Phenomenology of Vector-like Quark Models

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Contents of this talk

- Classification of vector-like t' models
  definitions, constraints, branching ratios
- Phenomenology of non-SM doublet model
  definition, constraints, flavor signals

This is an introduction to the next talk by Luca Panizzi on LHC signals of this model.

Reference:
(1) G. Cacciapaglia, A.Deandrea, D.Harada, and Y. Okada, JHEP 11 (2010) 159
(2) G. Cacciapaglia, A.Deandrea, L.Panizzi, N.Gaur ,D.Harada, and Y. Okada, arXive:1108.6329

Vector-like quark models

- Many new physics models predicts vector-like quarks, especially extra top-like quarks.
  Little Higgs models. Extra-dim models.
- Phenomenologically less constrained than the chiral fourth generation model because of "decoupling" feature.
- Copious production at LHC.

Our framework

- Include one vector-like representation of SU(2)xU(1).
- Study effects of new (large) Yukawa coupling constants.
- First consider only mixing between 3rd and 4th generation quarks. Later include mixings to light generation quarks.

Classification of vector-like models

SM Yukawa coupling

$$\mathcal{L}_{\text{Yuk}} = -y_u \, \bar{q}_L H^c u_R - y_d \, \bar{q}_L H d_R + h.c.$$

Inclusion of new Yukawa coupling

○ : t' model

q_L x H x ψ : ψ SU(2) singlet or triplet

$\psi = (1, \frac{2}{3}) = U$ $\psi = (3, \frac{2}{3}) = \{X, U, D\}^T$

$\psi = (1, -\frac{1}{3}) = D$ $\psi = (3, -\frac{1}{3}) = \{U, D, X\}^T$

u_R (d_R)x H x ψ : ψ SU(2) doublet

$\psi = (2, \frac{1}{6}) = \{U, D\}^T$ SM doublet : (Two new Yukawa couplings)

$\psi = (2, \frac{7}{6}) = \{X, U\}^T$ $\psi = (2, -\frac{5}{6}) = \{D, X\}^T$ Non-SM doublet

Vector-like: a pair of ψ_L and ψ_R is introduced.

Singlet case

$$\mathcal{L}_{\rm Yuk} = -y_u\,\bar{q}_L H^c u_R - \lambda\,\bar{q}_L H^c U_R - M\,\bar{U}_L U_R + h.c.$$

$$\mathcal{L}_{\rm mass} = -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - x\,\bar{u}_L U_R - M\,\bar{U}_L U_R + h.c.\,,$$

$$(x = \frac{\lambda v}{\sqrt{2}})$$

t-t' mixing

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix} = \begin{pmatrix} m_t & 0 \\ 0 & m_{t'} \end{pmatrix}$$

For large M; $\frac{y_u v}{\sqrt{2}} \sim m_t\,,$ $\quad m_{t'} \sim M\,;$

$$\sin\theta_u^L \sim \frac{x}{M}\,, \qquad \sin\theta_u^R \sim \frac{m_t x}{M^2}\,.$$

The u_R-U_R mixing case
=> The right-handed mixing angle is suppressed.
The left-handed angle can be large.
=> Sizable correction to the Wtb vertex.

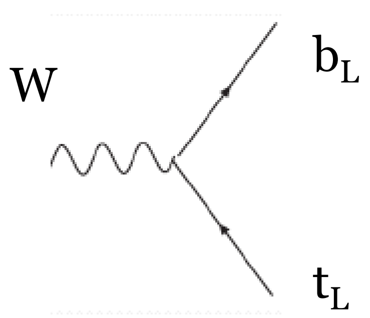
Triplet case

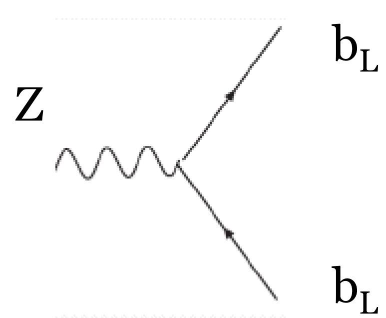
$$\mathcal{L}_{\text{Yuk}} = -y_u\,\bar{q}_L H^c u_R - \lambda\,\bar{q}_L \tau^a H^c \psi^a_R - M\,\bar{\psi}_L \psi_R + h.c.$$

$$= -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - \frac{\lambda v}{\sqrt{2}}\,\bar{u}_L U_R - \lambda v\,\bar{d}_L D_R - M\,(\bar{U}_L U_R + \bar{D}_L D_R + \bar{X}_L X_R) + h.c.$$

(Y=2/3 case: similar for Y=-1/3 case)

Large left-handed mixing for t-t'
Large left-handed mixing for b-b'
=>corrections to the Wtb and the Zbb vertexes





doublet case

SM doublet

$$\mathcal{L}_{\text{Yuk}} = -y_u\,\bar{q}_L H^c u_R - \lambda_u\,\bar{\psi}_L H^c u_R - \lambda_d\,\bar{\psi}_L H d_R - M\,\bar{\psi}_L\psi_R + h.c.$$

$$= -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - \frac{\lambda_u v}{\sqrt{2}}\,\bar{U}_L u_R - \frac{\lambda_d v}{\sqrt{2}}\,\bar{D}_L d_R - M\,(\bar{U}_L U_R + \bar{D}_L D_R) + h.c.$$

Two new Yukawa coupling constants

Small left-handed mixing angle for t-t' and b-b'
Large right-handed mixing angle for t-t' and b-b'
=> Zbb constraint to $x_b = \lambda_d v/\sqrt{2}$

Non-SM doublet

$$\mathcal{L}_{\text{Yuk}} = -y_u\,\bar{q}_L H^c u_R - \lambda\,\bar{\psi}_L H u_R - M\,\bar{\psi}_L\psi_R + h.c.$$

$$= -\frac{y_u v}{\sqrt{2}}\,\bar{u}_L u_R - \frac{\lambda v}{\sqrt{2}}\,\bar{U}_L u_R - M\,(\bar{U}_L U_R + \bar{X}_L X_R) + h.c.$$

Small left-handed mixing angle for t-t'
Large right-handed mixing angle for t-t'
=> No strong constraints from Wbt and Zbb

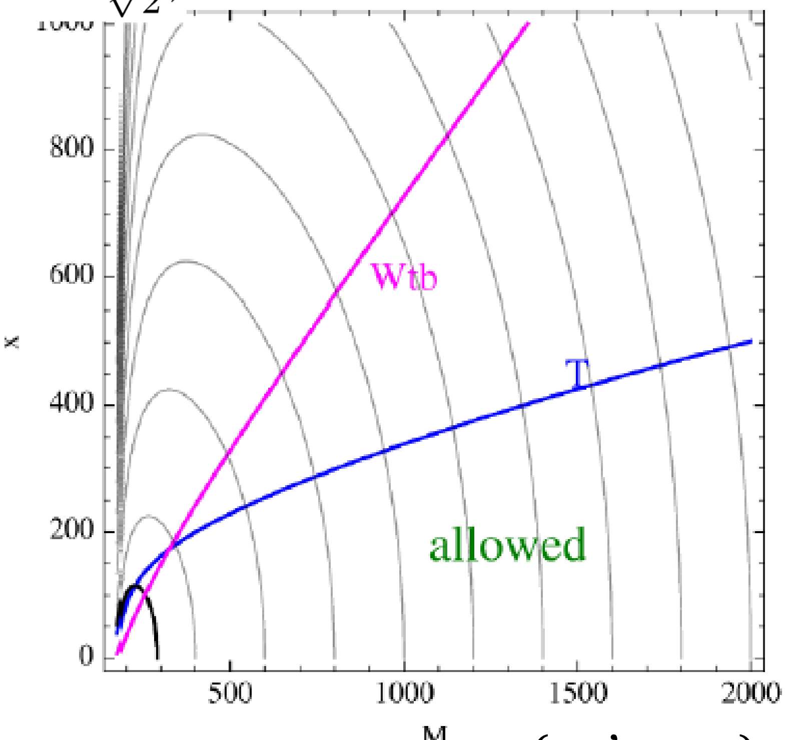
Allowed parameter space

We have derive allowed parameter regions based on Wtb, Zbb and the T parameter constrains

$$\delta g_{Wtb} \pm 20\%; \delta g^{L}_{Zbb}{}^{1\%}_{-0.2\%}; \delta g^{R}_{Zbb}{}^{20\%}_{-5\%}; -0.2 < \delta T < 0.4$$

T parameter : A constraint from precise electroweak measurements

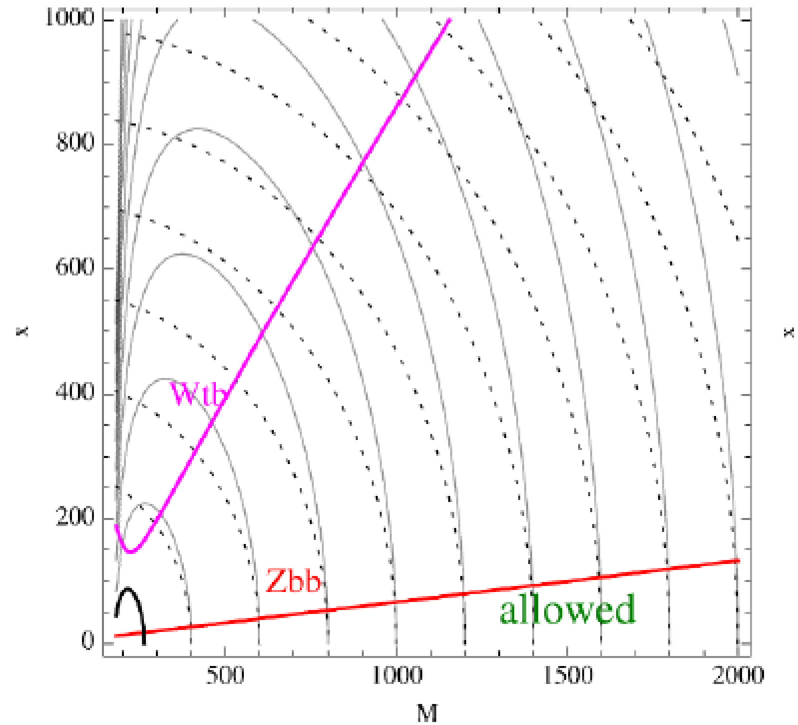
$(x = \frac{\lambda v}{\sqrt{2}})$ Singlet case



(~ t' mass)

Wtb and T parameter constraints are important .

Triplet (Y=2/3)case

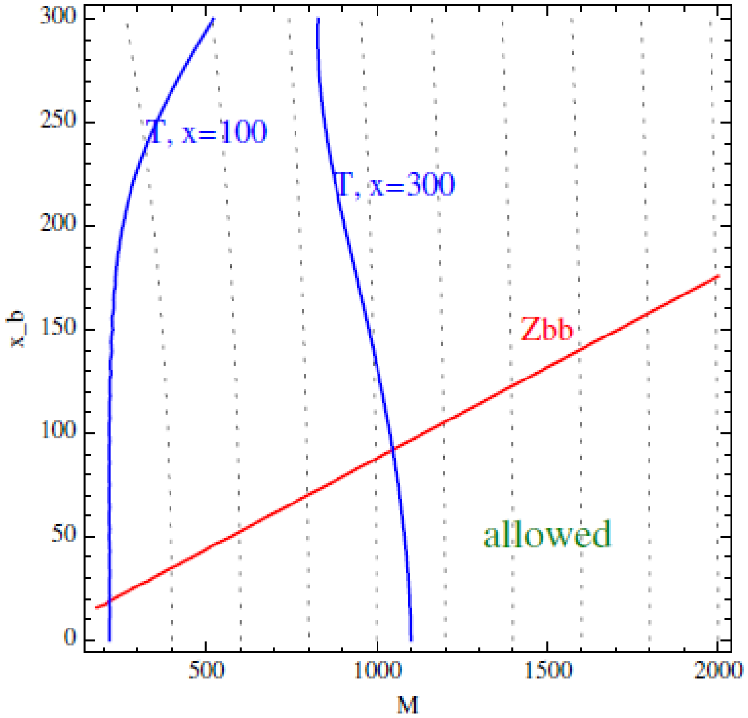


Zbb constaint is very strong

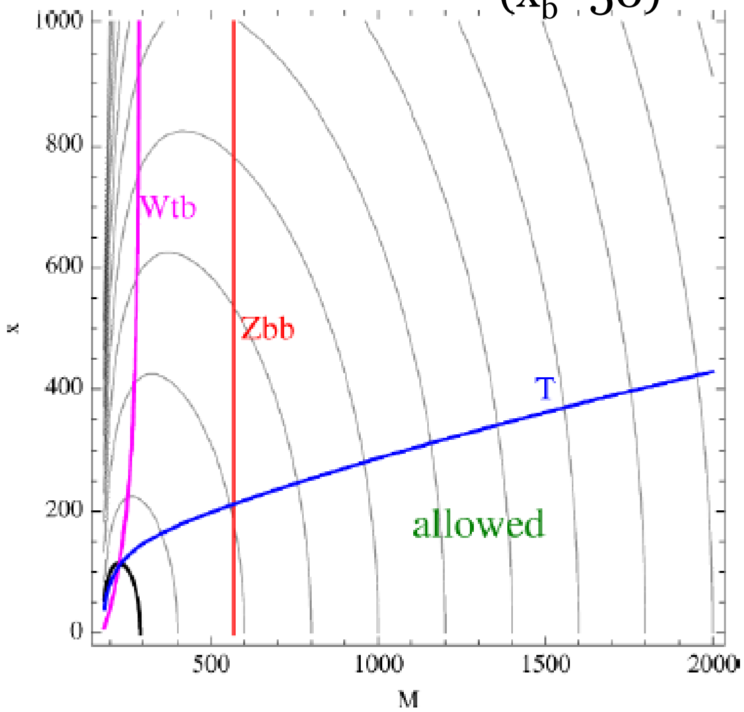
SM doublet

$$x_b = \frac{\lambda_d v}{\sqrt{2}}$$

$$x = \frac{\lambda_u v}{\sqrt{2}}$$

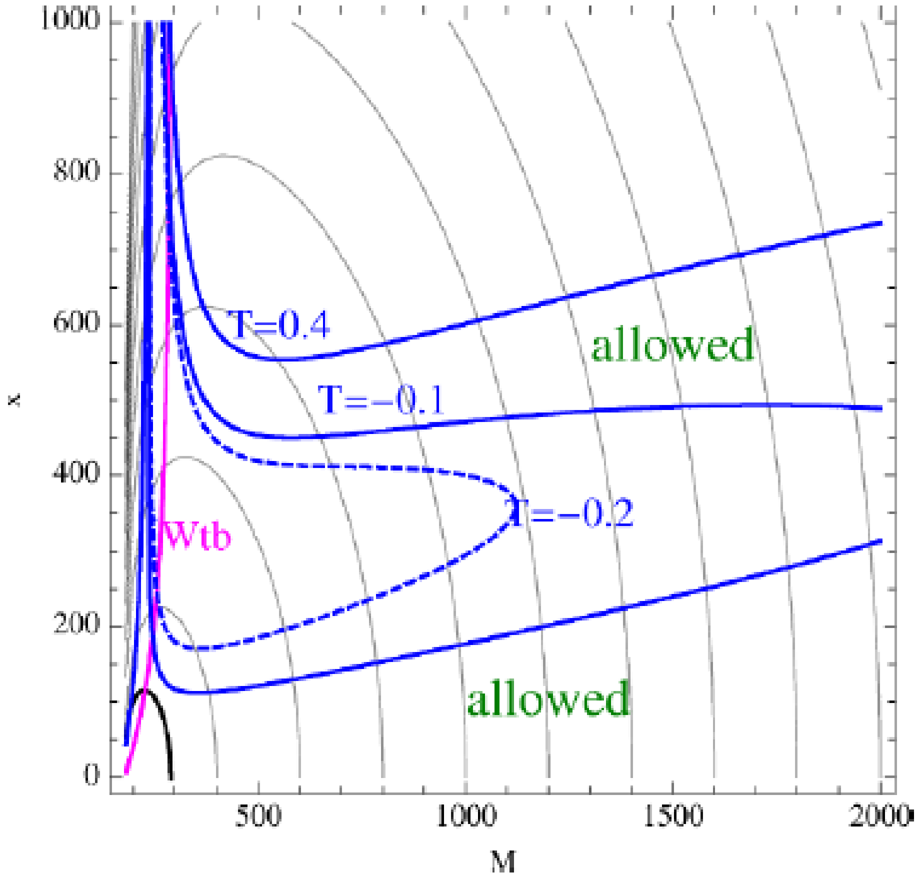


(x_b=50)



The Zbb vertex and the T parameter constrain x_b and x respectively.

Non-SM doublet



Only T parameter is a strong constraint. A large new Yukawa coupling constant is allowed.

Decay branching raitos

In all cases, t'->Wb, t'->Zt, t'->ht iare main decay modes.
Loop induced decays t'->t γ and t-> tg are $O(10^{-6})$ and $O(10^{-5})$

$m_{t'}$ =500 GeV

case	Wb	Zt	ht	γt	gt
Singlet, $x = 10$	0.50	0.17	0.33	4×10^{-6}	2.7×10^{-5}
Singlet, $x = 200$	0.50	0.15	0.29	3×10^{-6}	1.6×10^{-5}
SM doublet, $x = 10$	0.95	0.017	0.03	0.21×10^{-6}	0.2×10^{-5}
SM doublet, $x = 100$ (x_b=50)	0.24	0.26	0.50	4×10^{-6}	2.2×10^{-5}
Non-SM doublet, $x = 10$	0.09	0.37	0.61	6×10^{-6}	15×10^{-5}
Triplet A (Y=2/3), $x = 10$	0.36	0.22	0.42	7.2×10^{-6}	2.4×10^{-5}
Triplet B (Y=-1/3), $x = 10$	0.01	0.41	0.58	3.5×10^{-6}	7.1×10^{-5}

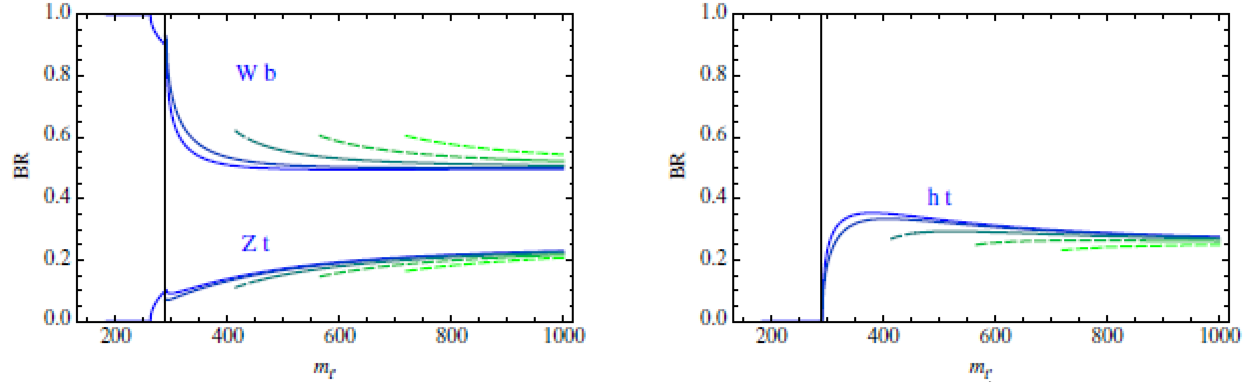
Large mass limit ($m_{t'}$ =∞)

Understood by the equivalence theorem (C.P.Yuan's talk)

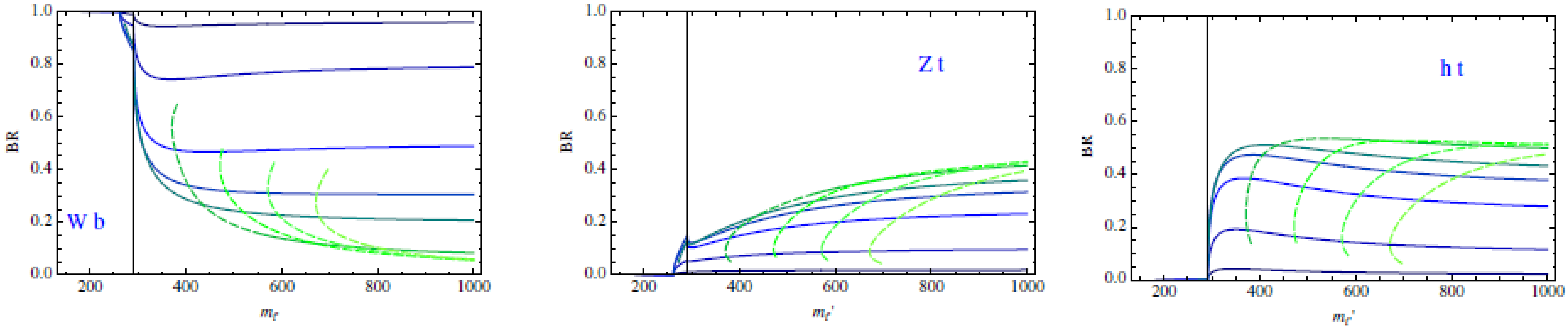
case	Wb	Zt	ht
singlet	0.5	0.25	0.25
SM doublet	$x_b^2/(x_b^2+x^2)$	$0.5x^2/(x_b^2+x^2)$	$0.5x^2/(x_b^2+x^2)$
Non-SM doublet	0	0.5	0.5
Triplet A	0.5	0.25	0.25
Triplet B	0	0.5	0.5

Singlet

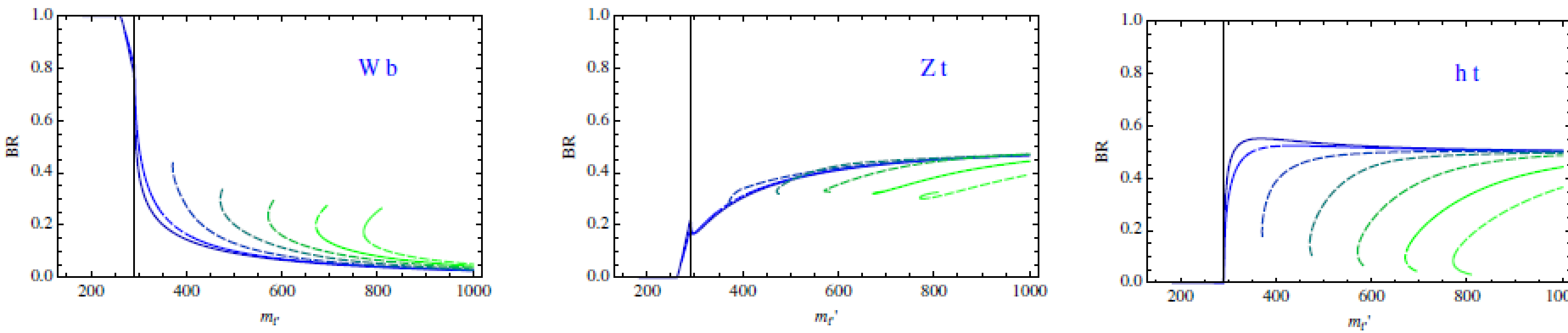
(x= 10, 100,200, 300,400GeV)



SM doublet (xb=50GeV, x= 10,25,50,75, 100,200, 300,400,500GeV)



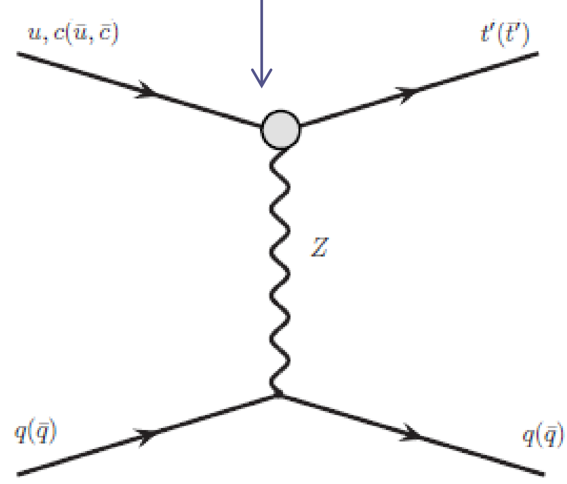
Non-SM doublet (x= 10, 100,200, 300,400,500,600GeV)



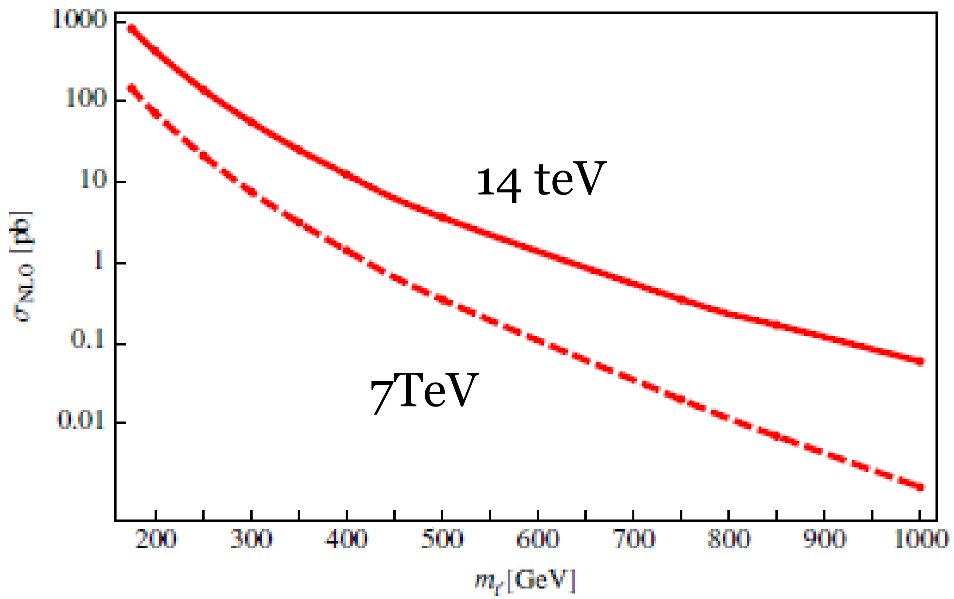
Phenomenology of non-SM doublet

- Parameter constraints are weak. A large new Yukawa coupling constant is allowed.
- A right-handed up-type flavor changing neutral current exists at the tree level.
- Possible large single t' production at LHC.
- Need to include t' mixing to light quarks

Zt'u and Zt'c vertexes



t' pair production cross section



Non-SM doublet model with three flavor mixing

$$\mathcal{L}_{\rm yuk} = -y_u^{i,j}\,\bar{Q}_L^i H^c u_R^j - y_d^{i,j}\,\bar{Q}_L^i H d_R^j - \lambda^j\,\bar{\psi}_L H u_R^j$$

$$\mathcal{L}_{\rm mass} = -(\bar{d}_L, \bar{s}_L, \bar{b}_L)\cdot \tilde{V}_{CKM}\cdot \begin{pmatrix} \tilde{m}_d & & \\ & \tilde{m}_s & \\ & & \tilde{m}_b \end{pmatrix} \cdot \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

$$- (\bar{u}_L, \bar{c}_L, \bar{t}_L, \bar{U}_L)\cdot \begin{pmatrix} \tilde{m}_u & & & 0 \\ & \tilde{m}_c & & 0 \\ & & \tilde{m}_t & 0 \\ x_1 & x_2 & x_3 & M \end{pmatrix} \cdot \begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \end{pmatrix} - M\,\bar{X}_L X_R + h.c.$$

We can take x_3 and M to be real and x_1 and x_2 to be complex.

Mixing matrixes

Off –diagonal part (1-4, 2-4 components) is suppressed by light quark masses,

$$M_u = V_L \cdot \begin{pmatrix} m_u & & & \\ & m_c & & \\ & & m_t & \\ & & & m_{t'} \end{pmatrix} \cdot V_R^\dagger \, .$$

Correction to the CKM matrix

$$\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \left(\bar{u}_L, \bar{c}_L, \bar{t}_L, \bar{U}_L\right) \cdot \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \\ 0 & 0 & 0 \end{pmatrix} \cdot \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

$$g_{WL}^{Ij} = \frac{g}{\sqrt{2}} V_{CKM}^{Ij} = \frac{g}{\sqrt{2}} V_L^\dagger \cdot \begin{pmatrix} & \tilde{V}_{CKM} & \\ & & \\ 0 & 0 & 0 \end{pmatrix}$$

Unitality of 3x3 matrix is a slightly violated

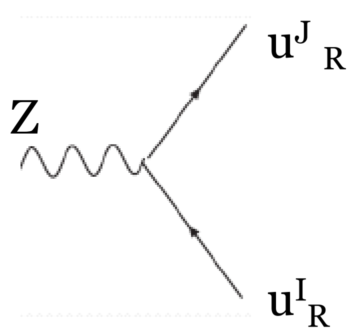
Z boson FCNC coupling

$$\mathcal{L}_Z = \frac{g}{c_W}\left(\bar{u}_L, \bar{c}_L, \bar{t}_L, \bar{U}_L\right)\cdot\left[\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)\begin{pmatrix}1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1\end{pmatrix} - \begin{pmatrix} & & & \\ & & & \\ & & & \\ & & & 1\end{pmatrix}\right]\gamma^\mu \cdot \begin{pmatrix}u_L \\ c_L \\ t_L \\ U_L\end{pmatrix} Z_\mu$$

$$g_{ZL}^{IJ} = \frac{g}{c_W}\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)\delta^{IJ} - \frac{g}{c_W}V_L^{*,4I}V_L^{4J}$$

$$g_{ZR}^{IJ} = \frac{g}{c_W}\left(-\frac{2}{3}s_W^2\right)\delta^{IJ} - \frac{1}{2}\frac{g}{c_W}V_R^{*,4I}V_R^{4J}$$

The most important phenomenological effects arise from the right-handed Z-boson FCNC coupling.



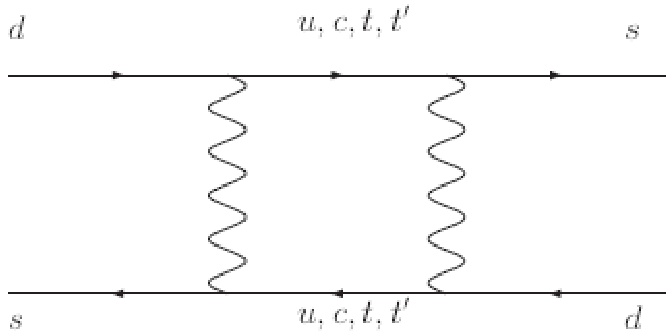
Constraints on V_R^{41} and V_R^{42}

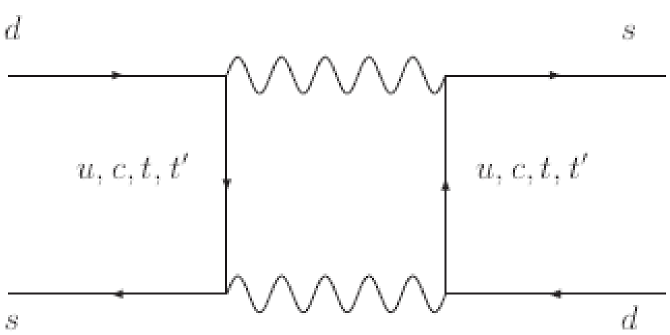
Constraints on V_R come from right handed Z-FCNC processes.
Most important processes are DD mixing and atomic parity violation .

D_0–$\bar{D}_0$ mixing	$\|V_R^{41}\|\|V_R^{42}\| < 3.2 \times 10^{-4}$
APV in Cs	$\|V_R^{41}\| < 7.8 \times 10^{-2}$
LEP1, charm couplings	$\|V_R^{42}\| < 0.2$
Tevatron: $t \to Zc, Zu$	$\|V_R^{43}\|\sqrt{\|V_R^{41}\|^2 + \|V_R^{42}\|^2} < 0.28\|V_{tb}\|$
D meson decays	none

Contribution to KK and BB mixing

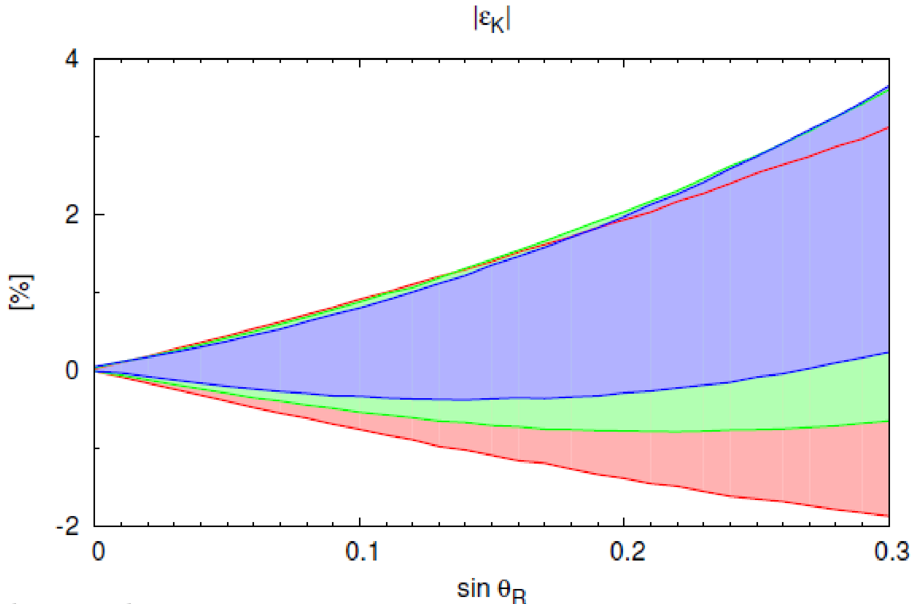
We have calculated Kaon, Bd, anf Bs mixing amplitudes including t’ loop contribution. Deviations from the SM is not very large in general. For the Bs mixing, we find that a sizable change of the Bs box phase is possible.
This can be distinguished at the LHCb experiment.





ε_K

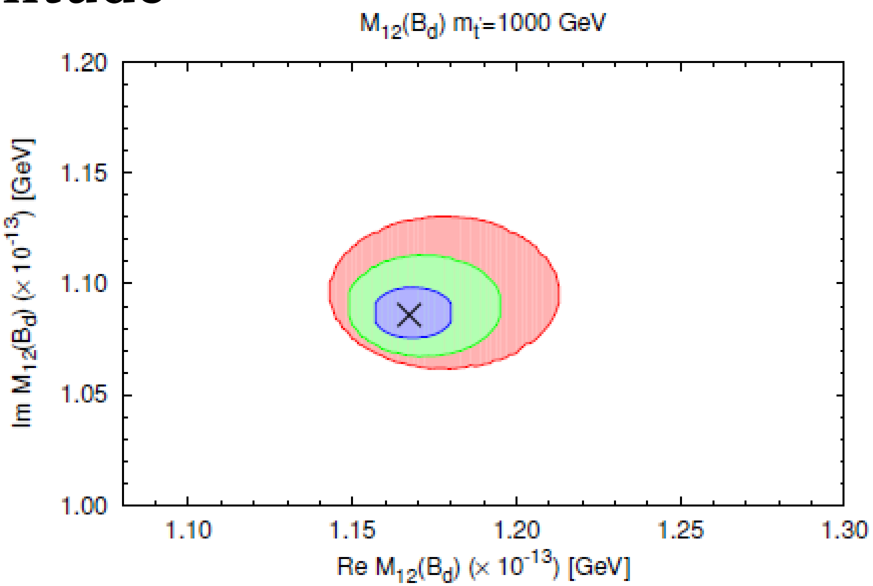
Less than 5%



M=350 GeV(blue)
500GeV(green)
1000GeV(red)

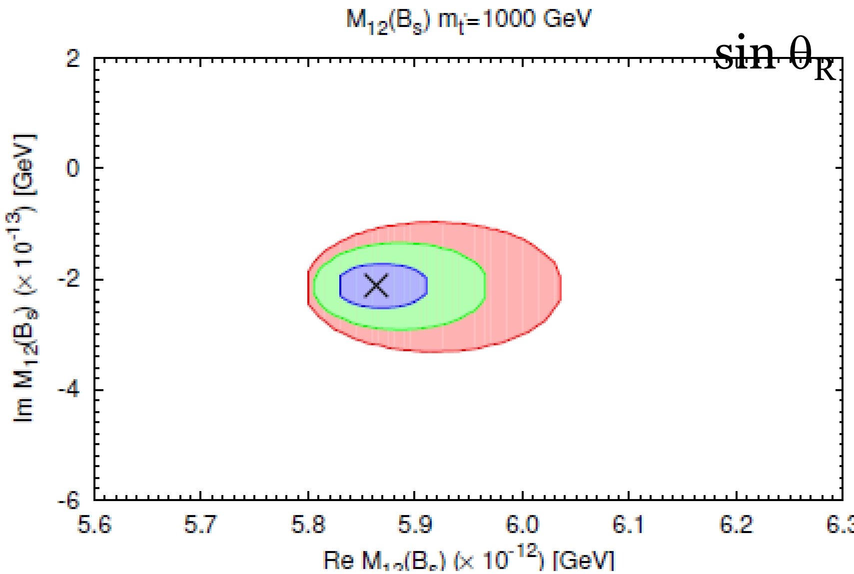
Bd mixing amplitude

A few %



$\sin\theta_R$ = 0.1 (blue)
0.2(green)
0.3(red)

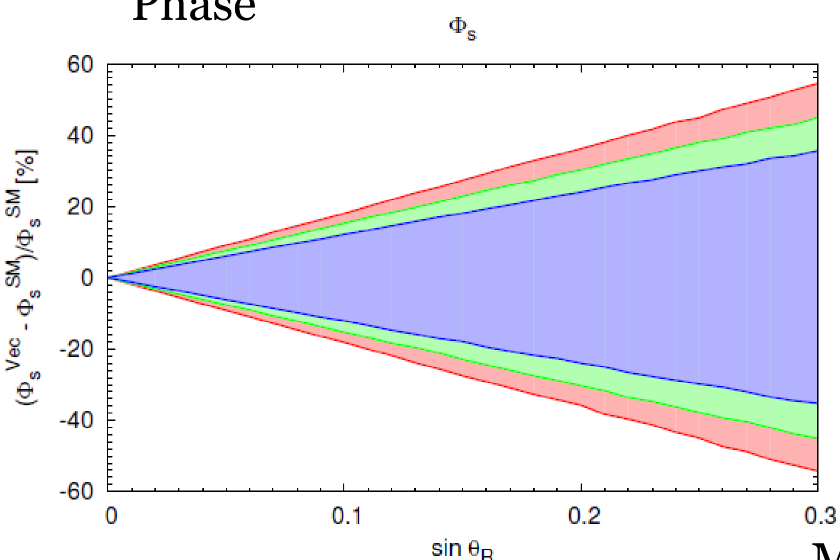
Bs mixing amplitude



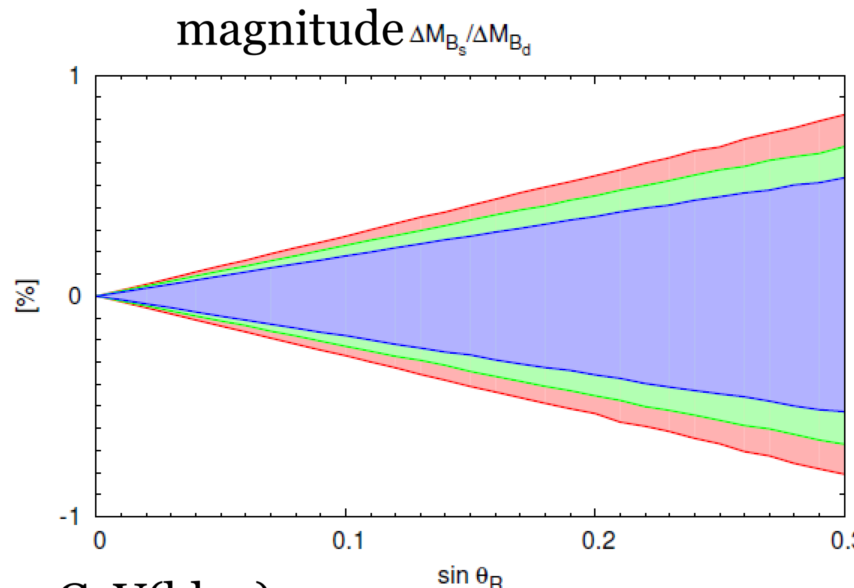
$\sin\theta_R$ = 0.1 (blue)
0.2(green)
0.3(red)

The phase of the Bs mixing can be different form the SM up to 60 %. Promising to be checked with CPV in Bs->J/ψ ϕ .

Phase



magnitude



M=350 GeV(blue)
500GeV(green)
1000GeV(red)

Summary

- We have clarified vector-like t' models.
- Phenomenological constraints on off-diagonal Yukawa coupling constants are quite different for various cases.
- FCNC decays t'->Zt, t'->ht are as important as or more important than t'->Wb.
- An interesting case is the non-SM doublet model where a large new Yukawa coupling constant is allowed.
- Right-handed Z boson FCNC processes and CP violation in the Bs mixing is promising flavor physics signals.
- Single t' production is an interesting possibility at LHC.