The Higgs Program at the International Linear Collider.

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Introduction

- discovery of Higgs-like boson is milestone in history of particles physics
- **main task**: identify boson and its connection to the SM

  → last particle of SM?
  → first particle beyond the SM?

- **goal**: model-independent and precise reconstruction of EWSB sector

  → investigate mass-coupling relation
  → any deviation clear indication of BSM

- **needed**: comprehensive program of model-independent and direct Higgs boson measurements

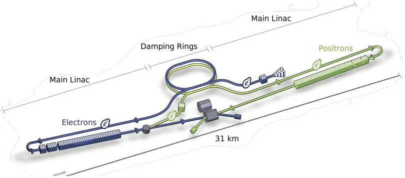
  m_H, g_{HZZ}, g_{HWW}, $g_{Hb\bar{b}}$, g_{Hgg}, $g_{H\gamma\gamma}$, $g_{H\tau\tau}$, $g_{Hc\bar{c}}$, $g_{Ht\bar{t}}$, $g_{H\mu\mu}$, g_{HHH}, Γ_H^{tot}, Γ_{invis}

- ILC is ideally situated to give a full understanding of Higgs, whatever nature it is

Chip Brock, Snowmass 2013

The International Linear Collider

- $\sqrt{s} = 250$ GeV – 500 GeV, (upgr. 1 TeV)
- 31 km for $\sqrt{s} = 500$ GeV
- polarised beams ($e^- = 0.8$, $e^+ \geq 0.3(0.6)$)



linearcollider.org

Japan shows great interest to host ILC

MEXT (Japans Ministry for Education, Culture, Sports, Science and Technology)

established expert committee to investigate issues raised by Science Council of Japan

- physics
- costs
- international sharing, ...

MEXT process is heading towards interim report

ILC Operating Scenario

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- studied impact of running scenarios on physics output

  optimise
  - Higgs precision measurements
  - top physics
  - new physics searches

- studied for running time of 20 years
  $\rightarrow$ then possible 1TeV upgrade

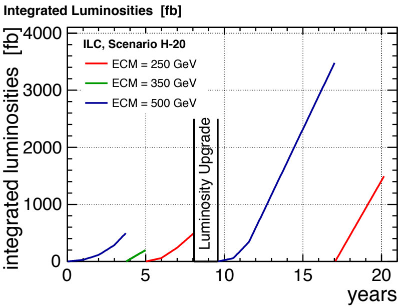
- energy stages between (250 - 500) GeV

Stage	ILC500			ILC500 LumiUP		
$\sqrt{s}$ [GeV]	500	350	250	500	350	250
$\mathcal{L}$ [fb^{-1}]	500	200	500	3500	-	1500
time [a]	3.7	1.3	3.1	7.5	-	3.1

preferred scenario full program

2000 fb^{-1} at 250GeV
200 fb^{-1} at 350GeV
4000 fb^{-1} at 500GeV

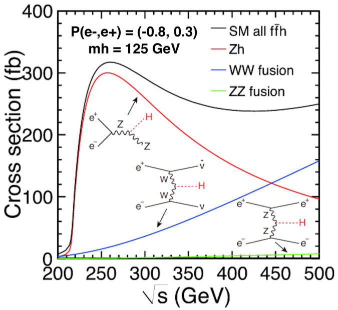
scenario will depend on physics results of LHC and early ILC



Single Higgs Production Processes

LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

each running energy offers
- independent set of variables
- various production processes

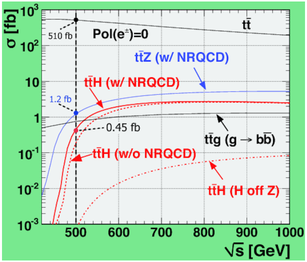


$\sqrt{s} \geq$ 250 GeV

- Higgs strahlung dominant
- beneficial for σ_{ZH} and m_H

$\sqrt{s} \geq$ 350 GeV

- $t\bar{t}$-production threshold
- WW fusion of similar size as ZH
- sensitivity to g_{HZZ} and g_{HWW}



$\sqrt{s} \geq$ 500 GeV

- process $e^+e^- \rightarrow t\bar{t}H$ accessible

  $\rightarrow$ top-Yukawa coupling g_{Htt}

Higgs production in Z Recoil : $m_H \rightarrow \sigma_{ZH} \rightarrow g_{HZZ}$

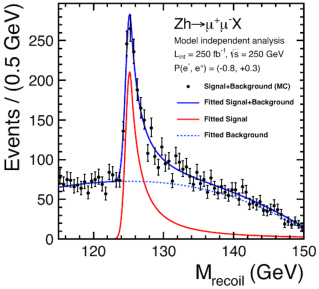
LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

How do we measure couplings? $\frac{N}{\mathcal{L}} = \sigma_i \cdot BR(H \rightarrow XX) = \sigma_i \cdot \frac{\Gamma(H \rightarrow XX)}{\Gamma^H_{tot}} \propto \frac{g_i^2 \cdot g_{HXX}^2}{\Gamma^H_{tot}}$

- **Higgs strahlung**: $e^+e^- \longrightarrow Z\,H$
- reconstruct recoil mass against Z boson
- **No Higgs reconstruction required!**

- observe **H → invisible/exotic**
  - → absolute measurement of BRs
  - → model-independent measurement of Γ^H_{tot}

- **precise m_H** measurement
- **model-independent** measurement of σ_{ZH}
  - → **direct** extraction of g_{HZZ} ($\sigma_{ZH} \propto g^2_{HZZ}$)

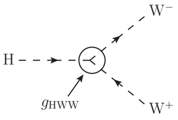


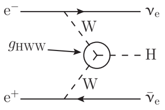
	ILC500	ILC500 LumiUP
Δm_H	25 MeV	15 MeV
$\Delta g_{HZZ}/g_{HZZ}$	0.58 %	0.31 %

Total Width Γ_H and g_{HWW} through WW fusion

LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

- **model-independent measurement of Γ^H_{tot}** $\rightarrow$ absolute normalisation of couplings
- need σ and Γ^H_{tot} to convert BRs into couplings
- too narrow to be measured directly
- energies above 350GeV, crucial input from 250GeV
- **WW fusion** $e^+e^- \rightarrow \nu\bar{\nu}H$ with $H \rightarrow b\bar{b}$

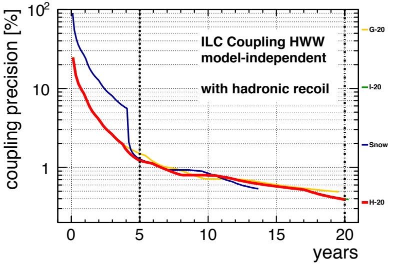




$$\Gamma^H_{tot} \propto \frac{\sigma_{ZH} \cdot \sigma^2_{\nu\bar{\nu}bb}}{\sigma_{\nu\bar{\nu}WW} \cdot \sigma^2_{Zbb}} \times \sigma_{ZH}$$

with:

$$\sigma_{Zbb} = \sigma_{ZH} BR(H \rightarrow bb)$$
$$\sigma_{\nu\bar{\nu}bb} = \sigma_{\nu\bar{\nu}H} BR(H \rightarrow bb)$$
$$\sigma_{\nu\bar{\nu}WW} = \sigma_{\nu\bar{\nu}H} BR(H \rightarrow WW)$$



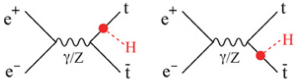
	ILC500	ILC500 LumiUP
$\Delta\Gamma_H$	3.8 %	1.8 %
$\Delta g_{HWW}/g_{HWW}$	0.81 %	0.42 %

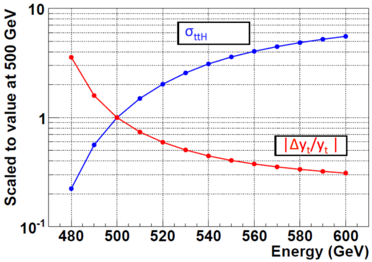
Top-Yukawa Coupling at 500 GeV

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- top quark heaviest particle in SM
  - couples most strongly to Higgs sector
  - g_{Htt} could contain special effects
- directly accessible through

$$e^+e^- \to t\bar{t}H \text{ (with } H \to b\bar{b})$$





- enhanced cross section at $\sqrt{s} = 500$ GeV
  - need full energy (close to production thr.)
- at $\sqrt{s} = 550$ GeV better precision on g_{Htt}
  - cross section enhanced by factor 4
  - main backgrounds decrease

$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	$\sim$ 9 %	$\sim$ 3 %

increasing $\sqrt{s}$ by 10%, for same $\int \mathcal{L}$
$\to$ precision improves by factor 2

Precision on Higgs Couplings

LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

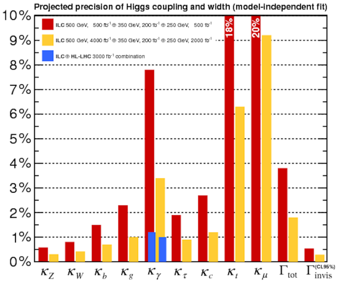
- production processes (ZH, $\nu\nu$H, ttH)
- staged running program

  500GeV with 500 fb^{-1} (4000 fb^{-1})
  350GeV with 200 fb^{-1} (-)
  250GeV with 500 fb^{-1} (1500 fb^{-1})

- direct and independent measurements

$$\sigma(\mathrm{ZH}) \,,\ \sigma \times \mathrm{BR}(\mathrm{H} \rightarrow \mathrm{XX})$$

- couplings and $\Gamma^{\mathrm{H}}_{\mathrm{tot}}$ via model-independent global fit



parameter	ILC500	ILC500 LumiUP
Γ(tot)	3.8 %	1.8 %
g(HZZ)	0.58 %	0.31 %
g(HWW)	0.81 %	0.42 %
g(Hbb)	1.5 %	0.7 %
g(Hcc)	2.7 %	1.2 %
g(Hgg)	2.3 %	1.0 %
g(H$\tau\tau$)	1.9 %	0.9 %
g(H$\gamma\gamma$) (w/ LHC)	7.8 % (1.2 %)	3.4 % (1.0 %)
g(H$\mu\mu$)	20 %	9.2 %
g(Htt)	18 %	6.3 %

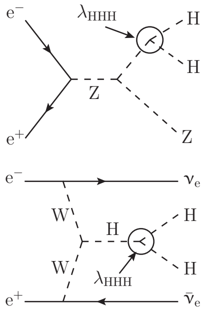
- most couplings reach precision of < 1 %
- running at 550GeV improves Δg_{Htt} to 3 %
- **completely model-independent** analysis
  $\rightarrow$ key: recoil mass measurement

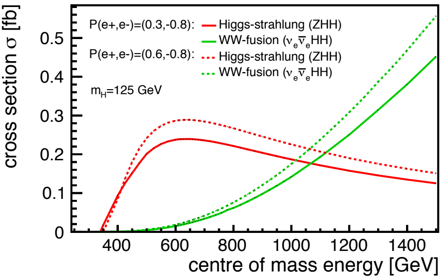
Higgs Self-Coupling Measurement at the ILC

- precise measurement of SM Higgs potential via Higgs self-coupling

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

- existence of HHH coupling → direct evidence of vacuum condensation
- one must observe double Higgs production





Higgs Self-Coupling Measurement at the ILC

- **measurement very challenging**:
  - → small production cross section, i.e. $\sigma(\mathrm{ZHH}) \approx 0.2\mathrm{fb}$ at 500GeV
  - → many jets in final state

- **irreducible diagrams with same final state, but w/o self-coupling vertex**
  - → do not concern self-coupling
  - → degrade sensitivity
  - → w/o interference factor would be 0.5

Higgs strahlung: $\frac{\Delta\lambda}{\lambda} = 1.64 \cdot \frac{\Delta\sigma_{\mathrm{ZHH}}}{\sigma_{\mathrm{ZHH}}}$

WW fusion : $\frac{\Delta\lambda}{\lambda} = 0.76 \cdot \frac{\Delta\sigma_{\mathrm{WW}}}{\sigma_{\mathrm{WW}}}$

studies are ongoing

potential improvement in analyses

- kinematic fitting
- jet-clustering
- matrix element method
- etc...

relative improvement of 20% expected

Existing full simulation analyses for 125 GeV

@ 500 GeV

- ZHH→Z(bb)(bb)
- ZHH→Z(bb)(WW)

@ 1 TeV

- $\nu\nu$HH →$\nu\nu$(bb)(bb)
- $\nu\nu$HH →$\nu\nu$(bb)(WW)

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ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

Existing full simulation analyses for 125 GeV

@ 500 GeV

- ZHH→Z(bb)(bb)
- ZHH→Z(bb)(WW)

@ 1 TeV

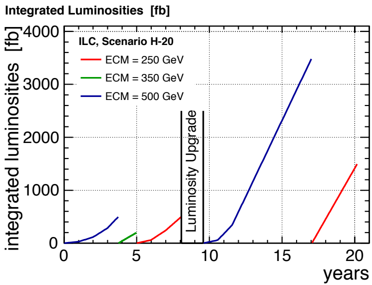
- ννHH →νν(bb)(bb)
- ννHH →νν(bb)(WW)

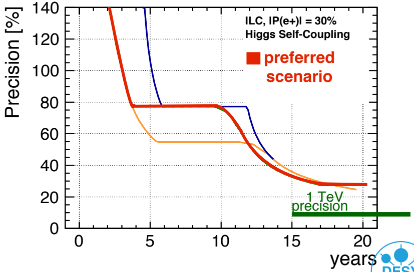
Standard Model Higgs self-coupling

before luminosity upgrade precision of 77 % on Higgs self-coupling

after full ILC program precision of 27% can be achieved

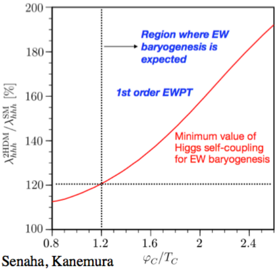
possible energy upgrade to 1 TeV could improve precision to 10% or better



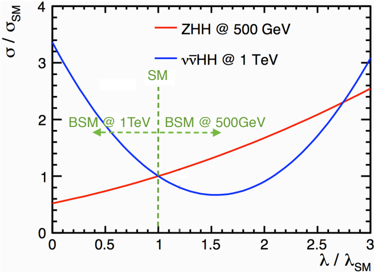


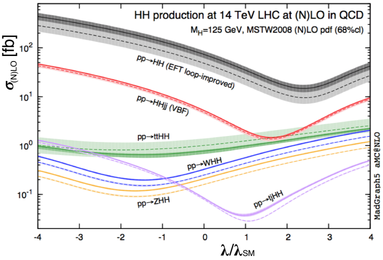
Sensitivity of Higgs self-coupling λ in BSM

- deviation from λ_{SM} indicates new physics
- WW fusion and ZHH complementary in sensitivity to new physics
- electroweak baryogengesis in THDM expect $\lambda \geq 1.2\lambda_{SM}$
- such scenarios difficult to be observed at LHC
- at ILC possible at 500 GeV with ZHH



Senaha, Kanemura





Sensitivity of Higgs self-coupling λ in BSM

BSM scenario: improved accuracy expected
(i.e. electroweak baryogenesis: $\lambda > \lambda_{SM}$)

$\lambda < \lambda_{SM} \rightarrow \nu\nu HH$ at 1 TeV

example: $\lambda = 0.5 \cdot \lambda_{SM}$

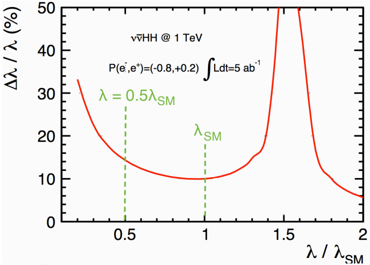
$\lambda > \lambda_{SM} \rightarrow ZHH$ at 500 GeV

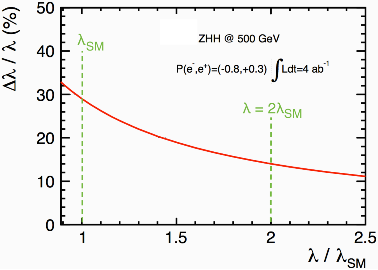
example: $\lambda = 2 \cdot \lambda_{SM}$

- σ_{ZHH} enhanced by 60%
- sensitivity factor reduced ($1.73 \rightarrow 1.08$)
- $\Delta\lambda/\lambda$ improved by factor of 2

both cases:

- λ can be measured to 14% precision
- 7σ discovery
- more than 3σ deviation from SM





Summary

- Higgs precision measurements → investigate EWSB sector
  → door to new physics

- ILC is state of the art precision machine
  → direct and model-independent measurements
  → Higgs couplings reach required precision $< 1\%$ level
  → $\sqrt{s} \geq 500$GeV necessary for $\Delta g_{Htt} < 3.0\%$
  → model-independent determination of Γ_{tot} to 1.8% precision

- recoil mass technique is key to model-independent analysis
  → precise and direct measurement of $\Delta\sigma_{ZH} < 2.5\%$ and $\Delta m_H = 15$MeV
  → Higgs to invisible/exotic → absolute branching ratios

- Higgs self-coupling measurement crucial to test EWSB
  → measurement very challenging
  → after full ILC program, achieve precision of 27% (upgrade to 1TeV, then $< 10\%$)
  → if electroweak baryogenesis $\lambda < 14\%$ already at 500GeV

- political development: Japanese government started reviews on ILC project

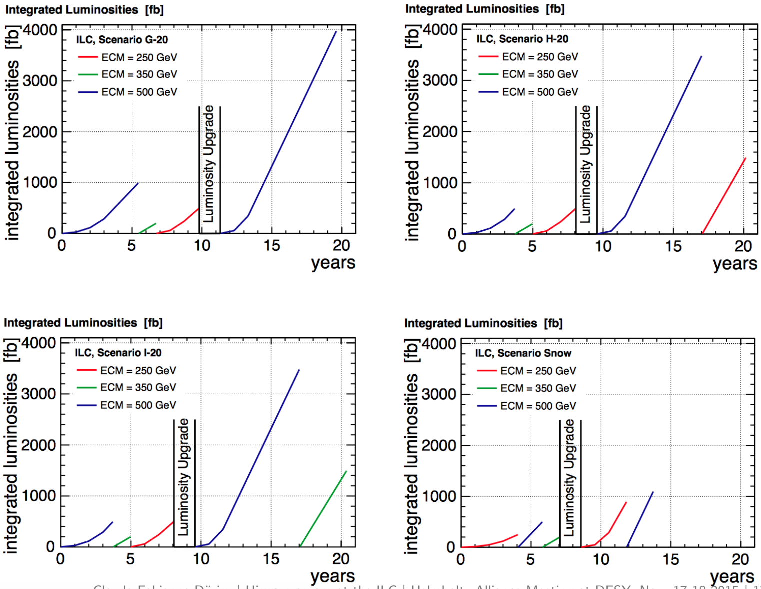
BACKUP SLIDES

Summary Table - Input Precisions to Higgs Coupling Fit

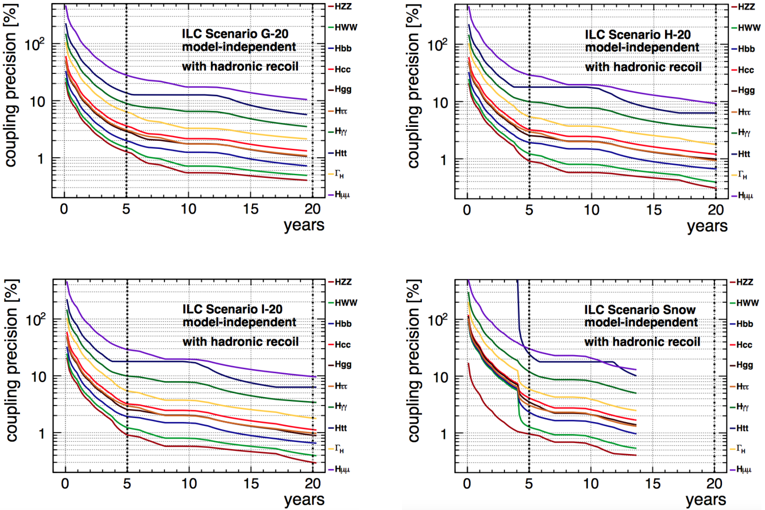
$\int \mathscr{L} dt$ at $\sqrt{s}$	$250\,\text{fb}^{-1}$ at 250 GeV		$330\,\text{fb}^{-1}$ at 350 GeV		$500\,\text{fb}^{-1}$ at 500 GeV		
$P(e^-, e^+)$	(-80%,+30%)						
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	[39] 2.0%	-	[10,40] 1.6%	-	3.0	-	-
BR(invis.) [41]	$< 0.9\%$	-	$< 1.2\%$	-	$< 2.4\%$	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$						
$h \to b\bar{b}$	1.2%	10.5%	1.3%	1.3%	1.8%	0.7%	28%
$h \to c\bar{c}$	8.3%	-	9.9%	13%	13%	6.2%	-
$h \to gg$	7.0%	-	7.3%	8.6%	11%	4.1%	-
$h \to WW^*$	6.4%	-	6.8%	5.0%	9.2%	2.4%	-
$h \to \tau^+\tau^-$	[42] 3.2%	-	[43] 3.5%	19%	5.4%	9.0%	-
$h \to ZZ^*$	19%	-	22%	17%	25%	8.2%	-
$h \to \gamma\gamma$	34%	-	34%	[44] 39%	34%	[44] 19%	-
$h \to \mu^+\mu^-$ [45]	72%	-	76%	140%	88%	72%	-

Table 13: Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV Higgs boson as provided as input to the coupling fit. All values obtained from full detector simulation studies at the given reference values of energy, integrated luminosity and polarisation. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

Running Scenarios



Running Scenarios



Running Scenarios

	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathscr{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-

	$\int \mathscr{L} dt$ [fb^{-1}]			
$\sqrt{s}$	G-20	H-20	I-20	Snow
250 GeV	500	2000	500	1150
350 GeV	200	200	1700	200
500 GeV	5000	4000	4000	1600

Table 1: Proposed total target integrated luminosities for $\sqrt{s} = 250, 350, 500$ GeV , based on 20 "real-time" years of ILC operation under scenarios G-20, H-20 and I-20. The total integrated luminosities assumed for Snowmass are listed for comparison based on 13.7 "real-time" years.

	total run time *before*	
	Lumi upgrade	potential TeV upgrade
Scenario	[years]	[years]
G-20	9.8	19.7
H-20	8.1	20.2
I-20	8.1	20.4
Snow	7.1	13.7

Table 5: Cumulative running times for the four scenarios, including ramp-up and installation of upgrades. Not included: calibration and physics runs at Z pole and WW-threshold or scanning of new physics thresholds.

Measured Parameters

$$\sigma_{ZH}$$

$$\sigma_{ZH} \times BR(H \to invisible)$$

$$\sigma_{ZH} \times BR(H \to VV), \sigma_{\nu\nu H} \times BR(H \to VV)$$

$$\sigma_{ZH} \times BR(H \to bb/cc), \sigma_{\nu\nu H} \times BR(H \to bb/cc)$$

$$\sigma_{ZH} \times BR(H \to \tau\tau/\mu\mu), \sigma_{\nu\nu H} \times BR(H \to \tau\tau/\mu\mu)$$

$$\sigma_{ZH} \times BR(H \to \gamma\gamma/gg), \sigma_{\nu\nu H} \times BR(H \to \gamma\gamma/gg)$$

$$\sigma_{ttH} \times BR(H \to bb)$$

$$\sigma_{ZHH} \times BR^2(H \to bb), \sigma_{\nu\nu HH} \times BR^2(H \to bb)$$

Global fit - Model-Independent Results

- staged running and various production processes provide many independent measurements $Y_i = \sigma \times BR(H \to XX)$, with error ΔY_i
- predicted values of measurements Y_i' can always be parametrized by couplings g_{HZZ}, g_{HWW}, g_{Htt} and Γ_H
- additional recoil mass measurement provide absolute cross section measurement of σ_{ZH}, independent of Higgs decay mode, all modes at ILC
- combined all measurements to extract 9 couplings (hzz, hww, hbb, hcc, hgg, h$\tau\tau$, h$\mu\mu$, htt, h$\gamma\gamma$) and width Γ_H
- model-independent global fit by constructing χ^2

$$\chi^2 = \sum_{i=1}^{i=N} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2$$

- estimated uncertainties from the ILC for a model-independent fit to the Higgs couplings in which all Higgs couplings, including couplings to invisible and exotic modes are separately taken as free parameters

Sensitivity of Higgs self-coupling λ in BSM

BSM scenario: improved accuracy expected
(i.e. electroweak baryogenesis: $\lambda > \lambda_{SM}$)

$\lambda < \lambda_{SM} \rightarrow \nu\nu HH$ at 1 TeV

example: $\lambda = 0.5 \cdot \lambda_{SM}$

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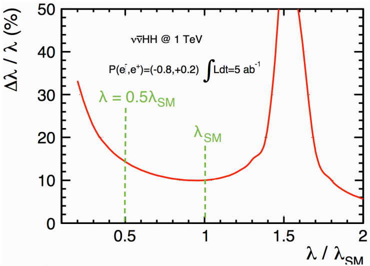
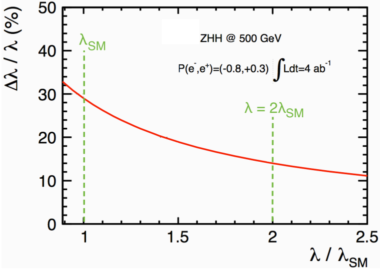
extrapolated measurement accuracy of current λ_{SM} measurement (J. Tian)





Higgs Self-Coupling Analyses at ILC

Existing DBD full simulation analyses

studies performed **with** low-p_T $\gamma\gamma \rightarrow$ hadrons beam background
without low-p_T $\gamma\gamma \rightarrow$ hadrons beam background

@ 500 GeV

- ZHH→Z(bb)(bb) for $m_H = 125$ GeV
- ZHH→Z(bb)(WW) for $m_H = 125$ GeV

@ 1 TeV

- $\nu\nu$HH →$\nu\nu$(bb)(bb) for $m_H = 125$ GeV
- $\nu\nu$HH →$\nu\nu$(bb)(WW) for $m_H = 125$ GeV

ILC white paper: Higgs self-coupling projections

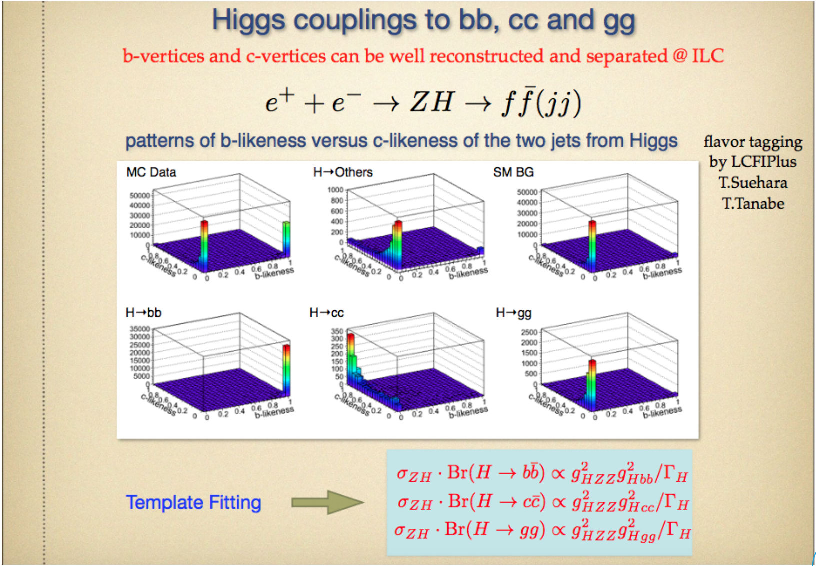
(full simulation w/ $m_H = 120$ GeV, extrapolated to $m_H = 125$ GeV)

	500 GeV			500 GeV+1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

500 GeV: 500 (1600)fb^{-1} $P(e^+e^-)=(0.3,-0.8)$
1 TeV: 1000 (2500)fb^{-1} $P(e^+e^-)=(0.2,-0.8)$

Scenario A: HH → bbbb ✔
Scenario B: adding HH → bbWW ✔, expect 20% relative improvement
Scenario C: analysis improvement (jet-clustering, kinematic fit, flavor tagging, matrix element method, etc.), expect 20% relative improvement (**ongoing**)

Higgs to bb, cc, gg (slide: Dr. Junping Tian, ICHEP 2014)



Prospects for other beam polarisations

- standard polarisation used in analysis $P(e^-, e^+)$=(-0.8, 0.3) with $\mathcal{L} = 2$ ab^{-1}
- rough estimation of Higgs self-coupling accuracy for other polarisations

Polarisation	no overlay		overlay	
$P(e^-, e^+)$	cross section	self-coupling	cross section	self-coupling
(-0.8, 0.0)	36.7%	60.1%	40.7%	66.7%
(0.8, 0.0)	37.2%	61.1%	41.7%	68.4%
combined	26.2%	42.9%	29.1%	47.8%
(-0.8, 0.3)	**32.6%**	**53.5%**	**35.5%**	**58.1%**
(0.8, -0.3)	33.5%	54.9%	37.1%	60.8%
combined	23.4%	38.3%	25.6%	42.0%
(-0.8, 0.6)	29.9%	49.2%	33.6%	55.1%
(0.8, -0.6)	30.6%	50.2%	33.8%	55.4%
combined	21.4%	35.1%	23.8%	39.1%

combined: $P(+) \cdot 2$ ab^{-1} + $P(-) \cdot 2$ ab^{-1}

- for $P(e^-)$= -0.8: increase $P(e^+) \rightarrow$ 10% improvement
  decrease $P(e^+) \rightarrow$ 10% worsening
- similar results for opposite polarisations

- **irreducible diagrams** with same final state, but do not concern self-coupling

example for ZHH:

- **cross-section σ(ZHH) as a function of λ**

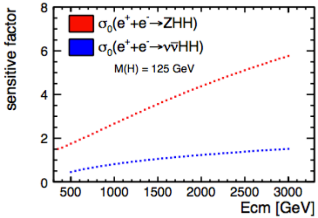
$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

a: Higgs self-coupling diagram

b: interference between diagrams

c: irreducible diagrams

- **precision of Higgs self-coupling for m_H = 125 GeV**



Higgs-strahlung:

$$\frac{\Delta\lambda}{\lambda} = 1.74 \cdot \frac{\Delta\sigma}{\sigma}$$

WW-fusion:

$$\frac{\Delta\lambda}{\lambda} = 0.85 \cdot \frac{\Delta\sigma}{\sigma}$$

w/o interference the factor would be 0.5

special weighting method improves sensitivity on coupling diagram