LCWS 00/Fermilab

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28/10/00

SUMMARY OF "HIGGS + SUSY HIGGS" SESSION

(experimental part)

1. Introduction
2. Mass + "large" cross sections
3. Spin
4. Branching Ratios
5. "tiny" cross sections ($t\bar{t}H$, ZHH)
6. Heavy SUSY Higgses
7. Interfacing Theory + Experiment
8. Conclusions

① Introduction

- e^+e^--Linear Collider (350 - 1000 GeV) turns the observation of a Higgs Boson into precision physics → establish EW symmetry breaking mechanism (→ talk by M. Battaglia)

- many studies done for the most preferred case: e^+e^- / $m_H \lesssim 160$ GeV / $\sqrt{s} \lesssim 500$ GeV

- this workshop:

  a) many updates for this case

  b) study the $\gamma\gamma$ - option

  c) studies of heavier Higgs Bosons ($H^\pm$, A, H)

② Mass + "large" cross sections

GARCIA-ABIA

- golden channel $e^+e^- \to HZ \to H\,l^+l^-$ (recoil mass technique) extensively studied
- model independence mandatory to extract g_{HZZ}, but not for mass measurement.

→ look into specific final states:

- $b\bar{b}\,l^+l^-$
- $b\bar{b}\,q\bar{q}$

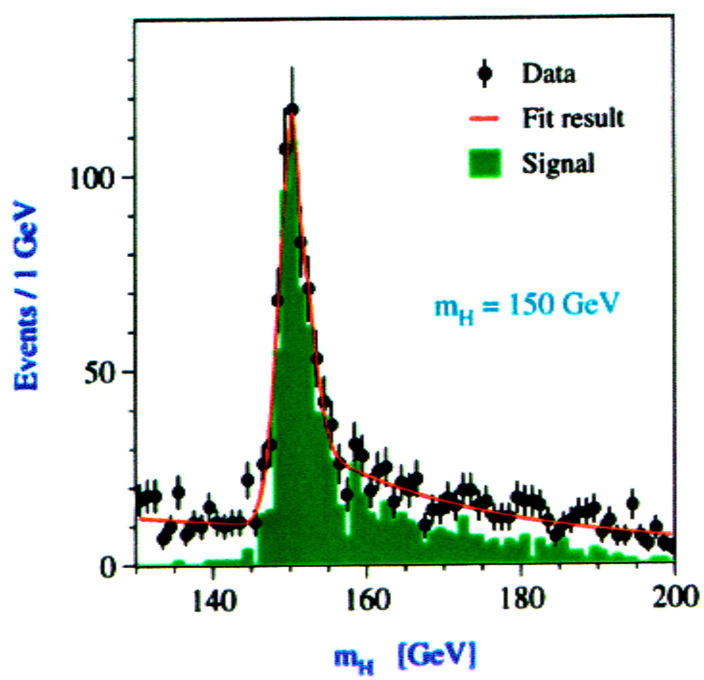
} lower $m_H \lesssim 150$ GeV

- $W^+W^-ll \to q\bar{q}q\bar{q}\,l^+l^-$
- $W^+W^-q\bar{q} \to q\bar{q}q\bar{q}q\bar{q}$

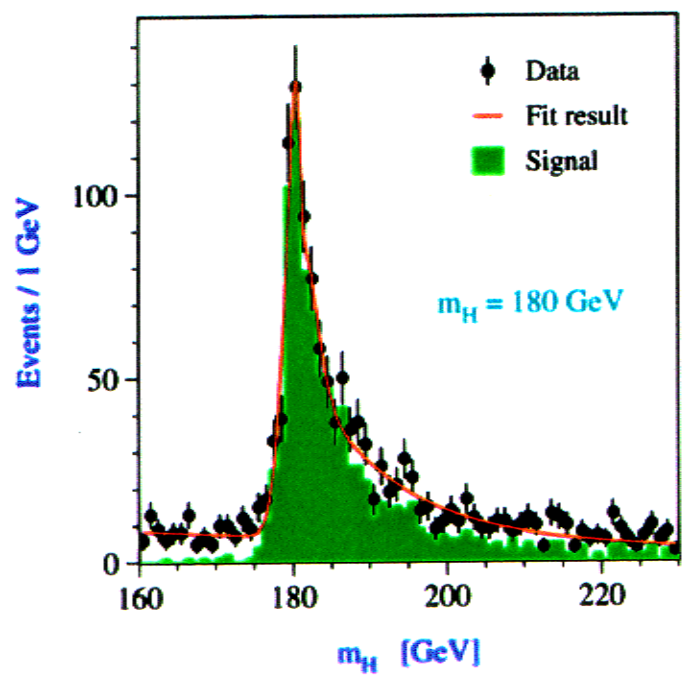
} larger $m_H \gtrsim 150$ GeV

$$ZH \rightarrow \ell^+\ell^-W^+W^-, \quad W^\pm \rightarrow q\bar{q}'$$

$\Delta m_H = 160$ MeV
$\Delta\sigma/\sigma = 4.0\,\%$

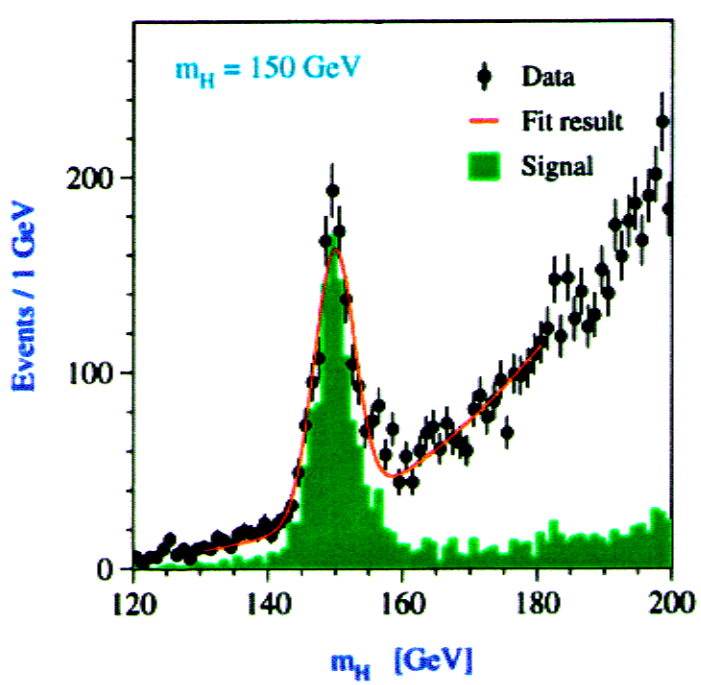


$\Delta m_H = 160$ MeV
$\Delta\sigma/\sigma = 3.3\,\%$

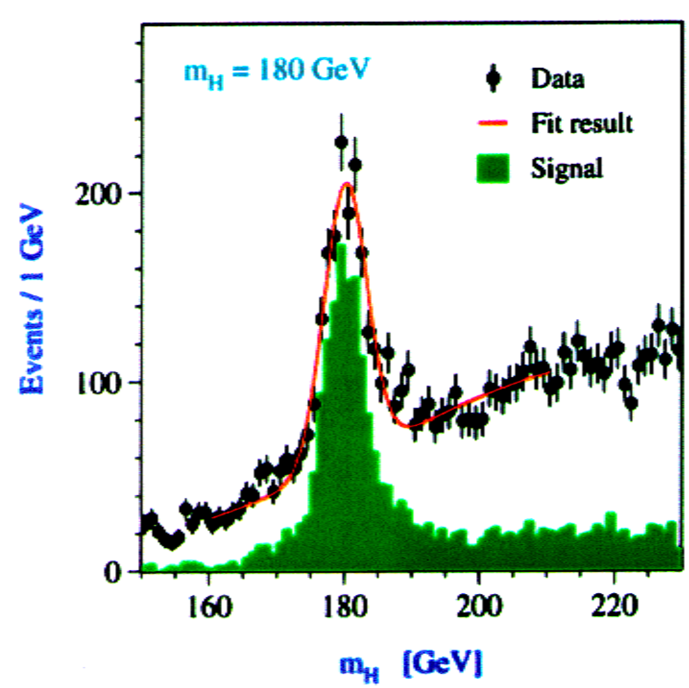


$$ZH \to q\bar{q}W^+W^-, \quad W^\pm \to q\bar{q}'$$

$\Delta m_H = 130$ MeV
$\Delta\sigma/\sigma = 3.4\,\%$



$\Delta m_H = 150$ MeV
$\Delta\sigma/\sigma = 2.9\,\%$



Conclusions

Absolute accuracy (in MeV) on the determination of m_H:

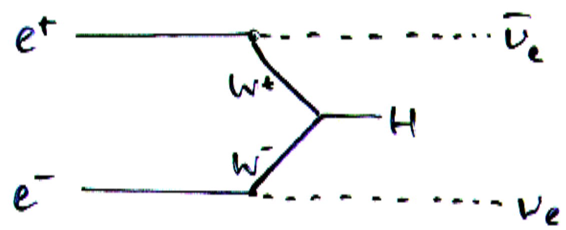
Decay mode $\quad m_H =$	120	150	180
recoil mass	110	90	95
$ZH \to \ell^+\ell^- q\bar{q}$	70	90	–
$ZH \to q\bar{q}b\bar{b}$	45	170	–
$ZH \to \ell^+\ell^- W^+W^-,\ W^\pm \to q\bar{q}'$	–	160	160
$ZH \to q\bar{q}W^+W^-,\ W^\pm \to q\bar{q}'$	–	130	150

Relative accuracy (in %) on the determination of $\sigma(ZH \to X)$:

Decay mode $\quad m_H =$	120	150	180
recoil mass	2.6	3.2	3.8
$ZH \to \ell^+\ell^- q\bar{q}$	3.0	4.7	–
$ZH \to q\bar{q}b\bar{b}$	1.1	3.4	–
$ZH \to \ell^+\ell^- W^+W^-,\ W^\pm \to q\bar{q}'$	–	4.0	3.3
$ZH \to q\bar{q}W^+W^-,\ W^\pm \to q\bar{q}'$	–	3.4	2.9

WW-Fusion cross section:

KD



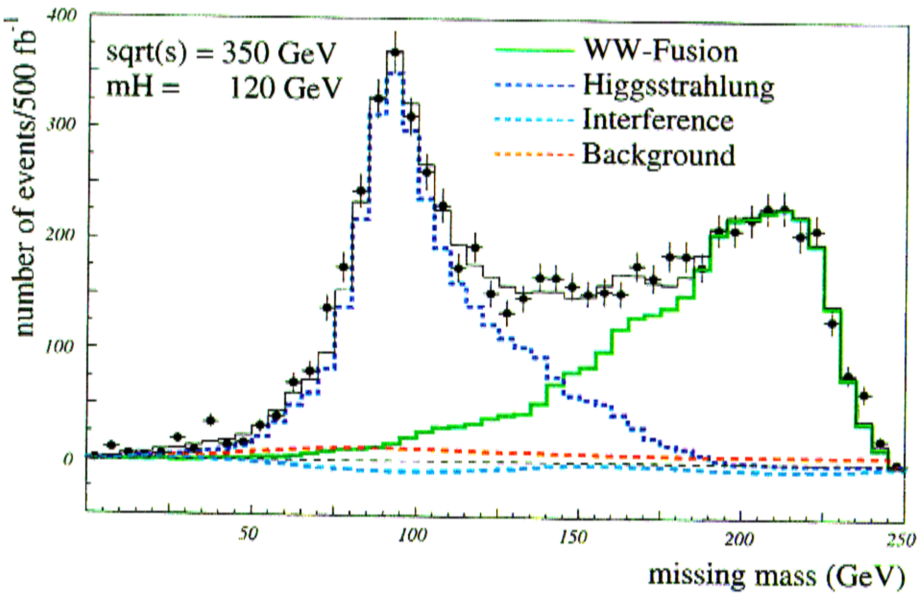
- probes g_{HWW}
- sensitive to Γ_{tot} (with $BR(H \to WW)$)
- $\sigma \sim \ln s$ → dominant at high $\sqrt{s}$
- dominant for large $\sqrt{s} - m_H$

⇒ full experimental study for $m_H \lesssim 160$ GeV of

$$e^+e^- \to H\nu_e\bar{\nu}_e \to b\bar{b}\nu_e\bar{\nu}_e$$

Analysis

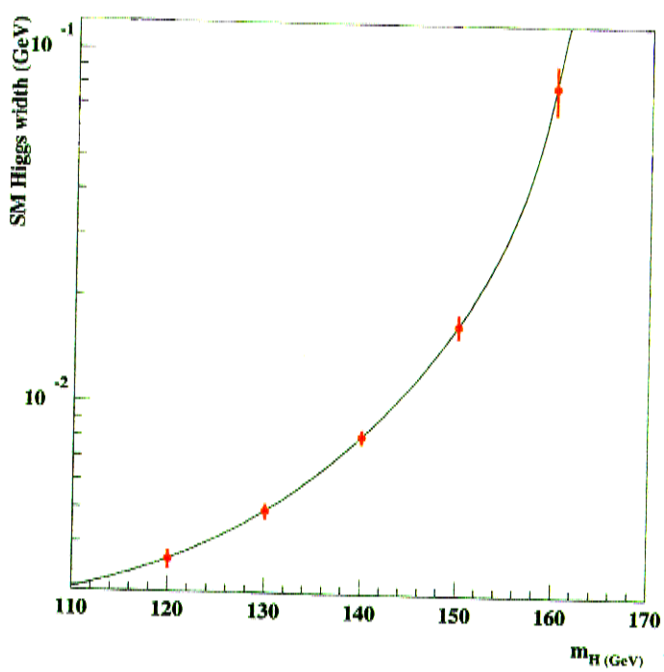
The final step: look at missing mass distribution:



- Determine the rate for WW-fusion from a shape fit to the contributions of WW-Fusion, Higgs-Strahlung and background.
- Interference currently treated as constant (could be fit as well)
- Systematics: background shape can be checked from anti-b-tagged selection
- Higgs-Strahlung shape can be checked with $HZ \rightarrow b\bar{b}\ell^+\ell^-$ events after removing the leptons
- Running with different beam polarisation has different effects on the background and Higgsstrahlung contributions!

Interpretation 1: the total width

m_H [GeV]	$\Delta\sigma_{fusion}/$	$\Delta BR(WW)/$	$\Delta\Gamma_H$
120	2.8 %	5.4 %	6.1 %
130	3.7 %	3.3 %	5.0 %
140	4.2 %	2.5 %	4.9 %
150	7.4 %	2.2 %	7.7 %
160	15.9 %	1.9 %	16.0 %

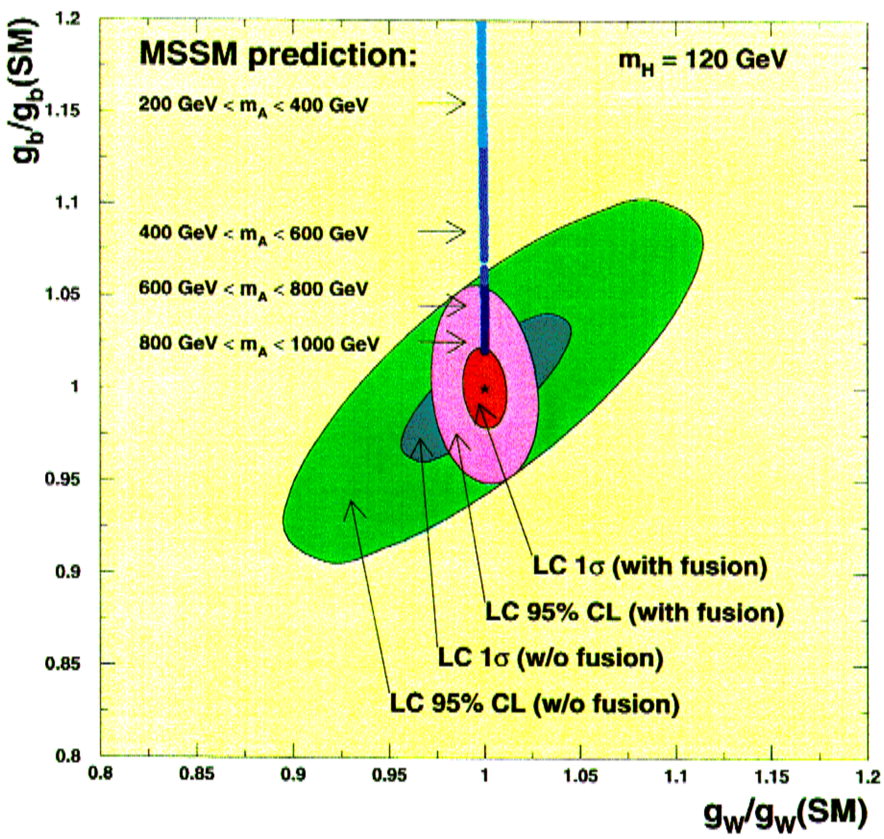


SOPCZAK LC better by factor o(5) in low-mass region

Interpretation 2: g_{HWW}

WW-Fusion measurement clearly increases sensitivity to g_{HWW}.

Global fit of to all Higgs boson couplings from all "available" measurements ("HFITTER"):



③ Spin

MILLER

Is it a scalar?

→ $H \to \gamma\gamma$ rules out Spin 1

→ $\frac{d\sigma(HZ)}{d\cos\theta \, d\phi^*}$? not conclusive: conspiracy of formfactors might "mimic" Spin 0 although it is something else...

→ $\beta = \frac{p_H}{E_{beam}}$ -dependence of cross section near threshold tells the final truth

→ should study how much $\int \mathcal{L} dt$ is needed at which β-points.

④ Branching Ratios

SCHREIBER

a) new and complete study of $H \to \gamma\gamma$.

good for: • rule out Spin 1

• $\Gamma_{tot} = \dfrac{\Gamma_{\gamma\gamma}}{BR(\gamma\gamma)}$

• sensitive to new physics (e.g. charged Higgs loop KRAWCZYK)

tough to measure: tiny signal, large background

• combine $q\bar{q}\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$

$\to \dfrac{\Delta BR(H \to \gamma\gamma)}{BR(H \to \gamma\gamma)} = 16\%$ (18%)

500 GeV 350 GeV

($m_H = 120$ GeV, 1 ab^{-1})

• difficult at higher m_H

• polarisation $\Rightarrow \sim 10\%$ (500 GeV)

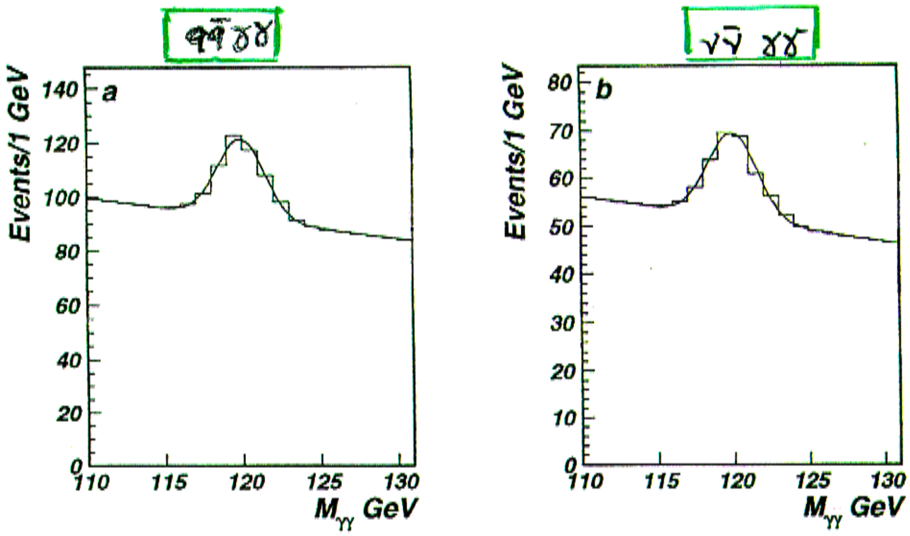


Figure 4: $M_{\gamma\gamma}$ invariant mass distributions for 350 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events

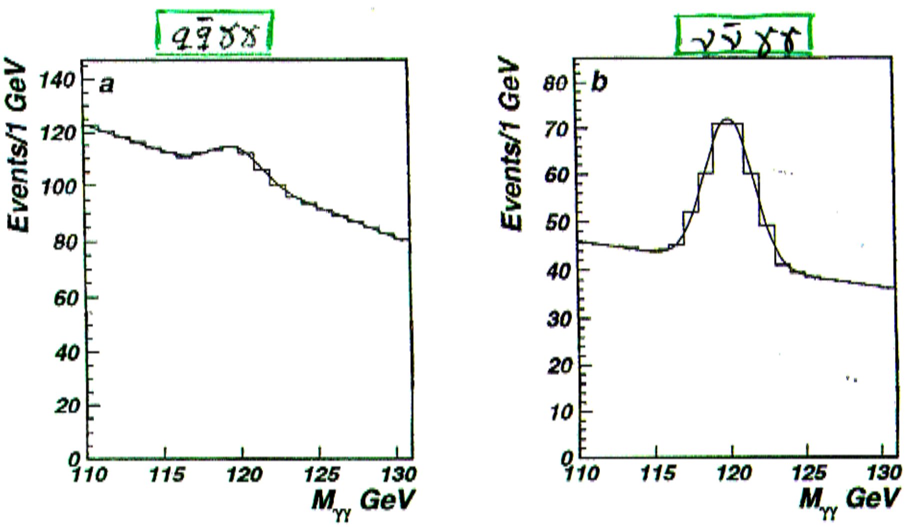


Figure 5: $M_{\gamma\gamma}$ invariant mass distributions for 500 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events

h) general BR study for US-detector started: BRAU

- very preliminary results (not optimized)
- cut based analysis

$m_H = 140$ GeV, $\sqrt{s} = 500$ GeV, 500 fb^{-1}

	position of innermost vtx-layer: 1.2 cm	2.4 cm
$H \to b\bar{b}$	3.6 %	4.4 %
$H \to \tau^+\tau^-$	14.7 %	17.6 %
$H \to c\bar{c}$	46 %	60 %
$H \to gg$	59 %	78 %
$H \to WW$	6.8 %	7.6 %

$\to$ room for improvement

⑤ The "tiny" cross sections

DAWSON

a) $e^+e^- \to t\bar{t}H$

"toy detector" study (hadron level + smearing)

→ $\frac{\delta g_{ttH}}{g_{ttH}} \approx O(20\%)$ at $\sqrt{s} = 1$ TeV
$1\,ab^{-1}$
(worse at 500 GeV)

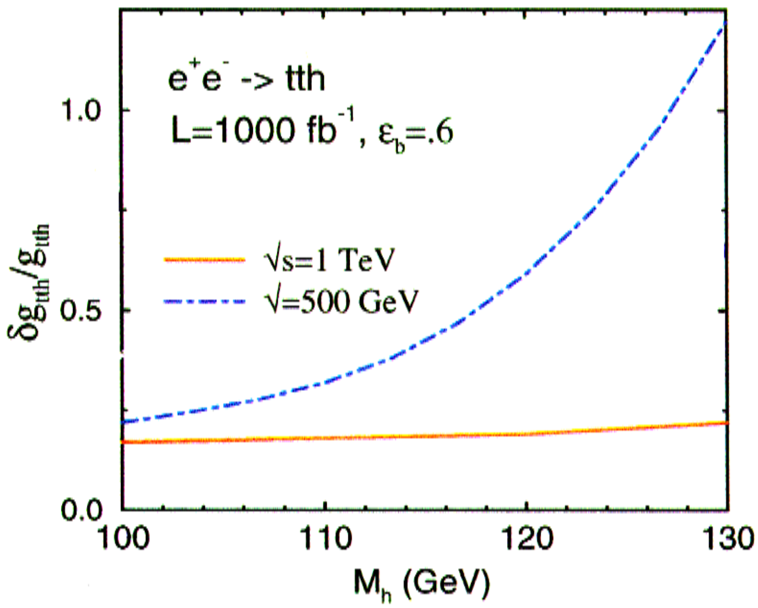
$100 \lesssim m_H \lesssim 130$ GeV

- tight cuts
- conservative detector resolution
- c.f. JUSTE + MERINO: $\frac{\delta g_{ttH}}{g_{ttH}} = 5.5\%$

($m_H = 120$, $1\,ab^{-1}$, 800 GeV)

with TDR detector + NN analysis

Combine hadronic and semi-leptonic channels:

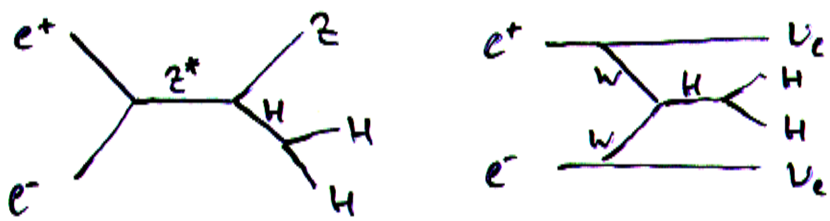


- Statistical error only in plot
- Interesting question is how well do you *need* to do?

- Juste and Merino (hep-ph/9910301): More sophisticated analysis with TESLA detector and neural net analysis
- Juste and Merino: $\sqrt{s} = 800\ GeV$; $M_h = 120\ GeV$

$$\frac{\delta g_{tth}}{g_{tth}} = 5.5\%$$

b) Higgs self coupling



MÜHLLEITNER

- complete calculation the processes in SM and MSSM

- cross sections o(0.1 fb) need the highest possible luminosity

GAY

- full experimental study using various methods including ANN's:

$$\rightarrow \frac{\Delta\sigma}{\sigma} \lesssim 20\% \qquad \text{for } 1\,ab^{-1}, \; m_H \lesssim 140 \text{ GeV}$$

$$\Rightarrow \frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} \approx 20\% \;!$$

SELECTIONS

iii) Six jets (clustered with DURHAM)

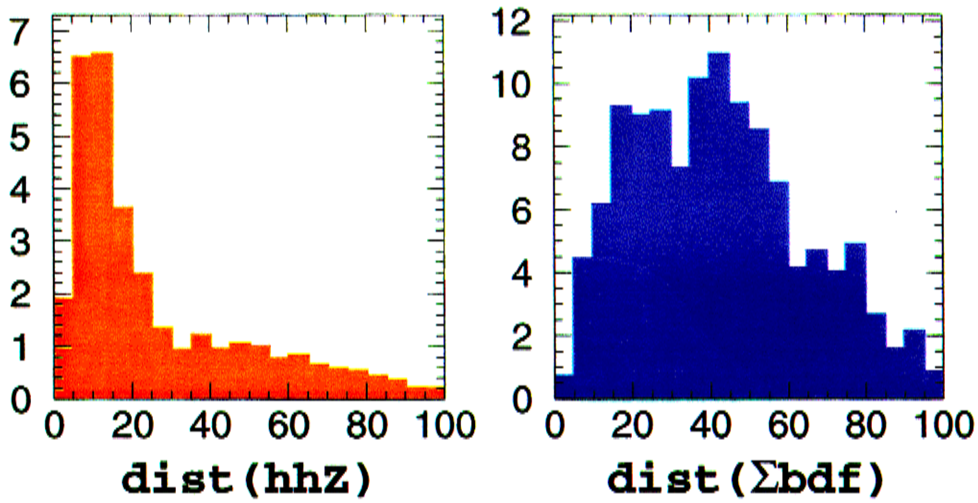
- **event forced in 6 jets topology**
- **jet b-tagging**

iv) Combinatory & masses

3 di-jets (hhZ) → 90 combinations

- **direct use of the reconstructed di-jets masses**
  - m_{56} **matches a** Z **mass**
  - **At least one b jet among the recoiling jets**
  - m_{12} **and** m_{34} **such that** $\|m_{12}\text{-}m_{34}\|$ **is minimum**
- **simply combined to form the *distance* Dist**

Dist$=\sqrt{((m_{12}-\cancel{100}\,120)^2+(m_{34}-\cancel{100}\,120)^2+(m_{56}-m_{Z})^2)}$



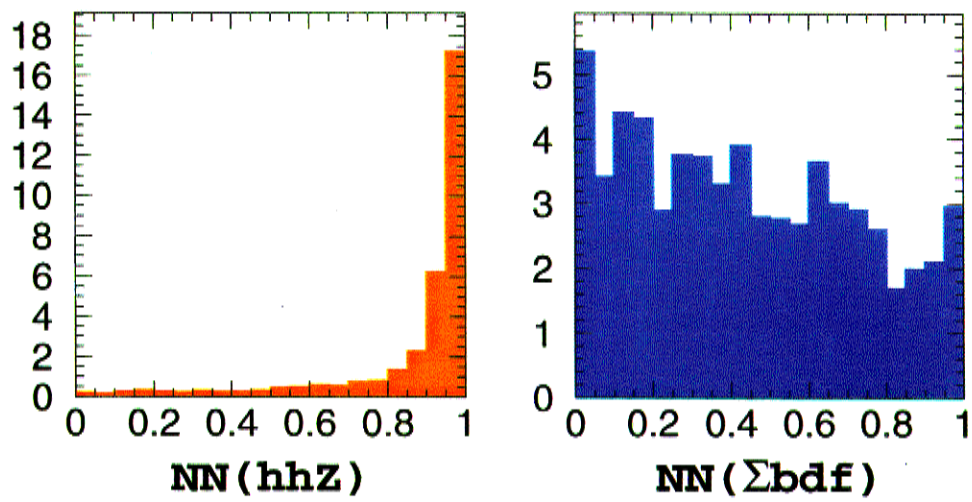
Selections

v) **Multivariable**

informations from

- **b-content of the system recoiling to the Z**
- **di-jet masses (m_{12}, m_{34}, m_{56})**

are combined in a multivariable analysis (NNet)



$\Delta\sigma/\sigma$

Cross-section (σ_{hhZ})measurement takes into account a caracteristic variable (DIST, $\mathrm{NN_{output}}$, ...)

	selection variable	$\Delta\sigma/\sigma$ $\mathcal{L}$= 500fb^{-1}	1000fb^{-1}	2000fb^{-1}
B	DIST	32.8 %	25.6 %	17.7 %
C	DIST	29.8 %	21.5 %	15.1 %
B	$\mathrm{N_{bjets}^{recoil\ syst.}}$	24.1 %	17.3 %	11.6 %
D	NN output	20.4 %	12.9 %	10.3 %

Table 4: Relative error ($\Delta\sigma/\sigma$) on σ_{hhZ} for different selections and integrated luminosities

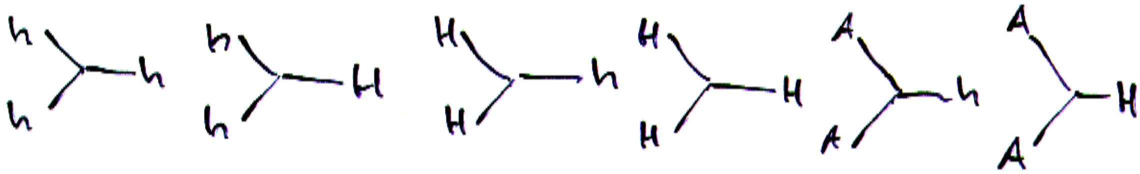
m_{h} (GeV/c^2)	σ_{hhZ} (fb)	$\mathrm{N_{hhZ}^{500}}$	ϵ_{hhZ}	$\Delta\sigma/\sigma$ $\mathcal{L}$= 500 fb^{-1}	1000 fb^{-1}	2000 fb^{-1}
120	0.186	93.	43%	24.1%	17.3%	11.6%
130	0.149	74.	43%	26.6%	19%	17.7%
140	0.115	57.	39%	32%	23 %	17%

Table 5: Relative error ($\Delta\sigma/\sigma$) on σ_{hhZ} with the selection B+$\mathrm{N_{bjets}^{recoil\ syst.}}$ for different Higgs boson masses and integrated luminosities; cross-sections are reported and ($\mathrm{N_{hhZ}^{500}}$) the expected number of hhZ events with $\mathcal{L}$=500fb^{-1}

MÜHLLEITNER

Higgs self couplings in MSSM:

more complicated structure:



- depend on SUSY parameters $\tan\beta$, α

→ might be supressed

→ study "sensitivity regions" in (m_A, $\tan\beta$)-plane with "non-zero" cross section

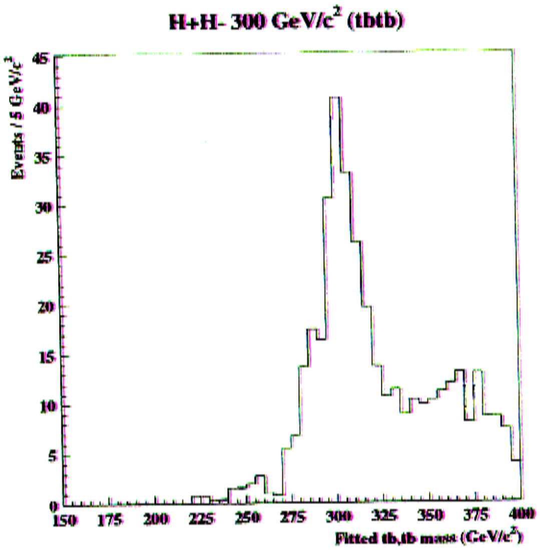
H^+H^- summary

Full reconstruction of eight jet events possible in $H^+H^- \to tbt\bar{b}$ and $H^+H^- \to W^+h^0W^-h^0$ decay channels.

High purity with few per cent signal efficiency with b-tagging and kinematical fits.

Estimated measurement precisions for 300 GeV/c^2 H^+H^- (500 pb^{-1} at 800 GeV at TESLA):

- Mass measurement: 1–2 GeV/c^2
- Cross-section measurement: 10-15 %



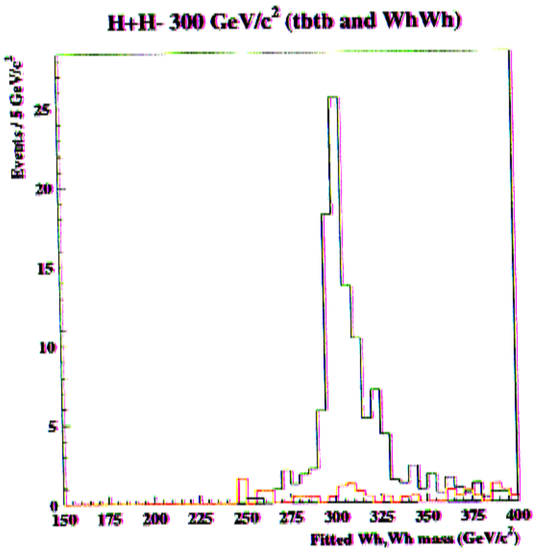


Fig. 1: Fitted mass of 300 in $t\bar{b}\bar{t}b$ decay channel. Fig. 2: Fitted mass in $W^+h^0W^-h^0$ channel. Red histogram shows the fraction of $t\bar{b}\bar{t}b$ events passing the $W^+h^0W^-h^0$ cuts.

⑥ Heavy SUSY Higgses

KIISKINEN

a) charged Higgs :

typically heavy in MSSM

→ decays: $H^+ \to t\bar{b}$ or $H^+ \to W^+ h$

→ 8-jet final state! mass reconstruction?

→

b) heavy H, A in MSSM:

MÜHLLEITNER

- can be s-channel produced in

$\gamma\gamma \to H$, $\gamma\gamma \to A$

- possibly higher mass reach ($\sim 80\% \sqrt{s_{ee}}$) than in e^+e^- (if only $e^+e^- \to HA$ is large)
- possibly H and A nearly mass degenerate

→ can they be disentangled ?

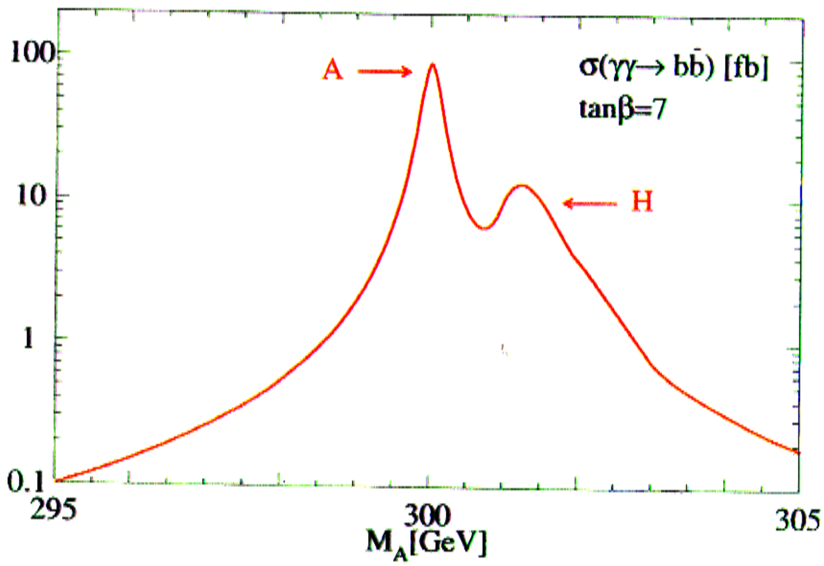
Separation of H and A

$\gamma\gamma \to b\bar{b}$

$M_A = 300$ GeV $M_H = 301.37$ GeV

$\tan\beta = 7$

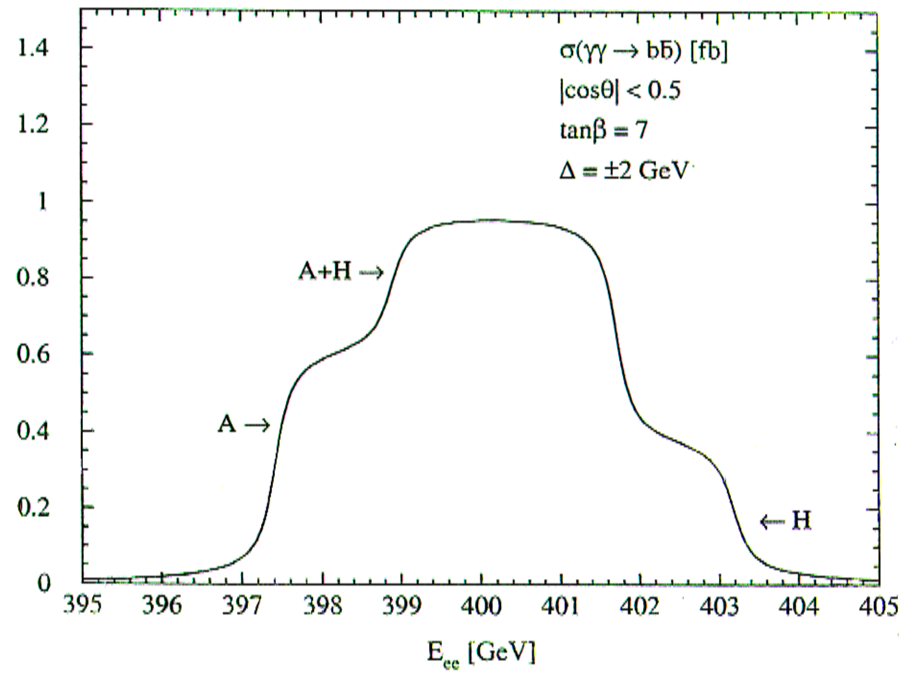
SUSY masses are large



Separation of H and A

via threshold scan

<u>Example:</u> $M_A = 300\,GeV$, $M_H = 301.37\,GeV$ $\tan\beta = 7$
SUSY masses are large



- Increase of the cross section when A-, H-threshold is reached

  ↝ Separation of H and A via threshold scan

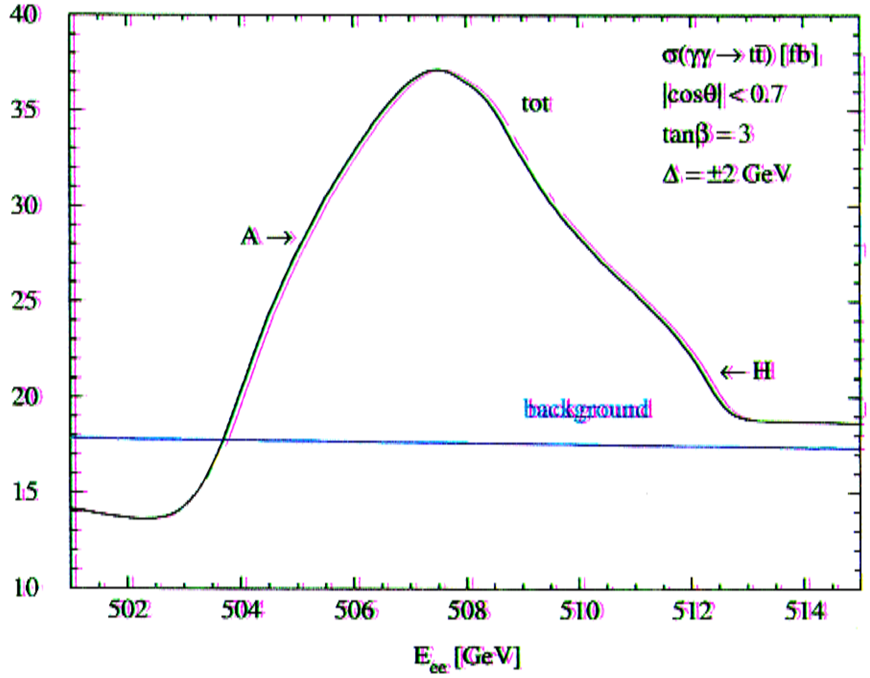
Separation of H and A

$e^+e^- \to \gamma\gamma \to t\bar{t}$

$M_A = 400$ GeV $M_H = 404.48$ GeV

$\tan\beta = 3$

SUSY masses are large



one step further:

ASAKAWA

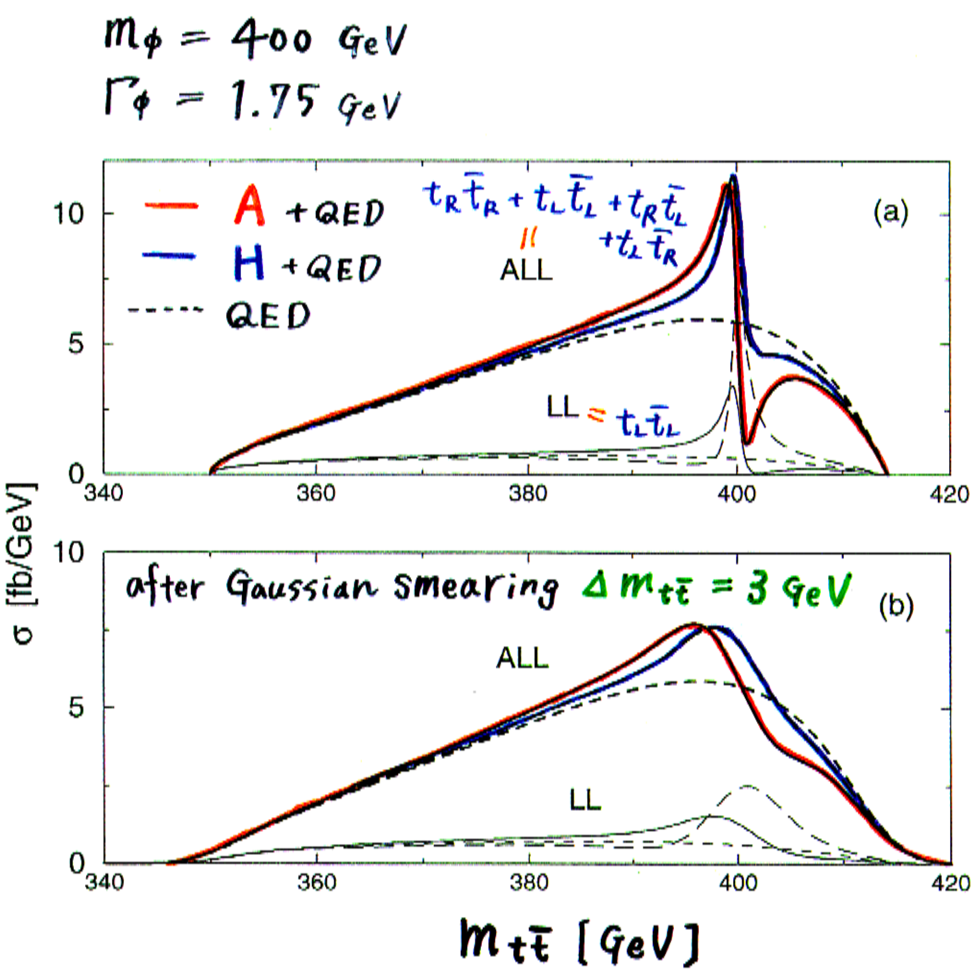
which one's A ?

which one's H ?

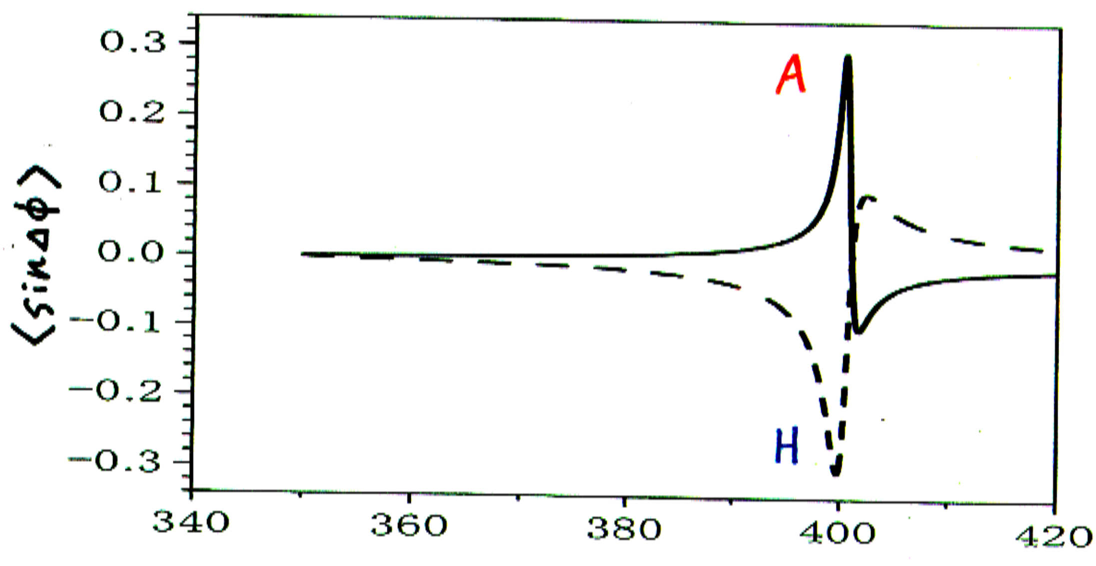
→ measure CP

two methods:

- top - Polarisation
- $t\bar{t}$ angular correlations



mϕ = 400 GeV
Γϕ = 1.75 GeV
A + QED
H + QED
QED
tRt̄R + tLt̄L + tRt̄L + tLt̄R
ALL
LL = tLt̄L
(a)
after Gaussian smearing Δmtt̄ = 3 GeV
(b)
ALL
LL
σ [fb/GeV]
0
5
10
340
360
380
400
420
mtt̄ [GeV]



0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
⟨sinΔφ⟩
A
H
340
360
380
400
420

⑦ Interfacing Theory + Experiment

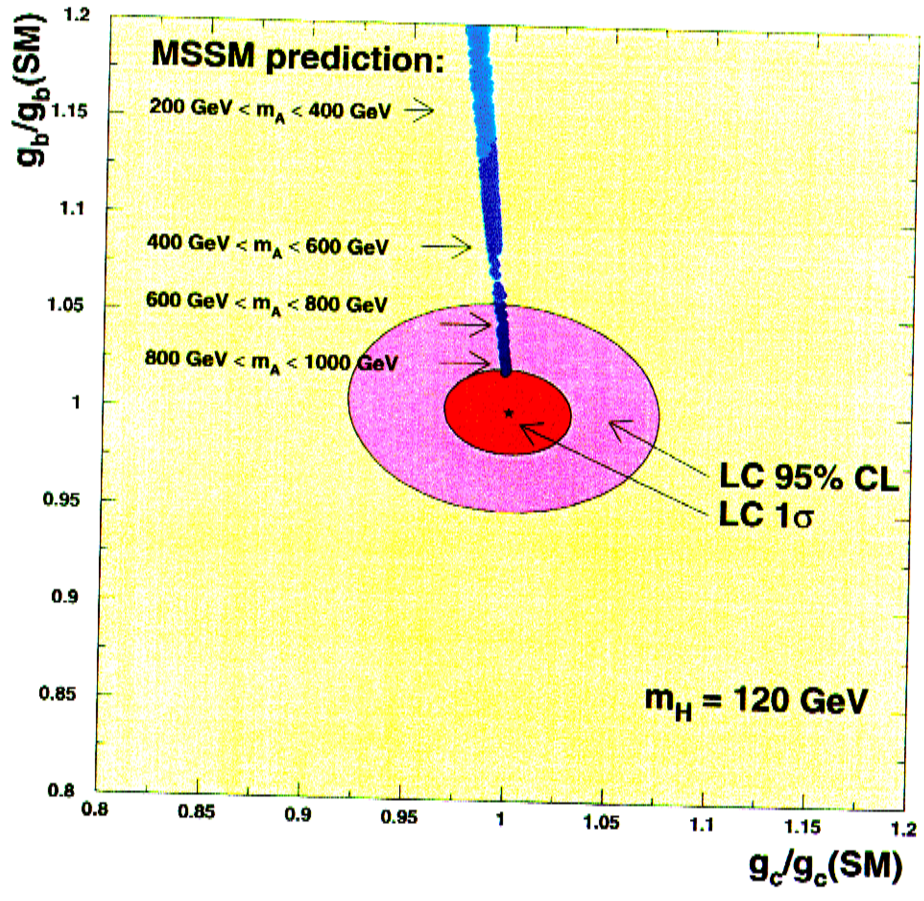
- framework needed to translate the entity of exp. measurements into model parameters ("couplings")
- ZFITTER very successful approach at LEP
- Let's build HFITTER
  - effort started
  - ideas from theory and experiment very welcome!

g_b vs. g_c

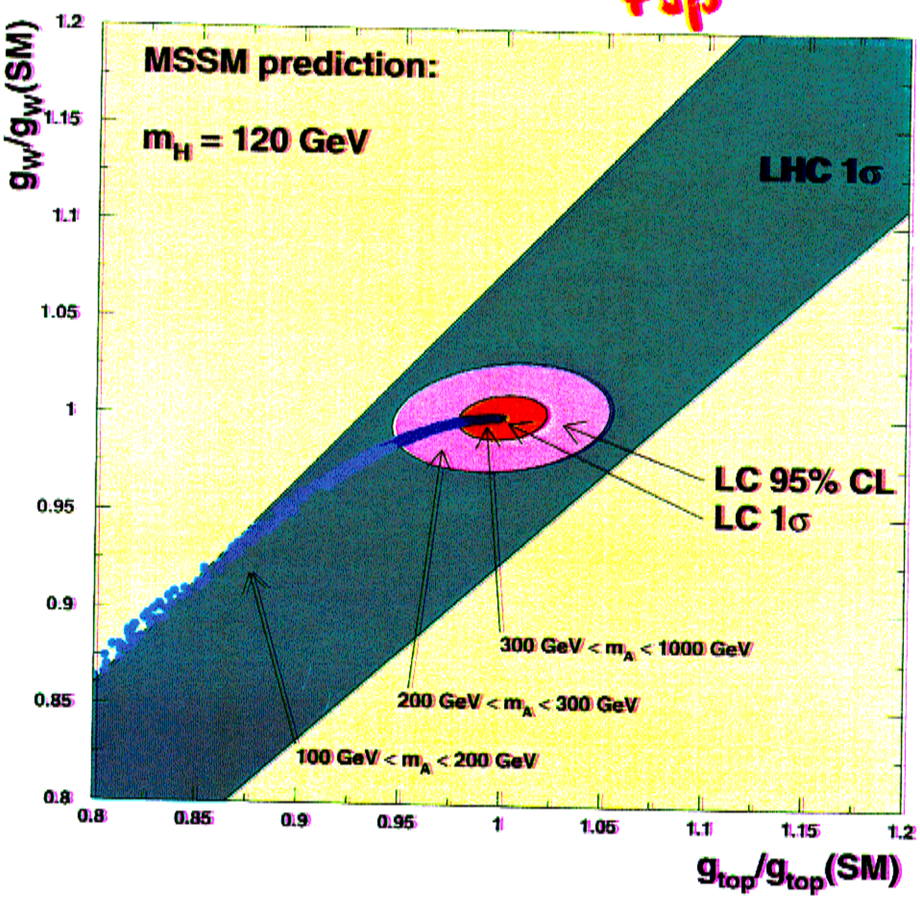
compare to MSSM prediction:

$g_{b,\tau} \sim \frac{\sin\alpha}{\cos\beta}$ $g_{c,t} \sim \frac{\cos\alpha}{\sin\beta}$ $g_{W,Z} \sim \sin(\beta-\alpha)$

- get $\alpha(m_A, \ldots)$ from 2-loop calculation (Heinemeyer, Hollik, Weiglein)



gw vs. gtop


MSSM prediction:
m_H = 120 GeV
LHC 1σ
LC 95% CL
LC 1σ
300 GeV < m_A < 1000 GeV
200 GeV < m_A < 300 GeV
100 GeV < m_A < 200 GeV
g_W/g_W(SM)
g_{top}/g_{top}(SM)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2

⑧ Conclusions

- preferred light Higgs scenario is proven to be confronted with precision tests at a linear collider

- many new/improved studies at this workshop → good !

- less preferred scenarios are slightly less studied (experimentally)

  → not so good !

- it might well be that
  - $m_H > 2m_Z$
  - H decays (partially) invisibly
  - more complicated Higgs sector (2HDM w/o SUSY, more singlets ...)
  - ...

→ **please join the club!**

the more experimental studies we have, the stronger we make our physics case.