CP violation with the fourth generation quarks

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Outline

Motivation

- the number of generations is not fixed by the theory (asymptotic freedom $\to n_{\rm gener} < 9$; neutrino counting at Z pole $\to n_\nu^{\rm light} \leq 3$)
- new information from the single top-quark production at Tevatron gives $|V_{tb}| > 0.74$ and still leaves open possibility that the unitarity of SM3 CKM matrix $V_{3\times 3} = V_{\rm CKM3}$ is slightly broken
- the simplest extension of SM3 $\to$ SM4:

$$\begin{pmatrix} t' \\ b' \end{pmatrix}_L , \quad \begin{pmatrix} \tau' \\ \nu_{\tau'} \end{pmatrix}_L , t'_R, b'_R, \tau'_R, \nu_{\tau'_R}$$

- current mass limits at 95% CL:

$$\begin{aligned} m_{b'} &> 338\ \mathrm{GeV}\ \ (\mathrm{CDF}\ :\ b' \to W\, t) \\ m_{t'} &> 335\ \mathrm{GeV}\ \ (\mathrm{CDF}\ :\ t' \to W\, jet) \\ m_{\tau'} &> 100.8\ \mathrm{GeV} \\ m_{\nu_{\tau'}} &> m_Z/2;\ 90.3\,(\mathrm{Dirac}), 80.5\,(\mathrm{Majorana})\ \mathrm{GeV} \end{aligned}$$

- fourth family is consistent with electroweak (EW) precision tests if the 4th fermion family has nondegenerate masses:

$$\delta S = \frac{1}{3\pi}\left(2 - \ln\frac{m_t'}{m_b'} - \frac{m_{\tau'}}{m_{\nu_{\tau'}}}\right)$$

i.e $m_t' > m_b'$ and/or $m_{\tau'} > m_{\nu_{\tau'}}$
S-T constraint gives:

$$m_{t'} - m_{b'} \simeq \left(1 + \frac{1}{5}\ln\frac{m_H}{115\,\mathrm{GeV}}\right) \times 55\ \mathrm{GeV}\,,$$

- 4th family is not excluded by the current measurements of CKM3 (or PMNS in the lepton sector): - even the most precise measurement of the 1st row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0011 = 1 - |V_{ub'}|^2$$

leaves a room for the possible extension from CKM3 to CKM4

$$\rightarrow |V_{ub'}| < 0.04$$

- 4th generation can be discovered at LHC: if $m_t' \simeq m_b'$, the signal is doubled and $m_{t',b'} \sim 500$ GeV can be discovered at 5σ significance with $400\,\mathrm{pb}^{-1}$ data although CPV phenomena are established in B and K systems by a single, CP-odd KM phase in the CKM3 matrix, there are several experimental results which are difficult to reconcile within SM3 and can be cured in SM4:

- $B \to K\pi$ decays

  $$\Delta A_{\rm CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\overline{B^0} \to K^-\pi^+) = (14.4 \pm 2.9)\%$$

  it is expected to be $\sim 2 - 5\%$ at most

- $\sin 2\beta$ values determined from different processes seems not to agree in SM3

  $\sin 2\beta_{SM3\ full\ fit} = 0.75 \pm 0.04$ vs
  gold-platted mode determination: $\sin 2\beta_{\psi K_s} = 0.672 \pm 0.024$ vs
  penguin-dominated modes $B \to (\phi, \eta', \pi^0, \omega, K_s K_s, ...)K_s$:
  $\sin 2\beta_{penguin} = 0.58 \pm 0.06$

- time-dependent CPV in $B_s \to J/\psi\phi$

  $\sin 2\Phi_{B_s}^{SM} = -0.04$ *vs* $\sin 2\Phi_{B_s}^{Tevatron} = -0.6$ at 2.8σ
  $\to$ now just 0.8σ from SM

- if the 4th generation quarks have a mass larger than the unitarity bound of $\sim$ 550 GeV, a heavy 4th family could naturally play a role in the dynamical breaking of EW symmetry by forming condensates, and the concept of a elementary Higgs scalar field would not be longer appropriate; the light Higgs would be excluded and the reason for the associate physics needed to protect the Higgs mass would be eliminated
- the 4th family might solve baryogenesis related problems, by visible increase of the measure of CP violation and the strength of the phase transition; the Jarlskog invariant in SM4 gets enhanced up to 15 orders of magnitude compared to the Jarlskog invariant in the SM3 (Hou, 2008)
- the 4th family of fermions is consistent with SU(5) gauge coupling unification at the scale of $O(10^{16})$ in the simplest GUTs without supersymmetry

CKM matrix with the 4th generation

$$V_{\mathrm{CKM4}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

standard CKM3 matrix is taken in the Wolfenstein parametrization:

$$\begin{aligned} V_{\mathrm{CKM3}} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\ &= \begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho-i\eta) \\ \lambda\left(-1+A^2\frac{\lambda^4}{2}(1-2(\rho+i\eta))\right) & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) & A\lambda^2 \\ A\lambda^3\left(1-(\rho+i\eta)\left(1-\frac{\lambda^2}{2}\right)\right) & A\lambda^2\left(-1+\frac{\lambda^2}{2}(1-2(\rho+i\eta))\right) & 1-A^2\frac{\lambda^4}{2} \end{pmatrix} \end{aligned}$$

Similar λ hierarchy for VCKM4?

general parametrization of VCKM4:

$$V_{\mathrm{CKM4}} = R_{34} \cdot R_{24} \cdot R_{14} \cdot V_{\mathrm{CKM3}}$$

where

$$R_{34} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_u & s_u \\ 0 & 0 & -s_u & c_u \end{pmatrix}, R_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_v & 0 & s_v e^{-i\phi_2} \\ 0 & 0 & 1 & 0 \\ 0 & -s_v e^{i\phi_2} & 0 & c_v \end{pmatrix}, R_{14} = \begin{pmatrix} c_w & 0 & 0 & s_w e^{-i\phi_3} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_w e^{i\phi_3} & 0 & 0 & c_w \end{pmatrix}$$

4th generation CKM parameters:

three new angles $s_{u,v,w} \equiv \sin\theta_{u,v,w}$ and $c_{u,v,w} \equiv \cos\theta_{u,v,w}$

two new phases $\phi_{2,3}$ $(s_{\phi_2,\phi_3} \equiv \sin\phi_{2,3})$

SM3 parameters λ, A, ρ and η are taken in the range of the global fit of CKM3

all matrix elements will depend on the new parameters; e.g.

$$V_{ud} = c_w \left(1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8}\right) - e^{i\phi_3} s_w (\lambda s_v e^{-i\phi_2} + A\lambda^3(\rho - i\eta) s_u c_v)$$

$$\Rightarrow \textbf{FIT}\ (m_{b'},\ m_{t'},\ s_u,\ s_v,\ s_w,\ s_{\phi_2},\ s_{\phi_3})$$

Fitting procedure

$$\chi^2(\alpha) = \sum_i \frac{(th(\alpha)_i - exp_i)^2}{(\Delta th_i)^2 + (\Delta exp_i^2)}$$

$\alpha = (s_u, s_v, s_w, s_{\phi_2}, s_{\phi_3})$

- we scan over $300 < m_{t'} < 1000$ GeV and take $m_{b'} = m_{t'} - 55\,\mathrm{GeV}$ (with $m_{l_4} - m_{\nu_4} \simeq 30 - 60$ GeV and $m_H = 115$ GeV)
  $\Delta th_i = 0$ is taken for simplicity
  VCKM4 (instead of VCKM3) is taken to be unitary matrix now
- fit is performed by the CERN Fortran minimization routine MINUIT

FIT:

- use of independent measurements of CKM3 elements and check of limits on the unitarity constraints of the CKM3 matrix in SM3:

$$
\begin{aligned}
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 &= 0.9999 \pm 0.0011 \quad \text{(1st row)} \\
|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 &= 1.136 \pm 0.125 \quad \text{(2nd row)} \\
|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 &= 1.002 \pm 0.005 \quad \text{(1st column)} \\
|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 &= 1.134 \pm 0.125 \quad \text{(2nd column)}
\end{aligned}
$$

- use of experimental constraints and data on different processes which involve t' and b' quarks in the loop:
- $K^0 - \bar{K}^0$ mixing - ΔM_K, ϵ_K and ϵ'/ϵ
- $D^0 - \bar{D}^0$ mixing - x_D
- $B^0_{d,s} - \bar{B}^0_{d,s}$ mixings - x_{B_d} and x_{B_s}
- BR of $K^+ \to \pi^+ \nu\bar{\nu}$ process
- BR of $B \to X_s\gamma$ process
- $\sin 2\beta$ from $B \to J/\psi K_s$

the fit above allows for a large mixing between the 3rd and the 4th generation
however this is excluded by the EW precision data; therefore,

- IN ADDITION: EW precision data constraints are taken into account (Chanowitz, 2009)

$$\max\left(\sin\theta_u\right) = \begin{cases} 0.35 \pm 0.001, & \text{for} \quad m_{t'} = 300 \quad \text{GeV} \\ 0.22 \pm 0.005, & \text{for} \quad m_{t'} = 400 \quad \text{GeV} \\ 0.17 \pm 0.007, & \text{for} \quad m_{t'} = 500 \quad \text{GeV} \\ 0.14 \pm 0.010, & \text{for} \quad m_{t'} = 600 \quad \text{GeV} \\ 0.11 \pm 0.10, & \text{for} \quad m_{t'} = 1000 \quad \text{GeV} \end{cases}$$

- we check the "pull of the data" [= (data central value - predicted value from the fit)/(data error)]

Results of the fitting procedure (the best fit for $\chi^2_{\min}/d.o.f \simeq 1$):

$m_{t'}\,(\mathrm{GeV})$	$\lvert\sin\theta_u\rvert$	$\chi^2_{\min}/d.o.f$
300	0.25 ± 0.04	0.85
350	0.13 ± 0.03	0.98
400	0.10 ± 0.02	0.84
450	0.10 ± 0.04	0.79
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
900	0.11 ± 0.02	1.76
1000	0.11 ± 0.02	2.07

$$d.o.f = 18 - 5 = 13$$

$m_{t'}\,(\mathrm{GeV})$	300	400	500	600	700
$\sin\theta_u$	0.25 ± 0.004	0.10 ± 0.02	0.10 ± 0.004	0.11 ± 0.03	0.11 ± 0.02
$\sin\theta_v$	0.010 ± 0.003	0.029 ± 0.001	0.034 ± 0.001	0.033 ± 0.008	0.031 ± 0.005
$\sin\theta_w$	0.002 ± 0.001	0.016 ± 0.002	0.015 ± 0.001	0.014 ± 0.001	0.012 ± 0.001
$\sin\phi_2$	-0.4 ± 0.4	0.97 ± 0.01	0.947 ± 0.002	0.91 ± 0.02	0.89 ± 0.04
$\sin\phi_3$	0.2 ± 0.3	0.99 ± 0.02	0.987 ± 0.001	0.96 ± 0.03	0.95 ± 0.03

95% C.L. results for the complete 4×4 CKM fitted matrices at $m_{t'} = 300, (400-)700$ GeV:

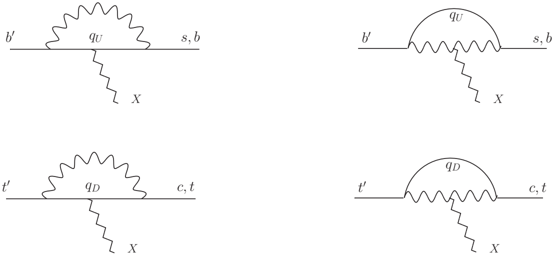
$$V_{\mathrm{CKM4}}(300) = \begin{pmatrix} 0.9742 & 0.2257 & 0.0035e^{-68.9^\circ i} & 0.0018e^{-12.4^\circ i} \\ -0.2255 & 0.9732 & 0.0414 & 0.0102e^{29.8^\circ i} \\ 0.0086e^{-24.1^\circ i} & -0.0416e^{0.7^\circ i} & \mathbf{0.9649} & 0.2589 \\ -0.0019e^{18.9^\circ i} & 0.0052e^{69.3^\circ i} & -0.2591 & 0.9658 \end{pmatrix}$$

$$V_{\mathrm{CKM4}}(700) \simeq \begin{pmatrix} 0.9741 & 0.2256 & 0.0035e^{-68.9^\circ i} & 0.0130e^{-72.9^\circ i} \\ -0.2258 & 0.9727 & 0.0414 & 0.0309e^{-62.9^\circ i} \\ 0.0088e^{-26.2^\circ i} & -0.0423e^{5.8^\circ i} & \mathbf{0.9920} & 0.1179 \\ -0.0056e^{74.7^\circ i} & 0.0309e^{-108.1^\circ i} & -0.1185e^{0.6^\circ i} & 0.9924 \end{pmatrix}$$

- $|V_{tb}| > 0.96$, which is much stronger constraint than the limit $|V_{tb}| > 0.74$ following from the single top quark production cross section measurement
- the less constrained SM3 elements V_{td} and V_{ts} come out with the values which do not contradict the global CKM3 fit

Rare FCNC processes involving the 4th generation

- SM processes involving the fourth generation quarks running in the loops: $t \to c(H, Z, \gamma, g)$
- FCNC decay processes of the fourth generation quarks: $t' \to (c, t)(H, Z, \gamma, g)$ $b' \to (s, b)(H, Z, \gamma, g)$



- *Generic diagrams for FCNC decays of the 4th generation quarks. X denotes possible decays to* $X = H, Z, \gamma, g$ *and quarks running in the loops are* $q_U = \{u, c, t, t'\}$ *and* $q_D = \{d, s, b, b'\}$.

- decay amplitudes will be normalized to the widths of the decaying quarks:

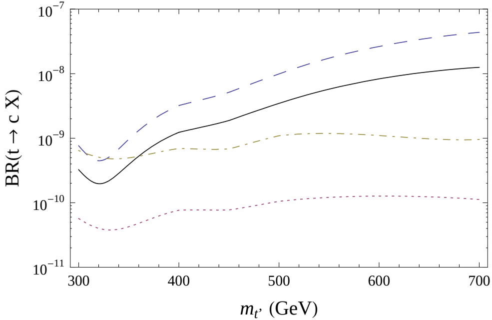
$$\mathrm{BR}(t \to cX) = \frac{\Gamma(t \to cX)}{\Gamma(t \to bW)} ,$$

$$\begin{aligned} \mathrm{BR}(t' \to (c,t)X) &= \frac{\Gamma(t' \to (c,t)X)}{\Gamma(t' \to bW) + \Gamma(t' \to sW)} , \\ \mathrm{BR}(b' \to (s,b)X) &= \frac{\Gamma(b' \to (s,b)X)}{\Gamma(b' \to tW^{(*)}) + \Gamma(b' \to cW)} , \end{aligned}$$

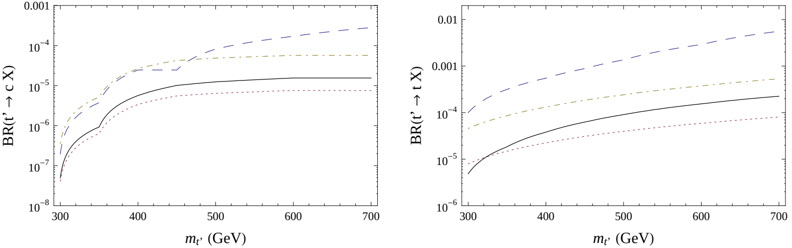
$b' \to tW^*$ is effective for $m_{b'} \leq 255$ GeV

- mases running in the loops are taken to be current quark masses, while the external masses are considered as pole masses (this makes a significant numerical difference only for $t \to cX$ decays with b-quark running in the loops)
- finite W-boson width is considered ($< 10\%$ correction)

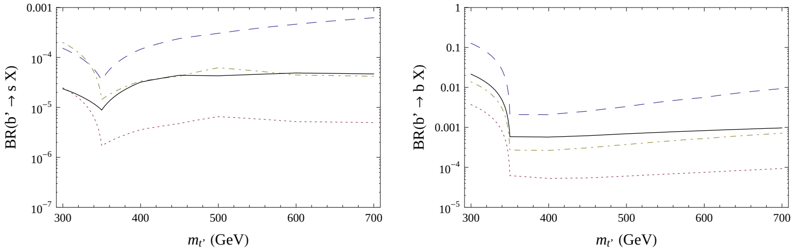
$$\mathrm{BR}_{SM}(t \to c\gamma) = 4.4 \cdot 10^{-14} \qquad \mathrm{BR}_{SM}(t \to cg) = 3.8 \cdot 10^{-12}$$
$$\mathrm{BR}_{SM}(t \to cZ) = 1.3 \cdot 10^{-14} \qquad \mathrm{BR}_{SM}(t \to cH) = 7.8 \cdot 10^{-15}$$



- **Branching ratios for rare top decays** *in the model with 4th generation as a function of* $m_{t'}$, *for* b' *of the mass* $m_{b'} = m_{t'} - 55$ *GeV running in the loops. X denotes possible decays to* $X = H$*(dashed line),* Z*(solid line),* γ*(dotted line),* g*(dashed-dotted line).*



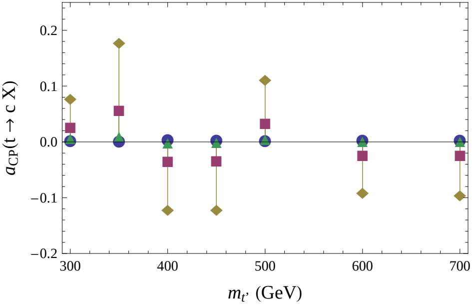
- **Branching ratios of $\mathbf{t}' \to (\mathbf{c}, \mathbf{t})\mathbf{X}$** *as a function of $m_{t'} = m_{b'} + 55$ GeV. X denotes possible decays to $X = H$(dashed line), Z(solid line), γ(dotted line), g(dashed-dotted line).*



- **Branching ratios of $b' \to (s,b)X$** *as a function of* $m_{t'} = m_{b'} + 55$ *GeV. X denotes possible decays to* $X = H$ *(dashed line),* Z *(solid line),* γ *(dotted line),* g *(dashed-dotted line).*

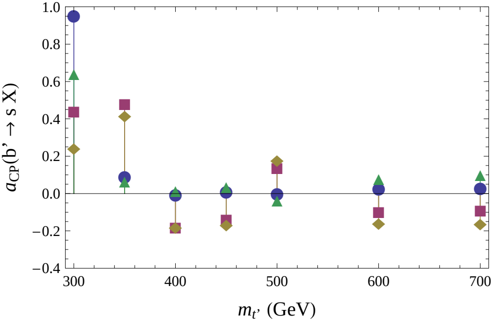
CP violation and baryogenesis

$$a_{CP} = \frac{\Gamma(Q \to qX) - \Gamma(\bar{Q} \to \bar{q}\bar{X})}{\Gamma(Q \to qX) + \Gamma(\bar{Q} \to \bar{q}\bar{X})}$$



- **Fourth generation effect on the a_{CP} of the rare top decays** *as a function of $m_{t'}$, for b' of the mass $m_{b'} = m_{t'} - 55$ GeV running in the loops. X denotes possible decays to $X = H(\bullet)$, $Z(\blacktriangle)$, $\gamma(\blacksquare)$, $g(\blacklozenge)$.*

a significant CPV is found only for $b' \to sX$ modes:



- **CP asymmetries in $\mathbf{b'} \to \mathbf{sX}$ decays** *as a function of* $m_{t'} = m_{b'} + 55$ *GeV. X denotes possible decays to* $X = H(\bullet)$, $Z(\blacktriangle)$, $\gamma(\blacksquare)$, $g(\blacklozenge)$.

- general features of CPV in SM4 & the baryogenesis:

  - in the chiral limit $m_{u,d,s} \to 0$, CP is conserved in SM3 (F. del Aguila, J.A. Aguilar-Saavedra, Branco 1997)

  CP violation then originate only with the 4th family from two new CP violating phases and three independent imaginary products:

$$
\begin{aligned}
B_1 &\equiv \mathrm{Im}\, V_{cb} V^*_{t'b} V_{t'b'} V^*_{cb'} \\
B_2 &\equiv \mathrm{Im}\, V_{tb} V^*_{t'b} V_{t'b'} V^*_{tb'} \\
B_3 &\equiv \mathrm{Im}\, V_{cb} V^*_{tb} V_{tb'} V^*_{cb'}
\end{aligned}
$$

  in our model:

$$
|B_{1,2,3}| \simeq \begin{cases} 5 \cdot 10^{-5} & \text{for } \; m_{t'} = 300 \;\; \mathrm{GeV} \\ 10^{-4} & \text{for } \; m_{t'} = [400 - 700] \;\; \mathrm{GeV} \end{cases}
$$

The area of the unitary quadrangle $A_{bb'}$, with the sides $V_{ub}V^*_{ub'}$, $V_{cb}V^*_{cb'}$, $V_{tb}V^*_{tb'}$, $V_{t'b}V^*_{t'b'}$, describing CPV in the chiral limit, is

$$A_{bb'} = \frac{1}{4}\{|B_1 + B_2| + |B_1 + B_3| + |B_2| + |B_3|\}$$

and with our fitted parameters amounts to

$$2A_{bb'} \simeq \begin{cases} 10^{-5} & \text{for } \; m_{t'} = 300 \;\; \mathrm{GeV}, \\ 4 \cdot 10^{-4} & \text{for } \; m_{t'} = [400 - 700] \;\; \mathrm{GeV} \end{cases}$$

the amount of CPV in SM3 $|\mathrm{Im}\, V_{ij}V^*_{kj}V_{kj}V^*_{il}| \leq 5 \times 10^{-5}$

- there is no large cumulative effect in the strength of CPV in the model with fourth generation !

BARYOGENESIS:

- the Jarlskog invariant (measures the CP violation in the model) for SM3:

$$J_{SM3} = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) 2A_{SM3}$$

($A_{SM3} \sim 10^{-5}$ is the area of any of six unitary triangles in SM3)

- for SM4, in the $d - s$ degeneracy limit $\Rightarrow$

$$J_{SM4}^{bs} = (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2) 2A_{SM4}^{bs}$$

$$\simeq \frac{m_t'^2}{m_c^2}\left(\frac{m_t'^2}{m_t^2} - 1\right)\frac{m_b'^4}{m_b^2 m_s^2}\frac{A_{SM4}^{bs}}{A_{SM3}} J_{SM3}$$

due to the large $m_{b'}, m_{t'}$ masses $\rightarrow$ $J_{SM4} \sim 10^{15} J_{SM3}$!!!

however: just adding the fermions reduce the EW phase transition if there are not some additional theories involved like supersymmetry or the theory with at least two Higgs doublets (Fok, Kribs (2008))

Conclusions

- we construct and employ a global unique fit of the unitary CKM4 mass matrix, by fitting the angles and the phases of CKM4
- the best fits are found for $300 \leq m_{t'} \leq 700$ GeV
- we have inspected FCNC decay processes of the 4th generation quarks, $b' \to s\,X,\ b' \to b\,X,\ t' \to c\,X,\ t' \to t\,X$, with $X = H,\ Z,\ \gamma,\ g$
- rare top decays $t \to cX$ get highly enhanced due to the presence of the 4th family quarks
- CPV effects for $t \to c\,X$ modes: $|a_{CP}(t \to cg)| \simeq 8 - 18\ \%$
- the largest CP partial rate asymmetries are found for $b' \to sX$ modes: $a_{CP}(b' \to s\ (H, Z; \gamma, g)) \leq 20\%$ at $m_{t'} > 400$ GeV
- from the experimental point of view the most promising decay mode is $b' \to s\,\gamma$: $a_{CP}(@3\sigma) \to N_{b'} \sim 10^7 - 10^8$
- there are fair chances for the 4th generation quarks b' and t' to be observed at LHC and that some branching ratios and CP asymmetries could be measured after a few years of operating the LHC at $\mathcal{O}(\mathrm{few}\,100)\,\mathrm{fb}^{-1}$