Higgs and Electroweak Symmetry Breaking

Experimental Aspects

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SLAC

LCWS 04, April 23, 2004

More Complete Picture of LC Capabilities is Emerging Through More Detalied Analyses:

- Beam Related Sys Errors in Higgs Mass Measurements
- Comprehensive Jet Flavor Tagging Analysis for BR($h \rightarrow bb,cc,gg$)
- Overlaid Events, Vertex Smearing & Crab Crossing in $\gamma\gamma \rightarrow h \rightarrow bb$
- LHC/LC Complementarity:
  - M_A Determination From Higgs Branching Ratios
  - Study of MSSM Higgs Bosons in the Intense-Coupling Regime
- New Results From Analyses at Ecm=1TeV:
  - Branching Fractions for Rare Higgs Decays
  - Improved Higgs Self Coupling Measurement

Beam Related Systematics in Higgs Mass Measurement

Alexei Raspereza

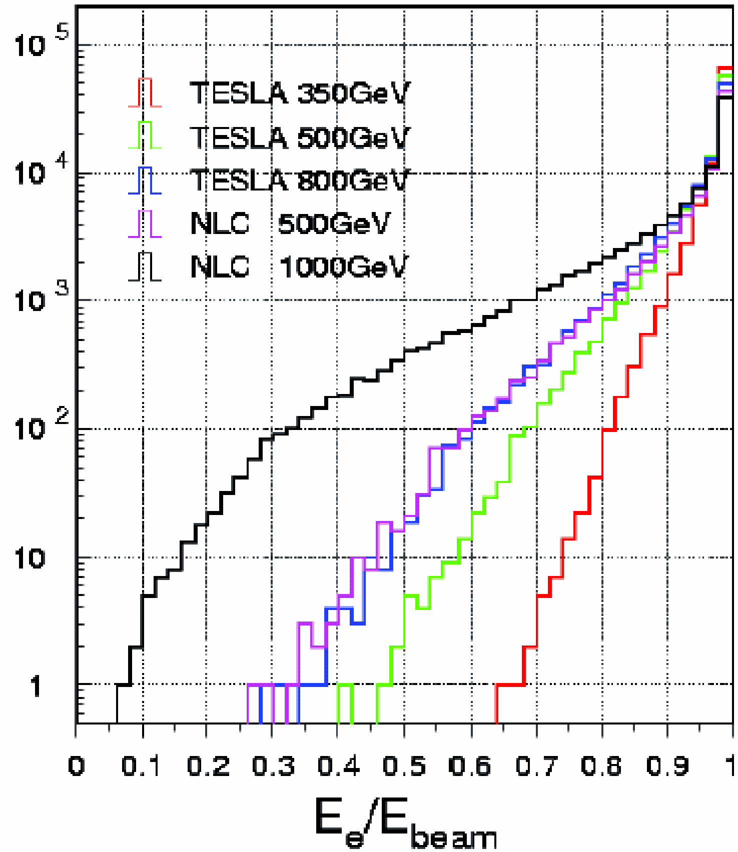
LC Workshop, Paris 20/4/2004

Differential Luminosity Spectrum

- Beamstrahlung → distortion of beam energy spectrum
- Parametrization :

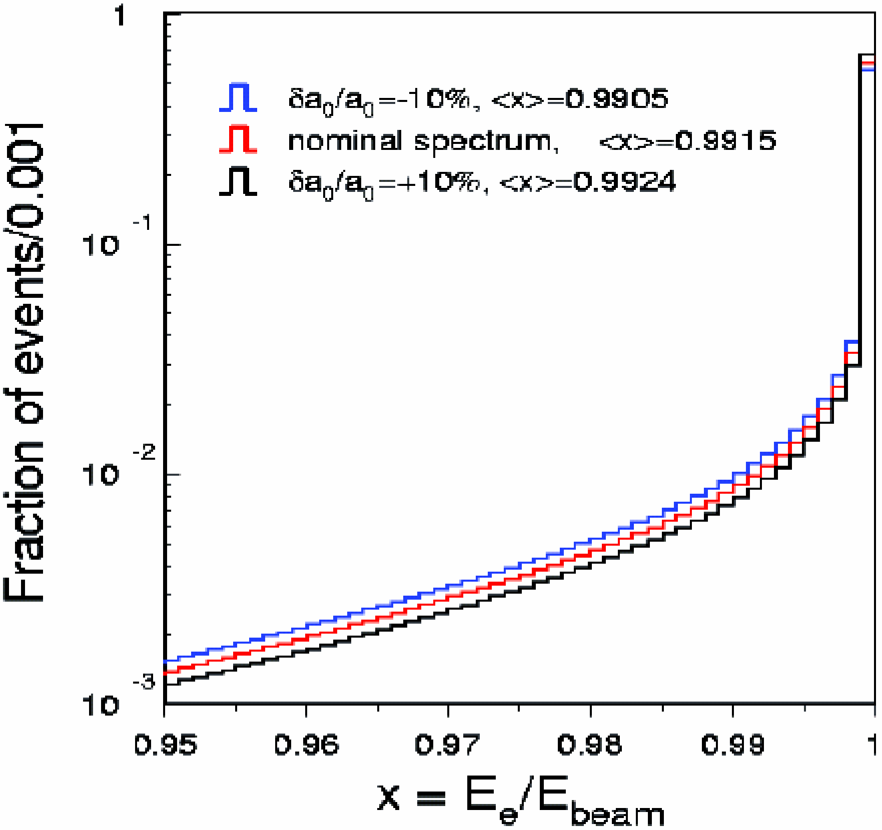
  $f(x) = a_0\delta(1-x)+a_1x^{a2}(1-x)^{a3}$, $x=E_e/E_{beam}$
- $\int f(x)dx = 1$ → 3 independent parameters: a_0, a_2, a_3
- acollinearity spectrum in Bhabha events → differential luminosity spectrum measurement
- K.Moenig, LC-PHSM-2000-60 :

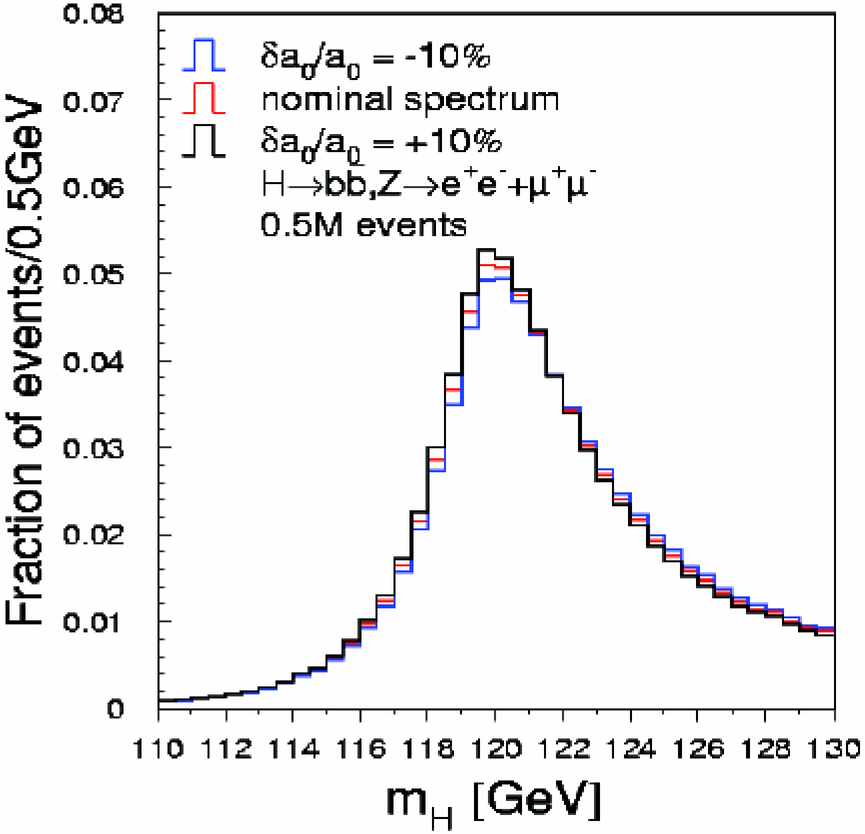
  $\delta a_i/a_i \leq 1\%$ with 3 fb^{-1} @ $\sqrt{s}$ = 500 GeV



$\sqrt{s}$ = 350 GeV : a_0=0.55, a_1=0.59, a_2=20.3, a_3=-0.63

Differential Luminosity Spectrum





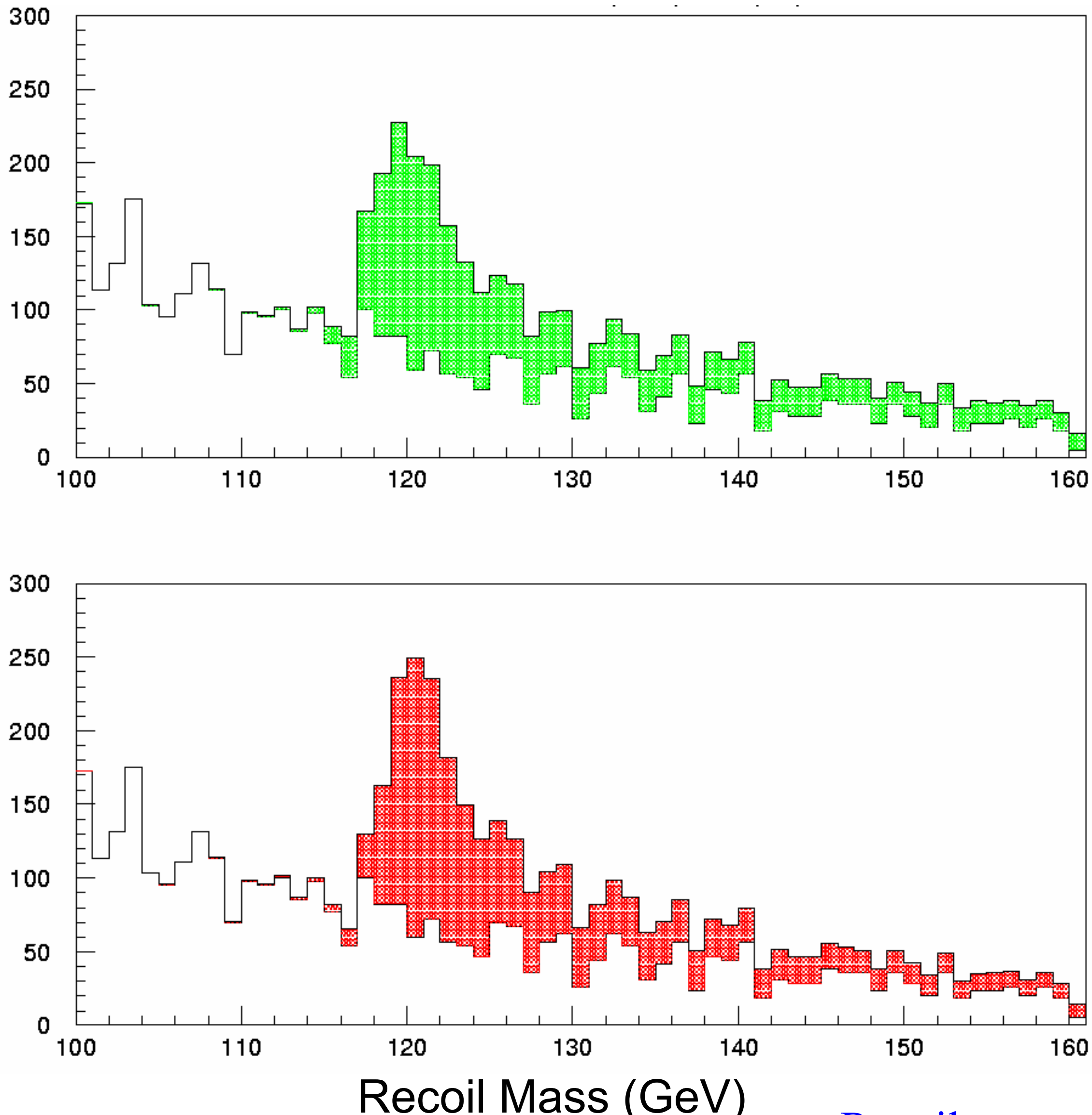
$\delta a_i \sim 10\%$: effect O(10MeV) on Higgs mass

$\delta a_i \leq 1\%$: effect of O(MeV) on Higgs mass

Simdet Detector Simulation of e+e- → Zh

$\sqrt{s} = 350\ GeV\ \ L = 500\ fb^{-1}$

$Z \to e^+e^-,\ \mu^+\mu^-$



Recoil Mass Results:

NLC

$$\frac{\delta E_e}{E_e} = 0.3\%$$

$$\delta M_h = 143\ MeV$$

TESLA

$$\frac{\delta E_e}{E_e} = 0.1\%$$

$$\delta M_h = 117\ MeV$$

Recoil mass energy scale error : $\delta M_h = 2.9\,\delta E_e$

M_H measurement using kinematic fit of qqll and qqbb

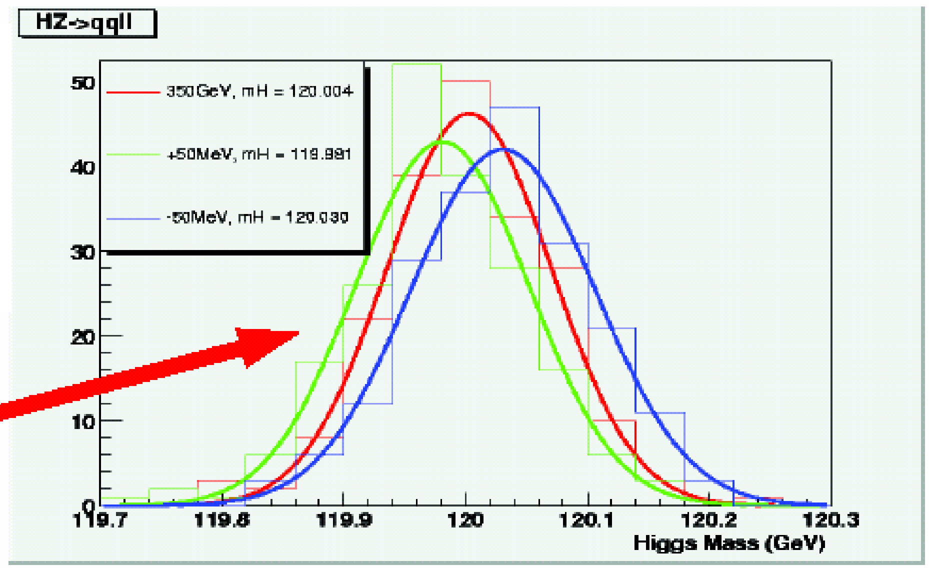
Energy scale error

$$\delta M_h = 1.0\,\delta E_e \quad (qqll)$$
$$\delta M_h = 0.8\,\delta E_e \quad (bbqq)$$

$\delta E_{e+} = \delta E_{e-} = \pm 25$ MeV results in a mass shift

~ 25 MeV for HZ qq*ll*

~ 20 MeV for HZ bbqq



Effect of beam spread

- statistical accuracy degrades

from 45 to 50 MeV in HZ $\rightarrow$ bbqq channel

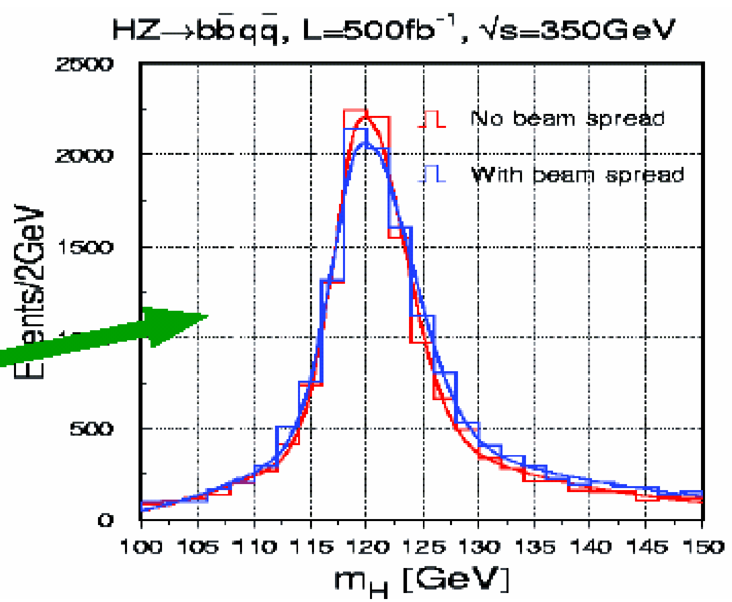
from 70 to 80 MeV in HZ $\rightarrow$ bb*ll* channel

if one assumes 0.5% beam spread for both e^+ and e^-

$\Rightarrow$ statistical accuracy degrades

from 72 to 76 MeV (6%) for TESLA$\rightarrow$ NLC (*bbll*)

from 46 to 48 MeV (4%) for TESLA$\rightarrow$ NLC (*bbqq*)



	δM_h in MeV		
	TESLA	TESLA	NLC
Decay mode	$\delta E/E=0$	$\delta E/E=0.1\%$	$\delta E/E=0.3\%$
recoil mass	110	117	143
$ZH \rightarrow l^+l^-q\bar{q}$	70	72	76
$ZH \rightarrow q\bar{q}b\bar{b}$	45	46	48
Combined	38	39	40

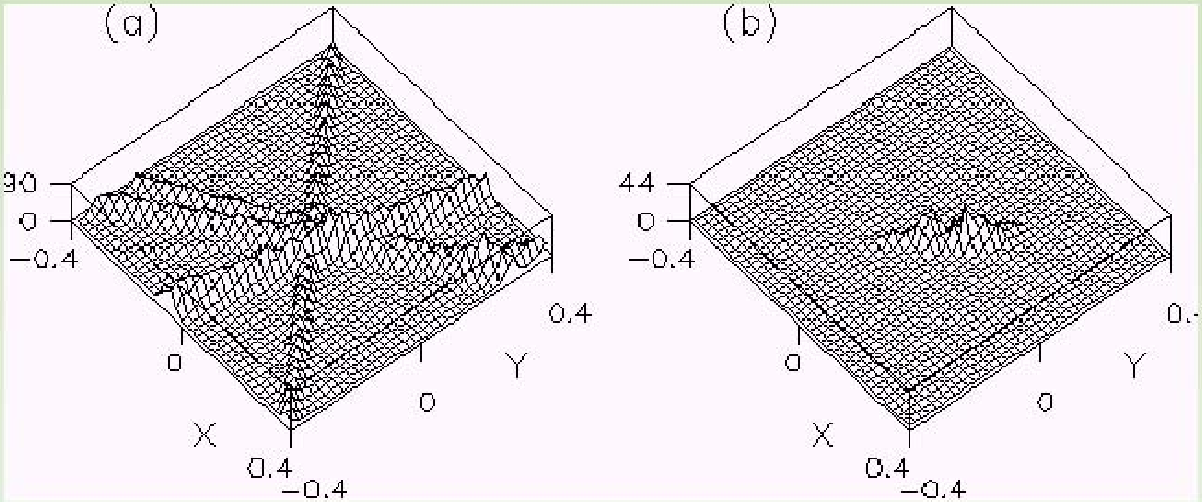
MSSM theory error on m_h : (S. Heinemeyer)

Current theory uncertainty: $\delta m_h^{\text{theo,today}} \approx 3$ GeV

Future theory uncertainty: $\delta m_h^{\text{theo,future}} \lesssim 0.5$ GeV necessary/possible

Future parametric uncertainty: $\delta m_h^{\text{para,future}} = \mathcal{O}(0.2 \text{ GeV})$ $(m_t,\ \alpha_s)$

Flavor Tag



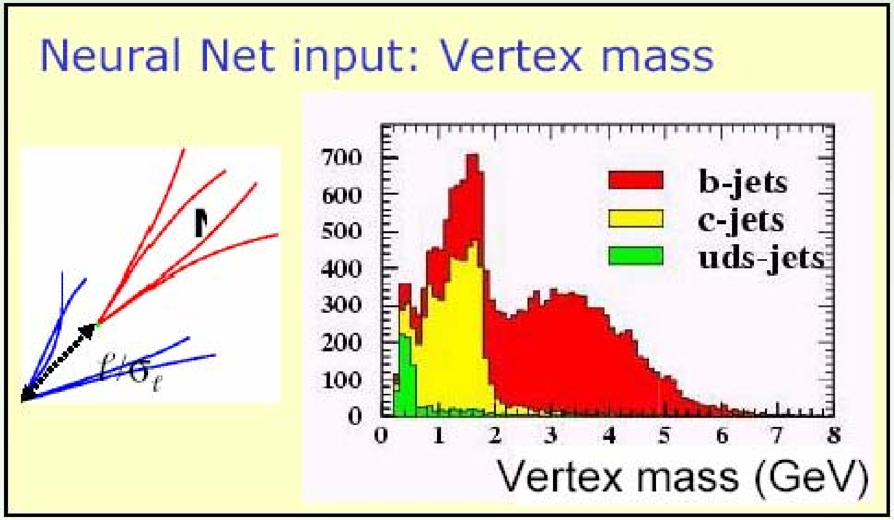
Vertex reconstruction:

ZVTOP (from SLD)

- Tracks interpreted as probability tubes
- Vertex: crossings of these tubes

Neural Net for Flavor-separation

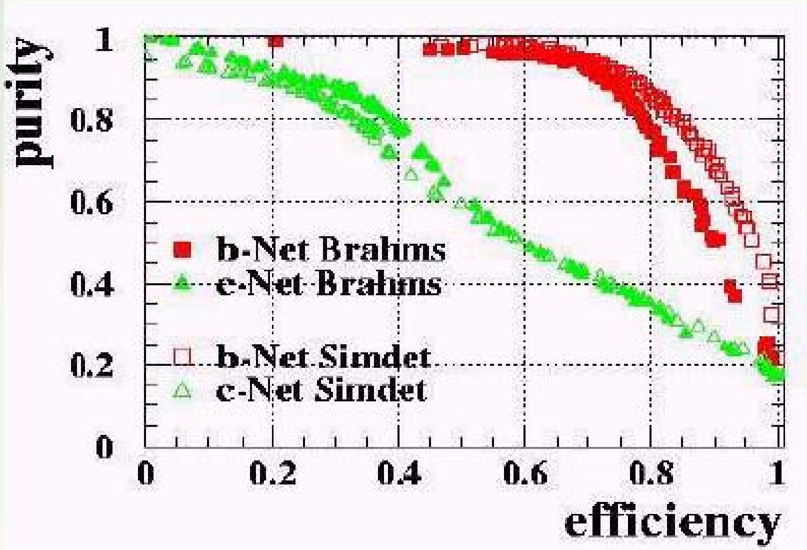
- Training:HZ→qqll events at 350 GeV
- Most important input variable: vertex mass



Neural Net performance

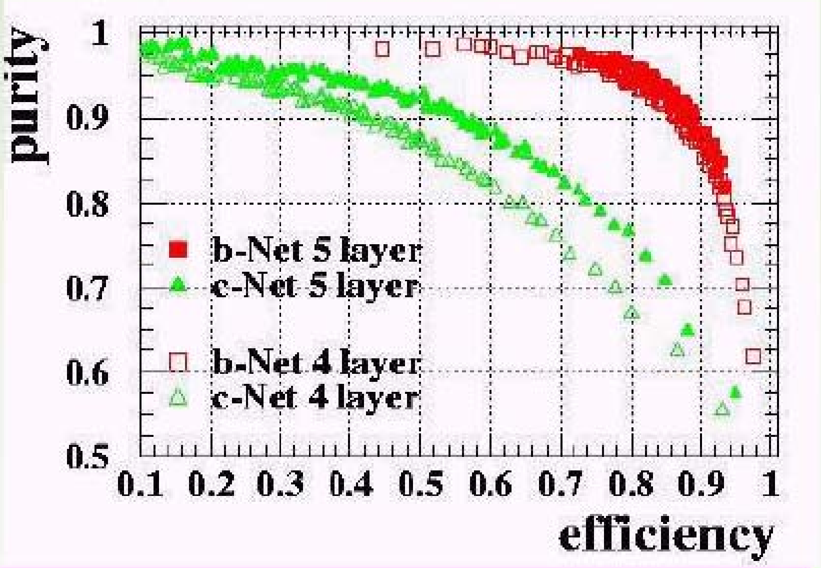
<u>Comparison of fast Simdet and full Brahms simulation</u>

- Simdet tuned with this Brahms version(91.2 GeV)
- C-Tag:Very good agreement
- B-Tag: Reasonable, differences: missing resolution tails



<u>Vertex Detector dependence</u>:

- Two jet tag for Higgs events at 350 GeV (net used for this analysis!)
- With/without innermost layer
- B-Tag: Very robust
- C-Tag: Very sensitive benchmark



Results

- <u>Combined result</u> (all 3 channels, m_H=120 GeV, ECM=350 GeV, 500fb^{-1}):
  - $\Delta(\sigma\ BR(H\rightarrow bb)/\sigma_{SM})$: 68.20± 0.75%
  - $\Delta(\sigma\ BR(H\rightarrow cc)/\sigma_{SM})$: 3.01 ± 0.36%
  - $\Delta(\sigma\ BR(H\rightarrow gg)/\sigma_{SM})$: 6.70 ± 0.55%
- <u>Individual channels:</u>

	$Z\rightarrow$all	$Z\rightarrow qq$	$Z\rightarrow ll$	$Z\rightarrow\nu\nu$
$\Delta(\sigma\ BR)/\sigma\ BR(bb)$	1.1%	1.5%	3.0%	2.1%
$\Delta(\sigma\ BR)/\sigma\ BR(cc)$	12.1%	17.5%	33.0%	20.5%
$\Delta(\sigma\ BR)/\sigma\ BR(gg)$	8.3%	14.4%	18.5%	12.3%

- Error checked with 10 independent samples: no bias observed
- Different background composition of different selection channels is helpful
- Missing: Correct treatment of other Higgs decay channels (WW, $\tau\tau$, ZZ), currently treaten as fixed background

Comparison

	$\Delta(\sigma BR)/(\sigma BR)(bb)$	$\Delta(\sigma BR)/(\sigma BR)(cc)$	$\Delta(\sigma BR)/(\sigma BR)(gg)$
This analysis	1.1%	12.1%	8.3%
TDR(Battaglia) *	0.9%	8.0%	5.1%
Snowmass(Brau,Potter)	1.6%	19.0%	10.4%

*For comparison: Subtracting 2.2% error on total Higgs cross section to get ???
and use standard model fraction of fusion channel

•TDR analysis (Marco Battaglia):

- Error for cc and gg 50% larger
- New selection more efficient in $qq\nu\nu$ and qqll
- Difference: rather optimistic flavor-tag parametrization, no jet-jet confusion/splitting included

•Snowmass analysis (Brau/Potter):

- Flavor tagging of American LC-group is a bit better (innermost layer at 1.2 cm)
- Differences:
  - More fancy analysis (used not all channels)
  - Cuts for flavor separation instead of 2-dim. Fit

Improved analysis on $\gamma\gamma \rightarrow$ ***higgs*** $\rightarrow b\bar{b}$

including overlaid events, vertex smearing and crab crossing for SM and MSSM

P. Nieżurawski, A. F. Żarnecki, M. Krawczyk

Faculty of Physics
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Overview

Our analysis of precision $\sigma(\gamma\gamma \to \textit{higgs} \to b\bar{b})$ measurement includes:

- realistic $\gamma\gamma$-spectra
- b-tagging
- overlaying events $\gamma\gamma \to \textit{hadrons}$ (OE)
- results for SM at $M_h = 120, 130, 140, 150, 160$ GeV
- results for MSSM at $M_A = 200, 250, 300, 350$ GeV
  with $\tan\beta = 7$, $M_2 = \mu = 200$ GeV (following M. Mühlleitner *et al.*)

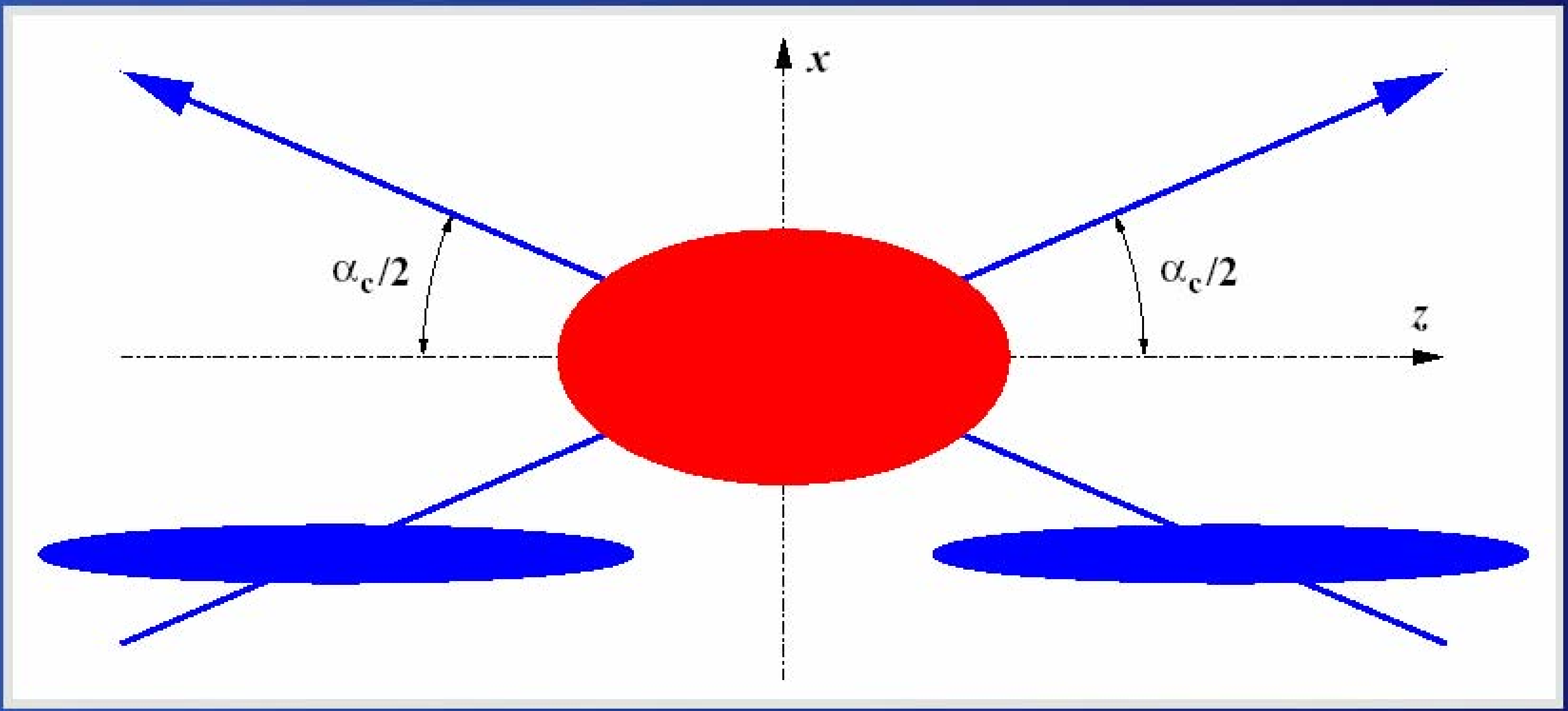
Recent development:

- crossing angle
- primary vertex distribution

Crab-wise crossing of beams

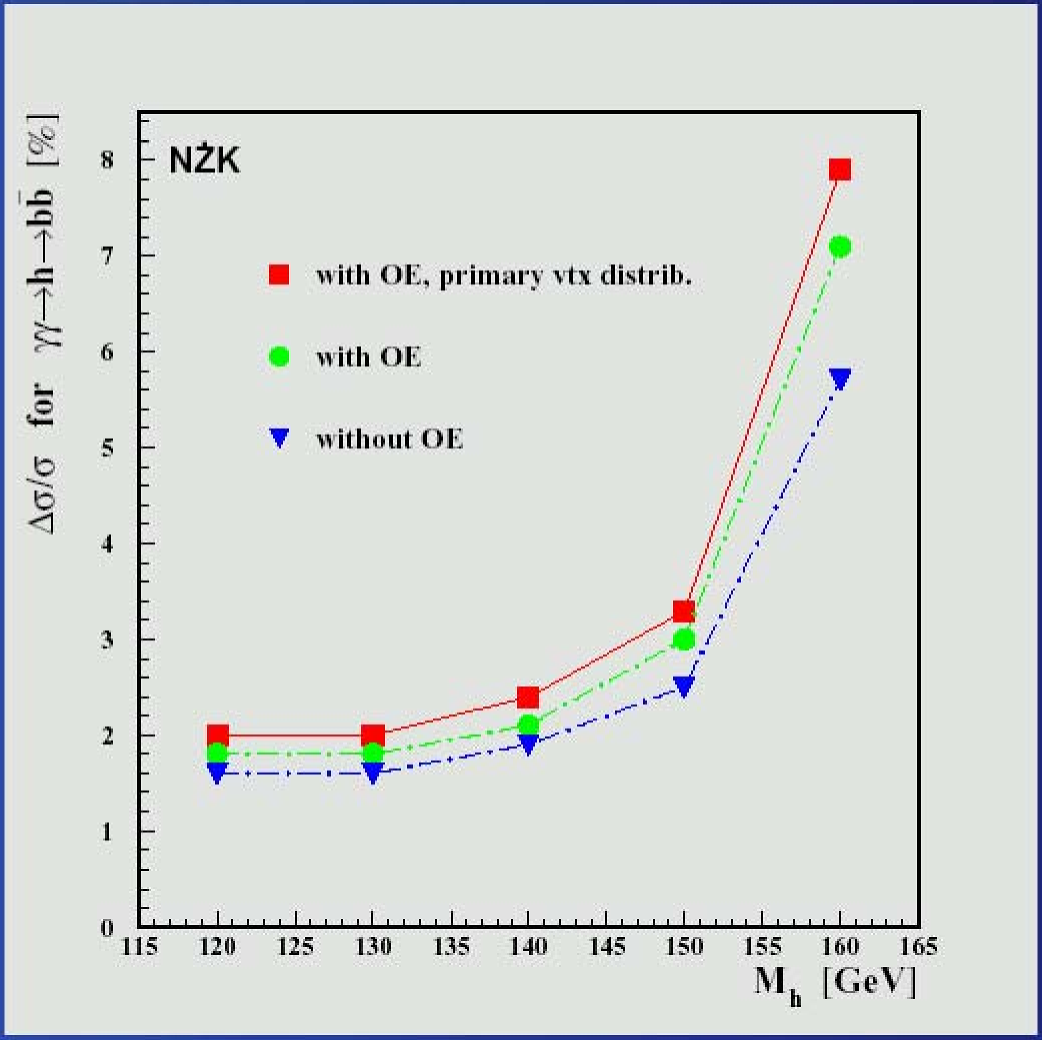
$$\sigma'_x = \sqrt{\tfrac{1}{2}(\sigma_x^2 + \sigma_z^2 \tan^2(\alpha_c/2))} \qquad \sigma'_y = \sigma_y/\sqrt{2} \qquad \sigma'_z = \sigma_z/\sqrt{2}$$

Bunch:	$\sigma_x = 140$ nm	$\sigma_y = 7$ nm	$\sigma_z = 0.3$ mm
Primary vertex:	$\sigma'_x = 3.6$ μm	$\sigma'_y = 5$ nm	$\sigma'_z = 0.2$ mm

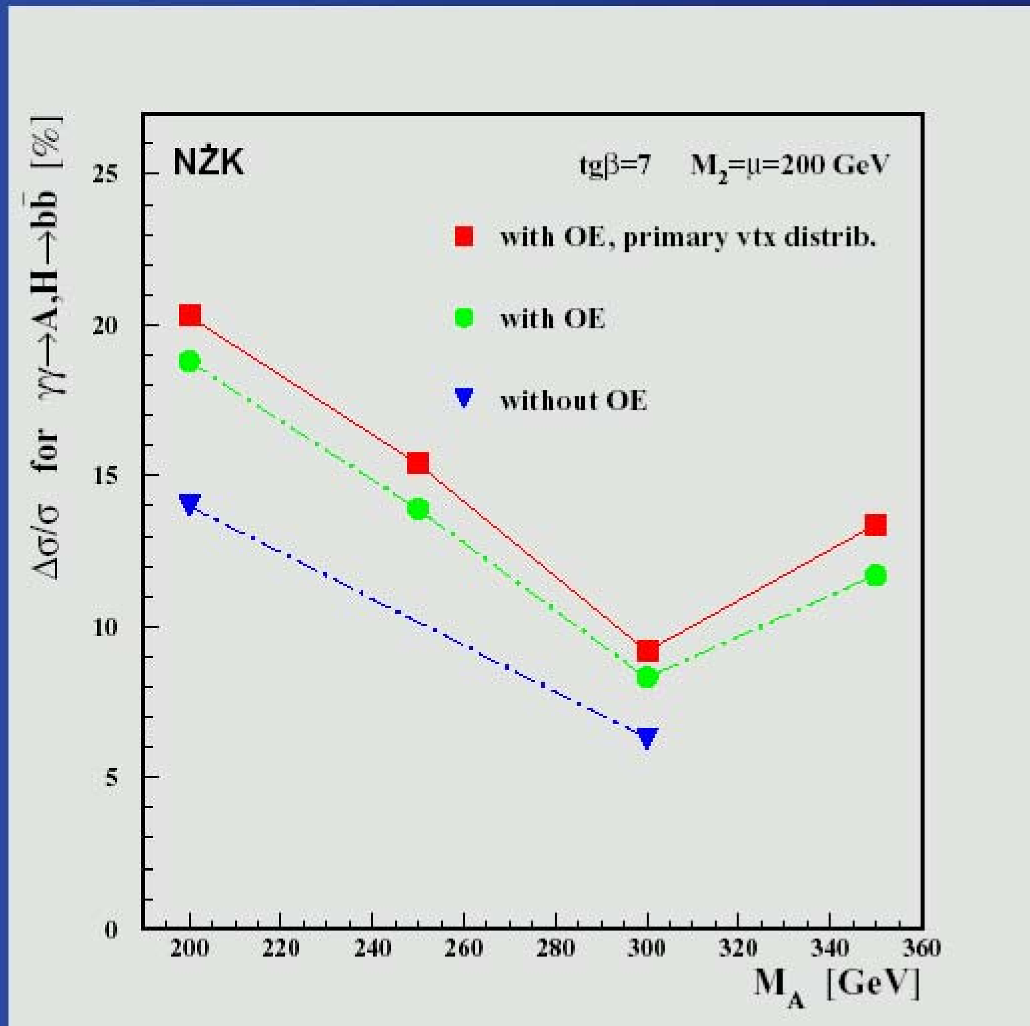


$\alpha_c = 34$ mrad

SM summary, $M_h = 120\text{-}160$ GeV



MSSM, M_A = 200-350 GeV



M_A determination from the Higgs branching ratios with full parametric uncertainties

K. Desch, E. Gross, S. Heinemeyer, G. Weiglein, L. Živković

Indirect constrains on M_A

- Several analyses have been performed:
  - D. Asner et al., Eur. Phys. Jour. **C 28** (2003) 27, hep-ex/0111056;
  - J. Guasch, W. Hollik and S. Peñaranda, Phys. Lett. **B 515** (2001) 367, hep-ph/0106027;
  - M. Carena, H. Haber, H. Logan and S. Mrenna, Phys. Rev. **D 65** (2002) 055005, E:*ibid* **D 65** (2002) 099902, arXiv:hep-ph/0106116.

- They all kept fixed all parameters except one under investigation (i.e. M_A) assuming that SUSY parameters enter without any experimental or theoretical uncertainty $\Rightarrow$ here we take into account all experimental and theoretical uncertainties

Indirect constrains on M_A

- Model is SPS1a with following errors assumed:

Δm_{sb1}	Δm_{sb2}	Δm_{gluino}	Δm_{st1}	Δm_h	$\tan\beta$
5.7 GeV	6.2 GeV	6.5 GeV	2 GeV	0.5 GeV	10%

From LC for $\tan\beta = 10$

We assume that we can measure lighter stop at LC, m ~ 400 GeV

Precise measurement of m_h with an error from theory included

- We compare theoretical prediction of

$$r \equiv \frac{[BR(h \to b\bar{b}) / BR(h \to WW^*)]_{MSSM}}{[BR(h \to b\bar{b}) / BR(h \to WW^*)]_{SM}}$$

with its prospective experimental measurements

- Even though the experimental error of the two BR's is larger than that of the individual ones, it has stronger sensitivity

Conclusions

- If we find just one Higgs boson at LHC, precision measurement at LC would allow to tell its nature (SM or MSSM)

- We could put constraints on the mass of the CP-odd Higgs boson
precision would be 20 (30)% for m_A equal to 600 (800) GeV

- If we find several Higgs bosons at LHC, precision measurement at LC would allow us to shed some light on the possible model

Search for the MSSM Higgses in the intense-coupling regime at a Linear Collider (TESLA)

Edward Boos

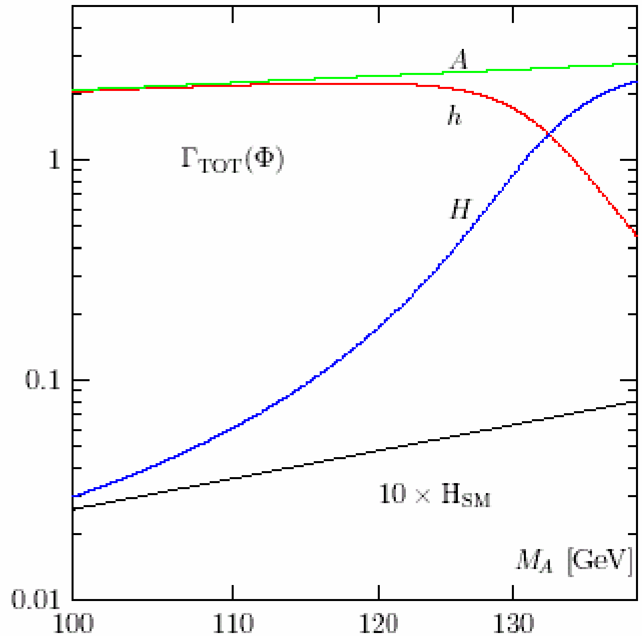
At least the lightest Higgs boson h must have a mass below some value of $130-135$ GeV
In the decoupling regime H, A and $H^\pm$ are heavy $M_A \sim M_H \sim M_{H^\pm}$
The lightest Higgs particle h is similar to the SM Higgs

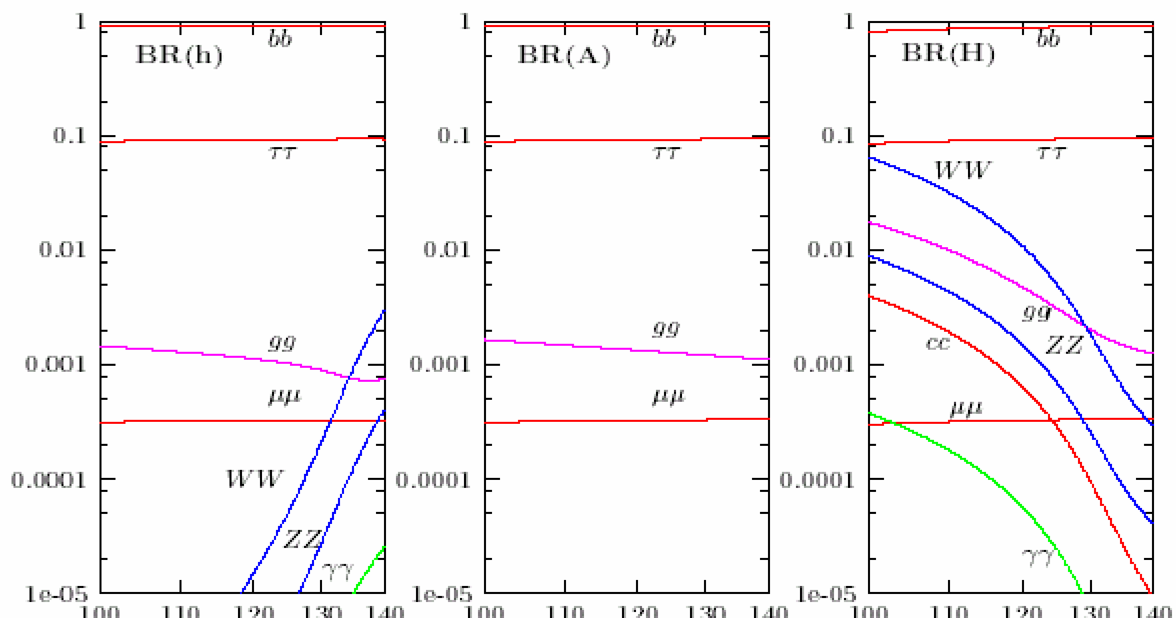
Another, more complex, situation is when pseudoscalar A boson is not much larger than h, and $\tan\beta$ is large.

Masses could be rather close.
Widths are large.
Couplings and Br-fractions in some cases are significantly different from SM or decoupling regime.
So, the phenomenology is different.

Such a scenario was called the Intense-coupling regime
(E.B., A.Djouadi, M.Mühlleitner, A.Vologdin)

Total Width and Branching Fractions





How to resolve?

At the LHC:

$\mathrm{Br}(h, H, A \to \gamma\gamma) \sim 10^{-5} - 10^{-6}$ - too small

$b\bar{b}$ and $\tau^+\tau^-$ modes - energy resolution is not enough

More promising - $\mu^+\mu^-$ Higgs decay in $b\bar{b} + h, H, A$ production:

$\mathrm{Br}(h, H, A \to \mu^+\mu^-) \sim 3 - 3.5\ 10^{-4}$, Energy resolution for muons $\sim 1 - 1.5\ GeV$, Tagging b-jets

At LC a multichannel analysis should be used:

1. $b\bar{b}l^+l^-$ mode using recoil mass for the Higgsstrahlung
2. $b\bar{b}b\bar{b}$ and/or $b\bar{b}\tau^+\tau^-$ modes for the Higgs pair production

Conclusions

- The intense coupling regime - one of the most difficult scenario to be resolved completely
  (At the LHC - one can separate states if mass differences are about 5 GeV or more)
- At LC - h and H masses could be measured to about 80-280 MeV accuracy at energies about 300 GeV and 500 fb^{-1} lumi in the 2 leptons + 2 b-jets mode using the recoil mass technique
- Mass of the A Higgs bosons can be measured to a similar accuracy in the 4 b-jet mode (Ah+AH) using measured values M_h and M_H and applying the "combinatorial mass difference" analysis

Higgs Coupling Measurements at 1 TeV (T. Barklow)

Take cue from Battaglia & DeRoeck results for $B_{h \to \mu\mu}$ at CLIC and investigate branching fraction measurements in WW fusion at a 1 TeV LC.

$$e^-_{pol} = -80\% \quad L = 500\,(1000)\ fb^{-1} \quad for \quad \sqrt{s} = 350\,(1000)\ GeV:$$

$\sqrt{s}$ (GeV)	e^+_{pol} (%)	Higgs Mass (GeV) 120	140	160	200
350	0	110280	89150	69975	37385
350	+50	159115	128520	100800	53775
1000	0	386550	350690	317530	259190
1000	+50	569750	516830	467900	382070

Results presented for $h \to b\bar{b}, W^+W^-, gg, \gamma\gamma, ZZ$

No results for $h \to c\bar{c}, \tau^+\tau^-$ since detailed charm-tagging beyond scope and Higgs mass resolution for $h \to \tau^+\tau^-$ severely degraded by neutrinos.

$$e^+e^- \rightarrow \nu_e \overline{\nu}_e h$$
$$\quad\quad\quad\quad |\!\rightarrow b\overline{b}$$

$M_h = 200\ GeV$

$\sqrt{s} = 1\ TeV$

$L = 1\ ab^{-1}$

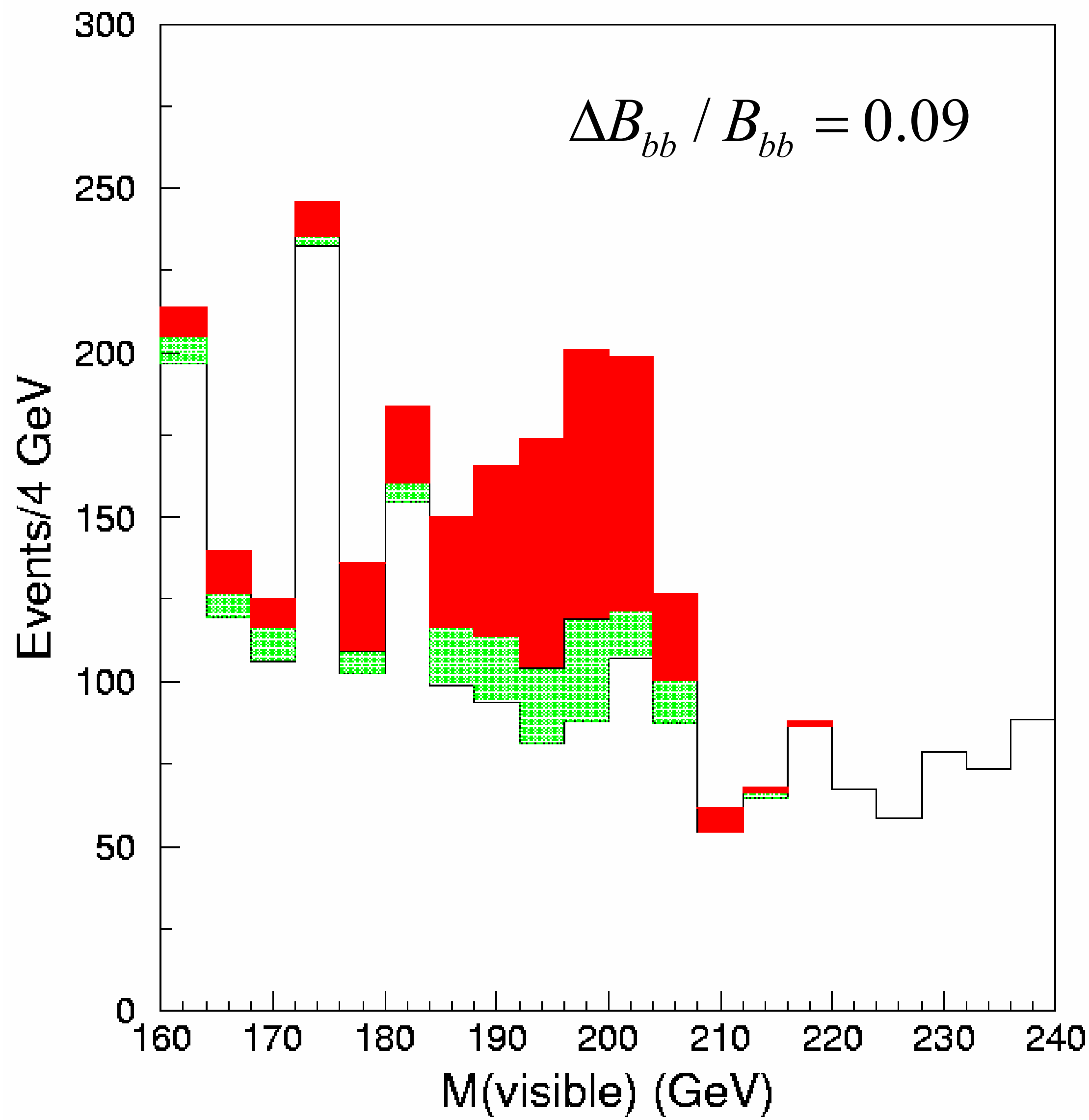
All 2,4,6-fermion and top-resonance 8-fermion backgrounds included

Background passing cuts (white histogram) is mostly

$$e^+e^- \rightarrow e^+e^-W^+W^-$$

Red histogram: $h \rightarrow b\overline{b}$

Green histogram: $h \rightarrow WW,\ ZZ$



$$e^+e^- \to \nu_e \overline{\nu}_e h$$
$$\quad\quad\quad\quad\quad\quad |\to \gamma\gamma$$

$M_h = 120\ GeV$

$\sqrt{s} = 1\ TeV$

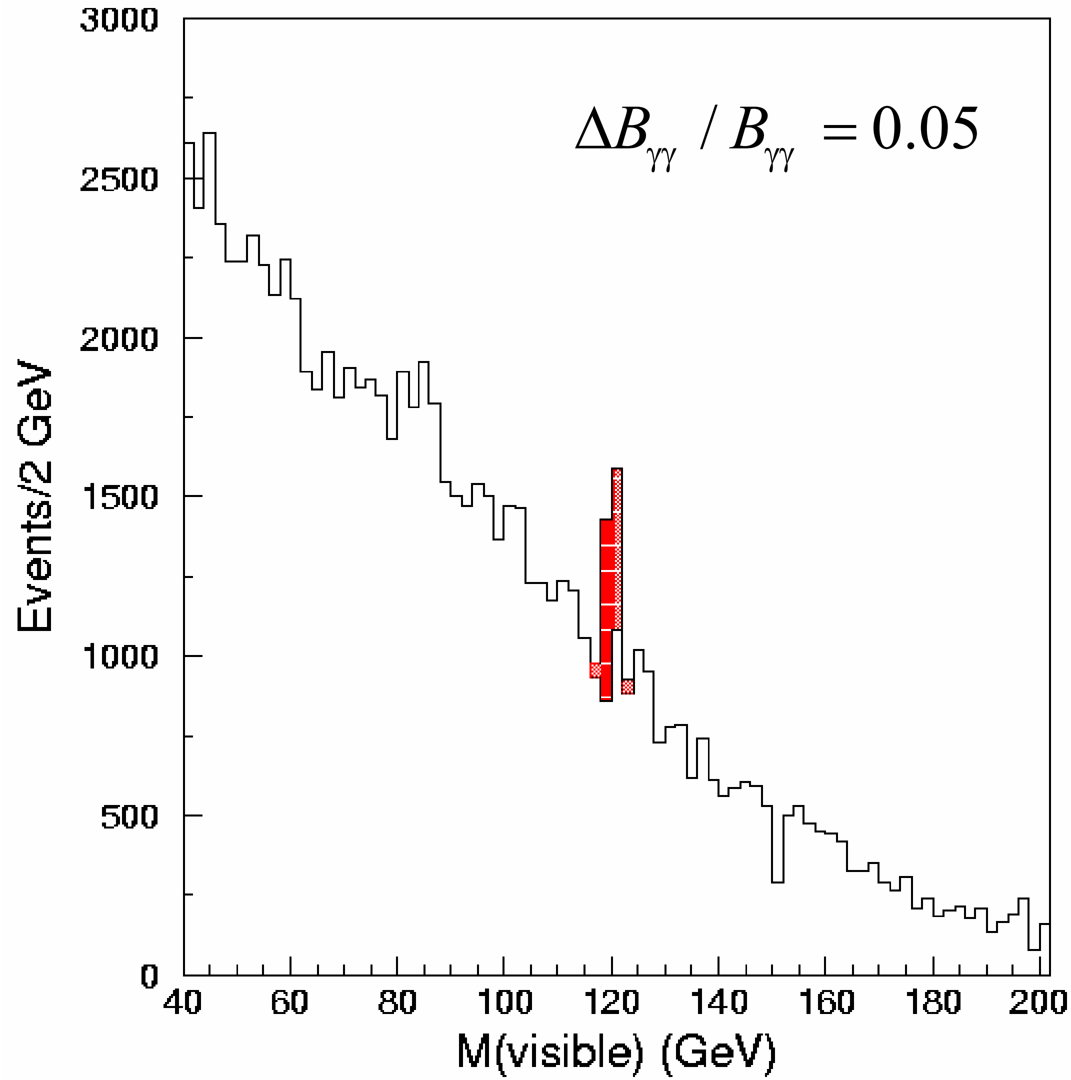
$L = 1\ ab^{-1}$

All 2,4,6-fermion and top-resonance 8-fermion backgrounds included

Non-Higgs background (white histogram) is mostly

$$e^+e^- \to \nu\nu\gamma\gamma$$

Red histogram: $h \to \gamma\gamma$



TESLA TDR:

Channel	$M_H = 120\,\mathrm{GeV}$	$M_H = 140\,\mathrm{GeV}$	$M_H = 160\,\mathrm{GeV}$
$H^0/h^0 \to b\bar{b}$	$\pm$ 0.024	$\pm$ 0.026	$\pm$ 0.065
$H^0/h^0 \to c\bar{c}$	$\pm$ 0.083	$\pm$ 0.190	
$H^0/h^0 \to gg$	$\pm$ 0.055	$\pm$ 0.140	
$H^0/h^0 \to \tau^+\tau^-$	$\pm$ 0.050	$\pm$ 0.080	

$\Gamma_{H\to X}$	$\mathrm{BR}(H \to X)$	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$	$160\,\mathrm{GeV}$
$WW = WW\nu\nu$	$H^0 \to WW$	± 0.061	± 0.045	± 0.134

1 TeV ANALYSIS:

	Higgs Mass (GeV)				
	115	120	140	160	200
$\Delta B_{bb}/B_{bb}$	± 0.015	± 0.016	± 0.018	± 0.020	± 0.090
$\Delta B_{WW}/B_{WW}$	± 0.024	± 0.020	± 0.018	± 0.010	± 0.025
$\Delta B_{gg}/B_{gg}$	± 0.021	± 0.023	± 0.035	± 0.146	
$\Delta B_{\gamma\gamma}/B_{\gamma\gamma}$	± 0.055	± 0.054	± 0.062	± 0.237	
$\Delta \Gamma_{tot}/\Gamma_{tot}$	± 0.035	± 0.034	± 0.036	± 0.020	± 0.050

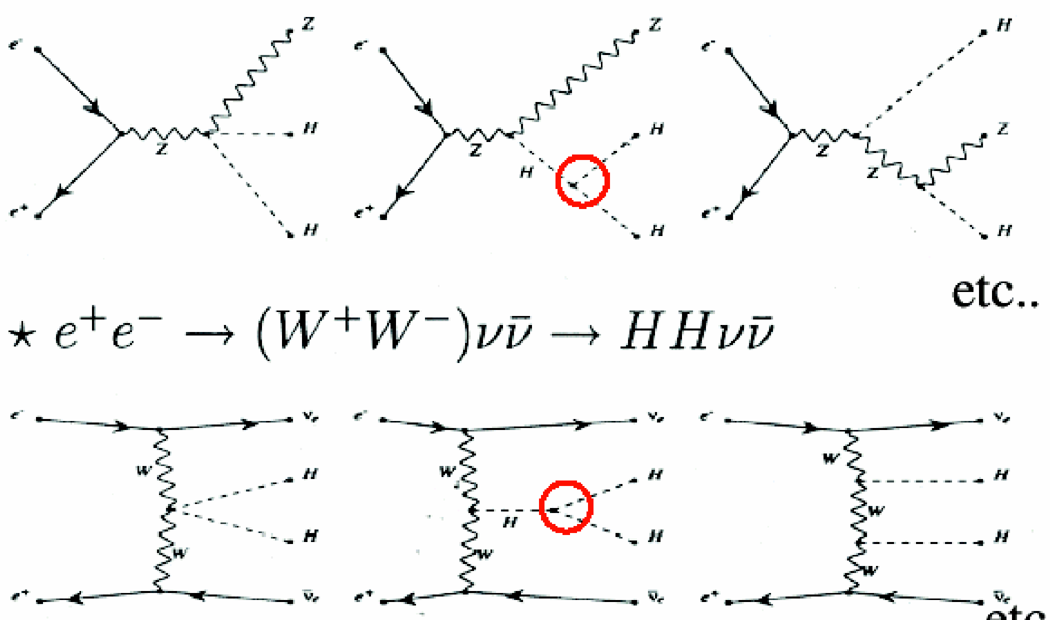
A study of Higgs self-coupling measurement at about 1 TeV

ICEPP, Univ. of Tokyo
S.Yamashita

@1TeV 2 main modes

★ $e^+e^- \to ZHH$

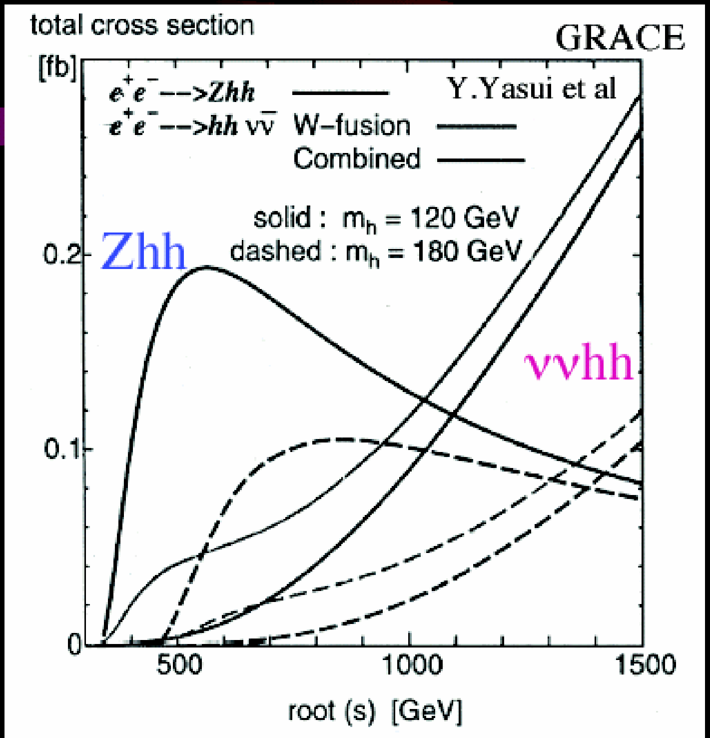
produced by GRACEFIG



etc..

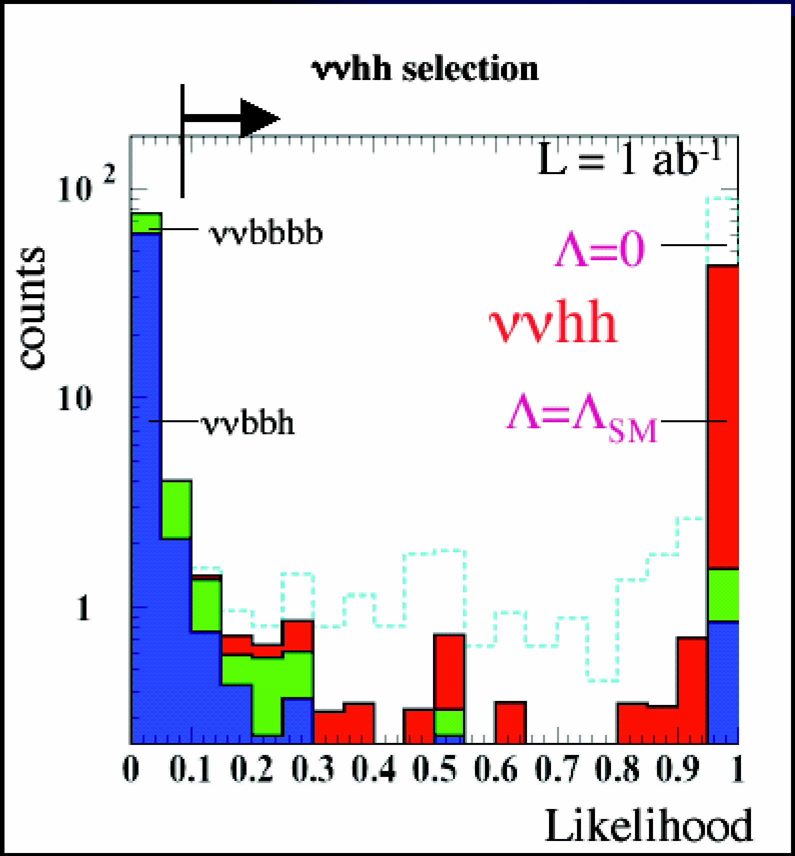
★ $e^+e^- \to (W^+W^-)\nu\bar{\nu} \to HH\nu\bar{\nu}$

etc.



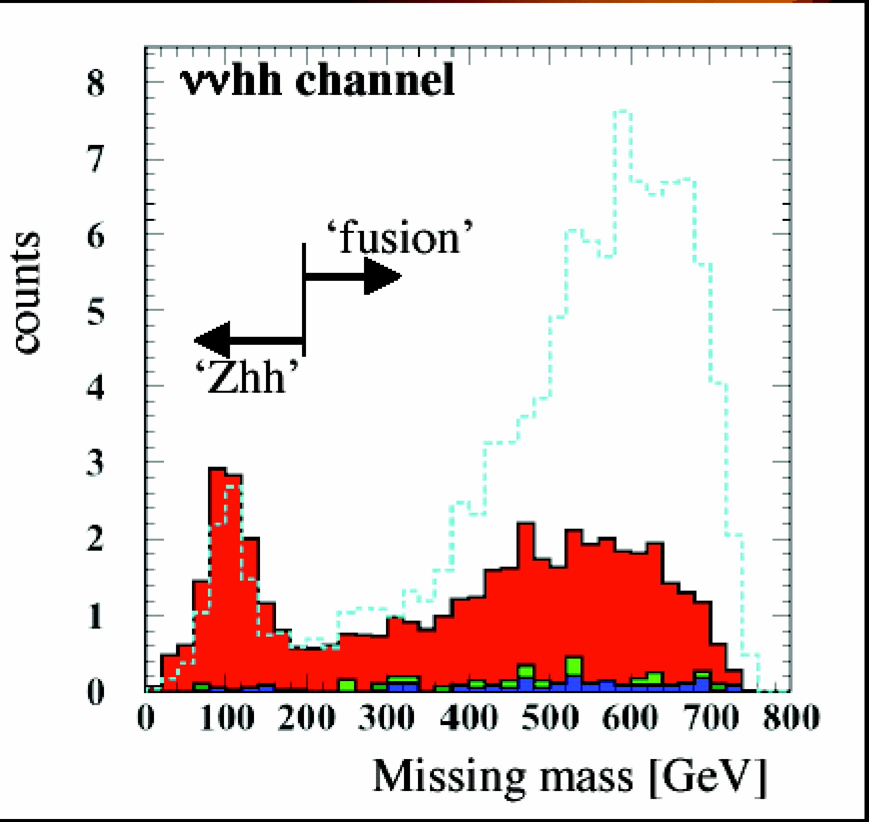
Likelihood selection
(~ OPAL Higgs scheme)

Using:
Compatibility to ννhh ννZZ ννZh etc..

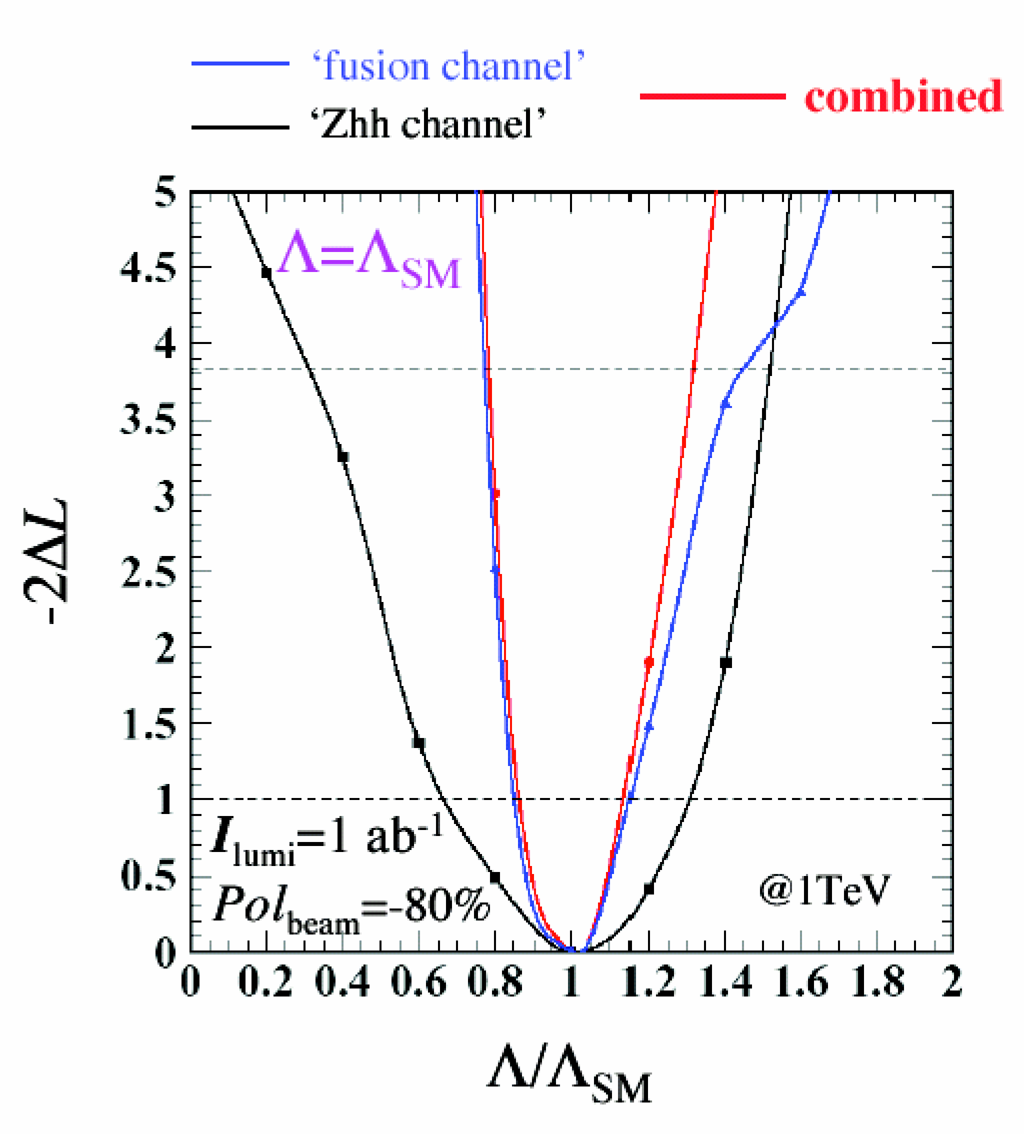


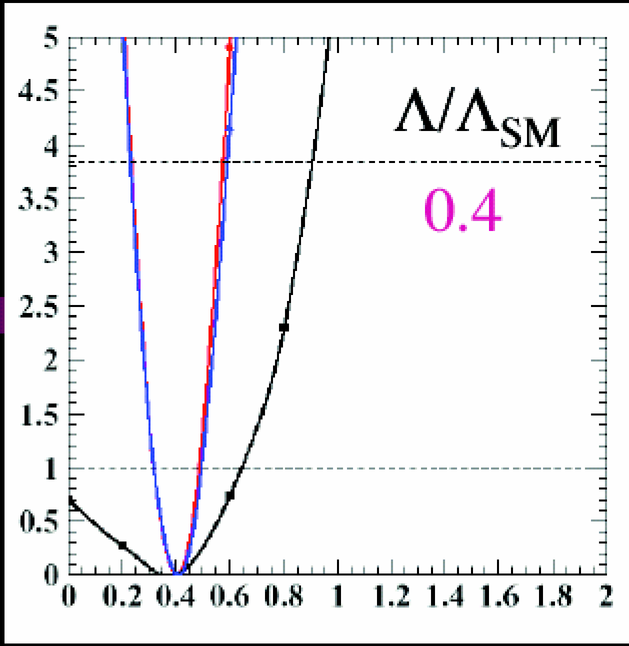
After Likelihood selection

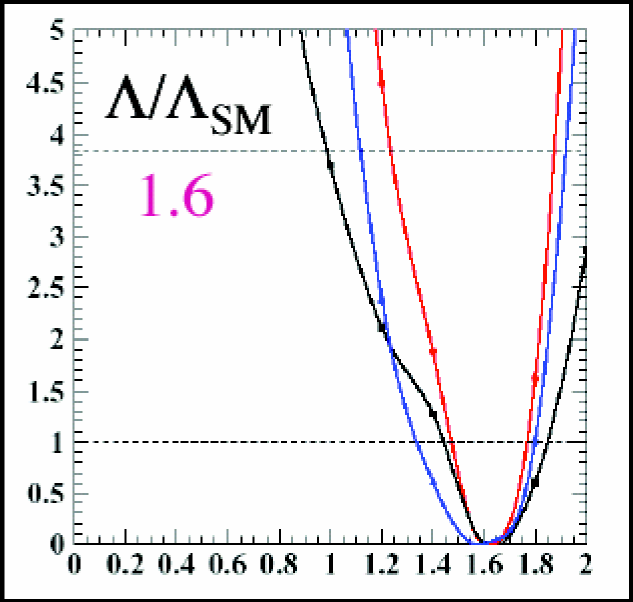
Separate 'Zhh' & 'fusion-channel'



Λ measurement sensitivity







- A quick simulation study has been performed for E_{cm}=1 TeV under the condition:
  - $\delta E_{jet}/E_{jet} \sim 30\%/\sqrt{E_{jet}(GeV)}$
  - 4b tag efficiency ~ 80%, eff for non-4b < a few %
  - $\mathcal{L}_{lumi}$=1 ab^{-1} e^- beam Pol ~ - 80 %

  only hh→bbbb decay mode (Br(hh→bbbb)~47%) analyzed.
- Likelihood selection → overall signal eff ~ 32 % for ννhh

  ~ 22 % for Zhh ($Z \to qq, l^+l^-$)
- For M_h=120 GeV: Λ measurement sensitivity (only hh→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)

- Analysis is premature, and can increase the sensitivity. - e.g. when non-b decay of Higgs is included (especially important for M_h>130 GeV)
- Relative phase (and sign) of Λ can be measured using interference comparing results from Zhh and fusion processes, or results of different E_{cm}'s.

At Jeju LCWS 2002 result was $\delta\Lambda/\Lambda$ = 0.20 for 2ab^{-1} at Ecm=500 GeV

Summary Higgs Experimental LCWS 2004

- Beam related systematic errors have been evaluated for the Higgs mass measurement.
- Jet flavor tagging efficiency, purity for Higgs decays appears to be understood.
- Very detailed systematic error study has been performed for $\gamma\gamma \rightarrow h \rightarrow bb$ and no problems found.
- Nice examples of LHC/LC complementarity found in Higgs physics.
- Ecm=1TeV can be used to probe rare Higgs decays and measure Higgs self-coupling to 10%.