# Higgs Self-Coupling Measurement at the ILC.

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LCWS 2013, University of Tokyo

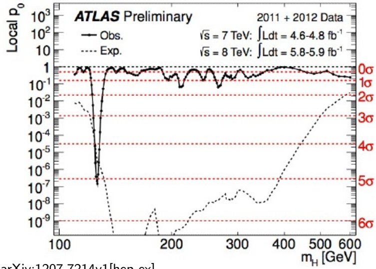
# Contents

# Introduction

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

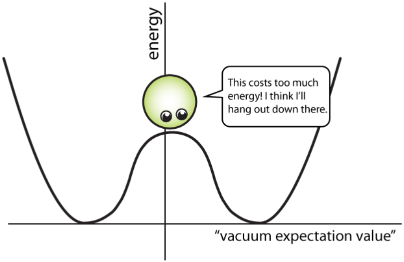
  missing: **Higgs potential**, which represents test of EWSB and mass generation

- 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

$\eta_H$: physical Higgs field

$v$: vacuum expectation value

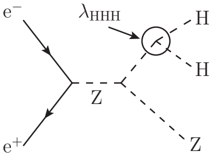
- trilinear $\lambda$ and quartic $\tilde{\lambda}$ Higgs couplings are defined as:

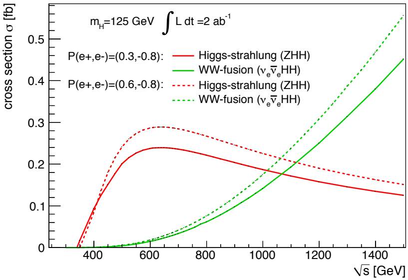
$$\lambda = \tilde{\lambda} = \lambda_{SM} = \frac{m_H^2}{2v^2}$$

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

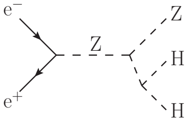
# Double Higgs production processes

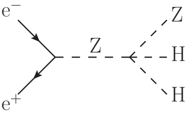
- **Higgs-strahlung**: dominant around $\sqrt{s} = 500$ GeV

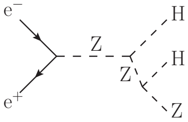



- **irreducible Feynman diagrams** which do not concern Higgs self-coupling




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

# Sensitivity of self-coupling to $\sigma$(ZHH)

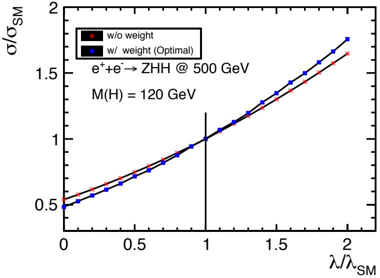
## cross-section $\sigma$(ZHH)

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

a: Higgs self-coupling diagram

b: interference between self-coupling and irreducible diagrams

c: irreducible diagrams




- precision of Higgs self-coupling:

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

$\mathrm{X} = 0.5$ without interference

$\mathrm{X} = 1.8$ for $m_\mathrm{H} = 120$ GeV at $\sqrt{s} = 500$ GeV

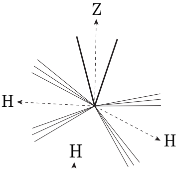
- new **weighting method** improves factor $\mathrm{X} = 1.66$

  (J.Tian:LCWS12 / ECFA13)

- better improvement expected for $\mathbf{m_H = 125}$ **GeV** at $\sqrt{s} = 500$ GeV, since without weighting $\mathrm{X} = 1.74$
  $\longrightarrow$ with weighting $\mathrm{X} = 1.64$

# Analysis strategy - Decay Channels

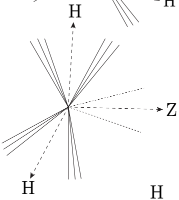
- Measurement at $\sqrt{s} = 500$ GeV and $\mathcal{L} = 2\ \text{ab}^{-1}$




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

2leptons 4jets mode ($10\% \times 60\% \times 60\% \approx 3.6\%$)

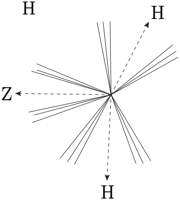
$Z \longrightarrow l\bar{l} \quad H \longrightarrow b\bar{b} \quad H \longrightarrow b\bar{b}$




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

2neutrino 4jet mode ($20\% \times 60\% \times 60\% \approx 7.2\%$)

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




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

6jets mode ($70\% \times 60\% \times 60\% \approx 25\%$)

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

# 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, $\mathcal{L} = 2\ \text{ab}^{-1}$ and $P(e^+e^-) = (0.3, -0.8)$
- here: investigated Higgs mass $m_H$= 120 GeV

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

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

## Next steps

- perform analysis with new $m_H = 125$ GeV samples
- consider low-$p_T$ $\gamma\gamma \to$ hadrons beam induced background
- 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-$p_T$ $\gamma\gamma \to$ hadrons background
3. force the other reconstructed particles into four jets
4. combine the four jets by choosing combination with smallest $\chi^2$

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

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 - Isolation Requirement

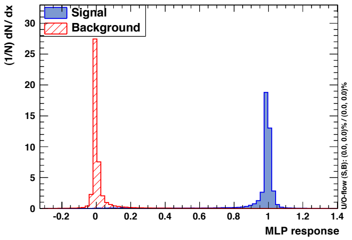
**old lepton selection** - isolation requirement**:**

- cut based on energy distributions in calorimeter

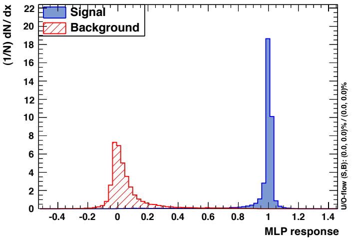
**new lepton selection** - isolation requirement**:**

- 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

**neural net output for electrons**

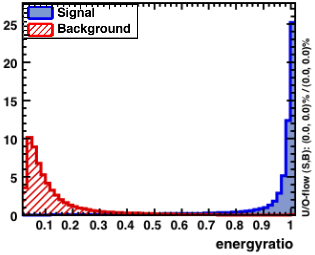



**neural net output for muons**

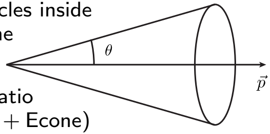


# New DiLeptonSelection - Isolation Requirement

**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

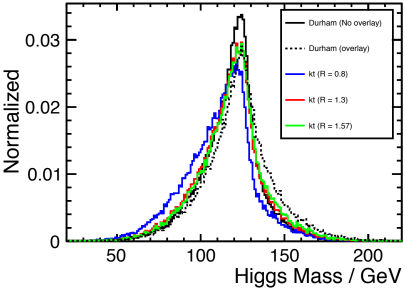
## Current Improvement

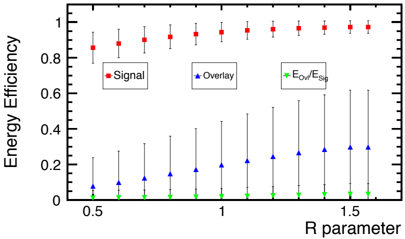
| efficiency (%) | eehh | μμhh | bbbb | eνbbqq | μνbbqq |
|---|---|---|---|---|---|
| new DBD | 86.99 | 89.11 | 0.00168 | 0.315 | 0.0196 |
| old DBD | 85.7 | 88.4 | 0.028 | 1.44 | 0.10 |
| old LoI | 81.9 | 85.4 | 0.43 | 2.71 | 1.94 |

**New lepton selection strategy increases signal efficiency.**

**Suppression of hadronic and one-lepton backgrounds is significantly improved.**

# Removal of beam induced $\gamma\gamma$ background




- low-$p_T$ $\gamma\gamma \rightarrow$ hadrons overlaid events per interaction:
  $$< N_{\gamma\gamma} >= 1.7$$
  (ILD/SiD standard, but overestimated)
- apply **FastJetClustering:**
  **$k_T$ExclusiveNJets4**
  which R-value?
- for $R \geq 1.2$ almost no increase in signal efficiency but in overlay
- best recovery of bare evts $R = 1.3$
- use only reconstructed particles in these 4 jets for analysis
- until now ZHH and ZZH samples with low-$p_T$ $\gamma\gamma \rightarrow$ hadrons overlaid

# Preliminary Preselection ($m_H$= 125 GeV)

Preselection for samples with overlaid low-$\mathbf{p_T}$ $\gamma\gamma \to$ hadrons background

| | eeHH | μμHH | eeqqH | μμqqH |
|---|---|---|---|---|
| expected no. of events | 13.50 | 13.52 | 75.34 | 75.53 |
| DiLeptonSelection | 11.74 | 12.05 | 68.41 | 67.26 |
| $k_T$ 1.3 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

| | eeHH | μμHH | eeqqH | μμqqH |
|---|---|---|---|---|
| expected no. of events | 13.50 | 13.52 | 75.34 | 75.53 |
| DiLeptonSelection | 11.92 | 12.83 | 68.51 | 67.91 |
| $k_T$ 1.3 ExclusiveNJets4 | - | - | - | - |
| combine four jets to two Higgs $\lvert M_H - 125\text{ GeV}\rvert < 80$ GeV | 11.42 | 12.11 | 63.75 | 66.56 |

**Exclusive $\mathbf{k_T}$ algorithm recovers event without $\gamma\gamma$-overlay very well.**

# Preliminary selection cuts for electron type

ZHH and ZZH samples with $\gamma\gamma$ background overlaid, other backgrounds not

- **cut1**: $|M_Z - 91\ \text{GeV}| < 32\ \text{GeV}$
- **cut2**: MVAllbb $> 0.66$
- **cut3**: MVAlvbbqq $> 0.69$
- **cut4**: bmax3 $> 0.2$
- **cut5**: MVAllbbbb $> 0.21$
- **cut6**: $|M_H - 125\ \text{GeV}| < 40\ \text{GeV}$

| | eebb | μμbb | eνbbqq | μνbbqq | τνbbqq | 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) |
| cut1 | 2383.93 | 0.049 | 426.935 | 0.337 | 23.439 | 1.799 | 0.296 | 7.081 | 62.234 | 2906.1 | 11.11 (3.696) |
| cut2 | 57.583 | 0 | 290.564 | 0.337 | 15.473 | 1.799 | 0.129 | 5.247 | 46.328 | 417.458 | 8.83 (3.519) |
| cut3 | 50.962 | 0 | 22.851 | 0 | 2.432 | 0.623 | 0.042 | 4.954 | 43.319 | 125.185 | 7.90 (3.361) |
| cut4 | 3.996 | 0 | 0.289 | 0 | 0.269 | 0.311 | 0.042 | 4.398 | 8.953 | 18.259 | 3.62 (2.986) |
| cut5 | 1.299 | 0 | 0 | 0 | 0.014 | 0.311 | 0.042 | 1.071 | 3.862 | 6.599 | 2.96 (2.482) |
| cut6 | 0.799 | 0 | 0 | 0 | 0.014 | 0.156 | 0 | 0.916 | 3.338 | 5.224 | 2.72 (2.303) |

**until cut5**:

| mode $ZHH \to l^- l^+ HH$ | signal | background (tt, ZZ, ZZH, ZZZ) | significance excess | significance measurement |
|---|---|---|---|---|
| old | 3.7 | 4.3 | $1.5\sigma$ | $1.1\sigma$ |
| new | 2.96 | 6.599 | $1.15\sigma$ | $0.96\sigma$ |

# Preliminary selection cuts for muon type

ZHH and ZZH samples with $\gamma\gamma$ background overlaid, other backgrounds not

- **cut1**: $|M_Z - 91\text{ GeV}| < 32\text{ GeV}$
- **cut2**: MVAllbb $> 0.38$
- **cut3**: MVAl$\nu$bbqq $> 0.75$
- **cut4**: bmax3 $> 0.2$
- **cut5**: MVAllbbbb $> 0.23$
- **cut6**: $|M_H - 125\text{ GeV}| < 40\text{ GeV}$

| | eebb | μμbb | eνbbqq | μνbbqq | τνbbqq | 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) |
| cut1 | 0 | 1363.42 | 0 | 61.695 | 2.178 | 0 | 0 | 7.385 | 64.826 | 1499.51 | 11.513 (3.783) |
| cut2 | 0 | 85.928 | 0 | 46.557 | 1.866 | 0 | 0 | 6.396 | 54.187 | 194.935 | 10.01 (3.726) |
| cut3 | 0 | 80.675 | 0 | 4.968 | 0.254 | 0 | 0 | 6.101 | 51.096 | 143.095 | 8.935 (3.618) |
| cut4 | 0 | 6.046 | 0 | 0 | 0 | 0 | 0 | 5.396 | 10.15 | 21.593 | 3.964 (3.211) |
| cut5 | 0 | 2.132 | 0 | 0 | 0 | 0 | 0 | 1.122 | 3.750 | 7.005 | 3.123 (2.599) |
| cut6 | 0 | 1.488 | 0 | 0 | 0 | 0 | 0 | 0.978 | 3.229 | 5.695 | 2.887 (2.421) |

**until cut5**:

| mode ZHH → $l^-l^+$HH | signal | background (tt, ZZ, ZZH, ZZZ) | significance excess | significance measurement |
|---|---|---|---|---|
| old | 4.5 | 6.0 | $1.5\sigma$ | $1.2\sigma$ |
| new | 3.123 | 7.005 | $1.17\sigma$ | $0.98\sigma$ |

# Summary and Outlook

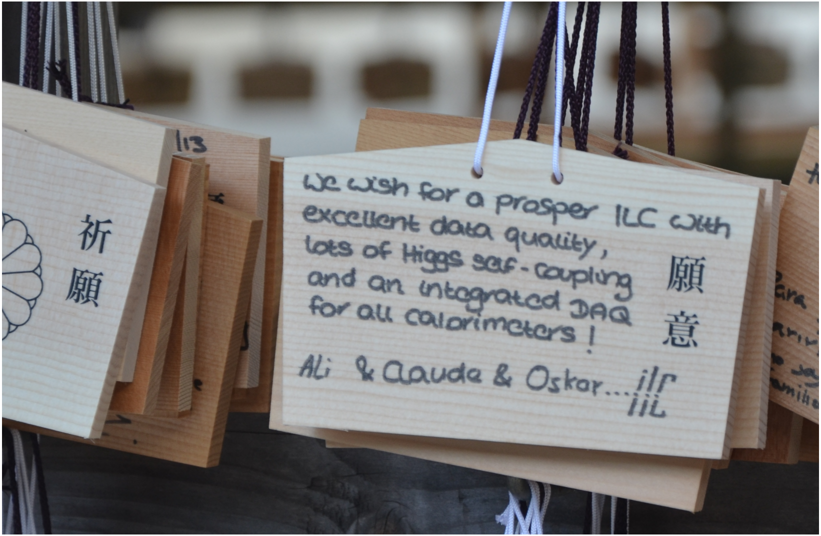
## Conclusion

- 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
- different starting points for improvement
- long term goal: precision of $< 40\%$

## Outlook

- perform entire analysis for $m_{\mathrm{H}} = 125$ GeV
- consider beam induced $\gamma\gamma$ background in all background samples
- improve neural net training and jet-pairing
- investigate kinematic fitting
- optimise the analysis strategy (current selections are optimised for ZHH, not for the self-coupling diagram)
- key algorithms: b-tagging, lepton selection, jet-finding, jet-clustering
- include the $\mathrm{H}\rightarrow\mathrm{WW}^{\star}$ mode (talk by Masakazu)

# Let us hope for the future....



# BACKUP SLIDES

# Higgs self-coupling measurement at LHC

for Higgs: $m_{\mathrm{H}} < 140$ GeV

dominant process:

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

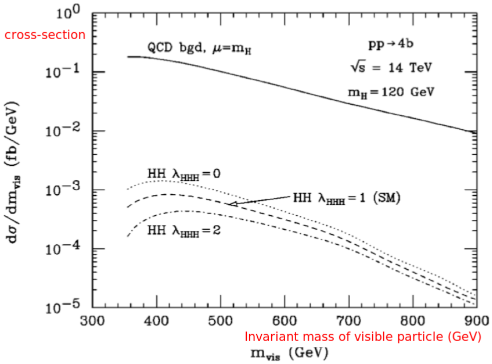
4b final state overwhelmed by the QCD background

solid: QCD 4b background

dashed: SM signal

dotted and dotted-dashed:

signal with different Higgs self-coupling




Phys.Rev.D68 (2003) 033001

LHC: $-6.8 < \Delta\lambda_{HHH} < 10.1$

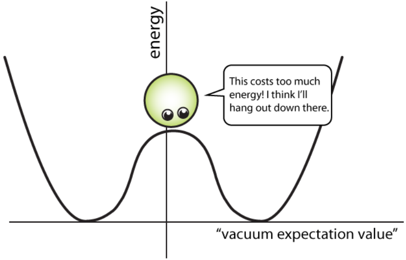
SLHC: $-3.1 < \Delta\lambda_{HHH} < 6.0$

VLHC: $-1.3 < \Delta\lambda_{HHH} < 2.4$ $\longrightarrow$ **recent results:** $\approx 30\%$

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

# Higgs mechanism

**Spontaneous symmetry breaking**




http://www.quantumdiaries.org

Example: Lagrangean

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

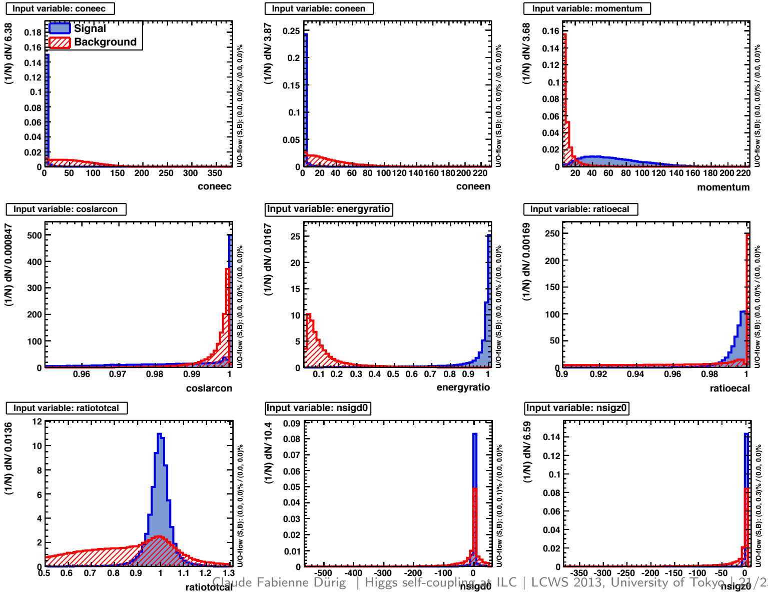
**invariant** under symmetry $\phi \longrightarrow -\phi$
but ground state is **not**!

**Higgs mechanism in the Standard Model (electroweak symmetry breaking)**

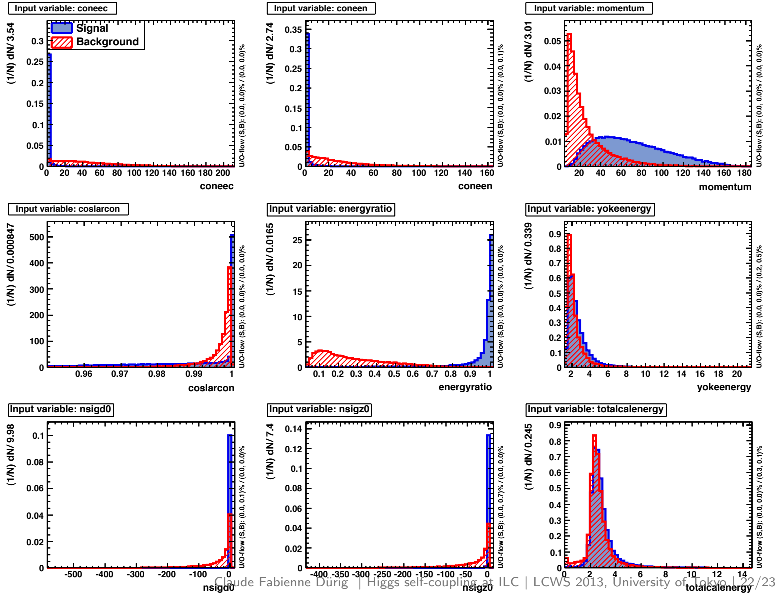
Start with 4 massless vector boson, coupling to Higgs field $\longrightarrow$ 3 massive vector bosons + 1 massless vector boson + 1 massive scalar

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

# 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 $\longrightarrow$ 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