Sensitivity to Anomalous VVH Couplings at the ILC

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This study was done mostly by Tomohisa Ogawa of KEK.

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We are at a big fork

Extension of Space-Time
SUSY / Extra-dimensions

- Fermionic Extra -dim. = SUSY
- Bosonic Extra -dim. = RS (ADD)

Key = Precision Higgs and Top couplings
SUSY particle discovery

Big step towards ultimate unification

The 1st Road: Existence of another dimension

Extension of Matter Structure
Composite Higgs

Atom
Nucleus
Nucleons

- quarks
- leptons
- gauge bosons

Jungle of new heavy composite particles in the TeV+ scale
New Strong Force

The 2nd Road: Existence of a new stratum of Nature

Electron
Higgs boson

The 3rd Road: Existence of a myriad of universes?

Completely New Principle
Multiverse + Anthropic Principle?

Key = precision m_t and m_h measurements

The 1st Road:
Existence of another dimension

No deviation from SM

We are here
Which way to go?
Decide the way by fingerprinting models with Precision Higgs Measurements

**Supersymmetry (MSSM)**
MSSM (tan β = 5, M_A = 700 GeV)
- Upward shift only for down-type fermions

**Composite Higgs (MCHM5)**
Minimal Composite Higgs Model 5 (f = 1.5 TeV)
- Downward shift for all the couplings

**Multi-verse? (Standard Model)**
Standard Model
- No deviation at all

**ILC Projection 250 GeV, 2 ab^{-1}, EFT fit [arXiv:1710.07621]**

Different models predict different deviation patterns
→ Deviation pattern tells us which way to go.

Complementary to direct searches at LHC: Depending on parameters, ILC’s sensitivity goes beyond that of LHC.
Precision Higgs coupling study is a torch to shine our way ahead.
Mass-produce Higgs bosons and study them in detail

250 GeV ILC as a Higgs Factory
250 GeV is a Special Energy
Single Higgs production cross section maximum

Production Cross Section as a fun. of $E_{cm}$

P($e^-, e^+)=(-0.8, 0.3)$, $M_h=125$ GeV

- $\text{SM all ffh}$
- $Z_h$
- $WW$ fusion
- $ZZ$ fusion

250 GeV: cross section maximum (~0.5 Million events for $2 \text{ ab}^{-1}$)

Mass-produce Higgs bosons and study them in detail!
**Recent Development: EFT Analysis**

**Potential drawback:**
It has been said that $\Gamma_h$ (Higgs total width) necessary for absolute coupling normalization requires $>350\text{GeV}$.

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

$$\Gamma(h \to WW^*) \propto \sigma(\nu \bar{\nu} h)$$

cross section: small at 250 GeV

**Solution:** **EFT (Effective Field Theory)**

**LHC Run II results** suggest that 250 GeV is likely in the validity range of the EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta \mathcal{L}$$

SU(2)$\times$U(1) inv.
dim.6 operators

# EFT coefficients to decide:
17 @ ILC

This ILC number is quite tractable:

- $W_L$ and $Z_L$ are NGBs from the Higgs sector. can use All the SM processes with W and Z to constrain EFT coefficients.

  (The importance of the $\sigma_{zh}$ measurement by recoil mass technique remains the same!)

- Beam polarization essentially doubles the number of usable observables.

  → can test the validity of the EFT

Absolute and model-independent Higgs coupling measurements possible with the 250 GeV data alone!
\[ \mathcal{L} = \mathcal{L}_{SM} + \Delta \mathcal{L} \]

\[
\Delta \mathcal{L} = \frac{c_H}{2v^2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) + \frac{c_T}{2v^2} (\Phi^\dagger \tilde{D}^\mu \Phi)(\Phi^\dagger \tilde{D}_\mu \Phi) - \frac{c_6 \lambda}{v^2} (\Phi^\dagger \Phi)^3 \\
+ \frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W^a_{\mu\nu} B^{\mu\nu} \\
+ \frac{g^2 c_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2} \epsilon_{abc} W^a_{\mu\nu} W^{b\nu}_\rho W^{c\rho\mu} \\
+ i \frac{c_{HL}}{v^2} (\Phi^\dagger \tilde{D}^\mu \Phi)(\bar{L} \gamma_\mu L) + 4i \frac{c_{HL}'}{v^2} (\Phi^\dagger t^a \tilde{D}^\mu \Phi)(\bar{L} \gamma_\mu t^a L) \\
+ i \frac{c_{HE}}{v^2} (\Phi^\dagger \tilde{D}^\mu \Phi)(\bar{e} \gamma_\mu e). 
\]

Manifestly SU(2)xU(1) gauge invariant

CP conserving

\[
+ \frac{g^2 \tilde{c}_{WW}}{m_W^2} \Phi^\dagger \Phi \tilde{W}^a_{\mu\nu} \tilde{W}^{a\mu\nu} + \frac{4gg' \tilde{c}_{WB}}{m_W^2} \Phi^\dagger t^a \Phi \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g^2 \tilde{c}_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} \tilde{B}^{\mu\nu} \\
+ \frac{g^3 \tilde{c}_{3W}}{m_W^2} \epsilon_{abc} W^a_{\mu\nu} W^{b\nu}_\rho \tilde{W}^{c\rho\mu}. 
\]

CP violating

\[
\Delta \mathcal{L}_h = -\eta_h \lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h \partial_\mu h \partial^\mu h + \eta_z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h + \frac{1}{2} \eta_2 \frac{m_Z^2}{v_0} Z_\mu Z^\mu h^2 \\
+ \eta_W \frac{2m_W^2}{v_0} W^\mu W^{-\mu} h + \eta_2W \frac{m_W^2}{v_0} W^\mu W^{-\mu} h^2 \\
+ \frac{1}{2} \left( \zeta_Z \frac{h}{v_0} + \frac{1}{2} \zeta_2Z \frac{h^2}{v_0} \right) \hat{Z}_{\mu\nu} \hat{Z}^{\mu\nu} + \left( \zeta_W \frac{h}{v_0} + \frac{1}{2} \zeta_2W \frac{h^2}{v_0} \right) \hat{W}_{\mu\nu} \hat{W}^{-\mu\nu} \\
+ \frac{1}{2} \left( \zeta_A \frac{h}{v_0} + \frac{1}{2} \zeta_2A \frac{h^2}{v_0} \right) \hat{A}_{\mu\nu} \hat{A}^{\mu\nu} + \left( \zeta_{AZ} \frac{h}{v_0} + \frac{1}{2} \zeta_2AZ \frac{h^2}{v_0} \right) \hat{A}_{\mu\nu} \hat{A}^{\mu\nu} \\
+ \frac{1}{2} \left( \tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_2Z \frac{h^2}{v_0} \right) \hat{\tilde{Z}}_{\mu\nu} \hat{\tilde{Z}}^{\mu\nu} + \left( \tilde{\zeta}_W \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_2W \frac{h^2}{v_0} \right) \hat{\tilde{W}}_{\mu\nu} \hat{\tilde{W}}^{-\mu\nu} \\
+ \frac{1}{2} \left( \tilde{\zeta}_A \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_2A \frac{h^2}{v_0} \right) \hat{\tilde{A}}_{\mu\nu} \hat{\tilde{A}}^{\mu\nu} + \left( \tilde{\zeta}_{AZ} \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_2AZ \frac{h^2}{v_0} \right) \hat{\tilde{A}}_{\mu\nu} \hat{\tilde{A}}^{\mu\nu}
\]

Coefficients, \( \eta \)'s and \( \zeta \)'s are given in terms of \( C \)'s and hence interrelated, for instance

\[
\eta_W = -\frac{1}{2} C_H \\
\eta_Z = -\frac{1}{2} C_H - C_T
\]

Nonzero \( C_T \) breaks custodial SU(2) Symmetry

Precision observables can determine \( C_T \)

which come to our rescue in \( \Gamma_h \) determination at 250 GeV where the WW-fusion cross section is small.

EFT Lagrangian After EW Symmetry Breaking

$$\Delta \mathcal{L}_h = -\eta_h \lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h \partial_\mu h \partial^\mu h + \left( \frac{m_Z^2}{v_0} Z_\mu Z^\mu h \right) + \frac{1}{2} \eta_2 z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h^2$$

$$+ \eta_W \frac{2m_W^2}{v_0} W^\mu W^- h$$

$$+ \eta_2 W \frac{m_W^2}{v_0} W^\mu W^- h^2$$

$$+ \frac{1}{2} \left( \zeta Z \frac{h}{v_0} + \frac{1}{2} \zeta_2 Z \frac{h^2}{v_0^2} \right) \hat{Z}_\mu \hat{Z}^\mu$$

$$+ \left( \frac{\zeta W}{v_0} + \frac{1}{2} \zeta_2 W \frac{h^2}{v_0^2} \right) \hat{W}^\mu \hat{W}^-$$

$$+ \frac{1}{2} \left( \zeta_A \frac{h}{v_0} + \frac{1}{2} \zeta_2 A \frac{h^2}{v_0^2} \right) \hat{A}_\mu \hat{A}^\mu$$

$$+ \left( \frac{\zeta_A Z}{v_0} + \frac{1}{2} \zeta_2 AZ \frac{h^2}{v_0^2} \right) \hat{A}_\mu \hat{Z}^\mu$$

Coefficients, \(\eta\)'s and \(\zeta\)'s are given in terms of \(C\)'s and hence interrelated, for instance:

$$\eta_W = -\frac{1}{2} C_H$$

Nonzero \(C_T\) breaks custodial SU(2) Symmetry

$$\eta_Z = -\frac{1}{2} C_H - C_T$$

Precision observables can determine \(C_T\)

which come to our rescue in \(\Gamma_h\) determination at 250 GeV where the WW-fusion cross section is small.

Search for Anomalous VVH Couplings is an essential part of the SM EFT Analysis
Anomalous ZZH/γZH couplings

A and Z are mixtures of B and W

B couples to $e_L$ and $e_R$ in the same way. W couples to $e_L$ only.

⇒ Beam polarization is essential to decompose them

Redefinition of coefficients

$$\mathcal{L}_{VVH} = \frac{m_Z^2}{v} (1 + \eta_Z) Z_{\mu} Z^\mu h + \frac{1}{2v} (\zeta_Z \hat{Z}_{\mu\nu} \hat{Z}^{\mu\nu} + \zeta_{AZ} \hat{A}_{\mu\nu} \hat{Z}^{\mu\nu}) h + \frac{1}{2v} (\tilde{\zeta}_Z \hat{Z}_{\mu\nu} \tilde{Z}^{\mu\nu} + \tilde{\zeta}_{AZ} \hat{A}_{\mu\nu} \tilde{Z}^{\mu\nu}) h$$

$$\eta_Z = \frac{v}{\Lambda} a_Z$$
$$\zeta_Z = \frac{v}{\Lambda} b_Z$$
$$\tilde{\zeta}_Z = \frac{v}{\Lambda} \tilde{b}_Z$$

Different $b_Z, \tilde{b}_Z$ for different beam polarizations

$$\left\{ \begin{array}{l}
e^{-}\bar{e}^e_K : 1 + 5.70 \zeta_{ZZ} + 7.70 \zeta_{AZ} = 1 + 5.70 b_Z^e e^h \\
e^{-}\bar{e}^e_L : 1 + 5.70 \zeta_{ZZ} - 9.05 \zeta_{AZ} = 1 + 5.70 b_Z^e e^l \end{array} \right. \quad (\Lambda=1\text{TeV})$$

$$v/\Lambda=1/4$$

Analysis strategy

With full detector simulation, decide acceptance $\eta$ and migration matrix $\tilde{f}$ and use them to translate theory to reconstructed distributions.

Then fit the translated theory distributions to the toy MC for SM to estimate ILC’s sensitivity to anomalous couplings.
ZH → \(\mu\mu H\) / \(qqH(bb)\)

**\(\mu\mu H\)**

- **ILD full simulation**
  - Observed M_{recoil} mass peak
  - Sharp recoil mass peak

**qqH**

- High stat. signal sample
  - \(e^+e^-\rightarrow qqH(H\rightarrow bb)\)
  - \(\sqrt{s}=250\text{GeV}, L_{\text{int}}=250\text{fb}^{-1}\)
  - H→bb

**Analysis on the Anomalous**

- Migration matrix \(f\)
- Acceptance \(\eta\)
- Probability for reconstruction
- \(\Delta\Phi\): angle btw Z prod. and Z decay planes

- Backgrounds after cuts
- Event Acceptance
- Probability for reconstruction
- \(\Delta\Phi\): angle btw Z prod. and Z decay planes
- Probability matrix of migration

- Backgrounds after cuts
- Event Acceptance
- Weighted probability for reconstruction
- \(\Delta\Phi\): angle btw Z prod. and Z decay planes
- Probability matrix of migration

- \(f\_\text{sl}\), and the cross-sections ofZZH→llqq
- Events/0.21
- Events/0.5
Anomalous ZZH/γZH couplings

3-parameter fit

\[ \mathcal{L}_{ZZH} = M_Z^2 \left( \frac{1}{V} + \frac{a_Z}{\Lambda} \right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda} \hat{Z}_{\mu\nu} \hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda} \tilde{Z}_{\mu\nu} \tilde{Z}^{\mu\nu} H \]  
\( (\Lambda=1\text{TeV}) \)

5-parameter fit

1σ bounds including 500 GeV operation

\[ ZH + ZZ \text{ at } 250 + 500 \text{ GeV with } H20 \]

\[ \begin{align*}
    a_Z & = \pm 0.0223 \quad (\eta_Z = \pm 0.5\%) \\
    \zeta_{ZZ} & = \pm 0.0067 \\
    \zeta_{AZ} & = \pm 0.0024 \\
    \tilde{\zeta}_{ZZ} & = \pm 0.0109 \\
    \tilde{\zeta}_{AZ} & = \pm 0.0006 
\end{align*} \]

ZZH / γZH structures can be measured to ~0.5% or much better

Anomalous WWH couplings

3-parameter fit

\[ \mathcal{L}_{WWH} = 2 M_W^2 \left( \frac{1}{v} + a_W \right) W_\mu W_-^\mu H + \frac{b_W}{\Lambda} \hat{W}_\mu^+ \hat{W}_\mu^{-\mu} H + \frac{\tilde{b}_W}{\Lambda} \hat{W}_\mu^+ \hat{W}^{-\mu} H \] 

(\Lambda=1\text{TeV})

\[ \sqrt{s}=250\text{ GeV}, \int L dt=250\text{ fb}^{-1} \]

P(e^-,e^+)=(80\%,+30\%)

vvh, h \rightarrow b\bar{b}

w/ ZZH variation and constraints

[Graph and data points]

6-parameter fit

1\sigma bounds
including 500GeV operation

SM-like structure can be measured to \sim 0.5 %

New structures to a few % or better

\[ \Delta\Phi(\text{decay planes } H \rightarrow WW^*) \] need to be reconstructed for bt

\[ \eta_W = (v/\Lambda) a_W, \text{ etc.} \]

[Graph with data points]

\[ \sqrt{s} = 250 + 500 \text{ GeV with } L_{\text{int}} = \text{H20 and } P(e^-,e^+) = \text{Both} \]

w/ ZZH contributions

w/ the shape \nu\bar{\nu}h + w/ the shape Zh, h \rightarrow WW^*

\[ \begin{pmatrix} a_W = [-0.024, 0.019] \\ b_W = [-0.070, 0.036] \\ \tilde{b}_W = [-0.175, 0.179] \\ a_Z = [-0.031, 0.031] \\ b_Z = [-0.0090, 0.0090] \\ \tilde{b}_Z = [-0.0093, 0.0093] \end{pmatrix} , \rho = \begin{pmatrix} 1 & 0.3907 & -0.0534 & -0.0445 & -0.0064 & 0.0003 \\ -1 & 1 & -0.0856 & -0.0128 & 0.0059 & 5.7E-5 \\ -1 & -1 & 1 & 0.045 & -0.0032 & 3.6E-5 \\ -1 & -1 & -1 & 1 & -0.9186 & -0.0018 \\ -1 & -1 & -1 & -1 & 1 & 0.0009 \\ -1 & -1 & -1 & -1 & -1 & 1 \end{pmatrix} \]

https://arxiv.org/abs/1506.07830
Sensitivity to Anomalous VVH Couplings

**ILC full operation (=H20 including 500 GeV data)**

\[ \Delta L_h = -\eta_h \lambda_0 v_0 h^3 + \frac{\theta}{v_0} h \partial_{\mu} h \partial^{\mu} h + \eta_Z \frac{m_Z^2}{v_0} Z_{\mu} Z^{\mu} h + \eta_Z \frac{m_Z^2}{v_0} \frac{m_Z^2}{v_0} Z_{\mu} Z^{\mu} h + 0.5\% (a_Z \sim 2\%) \]

\[ + \eta_W \frac{2m_W^2}{v_0} W_\mu^+ W_{-\mu} h + 0.5\% (a_W \sim 2\%) \]

\[ < 0.3\% (b_Z \sim 1\%) + \frac{1}{2} \left( \zeta_Z \frac{h}{v_0} + \frac{1}{2} \zeta_{2Z} \frac{h^2}{v_0^2} \right) \hat{Z}_{\mu \nu} \hat{Z}^{\mu \nu} + \left( \zeta_W \frac{h}{v_0} + \frac{1}{2} \zeta_{2W} \frac{h^2}{v_0^2} \right) W_{\mu}^+ W_{-\mu} \sim 1-2\% (b_W \sim 3-7\%) \]

\[ + \frac{1}{2} \left( \zeta_A \frac{h}{v_0} + \frac{1}{2} \zeta_{2A} \frac{h^2}{v_0^2} \right) \hat{A}_{\mu \nu} \hat{A}^{\mu \nu} + \left( \zeta_{AZ} \frac{h}{v_0} + \frac{1}{2} \zeta_{2AZ} \frac{h^2}{v_0^2} \right) \hat{A}_{\mu \nu} \hat{Z}^{\mu \nu} < 0.3\% \]

\[ < 0.3\% (\tilde{b}_Z \sim 1\%) + \frac{1}{2} \left( \tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_{2Z} \frac{h^2}{v_0^2} \right) \hat{Z}_{\mu \nu} \hat{Z}^{\mu \nu} + \left( \tilde{\zeta}_W \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_{2W} \frac{h^2}{v_0^2} \right) \hat{W}_{\mu}^+ \hat{W}_{-\mu} \sim 5\% (\tilde{b}_W \sim 17\%) \]

\[ + \frac{1}{2} \left( \tilde{\zeta}_A \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_{2A} \frac{h^2}{v_0^2} \right) \hat{A}_{\mu \nu} \hat{A}^{\mu \nu} + \left( \tilde{\zeta}_{AZ} \frac{h}{v_0} + \frac{1}{2} \tilde{\zeta}_{2AZ} \frac{h^2}{v_0^2} \right) \hat{A}_{\mu \nu} \hat{Z}^{\mu \nu} < 0.3\% \]

The values given above are from direct measurements just using the three single Higgs production processes.

A global fit including other SM processes with no Higgs in the final state such as e^+e^- \rightarrow W^+W^-, Z\gamma, etc. can further improve the sensitivity.
Summary

- Precision Higgs coupling study is a torch to shine our way ahead.

- **250 GeV ILC is an ideal torch**, which allows us **precision model-independent** measurements of various **absolutely normalized Higgs couplings** in the framework of dim-6 SM EFT.

- **One of the key elements** of the SM EFT analysis is **search for anomalous VVH couplings**.

- With full ILC program including 500 GeV operation, we can measure
  - **SM-like ZZH/WWH couplings to ~0.5%**
  - **New ZZH/γZH couplings to ~0.3%**
  - **New WWH couplings to ~1-2 % (CPC) and ~5% (CPV)**
Backup
EFT Lagrangian Before EW Symmetry Breaking

\[ \mathcal{L} = \mathcal{L}_{SM} + \Delta \mathcal{L} \]

\[ \Delta \mathcal{L} = \frac{c_H}{2v^2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) + \frac{c_T}{2v^2} (\Phi^\dagger \nabla_\mu \Phi)(\Phi^\dagger \nabla_\mu \Phi) - \frac{c_6 \lambda}{v^2} (\Phi^\dagger \Phi)^3 \]

\[ + \frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu \nu} W^{a \mu \nu} + \frac{4gg'c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W^a_{\mu \nu} B^{\mu \nu} \]

\[ + \frac{g'^2 c_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu \nu} B^{\mu \nu} + \frac{g^3 c_{3W}}{m_W^2} \epsilon_{abc} W^a_{\mu \nu} W^{b \nu} \rho W^{c \rho \mu} \]

\[ + i \frac{c_{HL}}{v^2} (\Phi^\dagger \nabla_\mu \Phi)(\overline{L} \gamma_\mu L) + 4i \frac{c'_{HL}}{v^2} (\Phi^\dagger t^a \nabla_\mu \Phi)(\overline{L} \gamma_\mu t^a L) \]

\[ + i \frac{c_{HE}}{\gamma^2} (\Phi^\dagger \nabla_\mu \Phi)(\overline{e} \gamma_\mu e) . \]

Manifestly SU(2)xU(1) gauge invariant

10 parameters of which C_6 only affects Higgs self-coupling analysis.

5 parameters to account for Higgs coupling to b, c, τ, μ, g.

+ 2 parameters to account for invisible and exotic Higgs decays.

+ 4 parameters to account for the shifts of g, g’, v, and λ

+ 2 parameters (CHL-type) to shift W, Z widths.
Observables (Shape of the Zh process)

\[ \mathcal{L}_{ZZH} = M_Z^2 \left( \frac{1}{v} + \frac{a_Z}{\Lambda} \right) Z_\mu Z^\mu h + \frac{b_Z}{2\Lambda} Z_{\mu\nu} Z^{\mu\nu} h + \frac{\tilde{b}_Z}{2\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h, \]

SM-like coupling  CP-conserving  CP-violating

Matrix Element

\[ \mathcal{M}^Z_{a_Z} \] does not change shape \(= -\epsilon_1 \cdot \epsilon_2 \)

\[ \mathcal{M}^Z_{b_Z} = Z_{1\mu\nu} Z_{2}^{\mu\nu} = (\partial_{1\mu} Z_{1\nu} - \partial_{1\nu} Z_{1\mu})(\partial_{2}^{\mu} Z_{2}^{\nu} - \partial_{2}^{\nu} Z_{2}^{\mu}) \]

\[ = -2\left[ -E_2 \sqrt{s} (-\epsilon_1 \cdot \epsilon_2) - 0 \right] = -2E_2 \sqrt{s} (\epsilon_1 \cdot \epsilon_2) \]

=> The larger E, the larger effect
Observables (Shape of the Zh process)

\[ \mathcal{L}_{ZZH} = M_Z^2 \left( \frac{1}{v} + \frac{a_Z}{\Lambda} \right) Z_\mu Z^\mu h + \frac{b_Z}{2\Lambda} Z_{\mu\nu} Z^{\mu\nu} h + \frac{\tilde{b}_Z}{2\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h, \]

SM-like coupling  CP-conserving  CP-violating

Matrix Element

\[ f^+ \]

\[ E_2 \]

\[ \otimes B_2 \]

\[ f^- \]

\[ e^+ \]

\[ E_1 \]

\[ B_1 \]

\[ e^- \]

\[ Z_1(q_1, \epsilon_1) \]

\[ Z_2(q_2, \epsilon_2) \]

\[ H \]

\[ f \]

\[ \Delta \Phi \]

Running hyper/weak charge

Field strengths

\[ \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \propto B_1 \cdot B_2 - E_1 \cdot E_2 \Rightarrow \text{tends to be parallel} \]

\[ \hat{F}_{\mu\nu} \tilde{F}^{\mu\nu} \propto E_1 \cdot B_2 \Rightarrow \text{tends to be perpendicular} \]

In the Laboratory frame

In the case of the Higgs-strahlung process, the initial and final state fermions, where the charges of each pair of fermions can individually imitate derived from the new tensor structures. A structure of an electromagnetic field tensor is assumed to be

\[ \text{as an analogues of the electromagnetism, which is} \]

\[ \text{when the Lorentz condition is considered} \]

\[ \text{impact of} b_z \]

\[ \text{impact of} \tilde{b}_z \]
Observables (Shape of the Zh process)

\[ \mathcal{L}_{ZZH} = M_Z^2 \left( \frac{1}{v} + \frac{a_Z}{\Lambda} \right) Z_\mu Z^\mu h + \frac{b_Z}{2\Lambda} Z_{\mu\nu} Z^{\mu\nu} h + \frac{\tilde{b}_Z}{2\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h, \]

SM-like coupling  CP-conserving  CP-violating

Since the Field strengths have momentum dependence
the effect increases with the energy

250GeV => 500GeV
Observables (Shape of the VV-fusion process)

production

\[ e^+ e^- \rightarrow Z_1(q_1, \epsilon_1) \]
\[ Z_2(q_2, \epsilon_2) \rightarrow e^+ e^- \]

\[ H \]

decay

\[ W_1(q_1, \epsilon_1) \rightarrow f^- f^- \]
\[ W_2(q_2, \epsilon_2) \rightarrow f^+ f^+ \]

Figure 33: Measurements of the Higgs boson coupling constants with fermions and gauge bosons

- In the H rest-frame
- In the lab-frame
- Helicity angle in the W rest-frame
**Observables (Cross-section)**

**Strong effect on the total cross section**

**Zh process**

![Zh process graph](image1)

**WW-fusion**

![WW-fusion graph](image2)

- **b**: Asymmetric variation, \((F_{\mu \nu} F^{\mu \nu})^2\) gives diff. terms with diff. signs

- **bt**: Symmetric variation, \((F_{\mu \nu} \tilde{F}^{\mu \nu})^2\) gives one term. or just imagine CP-even obs.

The Energy dependence also appears
Detector Effects

Take detector effects into account with acceptance and migration functions

e.g.) \( e^+e^- \rightarrow ZH \rightarrow qqH(bb) \) @ 250GeV

\[(\cos \theta_z, \cos \theta_f^*) : \text{helicity angle}\]

Detector response function

\[
\text{Observed} \quad N^{\text{Rec}}(x_j^{\text{Rec}}) = \sum_i f(x_j^{\text{Rec}}, x_i^{\text{Gen}}) \cdot N^{\text{Gen}}(x_i^{\text{Gen}}) \quad \text{Models}
\]

\[
N^{\text{Rec}}(x_j^{\text{Rec}}) = \sum_i f_{ji} \cdot N_i^{\text{Gen}} = \sum_i f_{ji} \cdot \eta_i \cdot N_i^{\text{Gen}}
\]

2 functions

Event acceptance: \( \eta \) and migration matrix: \( f \)

to take into account migration due to finite detector resolution

Theoretical distributions \( \Rightarrow \) observed distributions

with detector acceptance and resolution
Detector Effects

Take detector effects into account with acceptance and migration functions

Theoretical distributions \(\Rightarrow\) observed distributions with detector acceptance and resolution

1-dim observable \(\Delta \Phi\)

\[
N^{Rec}(x_j^{Rec}) = \sum_i f(x_j^{Rec}, x_i^{Gen}) \cdot N^{Gen}(x_i^{Gen})
\]

\[
N^{Rec}(x_j^{Rec}) = \sum_i f_{ji} \cdot N_i^{Gen} = \sum_i \bar{f}_{ji} \cdot \eta_i \cdot N_i^{Gen}
\]

Two functions:

\[
\eta_i \equiv \frac{N_i^{Accept}}{N_i^{Gen}} \quad \text{(Event acceptance)}
\]

\[
\bar{f}_{ji} \equiv \frac{N_{ji}^{Accept}}{N_i^{Accept}} \quad \text{(Migration matrix)}
\]
Shape Analysis

Kinematical “shape” information to test the deviation.

\[ \chi^2_{shape} = \sum_{j=1}^{\text{#bins}} \left( \frac{N_{SM}}{\Delta n_{SM}^{obs}(x_j)} \sum_{i=1}^{n} \left( \frac{1}{\sigma} \frac{d\sigma}{dx}(x_i) \cdot f_{ji} - \frac{1}{\sigma} \frac{d\sigma}{dx}(x_i; aV, bV, b\bar{V}) \cdot f_{ji} \right) \right)^2 \]

Poisson error for each bin (including SM Bkgs)

\[ \Rightarrow \text{full simulation information} \]

"Generator level" distribution from \( d\sigma/dX \) with and without anomalous couplings

"Detector level" distribution

\[ \rightarrow \text{Translate theory to} \]

\[ \Rightarrow \text{full simulation information} \]
Addition of Normalization Information

“Cross-section” information to test the deviation.

\[
\chi^2_{\text{norm}} = \left[ \frac{N_{SM} - N_{BSM}(a_V, b_V, \tilde{b}_V)}{\delta \sigma_{Zh/eeh} \cdot N_{SM}} \right]^2
\]

Relative errors of cross-section measurement
(SM Bkgs are taken into account)

=> full simulation information

\[\delta \sigma (Zh) = 2.0\% \text{ and } 3.0\% \text{ for } 250 \text{ and } 500 \text{ GeV} \]

As for \(\delta \sigma (\text{fusion})\)

=> Partial widths will vary due to anom-VVH
=> need to have some assumptions
=> keep model-independence by using BR measured model-independently

\[
\begin{align*}
\delta (\sigma_{eeh} \cdot BR_{hbb}) &= 27.0\% \text{ and } 4.0\% \\
& \text{ for } 250 \text{ and } 500 \text{ GeV} \\
\delta BR_{hbb} &= 2.9\% \text{ and } 3.5\% \\
& \text{ for } 250 \text{ and } 500 \text{ GeV}
\end{align*}
\]

by propagating error of \(\delta BR_{hbb}\)

\[
\begin{align*}
\delta \sigma_{eeh} \text{ are } 27.16\% \text{ and } 5.32\% \\
& \text{ for } 250 \text{ and } 500 \text{ GeV} \\
\delta \sigma_{\nu\nu h} &= 8.1\% \text{ and } 1.0\% \\
& \text{ for } 250 \text{ and } 500 \text{ GeV}
\end{align*}
\]

250 GeV 250 fb-1 for both Pol.
500 GeV 500 fb-1 for both Pol.