CP Violation in $b' \to s$ decays

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Based on:

A.A and W.S. Hou, arXiv:0908.0901; PRD80, 076005 2009

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Outline

- Motivations
- Mechanism of CPV
- Relevant CP Invariant Phase
- Numerical Results on CPV in $b' \to sX$, $X = Z, \gamma, g, H$
- Short report on “CP violation and the fourth generation” $b' \to \{b, s\}X$, $t' \to \{c, t\}X$ and $t \to cX$, $X = Z, \gamma, g, H$ by G. Eilam B. Melic and J. Trampetic, PRD’09
- Observability of CPV in $b' \to sX$
- Conclusions

Motivations:

- In the SM, the amount of CPV in CKM, may be enough to explain the observed size of CPV in B and K meson system.
- However, it is too small to generate the observable Baryon Asymmetry in the Universe (BAU). Therefore, models with extra CP violating phases are welcome [A.D. Sakharov '67].
- A 4th generation could enhance the invariant CPV measure of Jarlskog parameter by a factor of $10^{13} - 10^{15}$ [W.-S.Hou'08] [more detail in Chia-Hsien Shen talk]

Hints

- CPV in $B_s \to J/\psi\phi$ ($\sin 2\Phi_{B_s}$) (Chien-Yi Ma talk)
- CDF and DØ reported a large and negative value for $\sin 2\Phi_{B_s}$.
  [DØ PRL'08]: $2\Phi_{B_s} = -0.57^{+0.23}_{-0.30}(\text{stat})^{+0.08}_{-0.02}(\text{syst})$.
- The SM predicts $2\Phi^{\text{SM}}_{B_s} \simeq 2\arg(-V_{tb}V^*_{ts}/V_{cb}V^*_{cs}) \simeq -0.04 \pm 0.01$.
  While 4th generation SM can predict large and negative $\sin 2\Phi_{B_s}$
  W.-S.Hou et al, PRL , PRD '05 , A.A and W.-S.Hou'EPJC'03
- The difference in $\Delta A_{K\pi} \equiv A_{B^+\to K^+\pi^0} - A_{B^0\to K^+\pi^-} \neq 0$ is now established beyond 5σ [Lin, Unno, Hou, Chang Nature'08].
  (M. Nakao talk)
- It could be due to hadronic effects, but it could be also New Physics in the EW penguin amplitude such as 4th generation [Hou, Nagashima, Soddu PRL'05].

With the start of the LHC,

- If b' and t' have a mass within perturbativity range, due to their strong production, they will be copiously produced at LHC.
- Therefore, the LHC has the capability to produce b' and t' and measure some of their decays, including FCNC decays such as $b' \to bX$, $t' \to tX$, $\mathrm{Br} \in]10^{-2}, 10^{-4}[$, $t' \to cX$, $b' \to sX$ A.A and W.S. Hou'2006.
- The LHC has also the capability to establish CPV in top quark and may be also in b' if not too heavy and CPV not too small.
- CPV studies in $b' \to s$ transitions are complementarity with low energies processes $B_s \to J/\psi\phi$, $K_L \to \pi^0\bar{\nu}\nu$, D^0 mixing ...
- CPV in $b' \to s$ transitions is of Direct CPV type, unlike Direct CPV in B decays, the strong phases in $b' \to s$ transitions are calculable.

Mechanism of CPV:

Suppose an amplitude $\mathcal{M}$ with two components $\mathcal{M}_{1,2}$:

$$\begin{aligned}\mathcal{M} &= |\mathcal{M}_1|\, e^{i\delta_1} e^{i\phi_1} + |\mathcal{M}_2|\, e^{i\delta_2} e^{i\phi_2} \ , \\ \overline{\mathcal{M}} &= |\mathcal{M}_1|\, e^{i\delta_1} e^{-i\phi_1} + |\mathcal{M}_2|\, e^{i\delta_2} e^{-i\phi_2} \ ,\end{aligned}$$

δ_i absorptive "strong" phases, ϕ_i weak phases. One can easily show:

$$|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 = 4|\mathcal{M}_1||\mathcal{M}_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)$$

The CP asymmetry is then

$$A_{\rm CP} = \frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} = \frac{2|\mathcal{M}_1||\mathcal{M}_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + 2|\mathcal{M}_1||\mathcal{M}_2| \cos\delta \cos\phi},$$

It is clear that $A_{\rm CP}$ vanishes unless both the weak *and* "strong" phase differences $\phi \equiv \phi_2 - \phi_1 \neq 0$ and $\delta \equiv \delta_2 - \delta_1 \neq 0$.

$b' \to bX$ decays and CP violation

The CKM factors $V_{ub}^* V_{ub'}$ and $V_{cb}^* V_{cb'}$ are rather small, the unitarity relation imply

$$V_{tb}^* V_{tb'} \cong -V_{t'b}^* V_{t'b'}$$

then

$$\mathcal{M}_{b' \to b} \quad = \quad V_{t'b}^* V_{t'b'} \left[f(m_{t'}) - f(t) \right]$$

dominated by single amplitude.

$b' \to sX$, $t' \to \{c, t\}X$ decays and CP violation

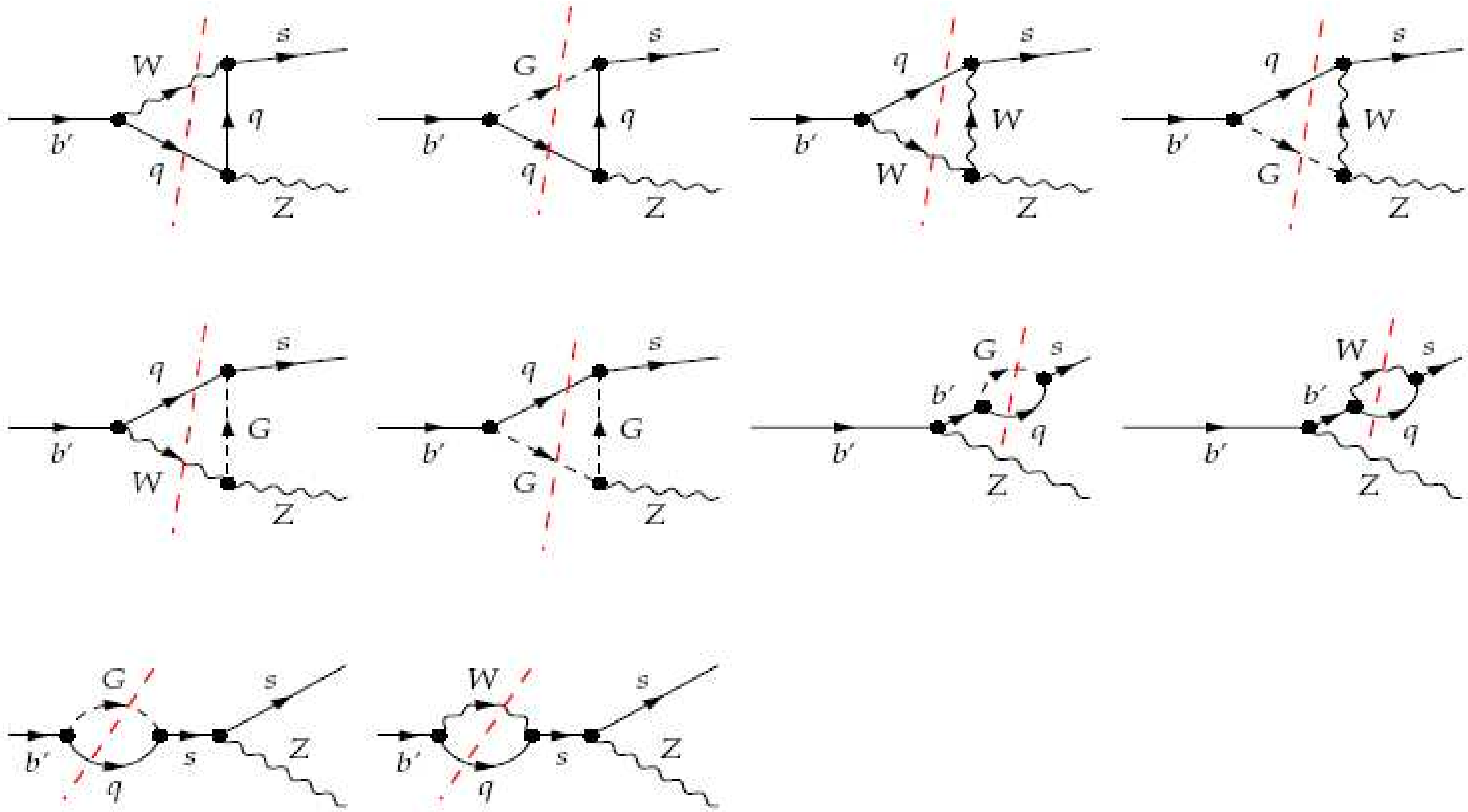
- Using the following unitarity relations:

$$\begin{aligned} V^*_{us}V_{ub'} + V^*_{cs}V_{cb'} &= -(V^*_{ts}V_{tb'} + V^*_{t's}V_{t'b'}), \\ V_{cd}V^*_{t'd} + V_{cs}V^*_{t's} + V_{cb}V^*_{t'b} &= -V_{cb'}V^*_{t'b'}. \\ V_{td}V^*_{t'd} + V_{ts}V^*_{t's} + V_{tb}V^*_{t'b} &= -V_{tb'}V^*_{t'b'}. \end{aligned}$$

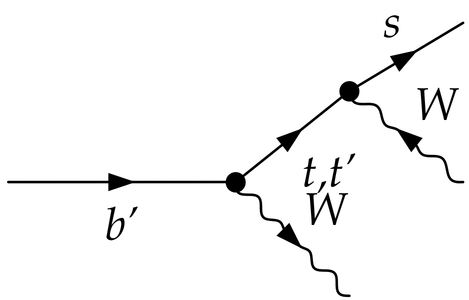
- The loop amplitudes for $b' \to s$ and $t' \to \{c, t\}$ transitions are

$$\begin{aligned} \mathcal{M}_{b'\to s} &\propto V^*_{ts}V_{tb'}[f(m_t) - f(0)] + V^*_{t's}V_{t'b'}[f(m_{t'}) - f(0)], \\ \mathcal{M}_{t'\to c} &\propto V_{cb'}V^*_{t'b'}[f(m_{b'}) - f(0)]. \\ \mathcal{M}_{t'\to t} &\propto V_{tb'}V^*_{t'b'}[f(m_{b'}) - f(0)]. \end{aligned}$$

- Both $V^*_{ts}V_{tb'}$ and $V^*_{t's}V_{t'b'}$ have CP phases. The phase difference, together with absorptive parts can lead to CPV in $b' \to s$ transitions.



Unlike B meson decays (with hadronic phases), the absorptive parts in this case are calculable perturbatively, while QCD corrections are also perturbative.


s
W
t,t′
W
b′

Calculation of Relevant CP Invariant Phase

The general amplitude of $b' \to sH$ can be written, as

$$\mathcal{M}_{sH} = V_{qs}^* V_{qb'} [H_L(m_q) \bar{u}_s \; L \; u_{b'} + H_R(m_q) \bar{u}_s \; R \; u_{b'}]$$

$H_{L,R}$ are form factors expressed in terms of Passarino-Veltman functions.

$H_L \propto m_s$ and $H_R \propto m_{b'}$.

$H_{L,R}$ are UV divergent, after GIM substraction the result is finite.
We denote the substracted quantities as

$$\Delta_H^{L,R}(Q,0) = H_{L,R}(Q) - H_{L,R}(m_c) \approx H_{L,R}(Q) - H_{L,R}(0) \; , \; Q = m_{t,t'}$$

In the case of $b' \to sV^0$:

$$
\begin{aligned}
M_{sV} \quad = \quad & V^*_{qs} V_{qb'} \{ k^\mu_{b'} \; [A_L(m_q) \bar{u}_s \; L \; u_{b'} + A_R(m_q) \bar{u}_s \; R \; u_{b'}] \\
& + k^\mu_s \; [B_L(m_q) \bar{u}_s \; L \; u_{b'} + B_R(m_q) \bar{u}_s \; R \; u_{b'}] \\
& + [C_L(m_q) \; \bar{u}_s \; L \; \gamma^\mu \; u_{b'} + C_R(m_q) \; \bar{u}_s \; R \; \gamma^\mu \; u_{b'}] \} \; ,
\end{aligned}
$$

$A_L, B_L, C_L \propto m_s$

Only $C_{L,R}$ terms are UV divergent. Similar to the Higgs case, the divergent terms cancel after GIM substraction.

In the case of $b' \to s\gamma$ and $b' \to sg$, from electromagnetic or color current conservation, we have:

$$
\begin{aligned}
(A_L + B_L)(m^2_{b'} - m^2_s)/2 + m_{b'} C_L - m_s C_R = 0. \\
(A_R + B_R)(m^2_{b'} - m^2_s)/2 - m_s C_L + m_{b'} C_R = 0.
\end{aligned}
$$

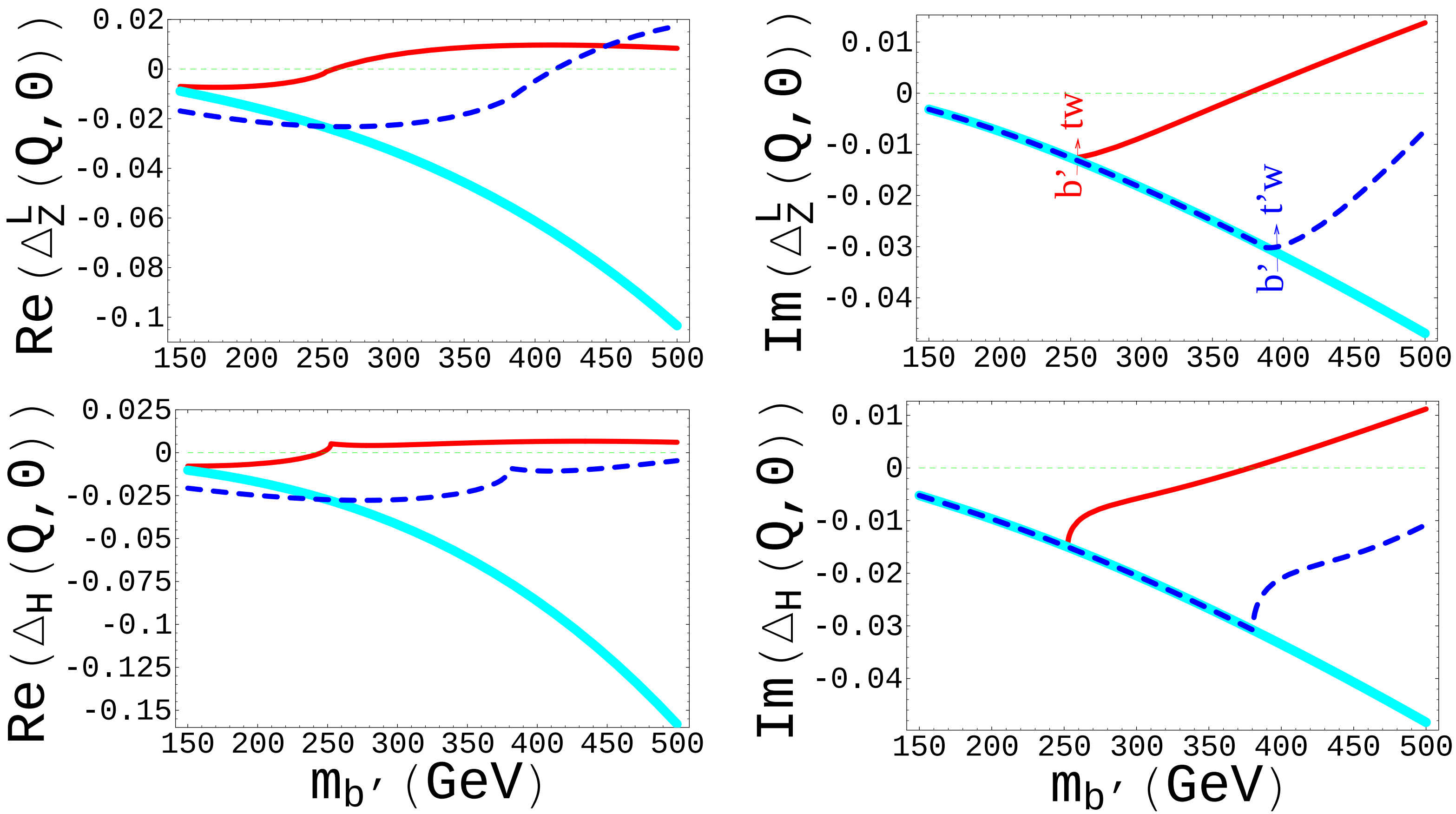


Figure 1: $\Delta_{Z,H}(Q,0)$, $m_H = 120$ GeV: Solid line is $Q = m_t$, cyan solid $Q = m_{t'} = m_{b'} + 50$ GeV, blue dash $Q = m_{t'} = 300$ GeV

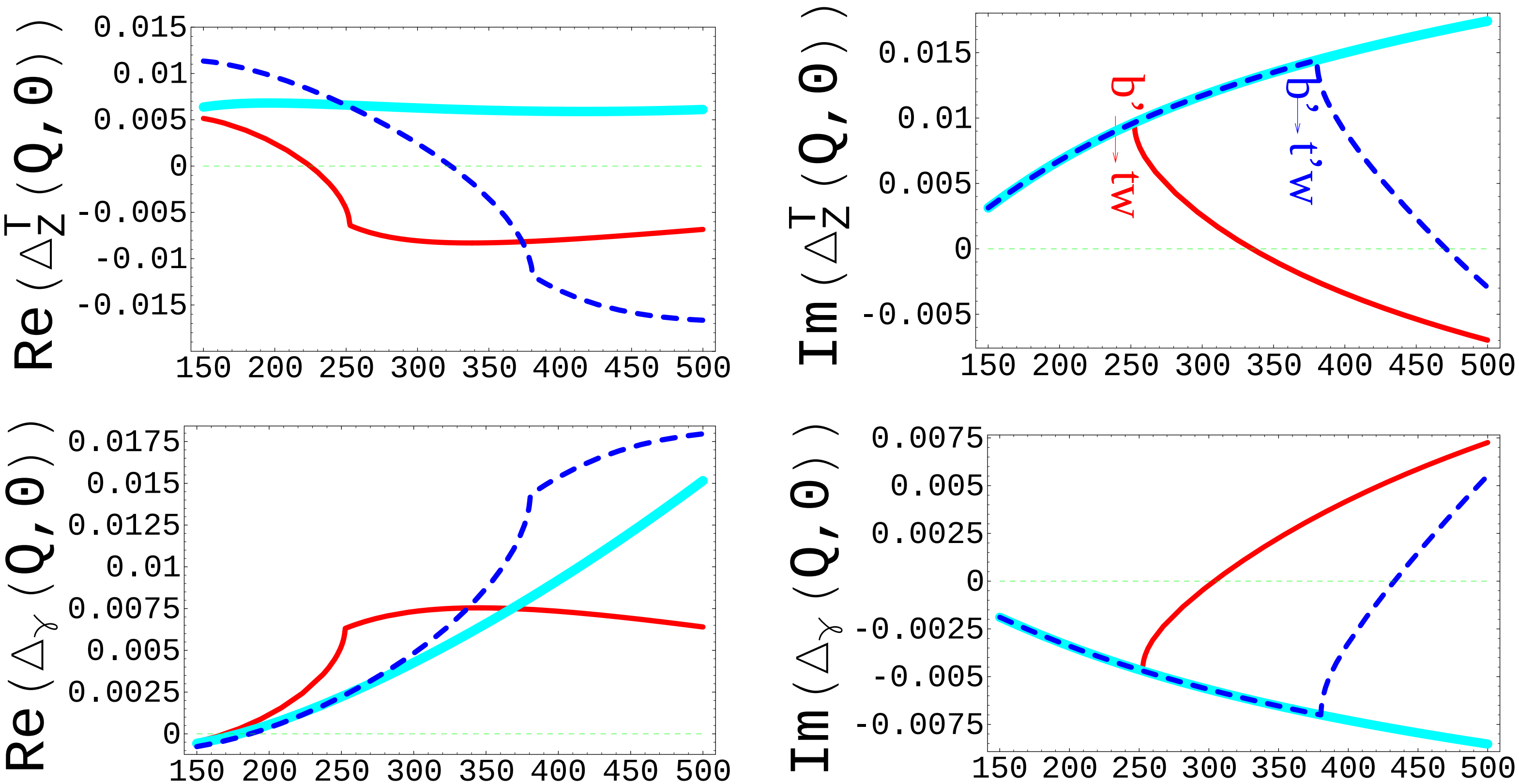


Figure 2: $\Delta_V^R(Q,0)$, $V = Z, \gamma$, $M_H = 120$ GeV Solid line is $Q = m_t$, cyan solid $Q = m_{t'} = m_{b'} + 50$ GeV, blue dash $Q = m_{t'} = 300$ GeV

CP conserving phase: $\sin\delta = \sin(\arg[\Delta(m_t)] - \arg[\Delta(m_{t'})])$

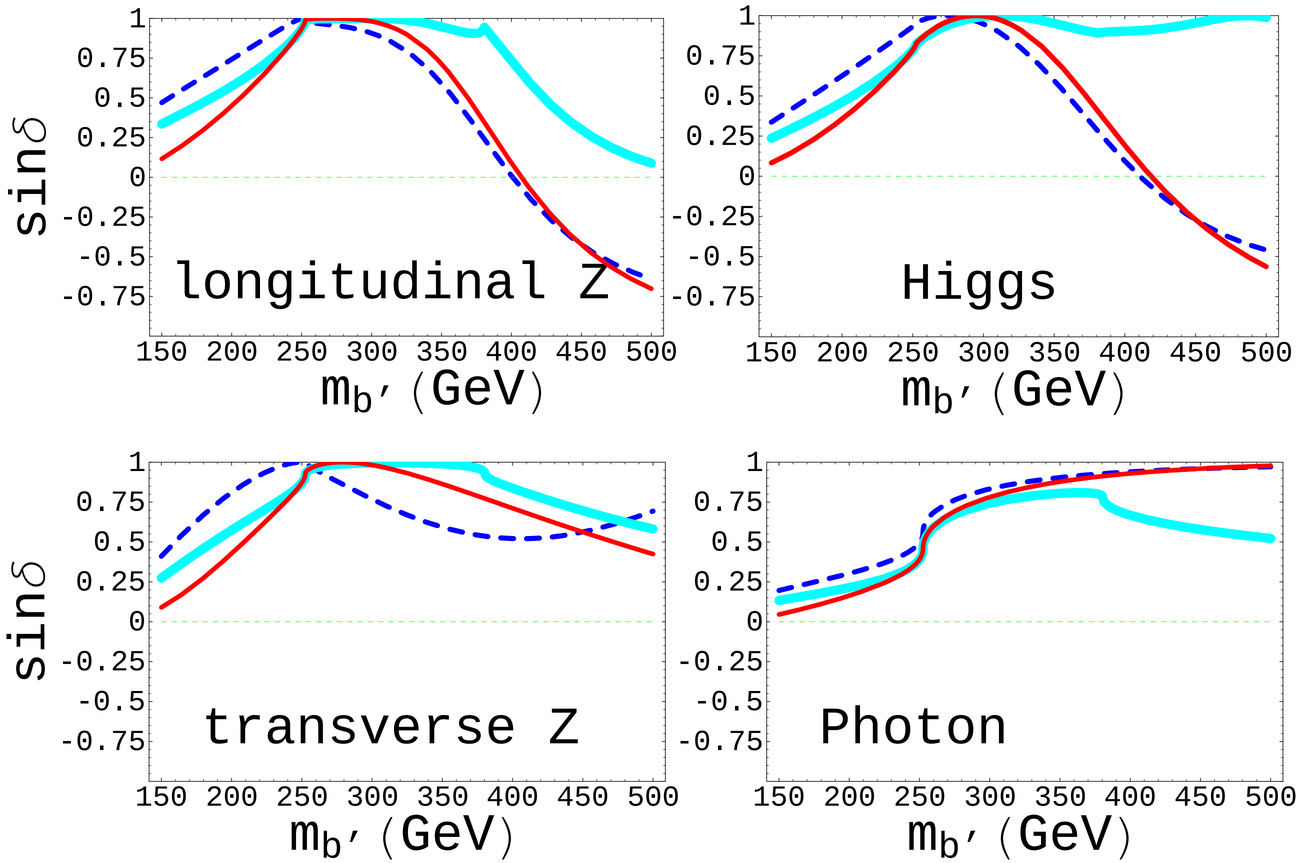


Figure 3: $M_H = 120$ GeV, Solid line is for $m_{t'} = m_{b'} + 50$ GeV cyan solid is for $m_{t'} = 300$ GeV, blue dash is for $Q = m_{t'} = 500$ GeV

Numerical results

The rate CP asymmetry A_{CP} is defined as:

$$\mathcal{A}_{\mathrm{CP}}(b' \to sX) = \frac{\Gamma(b' \to sX) - \Gamma(\bar{b}' \to \bar{s}X)}{\Gamma(b' \to sX) + \Gamma(\bar{b}' \to \bar{s}X)}.$$

$$\propto 2|\mathcal{M}_1||\mathcal{M}_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)$$

$V_{ts}^* V_{tb'}$ and $V_{t's}^* V_{t'b'}$ would have different CP violating phase:
$\sin(\phi_2 - \phi_1) \neq 0$

$\sin(\delta_2 - \delta_1)$ could be maximal.

HNS scenario

Motivated by CP violation problem in $B \to K^+\pi^-$ vs $K^+\pi^0$ modes, and taking into account other B physics observables, Hou, Nagashima,Soddu(HNS scenario)'05, with $m_{t'} \approx 300$ GeV, concluded that

$$\begin{pmatrix} 0.9745 & 0.2225 & 0.0038\, e^{-i\,60^\circ} & 0.0281\, e^{i\,61^\circ} \\ -0.2241 & 0.9667 & 0.0415 & 0.1164\, e^{i\,66^\circ} \\ 0.0073\, e^{-i\,25^\circ} & -0.0555\, e^{-i\,25^\circ} & 0.9746 & 0.2168\, e^{-i\,1^\circ} \\ -0.0044\, e^{-i\,10^\circ} & -0.1136\, e^{-i\,70^\circ} & -0.2200 & 0.9688 \end{pmatrix}$$

$$V_{t's} - 0.1136 e^{-i70^o} \quad , \quad V_{ts} \approx -0.055 e^{-i25^o} \quad , \quad V_{t'b} \approx 0.217 e^{-i1^o} \,,$$

$$V_{cb'} \approx 0.0415 \quad , \quad V_{ub'} \approx 0.0281 e^{i61^o} \quad , \quad V_{t'b'} \approx 0.97 \,,$$

HNS scenario for $\Delta\mathcal{A}_{K\pi}$

$$V_{t's} \approx -0.114 e^{-i70^o} \quad , \quad V_{ts} \approx -0.055 e^{-i25^o} \quad , \quad V_{t'b} \approx 0.22 e^{-i1^o} \ ,$$

$$V_{cb'} \approx 0.042 \quad , \quad V_{ub'} \approx 0.028 e^{i61^o} \quad , \quad V_{t'b'} \approx 0.97 \ ,$$

$$|V^*_{ts} V_{tb'}| = 0.012 \quad , \quad |V^*_{t's} V_{t'b'}| = 0.11$$

In our numerics we use:

i) $V^*_{t's} V_{t'b'}$ as free parameter in the range $|V^*_{t's} V_{t'b'}| < 0.12$,

ii) the CP phase is also free, if not its fixed to $\arg(-V^*_{t's} V_{t'b'}) = 70^\circ$,

iii) $V_{ts} = -0.1\, e^{-i\, 10^\circ}$ and $V_{tb'} = 0.1$

The result is not very sensitive to $\arg(V_{ts})$, but may affect the zero of A_{CP}

$V_{cb'}$ is fixed by:

$$V^*_{us} V_{ub'} + V^*_{cs} V_{cb'} \approx -(V^*_{ts} V_{tb'} + V^*_{t's} V_{t'b'})$$

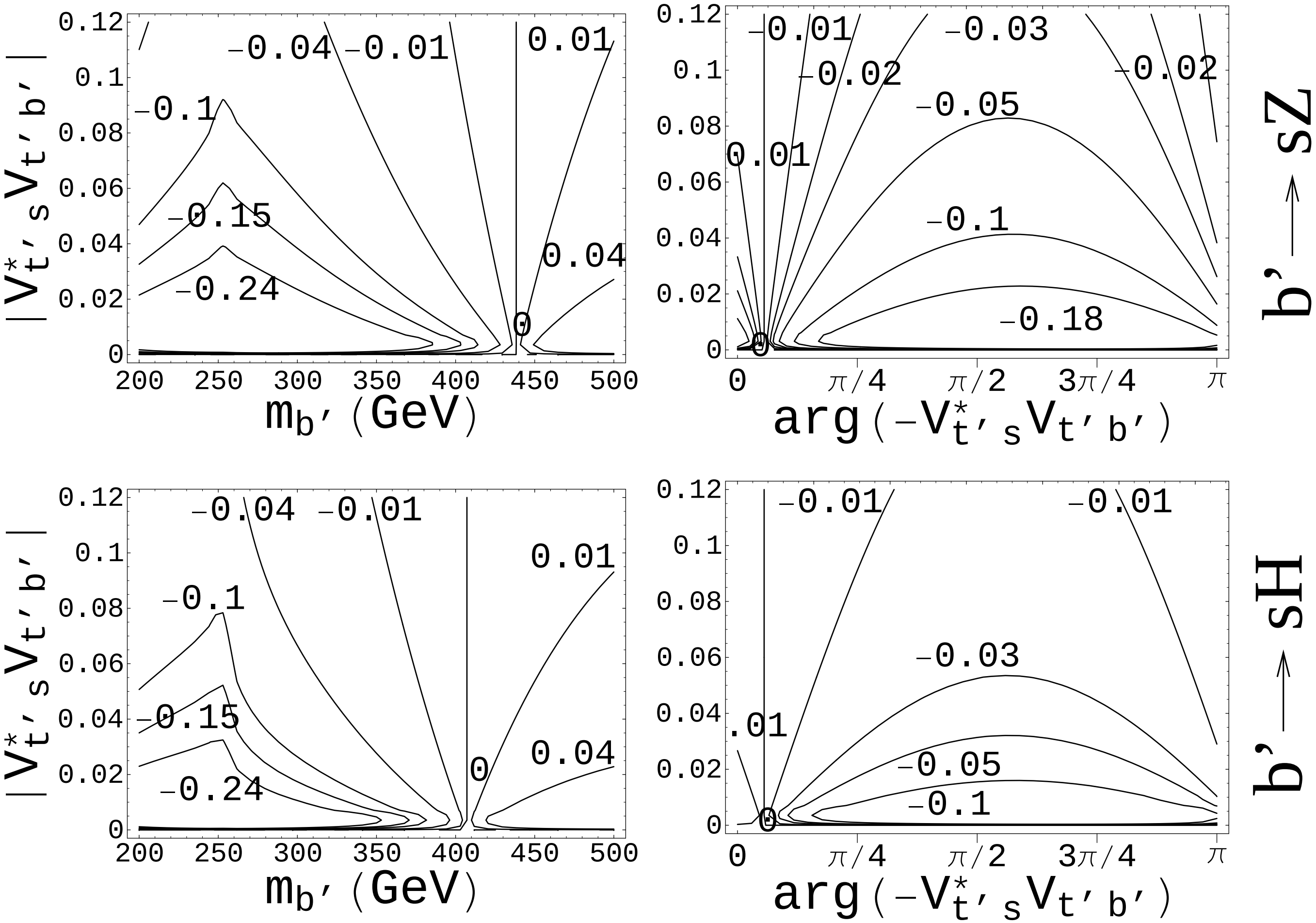


Figure 4: $m_{t'} = m_{b'} + 50$ GeV, $m_{b'} = 340$ GeV and $m_H = 120$ GeV, $V_{ts}V_{tb'} = -0.01\, e^{-i\,10^\circ}$ and $\arg(-V^*_{t's}V_{t'b'}) = 70^\circ$

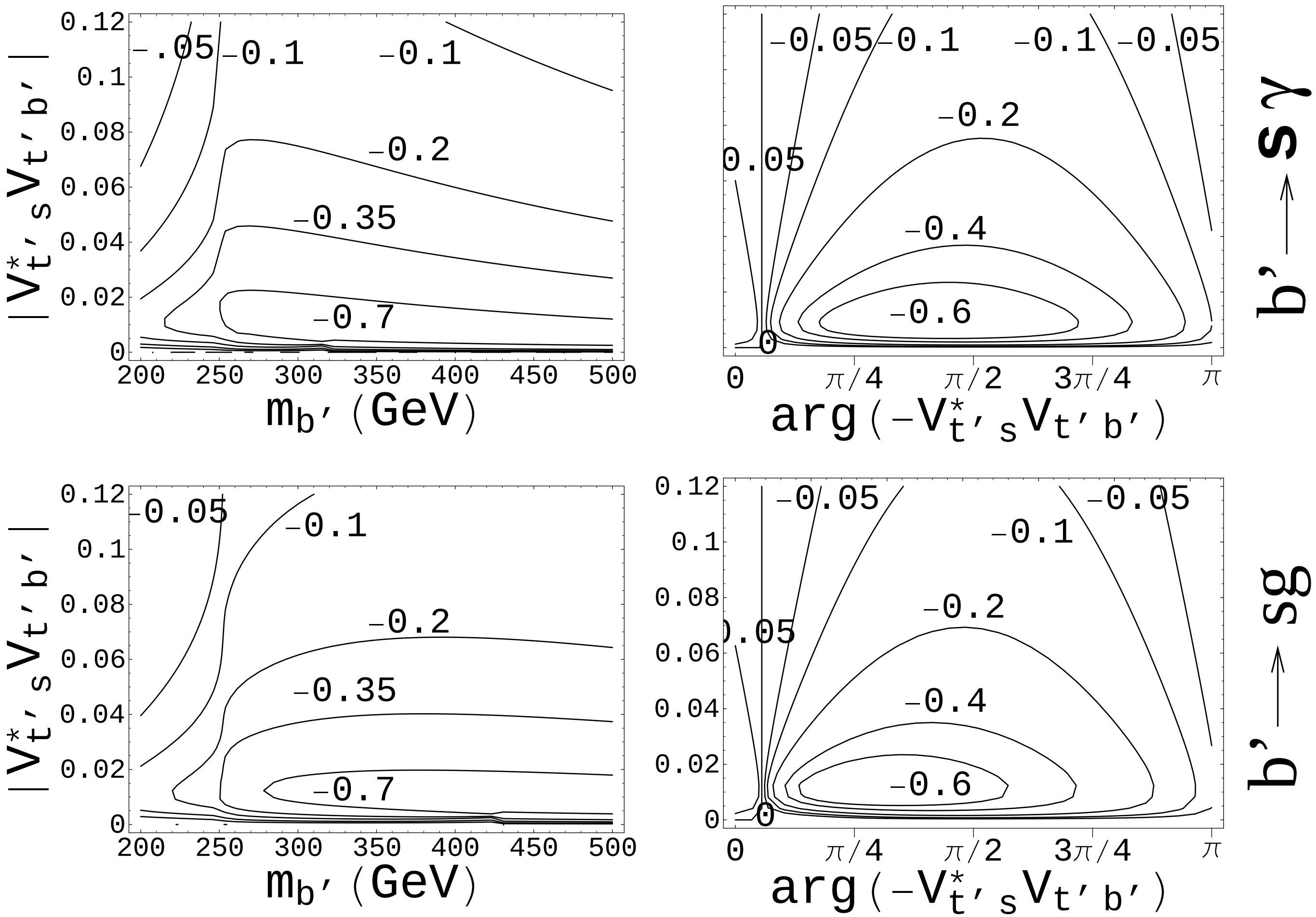


Figure 5: $m_{t'} = m_{b'} + 50$ GeV, $m_{b'} = 340$ GeV, $V^*_{ts}V_{tb'} = -0.01\, e^{i\,10^\circ}$ and $\arg(-V^*_{t's}V_{t'b'}) = 70^\circ$

Short report on “CP violation and the fourth generation” by G. Eilam, B. Melic and J. Trampetic, PRD’09

- CPV in FCNC processes $t \to c\,X$, $b' \to s\,X$, $b' \to b\,X$, $t' \to c\,X$, and $t' \to t\,X$, with $X = H, Z, \gamma, g$ is done, by constructing and employing global, unique fit for the 4th generation mass mixing matrix CKM4 at $300 \leq m_{t'} \leq 700$ GeV.

- The fit procedure includes (similar Bobrowski’09 , Lenz talk):
  1) Check of the unitarity of the CKM3 matrix in SM3
  2) $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$, $B^0_{d,s} - \bar{B}^0_{d,s}$ mixings
  3) $K^+ \to \pi^+ \nu\bar{\nu}$ and $B \to X_s \gamma$ processes
  4) $\sin 2\beta$ from $B \to J/\psi K$
  5) EW precision data constraint from Chanowitz’09 which restrict the mixing between 3th and 4th generation to be of the order Cabibbo angle.

$$V_{\rm CKM4} = R_{34} \cdot R_{24} \cdot R_{14} \cdot V_{\rm CKM3} \;;\quad R_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix}$$

$$R_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & s_{24}e^{-i\phi_2} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24}e^{i\phi_2} & 0 & c_{24} \end{pmatrix} \quad , \quad R_{14} =$$

$$\begin{pmatrix} c_{14} & 0 & 0 & s_{14}e^{-i\phi_3} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14}e^{i\phi_3} & 0 & 0 & c_{14} \end{pmatrix}$$

$s_{14,24,34}$ *and* $\phi_{2,3}$ need to be fitted.

$m_{t'}$(GeV)	$\lvert \sin\theta_{34} \rvert$	$\chi^2_{\rm min}/d.o.f$
300	0.25 ± 0.04	0.85
350	0.13 ± 0.03	0.98
400	0.10 ± 0.02	0.84
500	0.10 ± 0.04	0.80
600	0.11 ± 0.03	0.93
700	0.11 ± 0.02	1.17
800	0.11 ± 0.02	1.45
1000	0.11 ± 0.02	2.07

Table 1: Results of our fit on the mixing between the third and the fourth generation obtained including the EW constraints from Chanowitz'09.

V_{CKM4} for $m_{t'} = 300$ and 400 GeV respectively

$$\begin{pmatrix} 0.9742 & 0.2257 & 0.0035e^{-68.9^\circ i} & 0.0018e^{-12.4^\circ i} \\ -0.2255 & 0.9732 & 0.0414 & 0.0102e^{29.8^\circ i} \\ 0.0086e^{-24.1^\circ i} & -0.0416e^{0.7^\circ i} & 0.9649 & 0.2589 \\ -0.0019e^{18.9^\circ i} & 0.0052e^{69.3^\circ i} & -0.2591 & 0.9658 \end{pmatrix},$$

$$\begin{pmatrix} 0.9740 & 0.2256 & 0.0036e^{-68.9^\circ i} & 0.0164e^{-87.4^\circ i} \\ -0.2259 & 0.9728 & 0.0414 & 0.0290e^{-76.1^\circ i} \\ 0.0092e^{-27.7^\circ i} & -0.0414 & 0.9932 & 0.1079 \\ -0.0091e^{89.9^\circ i} & 0.0310e^{-94.6^\circ i} & -0.1082 & 0.9935 \end{pmatrix},$$

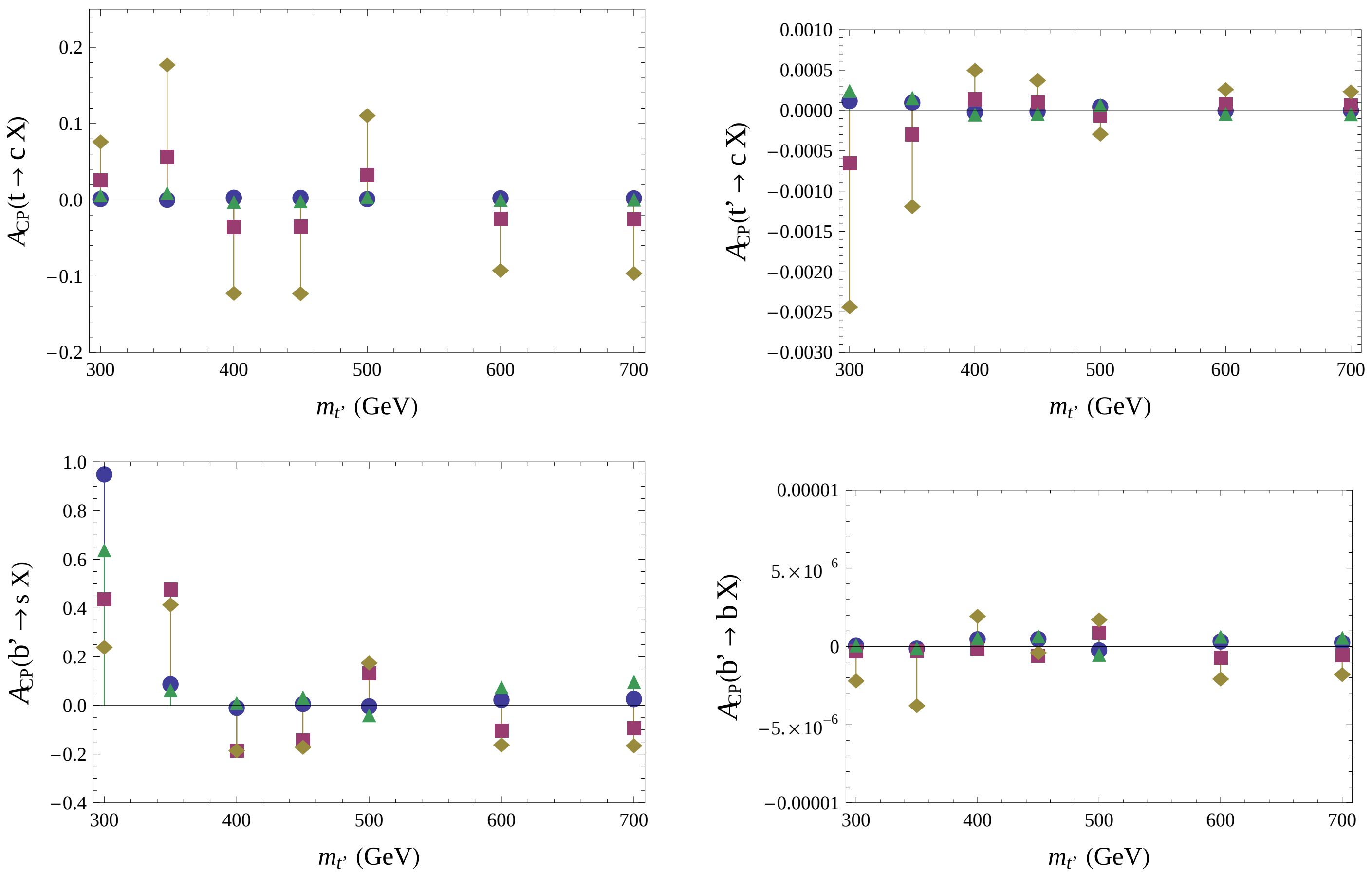


Figure 6: X denotes possible decays to $X = H(\bullet)$, $Z(\blacktriangle)$, $\gamma(\blacksquare)$, $g(\blacklozenge)$

Is it possible to observe CPV in b' at LHC , ILC?

Br for $b' \to sX$

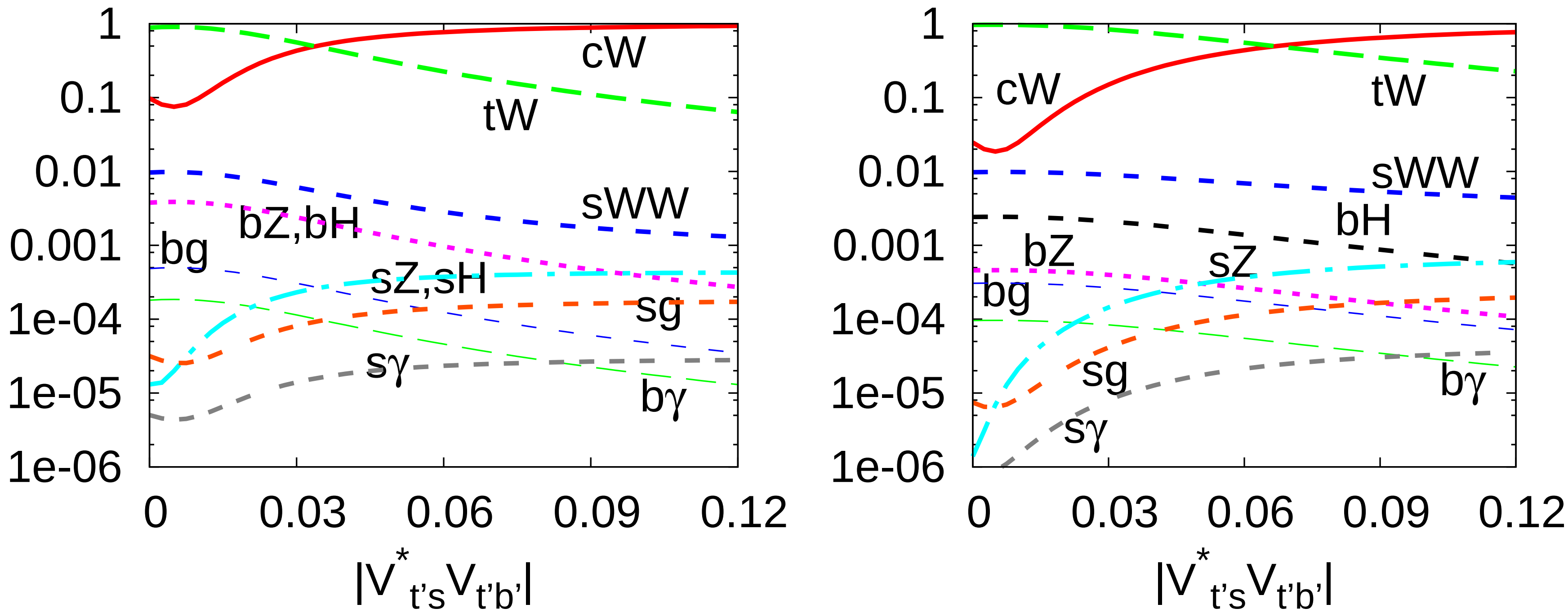
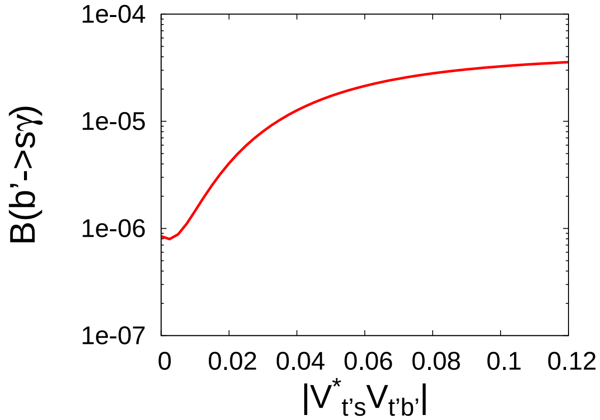
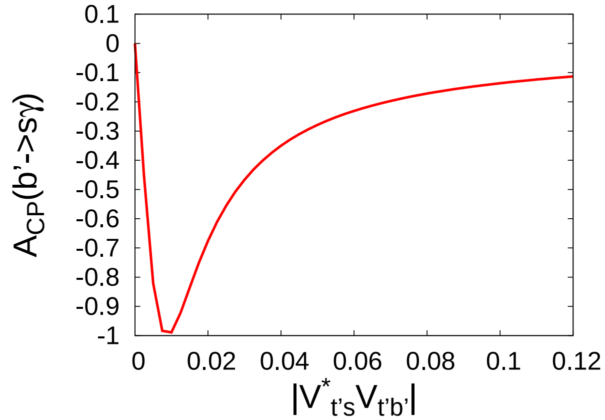
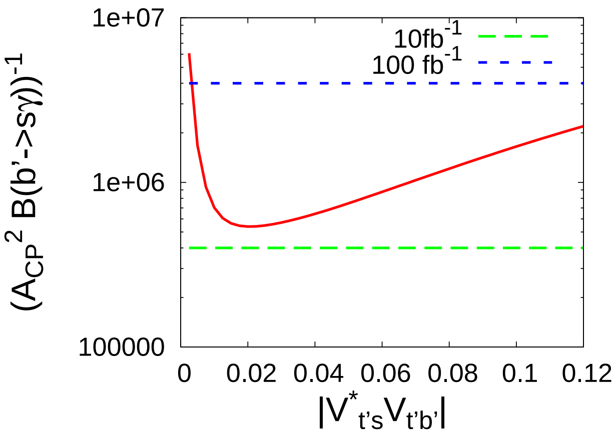


Figure 7: $m_{b'} = 260, 340$ GeV, $m_{t'} = m_{b'} + 50$ GeV,
$V_{ts}V_{tb'} = -0.01\, e^{-i\, 10^\circ}$ and $\arg(-V^*_{t's}V_{t'b'}) = 70^\circ$

Is it possible to observe CPV in b' at LHC , ILC?







$\sigma(e^+e^- \to b'\bar{b}') \times 1000 fb^{-1} = 65000$ events

Figure 8: $m_{b'} = 340$ GeV, $m_{t'} = m_{b'} + 50$ GeV, $V_{ts}V_{tb'} = -0.01\, e^{-i\,10^\circ}$ and $\arg(-V^*_{t's}V_{t'b'}) = 70^\circ$

Conclusions

- the LHC has the capability to produce b' and t' and measure some of their decays, including FCNC decays such as $b' \to bX$ and $t' \to tX$.
- the LHC has also the capability to probe CPV in top quark and also in $b' \to s$ transitions
- the best mode to probe CPV in b' decays is $b' \to s\gamma$ due to the presence of high energy single photon in the final state
- once CPA is measured, the CPV phase could be extracted with little theoretical uncertainty.

The longitudinal part of $b' \to sZ$ is:

$$
\begin{aligned}
Z_L^L &= A_L(m_{b'}^2 + m_Z^2)/2 + B_L(m_{b'}^2 - m_s^2 - m_Z^2)/2 - m_s C_R + m_{b'} C_L, \\
Z_L^R &= A_R(m_{b'}^2 + m_Z^2)/2 + B_R(m_{b'}^2 - m_s^2 - m_Z^2)/2 + m_{b'} C_R - m_s C_L,
\end{aligned}
$$

$$
\begin{aligned}
\Delta_V^L(Q,0) = Z_L^R(Q) - Z_L^R(m_c) \approx Z_L^R(Q) - Z_L^R(0), \\
\Delta_V^T(Q,0) = C_R(Q) - C_R(m_c) \approx C_{L,R}(Q) - C_{L,R}(0),
\end{aligned}
$$

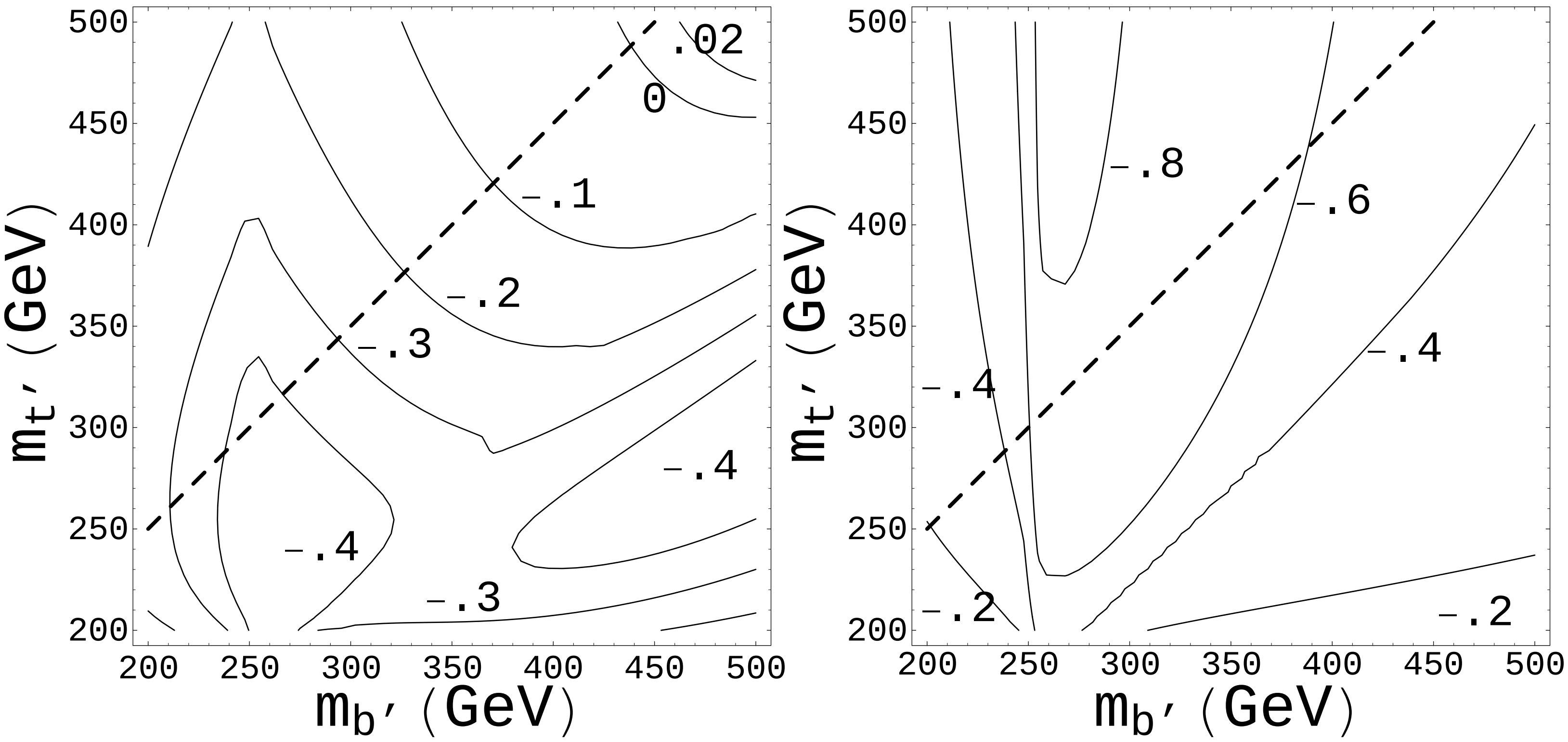


Figure 9: $V^*_{ts}V_{tb'} = -0.01e^{i10^o}$ and $\arg(-V^*_{t's}V_{t'b'}) = -0.02e^{i70^\circ}$. The dashed line is for $m_{t'} = m_{b'} + 50$ GeV