Gad Eilam (Technion, Haifa, Israel)

Workshop on CP Violation
Adelaide, Australia, July 1998*

CP VIOLATION IN THE TOP SECTOR

Thanks to my collaborators:

David Atwood, JoAnne Hewett, Roberto Mendel, Roger Migneron, Amarjit Soni and especially to Shaouly Bar-Shalom

*These slides are equal, to a good approximation, to the slides used by S. Bar-Shalom in his talk at the Joint Minerva-GIF Symposium, Jerusalem, Israel, May 1998

Outline

- Introduction or Why $\not{C}\not{P}\,|_t$?

- Models with non-standard $\not{C}\not{P}$: MHDM's, SUSY

- $\not{C}\not{P}$ in top decays: SM and beyond

- Top Electric (E,ZE,CE) Dipole Moments:
  expectations from MHDM's and SUSY

- Future collider experiments and $\not{C}\not{P}$ in:

  ♠ $t\bar{t}$ production and decay: TEV3, LHC, NLC

  ♠ Single top production and decay: TEV3

  ♠ $e^+e^- \to t\bar{t}H^0$, $t\bar{t}Z$, $t\bar{t}\nu_e\bar{\nu}_e$: TREE-LEVEL $\not{C}\not{P}$

- Summary and outlook

Introduction or Why $\not{CP}|_t$?

Just one experimental number:

$$Br(K_L \to 2\pi) = 2.9 \pm .3 \times 10^{-3} \tag{1}$$

(and a few more that followed...but all in neutral K system) induced much activity

In K asking *e.g.*: is mixing the only source of the small $\not{CP}$ observed?

In B asking *e.g.*: is the SM the only source of the large $\not{CP}$ expected?

In t asking *e.g.*: what extension of the SM causes the usually small $\not{CP}$ expected and in what observables is it best manifested?

Trying to answer the last question, there are already $\mathcal{O}(100)$ papers on $\not{CP}$ in the top sector.

- SM causes vanishingly small $\not{C}\not{P}$ in top systems:

  - No tree-level $\not{C}\not{P}$
  - $m_t >> m_{\text{other quarks}} \Longrightarrow$ loops are very small
    i.e. GIM is extremely effective
  - Practically no $\not{C}\not{P}$ in the lepton sector
    A good example:

    $d_f^{SM} \propto 3 - \text{loops effect} \Longrightarrow d_t^{SM} \lesssim 10^{-30}$ e-cm

- Phases are all over the place in extensions of the SM

- The top at 175 is the closest to NEW PHYSICS which may well be the cause of $\not{C}\not{P}$ m_t drives large $\not{C}\not{P}$ in ext. of SM:

  - MHDM's with $\not{C}\not{P}$ in neutral Higgs sector:
    $C_{Hff} \propto m_f \Longrightarrow$ top is best
  - SUSY with $\not{C}\not{P}$ in mixing of squarks:
    $m_{\tilde{q}_L} - m_{\tilde{q}_R}(\text{mix}) \propto m_q \Longrightarrow$ top is best

Future colliders are very attractive machines for searching for new physics in top systems
e.g.,

- Tevatron's runs $2-3$: $10^4 - 10^5$ $t\bar{t}$ events/year
- LHC: $10^7 - 10^8$ $t\bar{t}$ events/year
- e^+e^- NLC: $10^5 - 10^6$ $t\bar{t}$ events/year

New $\not{C}\not{P}$ effects driven by new thresholds if:
$m_t > M_{\text{new particles}}$
Useful for $\not{C}\not{P}$ in top decays
$\Longrightarrow$ absorptive cuts automatically provided

$\not{C}\not{P}\,|_t$ IS DIRECT !

Time scales:
$\Gamma(t \to bW) \simeq G_F \frac{m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2$
$\Longrightarrow \tau_t = \Gamma^{-1} < \tau_{QCD} = \frac{1}{\Lambda_{QCD}}$

Therefore, there are no t_{hadrons}

and:

- The info. carried by top spins is not diluted by hadronization
  $\Longrightarrow$ s_t as good as any four momentum p
  $\Longrightarrow$ Many momenta at hand allowing construction of a large # of $\not{C}\not{P}$ observables with spins of top

- Bonus: spins of top are highly correlated to top decays

Models With Non-Standard $\not{CP}$

$\not{CP}$ in neutral Higgs sector in MHDM's:

Generically for any 2HDM or 3HDM
(with or without NFC):

- $\not{CP}$ either explicit in:
  Higgs potential (*e.g.*, type II 2HDM),
  Higgs Yukawa couplings (*e.g.*, type III 2HDM)
  or spontaneous (*e.g.*, 3HDM)

- Scalar - PseudoScalar mixing
  $\Longrightarrow$ Higgs does not have a definite CP property

As a consequence:

$$\boxed{\mathcal{L}_{H^0 ff} = -\frac{g_W}{\sqrt{2}} \frac{m_f}{m_W} H^0 \bar{f} \left(a_f + i b_f \gamma_5 \right) f}$$

$\Longrightarrow$ $\not{CP}$ in $H^0 t\bar{t} \propto b_t$

e.g., type II 2HDM: $b_t \propto \frac{1}{\tan\beta}$, $\tan\beta \equiv v_u/v_d$

NOT MSSM

$\not{C}\not{P}$ in charged Higgs sector in MHDM's:

A generic parameterization for any MHDM (with or without NFC):

$$\mathcal{L}_{H^+ud} = \frac{g_W}{\sqrt{2}m_W} K_{ud} \times$$
$$H^+ \bar{u}(m_u U_u \mathbf{P}_L + m_d U_d \mathbf{P}_R) d$$

$$\mathcal{L}_{H^+\ell\nu_\ell} = \frac{g_W}{\sqrt{2}m_W} H^+ \bar{\nu}_\ell (m_\ell U_\ell \mathbf{P}_R) \ell$$

U_u, U_d, U_ℓ depend on the mixing parameters in the charged Higgs sector and are in general complex with at least 3 Higgs doublets

$\Longrightarrow$ H^+ $\not{C}\not{P}$ in top $\propto \Im\mathrm{m}(U_u^* U_d)$, $\Im\mathrm{m}(U_u^* U_\ell)$

$\not{CP}$ in the MSSM:

- $\not{CP}$ in $\tilde{f}_L - \tilde{f}_R$ mixing; useful parameterization:

$$\begin{aligned} \tilde{f}_L &= \cos\alpha_f \tilde{f}_1 - e^{i\beta_f} \sin\alpha_f \tilde{f}_2 \\ \tilde{f}_R &= e^{-i\beta_f} \sin\alpha_f \tilde{f}_1 + \cos\alpha_f \tilde{f}_2 \end{aligned}$$

$$\Longrightarrow \boxed{\not{CP} \propto \xi^f_{CP} \equiv \frac{1}{2} \sin(2\alpha_f) \sin\beta_f}$$

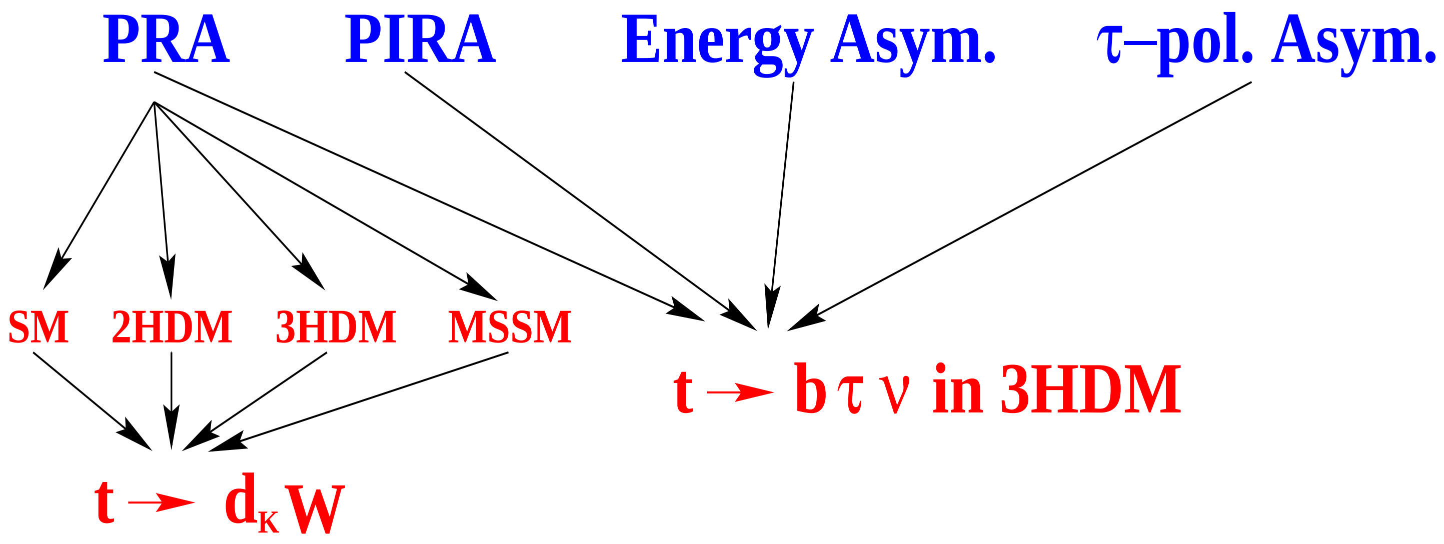
1. $\sin(2\alpha_f) \propto (m_f/M_{SUSY}) \to 0$ for $f \neq t$
   $\Longrightarrow$ useful only in stop sector

2. $\beta_t \propto \arg(A_t)$ $(A_t Q^3 H_2 U^3$ in $\mathcal{L}_{\text{soft}})$
   $\arg(A_t)$ typically small in SUGRA because of RGE $+ d_n$

   However: $\arg(A_t) \sim \mathcal{O}(1)$ OK with non-univ. A terms $\Rightarrow$ Maximal $\not{CP}$ in $\tilde{t}_L - \tilde{t}_R$ $(\xi^t_{CP} = \frac{1}{2})$?

- $\not{CP}$ via $\arg(\mu) = -\arg(B)$ $(\mu B H_1 H_2$ in $\mathcal{L}_{\text{soft}})$:
  However: due to $d_n < 1.1 \times 10^{-25}$ e-cm
  $\arg(\mu) \lesssim 10^{-2} - 10^{-3}$ practically inevitable for $m_{\text{squark}} \lesssim 1$ TeV!

$\not{C}\!\!\not{P}$ in top decays



$$\text{PRA} = \frac{\Gamma(t \to X) - \bar{\Gamma}(\bar{t} \to \bar{X})}{\Gamma(t \to X) + \bar{\Gamma}(\bar{t} \to \bar{X})}$$

$$\textbf{CPT} \implies \Gamma_{\text{total}} = \bar{\Gamma}_{\text{total}}$$
$$\textbf{CP} \implies \Gamma_{\text{partial}} = \bar{\Gamma}_{\text{partial}}$$

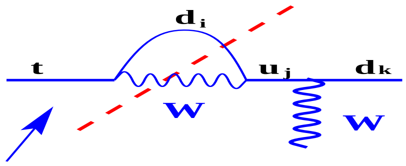
- PRA $\neq 0$ if $\not{C}\!\!\not{P}$

- CP-CPT connection: If PRA $\neq 0$, then from CPT there must exist a compensating PRA from another available decay channel.

$$\Downarrow$$

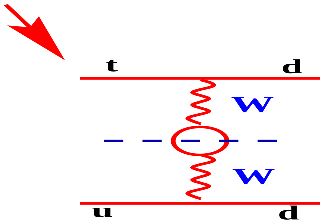
PRA$|_t$ is generally small because of CP-CPT connection and/or other reasons

PRA



SM: 1. PRA($t \to d_k W$) $\propto$ $\Im$m(penguin) $\times$ $\Re$e(tree)
at best $\sim 10^{-9}$ for small $t \to dW$ $(k = 1)$

2. PRA($t \to uq\bar{q}, cq\bar{q}$), $q = d, s, b$
despite W-resonance enhancement from
$\Im$m("tree") $\times\Re$e(penguin)

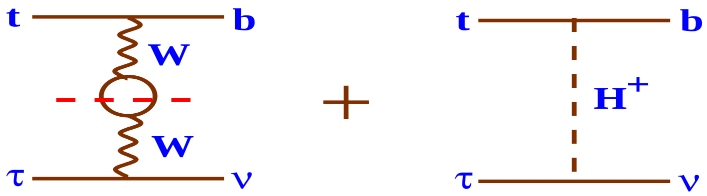


PRA $\sim 10^{-5}$ at best for small $t \to dc\bar{d}$

2HDM: 1. PRA($t \to d_k W$); add H^+ to SM W^+
$\Longrightarrow$ NO ENHANCEMENT OVER SM

$*$ No contribution from H^0 in a
2HDM with NFC, *e.g.*, type II

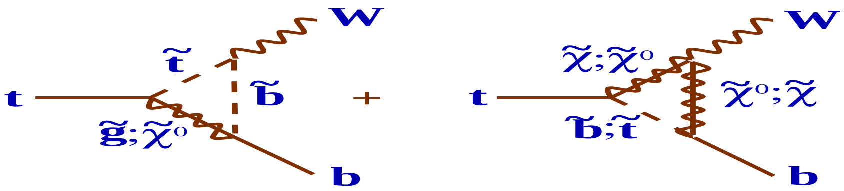
3HDM: PRA($t \to b\tau\nu_\tau$) $\propto$



+ loop; vertex,box

1. $\Im$m(W $-''$tree$''$) $\times$ $\Re$e(H $-$ tree) $\propto \Im\text{m}G_L^W \lesssim 10^{-8}$
2. $\Im\text{m}G_T^W \times \Re$e(tree x loop) $\sim 10^{-5}$

MSSM: PRA($t \to bW$) $\propto$ tree $\times$



♠ GK limit: $\tilde{t}\tilde{b}\tilde{g}$-loop $\propto \xi^t_{CP} \sim 1\%$, $m_{\tilde{g},\tilde{b}} = 100$ GeV
Requires the already excluded $m_t > m_{\tilde{t}} + m_{\tilde{g}}$

♠ CF limit: $\tilde{t}\tilde{b}\tilde{\chi}^0$-loop $\propto$ arg(μ) $\sim 2\%$, $m_{\tilde{b}} = 100$ GeV
Requires arg(μ) $\sim \mathcal{O}(1)$, NEDM $\Rightarrow$ BIG IF?

♠ BAS limit: Assumes arg(μ) $= 0$, degenerate $\tilde{b}$
PRA $\sim \tilde{t}\tilde{\chi}^+\tilde{\chi}^0$-loop $\propto \xi^t_{CP}$, at best $\lesssim 0.3\%$
for $M_{SUSY} \gtrsim 300$ GeV. Requires $m_t > m_{\tilde{t}} + m_{\tilde{\chi}^0}$!

Beyond PRA in $t \to b\tau\nu$ in 3HDM

Want to utilize W $-''$ tree$''$ $\times$ H $-$ tree but bypass G_L^W
$\Longrightarrow$ Useful alternatives even though PRA is small:

PIRA: $\boxed{\mathcal{A}_{pi} = \frac{\Gamma_{pi} - \bar{\Gamma}_{pi}}{\Gamma_{pi} + \bar{\Gamma}_{pi}} \; ; \; \Gamma_{pi} = \Gamma(t \to b\tau\nu) \,|_{\cos\theta_{b\tau} > 0}}$

Energy Asym.: $\boxed{\mathcal{A}_E = \frac{\langle E_{\tau^+} \rangle - \langle E_{\tau^-} \rangle}{\langle E_{\tau^+} \rangle + \langle E_{\tau^-} \rangle}}$

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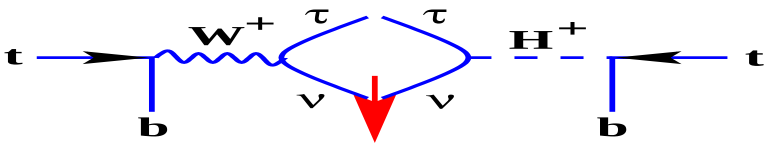
$\boxed{\mathcal{A}_E \sim \mathcal{A}_{pi}/3, \; \mathcal{A}_{pi} \sim \text{few} \times 10^{-3} \;\; >> \text{PRA}}$



Till now: $Tr\,[\gamma^\mu(\not{p}_\tau + m_\tau)(1 - \gamma_5)\not{p}_\nu] = 4 m_\tau p_\nu^\mu$

Transverse τ pol.: $\boxed{\mathcal{A}_Z = \frac{\tau^+(\uparrow) - \tau^+(\downarrow) - \tau^-(\uparrow) + \tau^-(\downarrow)}{\tau^+(\uparrow) + \tau^+(\downarrow) + \tau^-(\uparrow) + \tau^-(\downarrow)}}$

In τ r.f. such that t on $-\hat{x}$ and $\hat{x} - \hat{y}$ the decay plane
$\Rightarrow$ $\mathcal{A}_Z$ CP-odd T_N-odd $\Rightarrow$ no need for absorptive phase!
AVOID τ-SPIN SUMMATION (NO m_τ IN Tr[ ])

$\boxed{\Longrightarrow \mathcal{A}_Z \sim \frac{m_t}{m_\tau} \mathcal{A}_{E,pi}}$

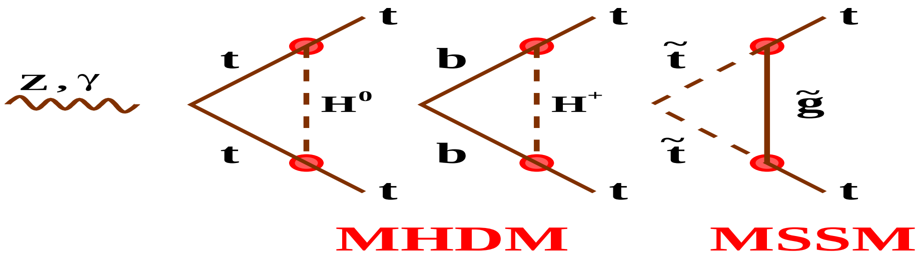
Within the allowed 3HDM:

$\boxed{\mathcal{A}_Z \sim \text{few} \times 10^{-1} \Longrightarrow \text{needs} \; \gtrsim 10^3 \; t\bar{t}\text{'s !!!}}$

Top E,ZE,CE Dipole Moments

Top EDM signifies the presence of CP-violation may be considered as a CP-odd form factor in the $\gamma t\bar{t}$, $Zt\bar{t}$ or $gt\bar{t}$ vertex that measures the effective coupling between the spin of a short-lived top quark and an off-shell external gauge field:

$$\boxed{\Gamma_\mu^{\gamma,Z,g} = i d_t^{\gamma,Z,g}(s)\bar{u}_t(p_t)\sigma_{\mu\nu}\gamma_5 p^\nu v_{\bar{t}}(p_{\bar{t}});\ \ p = p_t + p_{\bar{t}}}$$



♠ H^0 $\not{C}\!\!\not{P}$ in MHDM's:

$$\boxed{H^0 tt \propto m_t(a_t + i b_t \gamma_5) \Rightarrow d_t \propto m_t^2 a_t \times b_t}$$

♠ H^+ $\not{C}\!\!\not{P}$ in MHDM's:

$$\boxed{H^+ tb \propto (m_t U_t \mathbf{P}_R + m_b U_b \mathbf{P}_L) \Rightarrow d_t \propto m_t m_b \Im\text{m}(U_t U_b^*)}$$

and: $d_b \leftrightarrow d_t$ with $m_b \leftrightarrow m_t$

♠ MSSM $\not{C}\!\!\not{P}$ from $\tilde{t}_L - \tilde{t}_R$ mixing:

$$\boxed{\tilde{t}t\tilde{g} \propto (Z_1 \mathbf{P}_R + Z_2 \mathbf{P}_L) \Rightarrow d_t \propto \Im\text{m}(Z_1 Z_2^*) = \xi_{CP}^t}$$

Typical (optimal) $d_t^{\gamma,Z,g}$ within MHDM's and SUSY

♠ H^0 $\not{C}\not{P}$ in MHDM's: $d_t \propto a_t \times b_t$

d_t for $\boxed{a_t = b_t = 1,\ m_{H_i^0} \sim \mathcal{O}(1)\ \text{TeV},\ i > 1}$

♠ H^+ $\not{C}\not{P}$ in MHDM's: $d_t \propto \Im\text{m}(U_t U_b^*)$

d_t for $\boxed{\Im\text{m}(U_t U_b^*) = 5,\ m_{H_i^+} \sim \mathcal{O}(1)\ \text{TeV},\ i > 1}$

♠ MSSM $\not{C}\not{P}$: $d_t \propto \Im\text{m}(Z_1 Z_2^*) = \xi_{CP}^t$

d_t for $\boxed{\xi_{CP}^t = 0.5,\ m_{\tilde{t}_{1,2}} = 50, 400\ \text{GeV}}$

$d_t^{\gamma,Z}$ (e – cm) ⇓	neutral Higgs $m_{H^0} = 100 - 300$	charged Higgs $m_{H^+} = 200 - 500$	Supersymmetry $m_{\tilde{g}} = 200 - 500$
500 GeV $\lvert\text{Im}(d_t^\gamma)\rvert$	$(4.1 - 2.0) \times 10^{-19}$	$(29.1 - 2.1) \times 10^{-22}$	$(3.3 - 0.9) \times 10^{-19}$
1000 GeV	$(0.9 - 0.8) \times 10^{-19}$	$(15.7 - 1.0) \times 10^{-22}$	$(1.2 - 0.8) \times 10^{-19}$
500 GeV $\lvert\text{Re}(d_t^\gamma)\rvert$	$(0.3 - 0.8) \times 10^{-19}$	$(33.4 - 1.5) \times 10^{-22}$	$(0.3 - 0.9) \times 10^{-19}$
1000 GeV	$(0.7 - 0.2) \times 10^{-19}$	$(0.3 - 2.7) \times 10^{-22}$	$(1.1 - 0.3) \times 10^{-19}$
500 GeV $\lvert\text{Im}(d_t^Z)\rvert$	$(1.1 - 0.2) \times 10^{-19}$	$(15.8 - 2.5) \times 10^{-22}$	$(1.1 - 0.3) \times 10^{-19}$
1000 GeV	$(0.2 - 0.2) \times 10^{-19}$	$(9.2 - 1.2) \times 10^{-22}$	$(0.4 - 0.3) \times 10^{-19}$
500 GeV $\lvert\text{Re}(d_t^Z)\rvert$	$(1.6 - 0.2) \times 10^{-19}$	$(22.9 - 0.8) \times 10^{-22}$	$(0.1 - 0.3) \times 10^{-19}$
1000 GeV	$(0.2 - 1.4) \times 10^{-19}$	$(0.6 - 1.9) \times 10^{-22}$	$(0.4 - 0.1) \times 10^{-19}$

$*$ Recall $d_t^{SM} \lesssim 10^{-30}$ e-cm

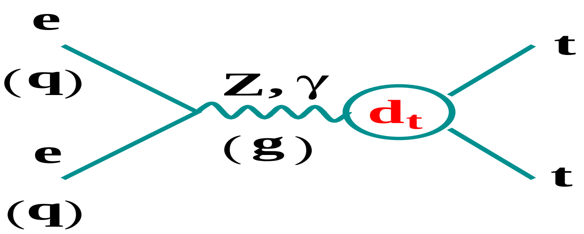
$*$ $d_t(H^+) \sim \left(\frac{m_b}{m_t}\right)^2 d_t(H^0)$ due to $t \to b$ in loop

$*$ In MHDM's $d_t^g \mid_{g_s-\text{cm}} = \frac{3}{2} d_t^\gamma \mid_{\text{e}-\text{cm}}$

(Not true for MSSM due to additional $g\tilde{g}\tilde{g}$–loop)

$\not{C}\not{P}$ in future collider experiments

Model independent in $e^+e^-,\ q\bar{q}\to t\bar{t}$



$+\ \not{C}\not{P}$ from $t \to bW$ but smaller then $\not{C}\not{P}$ from d_t

$$\Sigma(\phi)d\phi = \Sigma_0(\phi)d\phi +$$

$$\sum_{V=\gamma,Z}\left(\Re\mathrm{e}\, d_t^V(s)\Sigma_{\Re\mathrm{e}(d_t^V)}(\phi) + \Im\mathrm{m}\, d_t^V(s)\Sigma_{\Im\mathrm{m}(d_t^V)}(\phi)\right)\ d\phi$$

(In MSSM d_t not the whole story due to new boxes)

To minimize the statistical error use optimal observables

$$\boxed{\mathcal{O}_{\Re\mathrm{e}} = \Sigma_{\Re\mathrm{e}(d_t^V)}/\Sigma_0\ ,\ \mathcal{O}_{\Im\mathrm{m}} = \Sigma_{\Im\mathrm{m}(d_t^V)}/\Sigma_0}$$

Then $\Re\mathrm{e}, \Im\mathrm{m}\, d_t \sim 10^{-17}$ e-cm (1σ)

(with 10000 $t\bar{t}$ and $E_{CM} = 500$ GeV)

$*$ $\mathcal{O}_{\mathrm{opt}}$ by now used extensively

For NLC's $e^+e^- \to t\bar{t}$ and:

For Tevatron's $p\bar{p} \to t\bar{t}$

♠ The results improve by considering:

$\Sigma(t\bar{t}) \longrightarrow \Sigma(t\bar{t} \to b\ell\nu + bW_{had})$ + beam pol.

Get: $\Re\mathrm{e}, \Im\mathrm{m} d_t \sim$ few $\times\, 10^{-19} - 10^{-18}$ e-cm (1σ)

♠ Using optimization technique for:

Single leptonic energy spectrum: $\frac{1}{\sigma^{\pm}}\frac{d\sigma^{\pm}}{dE^{\ell^{\pm}}}$

Then: $\Im\mathrm{m} d_t^{\gamma,g} \sim 10^{-17}$ e-cm (1σ) in NLC,TEV3

♠ Other observables suggested:

e.g., Simple correlations ("naive" observables):

$$\not{C}\not{P} \quad T_N - odd\text{:} \;\; \hat{T}_{ij} = (\hat{q}_- - \hat{q}_+)_i \frac{(\hat{q}_- \times \hat{q}_+)_j}{|\hat{q}_- \times \hat{q}_+|} + (i \leftrightarrow j)$$

$$\not{C}\not{P} \quad T_N - even\text{:} \;\; \hat{Q}_{ij} = (\hat{q}_- + \hat{q}_+)_i (\hat{q}_- - \hat{q}_+)_j + (i \leftrightarrow j)$$

$(\hat{q}_\pm \equiv \hat{q}_{\ell^\pm}, \hat{q}_{b^\pm})$

and more...

$\not{C}\not{P}$ in $pp \to t\bar{t} + X$ beyond the SM

gg fusion dominates in a 14 TeV machine (LHC):

$$\Downarrow$$

$$g + g \to t + \bar{t} \to bW^{+} + \bar{b}W^{-} \to be^{+}\nu_e + \bar{b}e^{-}\bar{\nu}_e$$

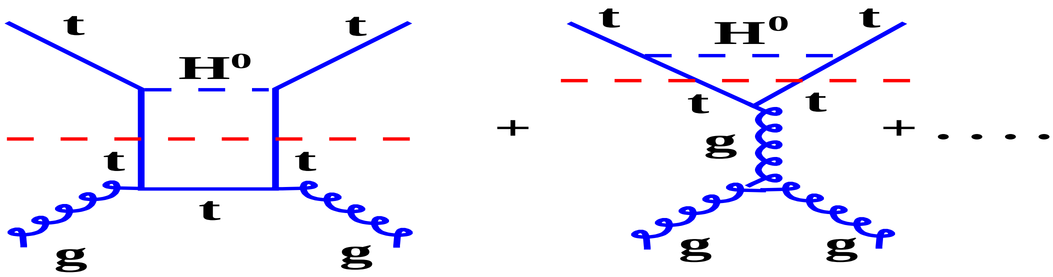
SP Signal; Energy (transverse) Asymmetry:

$$\boxed{\alpha_E = \frac{\langle E_{e^+}\rangle - \langle E_{e^-}\rangle}{\langle E_{e^+}\rangle + \langle E_{e^-}\rangle} \quad \left(\Delta N(E_T) = \frac{d\sigma/dE_T^{+} - d\sigma/dE_T^{-}}{d\sigma/dE_T^{+} + d\sigma/dE_T^{-}}\right)}$$

A simple signal in a very complicated reaction

α_E: $\not{C}\not{P}$ T_N-even $\to$ Needs absorptive parts

1. SP considers α_E in a 2HDM with H^0 $\not{C}\not{P}$
2. The necessary absorptive cuts are already there since $\hat{s} > 4m_t^2$ (no matter what m_{H^0} is !!!)



$$\boxed{\alpha_E \neq 0 \text{ due to } \# t_L \bar{t}_L \neq \# t_R \bar{t}_R}$$

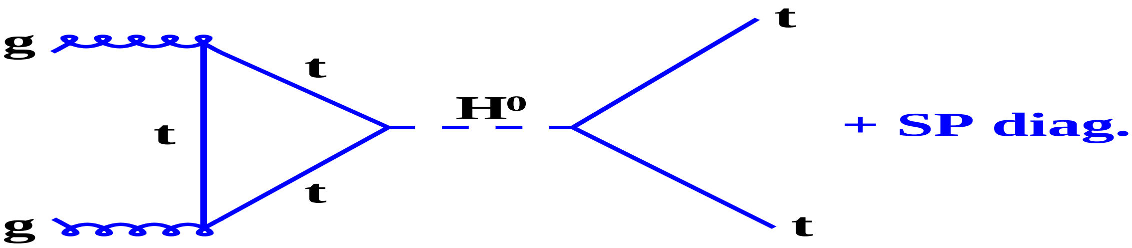
(Since $\hat{\sigma}_t || p_{e^+} \Longrightarrow \langle E_{e^+}^{t_R}\rangle > \langle E_{e^+}^{t_L}\rangle$)

$$\boxed{\alpha_E \sim \mathcal{O}(10^{-3}) \text{ possible} \Longrightarrow \gtrsim 10^7 \; t\bar{t} \text{ Needed}}$$

Recall LHC will give $\sim 10^7 - 10^8$ $t\bar{t}$ **!!!**

$*$ H^0 $\not{C}\not{P}$ in $pp \to t\bar{t} + X$ examined also by BB

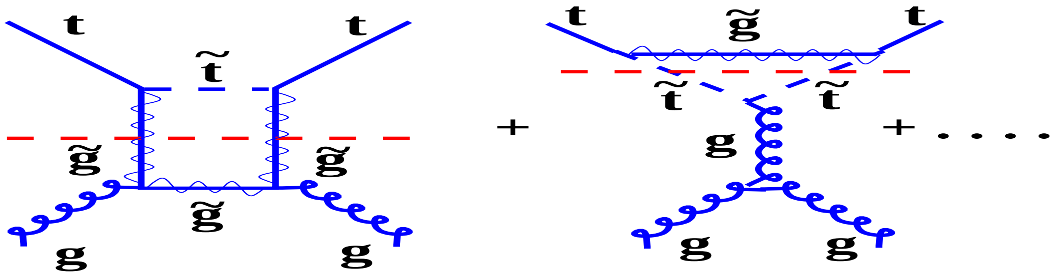
Including effects of s-channel H^0:



Then again $\langle (p_b - p_{\bar{b}}) \cdot (p_{\ell^+} \times p_{\ell^-}) \rangle \sim 10^{-3}$

$*$ MSSM $\not{C}\not{P}$ in $pp \to t\bar{t} + X$ examined by

utilizing $\not{C}\not{P}$ from $\tilde{t}_L - \tilde{t}_R$ mixing:



Then $\alpha_E \sim$ few $\times\, 10^{-3}$ is possible

However requires absorptive phases from cuts across gluinos or squarks

$*$ Model independent study ($\not{C}\not{P}$ from d_t^g) by AS

Find $d_t^g \sim 10^{-20}$ g_s-cm possible

However in $gg \to t\bar{t}$, $\not{C}\not{P}$ not necessarily $\propto d_t^g$

$*$ Some remarks on $\not{C}\not{P}$ in $pp \to t\bar{t} + X$:

1. Adding qq + gg fusion to SP's $\Delta N_{LR} \propto \alpha_E$
   $\alpha_E \to 10^{-2}$ optimistically with low $m_h, \tan\beta$

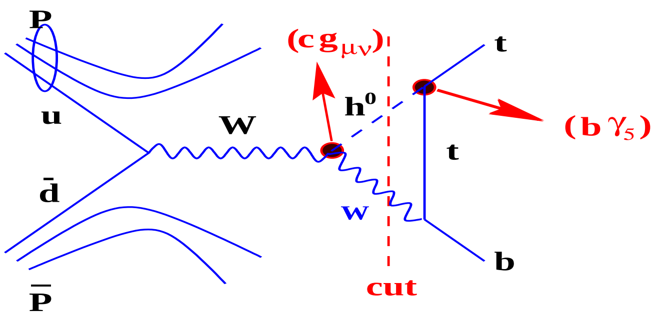
2. pp is not a CP eigenstate
   $\Longrightarrow E_t > E_{\bar{t}}$ without $\not{C}\not{P}$ in $q\bar{q} \to t\bar{t}$
   $\Longrightarrow$ QCD corrections can fake $\not{C}\not{P}$
   SP and BB find that this backg. not serious
   as long as SIGNAL $\gtrsim 10^{-3}$
   Mainly because gg fusion dominates
   and is free of such backg.

3. For SIGNAL $\sim \mathcal{O}(10^{-3})$ detector systematics
   can pose a problem
   Still remains to be seen whether
   such systematics can be overcome

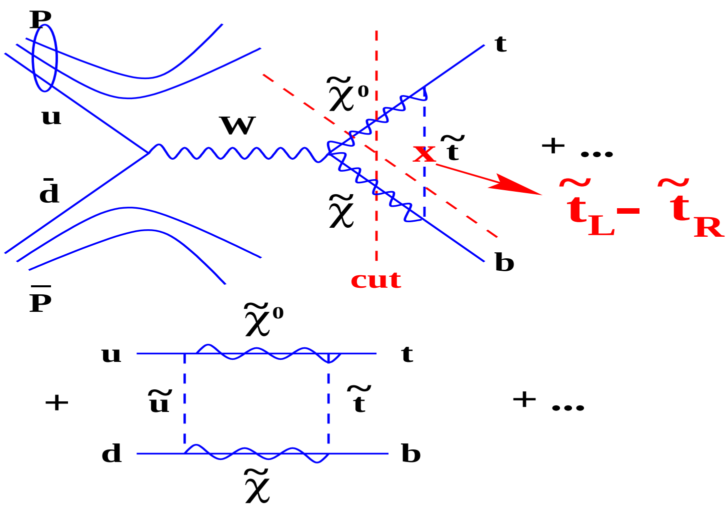
$\not{C}\not{P}$ in single top production in Tevatron run 3

The process: $u + \bar{d} \to t + \bar{b} \to bW^{+} + \bar{b}$

In 2HDM and MSSM



2HDM



MSSM

Key points:

1. $\not{C}\not{P}$ from t decay $<<$ $\not{C}\not{P}$ in tb production vertex (both 2HDM and MSSM)

2. In MSSM: box-loops $\not{C}\not{P}$ $<<$ triangle-loop $\not{C}\not{P}$

3. $\not{C}\not{P}$ in $tb \sim$ few % whereas $\not{C}\not{P}$ in $tt \sim$ few 0.1% (Advantage in confronting systematics)

(Recall $N_{needed} \propto \frac{1}{A^2} \Longrightarrow$ interesting with $\gtrsim 10^3$ tb's)
$\Longrightarrow$ Tevatron's run 3

The asymmetries (observables)

Rate (cross-section) asymmetry

$$\boxed{A_0 \equiv \frac{\sigma_{t\bar{b}} - \bar{\sigma}_{\bar{t}b}}{\sigma_{t\bar{b}} + \bar{\sigma}_{\bar{t}b}} \;;\; \not{C}\not{P}\;\; T_N\text{-even} \to \text{absorp. phase}}$$

Top polarization asymmetries

$$\boxed{A_i \equiv \frac{N(\uparrow_i) - N(\downarrow_i) + \bar{N}(\uparrow_i) - \bar{N}(\downarrow_i)}{N(\uparrow_i) + N(\downarrow_i) + \bar{N}(\uparrow_i) + \bar{N}(\downarrow_i)} \;;\; i = \hat{x}, \hat{y}, \hat{z}}$$

A_x, A_z $\not{C}\not{P}$ T_N-even, A_y $\not{C}\not{P}$ T_N-odd

****

$\hat{x} - \hat{z}$ the event plane

A_y – transverse top polarization asymmetry

Although in $p\bar{p} \to t\bar{b} + X$ $A_y < A_0$

A_y CAN PROBE TREE-LEVEL $\not{C}\not{P}$

SINCE IT DOESN'T REQUIRE ABSORPTIVE PHASE

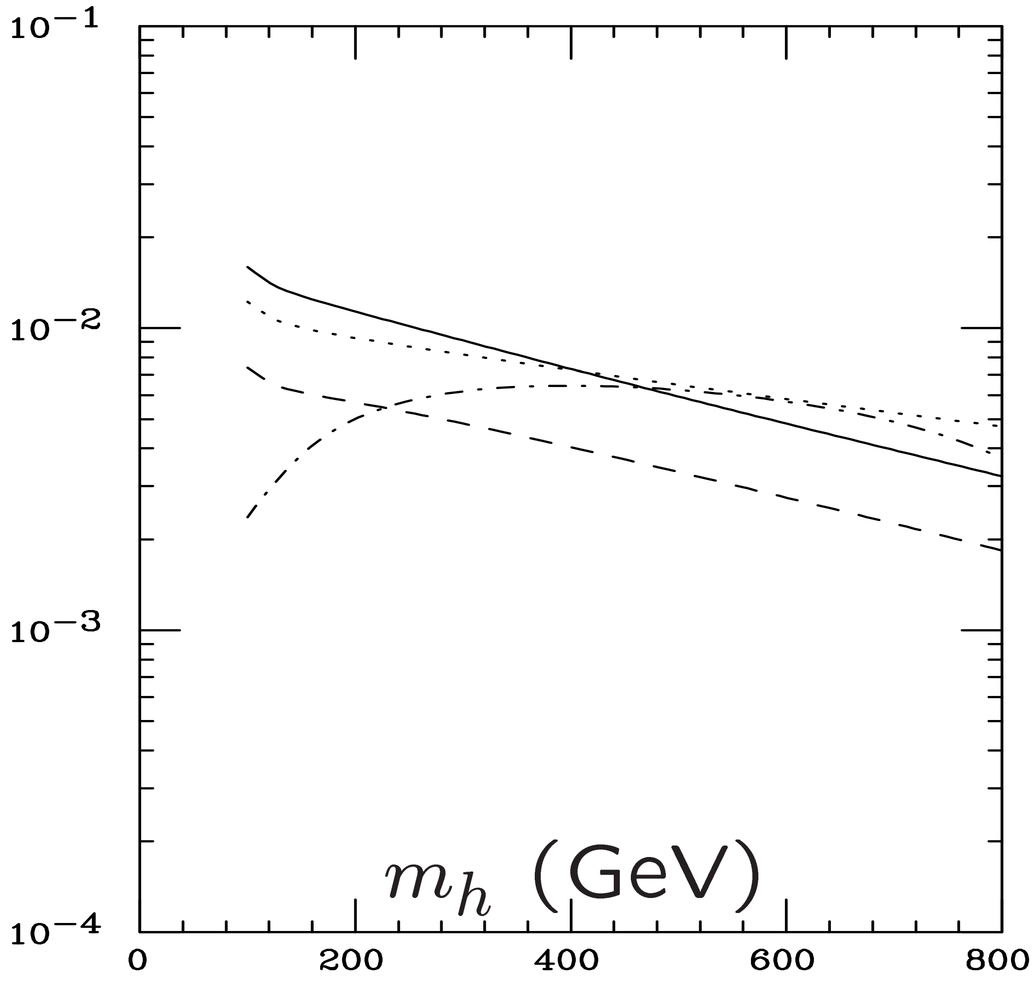
****

(Notice: $\not{C}\not{P}$ in tb f.s. will not work in LHC)

Contribution from 2HDM
Numerical results

$\sqrt{s} = 2$ TeV , $\tan\beta = 0.3$

solid: A_0, dotted: A_Z, dashed: A_X, dash-dotted: A_Y



$\boldsymbol{A_0(m_h \lesssim 300 \text{ GeV}) > 1\%}$

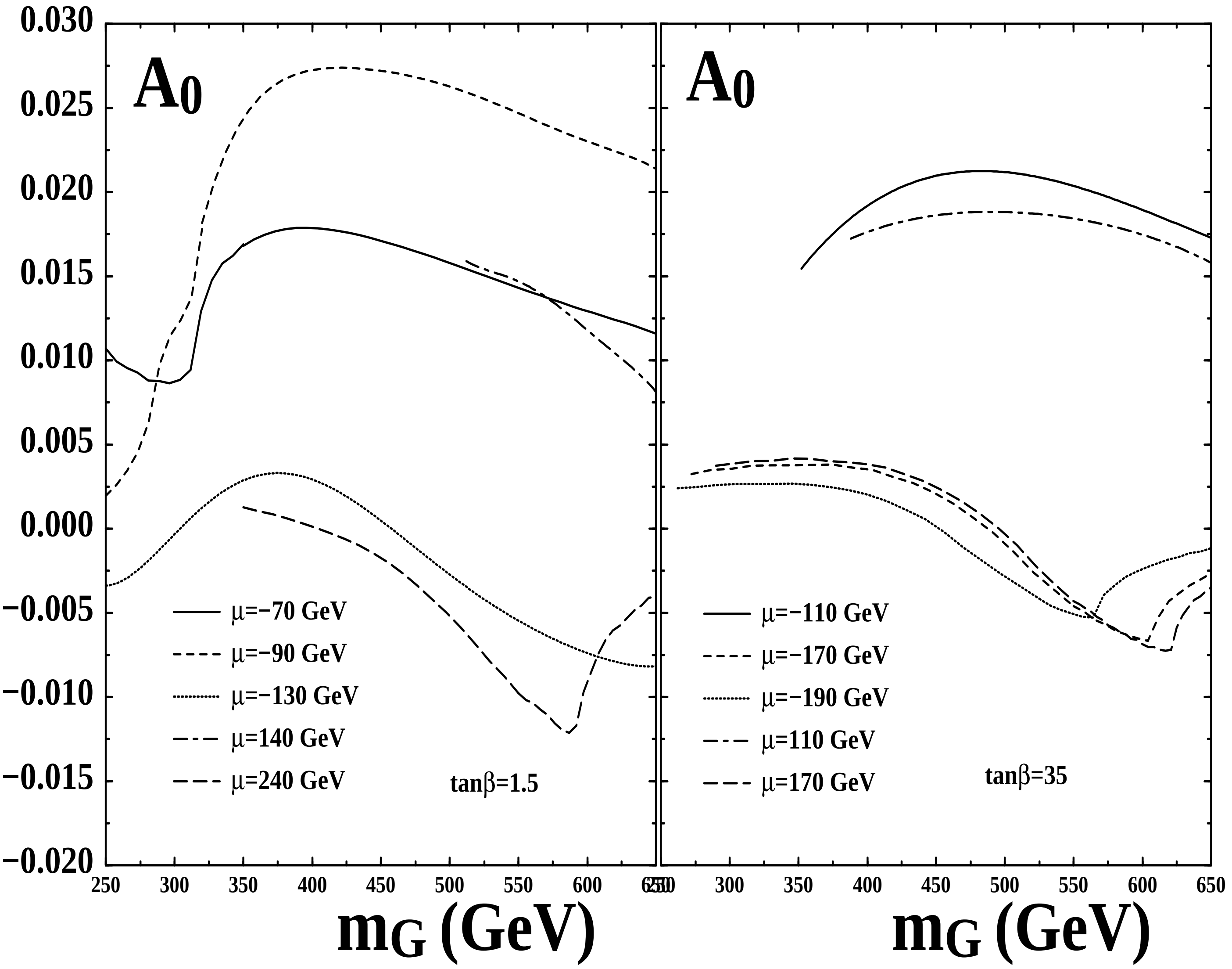
$\boldsymbol{A_Z(m_h \lesssim 200 \text{ GeV}) > 1\%}$

$\boldsymbol{A_Y(m_h \sim 400 \text{ GeV}) \sim 0.7\%}$

Contribution from MSSM
Numerical results

$$m_{\tilde{t}_1} = 50 \text{ GeV}, \; M_S = 400 \text{ GeV}, \; \xi^t_{CP} = 1/2$$

$\tan\beta = 1.5$ $\tan\beta = 35$

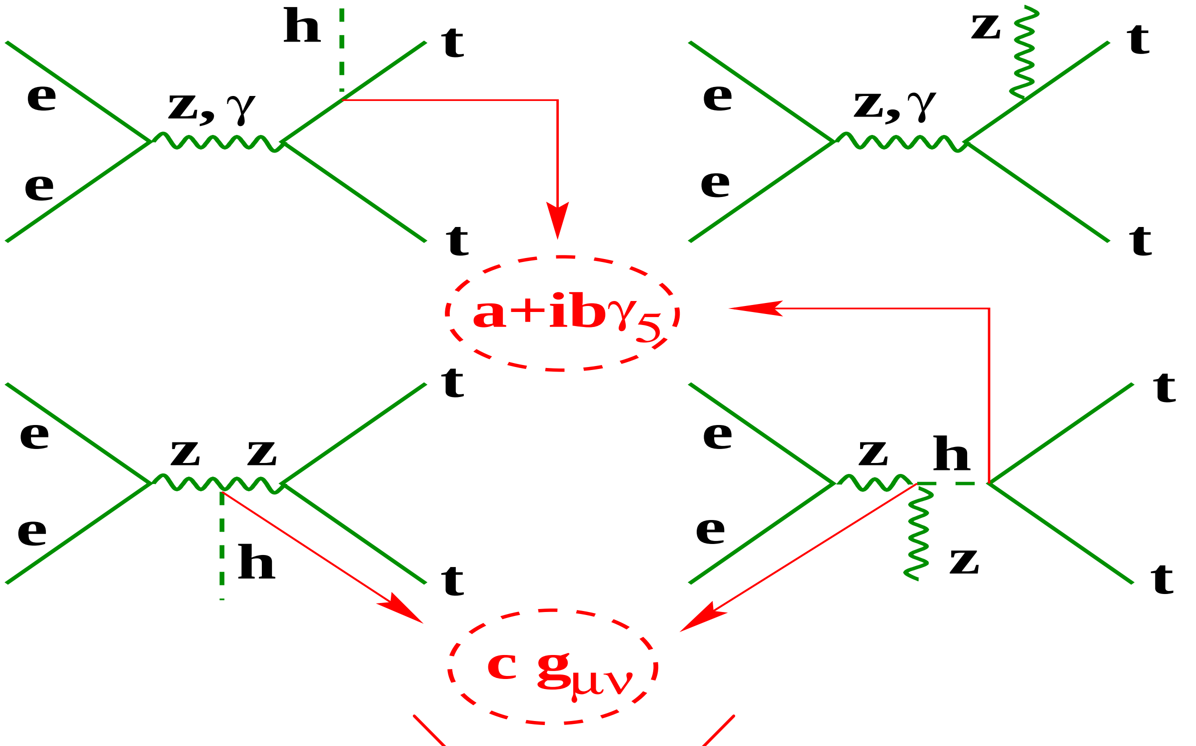


TREE-LEVEL $\not{C}\not{P}$ in a 2HDM

at a $\gtrsim 1$ TeV NLC

$$e^+e^- \to t\bar{t}h \qquad || \qquad e^+e^- \to t\bar{t}Z$$

($\not{C}\not{P}$ in real h emission) || ($\not{C}\not{P}$ through virtual h)



$$\boxed{\Sigma = \Sigma_+ + \Sigma_-(T_N - \mathrm{odd})}$$

$$\boxed{\Sigma_-(T_N - \mathrm{odd}) \propto b \times c \times \epsilon(p_e, p_{\bar{e}}, p_t, p_{\bar{t}})}$$

KEY POINTS

a) $e^+e^- \to tth, ttZ$ complementary reactions as for $\not{C}\!P$

b) $A \sim 5\% - 35\% \Longrightarrow$ may be the best bet for $\not{C}\!P$ searches in top systems

c) Not necessarily h discovery channels
But simple reactions in a "clean" environment especially if m_h already discovered by the time tth, ttZ are measured

d) tth needs $\tan\beta \lesssim \mathcal{O}(1)$, ttZ needs $\tan\beta \lesssim 0.5$

e) Will not work in pp collisions since $gg \to g \to t\bar{t}h$ dominates

f) Use optimal observables although "naive" momenta correlations almost as good due to simple structure of Σ_-

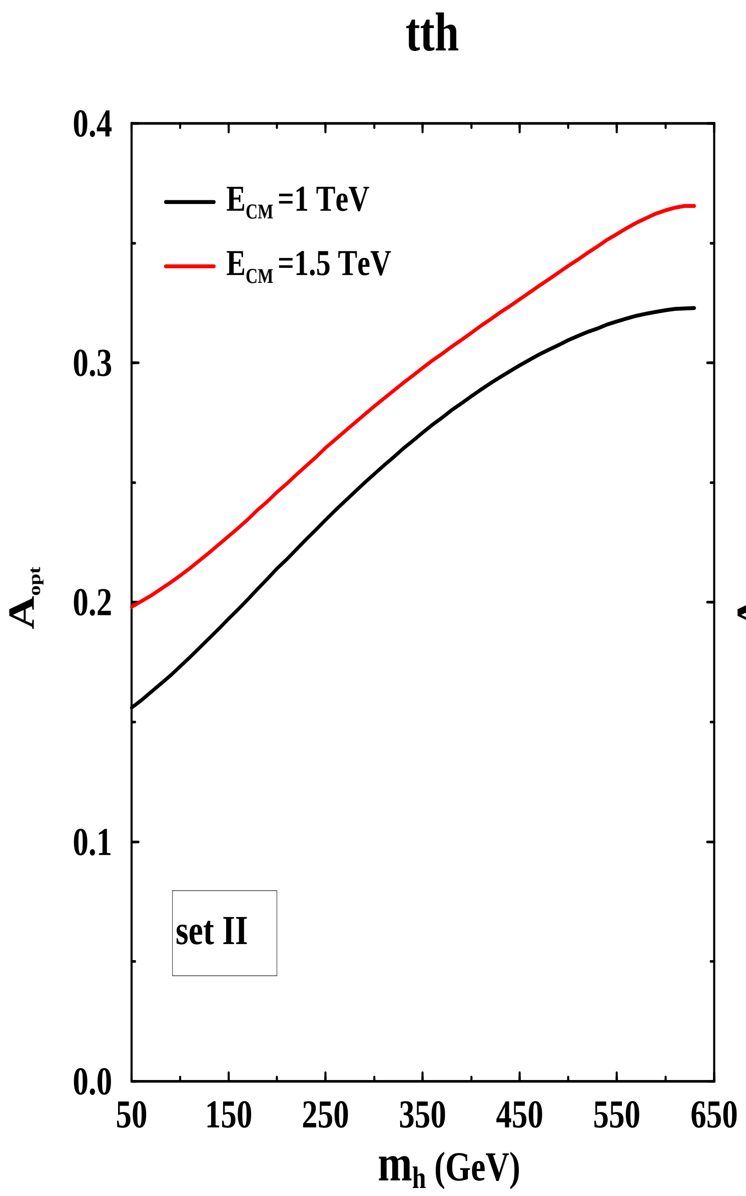
g) tth extended:
Using improved optimization technique to extract all Higgs couplings combinations by an optimal cross-section analysis

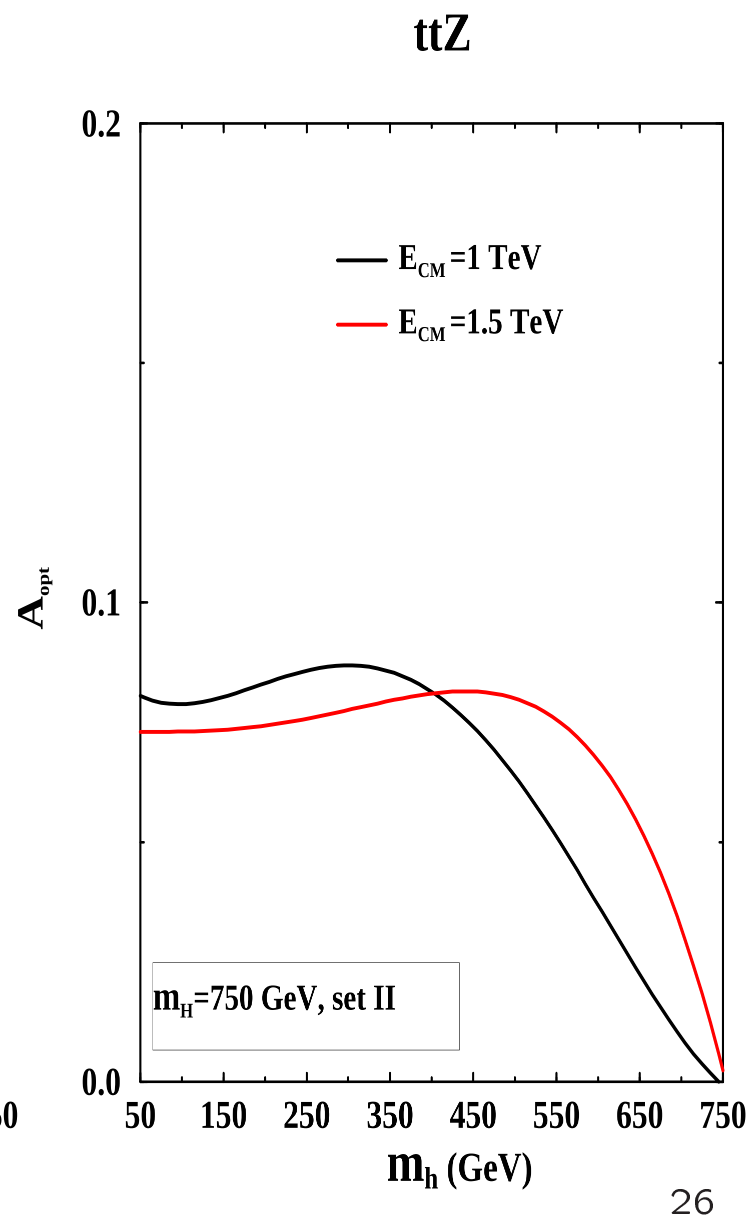
$e^+e^- \to t\bar{t}h,\ t\bar{t}Z$: Numerical results

Optimal observable $\Longrightarrow O_{opt} = \frac{\Sigma_-(T_N \text{ odd})}{\Sigma_+}$

(Set II: $\{\alpha_1, \alpha_2, \alpha_3\} = \{\pi/2, \pi/4, 0\}$)

$\tan\beta = 0.5$ || $\tan\beta = 0.3$





Expected statistical significance of $\not{C}\not{P}$ signal

$$N_{SD} = \sqrt{\sigma \mathcal{L}} \times A \; , \; \mathcal{L} = \epsilon L$$

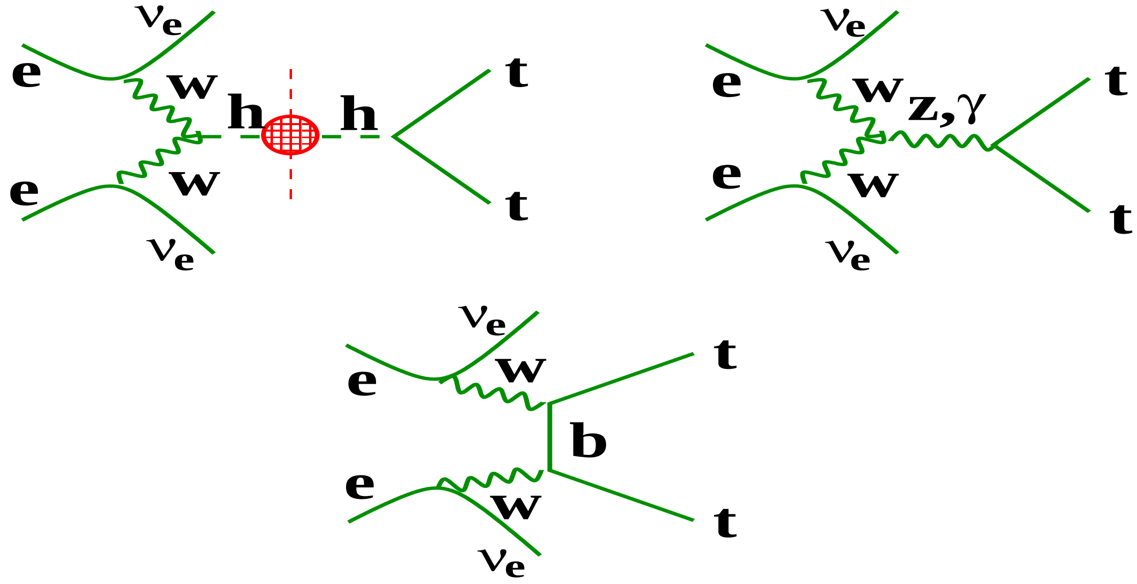
Use: $\epsilon = 0.5$, $\mathcal{L} = 200, 500$ fb^{-1} for $\sqrt{s} = 1, 1.5$ TeV

$\sqrt{s}$ (TeV) $\Downarrow$	j $\Downarrow$	$e^+e^- \to t\bar{t}h$, m_h (GeV): 100	160	360
1	-1	2.2	2.0	1.1
	unpol	2.0	1.9	1.0
	1	1.8	1.7	0.9
1.5	-1	4.0	3.9	3.2
	unpol	3.6	3.5	2.9
	1	3.2	3.1	2.6

Below results for $m_H = (750)1000$ GeV

$\sqrt{s}$ (TeV) $\Downarrow$	j $\Downarrow$	$e^+e^- \to t\bar{t}Z$, m_h (GeV): 100	160	360
1	-1	(1.8) 1.7	(1.8) 1.8	(2.2) 2.2
	unpol	(1.6) 1.6	(1.7) 1.6	(2.0) 2.0
	1	(1.5) 1.5	(1.5) 1.5	(1.8) 1.8
1.5	-1	(2.3) 2.9	(2.4) 3.0	(2.8) 3.3
	unpol	(2.1) 2.6	(2.1) 2.7	(2.5) 3.0
	1	(1.8) 2.3	(1.8) 2.3	(2.1) 2.6

$\not{CP}$ in $e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$:
another case of tree-level H^0 $\not{CP}$



Using top polarization (P_i) asymmetries

$$\boxed{\textit{e.g.,}\ \boldsymbol{A_y \equiv \tfrac{1}{2}(P_y - \bar{P}_y)\ ,\ A_x \equiv \tfrac{1}{2}(P_x + \bar{P}_x)}}$$

A_x $\not{CP}$ T_N-even, A_y $\not{CP}$ T_N-odd ($\sim$ tree-level)

$$\boxed{\boldsymbol{A_y(m_h \lesssim 300\ \mathrm{GeV}) \sim 30\%,\ A_x(m_h \gtrsim 400\ \mathrm{GeV}) \sim 10\%}}$$

$\Longrightarrow$ $N_{SD} \gtrsim 3\sigma$ possible in a 1.5 TeV e^+e^- machine

However may have difficulties in distinguishing and reconstructing $t, \bar{t}$ rest frames due to extra $2\nu_e$

Summary and Outlook

- SM $\not{C}\not{P}|_t$ has vanishing effects (GIM too effective)
  $\Longrightarrow$ Any observed $\not{C}\not{P}|_t$ is bound to Beyond SM

- Due to its "huge" mass top very sensitive to Beyond SM $\not{C}\not{P}$, *e.g.*, H^0 $\not{C}\not{P}$ $\propto m_t$ in $\times$HD's

- Challenging key points in future $\not{C}\not{P}|_t$ searches:

  1. Can $\boldsymbol{A \sim 10^{-3}}$ overcome detector systematics
  2. Can the double-hadronic $t\bar{t}$'s be reconstructed

- Perhaps the best bets are:

  1. H^0 $\not{C}\not{P}$: $\boldsymbol{e^+e^- \to t\bar{t}h, t\bar{t}Z}$ ($\gtrsim$ 1 TeV NLC)
  2. H^+ $\not{C}\not{P}$: $\boldsymbol{t \to b\tau\nu}$ (needs few $\times\boldsymbol{10^3 - 10^4}$ $\boldsymbol{t\bar{t}}$'s)
  3. SUSY $\not{C}\not{P}$: $\boldsymbol{p\bar{p} \to t\bar{b} + X}$, $\boldsymbol{pp \to t\bar{t} + X}$ (big ?)
     (For $\boldsymbol{t\bar{b}}$ $\boldsymbol{A} \gtrsim 1\%$ so at least systematics OK)

Summary and Outlook

(cont.)

♠ Effects of MHDM's or SUSY d_t have poor chances to be seen in a $500 - 1000$ GeV e^+e^- machine $\Longrightarrow$ Surprising if $d_t \gtrsim 10^{-17}$ e-cm is measured!!!

♠ More interesting $\not{CP}|_t$ items not discussed here:

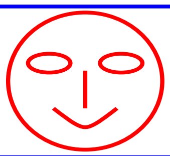
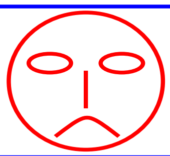
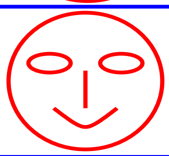
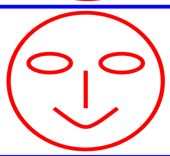
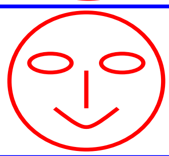
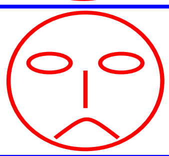
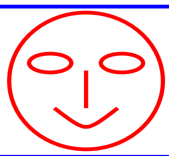
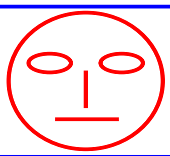
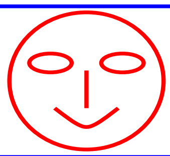
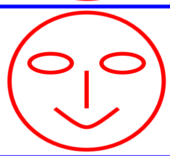
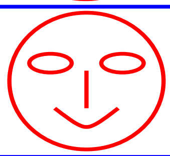
- $\not{CP}$ in $\boldsymbol{H^0 \to t\bar{t}}$

- $\not{CP}$ in $\boldsymbol{e^+e^- \to t\bar{t} + \mathrm{gluon}}$

- $\not{CP}|_t$ in Next to Next generation machines:
  - $\not{CP}$ in $\boldsymbol{\mu^+\mu^- \to H^0 \to t\bar{t}}$
  - $\not{CP}$ in $\gamma\gamma \to \boldsymbol{H^0 \to t\bar{t}}$
  - Effects of d_t^γ in $\gamma\gamma \to \boldsymbol{t\bar{t}}$

$\not\!\!{CP}|_t$ Vs. time

An optimistic time sheet

	~2005 TeV33	2005 LHC	~2010? 500 GeV NLC	$\longrightarrow$ +? $\geq$1 TeV NLC
$t \longrightarrow bW$ (MSSM $\not\!\!{CP}$)				
$t \longrightarrow b\tau\nu_\tau$ (H^+ $\not\!\!{CP}$)				
$p\bar{p} \longrightarrow t\bar{b}$ (MSSM $\not\!\!{CP}$)				
$e\bar{e}, pp(\bar{p}) \longrightarrow t\bar{t}$ (MSSM $\not\!\!{CP}$) + (H^0 $\not\!\!{CP}$)				
$e\bar{e} \longrightarrow t\bar{t}h$ (H^0 $\not\!\!{CP}$)				
$e\bar{e} \longrightarrow t\bar{t}Z$ (H^0 $\not\!\!{CP}$)				
$e\bar{e} \longrightarrow t\bar{t}\nu_e\nu_e$ (H^0 $\not\!\!{CP}$)				

THERE ARE SMILES!

BUT NO GOLDEN PLATED OBSERVABLE