at Fermilab, 2000. Oct. 25

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

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

Collaborators **K. Hagiwara** (KEK)
S. Ishihara (Hyougo Univ.)
B. A. Kniehl (Hamburg Univ.)

Introduction

We may expect to find

Higgs scalar boson at

e^+e^- linear colliders.

~~110~~ 113 GeV $\lesssim m_h \lesssim 250$ GeV

- SM Higgs (if $m_H < \sqrt{s} - m_Z$)
- MSSM $\sigma_{Zh} \gtrsim 80$ fb (Janot
- NMSSM $\sigma_{Zh} \gtrsim 45$ fb (J. Kamoshita, Y. Okada, M. Tanaka PLB

($\sqrt{s} = 300$ GeV)

Observed Scalar boson

ϕ

→ SM Higgs ?

→ MSSM Higgs ?

→ NMSSM Higgs ?

→ others ?

→ Two Higgs doublet model (THDM) ?

Search for deviations from SM prediction

General couplings and Form factors

Effective HZV interaction Lagrangian

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

$$\mathcal{L}_{\rm eff} = (1 + a_Z)\frac{g_Z m_Z}{2} H Z_\mu Z^\mu + \frac{g_Z}{m_Z}\sum_{V=Z,\gamma}\Big[b_V H Z_{\mu\nu} V^{\mu\nu} + c_V\left(\partial_\mu H Z_\nu - \partial_\nu H Z_\mu\right) V^{\mu\nu} + \tilde{b}_V H Z_{\mu\nu}\tilde{V}^{\mu\nu}\Big]$$

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 $\tilde{b}_\gamma$ ⋯ 2

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

Derive HZV vertex

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

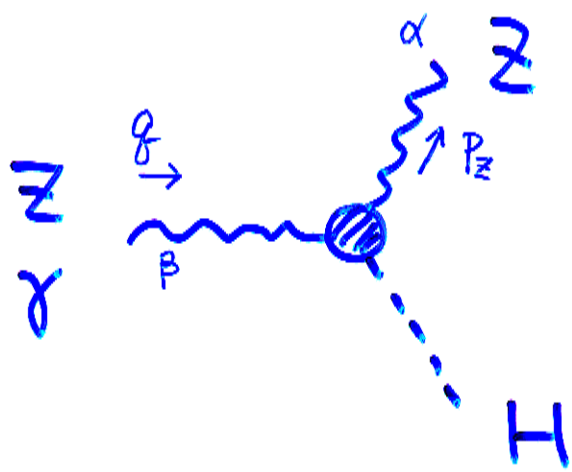
$$\Gamma^V_{\alpha\beta}(q, p_Z) = g_Z m_Z \left[h_1^V(q^2) g_{\alpha\beta} + \frac{h_2^V(q^2)}{m_Z^2} q_\alpha p_{Z\beta} + \frac{h_3^V(q^2)}{m_Z^2} \epsilon_{\alpha\beta\mu\nu} q^\mu p_Z^\nu \right],$$

CP even: a_Z, b_Z, c_Z, b_γ, c_γ

CP odd: $\tilde{b}_Z, \tilde{b}_\gamma$

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



$i\Gamma^V_{\alpha\beta}$ $(V = \gamma, Z)$

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.

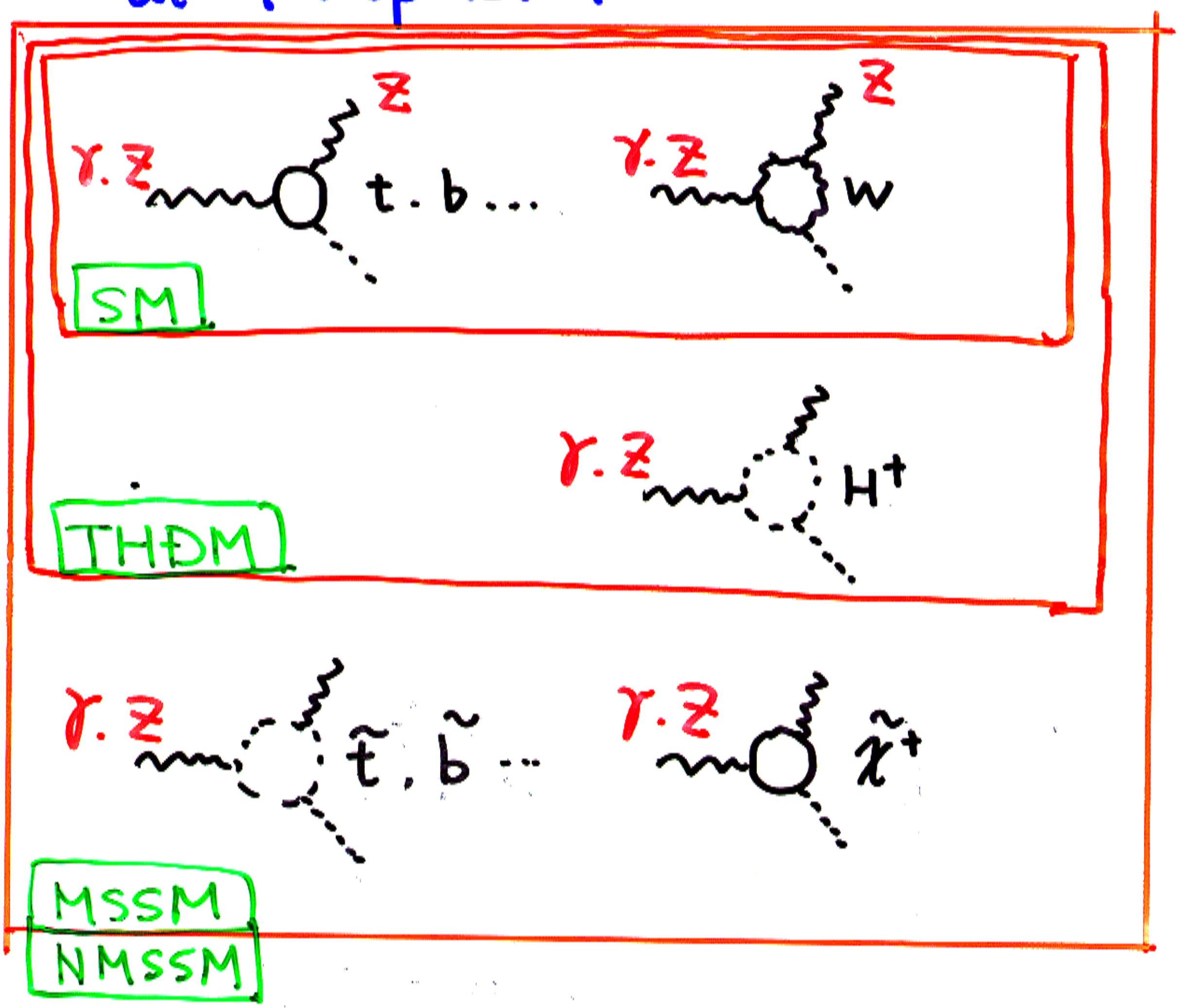
{ H-Z-Z , H-γ-Z } couplings

at tree level

$i g_Z m_Z g_{\mu\nu}$ in SM

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

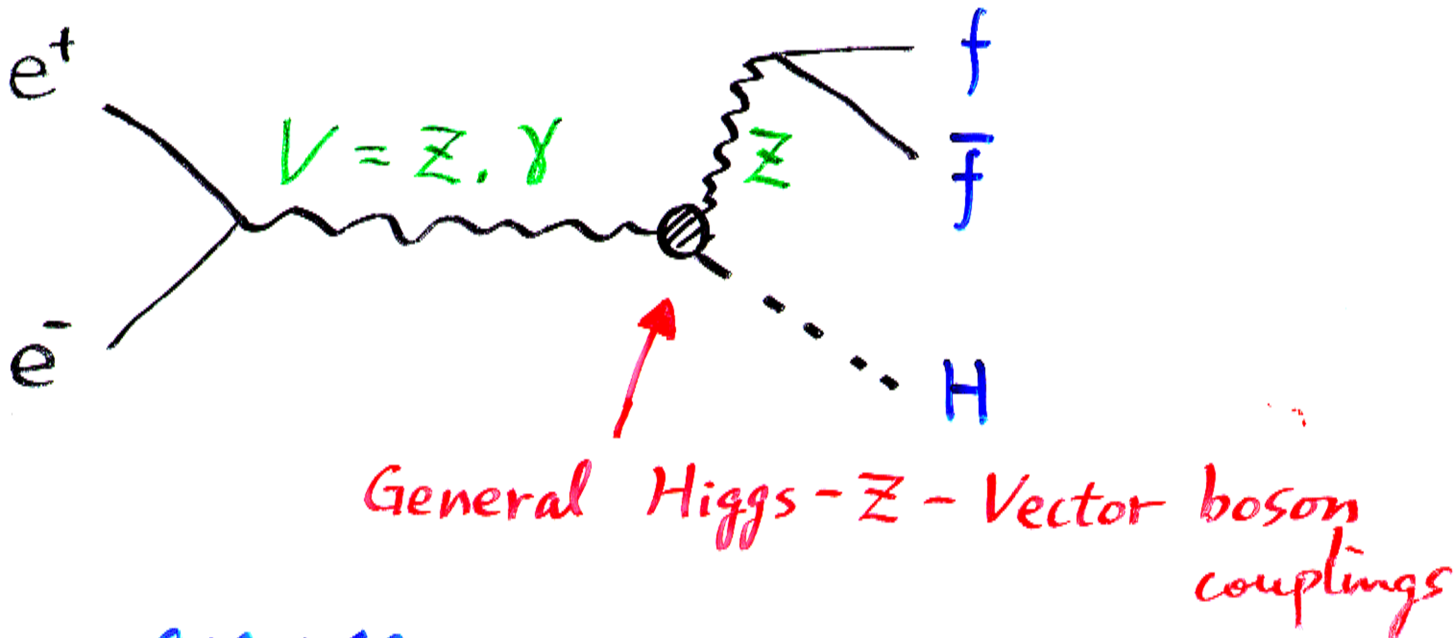
at 1-loop level



Cross section of $e^+e^- \to Hf\bar{f}$

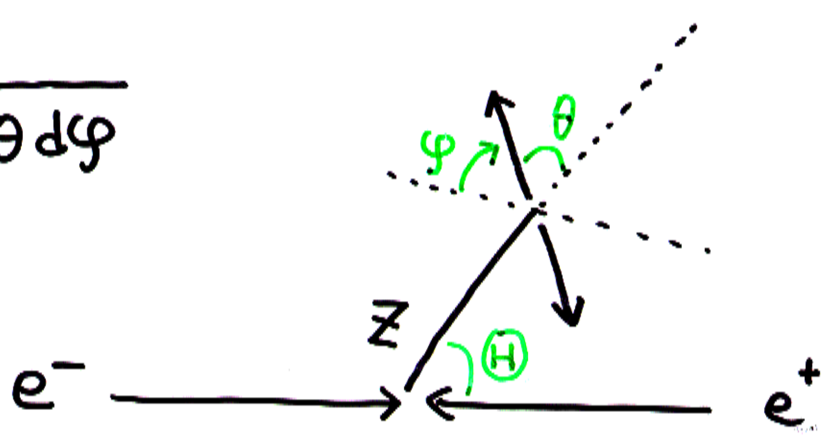
We consider the differential cross section of the production and decay process,

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



we use
(Optimal observable method)

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



Atwood, Soni PRD45 ('92)
Davier et al PLB 306 ('93)
Diehl, Nachtmann Z.Phys C62 ('94)
one parameter case

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:

$$\chi^2 = \sum_k \frac{(n_k - < n_k >)^2}{< n_k >},$$

where $< n_k >$ is the mean of n_k.

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

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, $< n_k >= L\Sigma^{SM}(\Phi_k)d\Phi_k$.

Then

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

continuity limit

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

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;

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

In case $P_{e^-} \neq 0$, $P_{e^+} = 0$,

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

$$F_1^{(V)} = \frac{r}{4}\sin^2\Theta\sin^2\theta,$$
$$F_2^{(V)} = \frac{r}{16}(1+\cos^2\Theta)(1+\cos^2\theta) - \frac{rPA_f}{4}\cos\Theta\cos\theta,$$
$$F_3^{(V)} = -\frac{r}{16}\sin 2\Theta\sin 2\theta\cos\varphi + \frac{rPA_f}{4}\sin\Theta\sin\theta\cos\varphi,$$
$$F_4^{(V)} = \frac{r}{8}\sin^2\Theta\sin^2\theta\cos 2\varphi,$$
$$F_5^{(V)} = -\frac{r}{16}\sin 2\Theta\sin 2\theta\sin\varphi + \frac{rPA_f}{4}\sin\Theta\sin\theta\sin\varphi,$$
$$F_6^{(V)} = \frac{r}{8}\sin^2\Theta\sin^2\theta\sin 2\varphi,$$
$$F_7^{(V)} = -\frac{rA_f}{8}(1+\cos^2\Theta)\cos\theta + \frac{rP}{8}\cos\Theta(1+\cos^2\theta),$$
$$F_8^{(V)} = \frac{rA_f}{8}\sin 2\Theta\sin\theta\cos\varphi - \frac{rP}{8}\sin\Theta\sin 2\theta\cos\varphi,$$
$$F_9^{(V)} = \frac{rA_f}{8}\sin 2\Theta\sin\theta\sin\varphi - \frac{rP}{8}\sin\Theta\sin 2\theta\sin\varphi.$$

where $P = P_{e^-}$,

$$r = \frac{1}{4}\frac{\beta_{HZ}}{32\pi s}\frac{3}{4\pi}\mathrm{Br}\left(Z \to f\bar{f}\right),$$

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

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

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

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

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

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

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

18 terms

$C_i^{(V,A)}$ 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^+

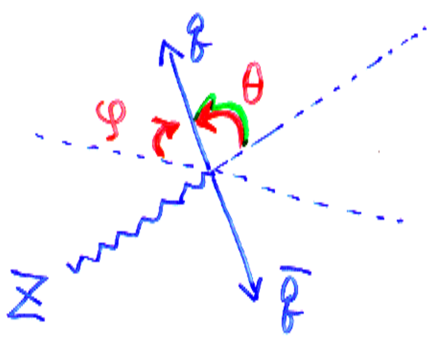
- general HZV couplings (from $\mathcal{L}_{eff}$)
- narrow width approximation for Z propagator
- SM amplitude for Z decay

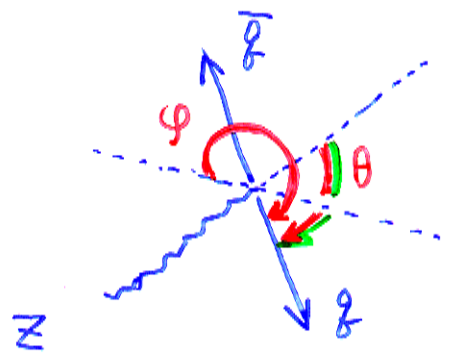
- f = light quark (jet)

(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

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

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

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

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

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

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

Constraints on HZV couplings

Three techniques taken into account:

① Helicity measurement of τ lepton

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

② Charge identification of b

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

③ Beam polarization

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

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

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

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

According to TESLA TDR

$\sqrt{s} = 500$ GeV, $L = 300\ fb^{-1}$, $m_H = 115$ 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
$\mathrm{Re}(b_Z + 0.016\,a_Z)$	0.00055	0.00029	0.00023
$\mathrm{Re}(c_Z + 0.016\,a_Z)$	0.00065	0.00017	0.00011
$\mathrm{Re}\,b_\gamma$	0.012	$\boxed{0.0019}$	0.00036
$\mathrm{Re}\,c_\gamma$	0.0054	$\boxed{0.00087}$	$\boxed{0.000077}$
$\mathrm{Re}\,\tilde{b}_Z$	0.0010	0.00096	0.00055
$\mathrm{Re}\,\tilde{b}_\gamma$	0.0061	0.0010	$\boxed{0.00066}$

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

$$\begin{array}{lcl} \mathrm{Re}(b_Z + 0.016\,a_Z) &=& 0 \pm 0.00055 \\ \mathrm{Re}(c_Z + 0.016\,a_Z) &=& 0 \pm 0.00065 \\ \mathrm{Re}\,b_\gamma &=& 0 \pm 0.012 \\ \mathrm{Re}\,c_\gamma &=& 0 \pm 0.0054 \\ \mathrm{Re}\,\tilde{b}_Z &=& 0 \pm 0.0010 \\ \mathrm{Re}\,\tilde{b}_\gamma &=& 0 \pm 0.0061 \end{array} \quad \begin{pmatrix} 1 & & & & & \\ -.77 & 1 & & & & \\ -.84 & .91 & 1 & & & \\ .70 & -.98 & -.93 & 1 & & \\ 0 & 0 & 0 & 0 & 1 & \\ 0 & 0 & 0 & 0 & -.39 & 1 \end{pmatrix}$$

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

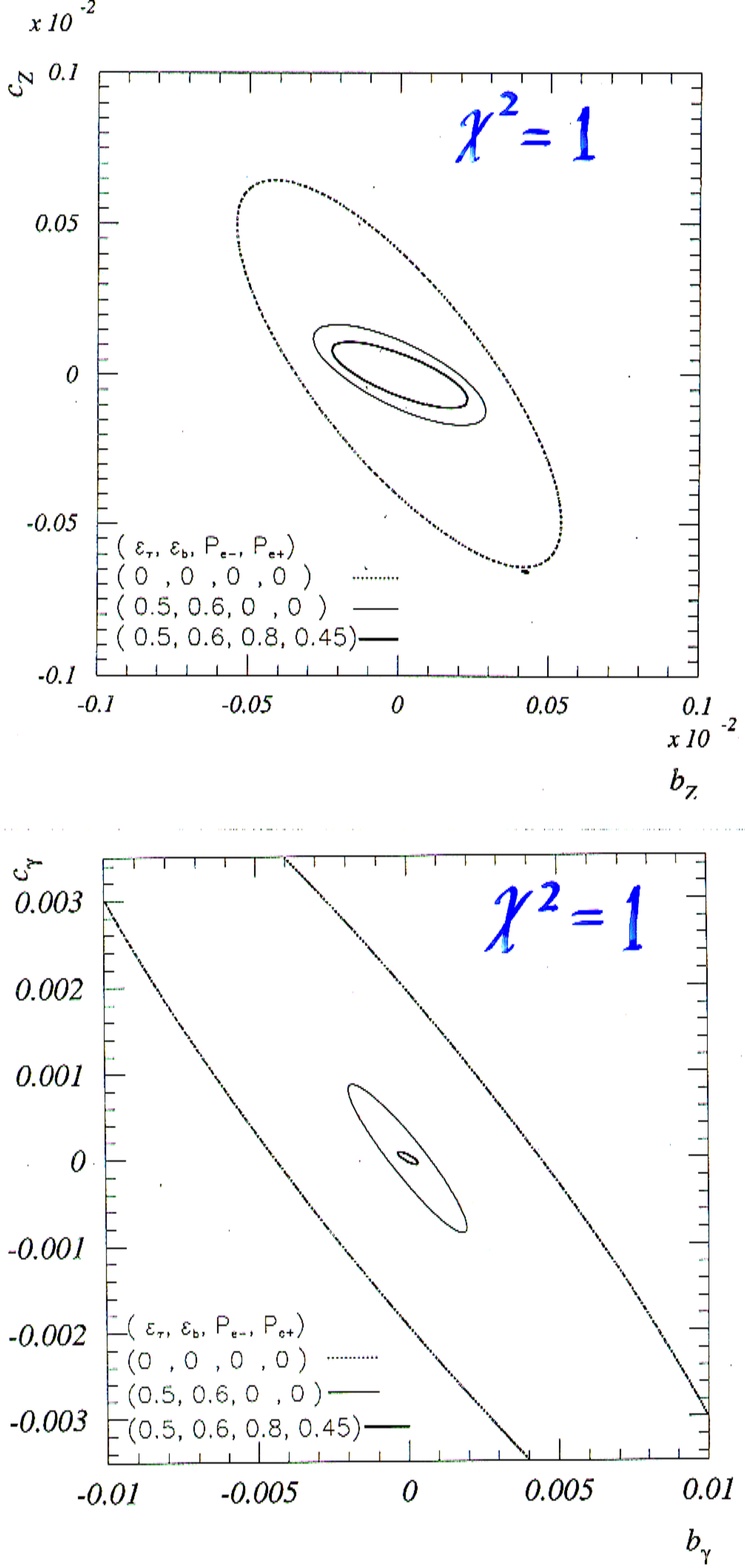
$$a_Z = 0 \pm 0.013$$

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

$$\begin{array}{lcl} \mathrm{Re}(b_Z + 0.016\,a_Z) &=& 0 \pm 0.00023 \\ \mathrm{Re}(c_Z + 0.016\,a_Z) &=& 0 \pm 0.00011 \\ \mathrm{Re}\,b_\gamma &=& 0 \pm 0.00036 \\ \mathrm{Re}\,c_\gamma &=& 0 \pm 0.00007 \\ \mathrm{Re}\,\tilde{b}_Z &=& 0 \pm 0.00055 \\ \mathrm{Re}\,\tilde{b}_\gamma &=& 0 \pm 0.00066 \end{array} \quad \begin{pmatrix} 1 & & & & & \\ -.75 & 1 & & & & \\ -.085 & .072 & 1 & & & \\ .065 & -.086 & -.83 & 1 & & \\ 0 & 0 & 0 & 0 & 1 & \\ 0 & 0 & 0 & 0 & -.093 & 1 \end{pmatrix}$$

In two Higgs doublet model,

$$a_Z = 0 \pm 0.0033$$



x 10 -2
c_Z
$\chi^2 = 1$
0.1
0.05
0
-0.05
-0.1
(ε_τ, ε_b, P_{e-}, P_{e+})
(0 , 0 , 0 , 0)
(0.5, 0.6, 0 , 0)
(0.5, 0.6, 0.8, 0.45)
-0.1
-0.05
0
0.05
0.1
x 10 -2
b_Z
c_γ
$\chi^2 = 1$
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
(ε_τ, ε_b, P_{e-}, P_{e+})
(0 , 0 , 0 , 0)
(0.5, 0.6, 0 , 0)
(0.5, 0.6, 0.8, 0.45)
-0.01
-0.005
0
0.005
0.01
b_γ

Conclusion

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

  Optimal errors

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

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

- As for HZγ couplings (b_γ, c_γ),

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

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

  $\sim 1/70$ (for c_γ) " " "

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

  Optimal error

  ~ 0.013 without any option

  ~ 0.0033 with full option

  on a_Z