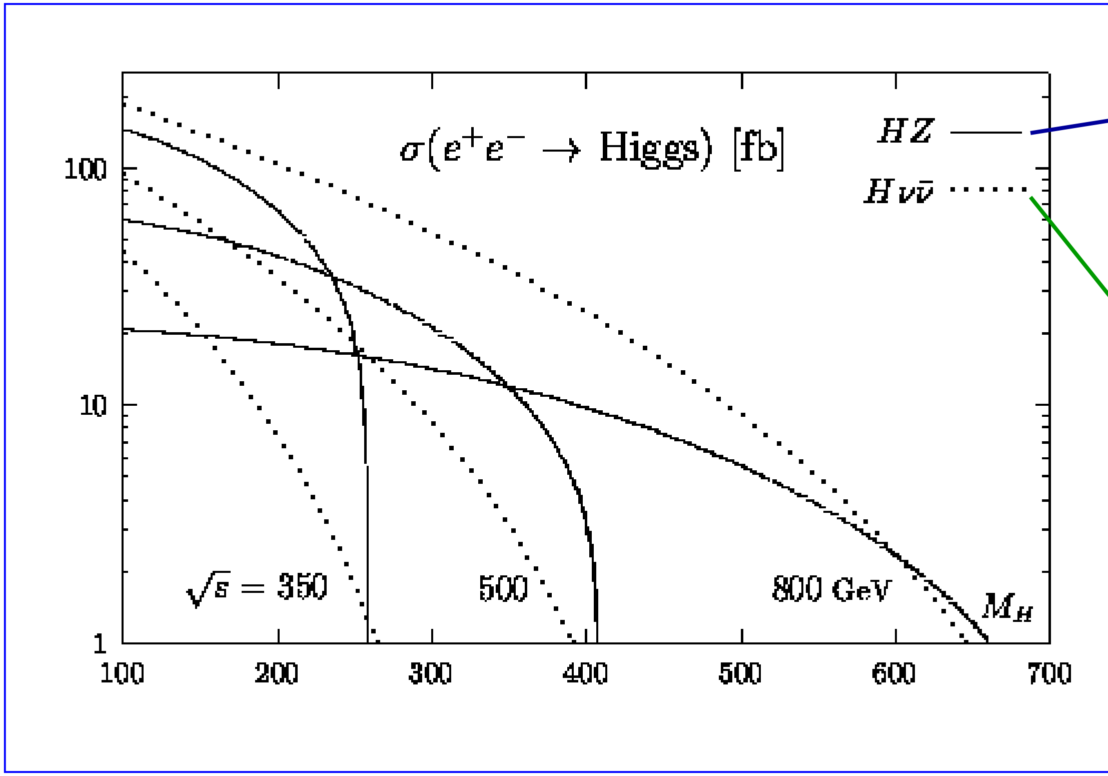
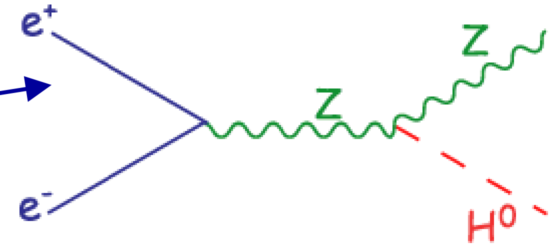
Higgs Measurements at ILC

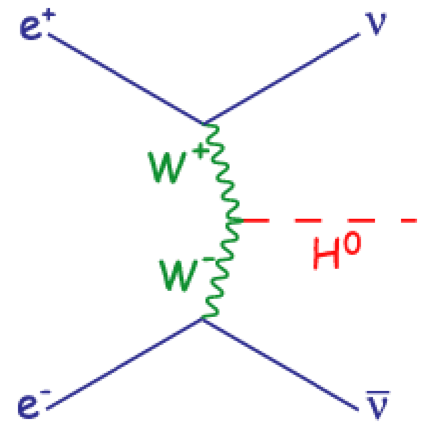
Higgs Physics at Future Colliders workshop
2004/2005

A.F.Żarnecki
01.12.2004

Higgs Production at a LC

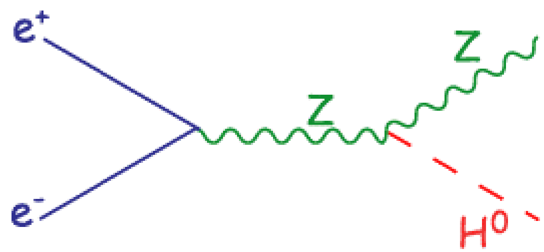






- The fusion process is dominant for higher CM energies (above 350 GeV)

Observing the Higgs Boson



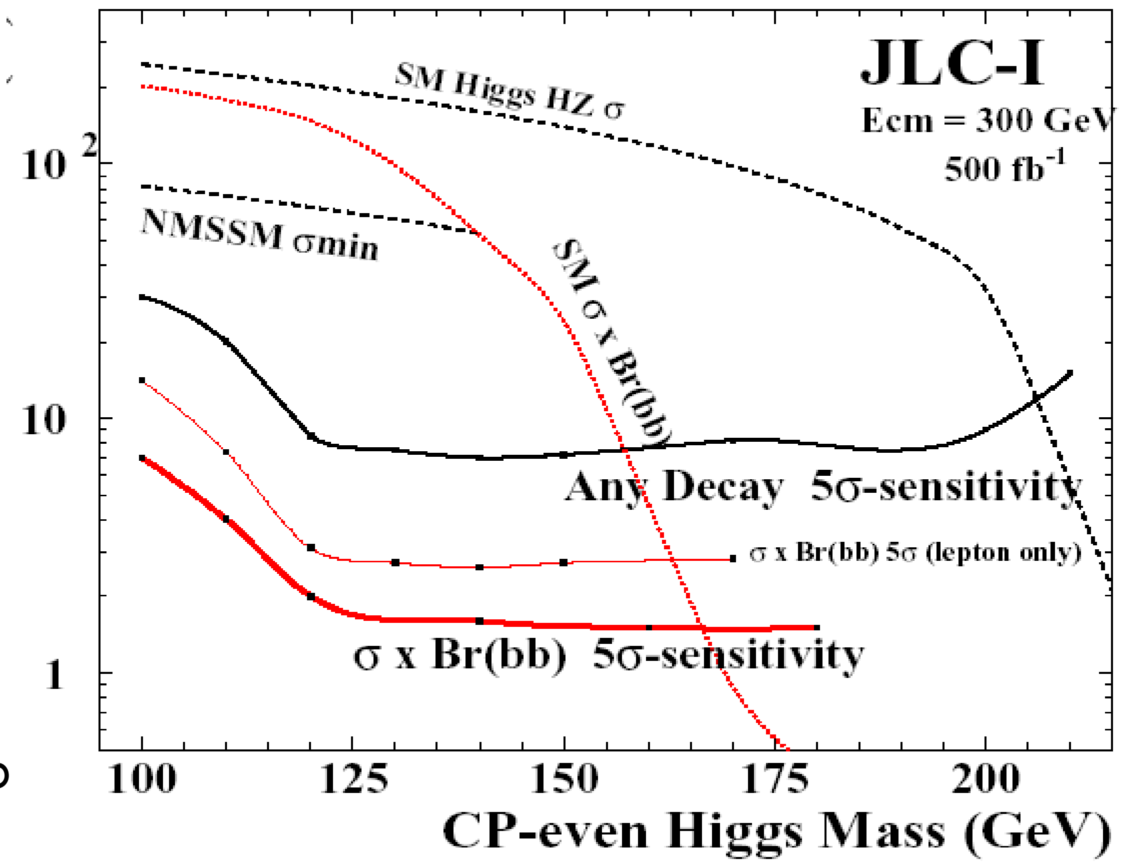
At 300 GeV the **Higgstrahlung** process dominates

Sensitivity to Higgs almost up to kinematic limit

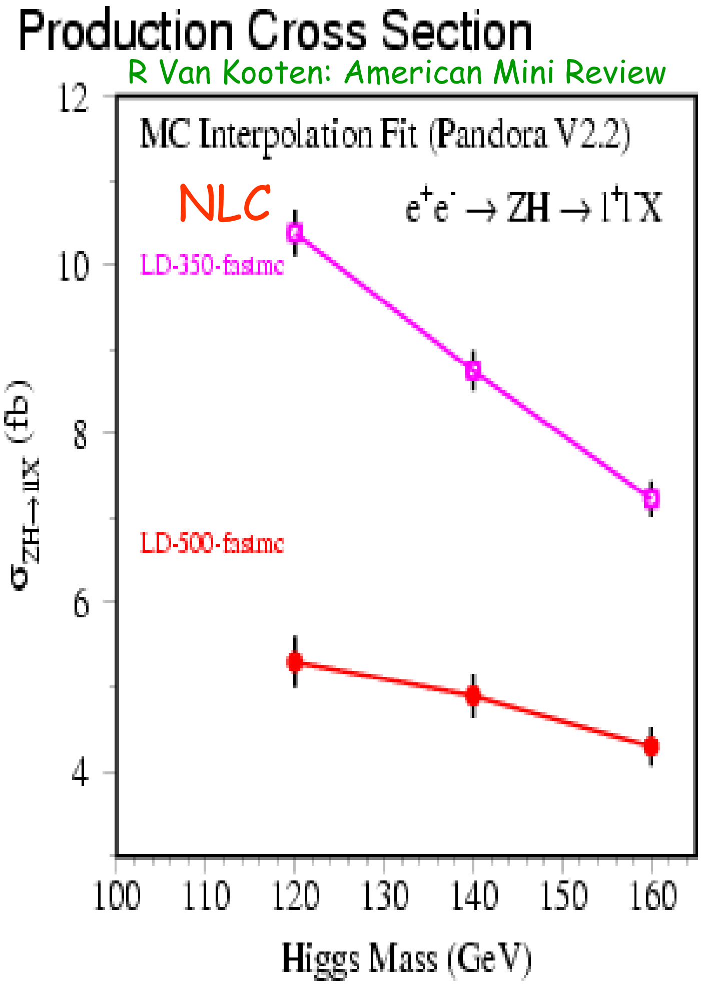
Up to ~~165 GeV for H→bb

High sensitivity for MSSM Higgs bosons

S Kiyoura: Asian Mini Review



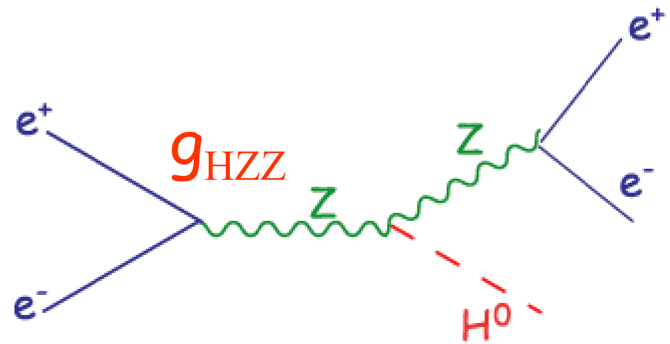
Measuring the Higgstrahlung Cross Section



- Full simulation
- Error bars give precision,

$\Delta\sigma/\sigma$ ~ 3.0% at 350 GeV

$\Delta\sigma/\sigma$ ~ 5.5% at 500 GeV (c.f. 4.7% fast MC simulation)



$\Delta\sigma/\sigma$, m_H=120 GeV

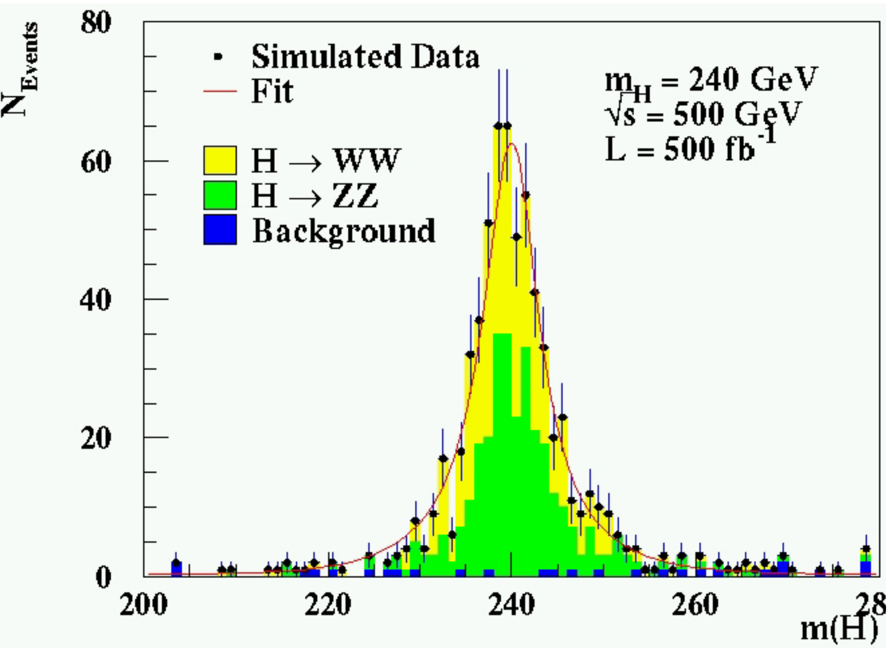
ECM	300	350	500
NLC		~3%	~5%
JLC	2.1%		2.9%
TESLA		2.6%	

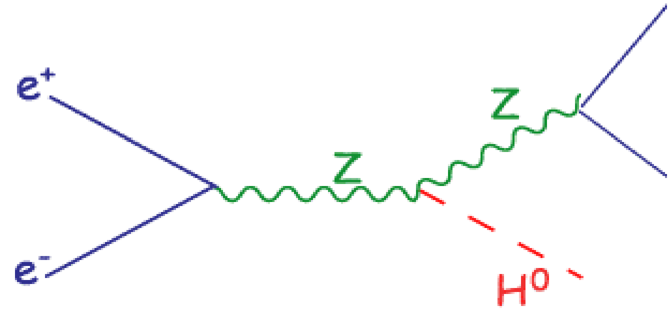
$\Rightarrow$ g_{HZZ} coupling measurement

Measuring the Higgs Boson Mass

m_H=240 GeV
Δm_H=200 MeV

Tesla, K Desch: European Mini Review





Δm_H , m_H=120 GeV

ECM	300	350	
NLC		90 MeV (llH)	
JLC	80 (40) MeV ll (Combined)		
TESLA		70 (40) MeV ll (Combined)	

(500/fb@350)

A Scalar Higgs Boson?

- For $\sqrt{s} \gtrsim m_H + m_Z$ (Threshold)

$$\sigma(ee \to HZ) \sim \beta_{ZH} \sim \sqrt{s - (m_H + m_Z)^2}$$

- For J=0 $\sigma \sim \beta$

  J=1 $\sigma \sim \beta^3$

  J=2 $\sigma \sim \beta^5$

- Threshold scan with $\int\mathcal{L}$ =20 fb^{-1}/point is sufficient to distinguish the different behavior

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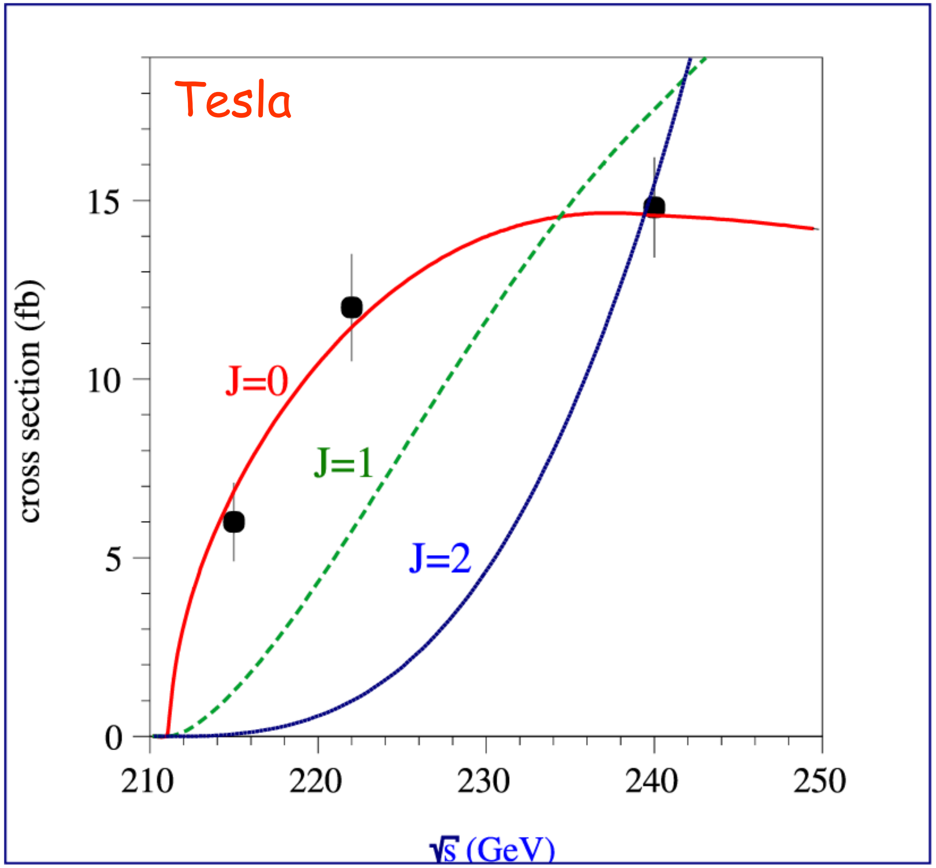
- Signal ZH→llqq
- E_{CM}=215, 222, 240 GeV
- $\Delta\sigma/\sigma$~20% per point

M.T. Dova, P. Garcia-Abia, W. Lohmann



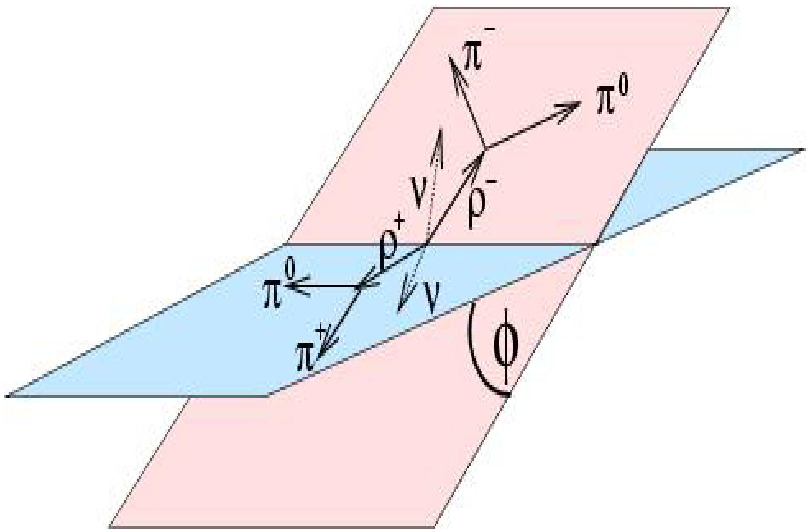
Higgs Parity

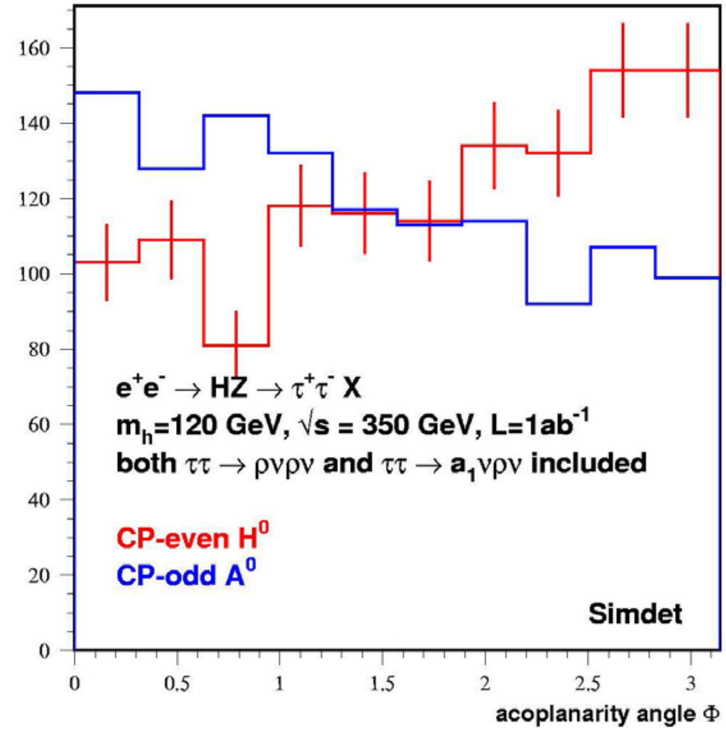
TDR: Spin from threshold scan
TDR: CP from angular distributions of ZH

New Ideas: Spin from $H \to ZZ$ Miller et al
CP from transverse polarisation correlations in $H \to \tau\tau$

Was, Worek
Bower
Imhof, KD

Observable: $\rho\rho$-acoplanarity:

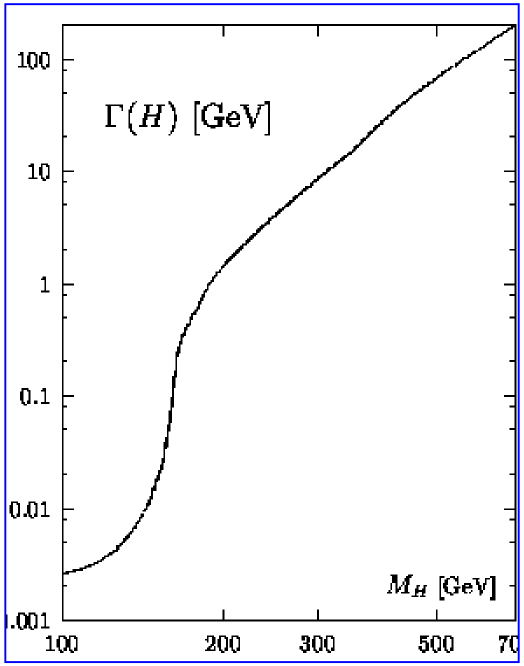




First estimate with detector simulation:

> 8σ separation between CP+ and CP- for 120 GeV Higgs (350GeV/1 ab^{-1})

Higgs Boson Total Decay Width Γ_H



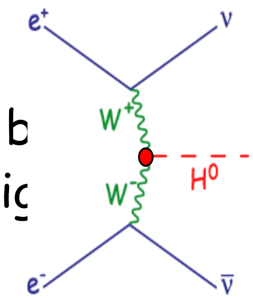
Tesla

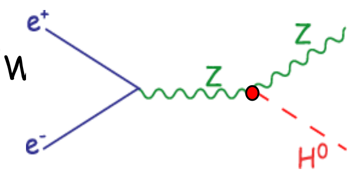
500/fb @
500 GeV
m_H=240
$\Delta\Gamma_H/\Gamma_H$=11%

- Above the ZZ threshold the width can be measured directly via a line shape
- For m_H<160 GeV the best accuracy is obtained from

$$\Gamma_H^{Total} = \frac{\Gamma(H \to WW)}{BR(H \to WW)}$$

- The partial width $\Gamma_{H\to WW}$ can b obtained directly from the Hi fusion production or making a plausible assumption $g_{HWW}=g_{HZZ}\cos\theta_W$ and use the Higgstrahlung process to measure g_{Hzz}





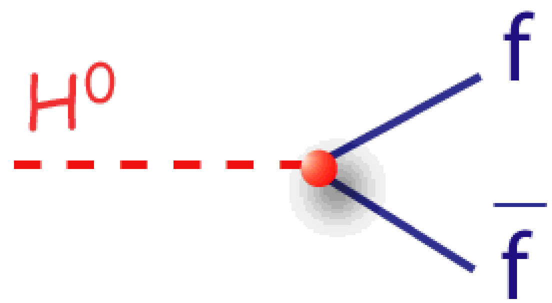
- For 160 GeV Higgs the drop in fusion based accuracy is due to the fact that bb Higgs decay is not dominant anymore

(500/fb)

Tesla TDR

m_H	$\delta\Gamma_{TOT}/\Gamma_{TOT}$ g_{HWW}	$\delta\Gamma_{TOT}/\Gamma_{TOT}$ $g_{HWW}=g_{HZZ}\cos\theta_W$	$\delta\Gamma_{TOT}/\Gamma_{TOT}$ $g_{H\gamma\gamma}$
120 GeV	6.1% (NLC 6.0%)	5.6% **(5.5% JLC)**	26%
160 GeV	13.4%	3.6%	

Higgs Decay Rates to Fermions



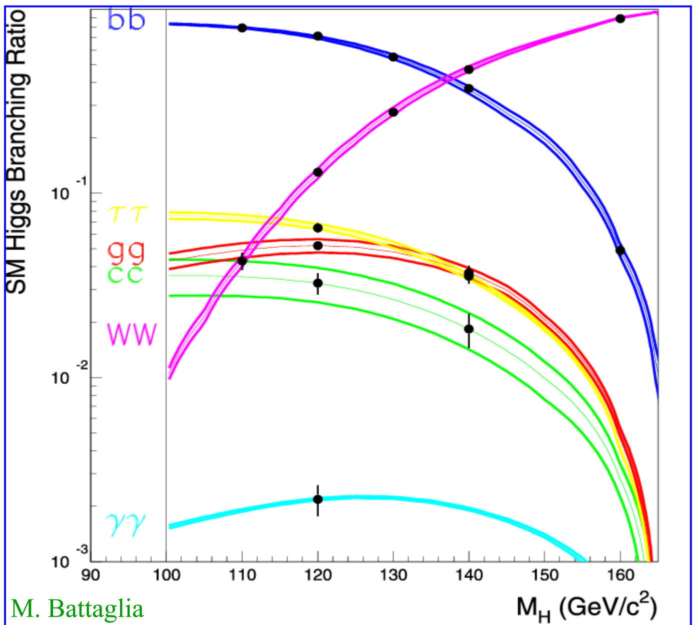
$g_{Hff} = m_f/v$

- The Higgs boson generates the fermion masses ("the God particle" :)
- one needs a precise determination of the coupling constants (including b/c discrimination, in order to tell a SUSY Higgs from a SM Higgs
- That is the power of the LC

Higgs Decay Rates

(500/fb@350 GeV) Tesla | 300GeV) | (500/fb@500 GeV)

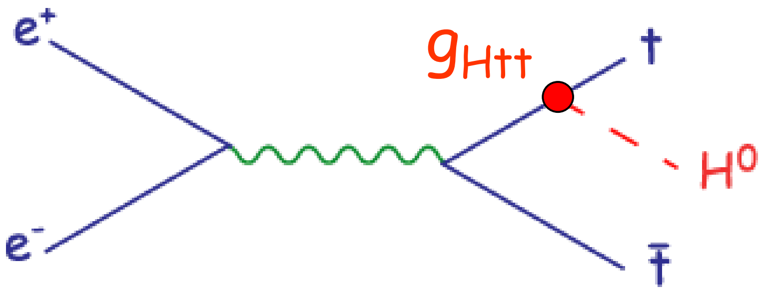
decays	BR (%)	δB/B (%) direct method (this note)	δB/B (%) indirect method from ref. [2]	δB/B (%) combined	JLC	NLC	Tesla Scaled	JLC
$b\bar{b}$	68.	1.9	2.4	1.5	1.1%	3%	5%	1.7%
$\tau\tau$	6.85	7.1	5.0	4.1	4.4%	8%	10%	
$c\bar{c}$	3.1	8.1	8.3	5.8		39%*	17%	22%
gluon-gluon	7.0	4.8	5.5	3.6		18%	11%	13%
$\gamma\gamma$	0.22	35.	26	21.				
WW*	13.3	3.6	4.2	2.7	5.1%	10%	10%	16%



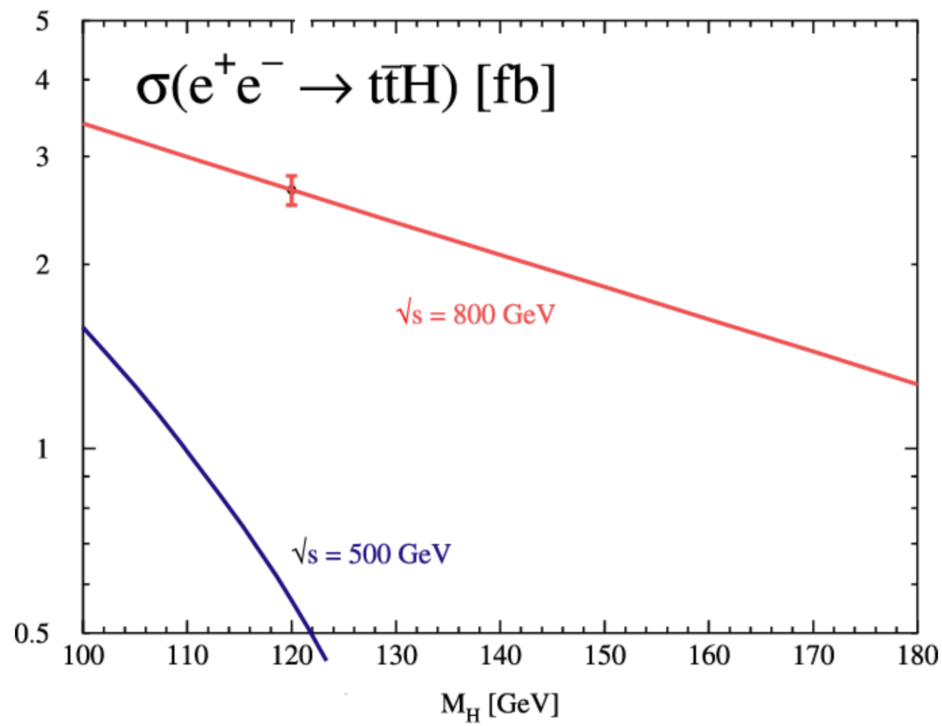
- Theoretical uncertainties come mainly from $m_q(m_H)$ and QCD corrections to hadronic decays
- One can assume that by the time of LC an improvement of at least factor ~2 on m_b and m_b-m_c will be achieved from B factories and LHC

•The scaling might be too optimistic because of the different kinematics (more boosted)
•NLC takes into account tracking ambiguity between jets

Light Higgs off Top Quark...



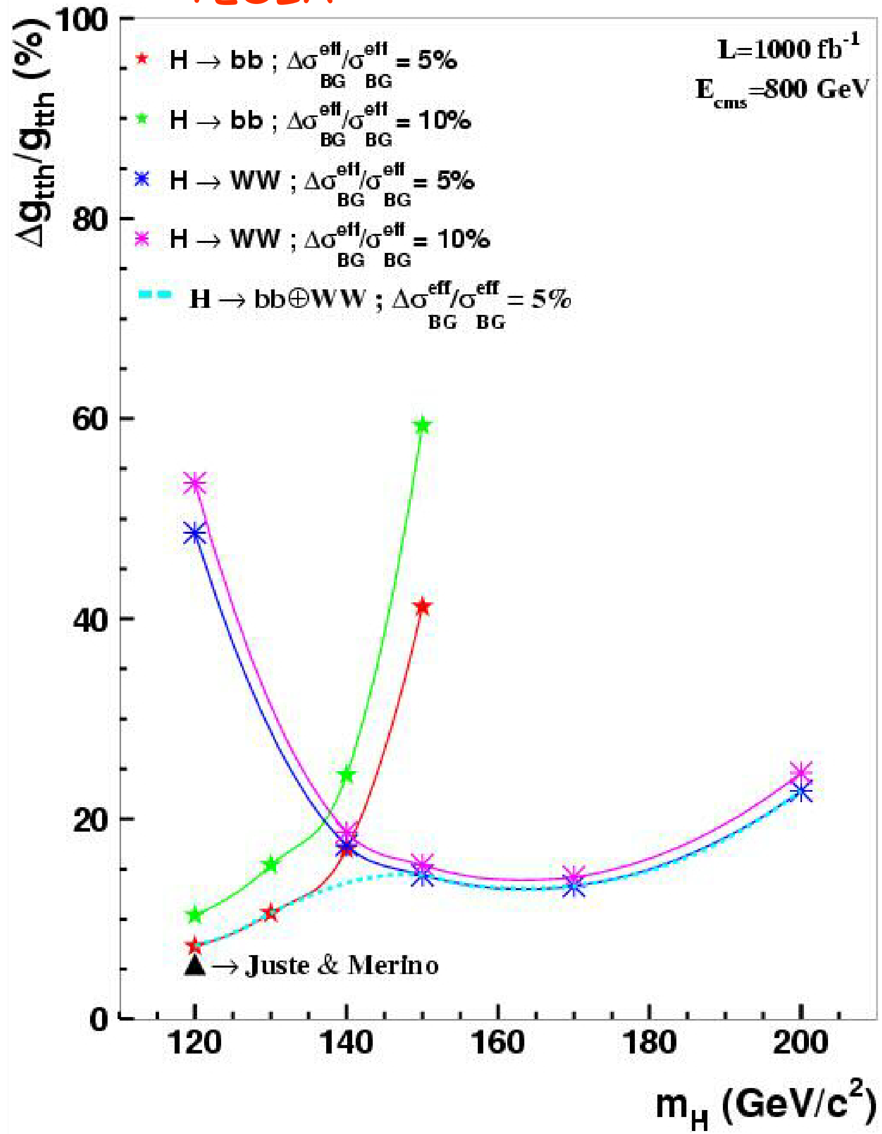
- Low production cross section → Needs high luminosity and high collision energy



ttH

- Signature:
  For low Higgs Mass ee→ttH →WbWb bb :
  2W bosons + 4 b jets
- For Heavier Higgs, H→WW,
  4W+2b final state
- JLC:
  $\delta g_{Htt}/g_{Htt}$=4.2% for m_H=120 GeV
  @ E_{CM}=700 GeV with 500 fb^{-1}
- TESLA:
  See plot (~7% for m_H=120 GeV)
  NLC: ~8%
- NLC: An attempt was done to measure this Yukawa coupling by a threshold scan of the tt cross section, results are poor (>20%).

TESLA

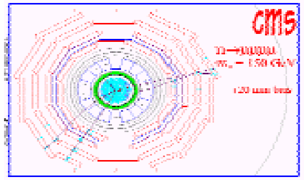


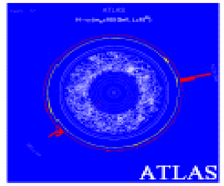
A Linear Collider ($\sqrt{s}$=300-1000 GeV) Will…

- Measure the Higgs properties:
  - Production rate
  - Mass
  - Spin
  - Lifetime (total width)
- Couplings to
  - Matter particles: g_{hff}
  - Gauge bosons: g_{hZZ}
- Establis the Higgs mechanism as the mechanism of electroweak Symmetry Breaking by measuring the Higgs coupling to itself : λ
- Due to its intrinsic limitations (E_{CM}, ee nature) some unique properties can be better probed by a $\gamma\gamma$ collider (H$\gamma\gamma$ coupling, Beyond the SM Heavy Higgs Bosons) and a Multi-TeV LC (CLIC) (Rare Higgs Decays…)

Higgs Boson Discovery

Tevatron
LHC
TESLA





Determine Mass and Quantum Numbers

LHC
TESLA

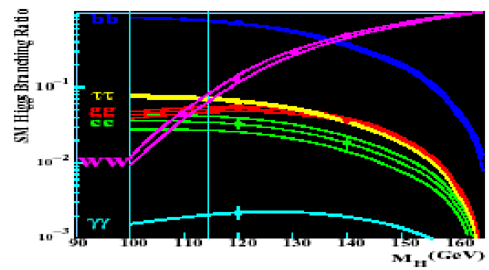
$$M_H^2 = 2\lambda v^2$$

$$J^{PC} = 0^{++}$$

Higgs Couplings

LHC
TESLA

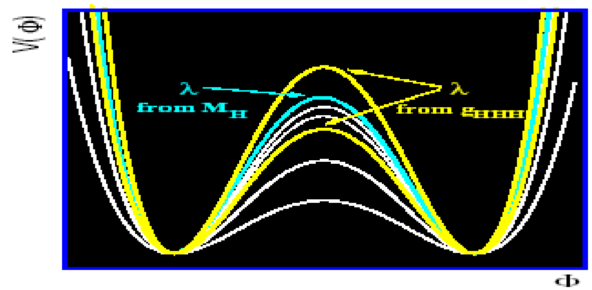
$$g_{ffH}/g_{FFH} = M_f/M_F$$



Higgs Potential

TESLA
multi–TeV LC

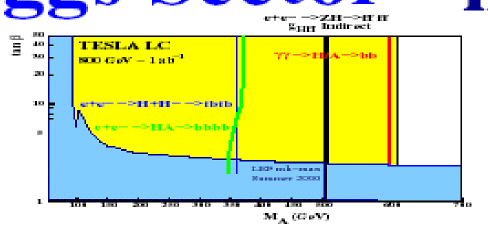
$$g_{HHH} = 3\lambda v$$

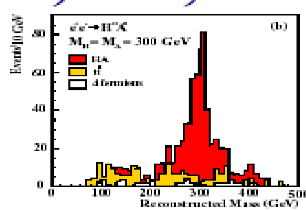


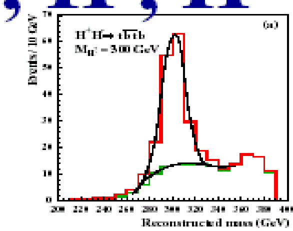
Extended Higgs Sector

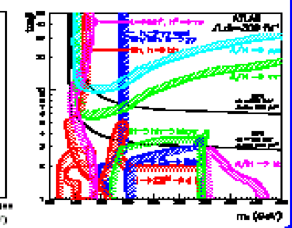
$$h^0, A^0, H^0, H^+, H^-$$

LHC
TESLA
multi–TeV LC









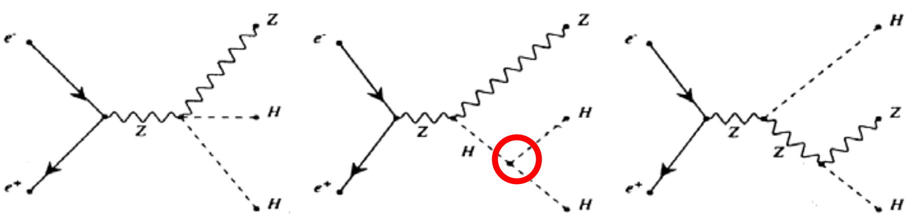
Higgs self-coupling

Y.Yasui

The first information on the Higgs potential

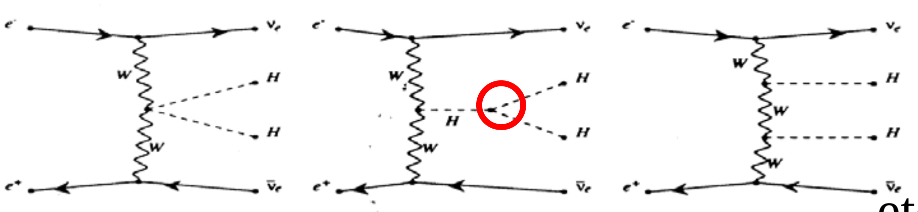
$\star\ e^+e^- \to ZHH$

produced by GRACEFIG

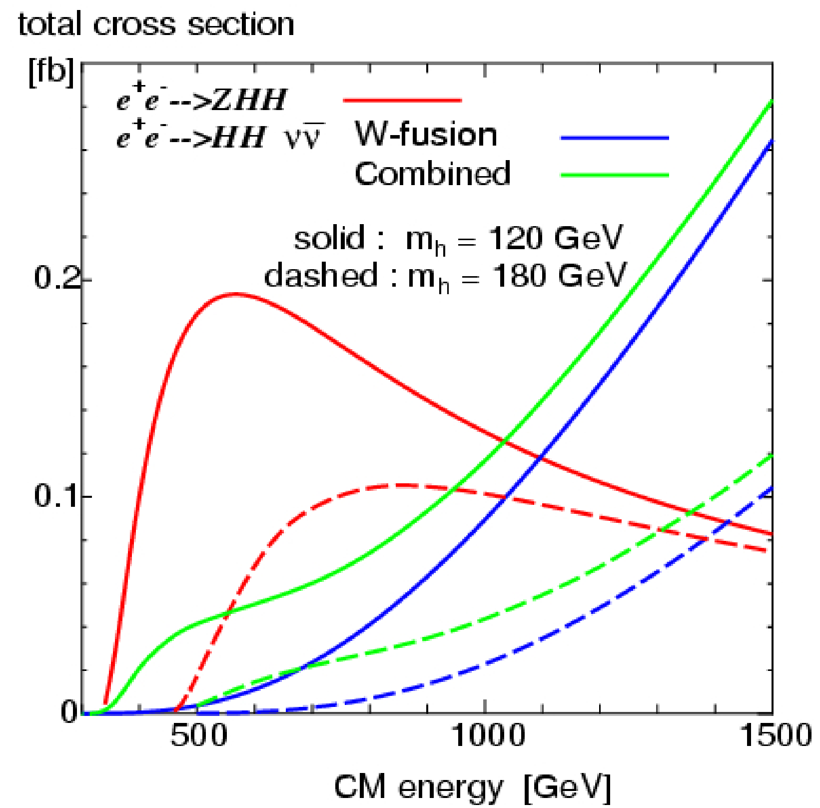


etc..

$\star\ e^+e^- \to (W^+W^-)\nu\bar{\nu} \to HH\nu\bar{\nu}$



etc..



Conditions of Baryogenesis

Evidence of the BAU

$$\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} \simeq (8.7^{+0.4}_{-0.3}) \times 10^{-11}$$

- 3 requirements for generation of the BAU (Sakharov conditions)

1. baryon number violation
2. C and CP violation
3. out of equilibrium

2 scenarios

(1) B-L-generation above EW phase transition. (Leptogenesis, etc)

(2) B-generation at the electroweak phase transition. (Electroweak baryogenesis)

-based on a testable model

Baryogenesis in the electroweak theory

- baryon number violation   sphaleron process
- C violation   chiral interation
- CP violation   KM-phase or other sources in the extension of the SM
- out of equilibrium   1st order phase transition with expanding bubble walls

In principle, SM fulfills the Sakharov conditions, BUT

• Phase transition is not 1st order for the current Higgs mass bound ($m_h > 114$ GeV)
• KM-phase is too small to generate the sufficient baryon asymmetry

$\Longrightarrow$ Extension of the minimal Higgs sector

THDM, MSSM, Next-to-MSSM, etc.

▷ THDM is a simple viable model   not so constrained

Finite temperature Higgs potential

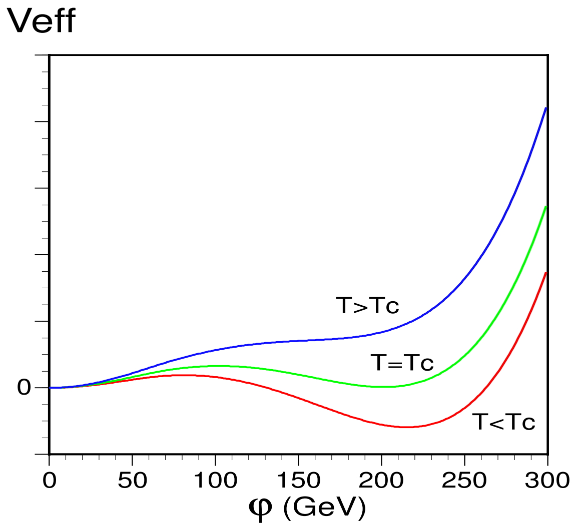
For $m_\Phi^2(v) \gg M^2, m_h^2(v)$ $\quad m_\Phi^2(\varphi) \simeq m_\Phi^2(v)\frac{\varphi^2}{v^2}, \quad (\Phi = H,\ A,\ H^\pm)$

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$

where

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + \underbrace{m_H^3 + m_A^3 + 2m_{H^\pm}^3}_{\text{additional contributions}})$$

At T_c, degenerate minima: $\quad \varphi_c = \frac{2ET_c}{\lambda_{T_c}}$



- The magnitude of E is relevent for the strongly 1st order phase transition

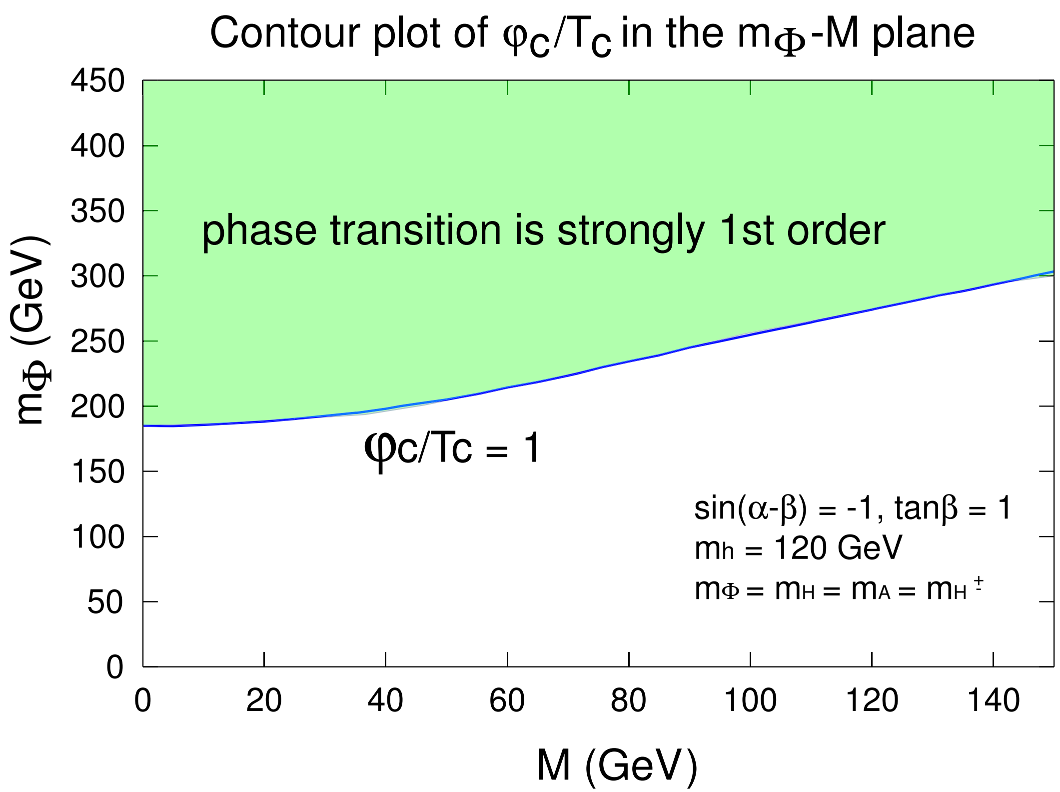
- **Strongly 1st order phase transition:** $\quad \frac{\varphi_c}{T_c} \gtrsim 1$

$\Rightarrow$ Not wash out the baryon density after EW phase transition

$\triangleright$ CP violation at the bubble wall $\quad \Rightarrow \quad$ Asymmetry of the charge flow

Contour plot of φ_c/T_c in the m_Φ-M plane

$$\sin^2(\alpha - \beta) = \tan\beta = 1,\ m_h = 120\ \text{GeV},\ m_\Phi \equiv m_A = m_H = m_{H^\pm}$$



- For $\mathbf{m_\Phi^2 \gg M^2, m_h^2}$,

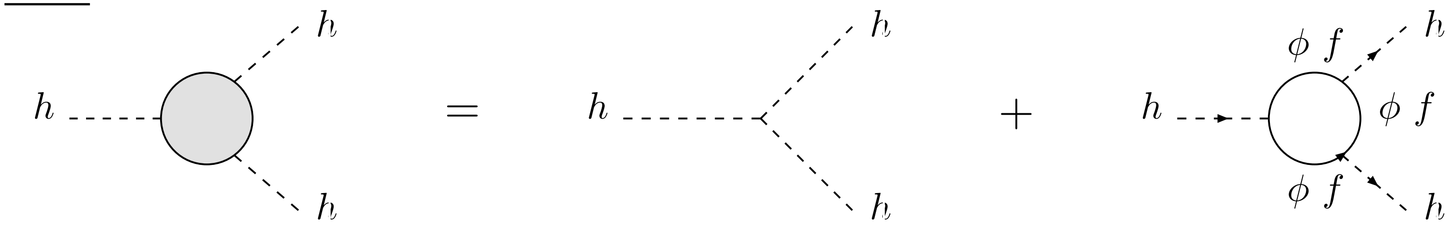
Strongly 1st order phase transition is possible due to the loop effect of the heavy Higgs bosons (**non-decoupling effect**). (φ^3-term is effectively large)

- What the magnitude of the λ_{hhh} coupling at T=0 in such a region?

Radiative corrections to λ_{hhh}

[S. Kanemura, S. Kiyoura, Y. Okada, E.S., C.-P. Yuan PL '03]

- hhh



$(\phi = h, H, A, H^{\pm}, \quad f = t, b)$

- For $\sin(\beta-\alpha)=1$,

$$\lambda_{hhh}^{\text{tree}} = -\frac{3m_h^2}{v}, \quad \text{(same form as in the SM)}$$

$$\lambda_{hhh} \sim -\frac{3m_h^2}{v}\left[1+\frac{c}{12\pi^2}\frac{m_\Phi^4}{m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3\right] \quad (\Phi = H, A, H^{\pm})$$

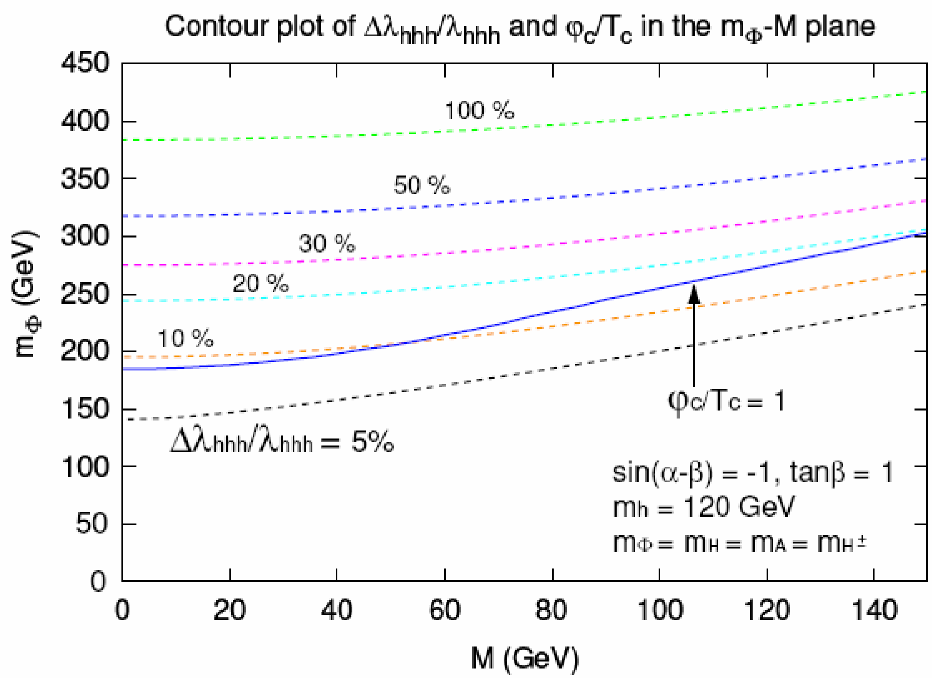
$(c = 1$ for neutral Higgs, $c = 2$ for charged Higgs$)$

For $\mathbf{m_\Phi^2 \gg M^2, m_h^2}$, the loop effect of the heavy Higgs bosons is enhanced by m_Φ^4, which does not decouple in the large mass limit. (**non-decoupling effect**)

Electroweak baryogenesis and the Higgs self-coupling in 2HDM

E.Senaha

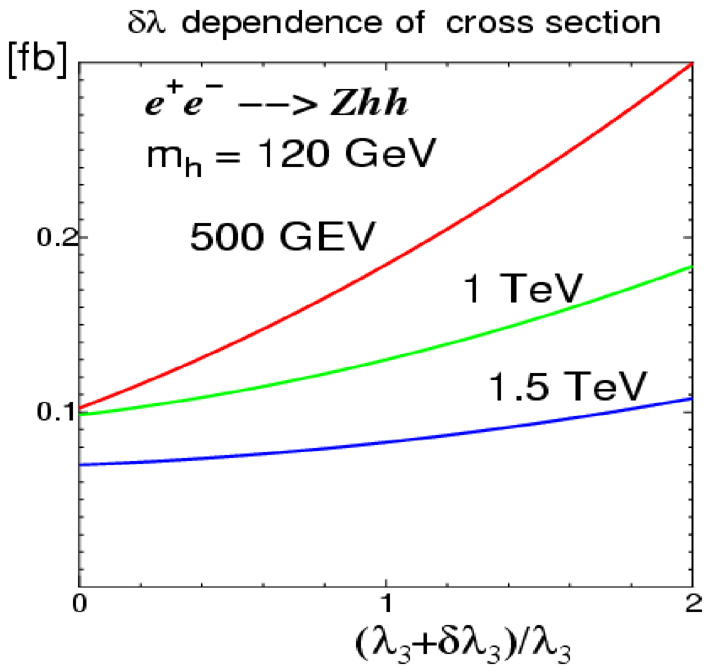
Baryon number asymmetry can be created at the EW phase transition in 2HDM.

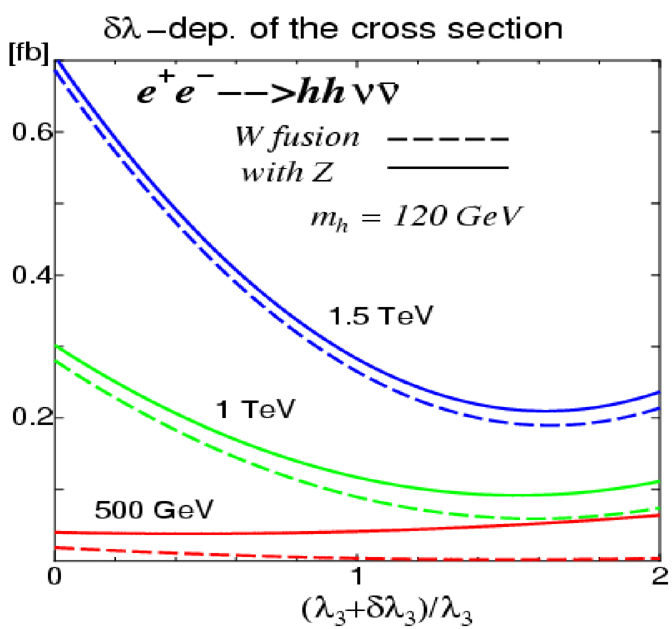


The condition of the strong first order phase transition
=>
A large radiation correction to the triple Higgs boson coupling.

$$V_{eff}(\phi, T) \leftrightarrow V_{eff}(\phi, 0)$$

$$\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$$

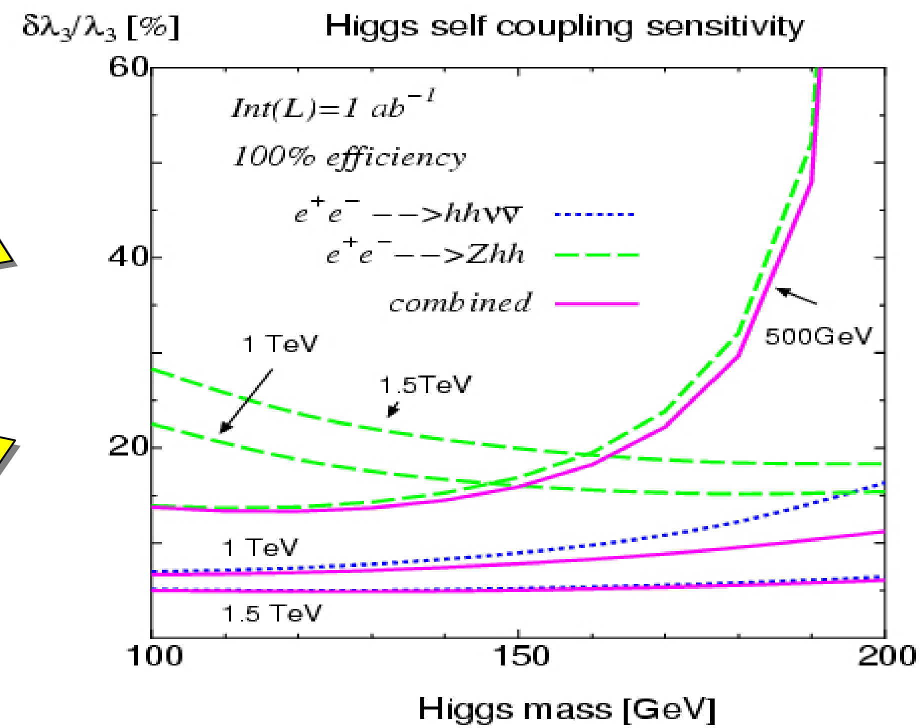




Assumption

- No bkg effects
- 100% signal efficiency

dominant for E_{CM} > 1TeV



by Yasui et.al.

New Strategy for simulation studies

1. Parton level Generator (tree level ⇔ *GRACE-loop*)
   - *LCGrace* talk by Yasui, ACFA 6th India 2003
     package for LC Higgs physics study:
     $M_h \leq 140$ GeV $e^+e^- \to 6f$
   - *based on the GRACE System*
     - *Bases* ⇒ Monte Carlo integration ⇒ Cross section
     - *Spring* ⇒ Events generator
2. Hadronizer
   - *Pythia* (interface from *Spring* to *Pythia6*)
3. Simulator (Quick Simulation → Full Simulation)
4. Analysis

Simulation Study

- E_{cm} = 1 TeV
  - main mode ⇒ W-fusion → **ννhh quick analyses**
    - only for hh decaying to 4b
- Higgs mass = 120 GeV
  - SM decay Br → **Br(hh→ 4b) ~ 47 %**
    - for 120 GeV SM Higgs
- ISR/BSR included
- Signal & bkg event generator
  - LCGrace (BASES+SPRING)
- Signal MC: X + hh
  - λ/λ_{SM} from 0.0 to 2.0 with 0.2 step
- Smearing simulation at parton level
  - Jet energy resolution ~ 30%/√E (GeV)
  - (detector R&D target value)

Signal characteristics

- Large missing energy, missing Pt
- Only 4 b jets
- M_1 jj ~ M_h M_2 jj ~ M_h
- No isolated lepton

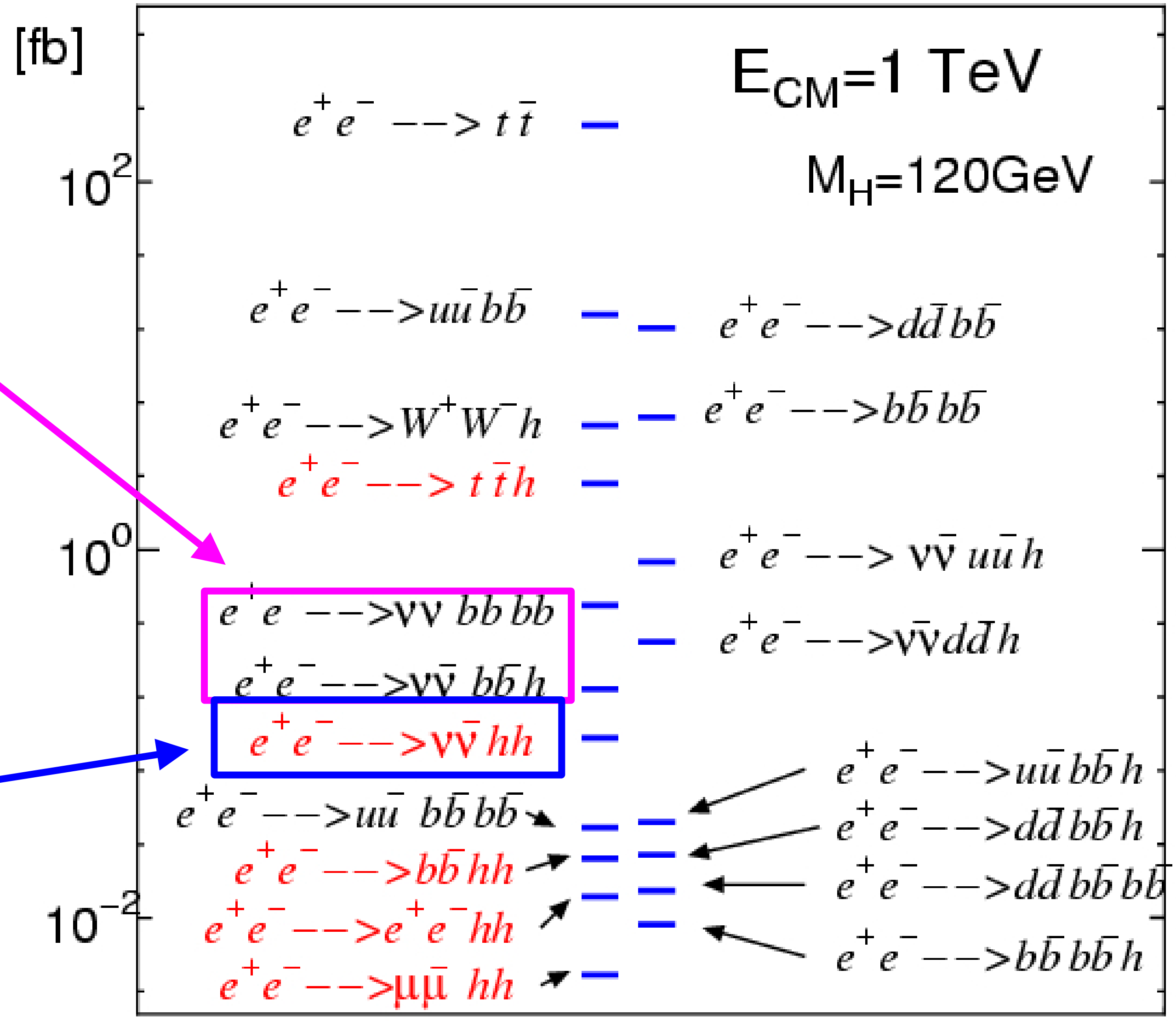
Signal and Background processes

By LCGrace

Main bkg processes
4b + missing

vvbbbb
(~ vvZZ, vvZγ*)
vvbbh
(~ vvZh)

Signal
(for SM)



vvhh Analysis Flow

1. Likelihood selection
   bkg further reduction

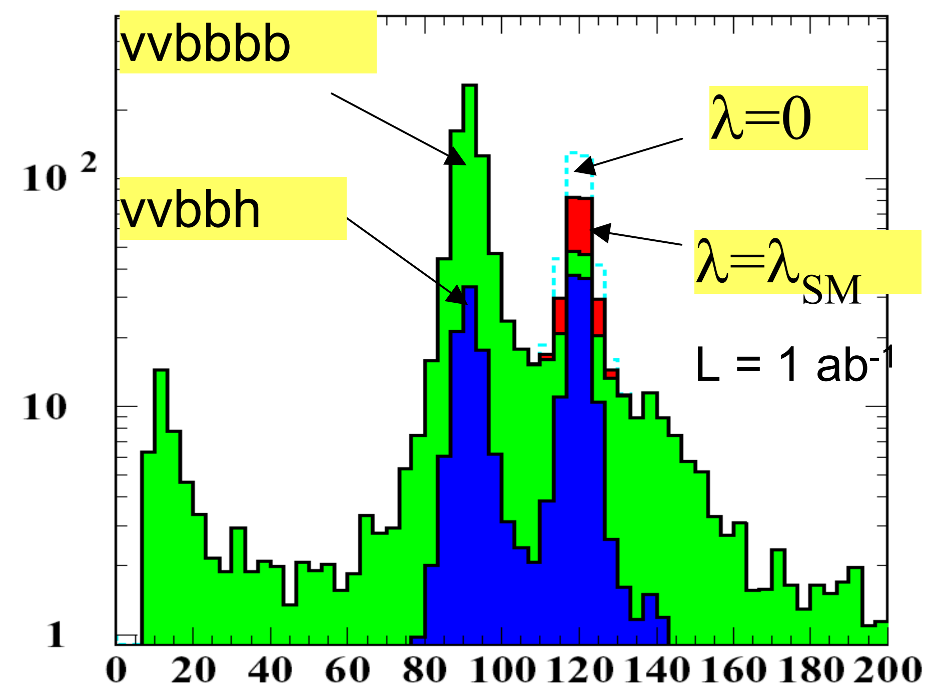
2. Separate Zhh & fusion
   different λ dependence
   (positive/negative interferences)

3. Combine with Zhh analyses
   for s-channel process

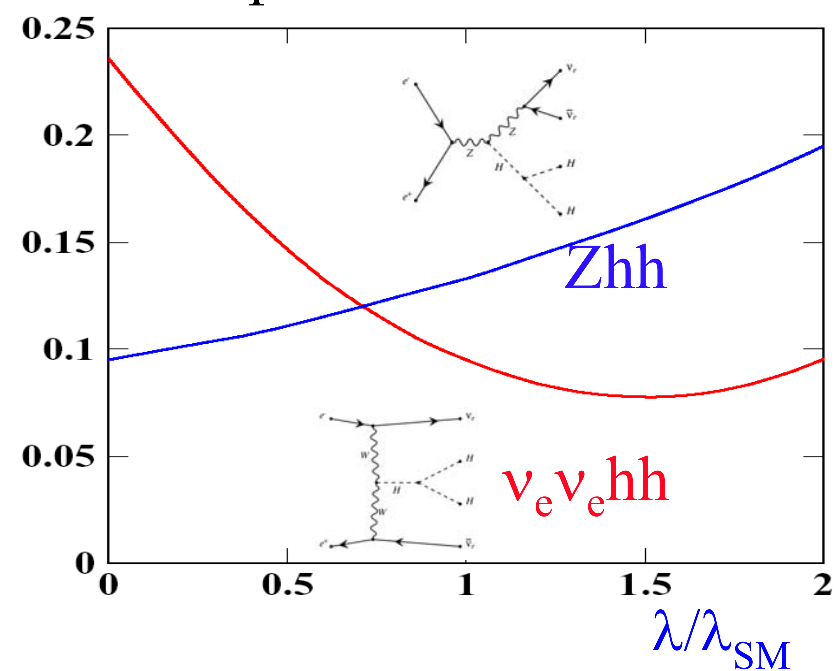
4. Check hh invariant mass

5. λ_{hhh} measurements

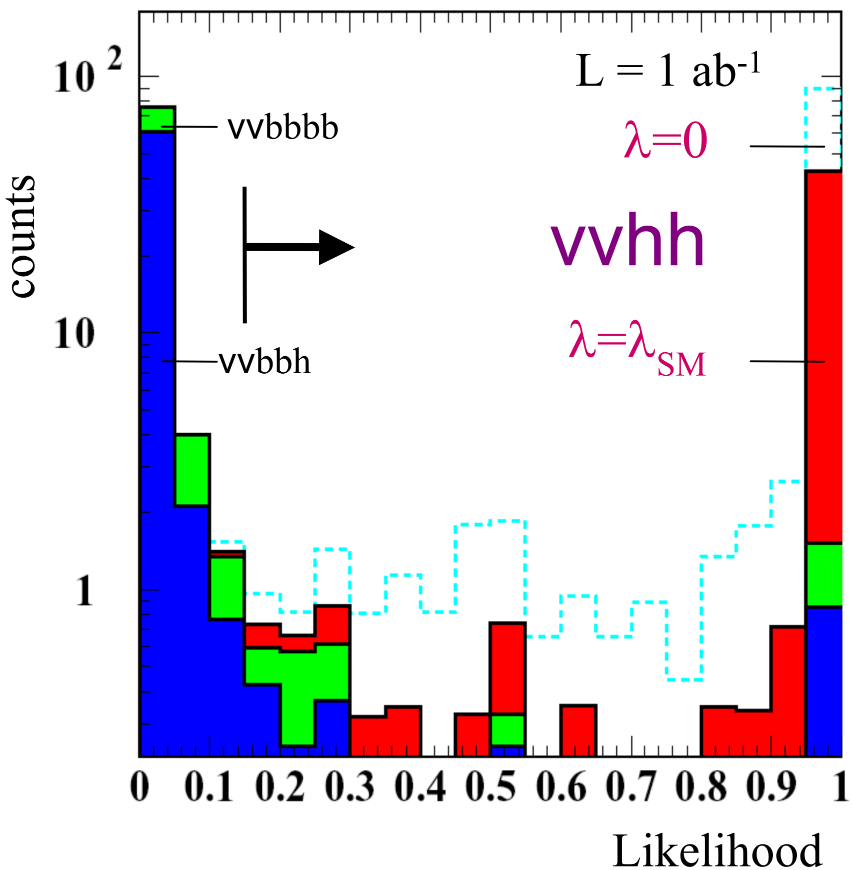
Reconstructed 'Higgs' mass



λ dep. of cross-section

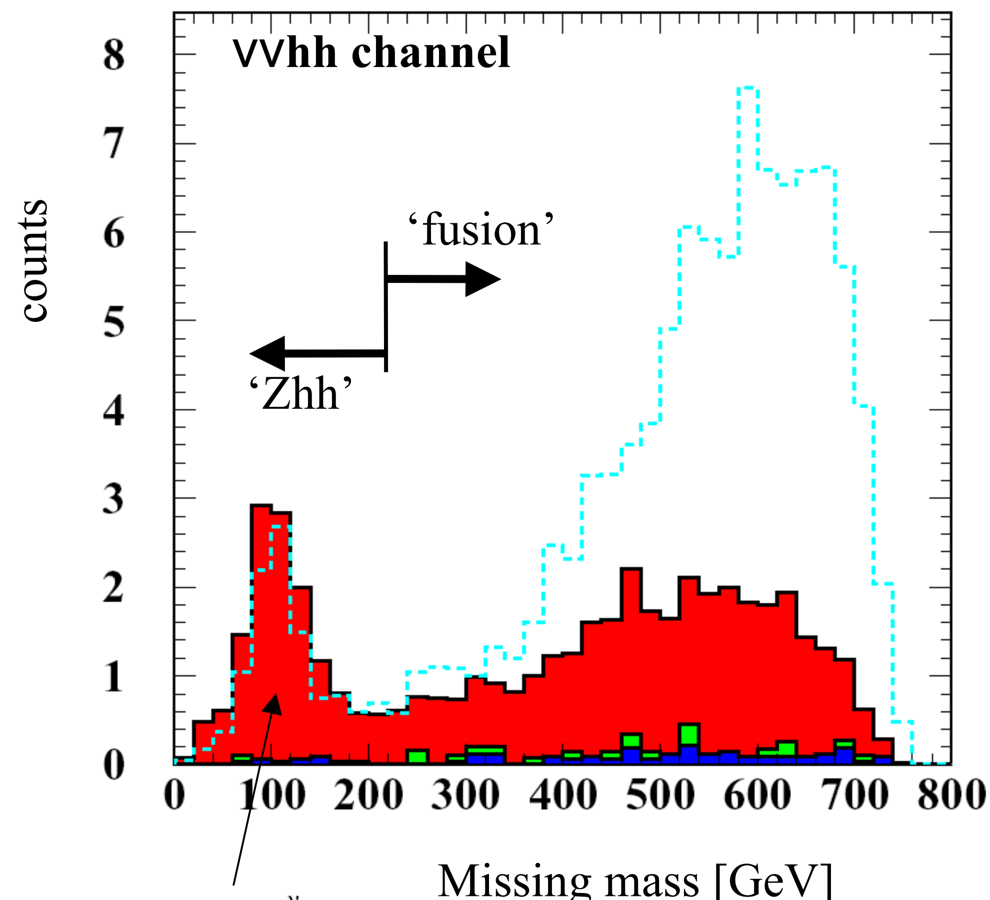


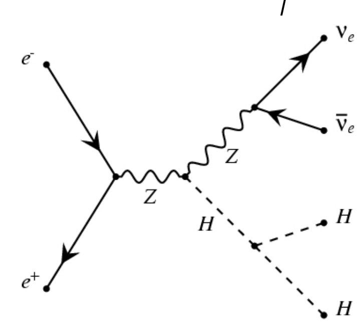
vvhh selection



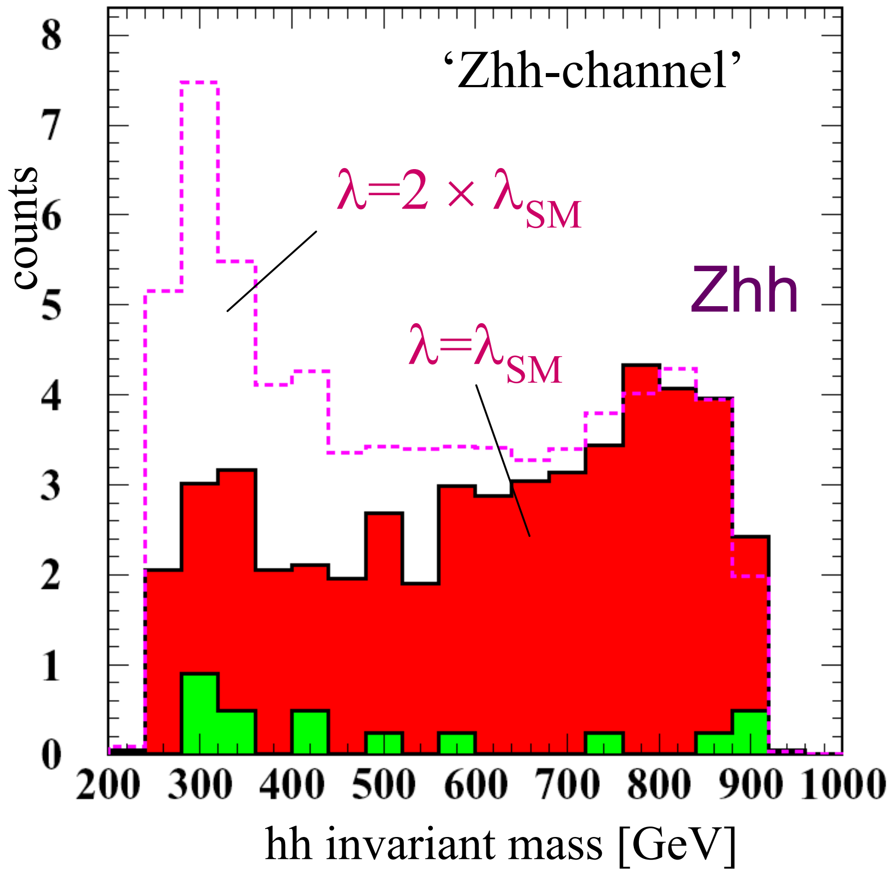
(~ OPAL Higgs scheme)

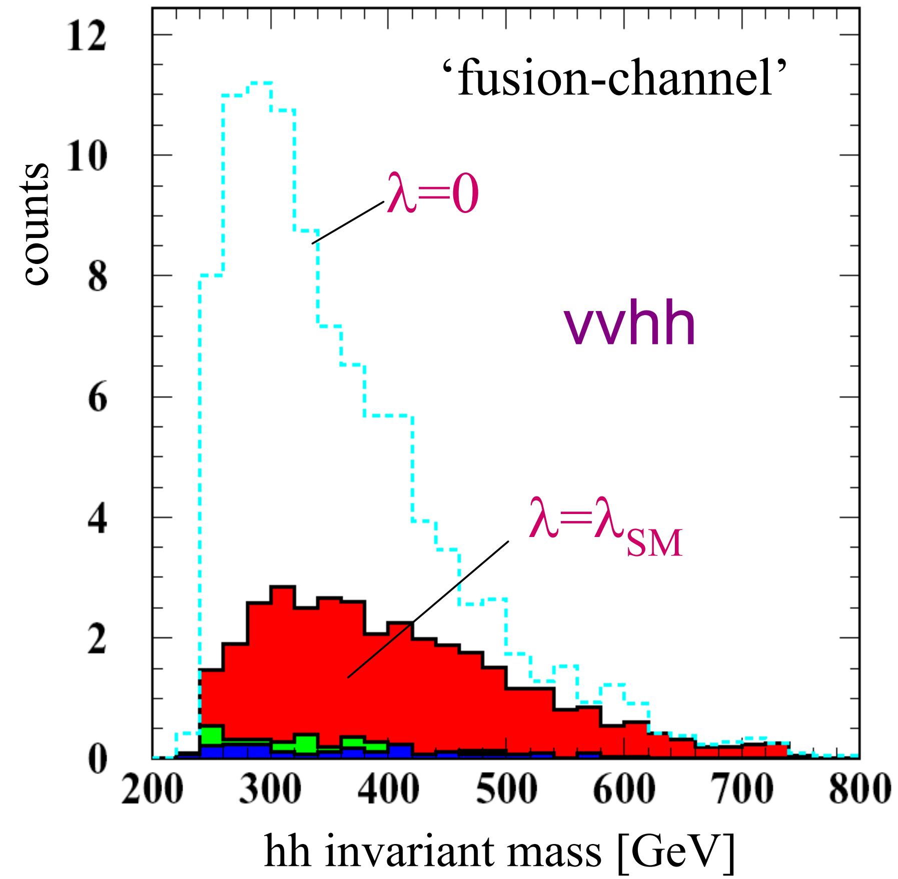
Separate Zhh & fusion



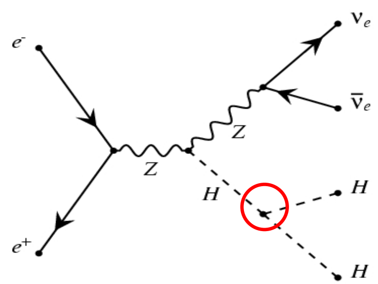


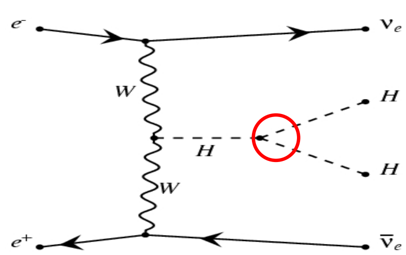
HH invariant mass distributions





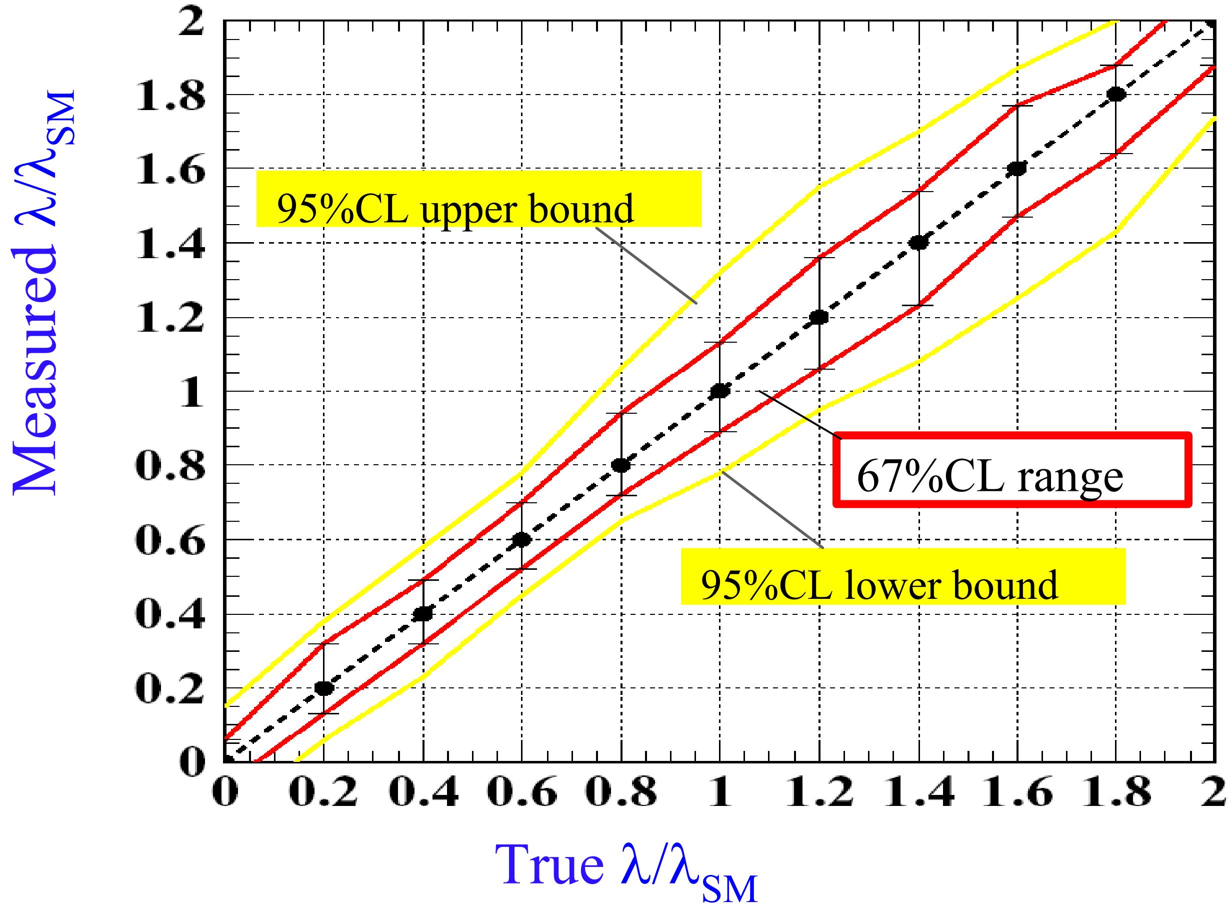
(= visible mass)





λ_{hhh} Measurement sensitivity

By Yamashita et.al. LCWS 2004



@1TeV

$\mathcal{I}_{lumi}$=1 ab^{-1}
Pol_{beam}= -80%

M_h=120 GeV
(SM Higgs Br)

Use only hh→ 4b
(Br(hh→ 4b)~47%)
Eff.(4b) 80%

Precise study ⇒ Radiative corrections are also important!!

⇒ Systematic study of the RC for Higgs physics at LC with GRACE

Summary

A quick simulation study has been performed for E_{cm}=1 TeV

For M_h=120 GeV: λ measurement sensitivity (only hh$\rightarrow$ bbbb only)

for $\lambda=\lambda_{SM}$	λ/λ_{SM}=1.0	+0.13 -0.11 (1σ)	0.78 - 1.32 (95%CL)
λ/λ_{SM}=0.6	0.6	+0.10 -0.07 (1σ)	0.45 - 0.77 (95%CL)
λ/λ_{SM}=1.4	1.4	+0.14 -0.18 (1σ)	1.08 - 1.70 (95%CL)

Still to be done:

- Non-b decay of the Higgs $\Rightarrow$ increase sensitivity
- **M_h>140GeV** $\Rightarrow$ W-par decay of the Higgs

  $\nu\nu hh \rightarrow$ 8f, 10f   *New version of Grace system*
- Radiative corrections (systematic study have been done)

  sizable $\Rightarrow$ include in the event generator
- New Physics study

Higgs at Linear Collider - Summary