

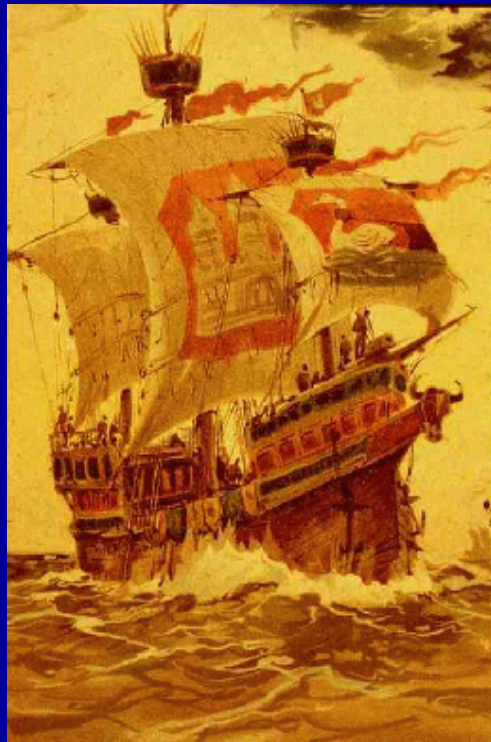
*10th International Conference on Supersymmetry
and Unification of Fundamental Interactions
June 17-23, 2002, DESY Hamburg*

The Higgs profile at the LC

from SM to SUSY

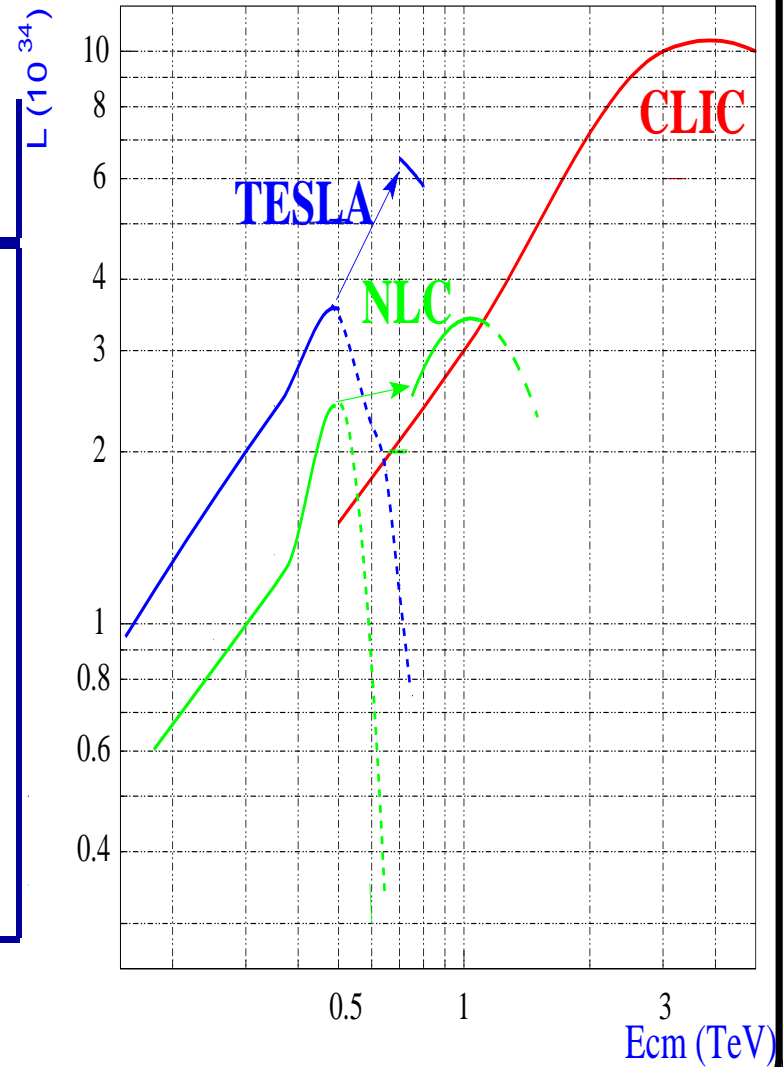
Marco Battaglia
CERN, Geneva, Switzerland

Linear Collider Projects and R&D



LC Project Parameters

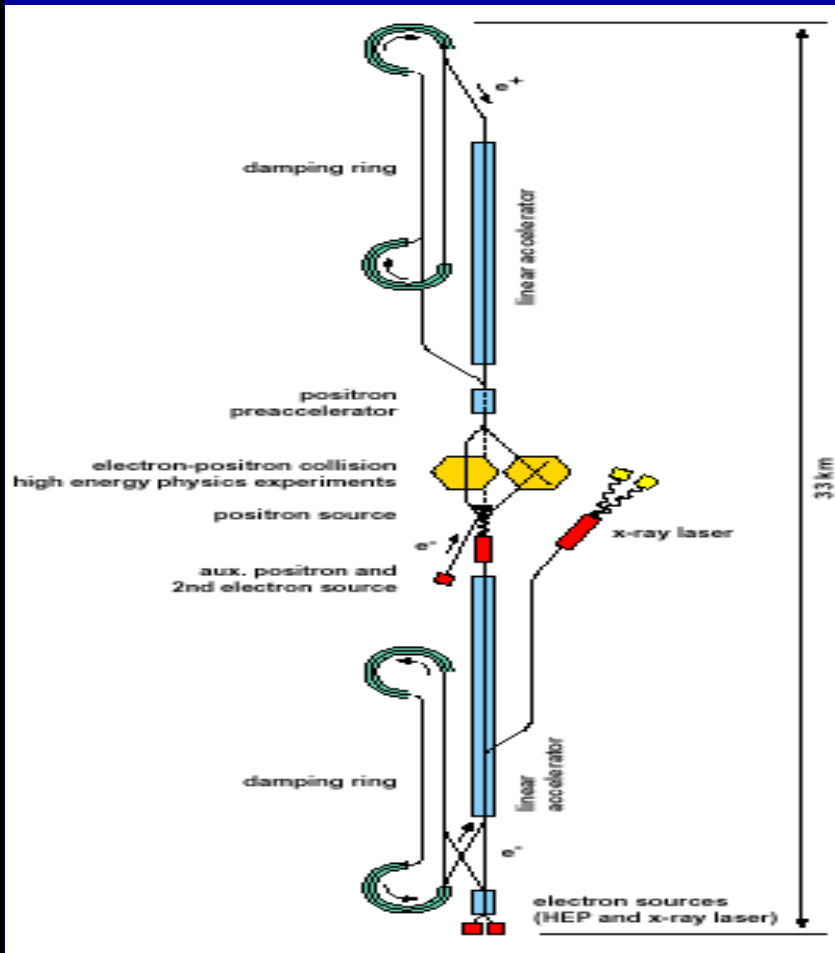
Parameters	TESLA SC	NLC Warm	CLIC TBA
\sqrt{s} (GeV)	500	500	3000
\mathcal{L} (10^{34} /cm ² s)	3.4	0.5-2.0	10.
RF (GHz)	1.3	11.3	30
f_{rep} (Hz)	5	120	200
N_b /Pulse	2820	95-190	154
Δt_b (ns)	337	2.8-1.4	0.67
σ_y/σ_z (n/ μ m)	5/300	4.6/120	1./30
Grad. (MV/m)	23.4	57-50	150
Length (km)	22/33	9/26	20/28



The TESLA Project

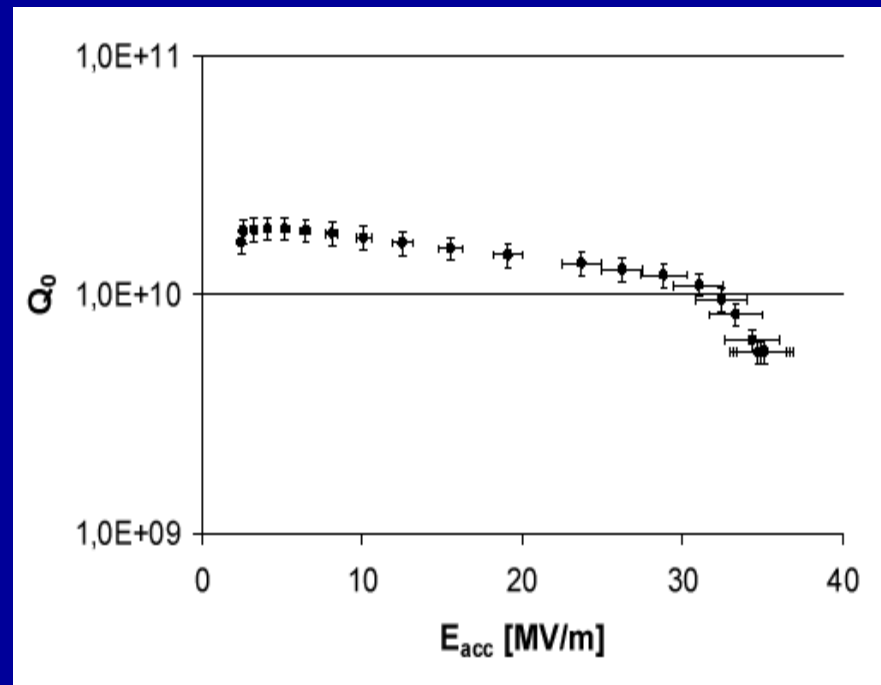


✧ Use of SC cavities offers high luminosity with more relaxed alignment requirements;



✧ Highest \sqrt{s} wrt Cavity Gradient:

500 GeV	23 MV/m	<i>Demonstrated</i>
800 GeV	35 MV/m	<i>R&D</i>

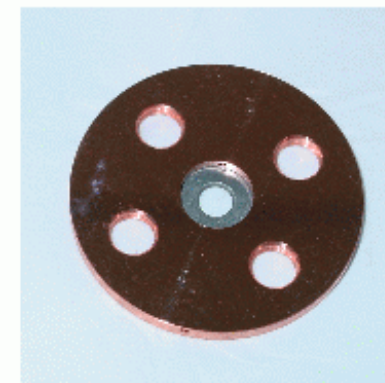
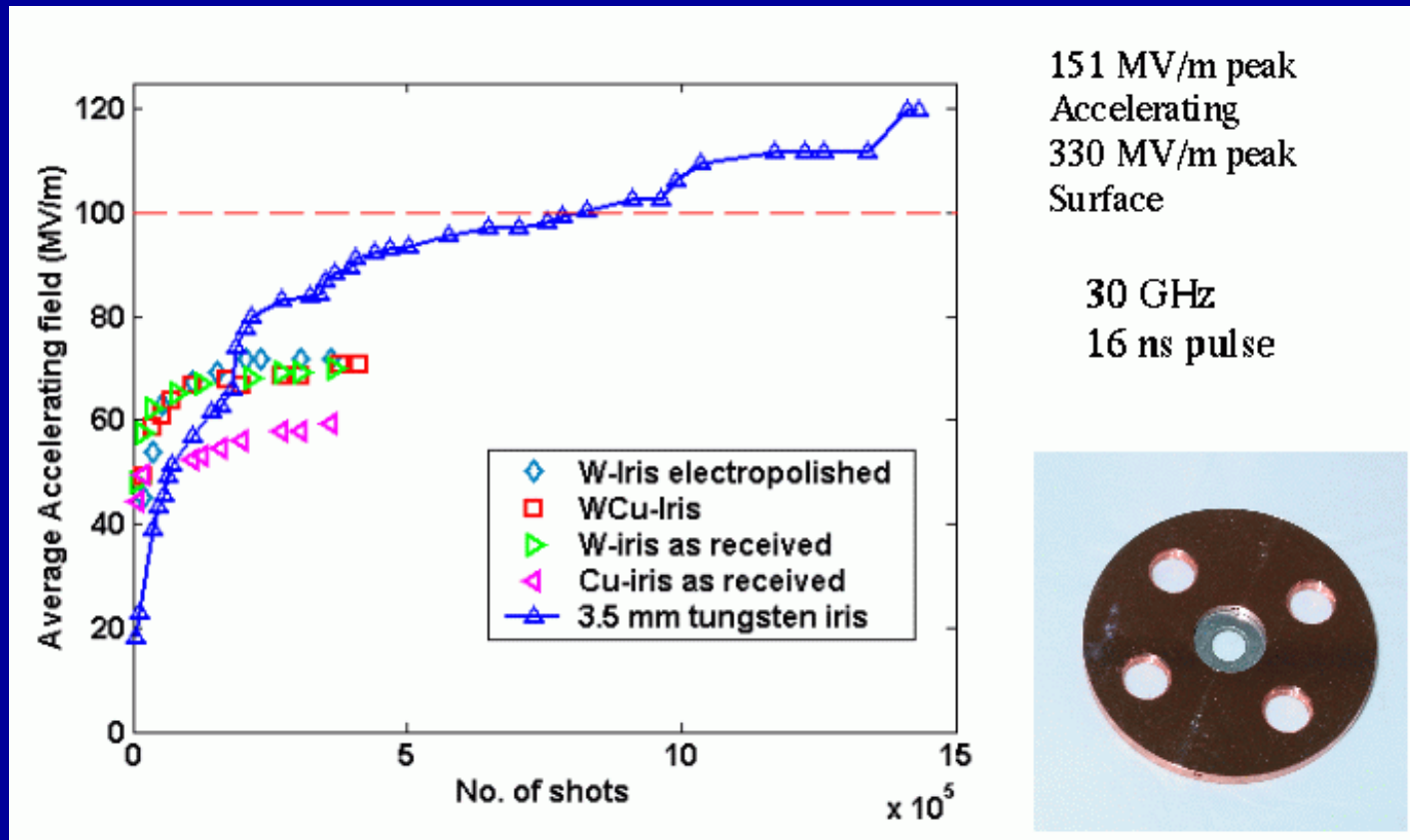


→ A.Wagner's Friday Lecture

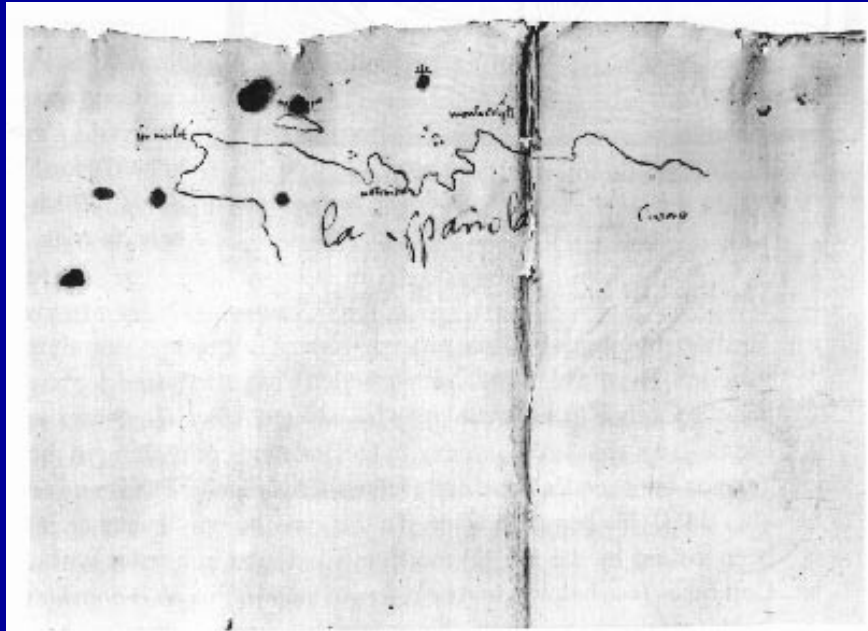
CLIC R&D towards Multi-TeV Collisions:



- ✧ Multi-TeV e^+e^- collisions will require efficient energy transfer at very high gradients;
- ✧ Two-beam acceleration scheme represents unique opportunity to extend the physics at e^+e^- colliders at constituent energies of the order of, and beyond, the LHC energy frontier.



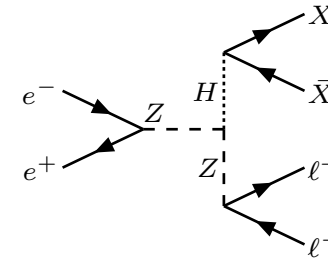
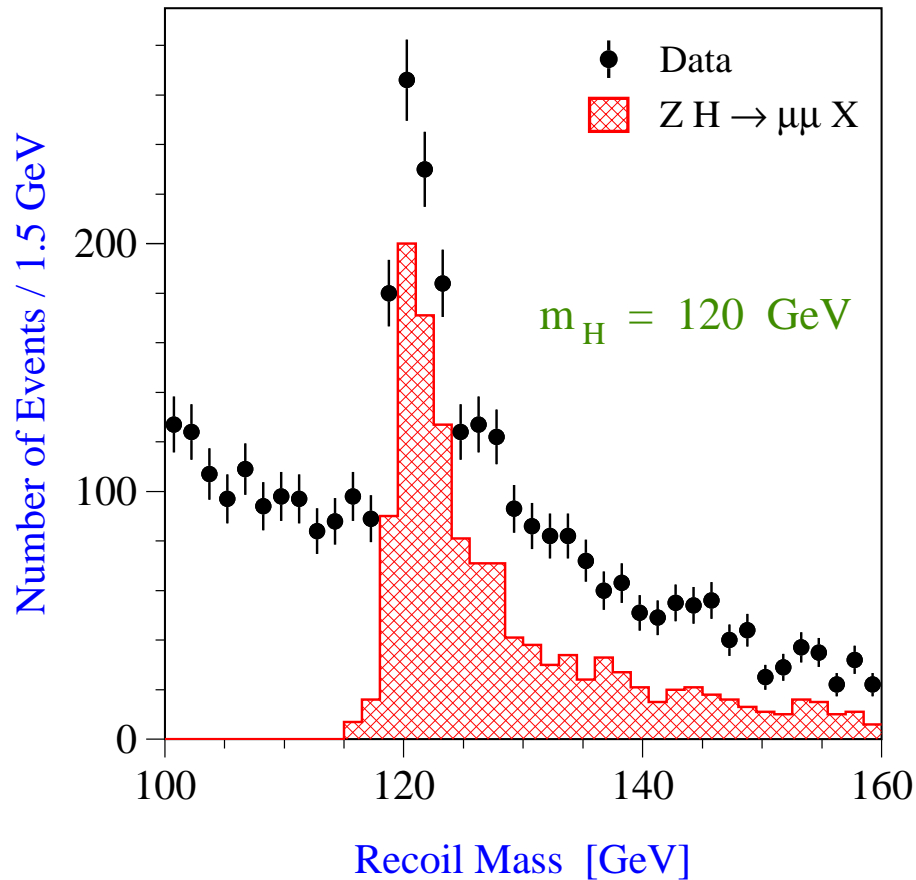
Observing the Higgs Boson



Columbus, 1492

Model Independent Higgs Boson Observation

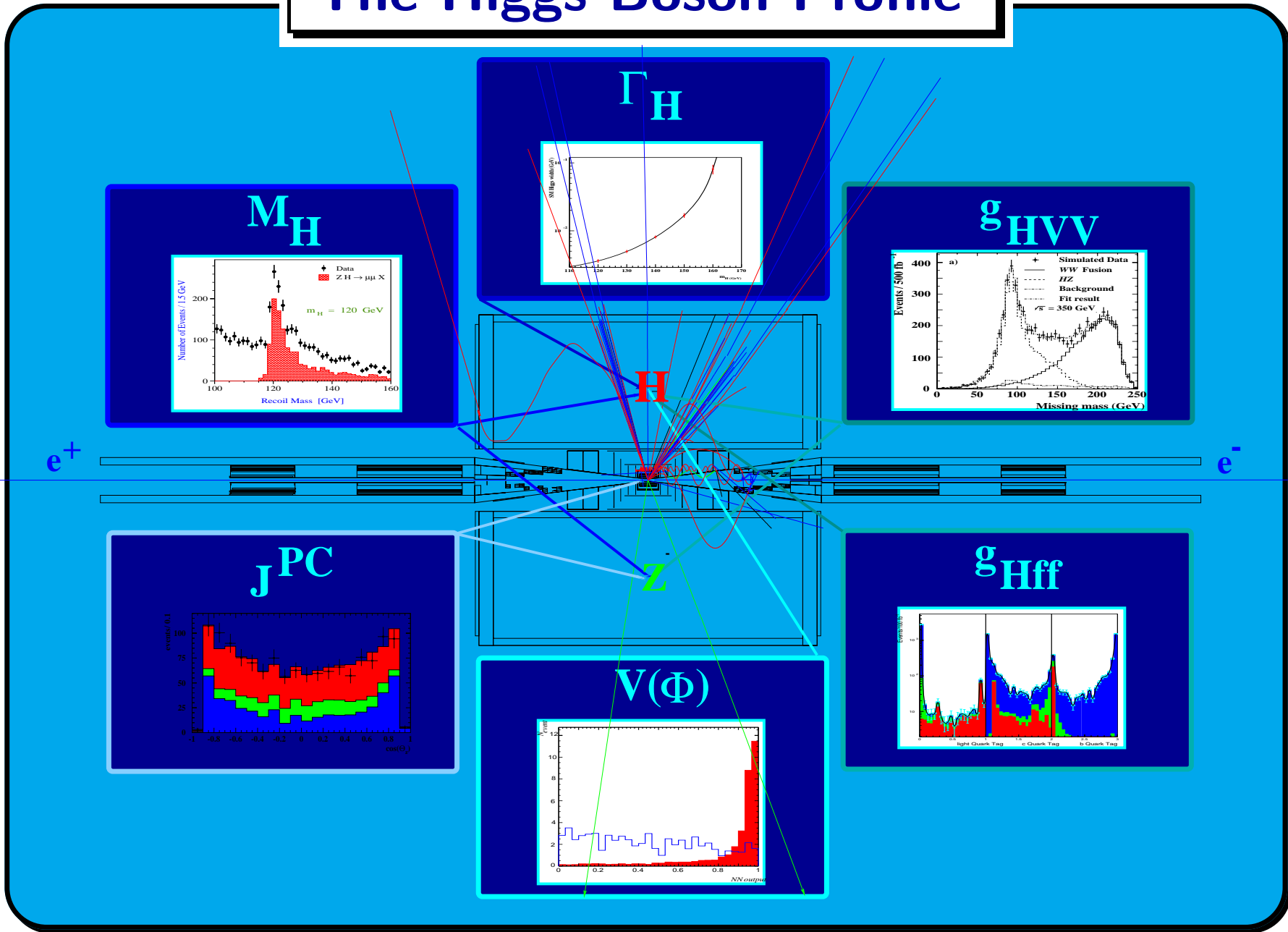
HIGGS SIGNAL
FROM RECOIL MASS TO $Z \rightarrow \mu^+ \mu^-$



NB. OF HIGGS BOSONS
OBSERVABLE AT LC IN 1.5 YEARS*
IN MODEL-INDEPENDENT WAY

M_H \sqrt{s}	350 GeV	500	800
120 GeV	4670	2020	740
160 GeV	3560	1780	685
200 GeV	2320	1500	645
250 GeV	230	1110	575
Max M_H	258	407	639

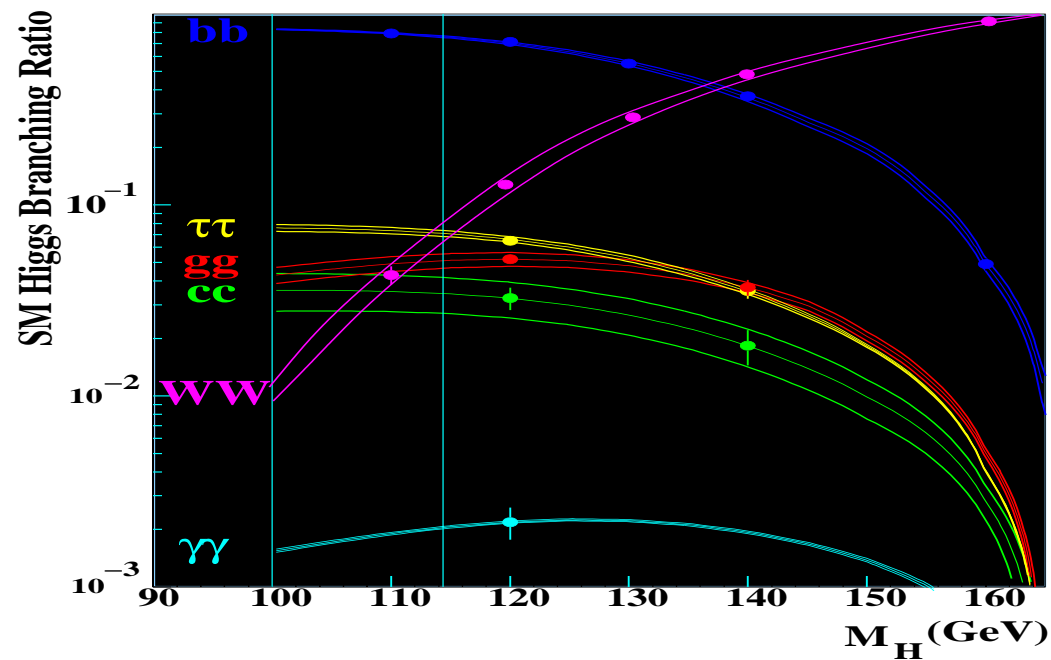
The Higgs Boson Profile



Probing the Higgs Mechanism

- ◆ LC has unique potential to verify that the Higgs boson does its job of providing gauge bosons, quarks and leptons with their masses;

$$\frac{g_{HXX}}{g_{HYY}} \propto \frac{M_X}{M_Y}$$



- ◆ Important to ensure sensitivity over wide mass range and a significant accuracy for all particle species.

Couplings to Gauge Bosons

$$\sigma_{e^+e^- \rightarrow HZ}$$

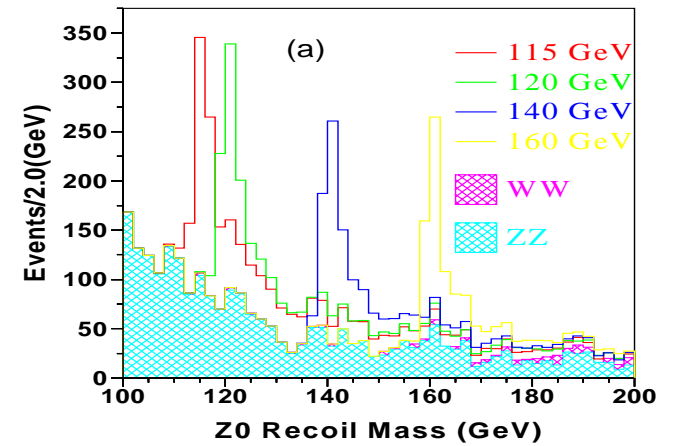
- ◆ Determination of Higgstrahlung cross-section to measure H coupling to Z and a key input to extract absolute BRs;
- ◆ use dilepton recoil mass from $Z^0 \rightarrow \ell^+\ell^-$ decay and impose beam-spot constraint to improve σ_p/p ;
- ◆ analysis is flavour blind and sensitive to non-standard decay modes such as $H \rightarrow$ invisible.

M_H GeV	Fit $\sigma_{HZ \rightarrow \ell^+\ell^-}$ (fb) /500 fb $^{-1}$	δ_{stat} % /500 fb $^{-1}$
120	$5.30 \pm 0.13(\text{stat}) \pm 0.12(\text{syst})$	± 2.4
140	$4.39 \pm 0.12(\text{stat}) \pm 0.10(\text{syst})$	± 2.7
160	$3.60 \pm 0.11(\text{stat}) \pm 0.08(\text{syst})$	± 3.0

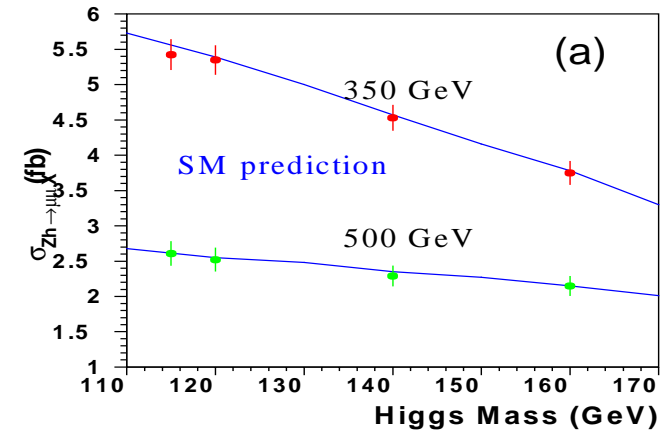
P Garcia et al. LC-PHSM-2001-054, T Abe et al. hep-ex/0106056

$\ell\ell$ RECOIL MASS

FOR $e^+e^- \rightarrow Z^0 H^0 \rightarrow \ell^+\ell^- X$
NLC at 350 GeV ($\mu^+\mu^- X$)



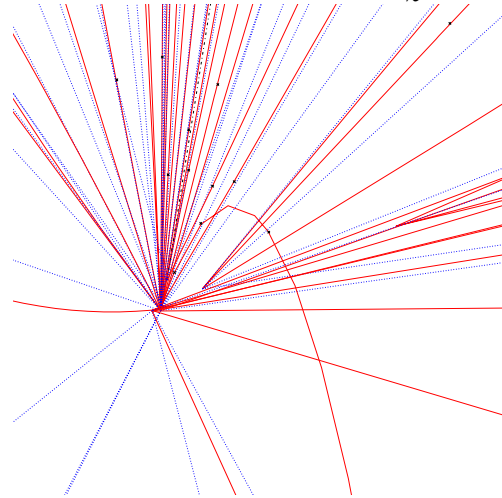
$e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^- X$



Couplings to Gauge Bosons

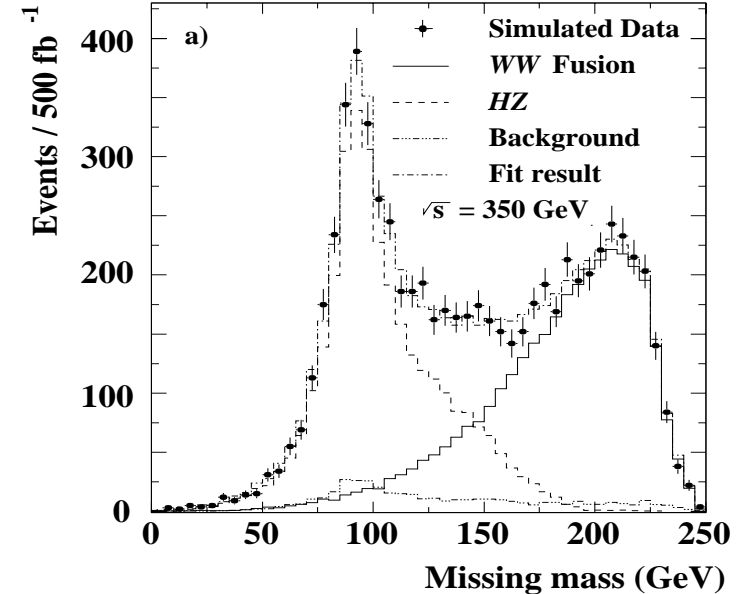
$$\sigma_{e^+e^- \rightarrow WW\nu\bar{\nu} \rightarrow H\nu\nu}$$

- ◆ Determination of WW -fusion reaction $\sigma_{e^+e^- \rightarrow WW\nu\bar{\nu} \rightarrow H\nu\bar{\nu}}$ to measure H coupling to W and a key input to extract Γ_H ;
- ◆ Select b -tagged hadronic events with large E_{miss}, M_{miss} at $\sqrt{s} = 350$ GeV;
- ◆ Extract $\sigma_{H\nu\nu}$ from χ^2 fit to missing mass distribution:
- ◆ Overlapped $\gamma\gamma \rightarrow$ hadrons bkg. suppressed by i.p. analysis if $\sigma_z^{beam} \gg \sigma_z^{ip}$



JET-JET MISSING MASS

FOR $e^+e^- \rightarrow H^0\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$



K.Desch, N.Meyer, LC-PHSM-2001-025

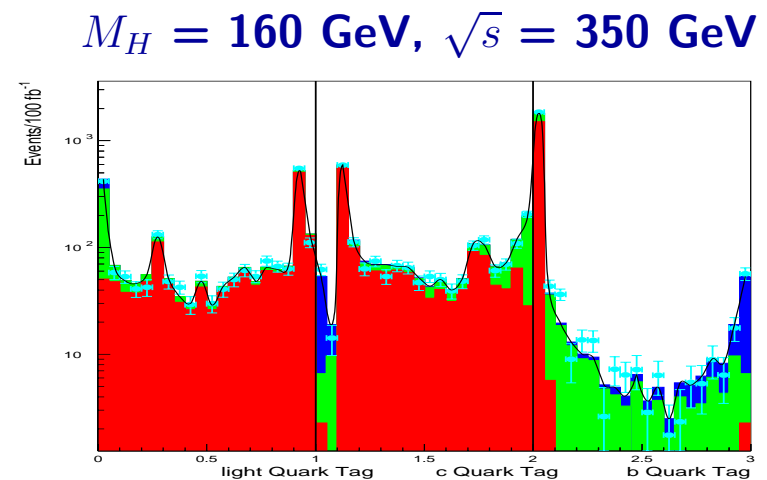
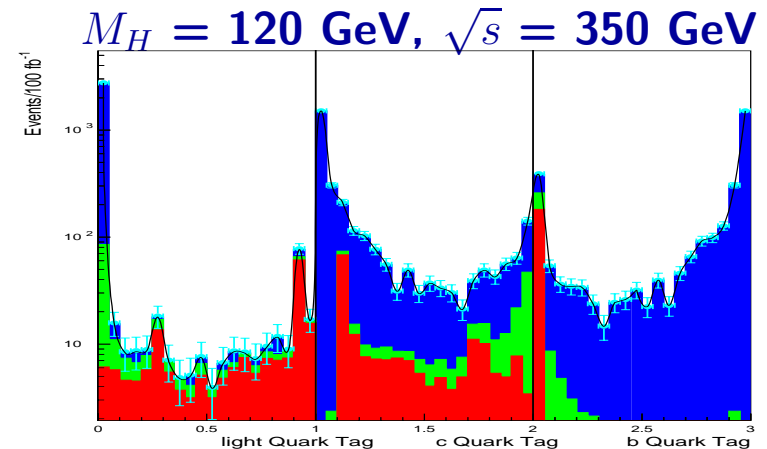
M_H GeV	Fitted Evt. / 500 fb ⁻¹	$\frac{\delta(\sigma_{H\nu\nu})}{\sigma_{H\nu\nu}}$ / 500 fb ⁻¹
120	3423 ± 83	± 2.6 %
140	1330 ± 71	± 5.3 %
150	663 ± 66	± 10.3 %

The Generation of Mass

The Quark Sector

- Compute $u\bar{u} + d\bar{d} + s\bar{s}$, $c\bar{c}$ and $b\bar{b}$ di-jet flavour tagging probs
- Fit hadronic branching fractions:
 - $\text{BR}(H \rightarrow b\bar{b})/\text{BR}(H \rightarrow \text{hadrons})$,
 - $\text{BR}(H \rightarrow c\bar{c})/\text{BR}(H \rightarrow \text{hadrons})$
 - $[\text{BR}(H \rightarrow gg)/\text{BR}(H \rightarrow \text{had.})]$
 - $[\text{BR}(H \rightarrow WW)/\text{BR}(H \rightarrow \text{had.})]$
- binned likelihood fit to bkg subtracted di-jet probs:

$\text{BR}(H(120) \rightarrow X)$	$\delta\text{BR}/\text{BR}$
$b\bar{b}$	0.024
$c\bar{c}$	0.085
gg	0.055

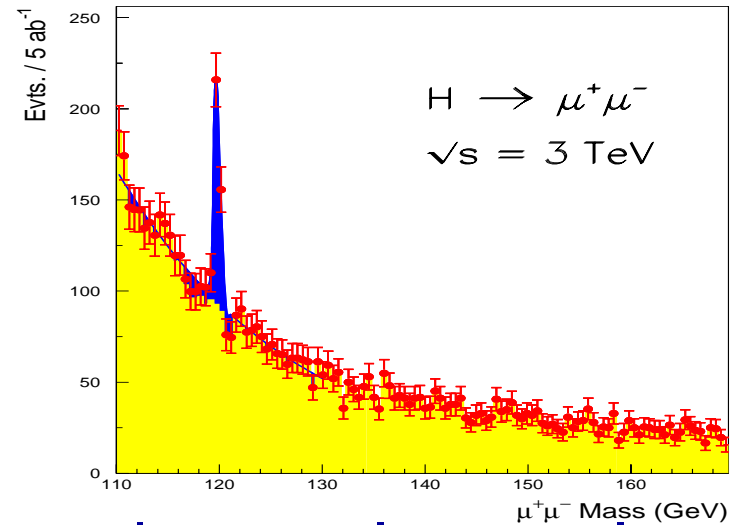
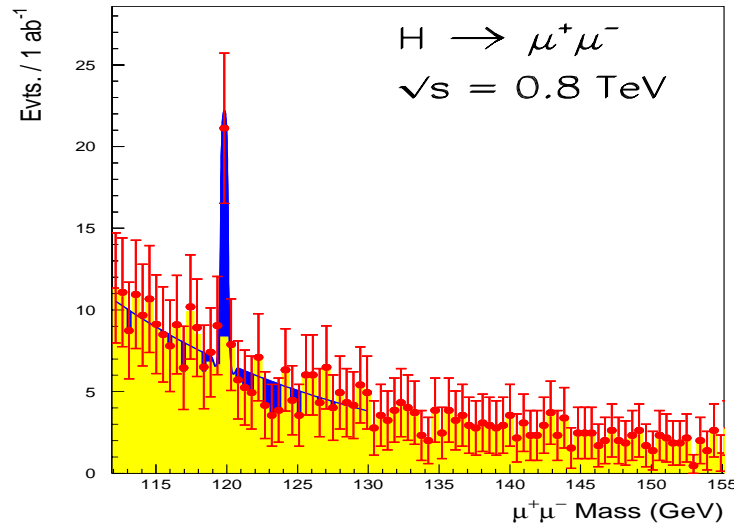


M B hep-ph/9910271
 JC Brient, LC-PHSM-2002-003
 J Brau et al, Snowmass 2001 Proceedings

The Generation of Mass

The Lepton Sector

- ✧ $BR(H \rightarrow \tau^+\tau^-)$ with τ -id based on multiplicity and kinematics;
- $BR(H \rightarrow \mu\mu)$ observable as **rare decay** at TeV-class and multi-TeV LC;



M_H	120 GeV	140 GeV	150 GeV
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (at 0.5 TeV)	0.027	0.050	
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (at 0.8 TeV)	0.150	-	-
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (at 3.0 TeV)	0.035	0.060	0.105

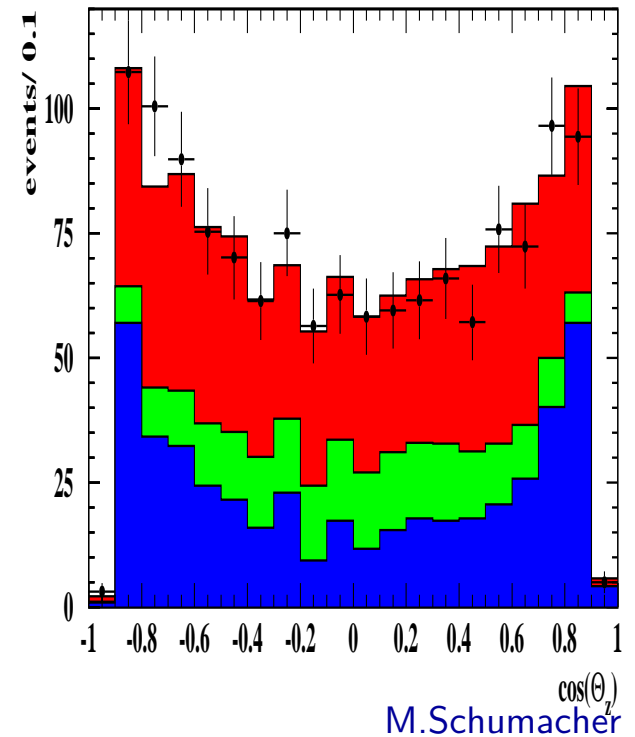
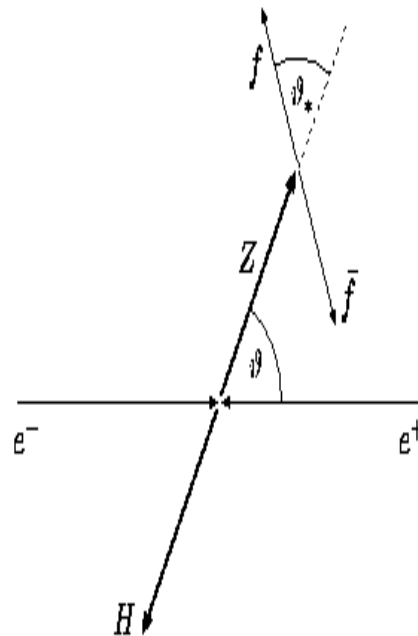
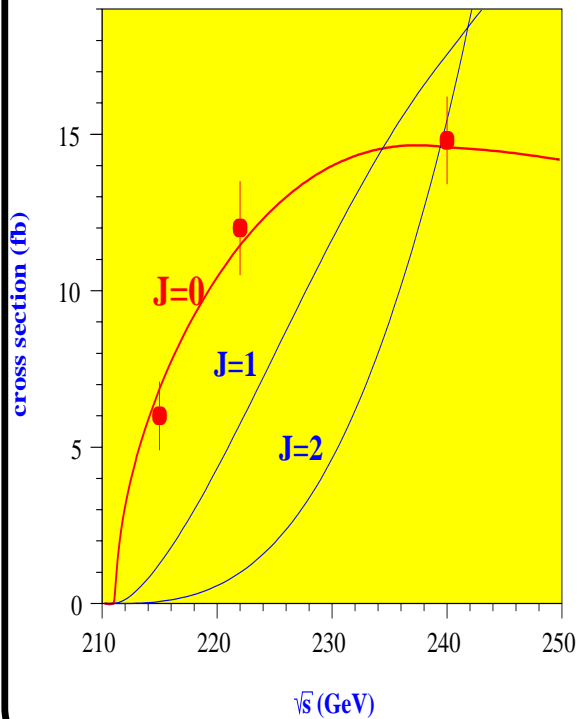
M B, hep-ph/9910271 and JC Brient, LC Note

M B and A De Roeck, hep-ph/0111307

- ✧ Test $g_{H\mu\mu}/g_{H\tau\tau}$ coupling ratio to **0.05-0.08** accuracy at multi-TeV LC, compared to **0.03-0.04** at FMC for $120 < M_H < 140 \text{ GeV}$.

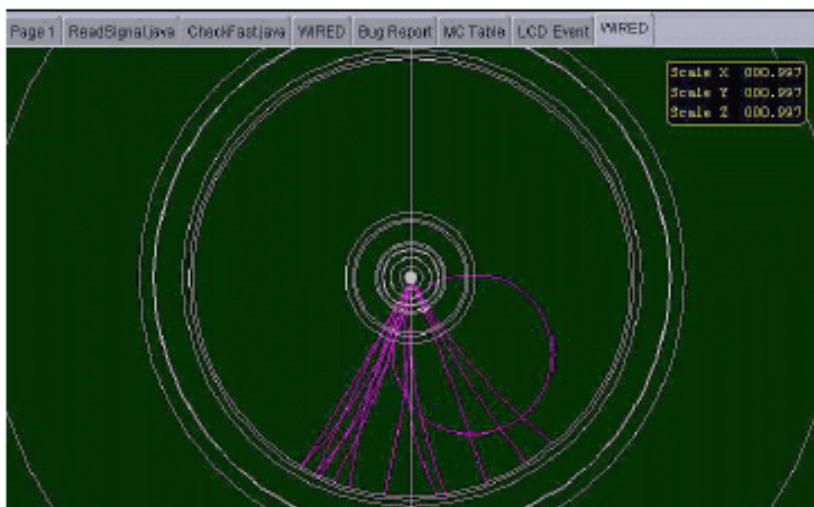
Higgs Quantum Numbers

- ◆ Spin, parity and charge-conjugation quantum numbers J^{PC} of Higgs bosons can be determined at LC in model-independent way.
- ◆ Observation of $\gamma\gamma \rightarrow H$ or $H \rightarrow \gamma\gamma$ sets $J \neq 1$ and $C = +$.
- ◆ Angular dependence $\frac{d\sigma_{ZH}}{d\theta} \propto \sin^2 \theta$ and rise of $\sigma_{ZH} \propto \beta \sim \sqrt{s - (M_H + M_Z)^2}$ allows to determine $J^P = 0^+$ and distinguish SM H from CP -odd 0^{-+} state A , or a CP -violating mixture.

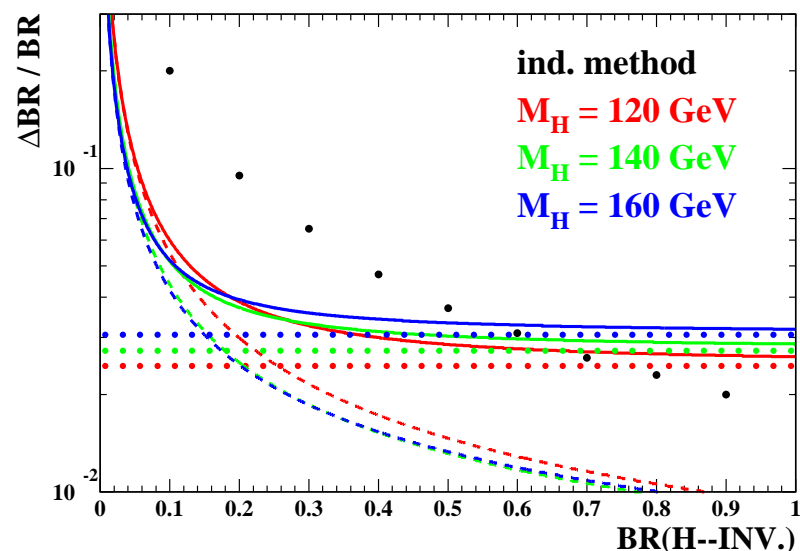


Invisible Decay Modes

- ✧ Several theoretical models motivate this analysis (possibly SUSY decays $\chi^0\chi^0$, but also signature from radion-Higgs mixing, stealth models, ...).
- ✧ Invisible Higgs decays detectable from visible decay modes (indirect) and analysis of system recoiling against the Z in $e^+e^- \rightarrow HZ$ (direct);



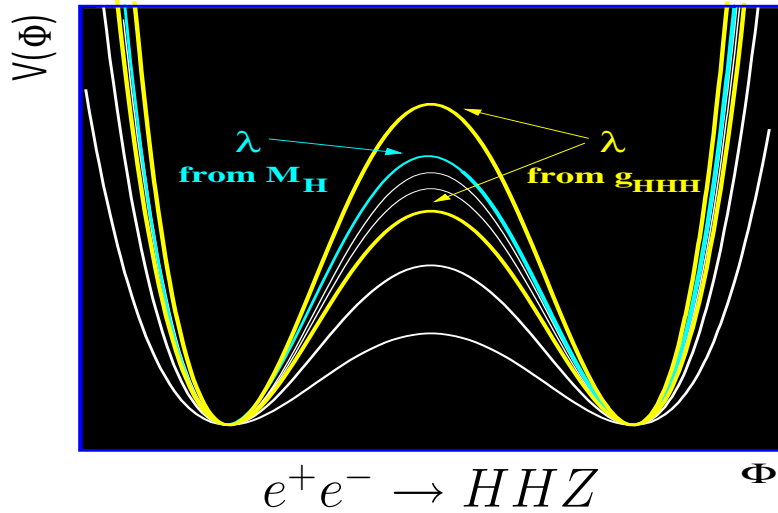
R van Kooten and M Schumacher



- ✧ Preferable to perform analysis at low \sqrt{s} to reduce bkg. (ZZ , WW)

Reconstruction of the Higgs Potential

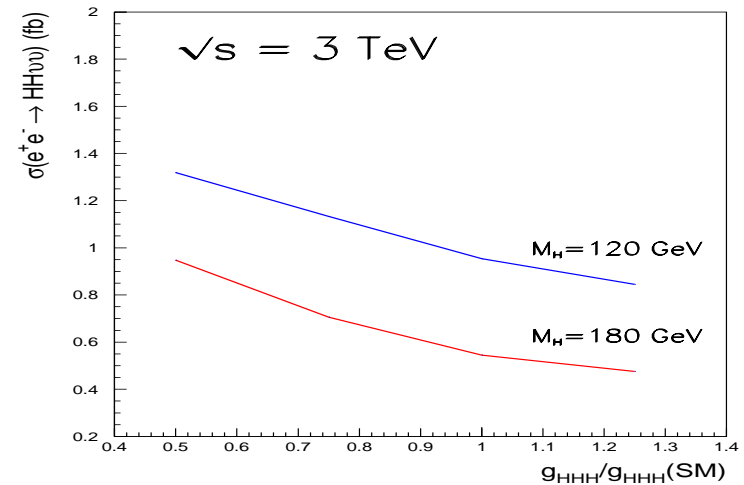
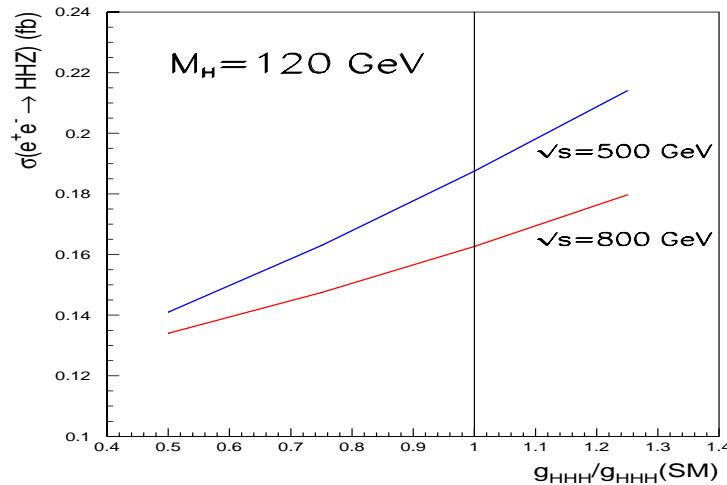
- ◆ Fundamental test of **shape of Higgs potential** through independent determination of g_{HHH} in double Higgs production (HHZ and $H\nu\nu$):



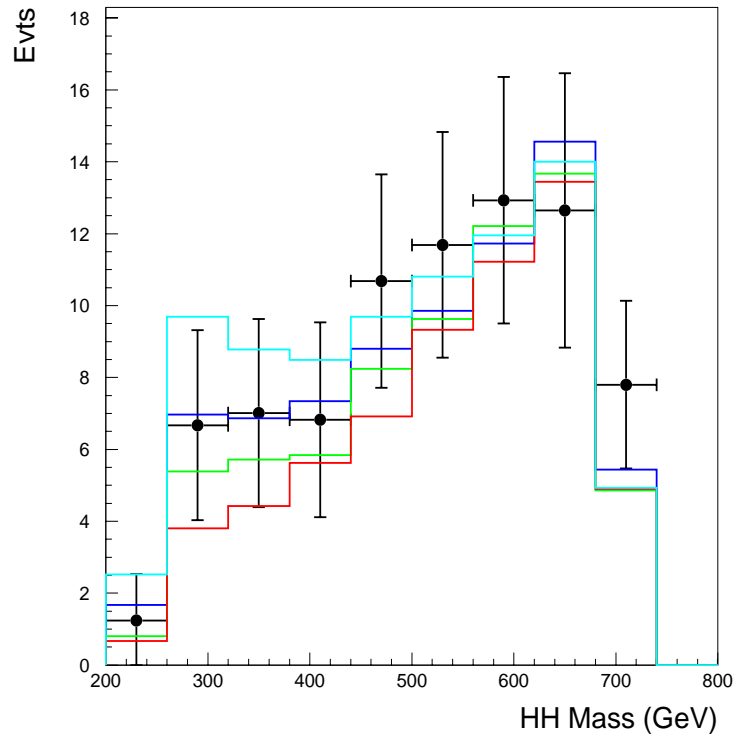
$$V(\Phi^*\Phi) = \lambda(\Phi^*\Phi - \frac{1}{2}v^2)^2$$

$$g_{HHH} = \frac{3}{2} \frac{M_H^2}{v}$$

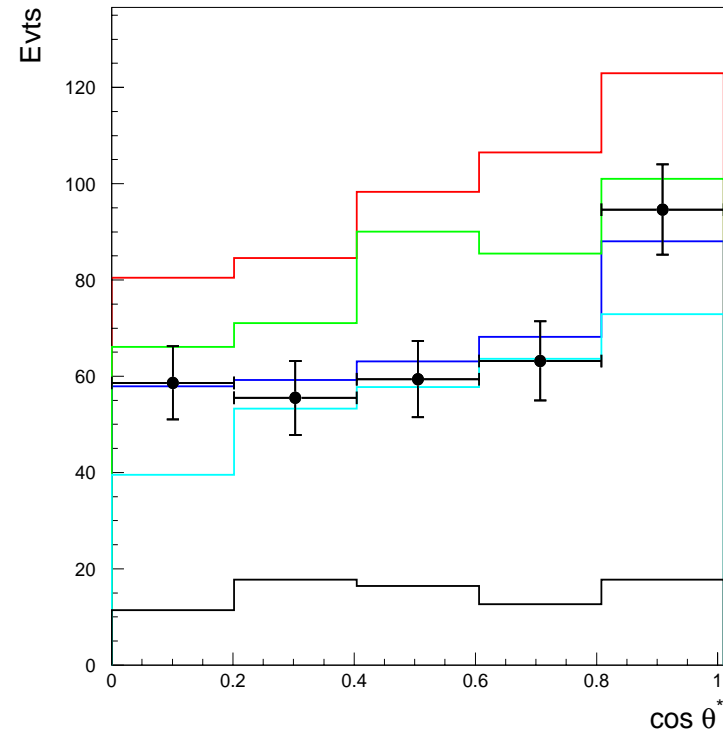
$$e^+e^- \rightarrow HH\nu\nu$$



0.5-0.8 TeV LC for $M_H = 120$



5 TeV CLIC for $M_H = 120-180$

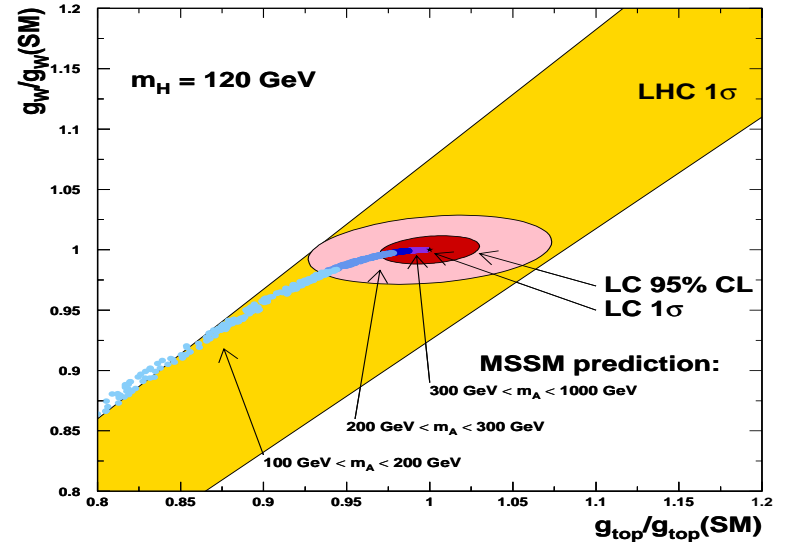
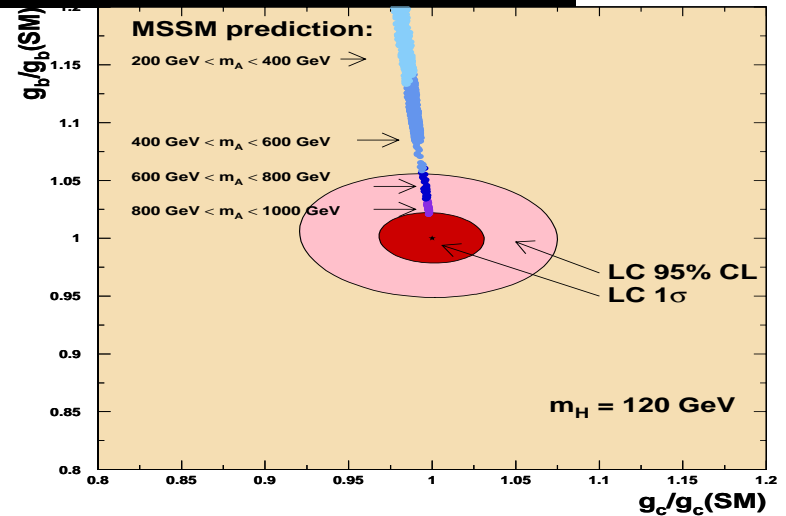


\sqrt{s} (TeV)	Counting	Fit	M_H (GeV)	Fit
0.5	± 0.23 (stat)	± 0.20 (stat)	120	± 0.075 (stat)
0.8	± 0.35 (stat)	± 0.29 (stat)	180	± 0.082 (stat)

C Castanier et al. hep-ex/0101028, M B et al. hep-ph/0111276

Precision Investigation of the Higgs Profile at a TeV-LC

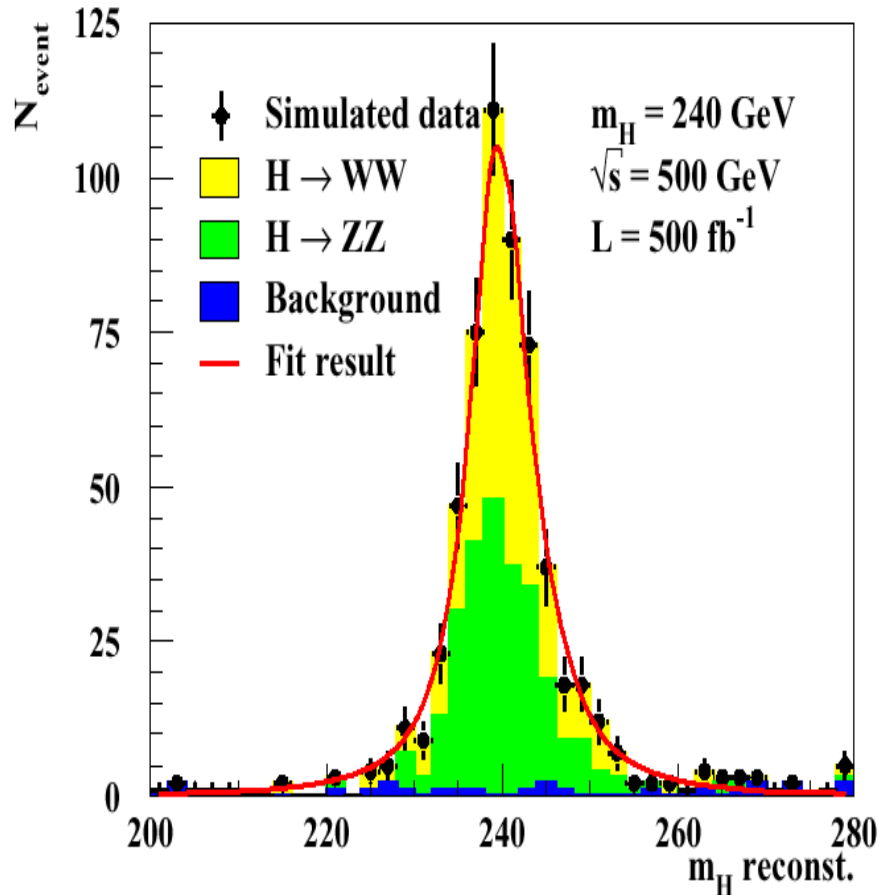
	M_H (GeV)	$\delta(X)/X$ LC-500-LC-3000 $0.5ab^{-1}$ - $5ab^{-1}$
M_H	120-180	$(3-5) \times 10^{-4}$
Γ_{tot}	120-140	0.04-0.06
g_{HWW}	120-160	0.01-0.03
g_{HZZ}	120-160	0.01-0.02
g_{Htt}	120-140	0.02-0.06
g_{Hbb}	120-160	0.01-0.03
g_{Hcc}	120-140	0.03-0.10
$g_{H\tau\tau}$	120-140	0.03-0.05
$g_{H\mu\mu}$	120-140	0.15 - 0.04-0.06
CP test	120	0.03
g_{HHH}	120	0.20 - 0.07



M B, K Desch hep-ph/0101165

What if the Higgs is heavier ?

- ✧ Analyse $HZ \rightarrow \ell^+ \ell^-$, $q\bar{q}$ recoil mass at 500 GeV and $H\nu\bar{\nu}$ at 800 GeV;
- ✧ Extract M_H , Γ_H and σ from fit to recoil mass, $H \rightarrow WW$ and ZZ branching fractions from fit to jet-jet mass in HZ and $H \rightarrow b\bar{b}$ in $H\nu\bar{\nu}$:



	M_H GeV	$\delta X/X$ LC-500/800 0.5/1 ab^{-1}
M_H	240	9×10^{-4}
Γ_H	240	0.12
$\sigma(e^+e^- \rightarrow HZ)$	240	0.04
$\text{BR}(H \rightarrow ZZ)$	240	0.10
$\text{BR}(H \rightarrow WW)$	240	0.07
$\text{BR}(H \rightarrow b\bar{b})$	200	0.16
$\text{BR}(H \rightarrow b\bar{b})$	220	0.27

N.Meyer, K.Desch, M.B. LC Notes in preparation

An Extended Higgs Sector

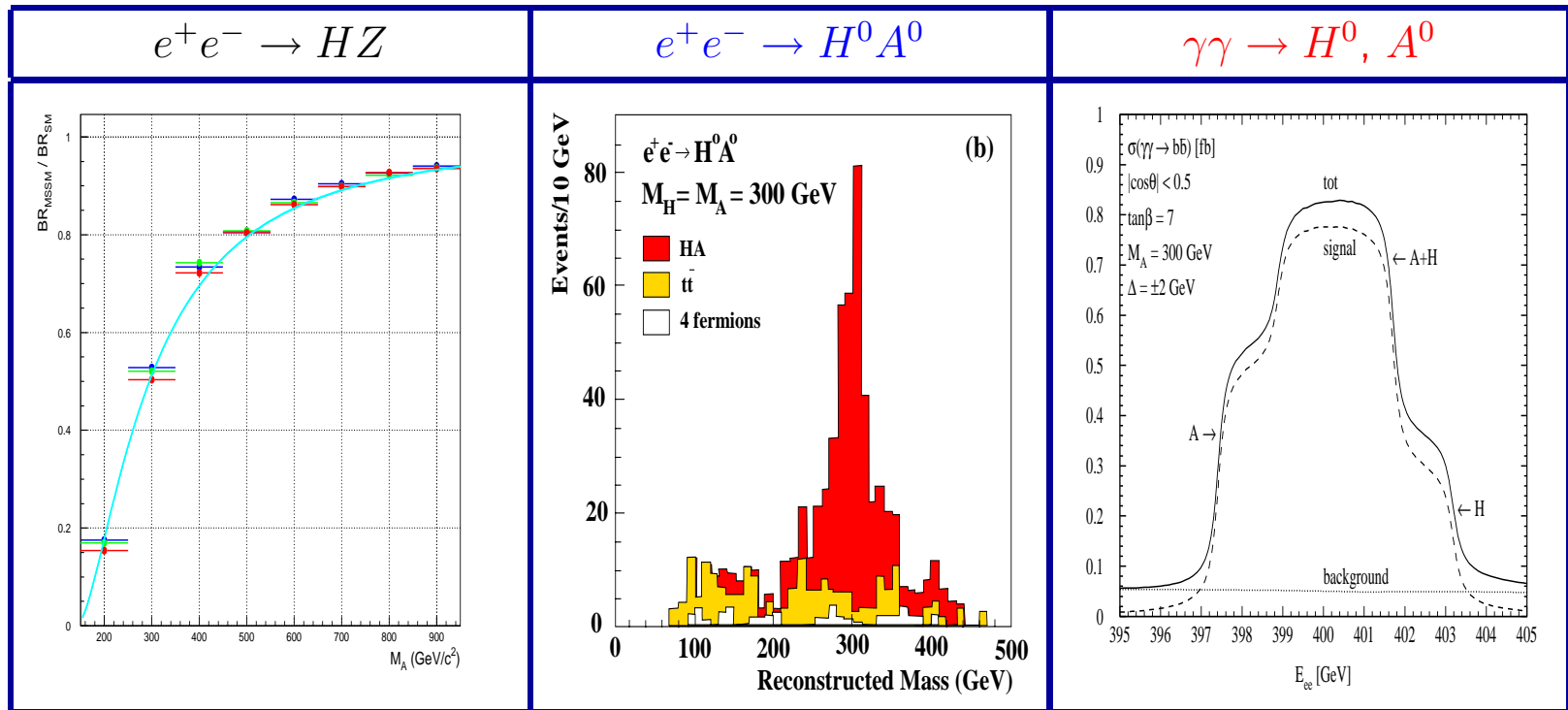


Blaeu, 1635

The Nature of the Higgs Boson

Indirect sensitivity to SUSY Higgs through highly accurate determinations of neutral Higgs boson couplings;

Direct observation of heavy Higgs bosons produced in e^+e^- and $\gamma\gamma$ collisions at LC and **study of their properties**:



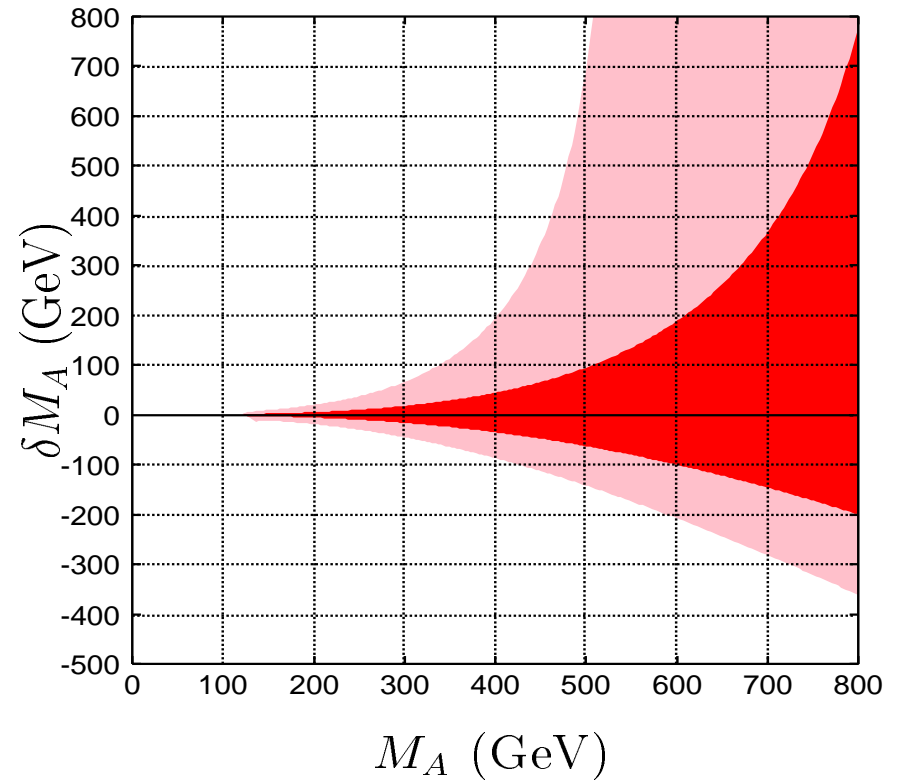
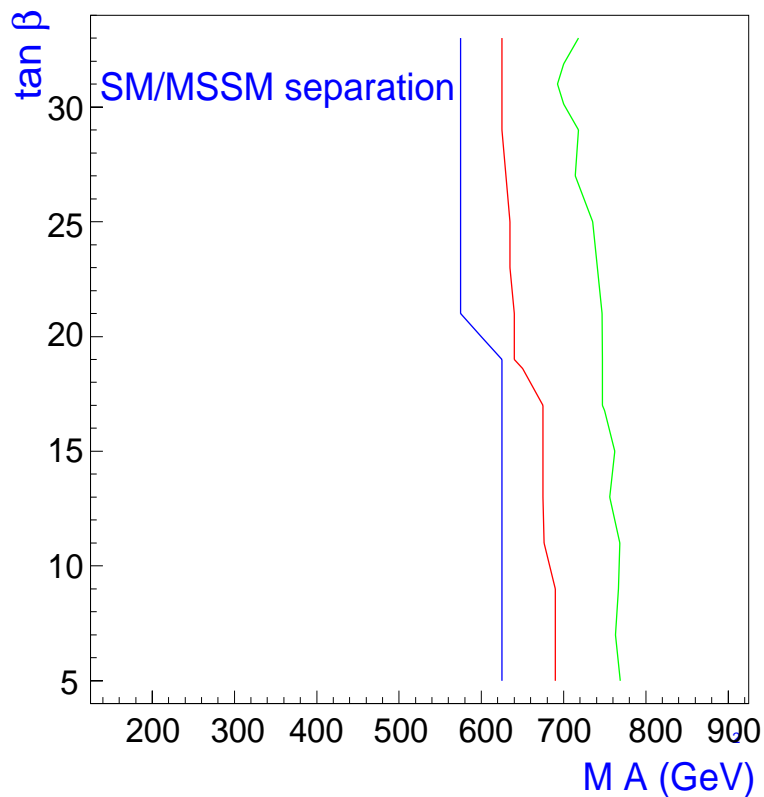
Telling the SM H^0 from a SUSY h^0

✧ Higgs couplings to fermions may reveal his SM or SUSY nature:

$$\frac{g_{Hf\bar{f}}}{g_{Hf'f'}} \propto \frac{m_f}{m_{f'}}$$

✧ in SUSY couplings to up-like and down-like fermions shifted w.r.t. their SM predictions:

$$\frac{BR(h \rightarrow f_u \bar{f}_u)}{BR(h \rightarrow f_d \bar{f}_d)} \propto \frac{1}{\tan^2 \alpha \tan^2 \beta} \simeq \frac{(M_h^2 - M_A^2)^2}{(M_Z^2 + M_A^2)^2}$$

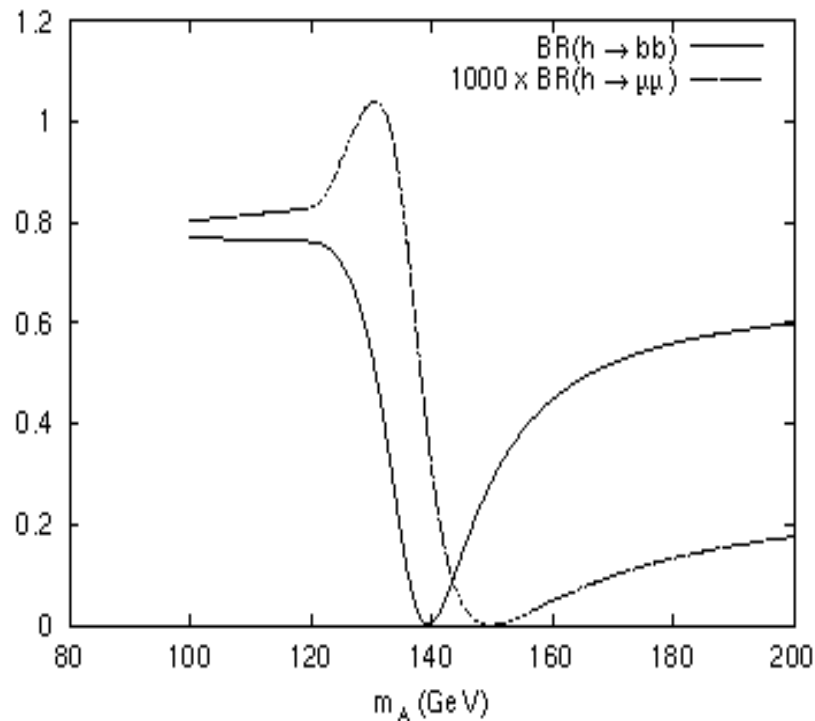


✧ iSUSY sbottom-gluino and stop-higgsino loops induce a shift of the effective b -quark mass in the hbb couplings:

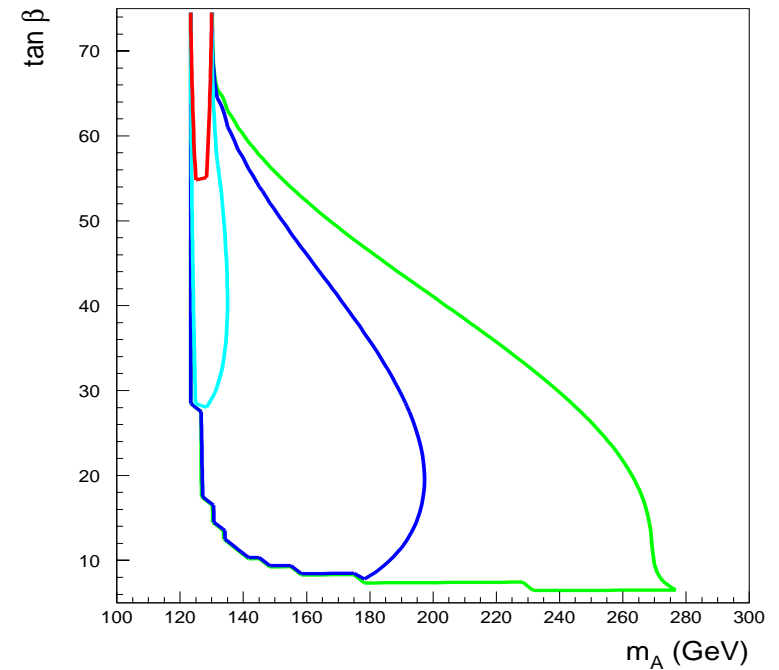
$$\Delta m_b \propto \mu M_{\tilde{g}} \tan \beta f(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}})$$

$BR(h \rightarrow b\bar{b}, \mu\mu)$ vs. M_A

$BR(h \rightarrow \mu\mu)/BR_{SM}$

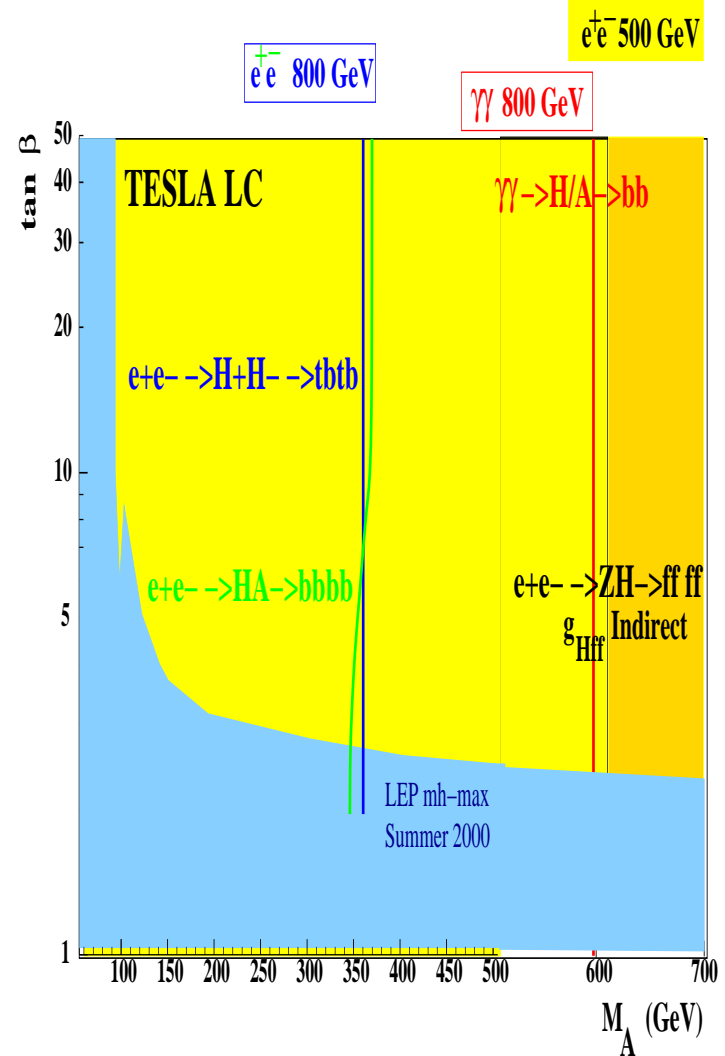
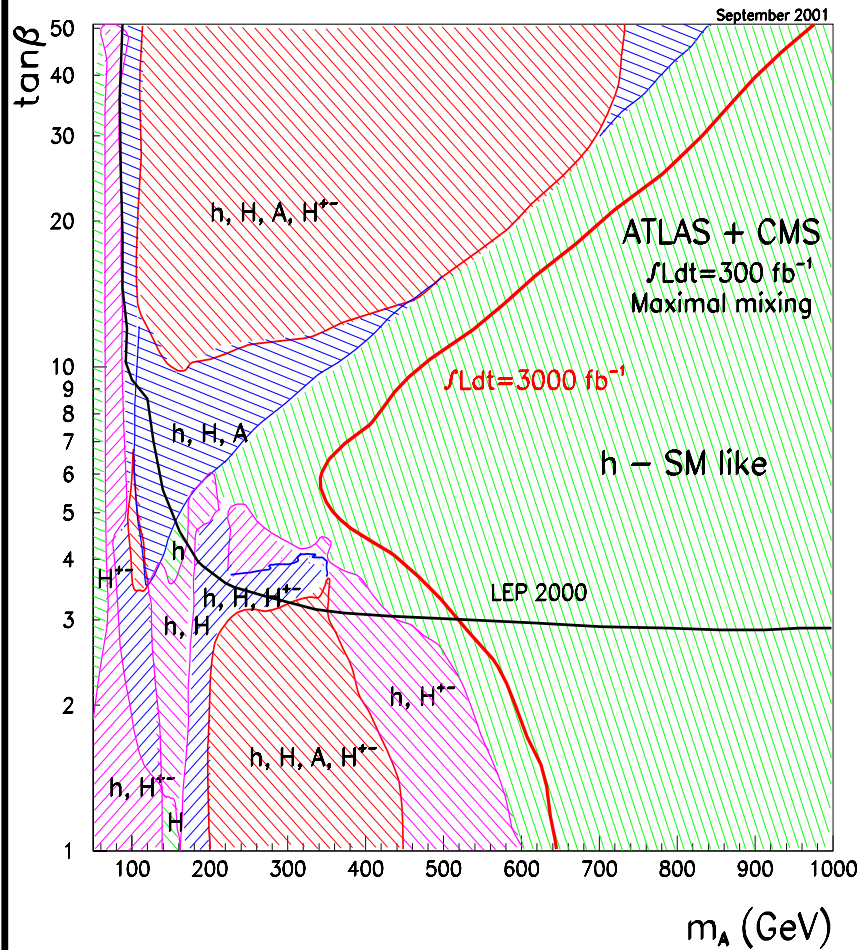


M.Carena



M.B., M.Spira

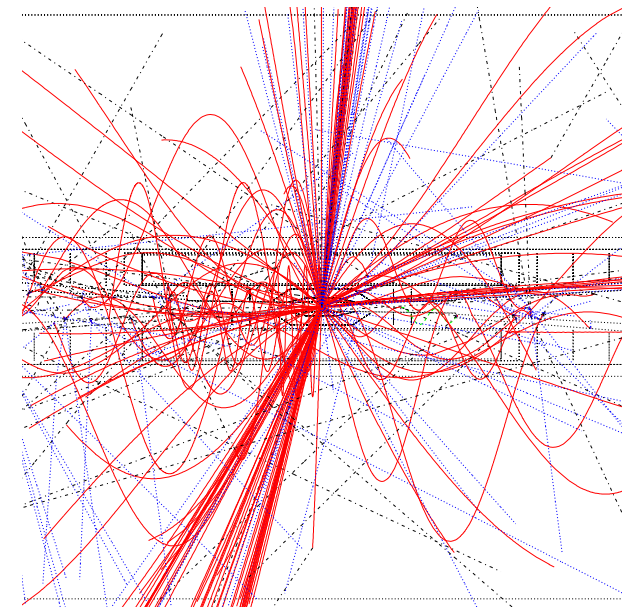
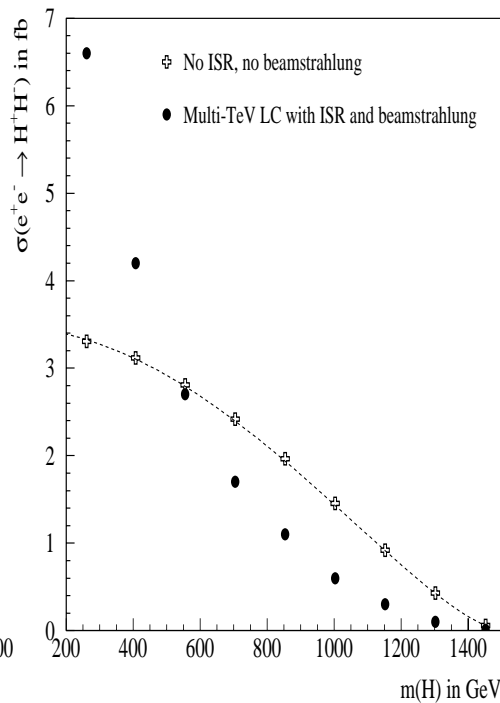
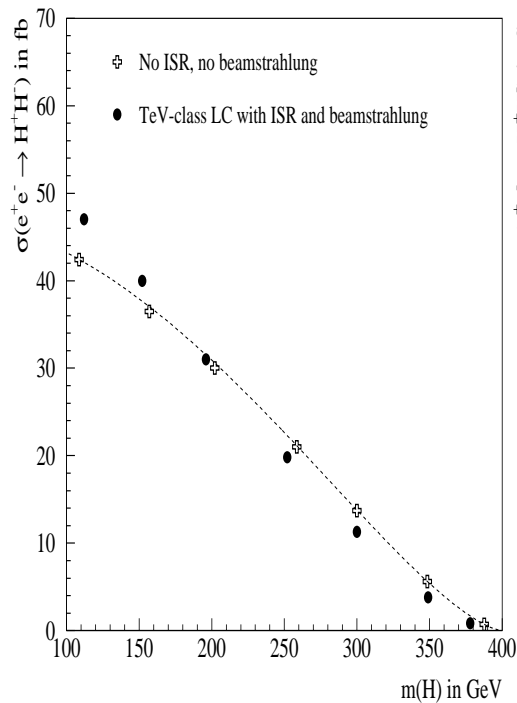
MSSM Higgs Sector at LHC and TeV-class LC



Charged Higgs Bosons H^\pm

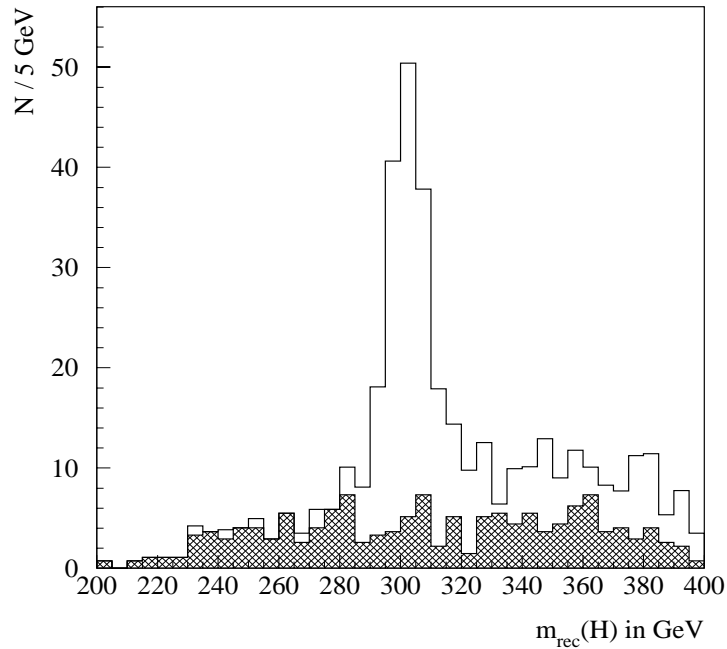
- ✧ Production cross section at threshold $\propto \beta^3$ and independent on model parameters;
- ✧ Main decay mode above threshold $H^- \rightarrow \bar{t}b$ results in challenging multi-jet final state:

$$H^+H^- \rightarrow t\bar{t}b\bar{b} \text{ AT 3 TEV}$$

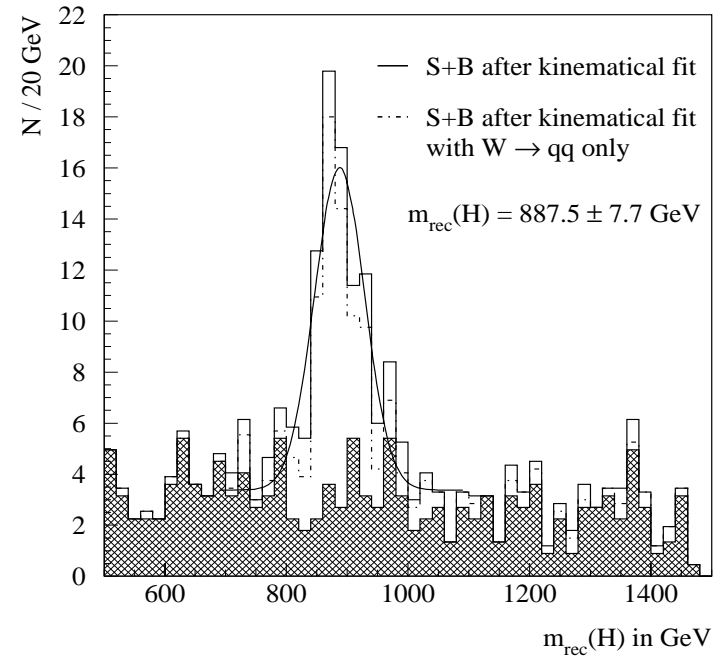


→ S.Kraml's Parallel Talk on Thursday

$\sqrt{s} = 0.8 \text{ TeV}$
 $M_{H^\pm} = 300 \text{ GeV}$



$\sqrt{s} = 3.0 \text{ TeV}$
 $M_{H^\pm} = 880 \text{ GeV}$



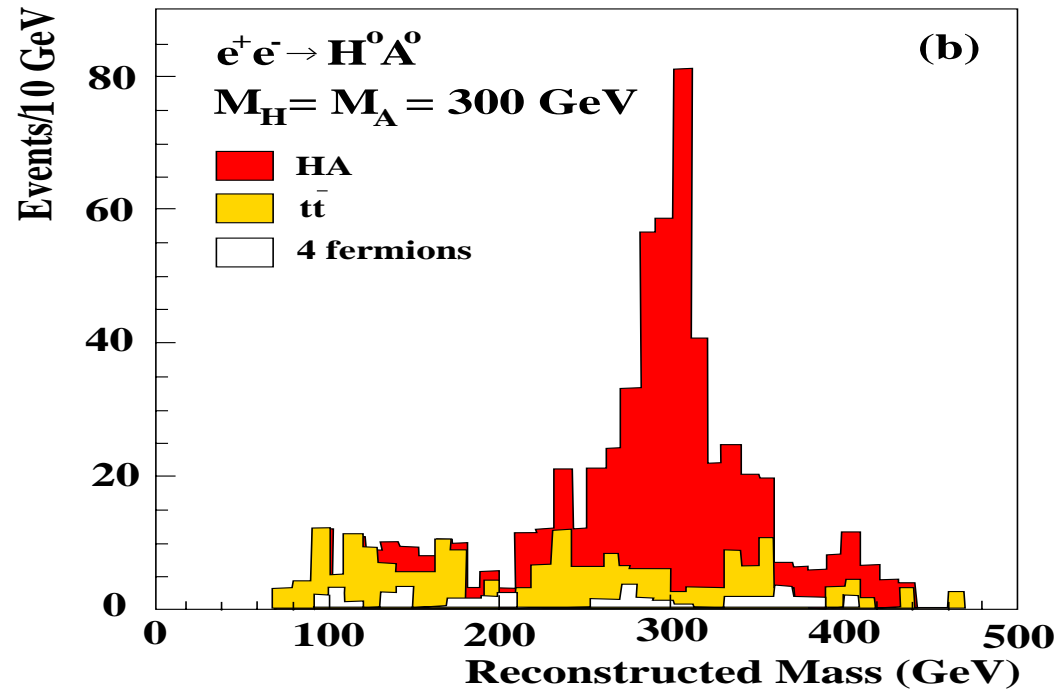
	$\sqrt{s} = 0.8 \text{ TeV}$ $M_{H^\pm} = 300 \text{ GeV}$	$\sqrt{s} = 3.0 \text{ TeV}$ $M_{H^\pm} = 880 \text{ GeV}$
M_{H^\pm}	0.01	0.01
$\sigma_{H^+H^-} \times \text{BR}(H^- \rightarrow \bar{t}b)$	0.08	0.15

M.B., A.Kiiskinen, A.Ferrari, hep-ex/0112015

Neutral Heavy Higgs Bosons H^0, A^0

$$e^+e^- \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b}$$

$$M_A = 300 \text{ GeV at } \sqrt{s} = 0.8 \text{ TeV}$$



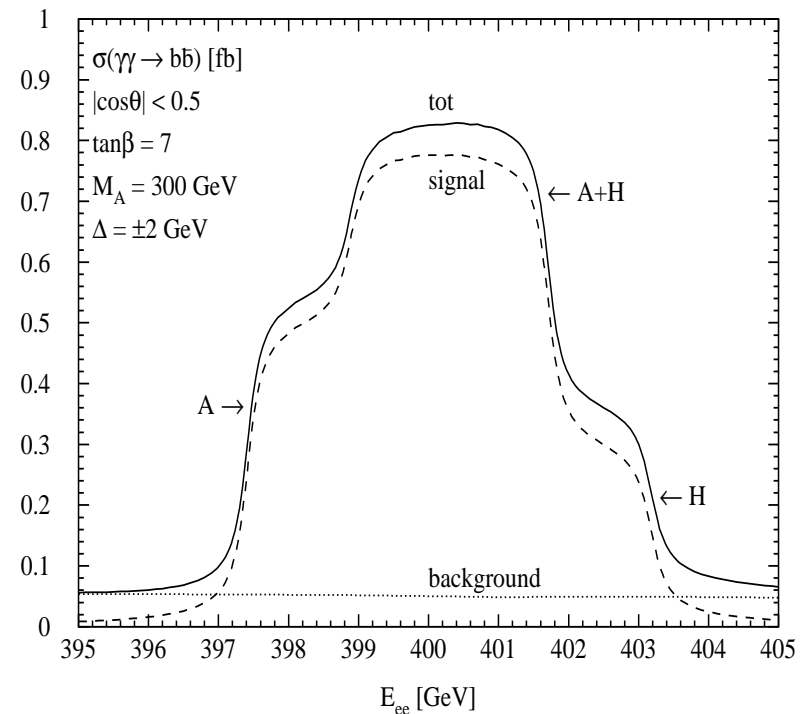
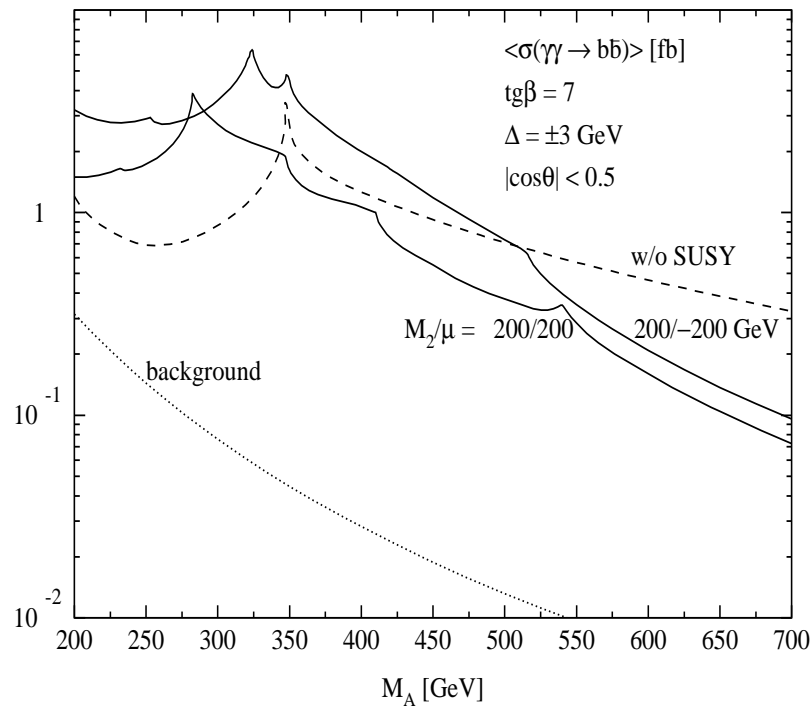
	$M_{H^\pm} = 260 \text{ GeV}$	$M_{H^\pm} = 340 \text{ GeV}$
M_A	0.001	0.002
$\sigma_{H^0 A^0} \times \text{BR}^2(H^0/A^0 \rightarrow b\bar{b})$	0.02	0.06

A.Andreazza, C.Troncon

→ M.Mühlleitner's Parallel Talks on Tuesday

Heavy Higgs Bosons at the Photon Collider

✧ Opportunity to operate a $\gamma\gamma$ Collider at the LC may significantly extend the reach in mass in Heavy Higgs boson searches through single production $\gamma\gamma \rightarrow H^0, \gamma\gamma \rightarrow A^0$:

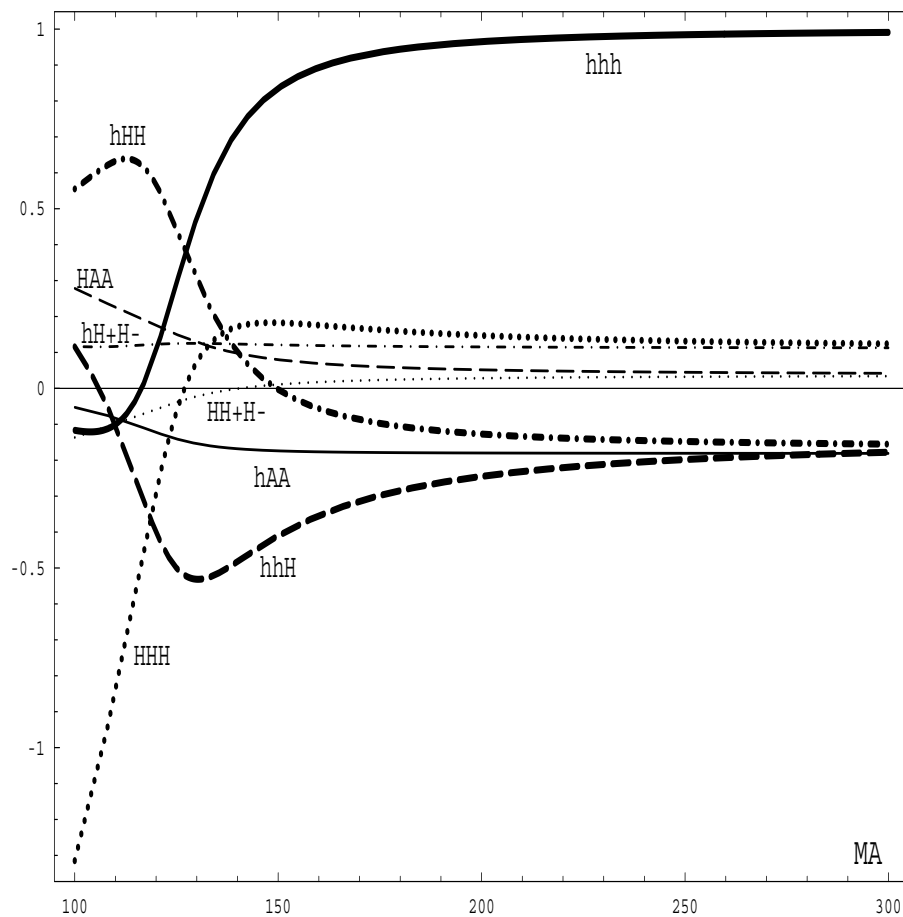


M.M.Mühlleitner *et al.* PLB 508 (2001)

→ S.Söldner-Rembold's Parallel Talk on Thursday

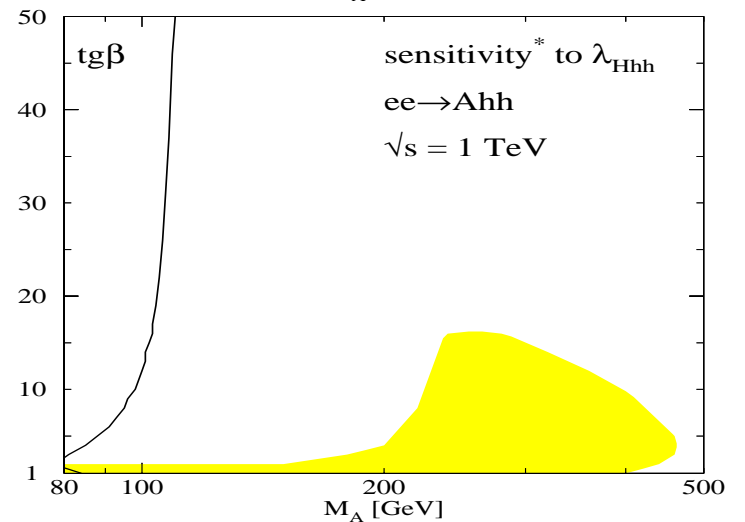
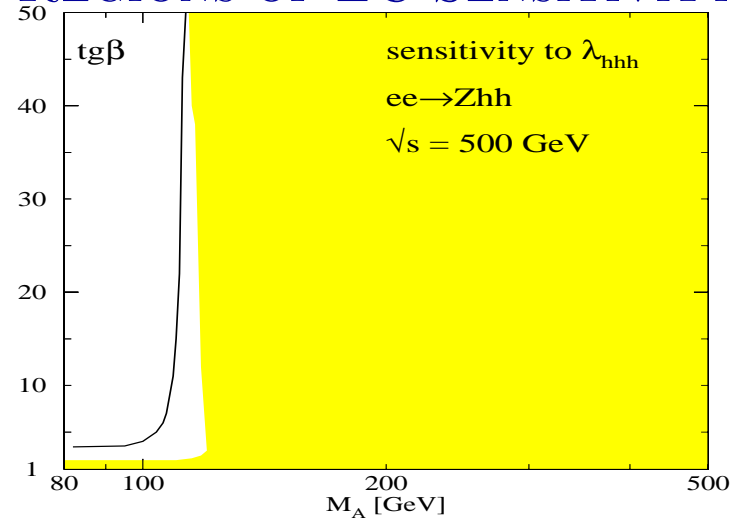
SUSY Higgs Self-Couplings

MSSM HIGGS SELF COUPLINGS NORMALIZED TO SM g_{HHH}



F.Boudjema, A.Semenov hep-ph/0201219

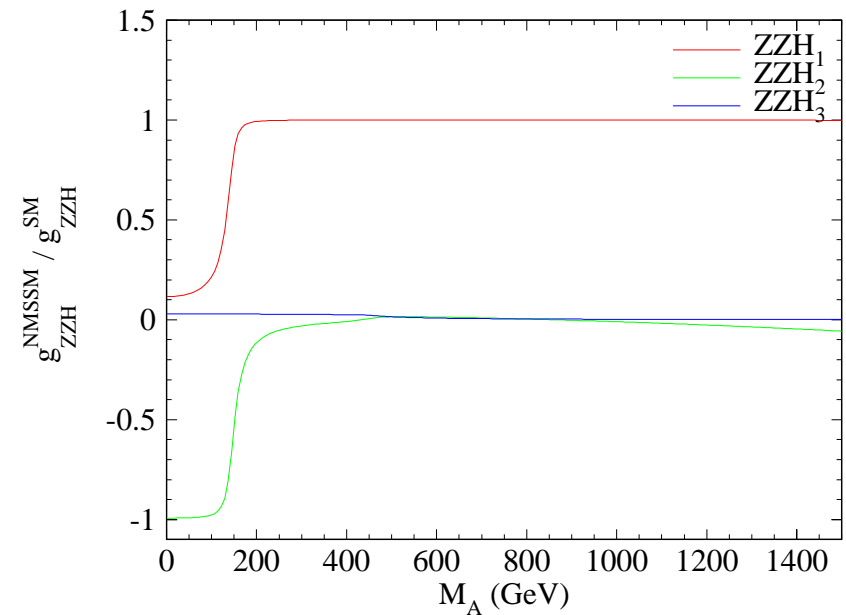
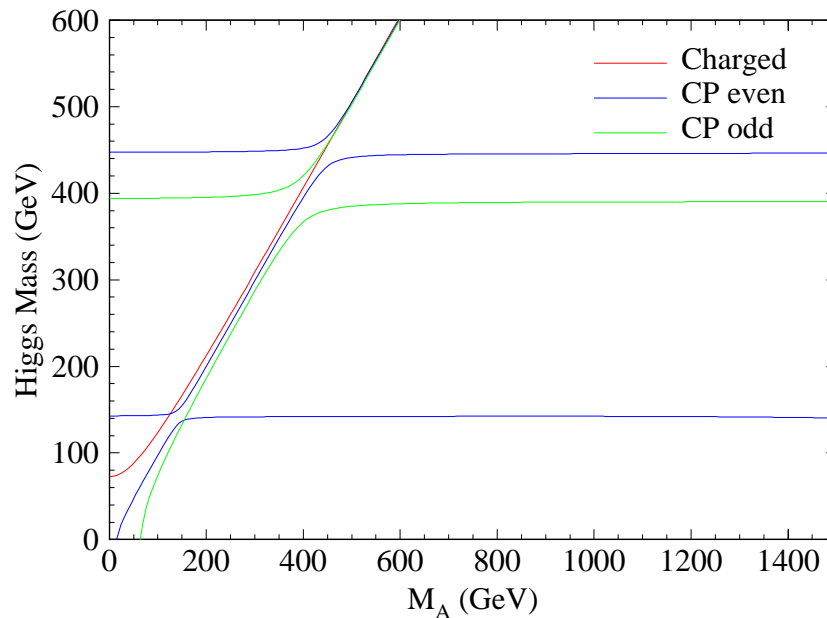
REGIONS OF LC SENSITIVITY



A.Djouadi *et al.* hep-ph/0001169

NMSSM

- ✧ Introduction of additional Higgs singlet may be motivated for natural explanation of value of μ term in MSSM Higgs potential;
- ✧ Interesting phenomenology with **two scalar Higgs bosons** possibly within reach of a TeV-class LC **one light pseudoscalar** and **four heavy bosons** almost degenerate in mass:



D.J.Miller

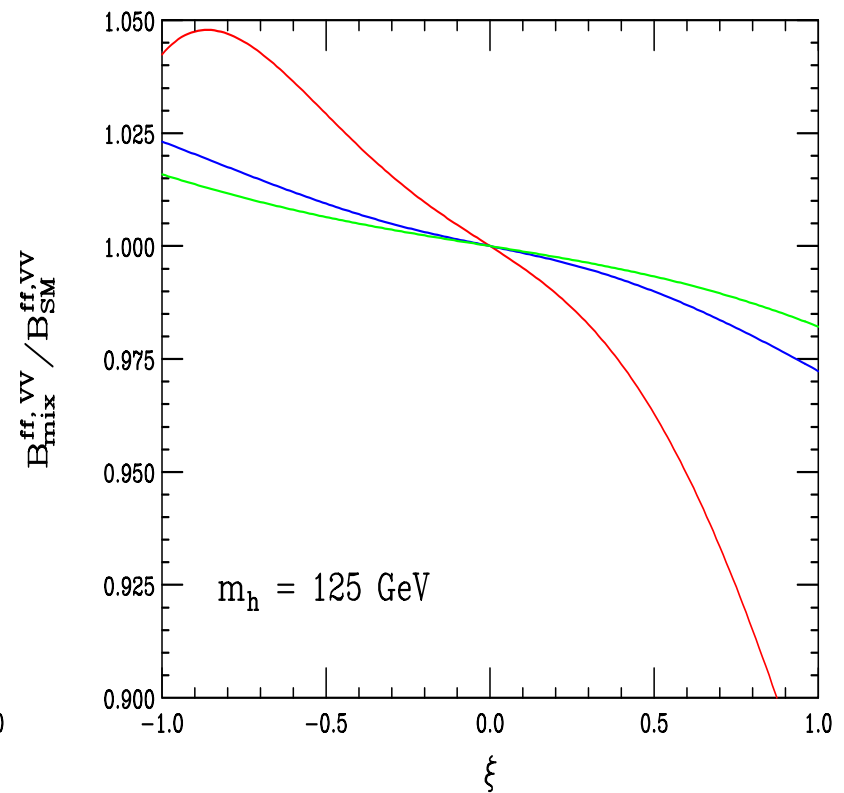
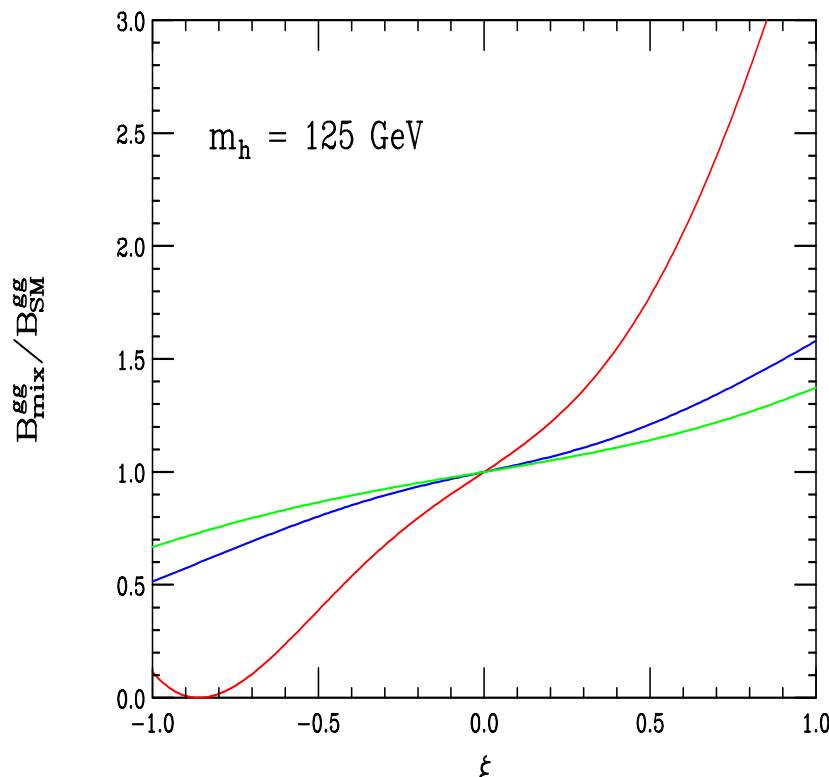
→ D.J.Miller's Parallel Talk on Tuesday

The Higgs Boson and the Radion

- ✧ Radion represents quantum excitation of brane separation in Randall-Sundrum model, which offers a solution to hierarchy problem;
- ✧ By **mixing with the Higgs field**, Radion modifies $BR(H \rightarrow X)$:

$$BR(H \rightarrow gg)$$

$$BR(H \rightarrow f\bar{f})$$



J.Hewett, T.Rizzo, hep-ph/0202155

→ T.Rizzo and J.Gunion's Parallel Talks on Monday

Conclusions



Münster, 1581