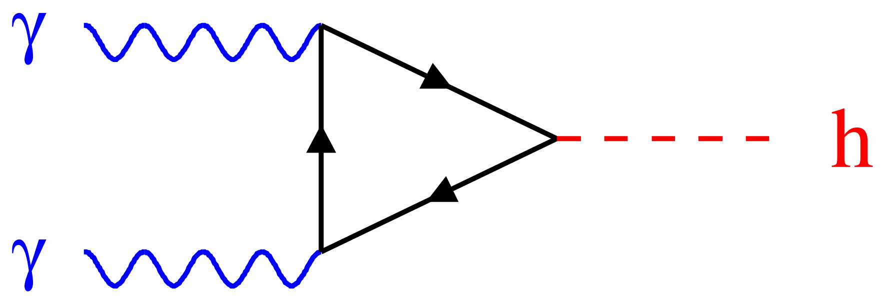
Understanding Light and Heavy Higgs at $\gamma\gamma$-Colliders

Mayda M. Velasco
Northwestern University



WIN-2002

$\gamma\gamma$-Colliders as Higss Factories at the LC? Why not?

⟹ #1 Feasable: Laser technology available... not just *'diet-coke'* break chat!

⟹ #2 Matter of principle: LC should be made versatile:

- $\gamma\gamma$ gives independent information on h_{SM} :
  - 2 Methods: $e^+e^- \to Zh_{SM}, \nu\nu h_{SM}$ & $\gamma\gamma \to h_{SM}$
  - Crucial! Specially, if $M_h \simeq 115 - 120$ GeV ... difficult at the LHC.
- $\gamma\gamma$ provides a larger mass reach for a fixed E_{ee}:
  - Can cover regions *not* accessible to LHC and/or LC for $M_{H,A}$ searches.
- Be ready for surprises! In $\gamma\gamma$:
  - we have ability to manipulate polarizations, both linear and circular.
  - access to possible $\not{C}\not{P}$ in the $\gamma\gamma \to h_{SM}, H, A$ loop.

Why $\gamma\gamma$-Colliders ? Physics Reasons

- Well defined $J = 0, 2$ final states,
  when starting with *circularly* ($\lambda = \pm 1$) polarized γ's

  $\Rightarrow$ important for controlling backgrounds,
  $\gamma\gamma \to f\bar{f}$ is a $J = 1$ state.

- Large cross section
  $\Rightarrow$ Neutral Higgs ($Y = h_{SM}, H, A$)

  $$\sigma(\gamma\gamma \to Y \to XX') \propto \Gamma^{Y}_{\gamma\gamma} Br(Y \to XX')(1 + \lambda_1\lambda_2)$$

  $\Rightarrow$ Charged Higgs $H^{\pm}$:

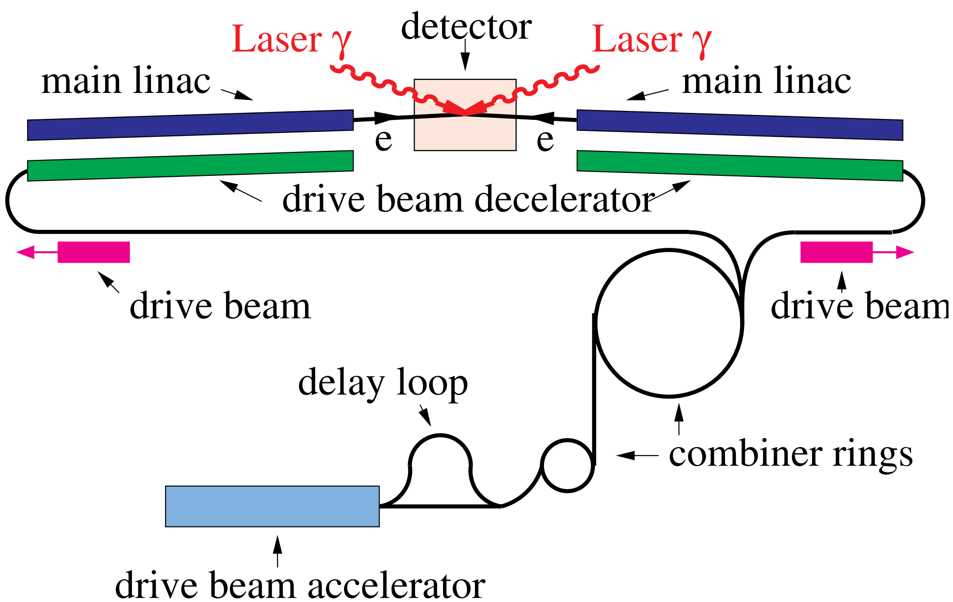
  $$\sigma(\gamma\gamma \to H^+H^-) \geq 10\sigma(e^+e^- \to H^+H^-) \quad L_{\gamma\gamma}^{E_{\gamma\gamma} \geq 0.6 E_{e^+e^-}} = \frac{L_{e^+e^-}}{3}$$

- Well defined CP-states, with *linearly* ($\lambda = 0$) polarized γ's
  $\Rightarrow$ ($\gamma_{||} \; || \; \gamma_{||}$) $\Rightarrow$ CP-even
  $\Rightarrow$ ($\gamma_{||} \perp \gamma_{||}$) $\Rightarrow$ CP-odd

Machines considered:

#1 Light Higgs Factory: CLICHE, TESLA & NLC

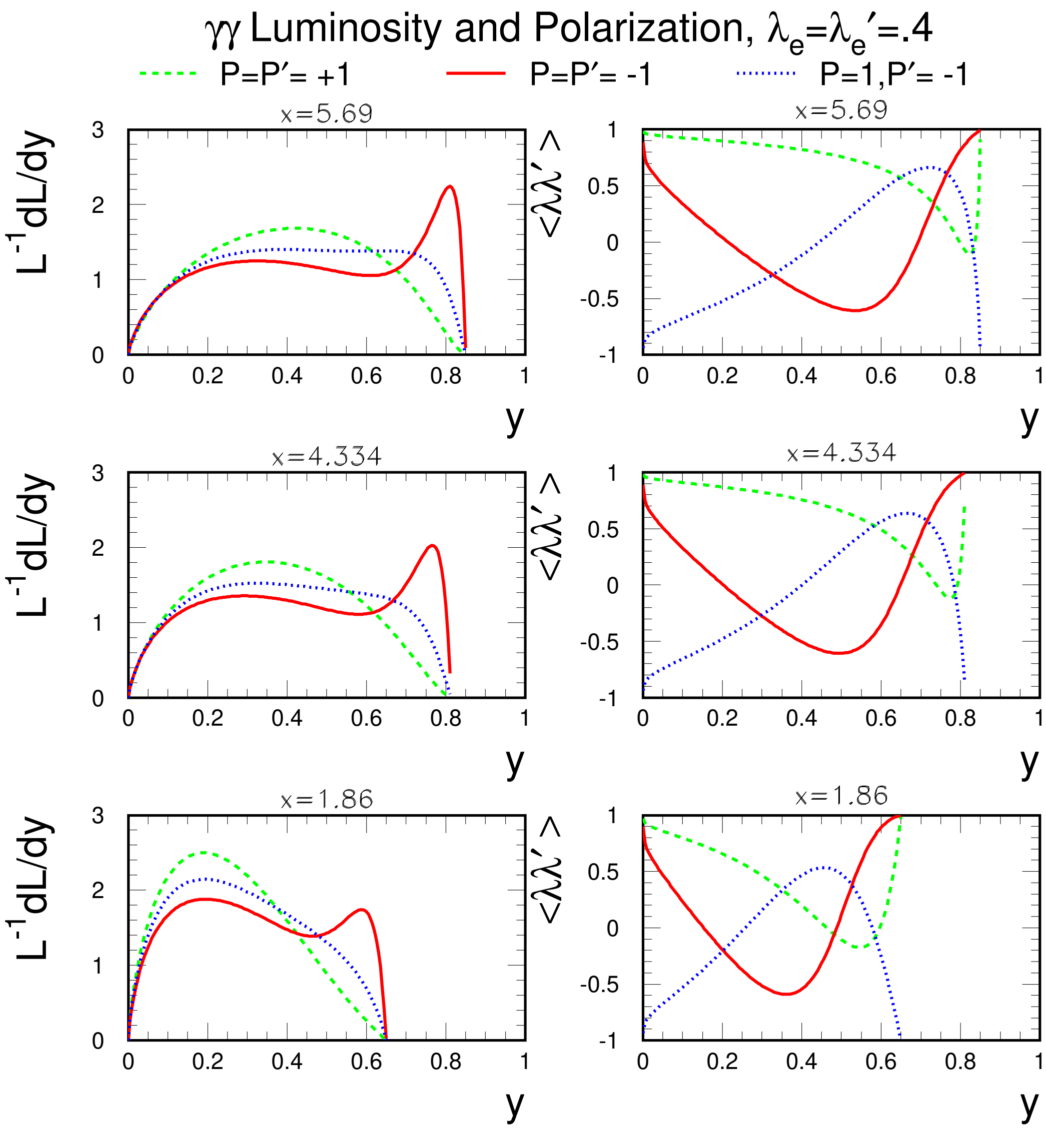
Machine	$E_{e^+e^-}$(GeV)	$M_{h_{SM}}$(GeV)	Yield/year	Ref.
CLICHE	150	115	22.5k	hep-ex/0110056
CLICHE	160	120	23.6k	Correct for $\Gamma_{\gamma\gamma}$
TESLA	160	120	21.0k	hep-ex/0101056
NLC	160	120	11.0k	hep-ex/0110055
e^+e^-	$350_{TESLA}(500_{NLC})$	120	3.5k(20k) Tag(Raw)	hep-ph/0101165



- CLICHE: Based on CLIC-1 test facility. Devoted $\gamma\gamma$-machine.
- NLC & TESLA: 2nd low energy interaction region.

#2 Heavy Higgs: NLC (hep-ph/0110320) ($L_{TESLA} \simeq 2 * L_{NLC}$)

Compton Laser Backscattering Facts



$$\boxed{E_e + w_o \rightarrow E_{e'} + E_\gamma}$$

$$x_{max} = \frac{4E_e w_o}{m_e^2}$$

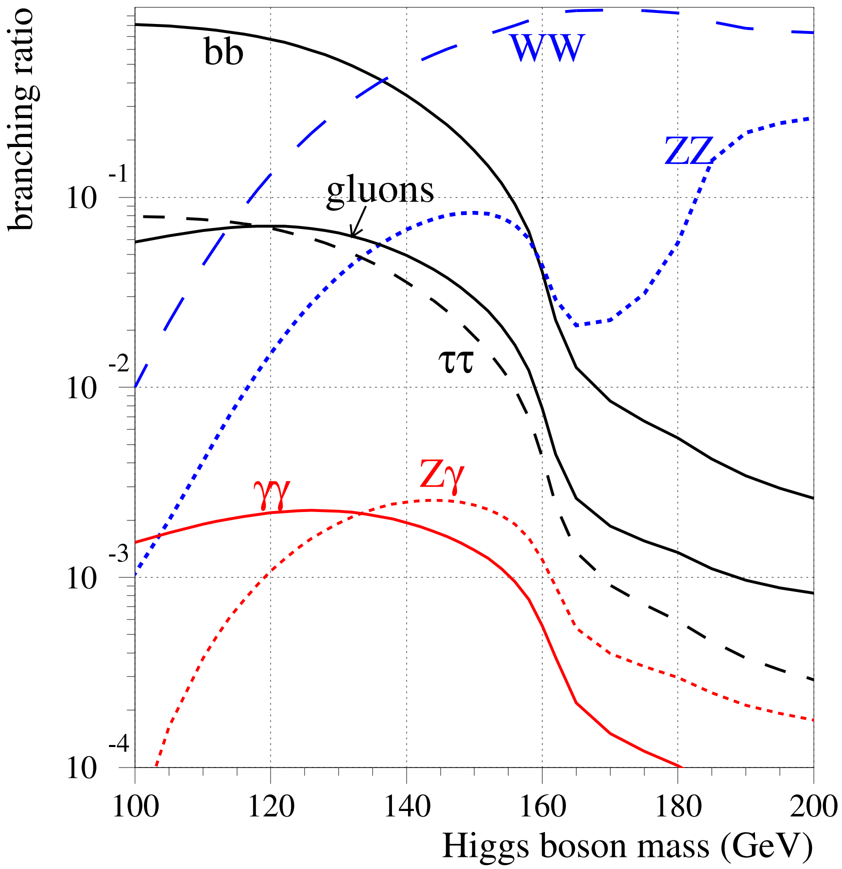
$$E_\gamma = \frac{x}{x+1} E_e$$

$$y_{max} = \frac{E_\gamma}{E_e}$$

Available:

$$\begin{aligned} w_o &= 1.17(3.53)\ eV \\ &= 1.0(0.351)\mu m\ laser \end{aligned}$$

SM Light Higgs

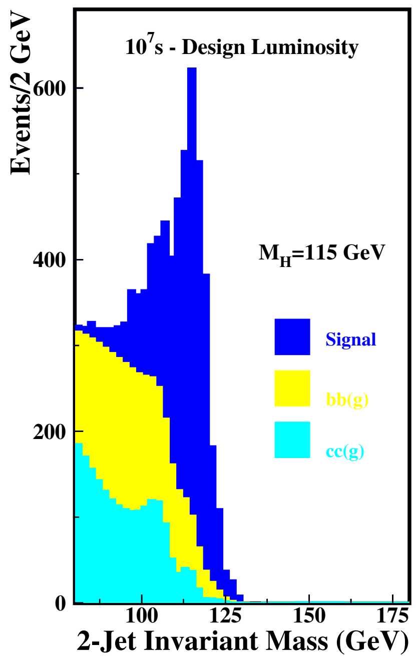


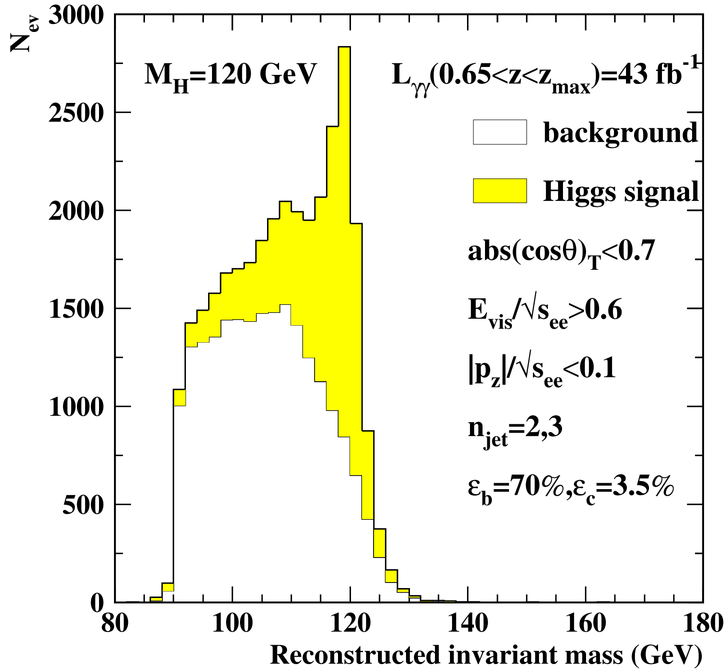
- $H \to b\bar{b}$ best statistics
  $\Rightarrow$ mass measurement with scanning method, $\Gamma_{\gamma\gamma}$ to 2% by combing with $BR(h \to b\bar{b})$, etc...
- $H \to W\bar{W}$
  $\Rightarrow$ CP-asymmetries, SUSY-constraints
- $H \to ZZ$
  $\Rightarrow$ preparing for higher mass H...

- $H \to \gamma Z$
  $\Rightarrow$ Further MSSM constraints
- $H \to \gamma\gamma$
  $\Rightarrow$ Model independent measurement of the Γ_{Total} (high statistics run).

$H \to c\bar{c}, \tau\bar{\tau}, gg$ not possible to measure at $\gamma\gamma$!

Selection for 120 GeV SM-Higgs ($h^0 \to b\bar{b}$) hep-ex/0110056 & hep-ph/0101056





CLICHE TESLA

signal = two b-quark jets

background = continuum b & c production

Ongoing work to understand better the $b\bar{b}g$ & $c\bar{c}$ final state.

$\boxed{2\% \text{ measurement of } \{\Gamma_{\gamma\gamma} \times Br(h \to b\bar{b})\} \text{ within a year!}}$

How to get Widths, Γ_{tot} & $\Gamma_{\gamma\gamma}$?

The event rate of $\gamma\gamma \to h \to b\bar{b}$ is proportional to:

$$\{\Gamma(h^0 \to \gamma\gamma) \times BR(h^0 \to \gamma\gamma)\}$$

Therefore with $BR(h^0 \to \gamma\gamma)$ from elsewhere we can get $\Gamma(h^0 \to \gamma\gamma)$

Similarly, event rate of $\gamma\gamma \to h \to \gamma\gamma$ is propotional to:

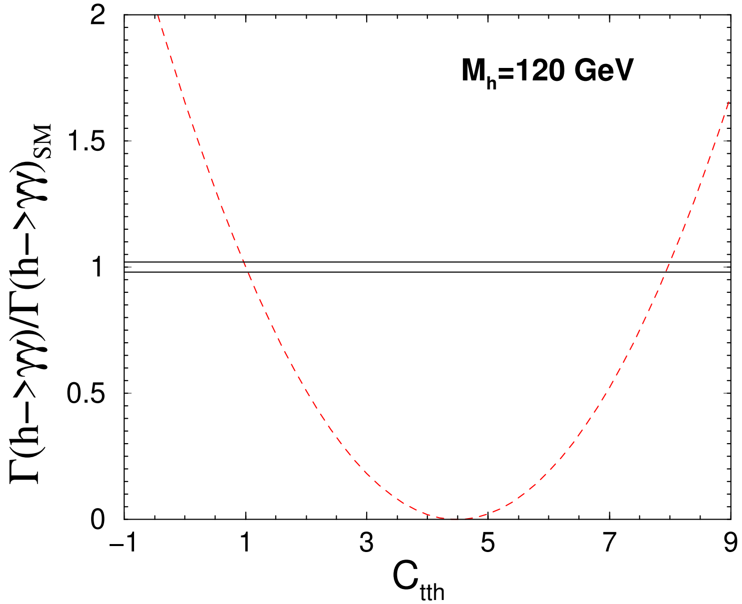
$$\Gamma^2_{\gamma\gamma}/\Gamma_{Total}$$

Therefore combining $b\bar{b}$ and $\gamma\gamma$ modes will give us Γ_{Total} in a model independent way.

Snowmass 1996, Gunion et al. hep-ph/9703330

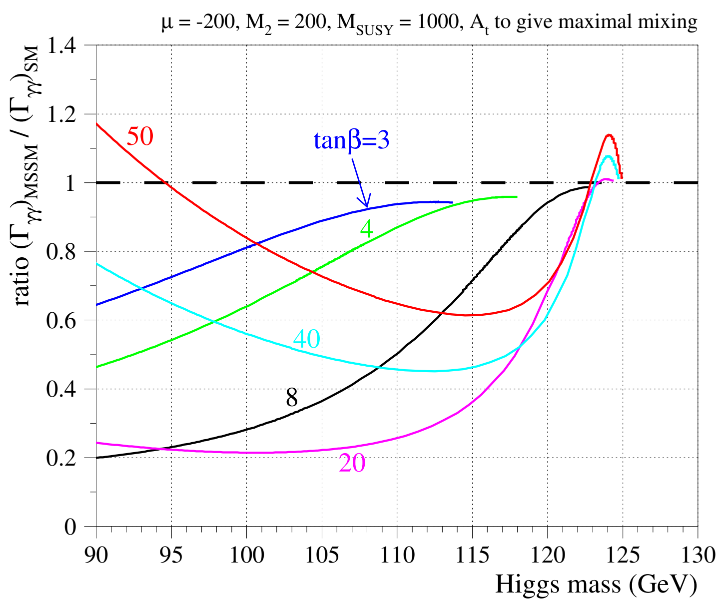
What we learn from Partial Width, $\Gamma_{\gamma\gamma}$?

Higgs coupling to mass is an essential prediction in Higgs-theory. $\Rightarrow$ We need to test it!!! Dawson, $\gamma\gamma$WS2001.



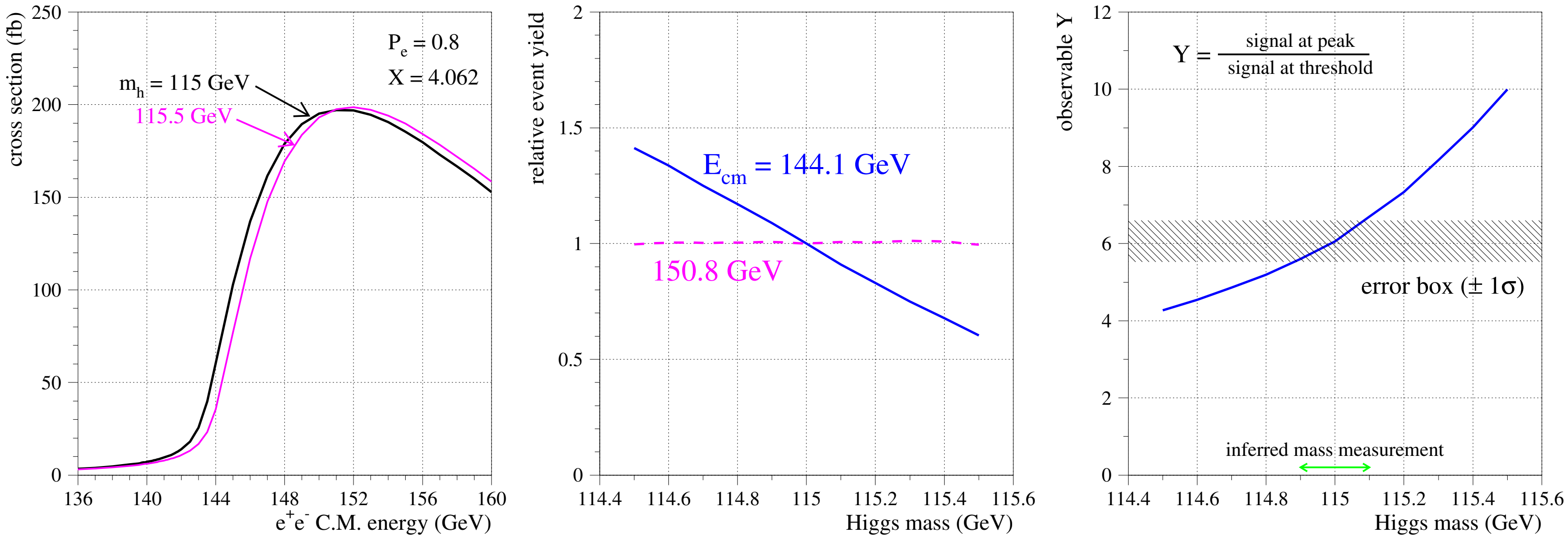
$\gamma\gamma \rightarrow h$ depends on the tth coupling, and a 2% measurement of this cross section results in a 4% constraint on Y_t.

The $h - \gamma\gamma$ coupling occurs only through loops, therefore can be sensitive to new physics. Example in the MSSM suppression are possible!



Mass measurement and distinguishing between $M_{h_{SM}}$ and $\Gamma_{\gamma\gamma}$

Take advantage of the sharp edge of the photon spectrum to pin down the Higgs mass from $h \to b\bar{b}$ events.
Problem: At a given $\sqrt{s_{ee}}$ a yield increase could be due to $M_{h_{SM}}$ **or** $\Gamma_{\gamma\gamma}$.
Solution: Use the point of zero sensitivity to $M_{h_{SM}}$ to detect changes in $\Gamma_{\gamma\gamma}$.

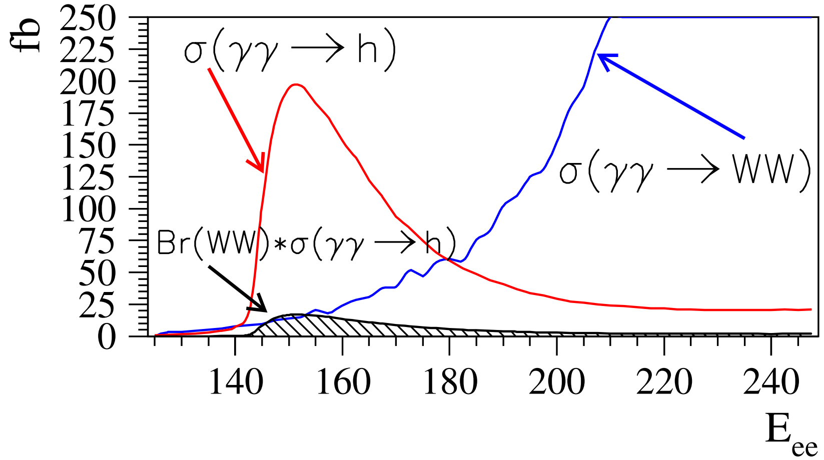


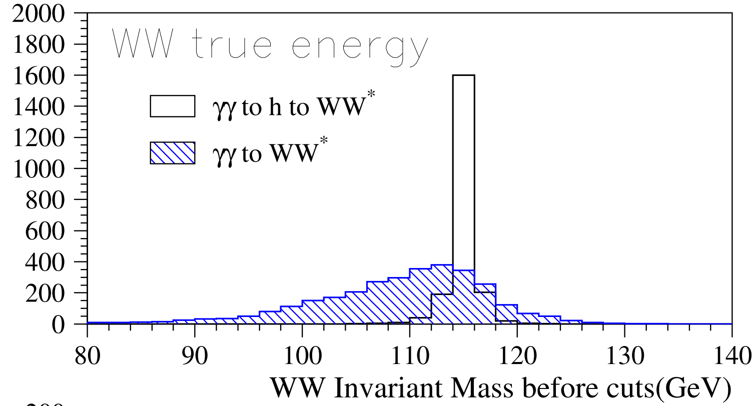
1 year at peak, 0.5 years at thereshold and 0.5 year below threshold gives $\Longrightarrow \Delta M_{h_{SM}} = 100$ MeV (`hep-ex/0110056`)

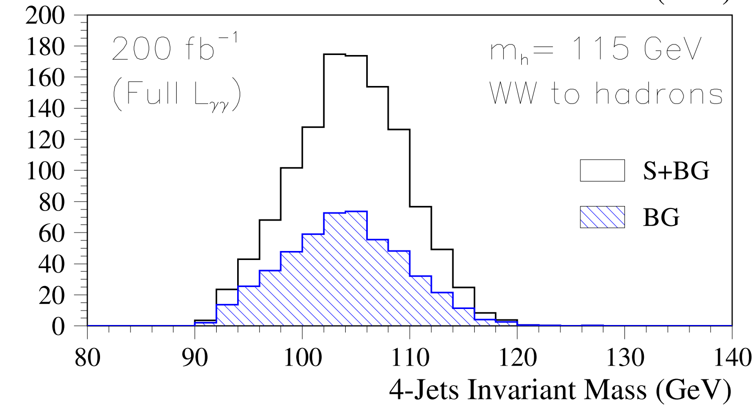
$\sigma(\gamma\gamma \to h \to WW)$ **vs** $\sigma(\gamma\gamma \to WW)$ hep-ex/0110056:

$\Rightarrow$ For the case of low mass H, it is an advantage to run in a *'Higgs Factory-Mode'* in order to reduce WW continuum.

$\Rightarrow$ Only hadronic modes used!



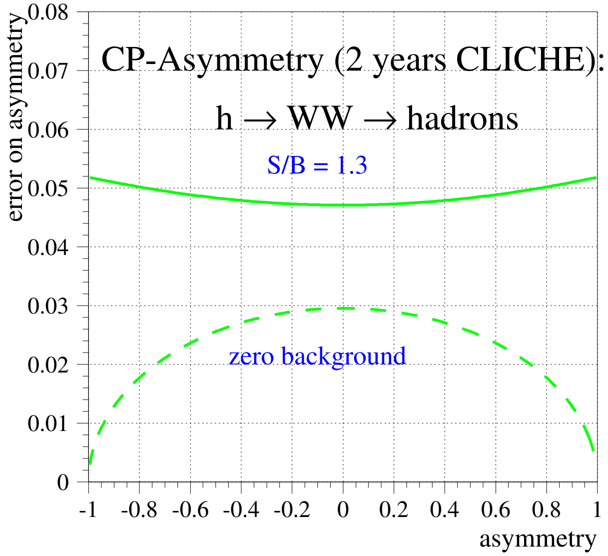




$\Rightarrow$ CLICHE: 115 GeV Higgs has a S/B of 1.3

$\Rightarrow$ 5% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to WW)\}$ within a year!

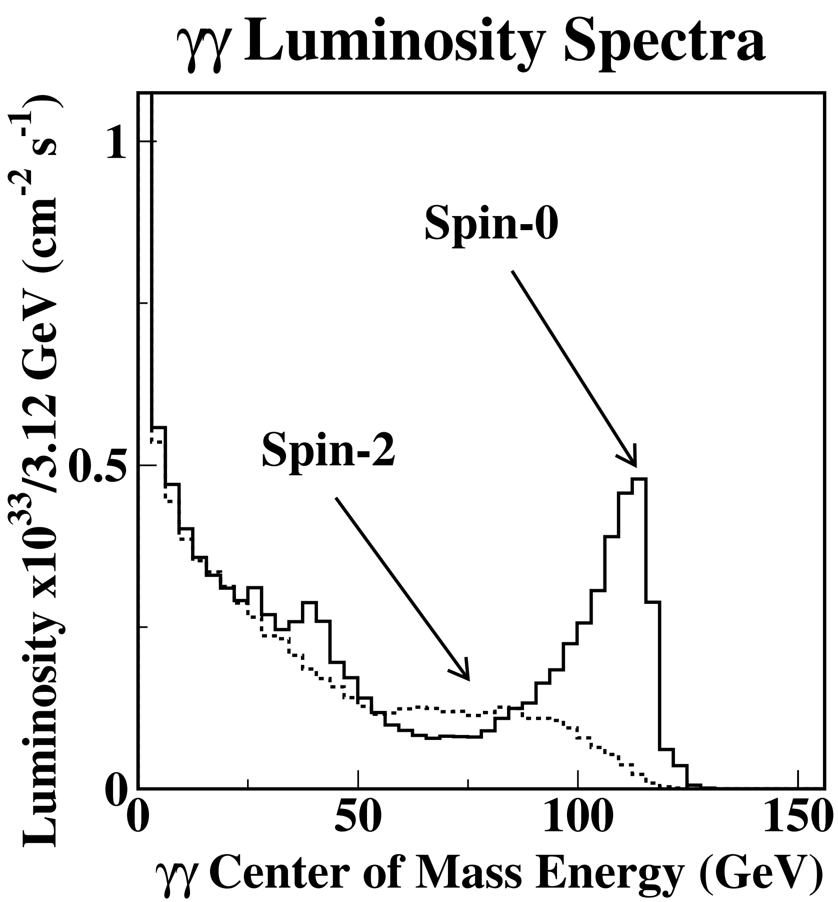
CP measurements from the $h \to WW$ events:



- $WW \to hadron + hadrons = 42\%$
- $WW \to had(charm - tag) + had(charm - tag) = 0.42\%$
- $WW \to had(charm - tag) + l\nu = 2.8\% (l = e, \mu)$
- $WW \to l\nu + l\nu = 4.5\% \ (l = e, \mu)$

Studied $WW \to l\nu + l\nu$ and got S/B=0.5 and 95% reconstruction efficiency, but still not enough to add with the hadronic mode for the CP-asymmetries.

CP of produced WWs:

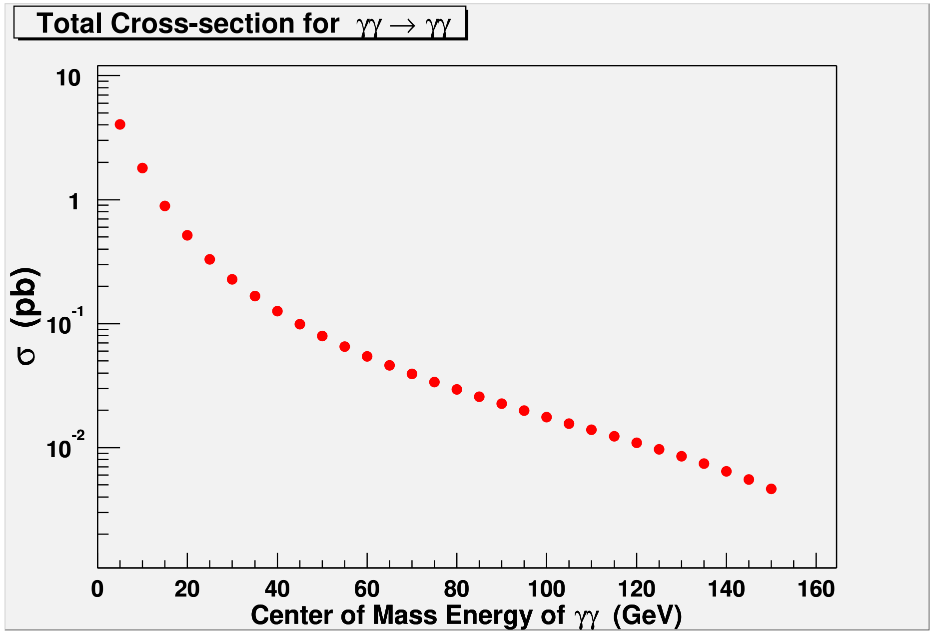


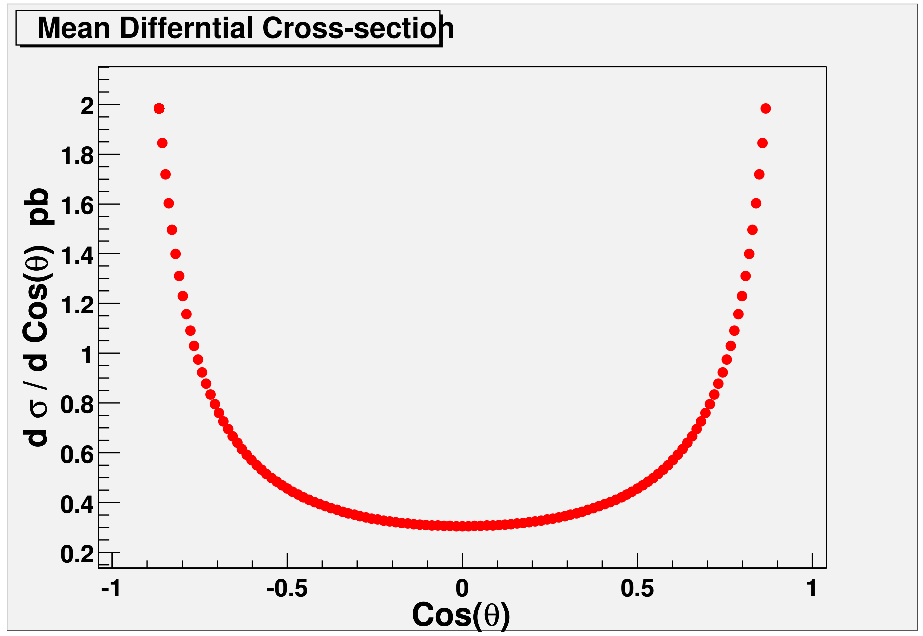
- J=0 $W_L W_L$ or $W_T W_T$
- J=1 $W_L W_T$ $(NOT\ PRESENT\ AT\ \gamma\gamma)$
- J=2 $W_T W_T$ suppressed.

⟹ Therefore, Angular correlation plots will not really help us to suppress the backgrounds... J=0 for both Signal and Background.
LHC kills the other ... J=1,2 with angular cuts.

Background for $h_{SM} \to \gamma\gamma$:

➡ Background calculation based on program from Thomas Hahn.





➡ Backgrounds falls rapidly, and has strong $cos\theta$ dependence.

➡ Assume $Br(h_{SM} \to \gamma\gamma)$=0.21%, and excellent calorimetry (CMS):

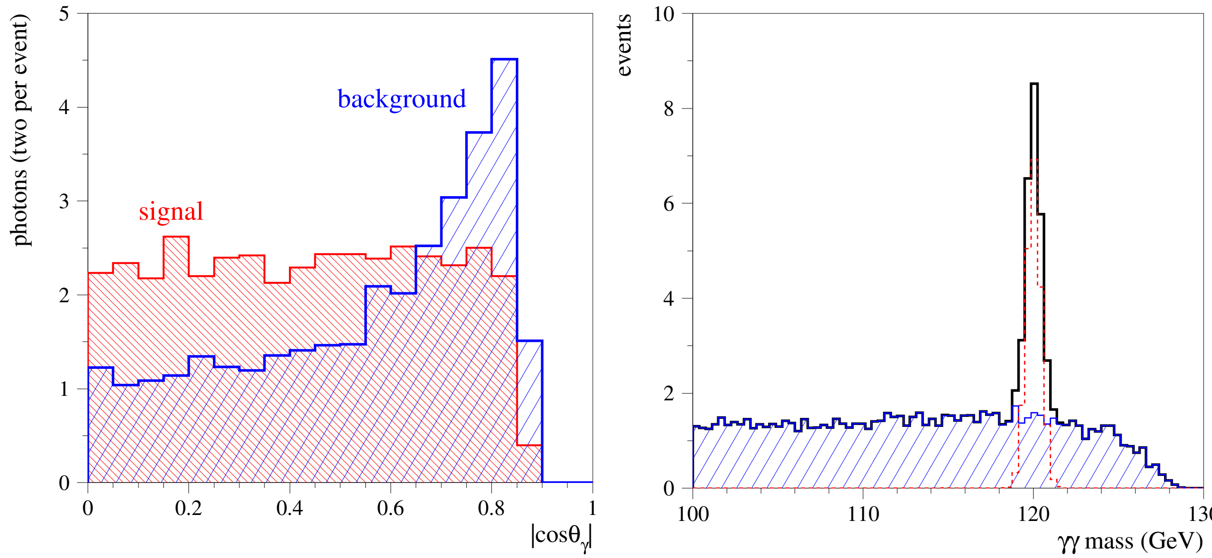
$$\frac{\sigma_E}{E} = \frac{0.015}{\sqrt{E}} \oplus 0.0045$$

$h_{SM} \to \gamma\gamma$ and Extracting mass and Γ_{Total}:

- Plots normalized to 0.5 year at CLICHE or TESLA.
- Cuts give S/B=1.3 and $\epsilon_S = 87\%$ with 40 signal events/year:

$118 < M_{\gamma\gamma} < 122$ GeV $\qquad |cos\theta| < 0.85$

21% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to \gamma\gamma)\}$ within a year!



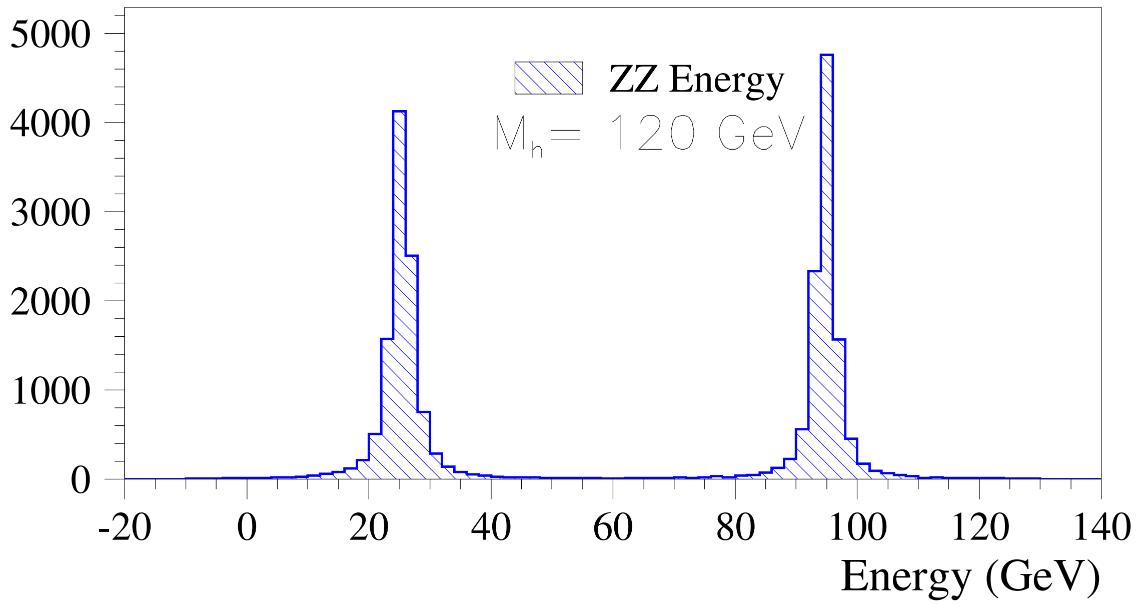
$$\{\Gamma_{\gamma\gamma} \times Br(h \to \gamma\gamma)\} \propto \frac{\Gamma^2_{\gamma\gamma}}{\Gamma_{Total}} \Leftarrow$$

Combined with the 2% measurement of $\Gamma_{\gamma\gamma}$

A model independent 13% measurement of Γ_{Total} within three years!

150 MeV mass measurement in 0.5 year! Schmitt, Stenz & Velasco

Can we see $h_{SM} \to ZZ^*$? $\Rightarrow$ more important for higher M_H.



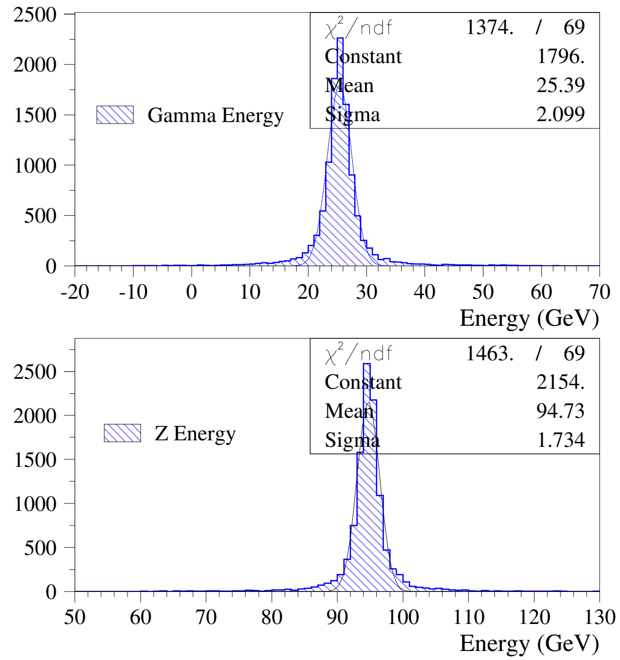
- Clean for 120 GeV Higgs $\sigma(\gamma\gamma \to H)Br(H \to ZZ^*)$=1.46 fb
- Z's well identified: Assume 70% of the Z are reconstructed and 90% of the Z^* (include $\nu\nu$), then we will have:

  440 events/year at CLICHE or TESLA
- What is the real Background from $\gamma\gamma \to ffff$?
- If we assume S/B=1 then:

  11% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to ZZ)\}$ within a year!

Velasco, work in progres

Can we do $H \to \gamma Z$?:



- Clean for 120 GeV Higgs !?
  $\sigma(\gamma\gamma \to H) Br(H \to \gamma Z)$=0.10 fb
  $\sigma(\gamma\gamma \to \gamma Z)$ <0.02 fb

- Z's well identified: Assume 70% of the Z are reconstructed and 90% of the γ, then we will have:
  16 events/year at CLICHE or TESLA

- What is the real Background from $\gamma\gamma \to \gamma f f$?

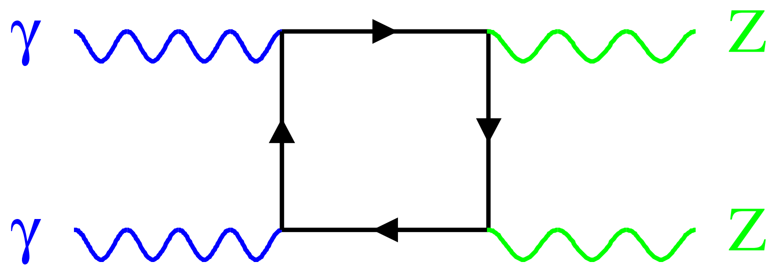
Assume S/B=1 then, 20% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to Z\gamma)\}$ in three years!

Velasco, work in progres

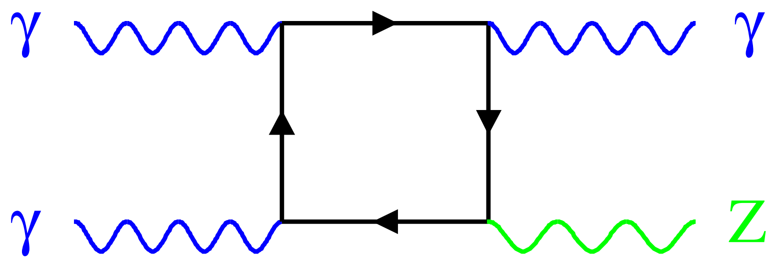
BG for $\gamma\gamma \to H \to ZZ$ & $\gamma\gamma \to H \to Z\gamma$:

$\Rightarrow$ Negligible:

$\sigma(\gamma\gamma \to ZZ^*) < 0.02$ fb



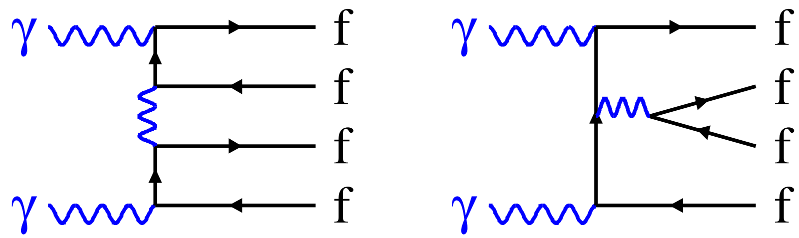
$\sigma(\gamma\gamma \to Z\gamma) < 0.02$ fb



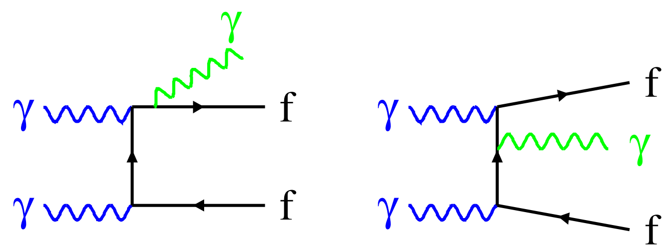
Mrenna, Logan work in progres

$\Rightarrow$ To consider:

$\Rightarrow$ $\gamma\gamma \to 4\mu = 0.16$nb, while $\gamma\gamma \to 4e = 6500$ nb, $\gamma\gamma \to 4q, 2q, 2l$ should be somewhere in between. Carimalo et. al.



$\Rightarrow$ $\sigma(\gamma\gamma \to \gamma f f) > 100$ fb



Summary for Light Higgs

After three years of data taking at nominal conditions for CLICHE or TESLA for $M_h = 120$ GeV.

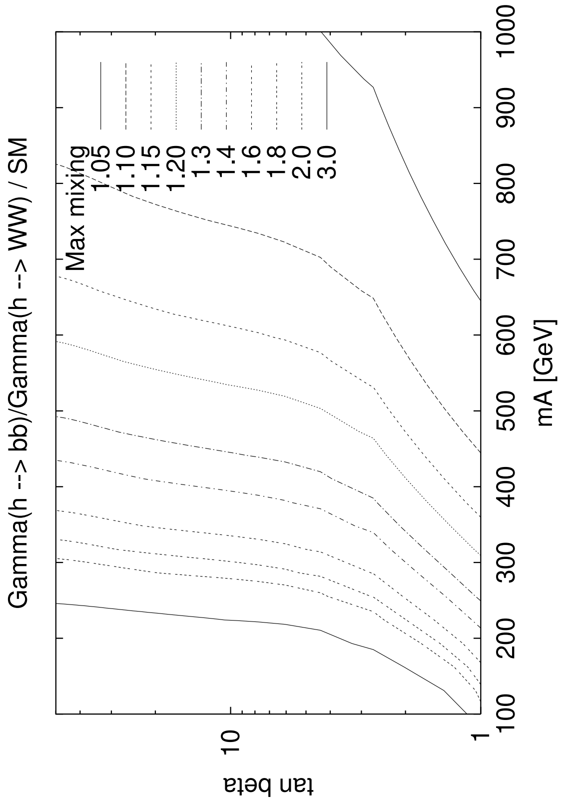
Measurement	Precision
$\Gamma_{\gamma\gamma} \times Br(h \to bb)$	0.012
$\Gamma_{\gamma\gamma} \times Br(h \to WW)$	0.035
$\Gamma_{\gamma\gamma} \times Br(h \to \gamma\gamma)$	0.121
$\Gamma_{\gamma\gamma} \times Br(h \to ZZ)$	0.064
$\Gamma_{\gamma\gamma} \times Br(h \to \gamma Z)$	0.20
$\Gamma_{\gamma\gamma}$ * $\times$	0.021
Γ_{Total} *	0.13
Mass ($\gamma\gamma$ decay)	61 MeV
CP asymmetry (WW decay)	0.035-0.040

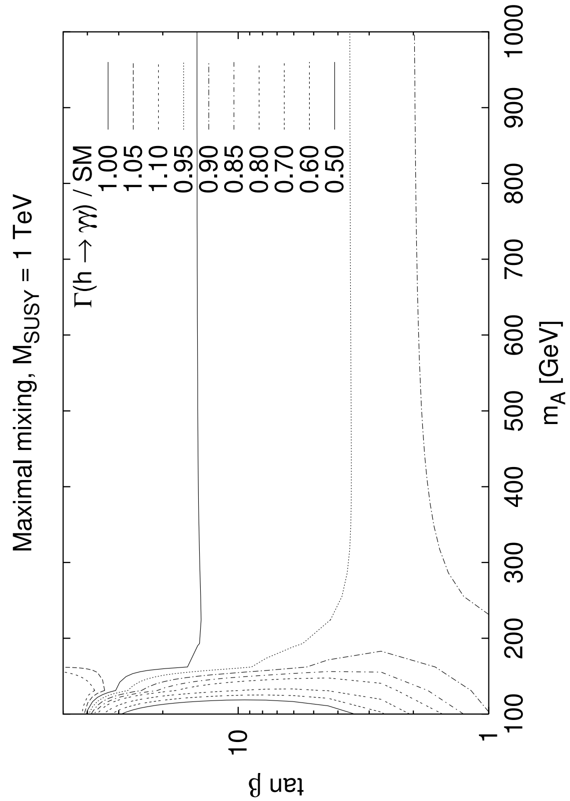
* Take $Br(h \to bb)$ from LC

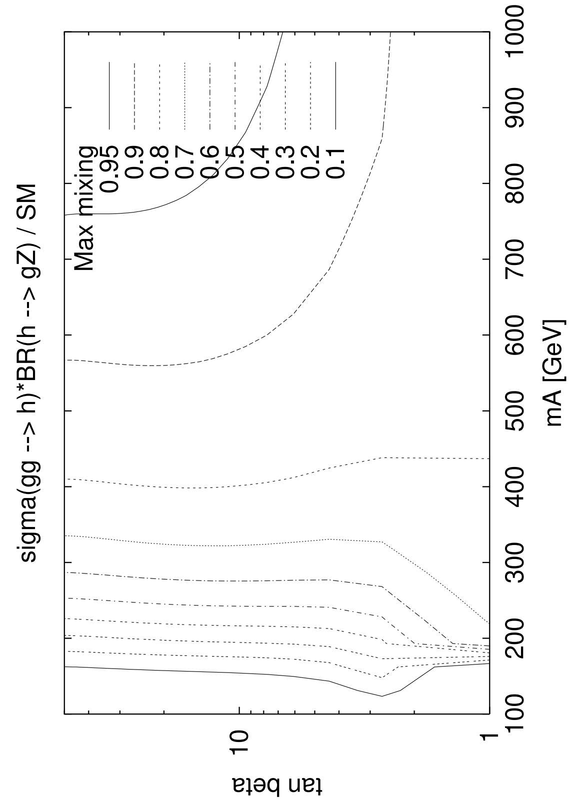
$\times$ 19% measurement at TESLA in 500 fb^{-1}

Examples of how to use this informations for Light Higgs

⇒ Heather Logan

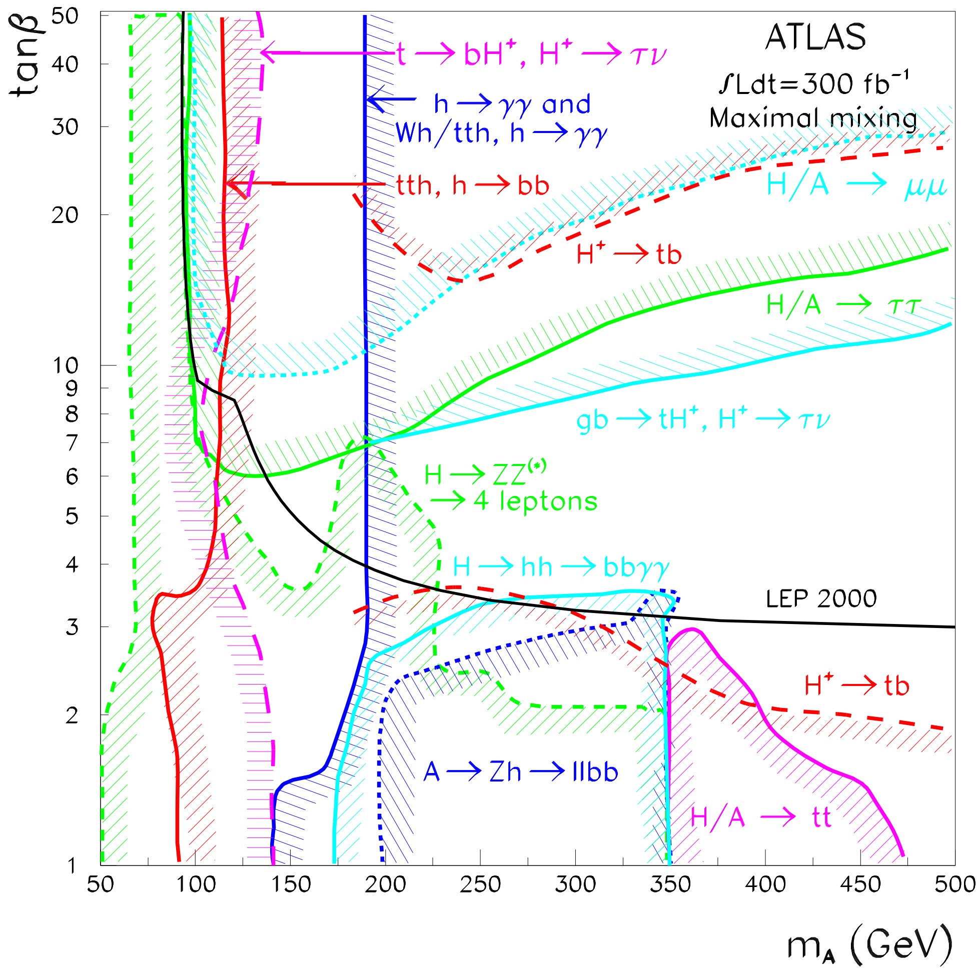






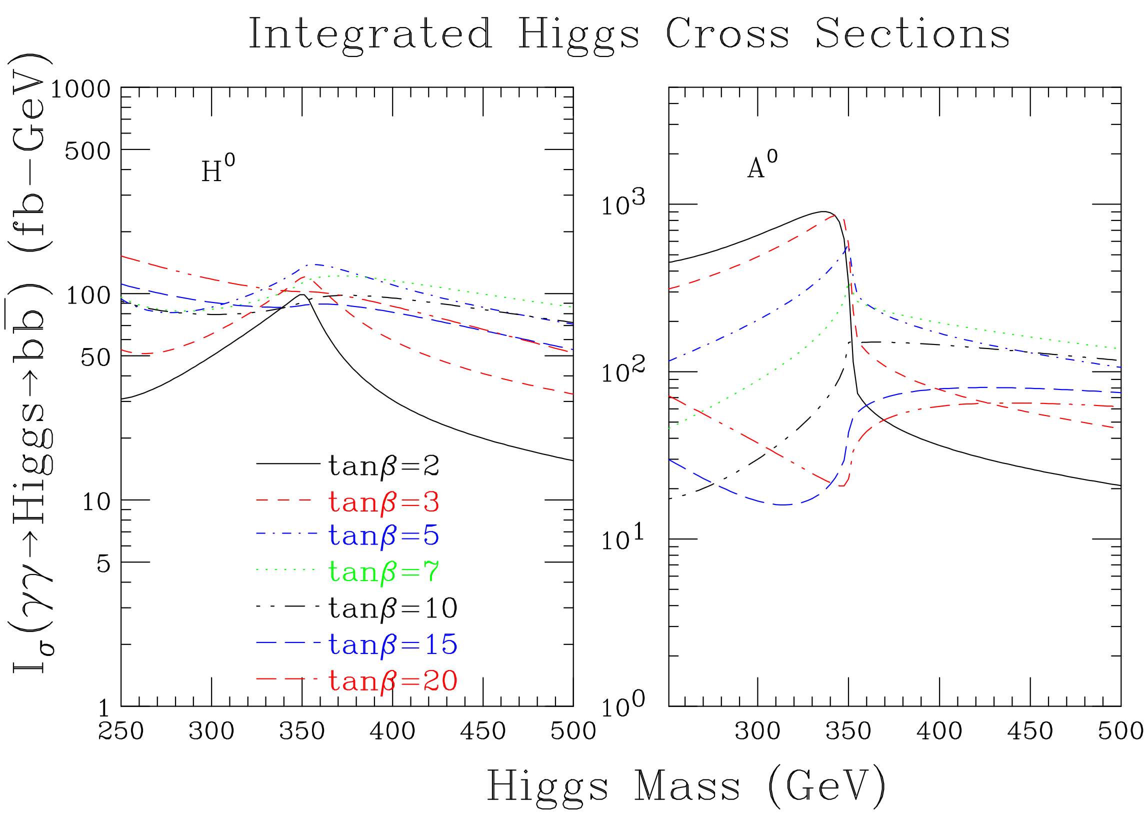
Neutral Heavy Higgses

Look at $\tan\beta$ regions that are not accessible to LHC:



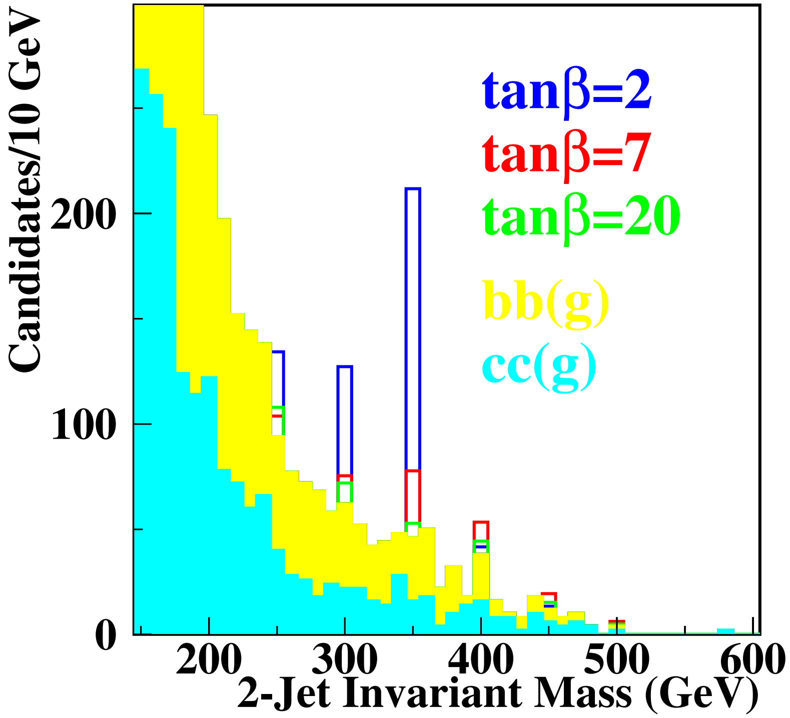
High Energy $\gamma\gamma$ could save the day!!!!!!!!

Neutral Heavy Higgses

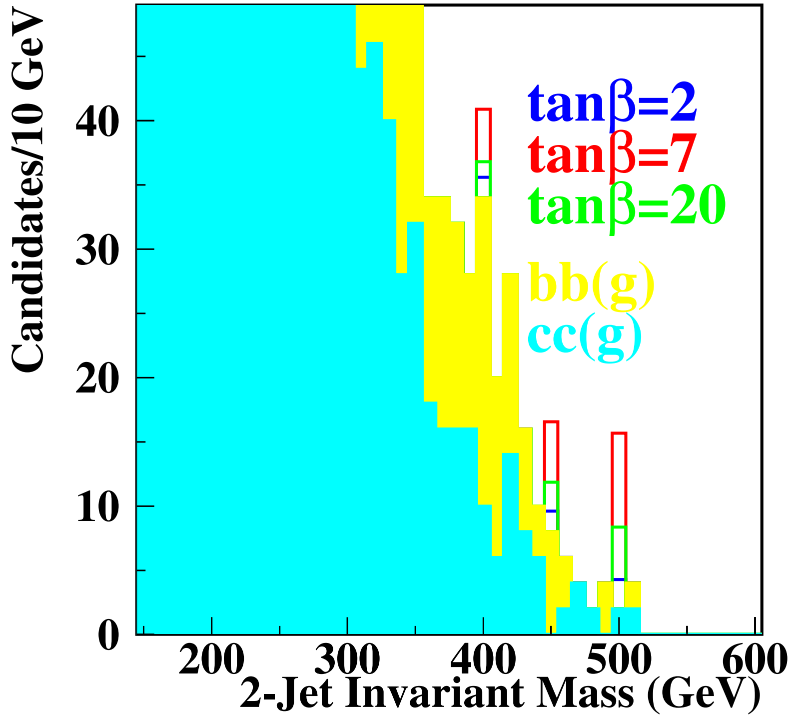


- Cross sections are not small, and backgrounds are manageable.
- H and A would be produced singly, the mass range is much greater than in e^+e^- – up to 80% of $\sqrt{s_{ee}}$.
- The $b\bar{b}$ final state confirmed by preliminary event simulations ($\gamma\gamma$WS2001) and hep-ph/0110320.

Heavy Higgs: $\gamma\gamma \rightarrow H^0, A \rightarrow b\bar{b}$, $\mathrm{E}_{ee} = 630$ GeV



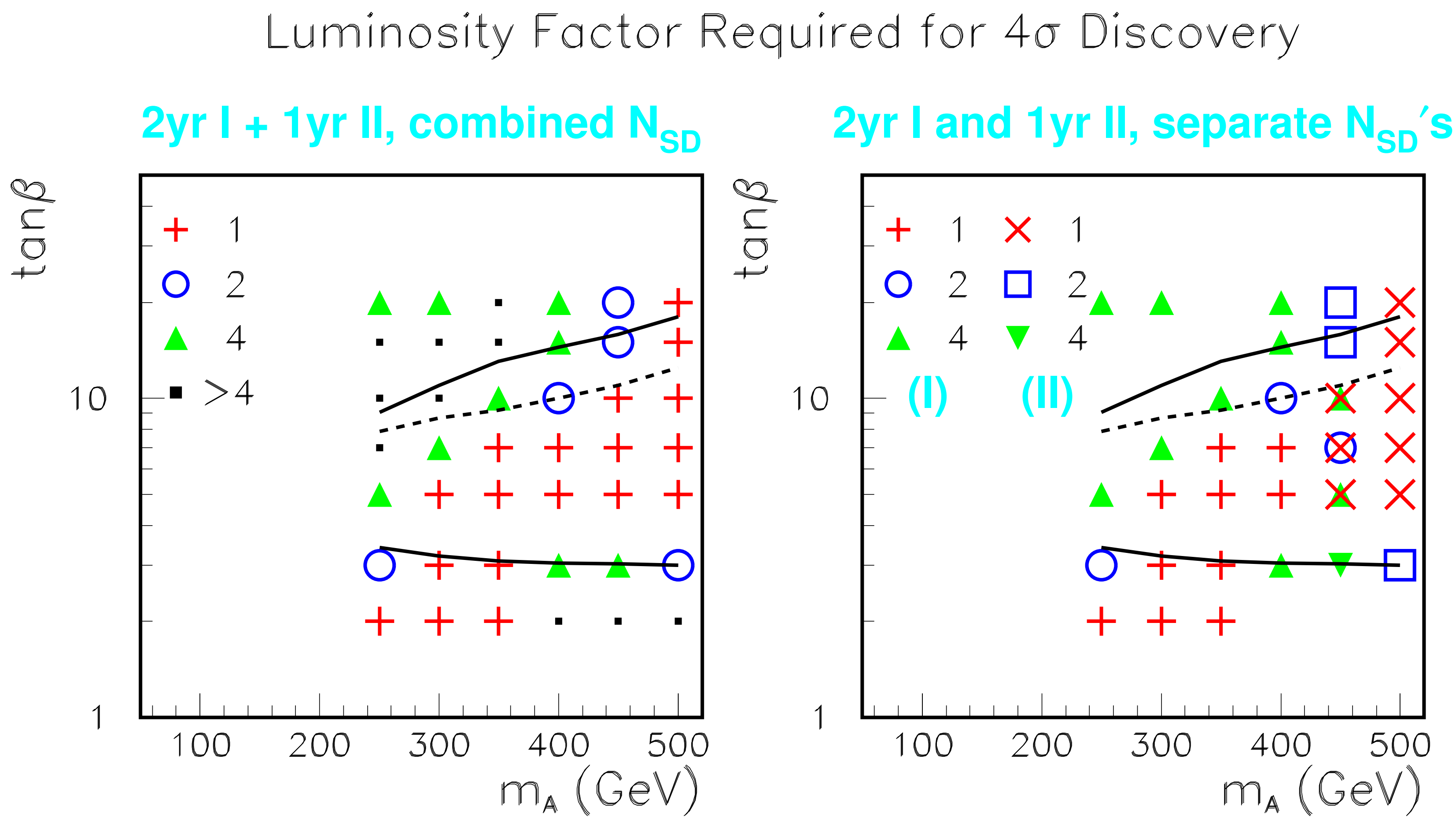
BROAD SPECTRUM I



PEAK SPECTRUM II

Next$\Rightarrow$ add the $H^0, A \rightarrow t\bar{t}$ selection... Gunion et al.

Convering full $\tan\beta$ and M_A plane with a $\mathrm{E}_{ee} = 630$ GeV

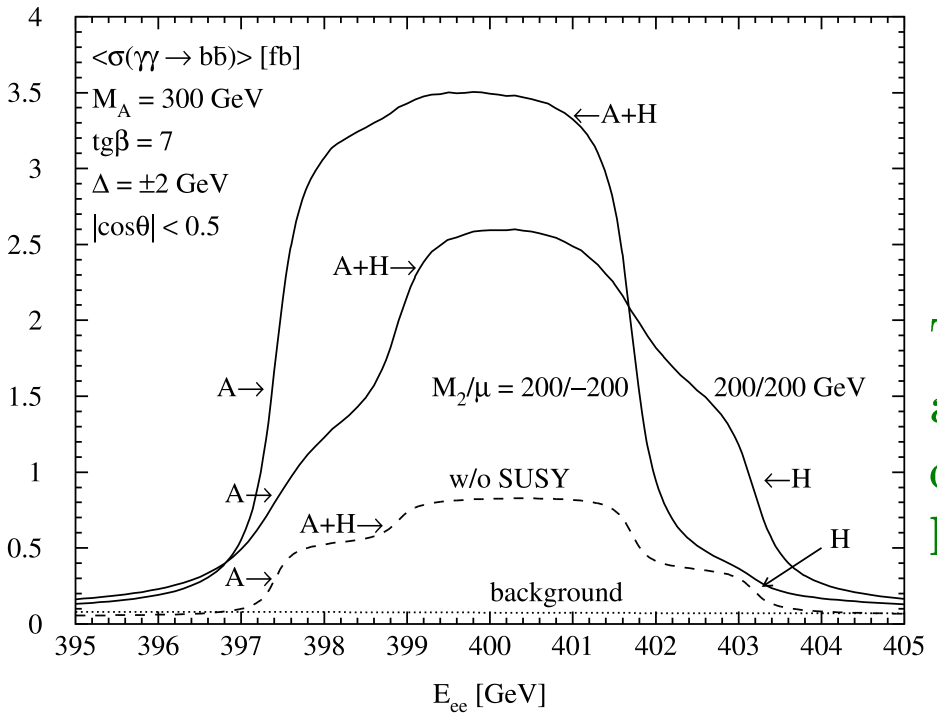


NLC is given by crosses, TESLA is crosses & circles & squares Gunion et al.

What if $M_A \simeq M_H$?

hep-ph/0101083

In the MSSM, the H and A bosons are very close in mass, test it by scanning...Can we get the mass splitting?:



$h_0, H \Rightarrow$ CP-even
$A \Rightarrow$ CP-odd

This lineshape is sensitive to CP mixing, and changes with different initial states of CP, therefore can turn ON/OFF using lineraly polarized γ's.

CP test in the Higgs Sector

CP Violation is the great enigma of high energy physics.

In the MSSM, CP violation in the Higgs sector comes through radiative corrections, with stop loops playing the main role. This effective CPV can be large, and has a major impact on the phenomenology.
⟹ Waiting for news from our theorist friends.

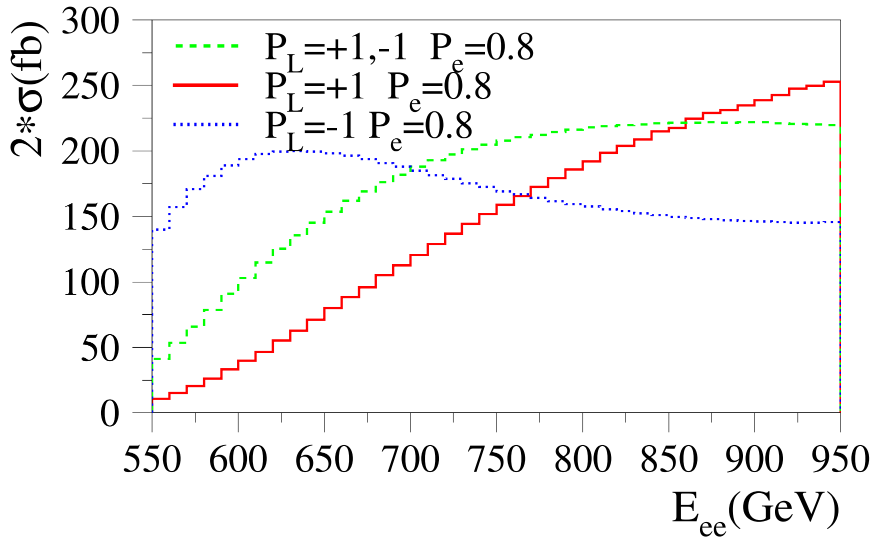
The best place to study CP violation in the Higgs sector is at a $\gamma\gamma$-collider – in fact, this is a unique capability of the $\gamma\gamma$-collider.

The technique exploits linear polarization of photon beams. These define a CP-even or CP-odd state depending on whether the polarization vectors are parallel or perpendicular.

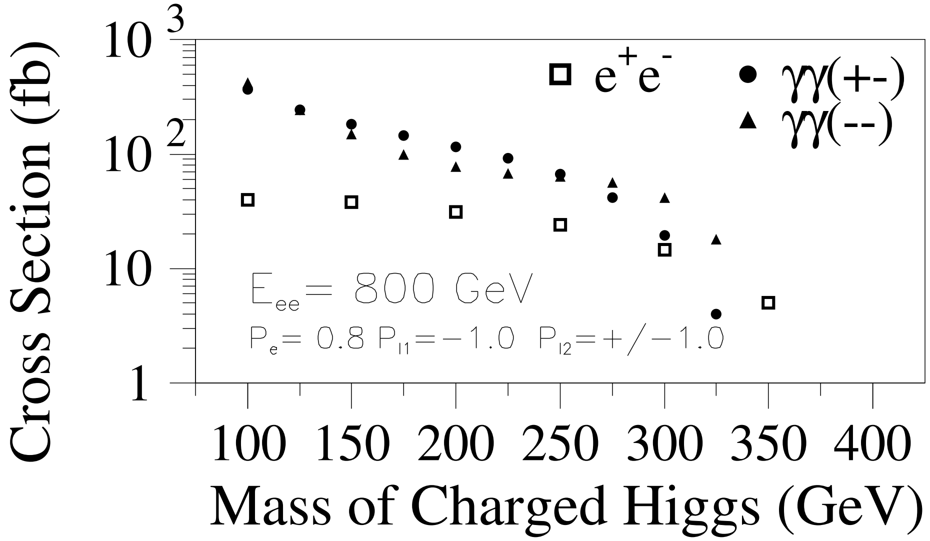
Charged Higgs, $H^{\pm}$

- Cross sections are 10× larger than in an e^+e^- machine.
- The sharp turn-on could allow a good measurement of the mass ($\tau\nu$ decays not great for mass measurements).

200 GeV Charged Higgs Pair



γγ to H⁺H⁻



Logan & Velasco

Conclusion I

Most of the physics needed to understand the EW sector can be done in a series of $\gamma\gamma$-colliders ...
Starting with a 'low' energy Higgs-Factory!

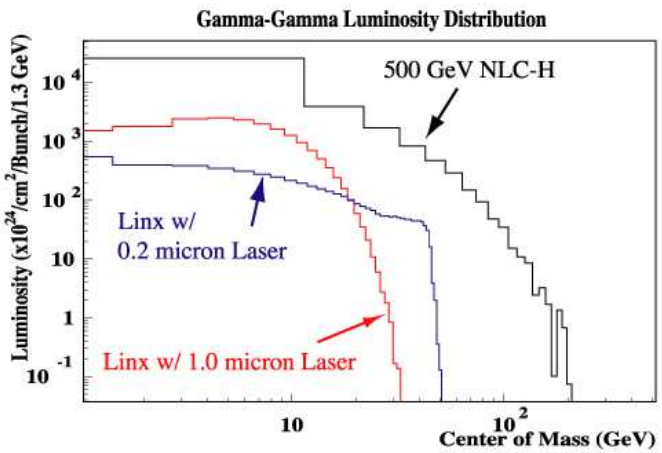
Three areas in which the $\gamma\gamma$-colliders would play a **crucial role** and even **unique role**:

1. Extraction of CP quantum numbers.
   The use of polarized photon beams is an extremely powerful physics tool which is unavailable at electron and proton machines.
2. Production of heavier Higgs states.
   Larger mass reach in difficult $tan\beta$ regions.
3. $\Gamma_{\gamma\gamma}$, the two-photon partial width.
   This will give a simple and powerful tool to study Yukawa couplings through the tth coupling.
4. Γ_{Total}, the total width. Model independent!

There are other important possibilities not discussed in this talk....

Conclusion II

A $\gamma\gamma$ Collider should appear
in the future of High Energy Physics
To make sure we are ready...



<u>LINX:</u> proposed facility at SLAC for engineering studies of IR issues (At SLC/SLD.)

- This issues are important for all LC-designs!
- Assuming 30 GeV beams, for $\gamma\gamma$ we can expect luminosity shown in figure. Important for both:
  - $\gamma\gamma$-physics
  - $\gamma\gamma$-collider development... Proof-of-Principle