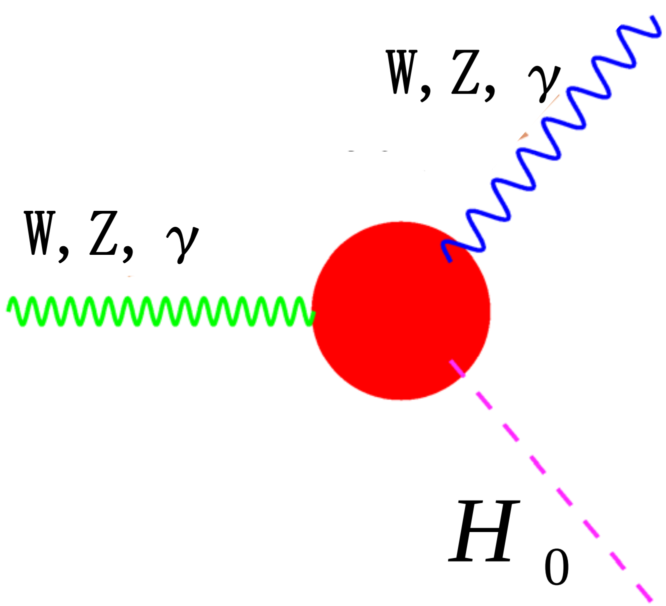
Presice measurement of the Higgs-boson electroweak couplings at Linear Collider and its physics impacts

Yu Matsumoto (GUAS,KEK) 2008,3,5
@TILC



Contents
1. Introduction
2. Analysis
3. Results
4. Conclusion

In collaboration with K.Hagiwara (KEK) and S.Dutta (Univ. of Delhi)

1-1. Motivation

New Physics

SM

Theory

TeV scale Physics

- Light Higgs
  - SUSY
  - Little Higgs
  - ・・・
- Heavy Higgs or Higgsless

Experiments

If the light Higgs exists, LC can probe the detail properties of the Higgs boson

LHC

Higgs discovery
Higgs partner

WW scattering

LC

Precise measurements of Higgs coupling

Tevatron

W, Z, top discovery

LEP

W and Z mass & couplings

1-2. Effective Lagrangian with Higgs doublet

New physics can be represented by higher mass dimension operators

$$L_{eff} = L_{SM} + L^{\dim 5} + L^{\dim 6} + L^{\dim 7} + L^{\dim 8} + \cdots,$$

contribute to majonara neutrino mass

contribute to

- four fermion coupling (Proton decay, FCNC, etc)
- purely gauge term (Triple gauge coupling, etc)
- Higgs electroweak couplings

We focused on this physics

We can write the effective Lagrangian including Higgs doublet as

$$L_{eff} = L_{SM} + \sum_i \frac{f_i}{\Lambda^2} O_i^{(6)}$$

New physics effects. Here we considered only dimension 6

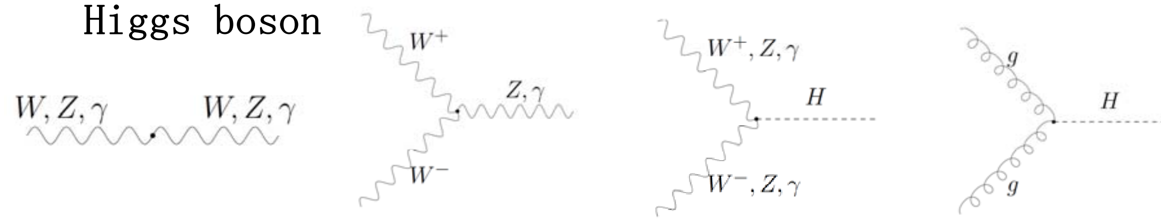
and the operators are …

1-3. dimension 6 operators including Higgs

Precision measurement (SLC, LEP, Tevatron)

Triple gauge couplings (LEP2, Tevatron)

2 point function, TGC, vertices include Higgs boson



Dimension 6 operators

LHC

LC

$\mathcal{O}$	WW	ZZ	$Z\gamma$	$\gamma\gamma$	$WW\gamma$	WWZ	HWW	HZZ	$HZ\gamma$	$H\gamma\gamma$	Hgg
$\mathcal{O}_{\phi,1} = \left[(D_\mu\Phi)^\dagger\Phi\right]\left[\Phi^\dagger(D^\mu\Phi)\right]$		√					√	√			
$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}^{\mu\nu}\hat{W}_{\mu\nu}\Phi$		√	√	√	√	√	√	√	√	√	
$\mathcal{O}_W = (D^\mu\Phi)^\dagger\hat{W}_{\mu\nu}(D^\nu\Phi)$					√	√	√	√	√		
$\mathcal{O}_B = (D^\mu\Phi)^\dagger\hat{B}_{\mu\nu}(D^\nu\Phi)$					√	√		√	√		
$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\Phi$	–	–	–	–	–	–	√	√	√	√	
$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}^{\mu\nu}\hat{B}_{\mu\nu}\Phi$		–	–	–				√	√	√	
$\mathcal{O}_{\phi,4} = (\Phi^\dagger\Phi)(D_\mu\Phi)^\dagger(D^\mu\Phi)$	–	–					√	√			
$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$							√	√			
$\mathcal{O}_{gg} = \Phi^\dagger\hat{G}^{\mu\nu}\hat{G}_{\mu\nu}\Phi$											√

1-4. Operators and Vertices, Form Factors

We exchange the operators into HVV interaction vertices as the experimental observables

$$L_{eff} = L_{SM} + \sum_i \frac{f_i}{\Lambda^2} O_i^{(6)} = (1 + a_{ZZ}) \frac{g_Z m_Z}{2} HZ_\mu Z^\mu + (1 + a_{WW}) g m_W HW_\mu^+ W^{-\mu}$$

$$+ \frac{g_Z}{m_Z}\left[\frac{b_{ZZ}}{2} HZ_{\mu\nu} Z^{\mu\nu} + \frac{c_{ZZ}}{2}((\partial_\mu H)Z_\nu - (\partial_\nu H)Z_\mu)Z^{\mu\nu}\right]$$

$$+ \frac{g_Z}{m_Z}\left[b_{Z\gamma} HZ_{\mu\nu} A^{\mu\nu} + c_{Z\gamma}((\partial_\mu H)Z_\nu - (\partial_\nu H)Z_\mu)A^{\mu\nu}\right]$$

$$+ \frac{g_Z}{m_Z}\left[b_{WW} HW_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{WW}}{2}(((\partial_\mu H)W_\nu^- - (\partial_\nu H)W_\mu^-)W^{+\mu\nu} + h.c.)\right] + \cdots$$

※ $(a_Z, b_Z, c_Z, b_\gamma, c_\gamma, b_{\gamma\gamma}, a_W, b_W, d_W)$ are the linear function of f_i

$$a_{ZZ} = \frac{v^2}{4\Lambda^2}(3f_{\phi1} + 3f_{\phi4} - 2f_{\phi2}),$$

$$b_{ZZ} = \frac{m_Z^2}{\Lambda^2}(-s_W{}^4 f_{BB} - s_W^2 c_W^2 f_{BW} - c_W{}^4 f_{WW}),$$

$$b_{Z\gamma} = \frac{m_Z^2}{\Lambda^2}(s_W^2 f_{BB} + \frac{1}{2}(c_W^2 - s_W^2) f_{BW} - c_W^2 f_{WW}) s_W c_W,$$

$$c_{ZZ} = \frac{m_Z^2}{2\Lambda^2}(-s_W^2 f_B + c_W^2 f_W),$$

$$c_{Z\gamma} = \frac{m_Z^2}{4\Lambda^2}(f_B - f_W) s_W c_W,$$

$$b_{\gamma\gamma} = \frac{m_Z^2}{\Lambda^2}(-f_{BB} + f_{BW} - f_{WW}) c_W^2 s_W^2,$$

$$a_{WW} = \frac{v^2}{4\Lambda^2}(-f_{\phi1} + 3f_{\phi4} - 2f_{\phi2}),$$

$$b_{WW} = \frac{m_Z^2 c_W^2}{\Lambda^2}(-f_{WW}),$$

$$c_{WW} = \frac{m_Z^2 c_W^2}{2\Lambda^2}(-f_W)$$

(dark green box / circle) : EW precision, S and T parameter

(light green box) : Triple Gauge Couplings

1-5. Optimal observable method

The differential cross section can be expressed by using non-SM couplings

$$\frac{d\sigma}{d\Omega} = \Sigma_{SM}(\Omega) + \sum_i c_i \Sigma_i(\Omega)$$

$c_i = (a_{WW}, a_{ZZ}, b_{WW}, b_{ZZ}, b_{Z\gamma}, b_{\gamma\gamma}, c_{WW}, c_{ZZ}, c_{Z\gamma})$

Ω is 3-body phase space

$$\begin{cases} N_{EXP}^k = L\Sigma_{SM}(\Omega_k)\Delta\Omega_k, \\ N_{TH}^k = L\Sigma_{SM}(\Omega_k)\Delta\Omega_k + L\sum_i c_i \Sigma_i(\Omega_k)\Delta\Omega_k \end{cases}$$

number of event in the k-th bin for experiment and theory

χ^2 can be expressed in terms of non-SM couplings

$$\chi^2(c_1,\cdots,c_n) = \sum_k \left(\frac{N_{EXP}^k - N_{TH}^k(c_i)}{\sqrt{N_{EXP}^k}} \right)^2 = \sum_k \left(\frac{L\sum_i c_i \Sigma_i(\Omega_k)\Delta\Omega_k}{\sqrt{L\Sigma_{SM}(\Omega_k)\Delta\Omega_k}} \right)^2$$

$$= \sum_{i,j} c_i c_j L \sum_k \frac{\Sigma_i(\Omega_k)\Sigma_j(\Omega_k)}{\Sigma_{SM}(\Omega_k)}\Delta\Omega_k = \sum_{i,j} c_i c_j L \int \frac{\Sigma_i(\Omega)\Sigma_j(\Omega)}{\Sigma_{SM}(\Omega)} d\Omega \equiv \sum_{i,j} c_i (V^{-1})_{ij} c_j$$

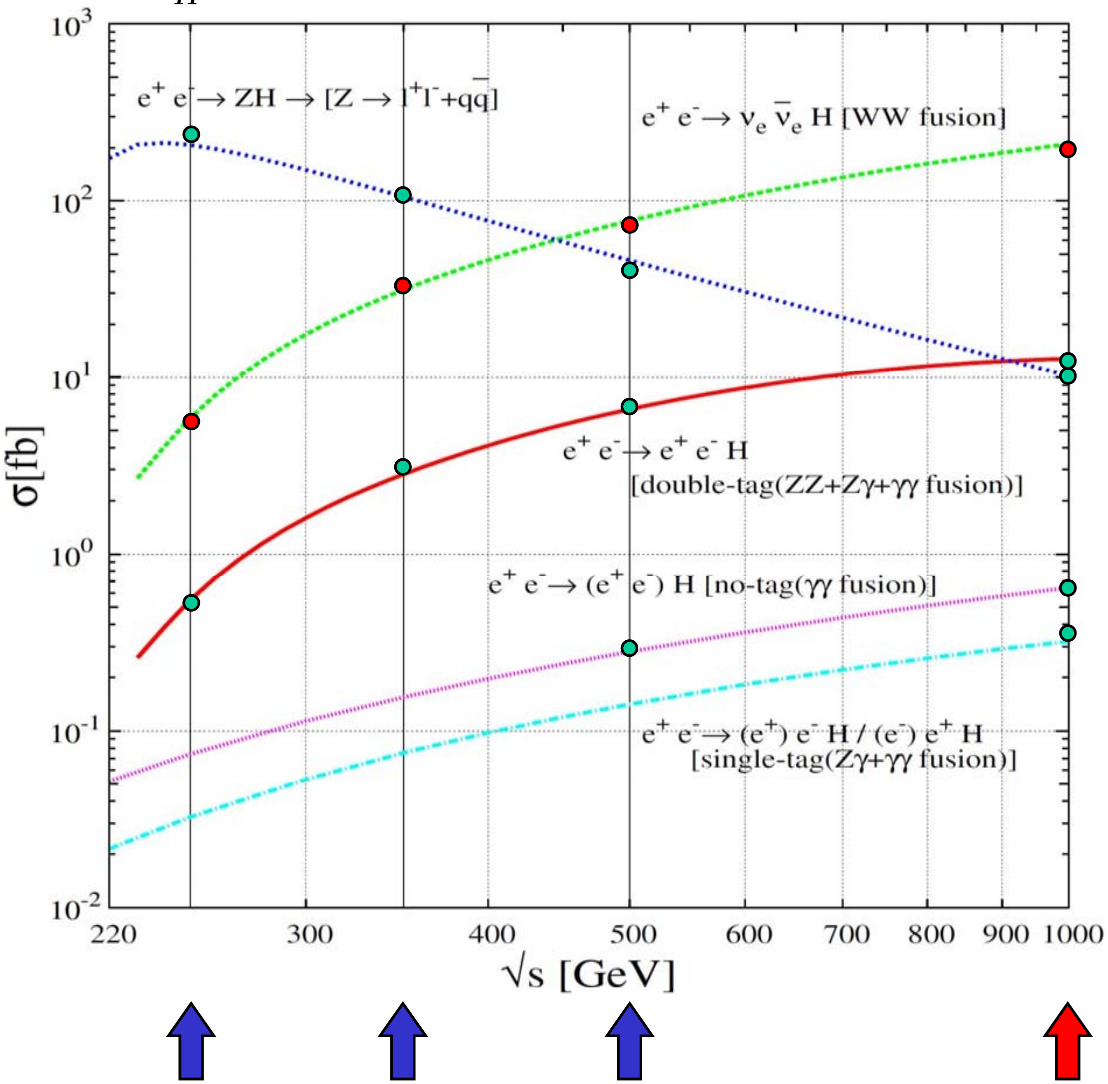
if V^{-1} is given, we can calculate Δc_i

$$\mathbf{\Delta c_i = \sqrt{V_{ii}}}$$

The large discrepancy between Σ_{SM} and $\Sigma_i(\Omega)$ makes V^{-1} larger ⇒ errors become small

2-0. Cross section

$m_H = 120\ GeV$



～ ILC phase I
phase II

- a_{WW}, b_{WW}, c_{WW} measurement

  2-1 : WW-fusion
  → 250GeV-1000GeV

- $a_{ZZ}, b_{ZZ}, c_{ZZ}, b_{Z\gamma}, c_{Z\gamma}$

  2-2: ZH production
  → 250GeV - 1000GeV

- $a_{ZZ}, b_{ZZ}, c_{ZZ}, b_{Z\gamma}, c_{Z\gamma}, b_{\gamma\gamma}$

  2-3: ZZ-fusion
  → 250GeV, 1000GeV

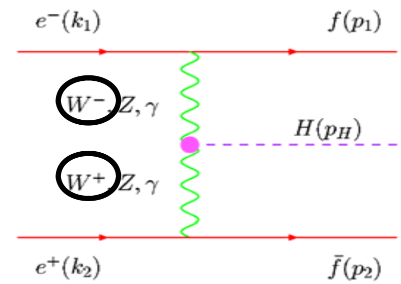
- $b_{\gamma\gamma}$

  2-4: γγ-fusion
  → 500GeV, 1000GeV

- $b_{Z\gamma}, c_{Z\gamma}, b_{\gamma\gamma}$

  Zγ-fusion
  → very small effect

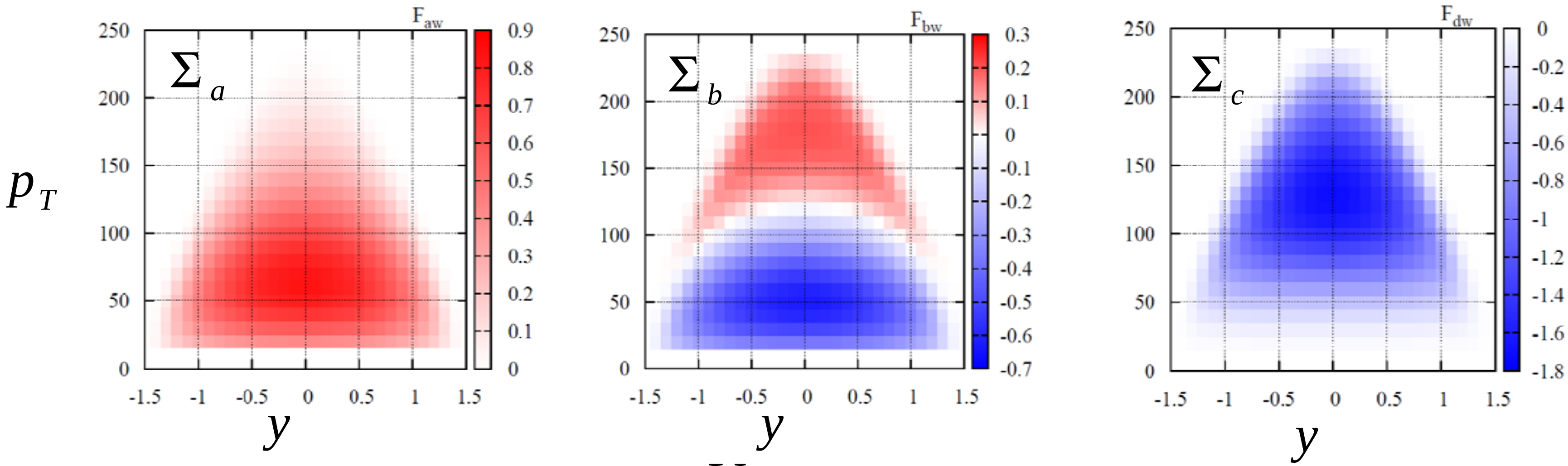
2-1. WW fusion process



In WW fusion process, the out going fermions are neutrinos.

The observable distributions should be

$$\frac{d\sigma}{dy\,dp_T} = \Sigma_{SM}(y, p_T) + a_{WW}\Sigma_a(y, p_T) + b_{WW}\Sigma_b(y, p_T) + c_{WW}\Sigma_c(y, p_T)$$



The eigenvectors and eigenvalues of V are

$\sqrt{s} = 500GeV$

$$.24a_{WW} + .045b_{WW} - .97c_{WW} = \pm.0019$$
$$.69a_{WW} - .71b_{WW} + .13c_{WW} = \pm.0056$$
$$.68a_{WW} + .70b_{WW} + .20c_{WW} = \pm.14$$

$\sqrt{s} = 1000GeV$

$$.14a_{WW} + .038b_{WW} - .99c_{WW} = \pm.00075$$
$$.71a_{WW} - .70b_{WW} + .072c_{WW} = \pm.0032$$
$$.69a_{WW} + .71b_{WW} + .12c_{WW} = \pm.066$$

2-1-2. Combined Results(1)

The results combining each collision energy with beam polarization $P_{e-}=0, P_{e+}=0$ are

$$\sqrt{s}=250GeV, L=100fb^{-1} + \sqrt{s}=350GeV, L=100fb^{-1} + \sqrt{s}=500GeV, L=500fb^{-1}$$

$$a_{WW}=\pm.025,\quad b_{WW}=\pm.026,\quad c_{WW}=\pm.0074 \quad \begin{pmatrix} 1 & & \\ .991 & 1 & \\ .993 & .998 & 1 \end{pmatrix};\quad \begin{array}{ll} .24a_{WW}+.042b_{WW}-.97c_{WW} & =\pm.00084 \\ .70a_{WW}-.70b_{WW}+.14c_{WW} & =\pm.0024 \\ .68a_{WW}+.71b_{WW}+.20c_{WW} & =\pm.037 \end{array}$$

There are strong correlation because there is a combination of anomalous couplings which has a large error at each energy experim

$$\sqrt{s}=250GeV, L=100fb^{-1} + \sqrt{s}=350GeV, L=100fb^{-1} + \sqrt{s}=500GeV, L=500fb^{-1} + \sqrt{s}=1TeV, L=500fb^{-1}$$

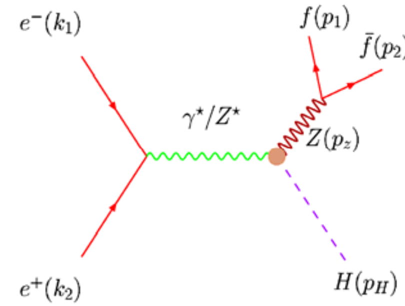
$$a_{WW}=.0072,\quad b_{WW}=.0076,\quad c_{WW}=.0014 \quad \begin{pmatrix} 1 & & \\ .97 & 1 & \\ .97 & .96 & 1 \end{pmatrix};\quad \begin{array}{ll} .15a_{WW}+.039b_{WW}-.99c_{WW} & =\pm.00031 \\ .72a_{WW}-.69b_{WW}+.082c_{WW} & =\pm.0012 \\ .68a_{WW}+.72b_{WW}+.13c_{WW} & =\pm.010. \end{array}$$

this means HWW coupling can be measured with 0.72% accuracy

$$\begin{array}{ll} c_{WW} & =.0014 \\ (a_{WW}-b_{WW})/\sqrt{2} & =.0013 \\ (a_{WW}+b_{WW})/\sqrt{2} & =.010 \end{array} \quad \begin{pmatrix} 1 & & \\ -.14 & 1 & \\ 97 & -.21 & 1 \end{pmatrix}$$

There are still strong correlation

2-2. ZH production process



The differential cross section is expressed as

$$\frac{d\sigma}{d\Omega} = \Sigma_{SM}(\Omega) + \sum_i c_i \Sigma_i(\Omega) \qquad \text{for } Z \rightarrow l\bar{l}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left[\Sigma_{SM}(\Omega) + \Sigma_{SM}(\tilde{\Omega})\right] + \sum_i c_i \frac{1}{2}\left[\Sigma_i(\Omega) + \Sigma_i(\tilde{\Omega})\right] \qquad \text{for } Z \rightarrow q\bar{q}$$

here
$$\begin{cases} \Omega(\theta_j, \varphi_j = \theta_q, \varphi_q) \\ \tilde{\Omega}(\theta_j, \varphi_j = \theta_{\bar{q}}, \varphi_{\bar{q}}) \end{cases}$$

$\sqrt{s} = 250GeV$

$.0097a_{ZZ}$	$+.056b_{ZZ}$	$+.027c_{ZZ}$	$+.53b_{Z\gamma}$	$+.85c_{Z\gamma}$	$= 0 \pm .00024$
$.15a_{ZZ}$	$+.89b_{ZZ}$	$+.42c_{ZZ}$	$-.032b_{Z\gamma}$	$-.052c_{Z\gamma}$	$= 0 \pm .00049$
$.013a_{ZZ}$	$-.094b_{ZZ}$	$+.20c_{ZZ}$	$-.83b_{Z\gamma}$	$+.51c_{Z\gamma}$	$= 0 \pm .0034$
$.055a_{ZZ}$	$-.42b_{ZZ}$	$+.88c_{ZZ}$	$+.19b_{Z\gamma}$	$-.12c_{Z\gamma}$	$= 0 \pm .0043$

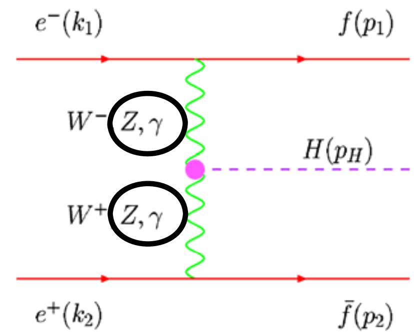
$\sqrt{s} = 500GeV$

$.0016a_{ZZ}$	$+.015b_{ZZ}$	$+.035c_{ZZ}$	$+.18b_{Z\gamma}$	$+.98c_{Z\gamma}$	$= 0 \pm .000098$
$.042a_{ZZ}$	$+.38b_{ZZ}$	$+.92c_{ZZ}$	$-.0085b_{Z\gamma}$	$-.037c_{Z\gamma}$	$= 0 \pm .00028$
$.0046a_{ZZ}$	$+.24b_{ZZ}$	$-.097c_{ZZ}$	$+.95b_{Z\gamma}$	$-.17c_{Z\gamma}$	$= 0 \pm .00086$
$.017a_{ZZ}$	$+.89b_{ZZ}$	$-.37c_{ZZ}$	$-.25b_{Z\gamma}$	$+.046c_{Z\gamma}$	$= 0 \pm .0010$

4 constraints for 5 couplings

- az cannot be measured independently
- $c_{Z\gamma}$ is most sensitive because its coefficient includes s
- c_{ZZ} , $c_{Z\gamma}$ become more sensitive when $\sqrt{s}$ is increase
- other couplings does not change so much because cross section decrease

2-3. eeH double-tag Z, Zγ, γγ fusion process



Final fermions are electron. we can use full information of $\Sigma_i(\Omega)$

$$\frac{d\sigma}{d\Omega} = \Sigma_{SM}(\Omega) + \sum_i c_i \Sigma_i(\Omega)$$

Double e+ e− tag conditions : $|\cos\theta_{e^\pm}| < 0.995 \quad p_T(e^\pm) > 1GeV$

$\sqrt{s} = 500GeV$

$$.0017a_{ZZ} + .00029b_{ZZ} - .0067c_{ZZ} - .0041b_{Z\gamma} + .9999c_{Z\gamma} - .0054b_{\gamma\gamma} = \pm.00080$$
$$.034a_{ZZ} - .20b_{ZZ} - .064c_{ZZ} - .61b_{Z\gamma} - .0070c_{Z\gamma} - .76b_{\gamma\gamma} = \pm.0041$$
$$.044a_{ZZ} - .28b_{ZZ} - .030c_{ZZ} + .78b_{Z\gamma} + .00c_{Z\gamma} - .55b_{\gamma\gamma} = \pm.0050$$
$$.19a_{ZZ} + .31b_{ZZ} - .93c_{ZZ} + .045b_{Z\gamma} - .0066c_{Z\gamma} - .029b_{\gamma\gamma} = \pm.0095$$
$$.34a_{ZZ} - .84b_{ZZ} - .23c_{ZZ} - .098b_{Z\gamma} - .00048c_{Z\gamma} + .33b_{\gamma\gamma} = \pm.019$$
$$.92a_{ZZ} + .27b_{ZZ} + .28c_{ZZ} + .012b_{Z\gamma} - .00010c_{Z\gamma} - .063b_{\gamma\gamma} = \pm.044$$

Because the distribution of a_{ZZ} is same to SM

$\sqrt{s} = 1000GeV$

$$.0020a_{ZZ} + .0016b_{ZZ} - .020c_{ZZ} - .019b_{Z\gamma} + .9996c_{Z\gamma} - .0061b_{\gamma\gamma} = \pm.00057$$
$$.0078a_{ZZ} + .033b_{ZZ} - .15c_{ZZ} - .95b_{Z\gamma} - .022c_{Z\gamma} - .26b_{\gamma\gamma} = \pm.0025$$
$$.089a_{ZZ} + .12b_{ZZ} - .97c_{ZZ} + .19b_{Z\gamma} - .017c_{Z\gamma} - .091b_{\gamma\gamma} = \pm.0031$$
$$.035a_{ZZ} - .67b_{ZZ} + .018c_{ZZ} + .17b_{Z\gamma} + .00012c_{Z\gamma} - .72b_{\gamma\gamma} = \pm.0036$$
$$.15a_{ZZ} - .72b_{ZZ} - .17c_{ZZ} - .17b_{Z\gamma} - .0019c_{Z\gamma} + .64b_{\gamma\gamma} = \pm.0082$$
$$.98a_{ZZ} + .12b_{ZZ} + .11c_{ZZ} + .011b_{Z\gamma} + .00c_{Z\gamma} - .063b_{\gamma\gamma} = \pm.027$$

6 constraints for 6 → all couplings can be measured

2-4. (ee)H no-tag γ γ fusion process

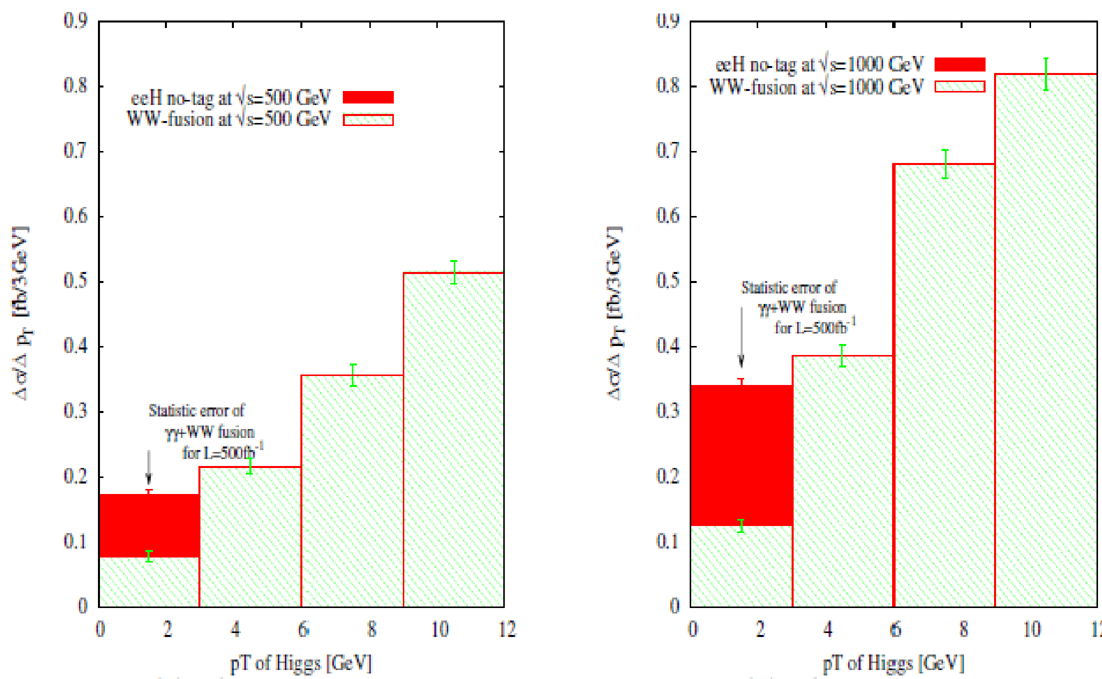
Parametrize the cross section by using the equivalent real photon fusion

$$\sigma^{ee\to(ee)H}(\sqrt{s}=500\ \mathrm{GeV}) = 150(\frac{b^{\mathrm{SM}}_{\gamma\gamma}}{2} + b_{\gamma\gamma})\ [\mathrm{fb}]$$

$$\sigma^{ee\to(ee)H}(\sqrt{s}=1\ \mathrm{TeV}) = 345(\frac{b^{\mathrm{SM}}_{\gamma\gamma}}{2} + b_{\gamma\gamma})\ [\mathrm{fb}]$$

here $b^{\mathrm{SM}}_{\gamma\gamma} = \frac{\alpha}{4\pi}|I| = 0.0038.$

is SM 1-loop contribution



(a) $\sqrt{s}$=500 GeV (b) $\sqrt{s}$=100 GeV

event contamination from WW fusion process

pTH resolution is set to 3 GeV

$$150 b_{\gamma\gamma} = \pm 0.0318, \to b_{\gamma\gamma} = 0 \pm 0.00022 \quad \mathrm{for}\sqrt{\mathrm{s}} = 500\ \mathrm{GeV}$$

$$345 b_{\gamma\gamma} = \pm 0.0324, \to b_{\gamma\gamma} = 0 \pm 0.000094 \quad \mathrm{for}\sqrt{\mathrm{s}} = 1\ \mathrm{TeV}.$$

2-5. Combined results (2)

Combined results with ZH process and eeH double-tag, (ee)H single-tag process

with beam polarization $|P_{e-}|=0.8, |P_{e+}|=0.0$

$$\sqrt{s}=250GeV, L=100fb^{-1}$$
$$+\sqrt{s}=350GeV, L=100fb^{-1}$$
$$+\sqrt{s}=500GeV, L=500fb^{-1}$$

$$\begin{array}{l} a_{ZZ}=0\pm.0045 \\ b_{ZZ}=0\pm.00048 \\ c_{ZZ}=0\pm.00020 \\ b_{Z\gamma}=0\pm.00030 \\ c_{Z\gamma}=0\pm.000072 \\ b_{\gamma\gamma}=0\pm.000095 \end{array} \quad \begin{pmatrix} 1 & & & & & \\ -.74 & 1 & & & & \\ -.40 & -.16 & 1 & & & \\ .0036 & -.064 & .066 & 1 & & \\ -.0036 & .047 & -.082 & -.81 & 1 & \\ .0090 & -.0080 & -.0023 & -.0017 & .0015 & 1 \end{pmatrix}$$

$$\sqrt{s}=250GeV, L=100fb^{-1}$$
$$+\sqrt{s}=350GeV, L=100fb^{-1}$$
$$+\sqrt{s}=500GeV, L=500fb^{-1}$$
$$+\sqrt{s}=1TeV, L=500fb^{-1}$$

$$\begin{array}{l} a_{ZZ}=0\pm.0032 \\ b_{ZZ}=0\pm.00034 \\ c_{ZZ}=0\pm.000063 \\ b_{Z\gamma}=0\pm.00018 \\ c_{Z\gamma}=0\pm.000023 \\ b_{\gamma\gamma}=0\pm.000038 \end{array} \quad \begin{pmatrix} 1 & & & & & \\ -.74 & 1 & & & & \\ -.22 & -.20 & 1 & & & \\ -.00095 & -.059 & .053 & 1 & & \\ -.0013 & .033 & -.089 & -.60 & 1 & \\ .0050 & -.0048 & -.00032 & -.0013 & .00085 & 1 \end{pmatrix}$$

The effect of ZH production process @250GeV

1. a_{ZZ} cannot be measured independently at one energy experiment
2. New physics term is proportional $(b_{Z\gamma}+c_{Z\gamma})$

Correlation goes small by combining other processes

It is possible to measure HZZ coupling with 0.32% accuracy

2-5. Combined results (3)

Comparison with polarization $|P_{e-}|=0.0, |P_{e+}|=0$ and $|P_{e-}|=0.8, |P_{e+}|=0.0$

- Combine up to $\sqrt{s}=1TeV$ with $|P_{e-}|=0.0, |P_{e+}|=0.0$

$a_{ZZ}=0\pm.0032$	1					
$b_{ZZ}=0\pm.00043$	$-.59$	1				
$c_{ZZ}=0\pm.00025$	$-.0044$	$-.29$	1			
$b_{Z\gamma}=0\pm.0027$	.00039	$-.58$	.61	1		
$c_{Z\gamma}=0\pm.00098$	$-.049$	.27	$-.98$	$-.64$	1	
$b_{\gamma\gamma}=0\pm.000038$	.0048	$-.0044$	$-.0023$	.00	.0023	1

- Strong correlation disappears → all couplings are measured independently
- $a_{ZZ}, b_{\gamma\gamma}$ dose not change by beam polarization

- Combine up to $\sqrt{s}=1TeV$ with $|P_{e-}|=0.8, |P_{e+}|=0.0$

$a_{ZZ}=0\pm.0032$	1					
$b_{ZZ}=0\pm.00034$	$-.74$	1				
$c_{ZZ}=0\pm.000063$	$-.22$	$-.20$	1			
$b_{Z\gamma}=0\pm.00018$	$-.00095$	$-.059$	.053	1		
$c_{Z\gamma}=0\pm.000023$	$-.0013$	.033	$-.089$	$-.60$	1	
$b_{\gamma\gamma}=0\pm.000038$	.0050	$-.0048$	$-.00032$	$-.0013$	.00085	1

- The error of $c_{ZZ}, b_{Z\gamma}, c_{Z\gamma}$ become much smaller when polarized beam is applied

$$c_{ZZ} \propto s_W^2 f_B + c_W^2 f_W \rightarrow 1/4$$

$$b_{Z\gamma} \propto s_W^2 f_{BB} - c_W^2 f_{WW} \rightarrow 1/15$$

$$c_{Z\gamma} \propto f_B - f_W \rightarrow 1/40$$

- Each couplings are measured with below accuracy

$$\Delta(a_{WW}, b_{WW}, c_{WW}) \approx (0.72, 0.76, 0.14)\%$$

$$\Delta(a_{ZZ}, b_{ZZ}, c_{ZZ}) \approx (0.3, 0.03, 0.006)\%$$

$$\Delta(b_{Z\gamma}, c_{Z\gamma}, b_{\gamma\gamma}) \approx (0.02, 0.002, 0.0004)\%$$

-1. Constraints on dim6-Operators, & Comparison with other experiments

measurement @ ILC

$$
\begin{aligned}
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\phi 1} &= 0 \pm 0.059 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\mathrm{BW}} &= 0 \pm 0.22 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\mathrm{W}} &= 0 \pm 0.016 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\mathrm{B}} &= 0 \pm 0.026 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\mathrm{WW}} &= 0 \pm 0.14 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta f_{\mathrm{BB}} &= 0 \pm 0.35 \\
\left(\tfrac{1\,\mathrm{TeV}}{\Lambda}\right)^2 & \Delta (3 f_{\phi 4} - 2 f_{\phi 2}) &= 0 \pm 0.075
\end{aligned}
\quad
\begin{pmatrix}
1. & & & & & & \\
-.44 & 1. & & & & & \\
.25 & .19 & 1. & & & & \\
.13 & -.33 & .32 & 1. & & & \\
.63 & -.90 & -.18 & .14 & 1. & & \\
-.53 & .98 & .19 & -.26 & -.96 & 1. & \\
.11 & -.042 & .15 & .017 & .16 & -.090 & 1.
\end{pmatrix}
$$

EW precision measurement gives stronger constraint about a several factor.

ILC is required Luminosity at ab-1 scale to get comparable constraint

Constraint from EW precision
asurement

$$
\begin{aligned}
T \to \Delta f_{\phi 1} &= 0 \pm 0.02 \\
S \to \Delta f_{BW} &= 0 \pm 0.13
\end{aligned}
\quad
\begin{pmatrix}
1. & \\
0.84 & 1.
\end{pmatrix}
$$

ILC results are enough.

LC is hopeful for reducing the anomalous Triple Gauge Coupling

Constraint from TGC (LEP L3)

$$
\begin{aligned}
-14.3 < \ & f_B < 9.0 \\
-9.1 < \ & f_W < 1.4
\end{aligned}
$$

most constrained combination

$$-.35 f_{\phi 1} + .93 f_{\mathrm{BW}} = 0.14 \pm 0.0033 \quad \text{(EWPM)}$$

$$
\begin{aligned}
.033(3f_{\phi 4} - 2f_{\phi 2}) + .15 f_{\phi 1} + .00047 f_{\mathrm{BW}} - .95 f_{\mathrm{W}} + .26 f_{\mathrm{B}} - .041 f_{\mathrm{WW}} + .011 f_{\mathrm{BB}} &= 0 \pm 0.012 \\
.021(3f_{\phi 4} - 2f_{\phi 2}) + .087 f_{\phi 1} + .47 f_{\mathrm{BW}} - .014 f_{\mathrm{W}} - .19 f_{\mathrm{B}} - .67 f_{\mathrm{WW}} - .54 f_{\mathrm{BB}} &= 0 \pm 0.014 \\
.068(3f_{\phi 4} - 2f_{\phi 2}) + .28 f_{\phi 1} - .39 f_{\mathrm{BW}} - .17 f_{\mathrm{W}} - .82 f_{\mathrm{B}} - .15 f_{\mathrm{WW}} + .19 f_{\mathrm{BB}} &= 0 \pm 0.020
\end{aligned}
\quad \text{(ILC)}
$$

4. Conclusion

- The t-channel and no-tag processes at high energy experiment are important to measure HWW, HZZ, $HZ\gamma$ and $H\gamma\gamma$ couplings
- We obtain the sensitivity to the ILC experiment on HVV couplings by using Optimal observable method

$$\Delta f_{\phi 1} = 0.059 \Leftrightarrow (0.02) \quad \Delta f_W = 0.016 \Leftrightarrow (5.3) \quad \Delta f_{WW} = 0.14$$
$$\Delta f_{BW} = 0.22 \Leftrightarrow (0.13) \quad \Delta f_B = 0.026 \Leftrightarrow (11) \quad \Delta f_{BB} = 0.35$$
$$\text{(EWPM)} \qquad \text{(TGC)} \qquad \Delta(3 f_{\phi 4} - 2 f_{\phi 2}) = 0.075$$

- The expected accuracy of the several dim6 operator combinations will be sensitive to quantum corrections

$$-.35 f_{\phi 1} + .93 f_{BW} = 0.14 \pm 0.0033 \quad \text{(EWPM)}$$

$$\begin{aligned}
.033(3f_{\phi4} - 2f_{\phi2}) \; +.15f_{\phi1} \; +.00047f_{BW} \; -.95f_W \; +.26f_B \; -.041f_{WW} \; +.011f_{BB} &= 0 \pm 0.012 \\
.021(3f_{\phi4} - 2f_{\phi2}) \; +.087f_{\phi1} \; +.47f_{BW} \; -.014f_W \; -.19f_B \; -.67f_{WW} \; -.54f_{BB} &= 0 \pm 0.014 \\
.068(3f_{\phi4} - 2f_{\phi2}) \; +.28f_{\phi1} \; -.39f_{BW} \; -.17f_W \; -.82f_B \; -.15f_{WW} \; +.19f_{BB} &= 0 \pm 0.020
\end{aligned} \quad \text{(ILC)}$$

- The polarization of electron beam make the constraint on $(c_{ZZ}, b_{Z\gamma}, c_{Z\gamma})$ much stronger. And the all couplings are measured very accurately with

3-2. Luminosity uncertainty

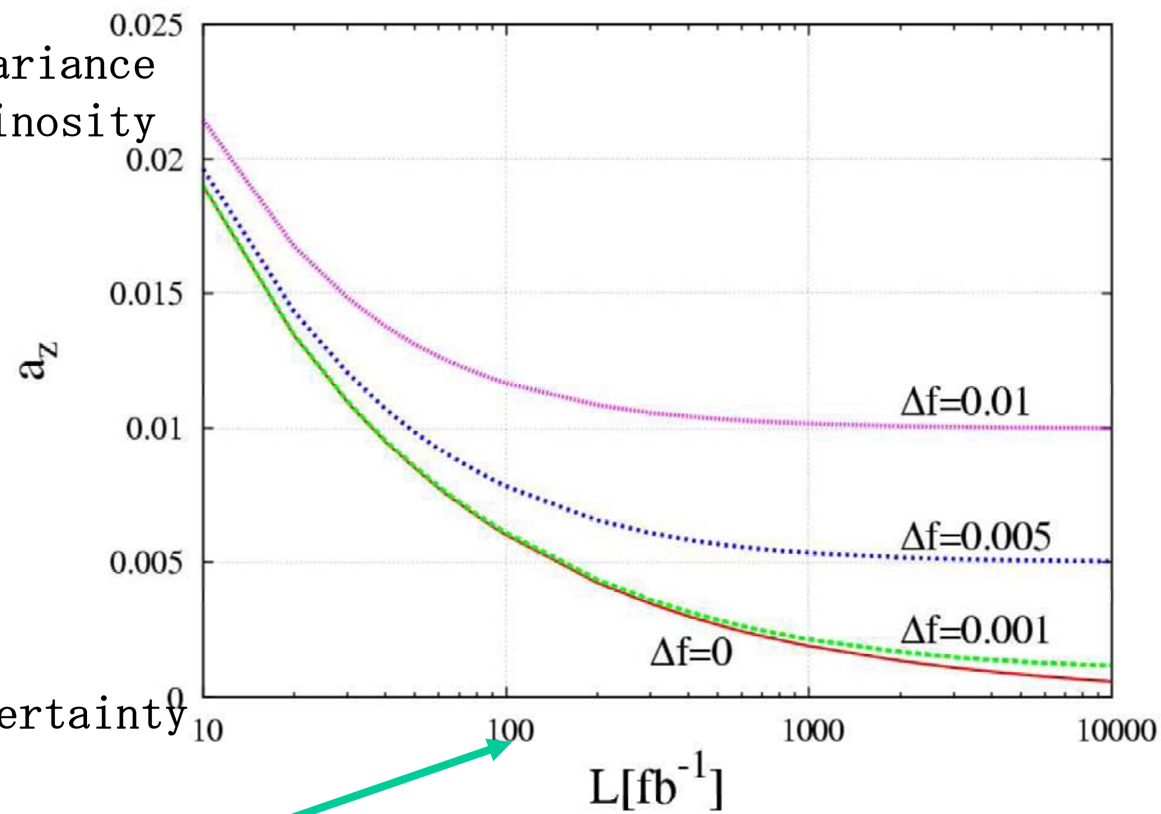
Redefine inverse of the covariance matrix with considering Luminosity uncertainty (=df)

$$M_{ij} \equiv L \int d\Phi F_i(\Phi) F_j(\Phi) \left[\frac{d\sigma^{SM}}{d\Phi}\right]^{-1}$$

$$\widetilde{M}_{ij} \equiv M_{ij} - \frac{M_{i1}M_{1j}(c_1^{SM})^2}{1 + M_{11}(c_1^{SM}\Delta f)^2}(\Delta f)^2$$

※ If df → ($\widetilde{M}_{ij} \to M_{ij}$

The luminosity error will dominate the statistic uncertainty



L ≈ 100 fb $^{-1}$ region

df < 1% is required
to get the error of az around 1%

L ≥ 100 fb $^{-1}$ region

df become dominant error.
To make statistic error and df to be same contribution, df<0.005 is required especially at ab-1 scale.

Comparison with polarization $|P_{e-}|=0.0, |P_{e+}|=0.0$ and $|P_{e-}|=0.8, |P_{e+}|=0.0$

$\sqrt{s}=250GeV$ with $|P_{e-}|=0.0, |P_{e+}|=0.0$

$$\mathrm{Re}\,(.078a_Z + .90b_Z + .42c_Z + .049b_\gamma + .079c_\gamma) = 0 \pm .00024$$
$$\mathrm{Re}\,(.028a_Z - .43b_Z + .90c_Z - .019b_\gamma + .076c_\gamma) = 0 \pm .0021$$
$$\mathrm{Re}\,(-.0087a_Z - .061b_Z - .088c_Z + .54b_\gamma + .83c_\gamma) = 0 \pm .0053$$
$$\mathrm{Re}\,(.0017a_Z - .023b_Z + .052c_Z + .84b_\gamma - .54c_\gamma) = 0 \pm .072$$

$\sqrt{s}=250GeV$ with $|P_{e-}|=0.8, |P_{e+}|=0.0$

$$\mathrm{Re}\,(.0027a_Z + .044b_Z + .13c_Z + .15b_\gamma + .98c_\gamma) = 0 \pm .000083$$
$$\mathrm{Re}\,(.020a_Z + .33b_Z + .94c_Z - .022b_\gamma - .13c_\gamma) = 0 \pm .00012$$
$$\mathrm{Re}\,(.0099a_Z + .94b_Z - .33c_Z + .097b_\gamma - .015c_\gamma) = 0 \pm .00057$$
$$\mathrm{Re}\,(-.00096a_Z - .093b_Z + .033c_Z + .98b_\gamma - .15c_\gamma) = 0 \pm .0097$$

Comparison with polarization $|P_{e-}|=0.0, |P_{e+}|=0$ and $|P_{e-}|=0.8, |P_{e+}|=0$

$\sqrt{s}=1TeV$ with $|P_{e-}|=0.0, |P_{e+}|=0.0$

$$
\begin{aligned}
\mathrm{Re}(\ & .042a_Z -.11b_Z +.94c_Z +.032b_\gamma -.28c_\gamma +.17b_{\gamma\gamma}) = \pm.0015 \\
\mathrm{Re}(\ & -.015a_Z +.68b_Z -.052c_Z -.049b_\gamma +.00012c_\gamma +.73b_{\gamma\gamma}) = \pm.0018 \\
\mathrm{Re}(\ & -.069a_Z +.70b_Z +.16c_Z -.18b_\gamma -.13c_\gamma -.65b_{\gamma\gamma}) = \pm.0039 \\
\mathrm{Re}(\ & -.018a_Z +.064b_Z +.30c_Z -.018b_\gamma +.95c_\gamma -.040b_{\gamma\gamma}) = \pm.0077 \\
\mathrm{Re}(\ & .99a_Z +.077b_Z +.055c_Z +.12b_\gamma -.0035c_\gamma -.039b_{\gamma\gamma}) = \pm.027 \\
\mathrm{Re}(\ & -.13a_Z +.16b_Z -.0056c_Z +.98b_\gamma +.0038c_\gamma -.083b_{\gamma\gamma}) = \pm.043
\end{aligned}
$$

$\sqrt{s}=1TeV$ with $|P_{e-}|=0.8, |P_{e+}|=0.0$

$$
\begin{aligned}
\mathrm{Re}(\ & .0022a_Z +.0035b_Z -.045c_Z -.019b_\gamma +.99c_\gamma -.013b_{\gamma\gamma}) = \pm.00057 \\
\mathrm{Re}(\ & -.043a_Z -.095b_Z +.96c_Z +.084b_\gamma +.049c_\gamma +.22b_{\gamma\gamma}) = \pm.0015 \\
\mathrm{Re}(\ & -.0087a_Z +.62b_Z -.13c_Z +.15b_\gamma +.0050c_\gamma +.76b_{\gamma\gamma}) = \pm.0018 \\
\mathrm{Re}(\ & .029a_Z -.42b_Z -.15c_Z +.88b_\gamma +.013c_\gamma +.14b_{\gamma\gamma}) = \pm.0025 \\
\mathrm{Re}(\ & -.068a_Z +.65b_Z +.16c_Z +.44b_\gamma +.0054c_\gamma -.59b_{\gamma\gamma}) = \pm.0044 \\
\mathrm{Re}(\ & .99a_Z +.058b_Z +.056c_Z +.0097b_\gamma -.00032c_\gamma -.028b_{\gamma\gamma}) = \pm.027
\end{aligned}
$$

2-5. e(e)H single-tag Zγ fusion process

Parametrize the cross section by using the equivalent real photon for un-tagged side

$$
\begin{aligned}
\sigma^{(e)eH} &= \frac{1}{4}\left(\frac{1+|P|}{2}\sigma^{e_R^-(e^+)H} + \frac{1-|P|}{2}\sigma^{e_L^-(e^+)H}\right) \\
&+\frac{1}{4}\left(\frac{1-|P|}{2}\sigma^{e_R^-(e^+)H} + \frac{1+|P|}{2}\sigma^{e_L^-(e^+)H}\right) + \frac{1}{4}\sigma^{(e^-)e_R^+H} + \frac{1}{4}\sigma^{(e^-)e_L^+H}.
\end{aligned}
$$

For 500 GeV

$$
\begin{aligned}
\sigma_{(e_R^-)e^+H} &= 0.0461 + 36.0b_{\gamma\gamma} + 7284{b_{\gamma\gamma}}^2 \\
&\quad -3.89(b_\gamma - c_\gamma) + 104(b_\gamma - c_\gamma)^2 - 1366b_{\gamma\gamma}(b_\gamma - c_\gamma)[\mathrm{fb}] \\
\sigma_{(e_L^-)e^+H} &= 0.0121 + 17.1b_{\gamma\gamma} + 7290{b_{\gamma\gamma}}^2 \\
&\quad +1.17(b_\gamma - c_\gamma) + 140(b_\gamma - c_\gamma)^2 + 1593b_{\gamma\gamma}(b_\gamma - c_\gamma)[\mathrm{fb}]
\end{aligned}
$$

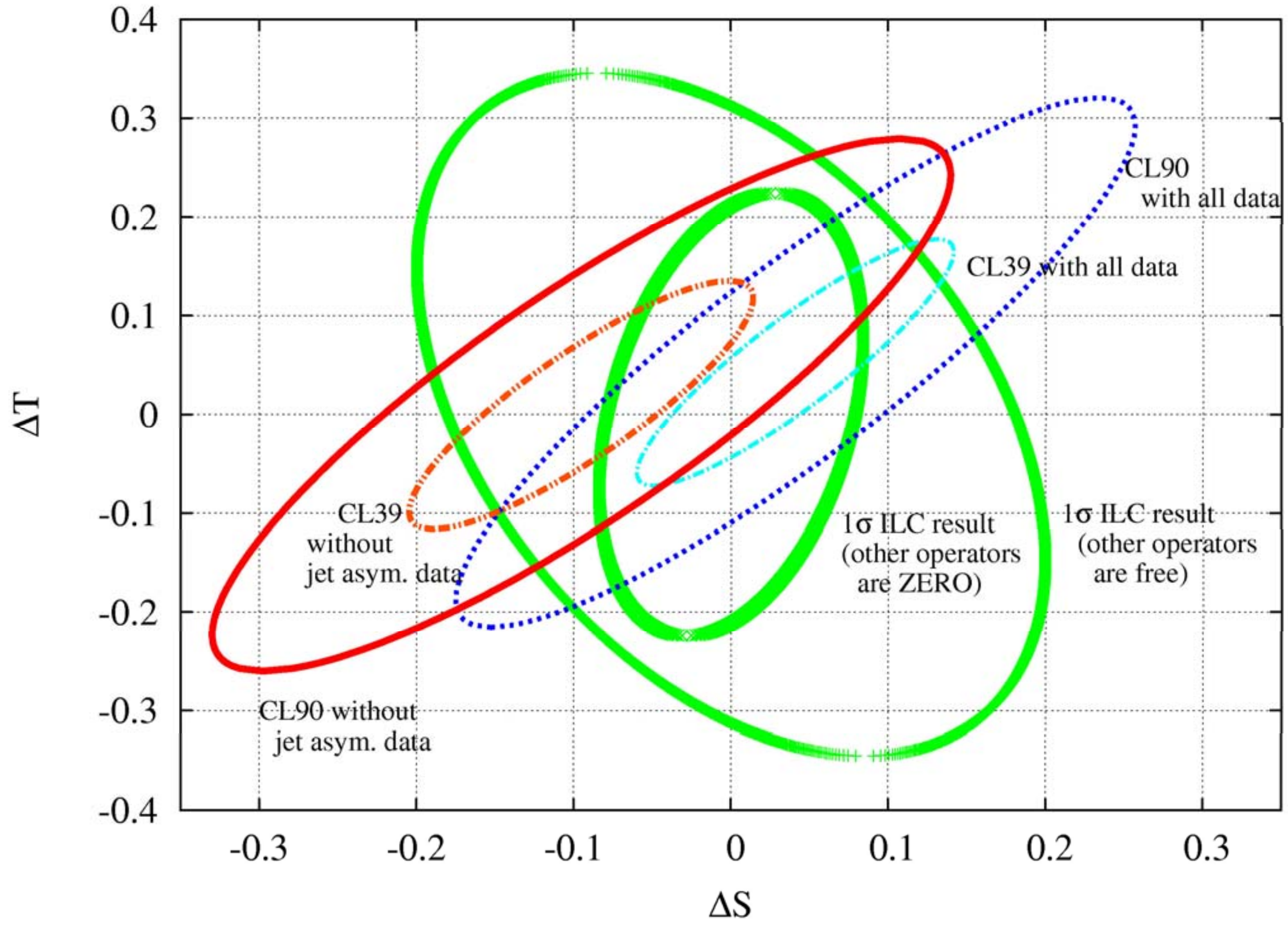
For 1 TeV

$$
\begin{aligned}
\sigma_{(e_R^-)e^+H} &= 0.099 + 68.1b_{\gamma\gamma} + 11901{b_{\gamma\gamma}}^2 \\
&\quad -11.1(b_\gamma - c_\gamma) + 340(b_\gamma - c_\gamma)^2 - 3640b_{\gamma\gamma}(b_\gamma - c_\gamma)[\mathrm{fb}] \\
\sigma_{(e_L^-)e^+H} &= 0.0097 + 17.3b_{\gamma\gamma} + 11868{b_{\gamma\gamma}}^2 \\
&\quad +1.95(b_\gamma - c_\gamma) + 460(b_\gamma - c_\gamma)^2 + 4209b_{\gamma\gamma}(b_\gamma - c_\gamma)[\mathrm{fb}]
\end{aligned}
$$

Add the contribution of this process to the total V^{-1}_{total}

Single-tag process is sensitive to $b_{\gamma\gamma}$ and $(b_\gamma - c_\gamma)$

3-3. ILC measurement
Contribution to the Tz and Sz



- When the ILC measurements is combined, it gives more strong constraint on the dSz and dTz