Measurement of the Higgs Self-coupling at the ILC

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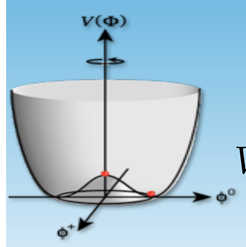
1. Discover the force that makes Higgs field condense in the vacuum



$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

EWSB

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

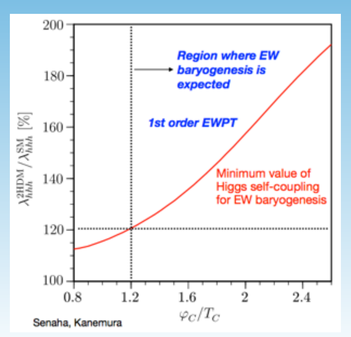
$\mathrm{SM}: \ \lambda = \frac{m_H^2}{2v^2}$

trilinear self-coupling, to be measured

quartic self-coupling, very challenging

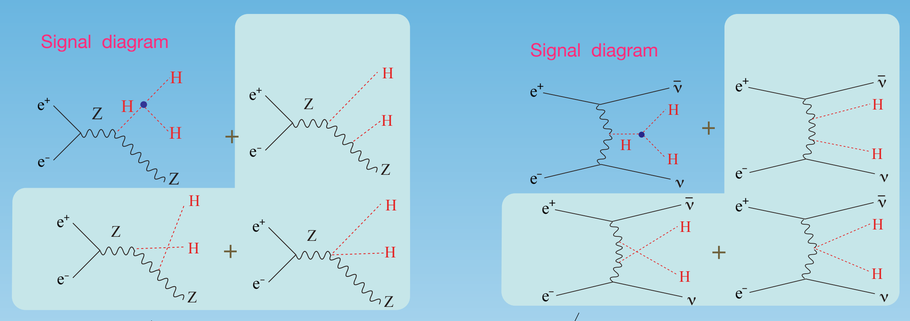
☆ *provide crucial test for the mechanism of EWSB and structure of Higgs potential*

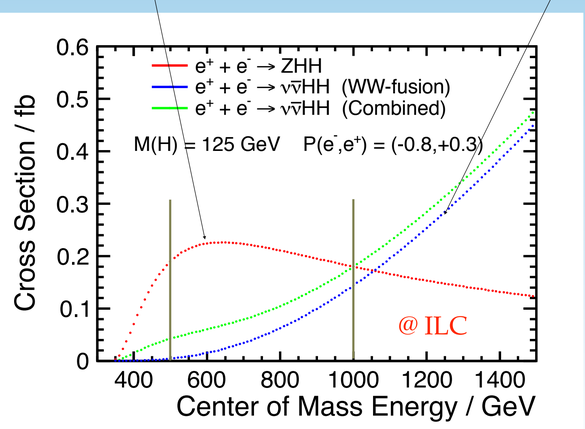
2. Large deviation on Higgs self-coupling can shed light on Electroweak Baryogenesis, 2HDM, Composite Higgs, etc.

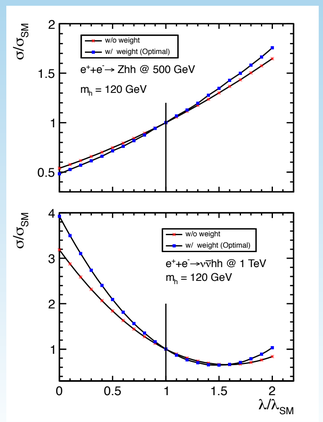


Model	$\Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$
Mixed-in Singlet	-18%
Composite Higgs	tens of %
MSSM	-2%, -15%
NMSSM	-25%

3. Feynman diagrams to measure trilinear Higgs self-coupling at ILC and their cross sections.

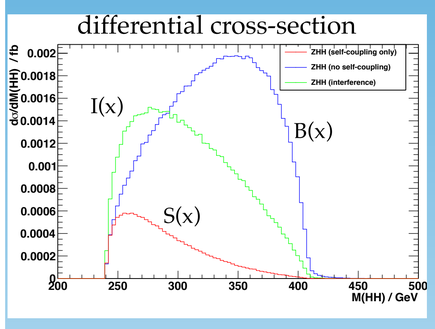






☆ *Higgs self-coupling processes help define the baseline centre-of-mass energy of ILC*

4. Extract self-coupling from measured cross section — a new general weighting method

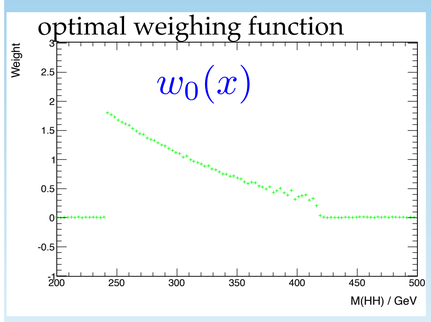


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x) \mathrm{d}x$$



equation of the optimal w(x) (variance principle):

$$\sigma(x)w_0(x)\int (I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int \sigma(x)w_0^2(x)\mathrm{d}x$$

general solution:

$$w_0(x) = c \cdot \frac{I(x)+2S(x)}{\sigma(x)}$$

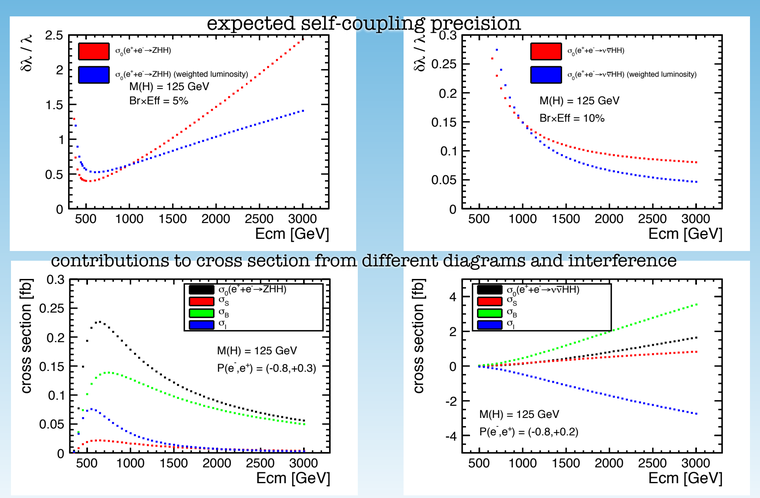
c: arbitrary normalization factor

$e^+ + e^- \to ZHH:$ $\quad \frac{\Delta\lambda}{\lambda}|_{\mathrm{SM}} = 1.80\frac{\Delta\sigma}{\sigma}$ $\xrightarrow{w_0(x)}$ $\frac{\Delta\lambda}{\lambda}|_{\mathrm{SM}} = 1.66\frac{\Delta\sigma}{\sigma}$

$e^+ + e^- \to \nu\bar{\nu}HH:$ $\quad \frac{\Delta\lambda}{\lambda}|_{\mathrm{SM}} = 0.85\frac{\Delta\sigma}{\sigma}$ $\qquad$ $\frac{\Delta\lambda}{\lambda}|_{\mathrm{SM}} = 0.76\frac{\Delta\sigma}{\sigma}$

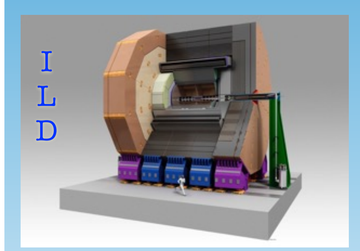
☆ *interference plays a crucial role in measurement of Higgs self-coupling*

5. Impact of centre-of-mass energies



☆ *for ZHH, the expected optimal energy is ~500 GeV (rather flat in 500-600 GeV)*
☆ *for vvHH, expected precision improves slowly as going to higher energies*

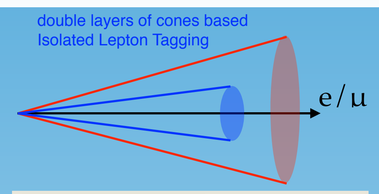
6. Analysis based on full detector simulation



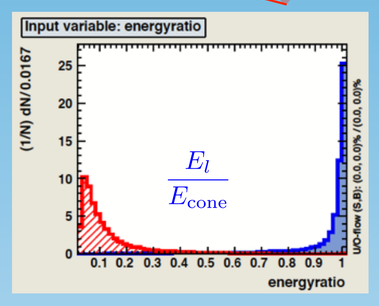
- event generator: Whizard (including realistic beam-beam interaction)
- detector simulation: Mokka (based on GEANT4, including realistic material budget, tuned by beam test)
- event reconstruction: Particle Flow Algorithm (PFA), realistic Jet Clustering, and MVA based Flavor Tagging
- full SM background processes are considered in analysis

decay modes	e⁺+e⁻ —> ZHH			e⁺+e⁻ —> vvHH
	Z—>ll	Z—>vv	Z—>qq	
HH—>bbbb	2.2%	6.7%	23%	33%
HH—>bbWW*	1.7%	5.0%	17%	25%

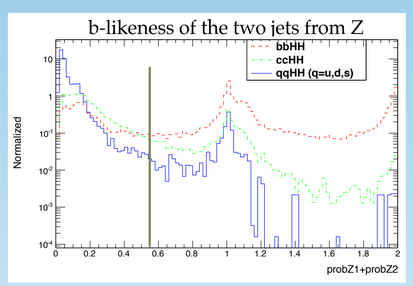
7. Event selection (general procedure for all channels)

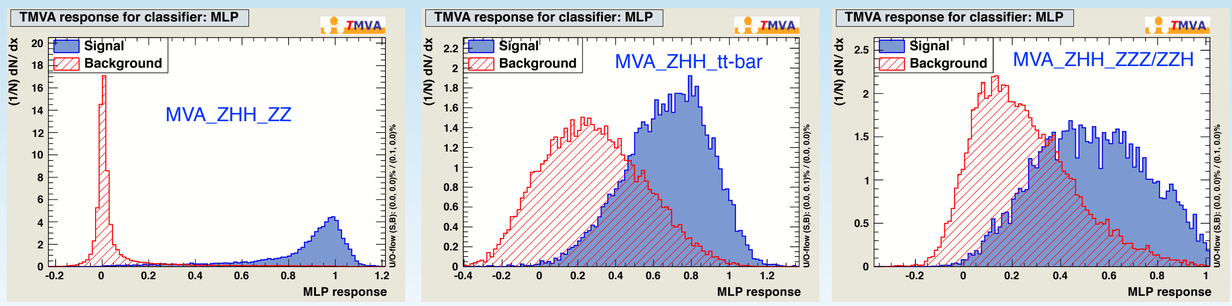


- pre-selection:
  - MVA based isolated electron/muon tagging (veto events if no isolated leptons in signal)
  - remove pile-up γγ—>low-pt hadrons based on kt-clustering or MVA algorithm
  - remained particles are clustered to several jets (4 or 6) based on Durham jet algorithm, and jets are flavor tagged using LCFIPlus package
  - reconstructed jets are paired to reconstruct Higgs or Z boson by minimizing χ^2 defined by the boson mass and resolution



- final-selection:
  - cut on missing energy and missing pt, depending on whether signal is from neutrino channel or not
  - three neural-nets are trained to suppress the dominant background events, which are categorized to three types, 4-fermions from ZZ/vvZ, 6-fermions from tt-bar, 6-fermions from ZZZ/vvZZ and ZZH/vvZH; cuts are applied on the output of neural-net for each event
  - to require b-jet, cuts are applied on the flavor tagging output for each jet
  - all cuts are optimized to give best significance of signal events





three neural-net outputs in analysis of ZHH—>qqbbbb

☆ *main backgrounds are 2~3 orders of magnitudes larger, sophisticated MVA tuning plays a central role of analysis.*

8. Results based on current analysis techniques

A. number of signal and background events in each mode (here only shown for HH—>bbbb)

$\int \mathrm{L}dt = 2\mathrm{ab}^{-1}$ $\quad P(e^-,e^+) = (-80\%,+30\%)@500\mathrm{GeV};(-80\%,+20\%)@1\mathrm{TeV}$ $\quad M(H) = 120\mathrm{GeV}$

Energy (GeV)	Modes	#signal	#background (tt, ZZ, ZZH/vvZH)	significance
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.1σ
		4.5	6	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.0σ
		18.8	90.6	1.8σ
1000	$\nu\bar{\nu}HH \to (\nu\bar{\nu}(b\bar{b})(b\bar{b})$	35.7	33.7	4.3σ

B. expected precisions on Higgs self-coupling with proposed scenarios of ILC at Baseline and Luminosity Upgrade

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Baseline	83%	21%
LumiUP	46%	13%

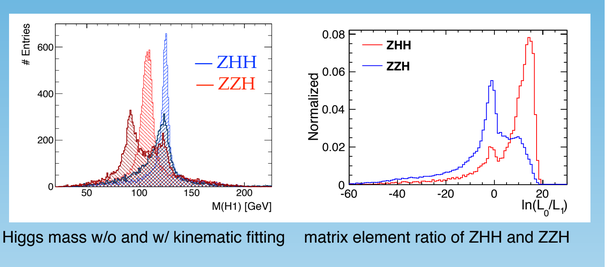
$\int \mathrm{L}dt \cdot \mathrm{fb}$	500 GeV	1 TeV
Baseline	500	1000
LumiUP	1600	2500

extrapolated to M(H)=125 GeV; including HH—>bbbb and HH—>bbWW*; beam polarizations help!

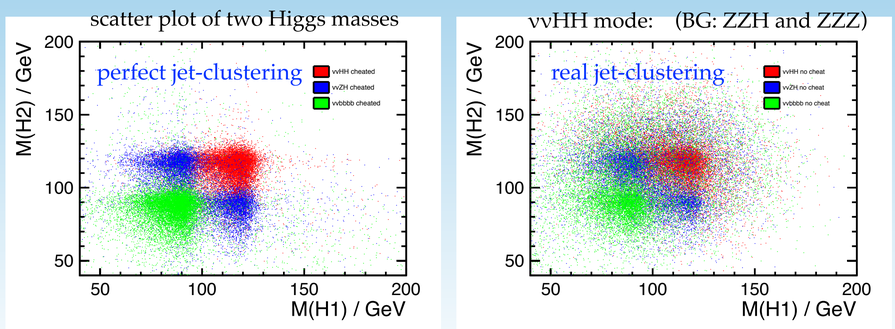
☆ *excess of double Higgs production > 7σ; significance of observing Higgs self-coupling > 5σ*

9. Prospects of ongoing improvements of analysis

- improve impact of pile-up events
- updating analysis with M(H)=125 GeV
- improve jet clustering: color-singlet jet clustering
- implement kinematic fitting
- optimize cuts for coupling instead of cross section
- apply matrix element method



Higgs mass w/o and w/ kinematic fitting — matrix element ratio of ZHH and ZZH



☆ *Higgs mass resolution is limited by jet clustering instead of detector resolution*
☆ *conservatively, Higgs self-coupling is expected to be measured better than 10% at ILC*

10. More information: S. Kanemura, et al. arxiv:1211.5883; R.S. Gupta, et al. arxiv: 1305.6397; J. Tian, LC-REP-2013-003; C. Dürig @ AWLC14; M. Kurata @ ECFA LC2013