Measuring the Higgs CP property at a Photon Linear Collider

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1. Introduction

Extension of SM in Higgs sector

$\Downarrow$

CP-odd Higgs boson(s)

and,

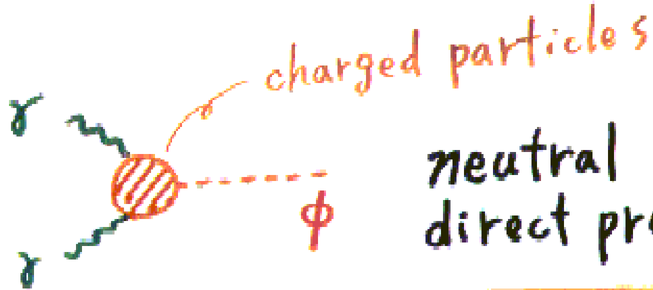
If there exists $\not{CP}$ in the Higgs potential,

Mass eigenstates of Higgs bosons
do NOT carry definite CP-parity.

Measuring CP property of Higgs bosons
is one of important subjects.

Photon colliders
give good opportunities.

$\gamma\gamma$ collisions can produce $J_z = 0$ resonances

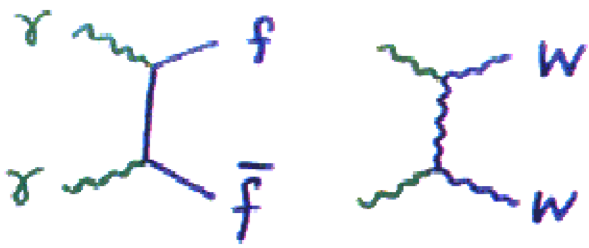


neutral Higgs
direct productio

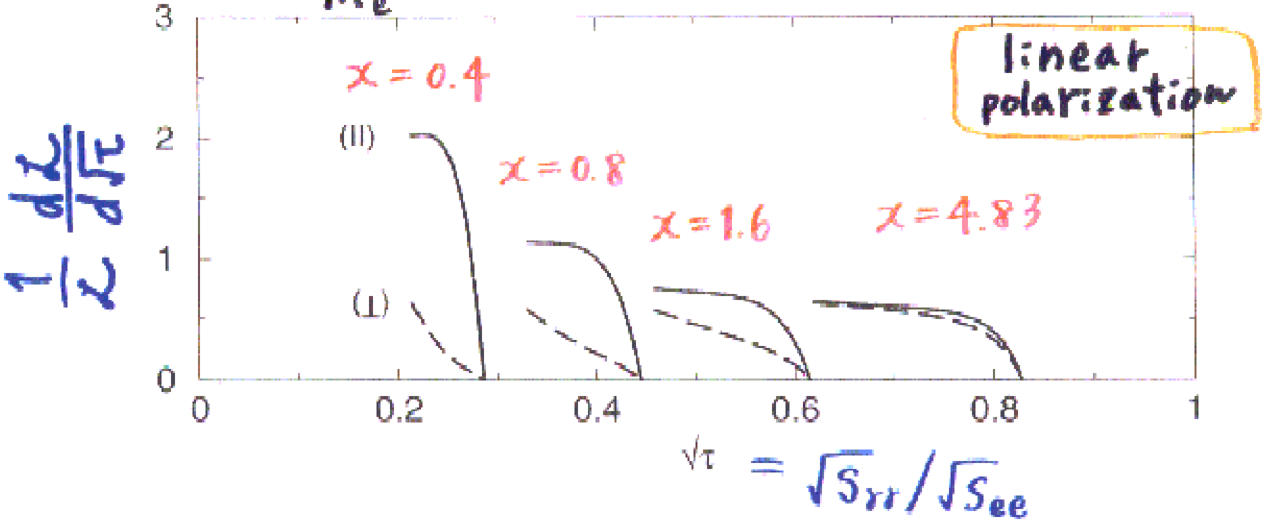
To probe CP property of Higgs bosons,

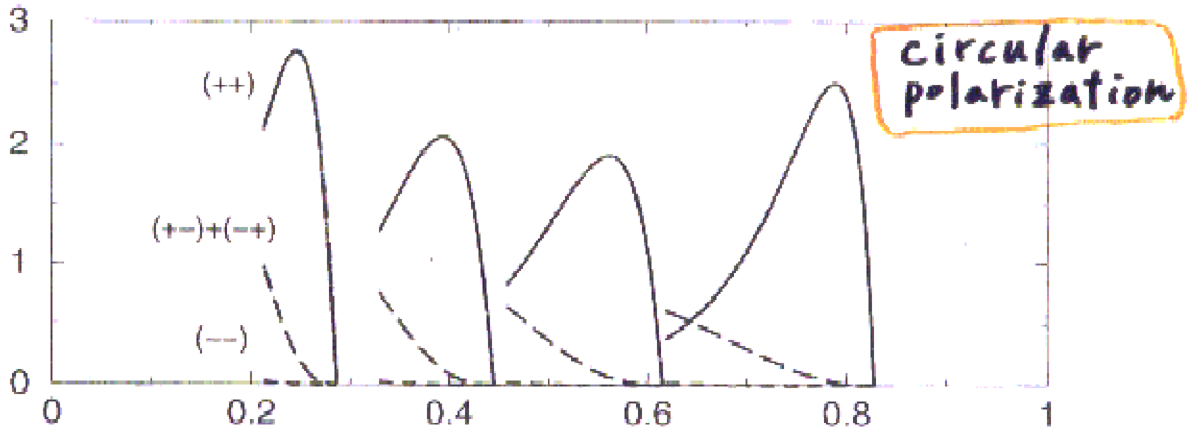
we here consider

- initial beam polarization { linear / circular
- interference effects with background processes
- helicity measurement (observation of angular correlation) for final particles



$x = \frac{4 E_e \omega_L}{m_e^2}$ — initial laser photon energy





⇓

in high $\sqrt{\tau}$ region

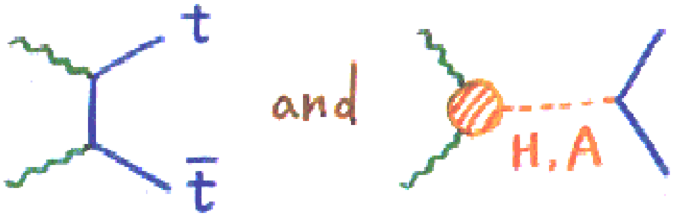
linear pol. △

circular pol. ○

2. CP invariant case

- E.A., Kamoshita, Sugamoto, Watanabe EPJC 14 (2000)
- E.A., Hagiwara

- circular polarization
- interference between

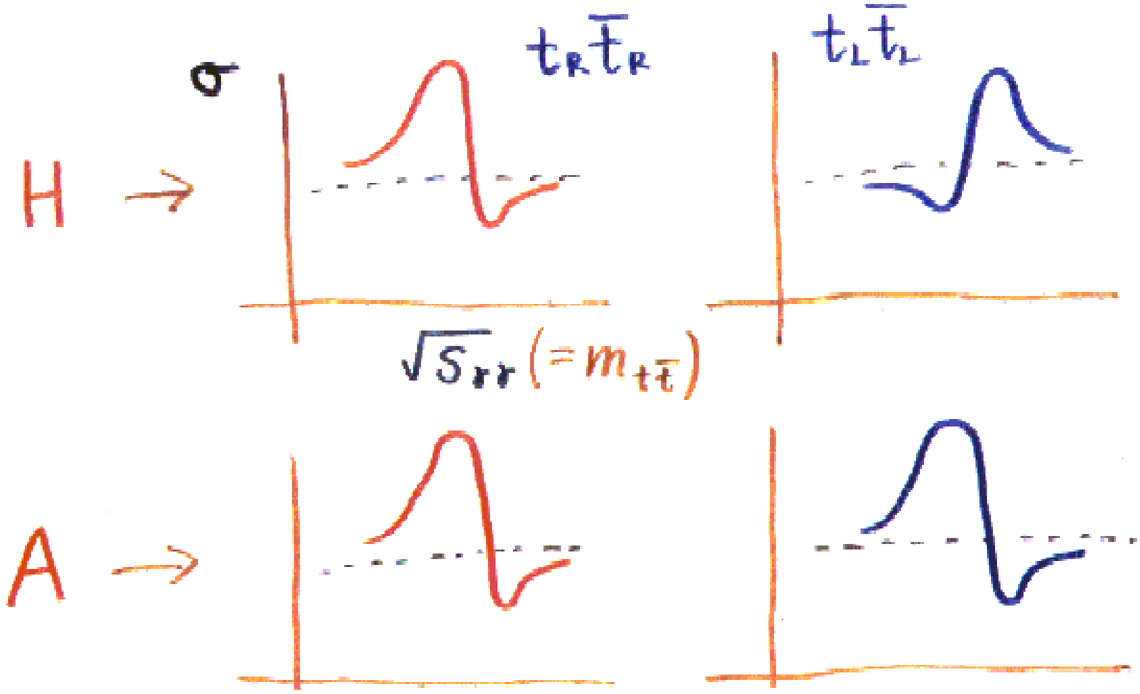


- helicity measurement of top quarks

(observing angular correlation of decay products)

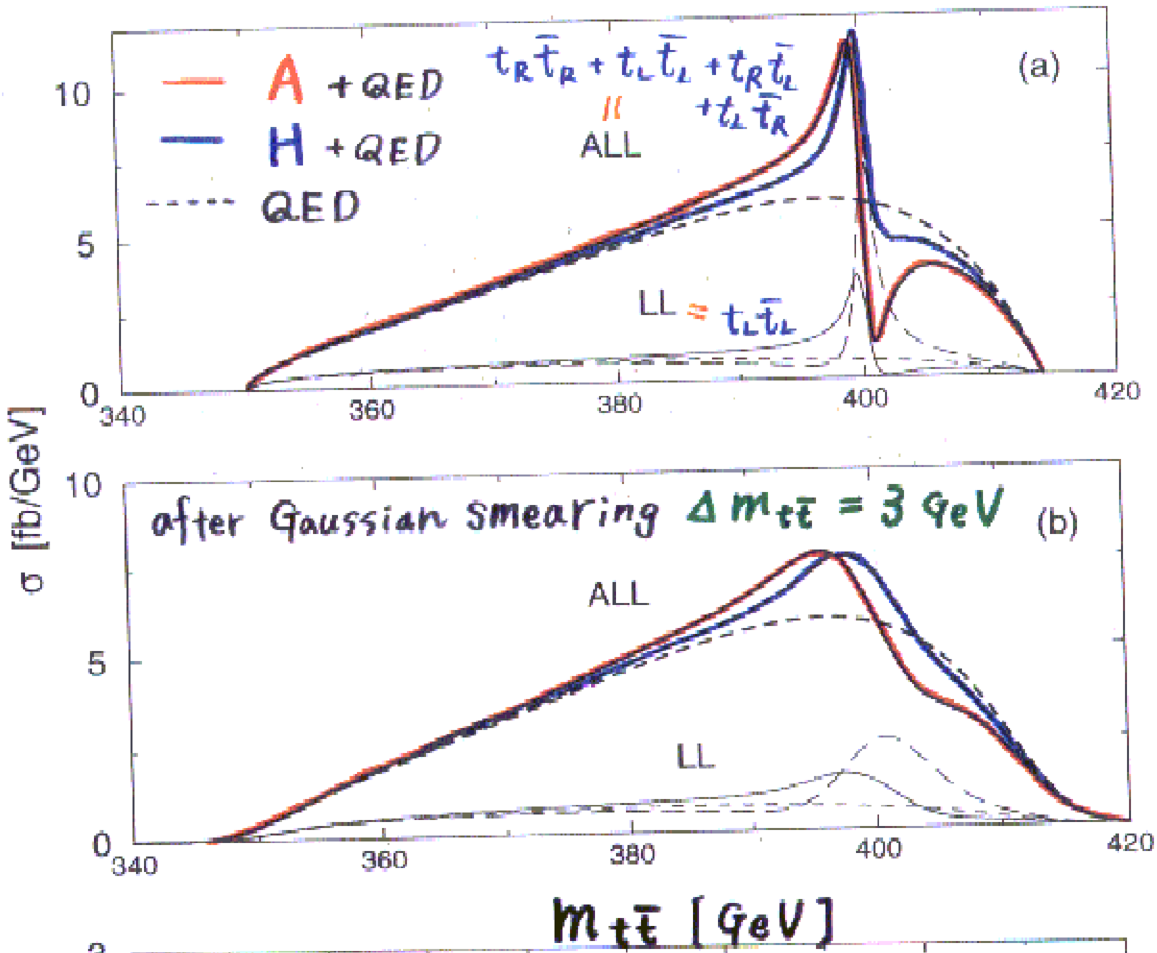
	$t_R \bar{t}_R$	$t_L \bar{t}_L$
$\gamma_+ \gamma_+$	M_H	$-M_H$
	M_A	M_A

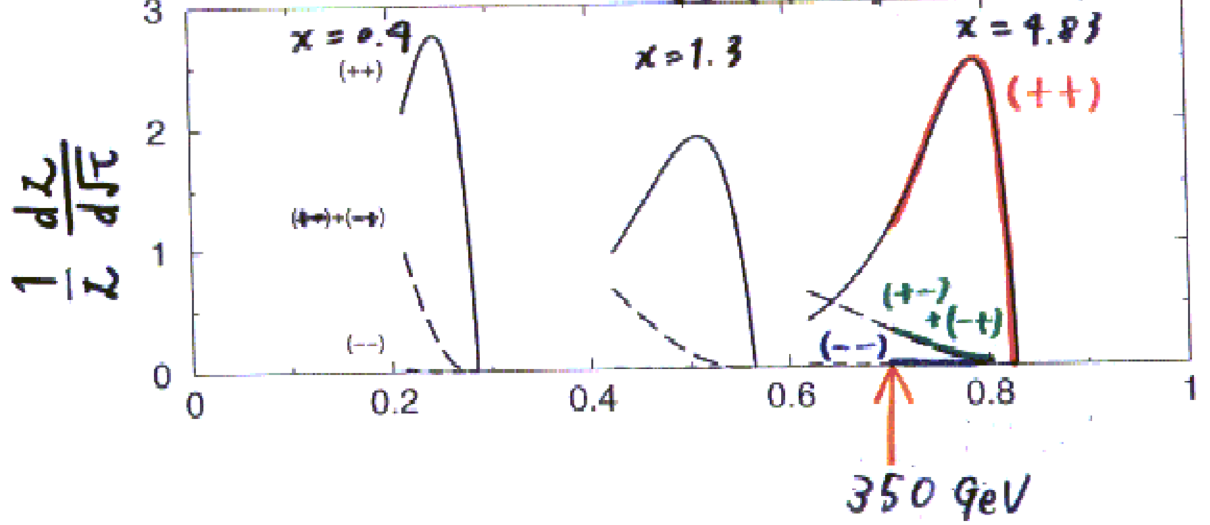
M_H, M_A : helicity amplitudes for $\gamma_+\gamma_+ \to H, A \to t_R \bar{t}_R$



$m_\phi = 400$ GeV

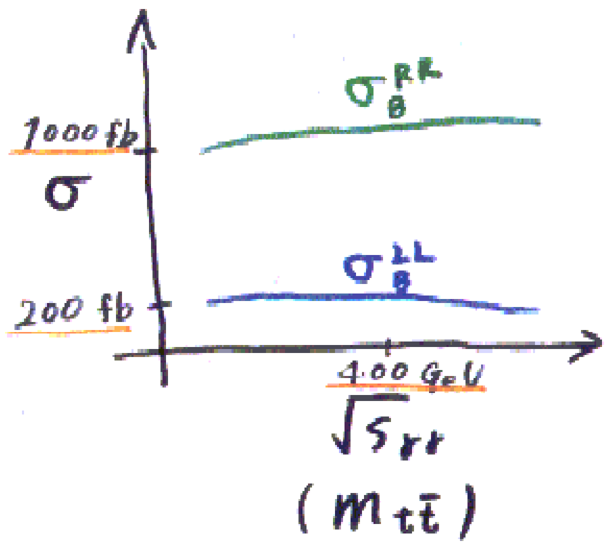
$\Gamma_\phi = 1.75$ GeV





$$M_B^{RR} = -8\pi\alpha Q_t^2 \frac{m_t(1+\beta_t)}{E_t(1-\beta_t^2\cos^2\theta)}$$

$$M_B^{LL} = -8\pi\alpha Q_t^2 \frac{m_t(1-\beta_t)}{E_t(1-\beta_t^2\cos^2\theta)}$$



- another observable

$\langle \sin(\bar{\phi}-\phi)\rangle$ is sensitive to CP-parity.

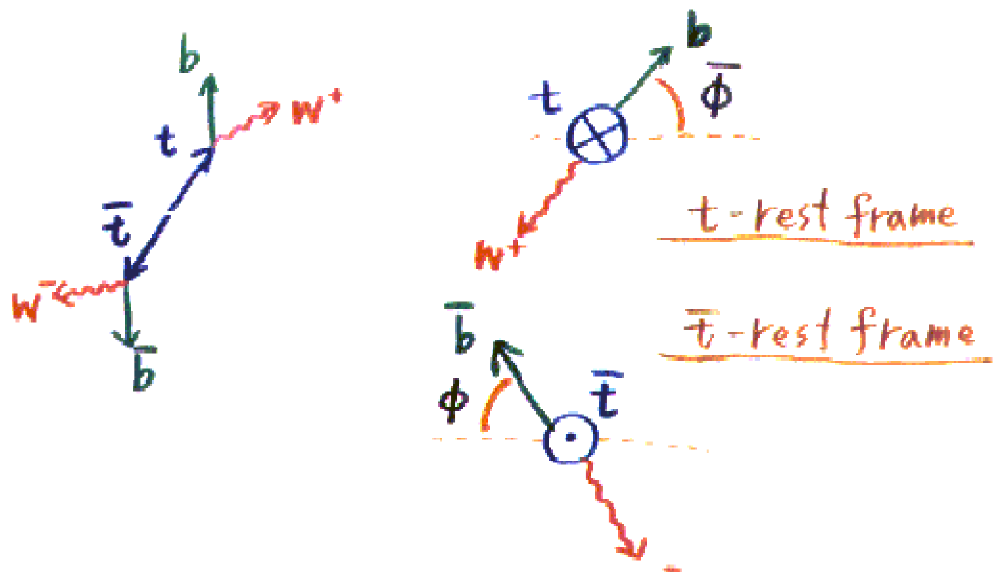
$$\langle \sin(\bar{\phi}-\phi)\rangle \propto \mathrm{Im}\left[\left(M_B^{RR}+M_\phi^{RR}\right)\left(\underbrace{\cancel{M_B^{LL}}}_{\text{small}}+M_\phi^{LL}\right)^*\right]$$
$$= \mathrm{Im}\left[M_B^{RR}\cdot M_\phi^{LL*} \pm \underbrace{\cancel{|M_\phi|^2}}_{\text{real}}\right]$$

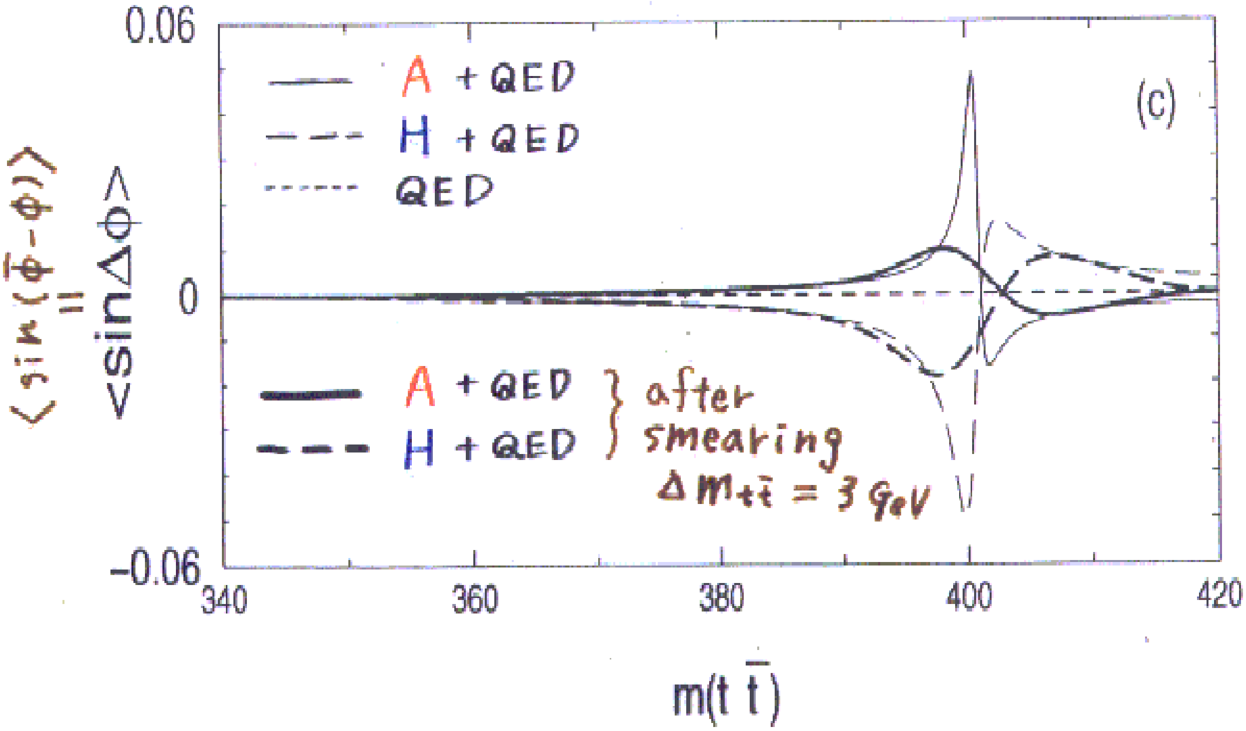
for H

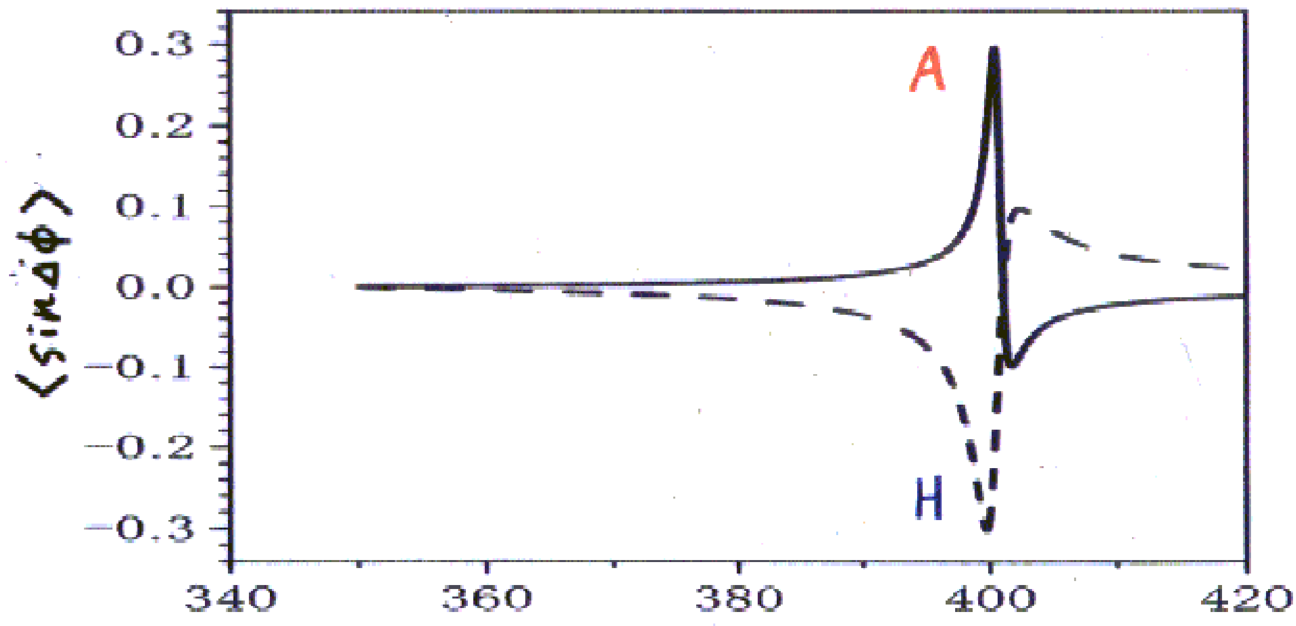
$$\langle \sin(\bar{\phi}-\phi)\rangle \propto -\mathrm{Im}\left[M_B^{RR}\cdot M_H\right]$$

for A

$$\langle \sin(\bar{\phi}-\phi)\rangle \propto \mathrm{Im}\left[M_B^{RR}\cdot M_A\right]$$







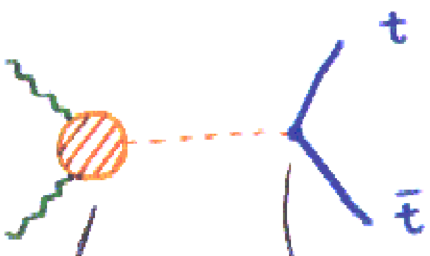
$m_\phi = 400$ GeV

$\Gamma_\phi = 1.75$ GeV

3. CP non-invariant case

E. A., S.Y. Choi, K. Hagiwara, J.S. Lee

hep-ph/0005313
(to be published in PRD)



$$\bar{\Psi}_t \left(S_t + i\gamma_5 P_t \right) \Psi_t \phi$$

$$S_\gamma \phi F^{\mu\nu} F_{\mu\nu} + P_\gamma \phi F^{\mu\nu} \tilde{F}_{\mu\nu}$$

S_t, P_t : real
S_γ, P_γ : complex

$\Downarrow$

6 parameters

$\left\{ \begin{array}{l} \bullet\ \text{circular pol.} \\ \bullet\ \text{top helicity measurement} \end{array} \right.$

photon beam helicities

t and $\bar{t}$ helicities

$$\left|\mathcal{M}^{(\overbrace{++}\,;\,\overbrace{++})}\right|^2 = \overline{|\mathcal{M}|}^2_0 \left[1 + \mathcal{A}_0 + \mathcal{A}_1 - (1+\beta)(\mathcal{A}_2 - \mathcal{A}_3)\right]$$
$$\left|\mathcal{M}^{(--;--)}\right|^2 = \overline{|\mathcal{M}|}^2_0 \left[1 + \mathcal{A}_0 - \mathcal{A}_1 + (1+\beta)(\mathcal{A}_2 - \mathcal{A}_3)\right]$$
$$\left|\mathcal{M}^{(++;--)}\right|^2 = \overline{|\mathcal{M}|}^2_0 \left[1 - \mathcal{A}_0 + \mathcal{A}_1 + (1-\beta)(\mathcal{A}_2 + \mathcal{A}_3)\right]$$
$$\left|\mathcal{M}^{(--;++)}\right|^2 = \overline{|\mathcal{M}|}^2_0 \left[1 - \mathcal{A}_0 - \mathcal{A}_1 - (1-\beta)(\mathcal{A}_2 + \mathcal{A}_3)\right]$$

$$\begin{aligned}
\overline{|\mathcal{M}|}^2_0 &= (1+\beta^2)A^2_{\rm cont} + (\beta^2 S_t^2 + P_t^2)(|S_\gamma|^2 + |P_\gamma|^2)\,|A_\phi|^2 \\
&\quad + 2A_{\rm cont}\left[\beta^2 S_t\,\mathcal{R}(A_\phi S_\gamma) + P_t\mathcal{R}(A_\phi P_\gamma)\right], \\
\mathcal{A}_0 &= 2\beta A_{\rm cont}\left\{A_{\rm cont} + [S_t\,\mathcal{R}(A_\phi S_\gamma) + P_t\,\mathcal{R}(A_\phi P_\gamma)]\right\} \Big/ \overline{|\mathcal{M}|}^2_0, \\
\mathcal{A}_1 &= 2\,|A_\phi|^2\left\{(\beta^2 S_t^2 + P_t^2)\,\mathcal{I}(S_\gamma P_\gamma^*)\right\} \Big/ \overline{|\mathcal{M}|}^2_0, \\
\mathcal{A}_2 &= 2\beta A_{\rm cont}\left\{S_t\,\mathcal{I}(A_\phi P_\gamma)\right\} \Big/ \overline{|\mathcal{M}|}^2_0, \\
\mathcal{A}_3 &= 2A_{\rm cont}\left\{P_t\,\mathcal{I}(A_\phi S_\gamma)\right\} \Big/ \overline{|\mathcal{M}|}^2_0,
\end{aligned}$$

$$A_{\rm cont} = \frac{16\pi\alpha Q_t^2 m_t}{\sqrt{s}\,(1-\beta^2\cos^2\theta)}$$

$$A_\phi = \frac{e\alpha}{4\pi}\,\frac{m_t}{m_W}\,\frac{s}{s - m_\phi^2 + i m_\phi \Gamma_\phi}$$

· **circular + linear pol.**

$$\overline{|\mathcal{M}|^2} = \overline{|\mathcal{M}|_0^2}' \Big\{ \left(1 + \zeta_2\tilde{\zeta}_2\right) + \mathcal{B}_1\left(\zeta_2 + \tilde{\zeta}_2\right) + \mathcal{B}_2\left(\zeta_1\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_1\right) - \mathcal{B}_3\left(\zeta_1\tilde{\zeta}_1 - \zeta_3\tilde{\zeta}_3\right)$$
$$+ \sin^2\Theta \Big[-\mathcal{C}_0\left(\zeta_2\tilde{\zeta}_2 - \zeta_3\tilde{\zeta}_3\right) + \mathcal{C}_1\left(\zeta_1 + \tilde{\zeta}_1\right) + \mathcal{C}_2\left(\zeta_3 + \tilde{\zeta}_3\right)$$
$$+ \mathcal{C}_3\left(\zeta_1\tilde{\zeta}_2 + \zeta_2\tilde{\zeta}_1\right) + \mathcal{C}_4\left(\zeta_2\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_2\right) \Big] \Big\},$$

P_c : degree of circular pol.

P_t : degree of linear pol.

Stokes parameters

$\zeta_1 \propto P_t \sin 2\kappa \quad \zeta_2 \propto P_c \quad \zeta_3 \propto P_t \cos 2\kappa$

$$\mathcal{B}_1 = \left(\mathcal{A}_1 - \beta\mathcal{A}_2 + \mathcal{A}_3\right) \overline{|\mathcal{M}|_0^2} \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$\mathcal{B}_2 = 2\Big\{ |A_\phi|^2 \left(\beta^2 S_t^2 + P_t^2\right) \mathcal{R}(S_\gamma P_\gamma^*) + A_{\rm cont}\left[\beta^2 S_t \mathcal{R}(A_\phi P_\gamma) + P_t \mathcal{R}(A_\phi S_\gamma)\right] \Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$= 2\left\{ |A_\phi|^2 (\beta^2 S_t^2 + P_t^2)\, \mathcal{I}(S_\gamma P_\gamma^*) + A_{\rm cont}\left[-\beta^2 S_t\, \mathcal{I}(A_\phi P_\gamma) + P_t\, \mathcal{I}(A_\phi S_\gamma)\right]\right\} \Big/ \overline{|\mathcal{M}|_0^2}'$$

$$\mathcal{B}_3 = \Big\{ (-1 + \beta^2 - \beta^2\sin^4\Theta) A_{\rm cont}^2 + (\beta^2 S_t^2 + P_t^2)(|S_\gamma|^2 - |P_\gamma|^2)|A_\phi|^2$$
$$+ 2A_{\rm cont}\left[\beta^2 S_t \mathcal{R}(A_\phi S_\gamma) - P_t \mathcal{R}(A_\phi P_\gamma)\right] \Big\} \Big/ \overline{|\mathcal{M}|_0^2}'.$$

CP-odd observables

$$\mathcal{C}_0 = 2\beta^2 \sin^2\Theta A_{\rm cont}^2 \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$\mathcal{C}_1 = 2\beta^2 A_{\rm cont}\Big\{ S_t \mathcal{R}(A_\phi P_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$\mathcal{C}_2 = 2\beta^2 A_{\rm cont}\Big\{ A_{\rm cont} + S_t \mathcal{R}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$\mathcal{C}_3 = 2\beta^2 A_{\rm cont}\Big\{ S_t \mathcal{I}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$

$$\mathcal{C}_4 = -2\beta^2 A_{\rm cont}\Big\{ S_t \mathcal{I}(A_\phi P_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}'.$$

- circular + linear pol.
- top helicity measurement

$$\Delta = \frac{\overline{|\mathcal{M}|^2}(\lambda = \bar{\lambda} = +) - \overline{|\mathcal{M}|^2}(\lambda = \bar{\lambda} = -)}{\overline{|\mathcal{M}|_0^2}'}$$

$$\Delta = \mathcal{D}_1\left(1 + \zeta_2\tilde{\zeta}_2\right) + \mathcal{D}_2\left(\zeta_2 + \tilde{\zeta}_2\right) + \mathcal{D}_3\left(\zeta_1\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_1\right) - \mathcal{D}_4\left(\zeta_1\tilde{\zeta}_1 - \zeta_3\tilde{\zeta}_3\right)$$
$$+ \sin^2\Theta\Big[\mathcal{E}_1\left(\zeta_1 + \tilde{\zeta}_1\right) + \mathcal{E}_2\left(\zeta_3 + \tilde{\zeta}_3\right) + \mathcal{E}_3\left(\zeta_1\tilde{\zeta}_2 + \zeta_2\tilde{\zeta}_1\right) + \mathcal{E}_4\left(\zeta_2\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_2\right)\Big]$$

$$\mathcal{D}_1 = 2\beta A_{\rm cont}\Big\{ - S_t\,\mathcal{I}(A_\phi P_\gamma) + P_t\,\mathcal{I}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{D}_2 = 2\beta A_{\rm cont}\Big\{ A_{\rm cont} + [S_t\,\mathcal{R}(A_\phi S_\gamma) + P_t\,\mathcal{R}(A_\phi P_\gamma)]\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{D}_3 = 2\beta A_{\rm cont}\Big\{ - S_t\,\mathcal{I}(A_\phi S_\gamma) + P_t\,\mathcal{I}(A_\phi P_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{D}_4 = 2\beta A_{\rm cont}\Big\{ S_t\,\mathcal{I}(A_\phi P_\gamma) + P_t\,\mathcal{I}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}'.$$
$$\mathcal{E}_1 = 2\beta A_{\rm cont}\Big\{ P_t\,\mathcal{I}(A_\phi P_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{E}_2 = 2\beta A_{\rm cont}\Big\{ P_t\,\mathcal{I}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{E}_3 = -2\beta A_{\rm cont}\Big\{ P_t\,\mathcal{R}(A_\phi S_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}',$$
$$\mathcal{E}_4 = 2\beta A_{\rm cont}\Big\{ A_{\rm cont} + P_t\,\mathcal{R}(A_\phi P_\gamma)\Big\} \Big/ \overline{|\mathcal{M}|_0^2}'.$$

· circular pol.
· top helicity measurement

$\tan\beta$	$\hat{\sigma}_0[+]$	$\overline{\mathcal{A}}_0[+]$	$\overline{\mathcal{A}}_1[-]$	$\overline{\mathcal{A}}_2[-]$	$\overline{\mathcal{A}}_3[-]$
3	0.88 pb	0.45	0.13	−0.17	0.26
10	0.62 pb	0.91	0.00	−0.02	0.03

measurable CP-odd obs.

$(-A_2 + \beta_t A_3)$

$(A_1 - \beta_t A_2 + A_3)$

· circular + linear pol.

$\tan\beta$	$\overline{\mathcal{B}}_1[-]$	$\overline{\mathcal{B}}_2[-]$	$\overline{\mathcal{B}}_3[+]$	$\overline{\mathcal{C}}_0[+]$	$\overline{\mathcal{C}}_1[-]$	$\overline{\mathcal{C}}_2[+]$	$\overline{\mathcal{C}}_3[+]$	$\overline{\mathcal{C}}_4[-]$
3	0.46	−0.27	−0.60	0.17	0.13	0.09	0.17	0.06
10	0.03	0.00	−0.47	0.24	0.01	0.30	0.04	0.00

· circular + linear pol.
· top helicity measurement

$\tan\beta$	$\overline{\mathcal{D}}_1[-]$	$\overline{\mathcal{D}}_2[+]$	$\overline{\mathcal{D}}_3[+]$	$\overline{\mathcal{D}}_4[-]$	$\overline{\mathcal{E}}_1[+]$	$\overline{\mathcal{E}}_2[-]$	$\overline{\mathcal{E}}_3[-]$	$\overline{\mathcal{E}}_4[+]$
3	0.32	0.41	−0.45	0.03	−0.04	0.10	0.09	0.40
10	0.03	0.80	−0.09	0.00	−0.00	0.01	0.01	0.46

$|A| = 1$ TeV $\quad \Phi = \frac{\pi}{2}$

$|\mu| = 2$ TeV $\quad \| \ \arg(A_t \mu e^{i\xi})$

$m_{susy} = 0.5$ TeV

$\tan\beta = 3$

$m_\phi = 500$ GeV $\quad \Gamma_\phi = 1.9$ GeV

$S_\gamma = -1.3 - 1.2i \quad P_\gamma = -0.57 + 1.1i$

$S_t = 0.33 \quad P_t = 0.15$

$\tan\beta = 10$

$m_\phi = 500$ GeV $\quad \Gamma_\phi = 1.1$ GeV

$S_\gamma = -0.39 - 0.35i \quad P_\gamma = -0.06 + 0.14i$

$S_t = 0.11 \quad P_t = 0.02$

4. Summary

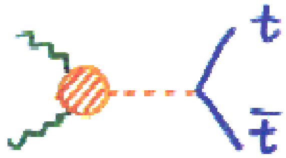
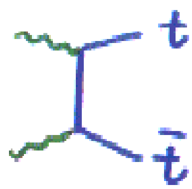
We have studied

how to measure Higgs CP property

in high $\sqrt{\tau}$ region.

→ degree of linear polarization is not so good.

To observe interference effect

between  and 

can be a powerful method

especially in CP invariant case.

In CP violating case,

linear polarization is also needed

to determine $S_\gamma, P_\gamma, S_t, P_t$ completely.

even without linear polarization

possible to judge whether

there exists sizable $\not{C}P$ or not.