Higgs Self-Coupling Measurement at the ILC.

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34th General Physics Meeting, KEK Japan

Universität Hamburg
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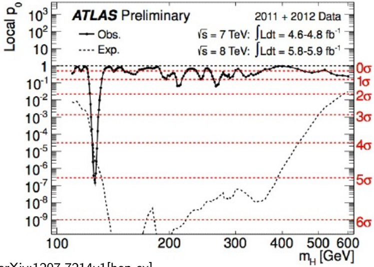
Introduction

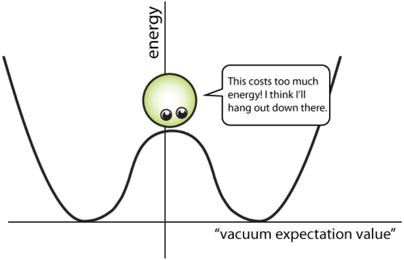
- discovery of the Higgs in 2012
- Higgs properties can be measured precisely at ILC (m_H, Γ_H^{tot}, etc.)

  missing: **Higgs potential**, which represents test of EWSB and mass generation
- to probe shape of Higgs potential we need to determine the **Higgs self-coupling**



arXiv:1207.7214v1[hep-ex]

Trilinear Higgs self-coupling



http://www.quantumdiaries.org

Higgs potential after spontaneous symmetry breaking for physical Higgs field:

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

G_F: Fermi constant
η_H: physical Higgs field
v: vacuum expectation value

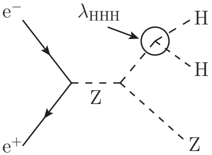
- trilinear λ and quartic $\tilde{\lambda}$ Higgs couplings are defined as:

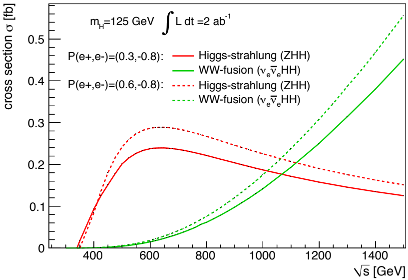
$$\lambda = \tilde{\lambda} = \lambda_{SM} = \frac{m_H^2}{2v^2}$$

- verify the shape of Higgs potential $\longrightarrow$ measure three terms
- to measure λ one must observe double Higgs production at lepton or hadron colliders

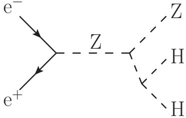
Double Higgs production processes

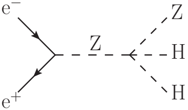
- **Higgs-strahlung**: dominant around $\sqrt{s} = 500$ GeV

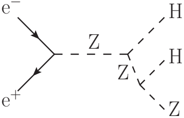




- **irreducible Feynman diagrams** which do not concern Higgs self-coupling







- **Interference** between Higgs self-coupling and irreducible diagrams make measurement complicated

Sensitivity of self-coupling to σ(ZHH)

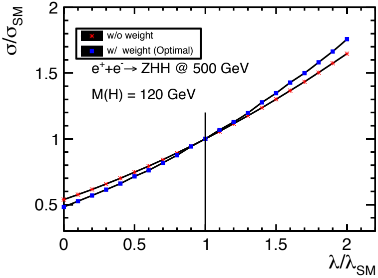
cross-section σ(ZHH)

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

a: Higgs self-coupling diagram

b: interference between self-coupling and irreducible diagrams

c: irreducible diagrams



- precision of Higgs self-coupling:

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

$X = 0.5$ without interference

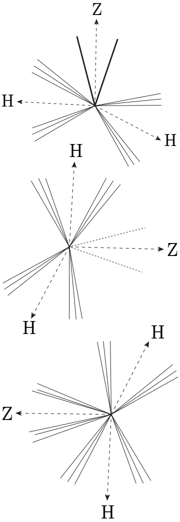
$X = 1.8$ for $m_H = 120$ GeV at $\sqrt{s} = 500$ GeV

- new **weighting method** improves factor $X = 1.66$
(J.Tian:LCWS12 / ECFA13)

- better improvement expected for **m_H = 125 GeV** at $\sqrt{s} = 500$ GeV, since without weighting $X = 1.74$

Analysis strategy - Decay Channels

- Measurement at $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2\ \text{ab}^{-1}$



$e^+e^- \rightarrow ZHH \rightarrow l^-l^+HH$

2leptons 4jets mode ($10\% \times 70\% \times 70\% \approx 4.9\%$)

$Z \longrightarrow l\bar{l} \quad H \longrightarrow b\bar{b} \quad H \longrightarrow b\bar{b}$

$e^+e^- \rightarrow ZHH \rightarrow \nu\bar{\nu}HH$

2neutrino 4jet mode ($20\% \times 70\% \times 70\% \approx 9.8\%$)

$Z \longrightarrow \nu\bar{\nu} \quad H \longrightarrow b\bar{b} \quad H \longrightarrow b\bar{b}$

$e^+e^- \rightarrow ZHH \rightarrow q\bar{q}HH$

6jets mode ($70\% \times 70\% \times 70\% \approx 34\%$)

$Z \longrightarrow q\bar{q} \quad H \longrightarrow b\bar{b} \quad H \longrightarrow b\bar{b}$

Previous Linear Collider Studies for $m_H = 120$ GeV

Previous Linear Collider Higgs self-coupling studies for $m_H = 120$ GeV:

- ZHH at 500 GeV with $\mathcal{L} = 2\ \mathrm{ab}^{-1}$ based on fast simulation:

  precision of 18% on Higgs self-coupling
  includes leptonic and hadronic Z-channel
  (arXiv:hep-ex/0101028v1)

- ZHH at 500 GeV with $\mathcal{L} = 2\ \mathrm{ab}^{-1}$ based on full simulation:

  precision of 160% on Higgs self-coupling
  only includes hadronic Z-decay mode
  (arXiv:hep-ex/0901.4895v1)

- **recent study**:

  ZHH at 500 GeV with $\mathcal{L} = 2\ \mathrm{ab}^{-1}$ based on DBD full simulation:

  precision of 44% on Higgs self-coupling
  complete investigation of all Z-channels
  (LC-REP-2013-003)

Current Status (m_H=120 GeV)

- Measurement at $\sqrt{s} = 500$ GeV, $\mathcal{L} = 2$ ab^{-1} and $P(e^+e^-) = (0.3, -0.8)$
- here: investigated Higgs mass $m_{\mathrm{H}} = 120$ GeV

modes	signal	background	significance	
		(tt, ZZ, ZZH, ZZZ)	excess	measurement
ZHH → l^-l^+HH	3.7	4.3	1.5σ	1.1σ
	4.5	6.0	1.5σ	1.2σ
ZHH → $\nu\bar{\nu}$HH	8.5	7.9	2.5σ	2.1σ
ZHH → $q\bar{q}$HH	13.6	30.7	2.2σ	2.0σ
	18.8	90.6	1.9σ	1.8σ

- cross-section: $\frac{\delta\sigma_{\mathrm{ZHH}}}{\sigma_{\mathrm{ZHH}}} = 27\% \ (> 3.5\sigma)$ Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 44\%$

Next steps

- perform analysis with new $m_{\mathrm{H}} = 125$ GeV samples
- consider low-p_T $\gamma\gamma \rightarrow$ hadrons overlay
- different starting points for improvement

Selection strategy for leptonic channel

1. select two isolated charged leptons consistent with M_Z

$$|M_{2\text{lep}} - M_z| < 40\ \text{GeV}$$

2. remove low-p_T $\gamma\gamma \rightarrow$ hadrons overlay
3. force the other reconstructed particles into four jets
4. combine the four jets by choosing combination with smallest χ^2

$$\chi^2 = \frac{(M(j_i j_j) - M(H))^2}{\sigma_H^2} + \frac{(M(j_k j_l) - M(H))^2}{\sigma_H^2}$$

require: $|M_\text{H} - 125\ \text{GeV}| < 80\ \text{GeV}$

5. neural net analysis performed separately for signal and each background, output classifiers are used to suppress background

divide background into four different categories:

jets-poor background (llqq)
semileptonic ttbar background (lvbbqq)
full-hadronic background (6-jets and 4-jets)
backgrounds with same final states (ZZH/ZZZ)

New DiLeptonSelection

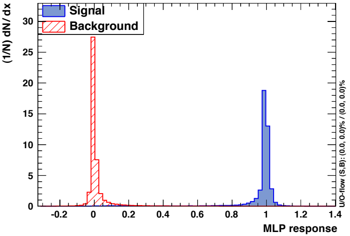
old lepton selection:

- cut based on energy distributions in calorimeter

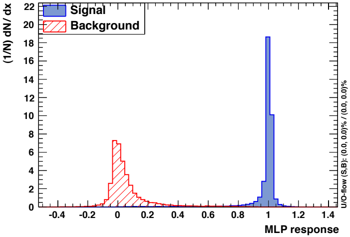
new lepton selection:

- neural net based (MVA)
- train neural net with samples for **signal**: eeHH and μμHH (with $\gamma\gamma$-overlay)
  background: bbbb and lνbbqq (no $\gamma\gamma$-overlay)
- MVA output is written to lepton collection, can be optimised in final selection
- two leptons consistent with M_Z

neural net output for electrons

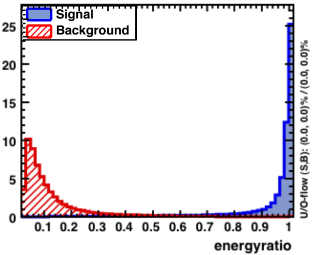


neural net output for muons

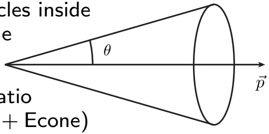


New DiLeptonSelection

Example of input variable: energyratio



- define cone around direction of rec. particle and sum up energy of particles inside this cone



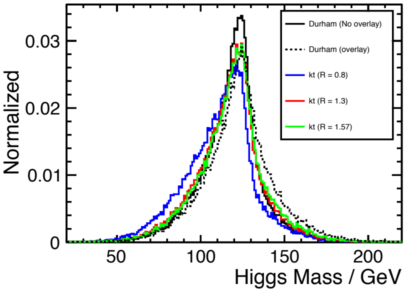
- energyratio is E/(E + Econe)
- isolated lepton has small Econe, so energyratio close to one

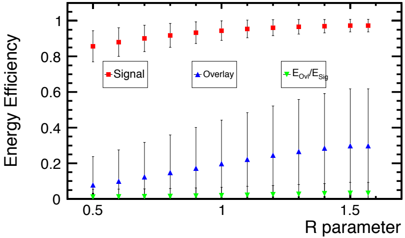
Current Improvement

efficiency (%)	eehh	μμhh	bbbb	eνbbqq	μνbbqq
new DBD	86.99	89.11	$1.682 \cdot 10^{-5}$	$3.15 \cdot 10^{-3}$	$1.96 \cdot 10^{-4}$
old DBD	85.7	88.4	0.028	1.44	0.10
old LoI	81.9	85.4	0.43	2.71	1.94

New lepton selection strategy increases signal efficiency.
Suppression of hadronic and one-lepton backgrounds is significantly improved.

$\gamma\gamma$ overlay removal





- low-p_T $\gamma\gamma \rightarrow$ hadrons overlaid events per interaction:

  $< \mathbf{N_{\gamma\gamma}} >= \mathbf{1.7}$

  ILD/SiD standard → overestimated

- **apply FastJetClustering**:

  $\mathbf{k_T}$ ExclusiveNJets4

  → which R-value?

- for $R \geq 1.2$ almost no increase in signal efficiency but in overlay

  → **best: $\mathbf{R = 1.3}$**

- use reconstructed particles in these 4 jets for analysis

- until now ZHH and ZZH samples with overlay

Preliminary selection cuts (m_H= 125 GeV)

Preselection for samples with $\gamma\gamma$-overlay

	eeHH	μμHH	eeqqH	μμqqH
expected no. events	13.50	13.52	75.34	75.53
lepton selection	11.74	12.05	68.41	67.26
k_T ExclusiveNJets4	11.61	12.04	64.66	67.23
combine four jets to two Higgs $\lvert M_H - 125\text{ GeV}\rvert < 80$ GeV	11.09	11.51	62.84	65.24

Comparison to samples without $\gamma\gamma$-overlay missing :($\longrightarrow$ latest LCWS Thu. 14.11.13

Preliminary selection cuts ($m_{\mathrm{H}} = 125$ GeV)

ZHH and ZZH samples with $\gamma\gamma$ background overlaid, other backgrounds in production

electron type:

	e1e1bb	e2e2bb	evbbqq	μvbbqq	τvbbqq	bbqqqq	bbbb	llbbbb	llqqh	bgrd	signal (llbbbb)
generated	$4.21 \cdot 10^6$	$1.00 \cdot 10^6$	$1.49 \cdot 10^6$	$1.47 \cdot 10^6$	931701	$2.89 \cdot 10^6$	978472	106940	151500		293165
expected	284117	49565.7	248454	245936	245708	624060	40234.4	69.51	150.87	$1.74 \cdot 10^6$	40.503
preselection	2697.42	1414.96	519.97	74.967	31.614	4.209	0.381	14.971	128.084	4886.58	22.86 (7.531)
ltype = 11	2697.42	0.099	519.977	1.202	29.153	4.209	0.381	7.359	62.811	3322.62	11.24 (3.724)
$\lvert M_Z - 91\ \mathrm{GeV}\rvert < 32\ \mathrm{GeV}$	2383.93	0.049	426.935	0.337	23.439	1.799	0.296	7.081	62.234	2906.1	11.11 (3.696)
MVAllbb > 0.66	57.583	0	290.564	0.337	15.473	1.799	0.129	5.247	46.328	417.458	8.83 (3.519)
MVAlvbbqq > 0.69	50.962	0	22.851	0	2.432	0.623	0.042	4.954	43.319	125.185	7.90 (3.361)
bmax3 > 0.2	3.996	0	0.289	0	0.269	0.311	0.042	4.398	8.953	18.259	3.62 (2.986)
MVAllbbbb > 0.21	1.299	0	0	0	0.014	0.311	0.042	1.071	3.862	6.599	2.96 (2.482)
$\lvert M_H - 125\ \mathrm{GeV}\rvert < 40\ \mathrm{GeV}$	0.799	0	0	0	0.014	0.156	0	0.916	3.338	5.224	2.72 (2.303)

muon type:

	e1e1bb	e2e2bb	evbbqq	μvbbqq	τvbbqq	bbqqqq	bbbb	llbbbb	llqqh	bgrd	signal (llbbbb)
generated	$4.21 \cdot 10^6$	$1.00 \cdot 10^6$	$1.49 \cdot 10^6$	$1.47 \cdot 10^6$	931701	$2.89 \cdot 10^6$	978472	106940	151500		293165
expected	284117	49565.7	248454	245936	245708	624060	40234.4	69.51	150.87	$1.74 \cdot 10^6$	40.503
preselection	2697.42	1414.96	519.97	74.967	31.614	4.209	0.381	14.971	128.084	4886.58	22.86 (7.531)
ltype = 13	0	1414.96	0	73.765	2.461	0	0	7.612	65.274	1563.97	11.616 (3.807)
$\lvert M_Z - 91\ \mathrm{GeV}\rvert < 32\ \mathrm{GeV}$	0	1363.42	0	61.695	2.178	0	0	7.385	64.826	1499.51	11.513 (3.783)
MVAllbb > 0.38	0	85.928	0	46.557	1.866	0	0	6.396	54.187	194.935	10.01 (3.726)
MVAlvbbqq > 0.75	0	80.675	0	4.968	0.254	0	0	6.101	51.096	143.095	8.935 (3.618)
bmax3 > 0.2	0	6.046	0	0	0	0	0	5.396	10.15	21.593	3.964 (3.211)
MVAllbbbb > 0.23	0	2.132	0	0	0	0	0	1.122	3.750	7.005	3.123 (2.599)
$\lvert M_H - 125\ \mathrm{GeV}\rvert < 40\ \mathrm{GeV}$	0	1.488	0	0	0	0	0	0.978	3.229	5.695	2.887 (2.421)

Summary and Outlook

Conclusion

- direct determination of Higgs potential through double Higgs production
- measurement of Higgs self-coupling challenging
- recent DBD full simulation gives precision of 44% at $\sqrt{s} = 500$ GeV
- starting points for improvement
- long term goal: precision of $< 40\%$

Outlook

- perform analysis for $m_{\mathrm{H}} = 125$ GeV
- consider low-p_T $\gamma\gamma \rightarrow$hadrons overlay
- key algorithms: b-tagging, lepton selection, jet-finding, jet-clustering
- investigate kinematic fitting
- include the H→WW* mode (talk by Masakazu)
- optimise the analysis strategy (current selections are optimised for ZHH, not for the self-coupling diagram)

BACKUP SLIDES

Higgs self-coupling measurement at LHC

for Higgs: $m_H < 140$ GeV

dominant process:

$p + p \rightarrow HH \rightarrow b\bar{b}b\bar{b}$

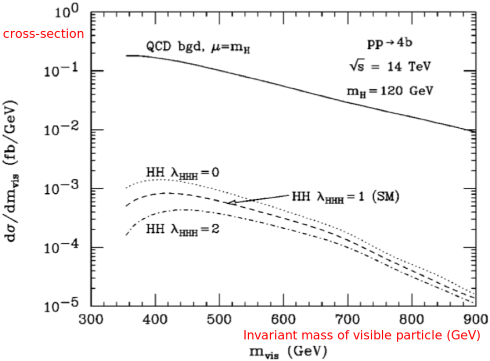
4b final state overwhelmed by the QCD background

solid: QCD 4b background

dashed: SM signal

dotted and dotted-dashed:

signal with different Higgs self-coupling



Phys.Rev.D68 (2003) 033001

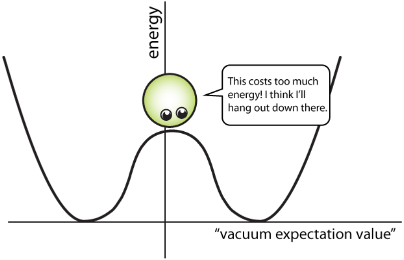
$$\text{LHC:} \quad -6.8 < \Delta\lambda_{HHH} < 10.1$$
$$\text{SLHC:} \quad -3.1 < \Delta\lambda_{HHH} < 6.0$$
$$\text{VLHC:} \quad -1.3 < \Delta\lambda_{HHH} < 2.4$$

⟶ **recent results:** ≈ 30%

$(\Delta\lambda_{HHH} = \frac{\lambda}{\lambda_{SM}} - 1)$

Higgs mechanism

Spontaneous symmetry breaking



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Example: Lagrangean

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\mu\phi^2 - \frac{1}{4}\lambda\phi^4$$

invariant under symmetry $\phi \longrightarrow -\phi$
but ground state is **not**!

Higgs mechanism in the Standard Model (electroweak symmetry breaking)

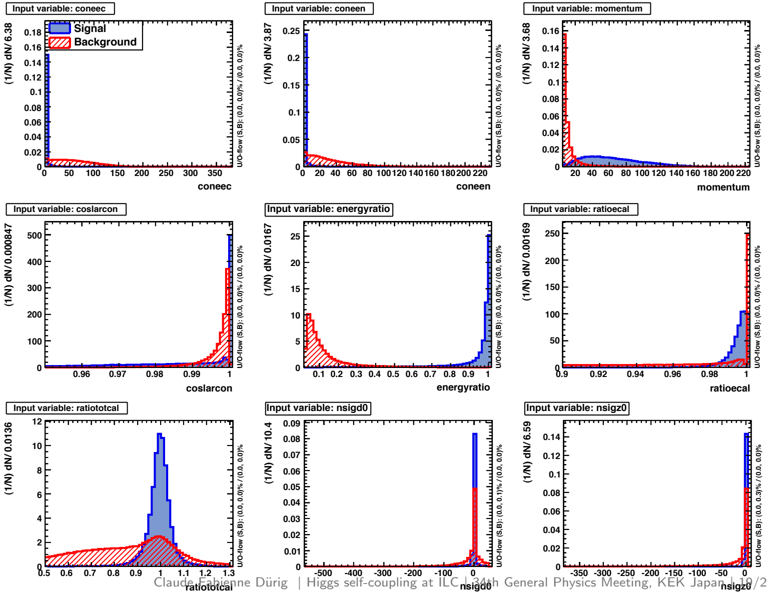
Start with 4 massless vector boson,
coupling to Higgs field

$\longrightarrow$

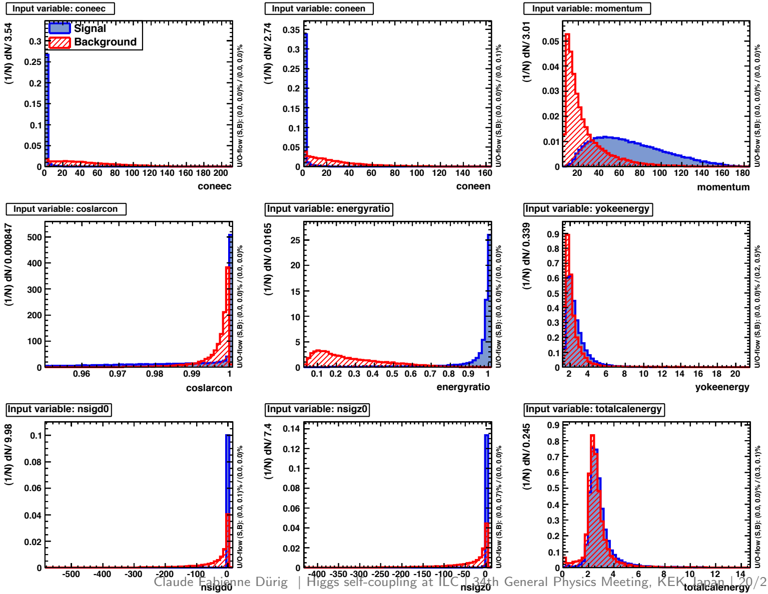
3 massive vector bosons
+ 1 massless vector boson
+ 1 massive scalar

$$W^{\pm}, Z^0 + H$$

NN training - Electrons



NN training - Muons



Main Difficulties in Analysis

general difficulties

- irreducible SM diagrams: significantly degrade the coupling sensitivity
- production cross-sections are small ⟶ high luminosities needed
- very large SM background

new difficulties

- Higgs mass reconstruction: wrong jet-pairing, mis-clustering
- flavor tagging and isolated lepton selection: need very high efficiency and purity
- neural net training: separated neural-nets, large statistics needed