

Prospects of Measuring Effective Couplings through Higg Boson Production at Future Linear Colliders

Speaker **J. Kamoshita** (Ochanomizu Univ.)

K. Hagiwara (KEK)

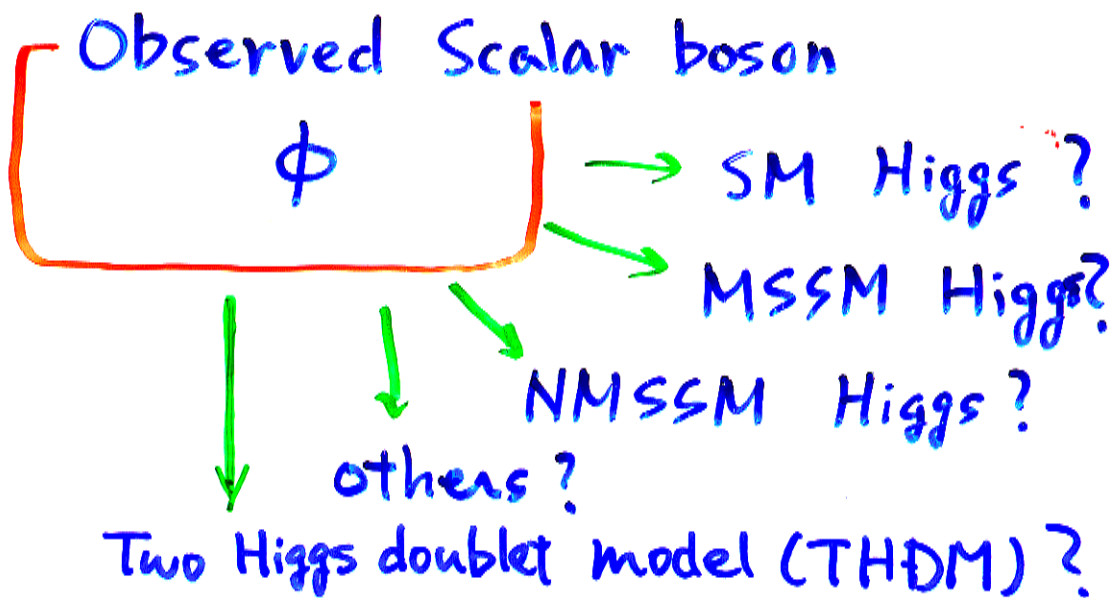
Collabrators **S. Ishihara** (Hyougo Univ.)

B. A. Kniehl (Hamburg Univ.)

Introduction

We may expect to find Higgs scalar boson at e^+e^- linear colliders.

- SM Higgs \leftarrow $113 \text{ GeV} \lesssim m_h \lesssim 250 \text{ GeV}$
(if $M_H < \sqrt{s} - m_Z$)
- MSSM $\sigma_{ZH} \gtrsim 80 \text{ fb}$ (Janot)
- NMSSM $\sigma_{ZH} \gtrsim 45 \text{ fb}$ (J. Kamoshita, Y. Okada, M. Tanaka, PLB)
($\sqrt{s} = 300 \text{ GeV}$)



Search for deviations from SM prediction

General couplings and Form factors

Effective HZV interaction Lagrangian

dim-5 \oplus $U(1)_{em}$

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & (1 + \underline{a_Z}) \frac{g_Z m_Z}{2} H Z_\mu Z^\mu \\ & + \frac{g_Z}{m_Z} \sum_{V=Z,\gamma} \left[\underline{b_V} H Z_{\mu\nu} V^{\mu\nu} \right. \\ & \quad + \underline{c_V} (\partial_\mu H Z_\nu - \partial_\nu H Z_\mu) V^{\mu\nu} \\ & \quad \left. + \underline{\tilde{b}_V} H Z_{\mu\nu} \tilde{V}^{\mu\nu} \right] \end{aligned}$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $\tilde{V}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta}$ with the convention $\epsilon_{0123} = +1$. We have neglected the scalar component of the vector bosons by putting

$$\partial_\mu Z^\mu = \partial_\mu V^\mu = 0.$$

CP even couplings: a_Z, b_Z, c_Z, b_γ and c_γ 5

CP odd couplings: \tilde{b}_Z and \tilde{b}_γ 2

In the SM, $a_Z = b_V = c_V = \tilde{b}_V = 0$ at the tree level.

Derive HZZ vertex

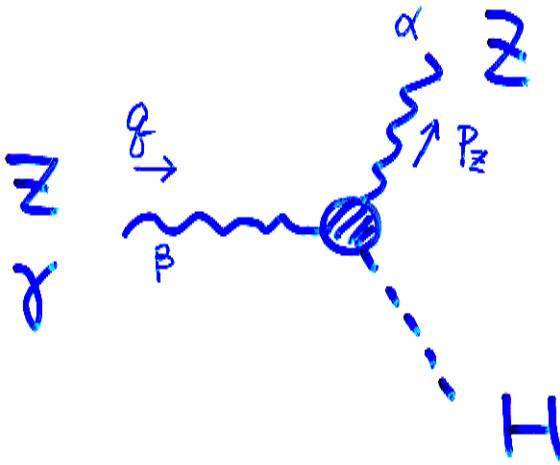
Form factors : h_1^V , h_2^V , h_3^V ($V = Z, \gamma$)

$$\Gamma_{\alpha\beta}^V(q, p_Z) = g_Z m_Z \left[\underbrace{h_1^V(q^2)}_{\text{CP even}} g_{\alpha\beta} + \underbrace{\frac{h_2^V(q^2)}{m_Z^2}}_{\text{CP even}} q_\alpha p_{Z\beta} + \underbrace{\frac{h_3^V(q^2)}{m_Z^2}}_{\text{CP odd}} \epsilon_{\alpha\beta\mu\nu} q^\mu p_Z^\nu \right],$$

$\left. \begin{array}{l} \text{CP even} \\ a_Z, b_Z, c_Z \\ b_\gamma, c_\gamma \end{array} \right\}$
 $\left. \begin{array}{l} \text{CP odd} \\ \tilde{b}_Z, \tilde{b}_\gamma \end{array} \right\}$

CP even form factor: h_1^Z, h_2^Z, h_1^γ and h_2^γ 4

CP odd form factor: h_3^Z and h_3^γ 2



$$i \Gamma_{\alpha\beta}^V$$

($V = \gamma, Z$)

Expression of the form factors in terms of the seven couplings of the effective Lagrangian:

$$h_1^Z(s) = (1 + a_Z) + 2c_Z \frac{s + m_Z^2}{m_Z^2} + 2(b_Z - c_Z) \frac{s + m_Z^2 - m_H^2}{m_Z^2},$$

$$h_2^Z(s) = -4(b_Z - c_Z),$$

$$h_3^Z(s) = -4\bar{b}_Z,$$

$$h_1^\gamma(s) = 2c_\gamma \frac{s}{m_Z^2} + (b_\gamma - c_\gamma) \frac{s + m_Z^2 - m_H^2}{m_Z^2},$$

$$h_2^\gamma(s) = -2(b_\gamma - c_\gamma),$$

$$h_3^\gamma(s) = -2\bar{b}_\gamma$$

Higgs - Gauge Couplings.

{ H-Z-Z, H-γ-Z } couplings

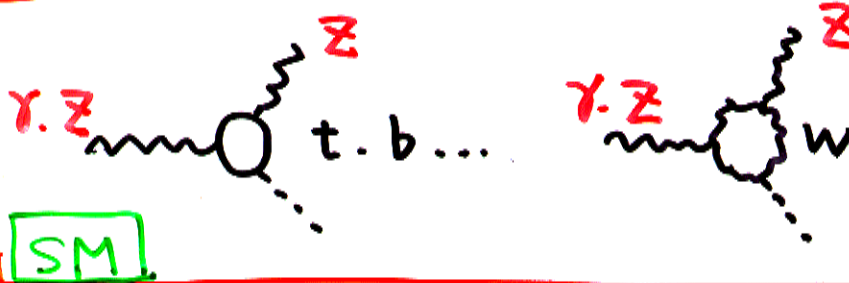
at tree level



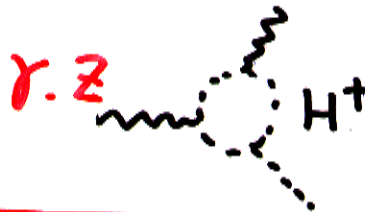
$$i g_Z M_Z g_{\mu\nu} \quad \text{in SM}$$

$$i g_Z M_Z \sin(\beta - \alpha) g_{\mu\nu} \quad \text{in MSSM THDM etc.}$$

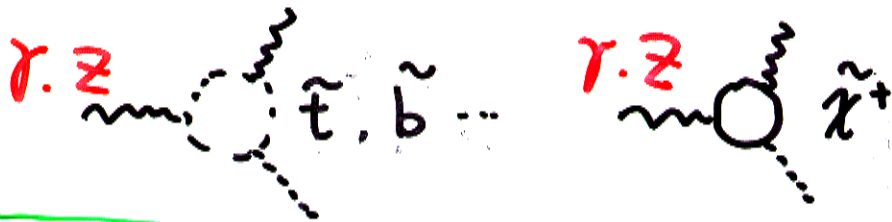
at 1-loop level



SM



THDM



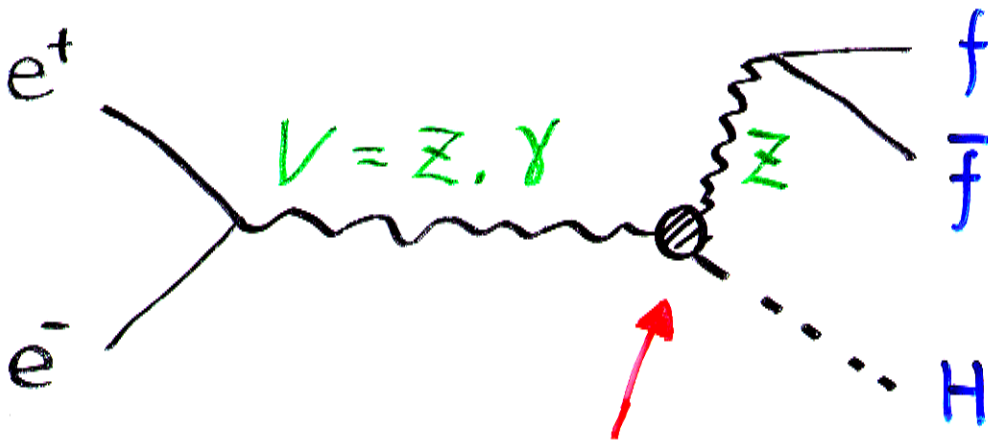
MSSM
NMSSM

Cross section of $e^+e^- \rightarrow H f \bar{f}$

We consider the differential cross section of the production and decay process,

$$e^-\left(p_e, \frac{\sigma}{2}\right) + e^+\left(p_{\bar{e}}, -\frac{\sigma}{2}\right) \rightarrow Z^*/\gamma^*(q) \rightarrow H(p_H) + Z(p_Z, \lambda),$$

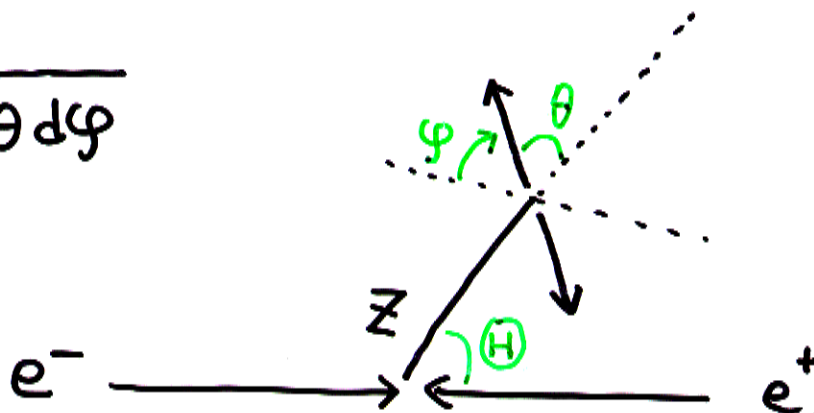
$$Z(p_Z, \lambda) \rightarrow f\left(p_f, \frac{\sigma'}{2}\right) + \bar{f}\left(p_{\bar{f}}, -\frac{\sigma'}{2}\right),$$



General Higgs - Z - Vector boson couplings

we use
Optimal observable method

$$\frac{d\sigma}{d\cos\Theta d\cos\theta d\varphi}$$



Atwood, Soni PRD45 ('92) } one parameter case
 Davier et al PLB 306 ('93) }
 Diehl, Nachtmann Z.Phys C62 ('94) }
 Gunion, Grzadkowski, He PRL77 ('96) many-parameter case.

Optimal observable method and least squares method

When the measurement is the number of event in k -th bin, the χ^2 function:

$$\chi^2 = \sum_k \frac{(n_k - \langle n_k \rangle)^2}{\langle n_k \rangle},$$

where $\langle n_k \rangle$ is the mean of n_k .

Now we consider the process of $e^+e^- \rightarrow H\bar{l}l$. ($Hf\bar{f}$)

The number of event in k -th bin: $n_k = L \Sigma(\Phi_k) d\Phi_k$,

where L : luminosity, $\Sigma(\Phi_k)$: differential cross section, $d\Phi_k$: phase space volume.

If we take Standard Model for a basis, $\langle n_k \rangle = L \Sigma^{SM}(\Phi_k) d\Phi_k$.

Then

$$\chi^2 = L \sum_k d\Phi_k \frac{(\Sigma(\Phi_k) - \Sigma^{SM}(\Phi_k))^2}{\Sigma(\Phi_k)^{SM}}$$

$$\chi^2 = L \int d\Phi \frac{(\Sigma(\Phi) - \Sigma^{SM}(\Phi))^2}{\Sigma(\Phi)^{SM}}$$

↓ continuity limit

Differential cross section

$$\Sigma(\Phi) = \sum_i c_i F_i(\Phi)$$

c_i : model dependent coefficients,

$F_i(\Phi)$: known functions of the phase space variables Φ .

Inverse of covariance matrix for c_i ;

$$(V^{-1})_{ij} = \frac{1}{2} \frac{\partial \chi^2}{\partial c_i \partial c_j} \Big|_{c_{i,j} = \langle c_{i,j} \rangle} = L \int d\Phi \frac{F_i(\Phi) F_j(\Phi)}{\Sigma^{SM}(\Phi)}$$

In case $P_e^- \neq 0, P_e^+ = 0,$

The functions $F_i^{(V)}$ are defined as

$$F_1^{(V)} = \frac{r}{4} \sin^2 \Theta \sin^2 \theta,$$

$$F_2^{(V)} = \frac{r}{16} (1 + \cos^2 \Theta)(1 + \cos^2 \theta) - \frac{r P A_f}{4} \cos \Theta \cos \theta,$$

$$F_3^{(V)} = -\frac{r}{16} \sin 2\Theta \sin 2\theta \cos \varphi + \frac{r P A_f}{4} \sin \Theta \sin \theta \cos \varphi,$$

$$F_4^{(V)} = \frac{r}{8} \sin^2 \Theta \sin^2 \theta \cos 2\varphi,$$

$$F_5^{(V)} = -\frac{r}{16} \sin 2\Theta \sin 2\theta \sin \varphi + \frac{r P A_f}{4} \sin \Theta \sin \theta \sin \varphi,$$

$$F_6^{(V)} = \frac{r}{8} \sin^2 \Theta \sin^2 \theta \sin 2\varphi,$$

$$F_7^{(V)} = -\frac{r A_f}{8} (1 + \cos^2 \Theta) \cos \theta + \frac{r P}{8} \cos \Theta (1 + \cos^2 \theta),$$

$$F_8^{(V)} = \frac{r A_f}{8} \sin 2\Theta \sin \theta \cos \varphi - \frac{r P}{8} \sin \Theta \sin 2\theta \cos \varphi,$$

$$F_9^{(V)} = \frac{r A_f}{8} \sin 2\Theta \sin \theta \sin \varphi - \frac{r P}{8} \sin \Theta \sin 2\theta \sin \varphi.$$

where

$$P = P_e^-,$$

$$r = \frac{1}{4} \frac{\beta_{HZ}}{32\pi s} \frac{3}{4\pi} \text{Br}(Z \rightarrow f\bar{f}),$$

and A_f is the left-right asymmetry of $Z \rightarrow f\bar{f}$,

$$A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}.$$

$$\beta_{HZ} = \sqrt{1 - 2 \frac{m_Z^2 + m_H^2}{s} + \left(\frac{m_Z^2 - m_H^2}{s} \right)^2}.$$

$$F_i^{(V)} = \alpha_i + P\beta_i \iff F_i^{(A)} = P\alpha_i + \beta_i$$

$F_1^{(A)}, F_4^{(A)}, F_6^{(A)}$ vanish (if $P=0$) $\Rightarrow C_1^{(A)}, C_4^{(A)}, C_6^{(A)}$ unmeasurable

Angular distributions $e^+e^- \rightarrow Hf\bar{f}$

$$\frac{d\sigma}{d\cos\Theta d\cos\theta d\varphi} = \sum_{i=1}^9 \left[C_i^{(V)} F_i^{(V)}(\Theta, \theta, \varphi) + C_i^{(A)} F_i^{(A)}(\Theta, \theta, \varphi) \right]$$

$C_i^{(V,A)}$ are model-dependent coefficients.

$F_i^{(V,A)}$ depend on 'f': flavor of the final state fermion

P_{e^-} : polarization of e^-

P_{e^+} : " " e^+

↑ 18 terms

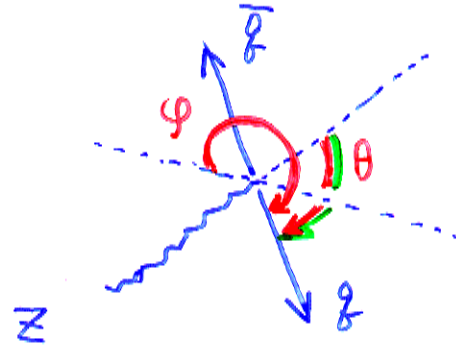
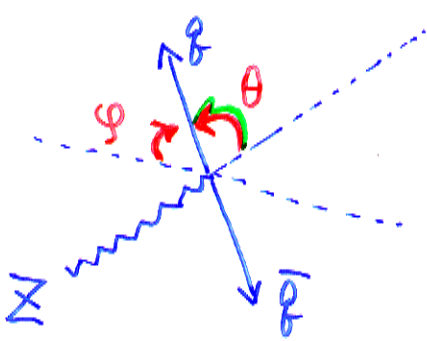
- general $H\bar{Z}V$ couplings ($\overset{\text{from}}{L_{\text{eff}}}$)
- narrow width approximation for \bar{Z} propagator
- SM amplitude for \bar{Z} decay

- $f = \text{light quark (jet)}$

(cannot distinguish q, \bar{q})

$$F_i^{(V,A)}(\Theta, \theta, \varphi) = \frac{1}{2} \left[F_i^{(V,A)}(\Theta, \theta, \varphi) + F_i^{(V,A)}(\Theta, \pi - \theta, \varphi + \pi) \right]$$

(corresponds to the case $A_f = 0$)



- $f = \nu$

(can only measure Θ)

Integrate over θ, φ

$$\frac{d\sigma}{d\cos\Theta} = \sum_{i=1,2,7} \left[C_i^{(V)} \tilde{F}_i^{(V)}(\Theta) + C_i^{(A)} \tilde{F}_i^{(A)}(\Theta) \right]$$

$$\tilde{F}_1^{(V)} = \frac{2\pi\Gamma}{3} \sin^2\Theta$$

$$\tilde{F}_2^{(V)} = \frac{\pi\Gamma}{3} (1 + \cos^2\Theta)$$

$$\tilde{F}_7^{(V)} = \frac{2\pi\Gamma}{3} P \cos\Theta$$

$$\tilde{F}_i^{(A)} = P \tilde{F}_i^{(V)} \quad (i=1,2)$$

$$\tilde{F}_7^{(A)} = \frac{2\pi\Gamma}{3} \cos\Theta$$

Constraints on HZV couplings

Three techniques taken into account:

① Helicity measurement of τ lepton

Assume $\epsilon_{\tau} = 50\%$ for τ^{\pm} .

② Charge identification of b

Assume $\epsilon_b = 60\%$ for b, \bar{b}

③ Beam polarization

Assume $|P_{e^{-}}| = 80\%$

$|P_{e^{+}}| = 45\%$

$$\left(\begin{array}{l} \sqrt{s} = 500 \text{ GeV} \\ L = 300 \text{ fb}^{-1} \\ m_H = 115 \text{ GeV} \end{array} \right)$$

$\epsilon_{\tau}, \epsilon_b, |P_{e^{-}}|, |P_{e^{+}}|, \sqrt{s}, L$

According to TESLA TDR

$$\sqrt{s} = 500 \text{ GeV}, L = 300 \text{ fb}^{-1}, m_H = 115 \text{ GeV}$$

Optimal Errors on the general HZV couplings

ϵ_τ	—	0.5	0.5
ϵ_b	—	0.6	0.6
P_{e^-}	—	—	0.8
P_{e^+}	—	—	0.45

$\text{Re}(b_z + 0.016 a_z)$	0.00055	0.00029	0.00023
$\text{Re}(C_z + 0.016 a_z)$	0.00065	0.00017	0.00011
$\text{Re} b_\gamma$	0.012	0.0019	0.00036
$\text{Re} C_\gamma$	0.0054	0.00087	0.000077
$\text{Re} \tilde{b}_z$	0.0010	0.00096	0.00055
$\text{Re} \tilde{b}_\gamma$	0.0061	0.0010	0.00066

For $(\epsilon_\tau, \epsilon_b, P_{e^-}, P_{e^+}) = (0, 0, 0, 0)$

$$\begin{aligned} \text{Re}(b_z + 0.016 a_z) &= 0 \pm 0.00055 \\ \text{Re}(C_z + 0.016 a_z) &= 0 \pm 0.00065 \\ \text{Re} b_\gamma &= 0 \pm 0.012 \\ \text{Re} C_\gamma &= 0 \pm 0.0054 \\ \text{Re} \tilde{b}_z &= 0 \pm 0.0010 \\ \text{Re} \tilde{b}_\gamma &= 0 \pm 0.0061 \end{aligned} \quad \begin{bmatrix} 1 & & & & & & \\ -.77 & 1 & & & & & \\ -.84 & .91 & 1 & & & & \\ .70 & -.98 & -.93 & 1 & & & \\ 0 & 0 & 0 & 0 & 1 & & \\ 0 & 0 & 0 & 0 & -.39 & 1 & \end{bmatrix}$$

In two Higgs doublet model, e.g. MSSM, $b_V = C_V = \tilde{b}_V = 0$ at tree level

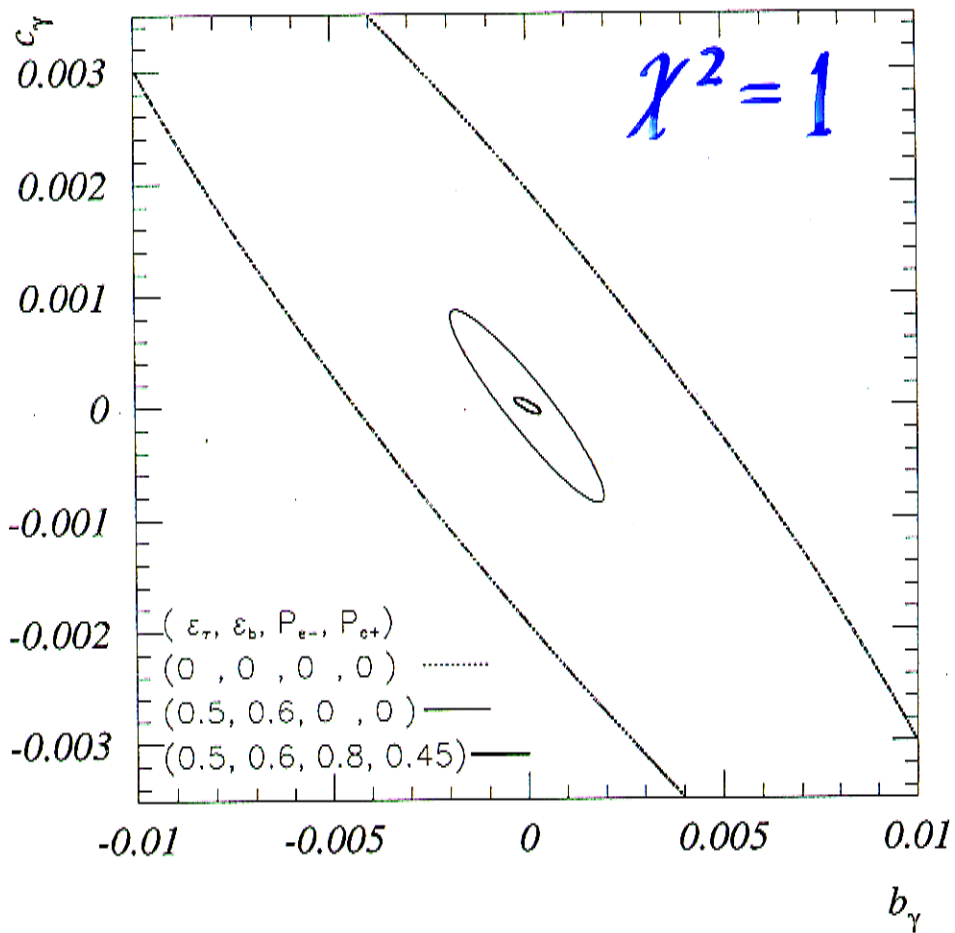
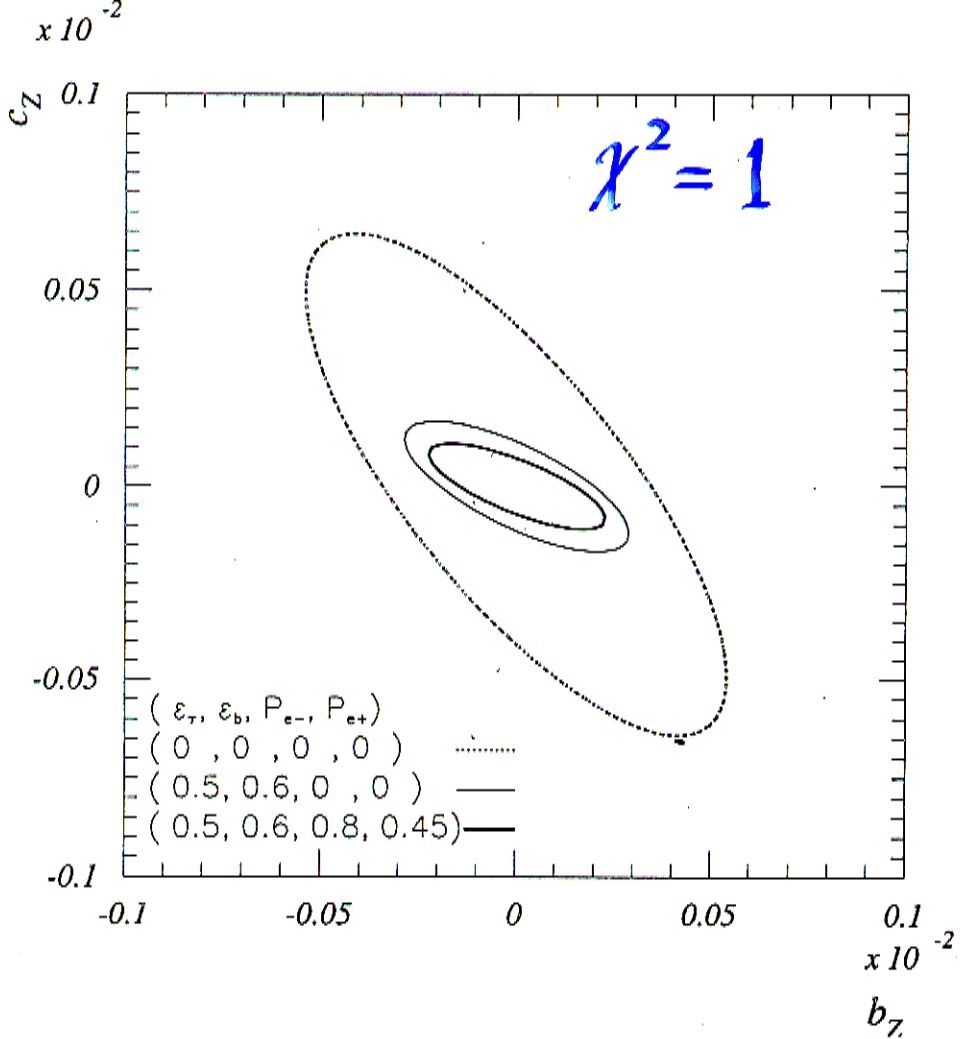
$$a_z = 0 \pm 0.013$$

For $(\epsilon_\tau, \epsilon_b, P_{e^-}, P_{e^+}) = (0.5, 0.6, 0.8, 0.45)$

$$\begin{aligned} \text{Re}(b_z + 0.016 a_z) &= 0 \pm 0.00023 \\ \text{Re}(C_z + 0.016 a_z) &= 0 \pm 0.00011 \\ \text{Re} b_\gamma &= 0 \pm 0.00036 \\ \text{Re} C_\gamma &= 0 \pm 0.00007 \\ \text{Re} \tilde{b}_z &= 0 \pm 0.00055 \\ \text{Re} \tilde{b}_\gamma &= 0 \pm 0.00066 \end{aligned} \quad \begin{bmatrix} 1 & & & & & & \\ -.75 & 1 & & & & & \\ -.085 & .072 & 1 & & & & \\ .065 & -.086 & -.83 & 1 & & & \\ 0 & 0 & 0 & 0 & 1 & & \\ 0 & 0 & 0 & 0 & -.093 & 1 & \end{bmatrix}$$

In two Higgs doublet model,

$$a_z = 0 \pm 0.0033$$



Conclusion

- For $m_H = 115 \text{ GeV}$, $\sqrt{s} = 500 \text{ GeV}$, $L = 300 \text{ fb}^{-1}$

Optimal errors

$\sim 5 \cdot 10^{-3}$, $\sim 10^{-2}$ on HZZ , HZY couplings
(without any option)

$\sim 10^{-4}$, 10^{-4} " " "
(with full option)

- As for HZY couplings (b_τ , c_τ),

$\sim 1/6$ with $\epsilon_\tau = 50\%$ and $\epsilon_b = 60\%$

$\sim 1/33$ (for b_τ) with full option

$\sim 1/20$ (for c_τ) " " "

- In THDM, e.g. MSSM. at tree level

Optimal error

~ 0.013 without any option

~ 0.0033 with full option

on a_z