamma\gamma$ 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.