Bounds and Decays of New Heavy Vector-like Top Partners

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Physics Beyond the Standard Model and Predictable Observables
@Kobe January. 7. 2011

JHEP 1011:159,2010

My talk plan

Ⅰ Introduction

Ⅱ Chiral 4th generation model

Ⅲ Vector-like 4th generation model

Ⅳ Summary

Introduction

The standard model for elementary particles is very successful in describing high energy phenomena up to O(100) GeV.

However, there is one notable exception in the quark sector.
The forward-backward asymmetry of the bottom quark shows a 2.9 sigma deviation from the value predicted by the SM.

LEP observed value for the bottom quark forward-backward asymmetry is

$$A^b_{FB} = 0.0992 \pm 0.0016$$

SM expectation value is $A^b_{FB}(SM) \simeq 0.1036$ ⇨ $2.9\ \sigma$

The discrepancy of the measured forward-backward asymmetry of bottom quark with the SM can be reduced through the introduction of new vector-like quark with non-trivial mixing with the third generation

"Beautiful Mirrors Model" Choudhury, Tait, Wagnerr '01

Recent Tevatron experiments also show an unexpected forward-backward asymmetry of pair produced top quarks.

Introduction

There are heavy vector-like fermion in many models of new physics.

cf. Little Higgs model, Extra Dimension scenario, …

In the Little Higgs model, the Yukawa coupling of new T are given by

$$\lambda_1(i\bar{Q}ht_R + f\bar{T}_L t_R - \frac{1}{2f}\bar{T}_L t_R h h^\dagger) + \lambda_2 f(\bar{T}_L T_R)$$

We introduce an effective lagrangian involving the new top Yukawa couplings.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

SM Yukawa coupling

$$-\mathcal{L}_{\text{Yukawa}} = y_u \bar{q}_L \tilde{\Phi} u_R + y_d \bar{q}_L \Phi d_R + \text{h.c.}$$

We study the radiative decay of a heavy fermion to a photon plus a light fermion.

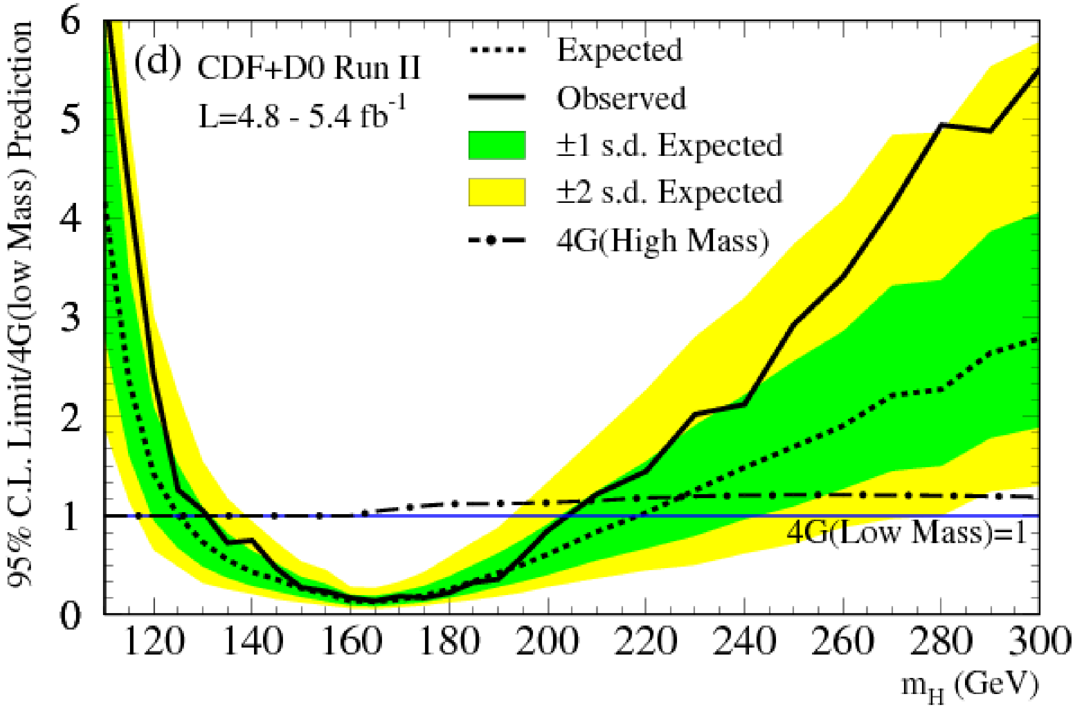
$t' \to t\gamma$ process

Chiral 4th generation model

Higgs searches at Tevatron in SM4

gg → H → WW

arXiv:1005.3216 [hep-ex]



$m_{b'} = 400$ GeV

$m_{t'} = m_{b'} + 50$ GeV $+ 10\log(m_H/115 \text{ GeV})$ GeV

Low mass scenario

$m_{\nu'} = 80$ GeV

$m_{l'} = 100$ GeV

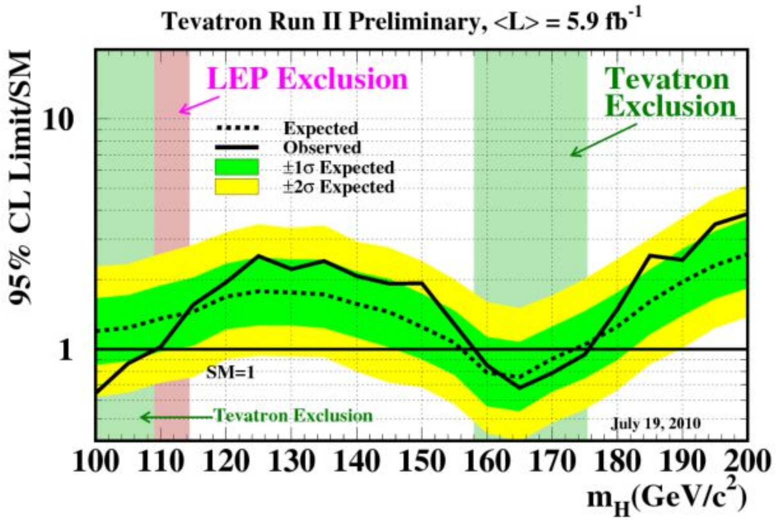
High mass scenario

$m_{\nu'} = m_{l'} = 1$ TeV

CDF+D0 combination

Low mass $131 < m_H < 204$ GeV

High mass $131 < m_H < 208$ GeV excluded



4th leptons do affect decay branching ratios of Higgs boson

New Physics effect on hhh coupling

Higgs mass is the only free parameter in the Higgs potential.

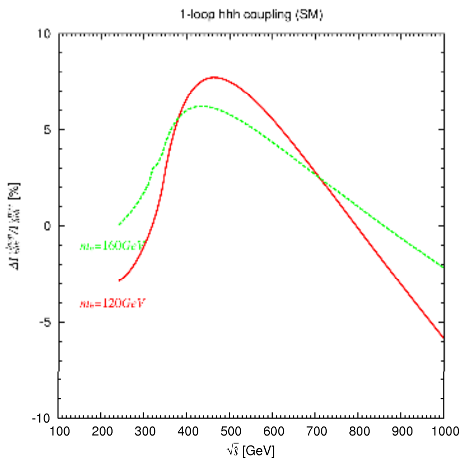
Effective Higgs potential

$$V = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\lambda_{hhh} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots.$$

In the SM, tree level hhh (hhhh) couplings are uniquely defined by Higgs boson mass.

$$\lambda_{hhh}^{\rm SM} = \frac{3m_h^2}{v} \qquad \lambda_{hhhh}^{\rm SM} = \frac{3m_h^2}{v^2}$$

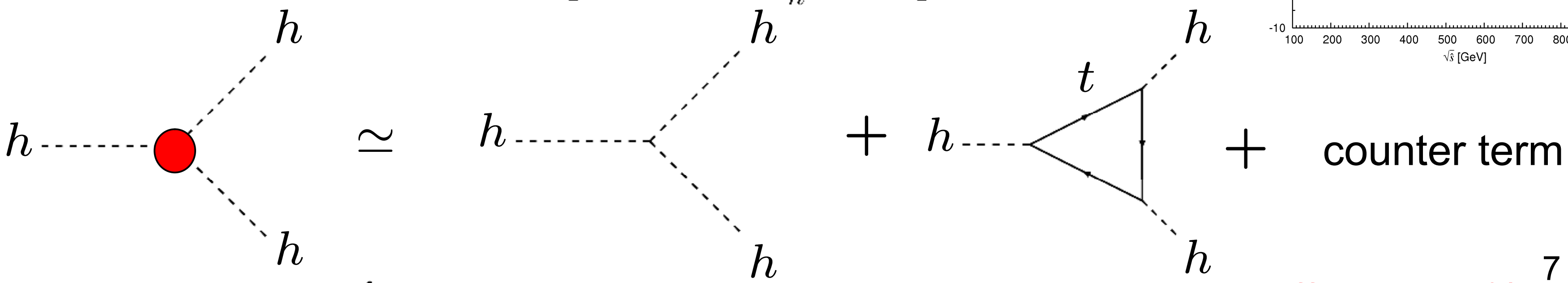
- Non-decoupling effect



In the SM, top loop correction is known as non-decoupling effect.

Effective hhh coupling

$$\Gamma_{hhh}^{\rm SM} \simeq \frac{3m_h^2}{v} - \frac{N_c m_t^4}{\pi^2 v^3} = \frac{3m_h^2}{v}\left[1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right] \equiv \lambda_{hhh}^{\rm SM}(1+\delta\kappa)$$



m_t^4 term appears in 1-loop correction

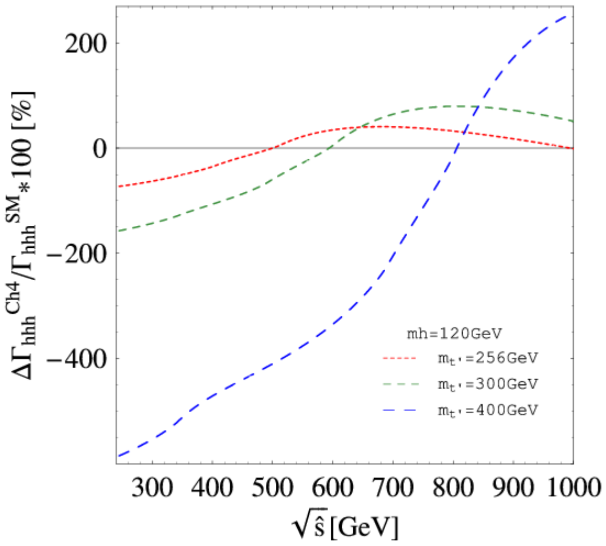
loop effect ~ -10%

Effective hhh coupling in 4th generation model

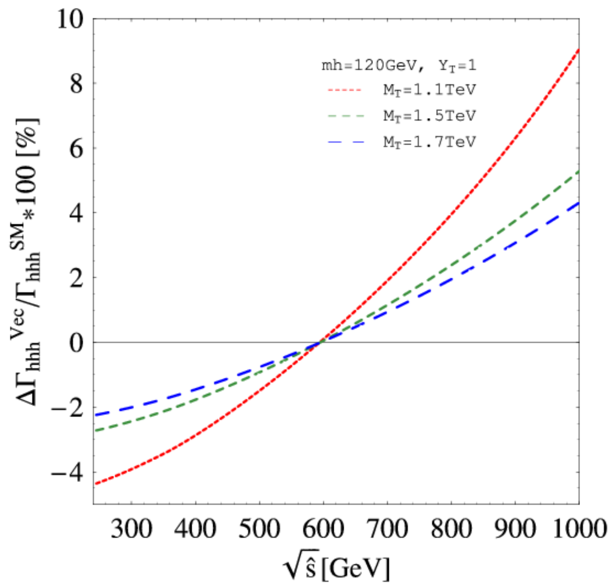
E. Asakawa, D. H, S. Kanemura, Y. Okada, K. Tsumura
Phys. Rev. D82, 115002 (2010)

For $m_h = 120$ GeV

Chiral 4th generation



Vector-like 4th generation



Effective hhh coupling

Chiral 4th generation

$$\Gamma^{\mathrm{Ch4}}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{N_c(m_{t'}^4+m_{b'}^4)}{3\pi^2 v^2 m_h^2} - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

Vector-like 4th generation

$$\Gamma^{\mathrm{Vec}}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\frac{m_t^2}{M^2} - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

$(M \geq 1$ TeV$)$

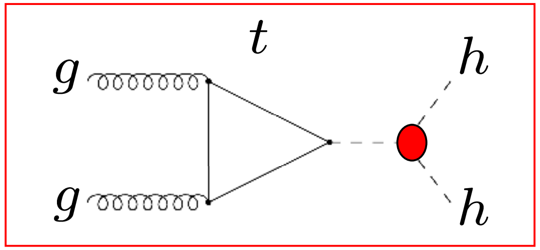
Gluon fusion process in 4th generation model

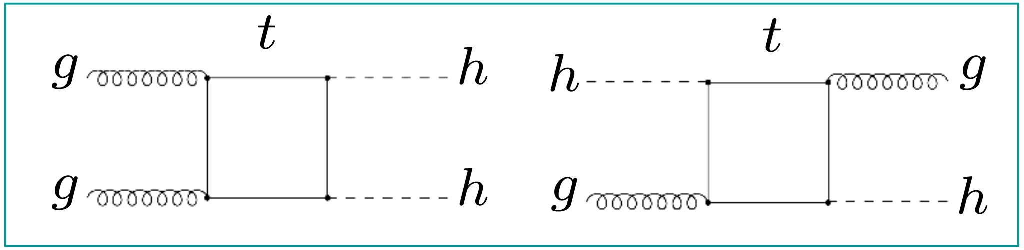
$$gg \to hh$$

$\mathcal{M}(l_1, l_2)$ top loop diagrams

triangle

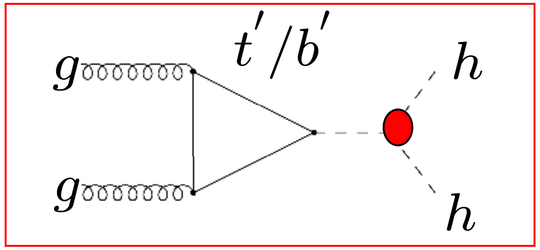
box

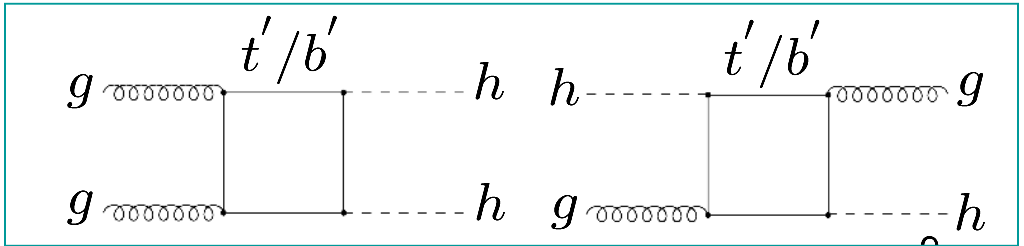




$\Delta\mathcal{M}(l_1, l_2)$ Additional one-loop diagrams

4th generation



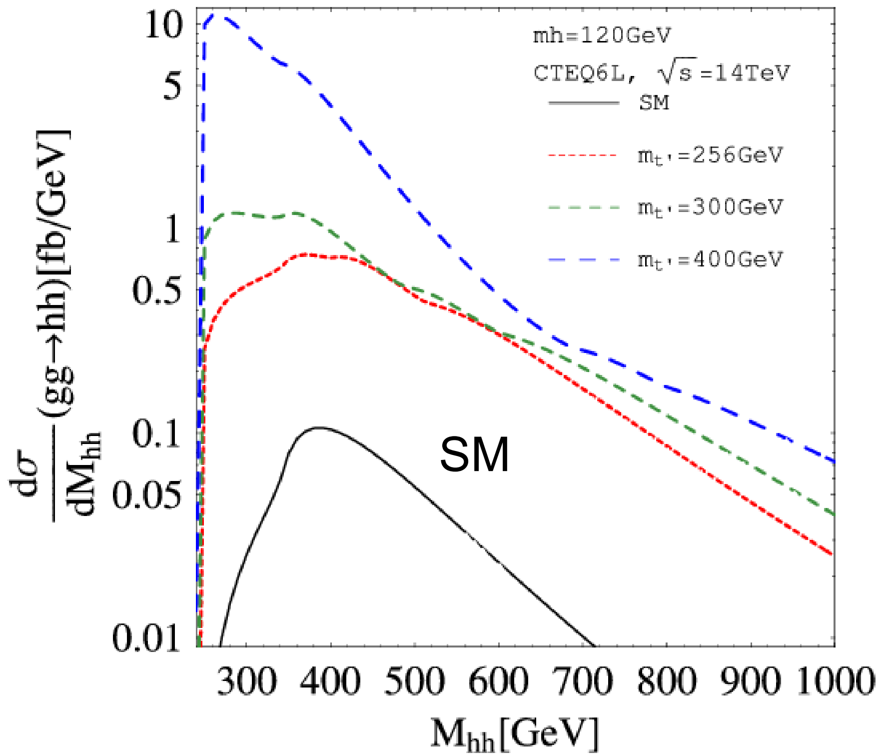


Gluon fusion process in 4th generation model

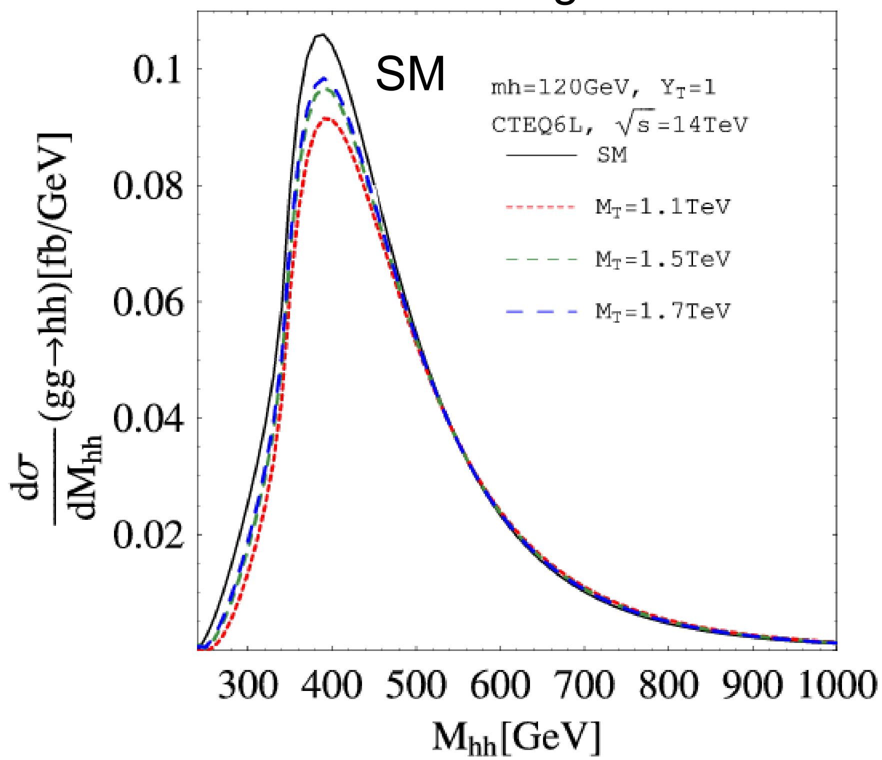
Invariant mass distribution of gluon fusion process

For $m_h = 120$ GeV

Chiral 4th generation



Vector-like 4th generation



The cross section of the chiral 4th generation model can be 10-100 times larger than that of the SM.

In the vector-like 4th generation model, the deviations of the cross section from the SM value are at most 5%, which can not be large because of their decoupling nature.

Vector-like 4th generation model

New Yukawa coupling

Effective lagrangian $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \Delta\mathcal{L}$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

1. Singlet $U_L \quad U_R \quad D_L \quad D_R$

$$-\Delta\mathcal{L} = \lambda_u \bar{q}_L \tilde{\Phi} U_R + \lambda_d \bar{q}_L \Phi D_R + M_u \bar{U}_L U_R + M_d \bar{D}_L D_R + \text{h.c.}$$

2. SM doublet $\psi = \begin{pmatrix} U \\ D \end{pmatrix}$

$$-\Delta\mathcal{L} = \lambda_u \bar{\psi}_L \tilde{\Phi} u_R + \lambda_d \bar{\psi}_L \Phi d_R + M \bar{\psi}_L \psi_R + \text{h.c.}$$

3. Non-SM doublet $\psi_1 = \begin{pmatrix} X \\ U \end{pmatrix} \qquad \psi_2 = \begin{pmatrix} D \\ Y \end{pmatrix}$

X with charge 5/3

Y with charge -4/3

$$-\Delta\mathcal{L} = \lambda_u \bar{\psi}_{1L} \Phi u_R + \lambda_d \bar{\psi}_{2L} \tilde{\Phi} d_R + M_1 \bar{\psi}_{1L} \psi_{1R} + M_2 \bar{\psi}_{2L} \psi_{2R} + \text{h.c.}$$

4. Triplet

$$\psi_1 = \begin{pmatrix} X \\ U \\ D \end{pmatrix} \qquad \psi_2 = \begin{pmatrix} U \\ D \\ Y \end{pmatrix}$$

$$-\Delta\mathcal{L} = \sum_{a=1}^{3} \lambda \bar{q}_L (\psi_R^a \tau^a) \tilde{\Phi} + M \bar{\psi}_L^a \psi_R^a + \text{h.c.}$$

or

$$-\Delta\mathcal{L} = \sum_{a=1}^{3} \lambda \bar{q}_L (\psi_R^a \tau^a) \Phi + M \bar{\psi}_L^a \psi_R^a + \text{h.c.}$$

Two Fermion mixing

We will give some general formulas applicable to the two fermion mixing case.

SM fermion $q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad t_R \quad b_R$

$+$

Heavy fermion ψ Singlet, SM doublet, Non-SM doublet, Triplet

The mixing will generate 4 mixing matrices

$$V^{L,R}_{u,d} = \begin{pmatrix} \cos\theta^{L,R}_{u,d} & -\sin\theta^{L,R}_{u,d} \\ \sin\theta^{L,R}_{u,d} & \cos\theta^{L,R}_{u,d} \end{pmatrix} \qquad \begin{pmatrix} f_l \\ F_H \end{pmatrix} = V \begin{pmatrix} f \\ F \end{pmatrix}$$

f_l, f_H mass eigenstates

f SM fermion

F Heavy fermion

Two Fermion mixing

There are only two possible Yukawa coupling involving either the left-handed or the right-handed SM fermions.

Singlet, Triplet — SM doublet, Non SM doublet

$$\lambda \bar{q} H \psi \quad \text{or} \quad \lambda \bar{\psi} H \{u, d\}_R$$

Mass matrix

$$\mathcal{M} = \begin{pmatrix} \frac{yv}{\sqrt{2}} & \frac{\lambda v}{\sqrt{2}} \\ 0 & M \end{pmatrix} \quad \text{or} \quad \mathcal{M} = \begin{pmatrix} \frac{yv}{\sqrt{2}} & 0 \\ \frac{\lambda v}{\sqrt{2}} & M \end{pmatrix}$$

Mixing angle

The mixing angles are different in the left- and right-handed sector

$$\sin\theta_u^L = \frac{Mx}{\sqrt{(M^2-m_t^2)^2+M^2x^2}} \qquad \sin\theta_u^R = \frac{Mx}{\sqrt{(M^2-m_t^2)^2+M^2x^2}}$$

or

$$\sin\theta_u^R = \frac{m_t}{M}\sin\theta_u^L \qquad \sin\theta_u^L = \frac{m_t}{M}\sin\theta_u^R$$

right-handed angle is smaller — left-handed angle is smaller

Mass eigenstate

$$\frac{y^2v^2}{2} = m_t^2\left(1+\frac{x^2}{M^2-m_t^2}\right) \qquad m_{t'} \geq M \geq m_t$$

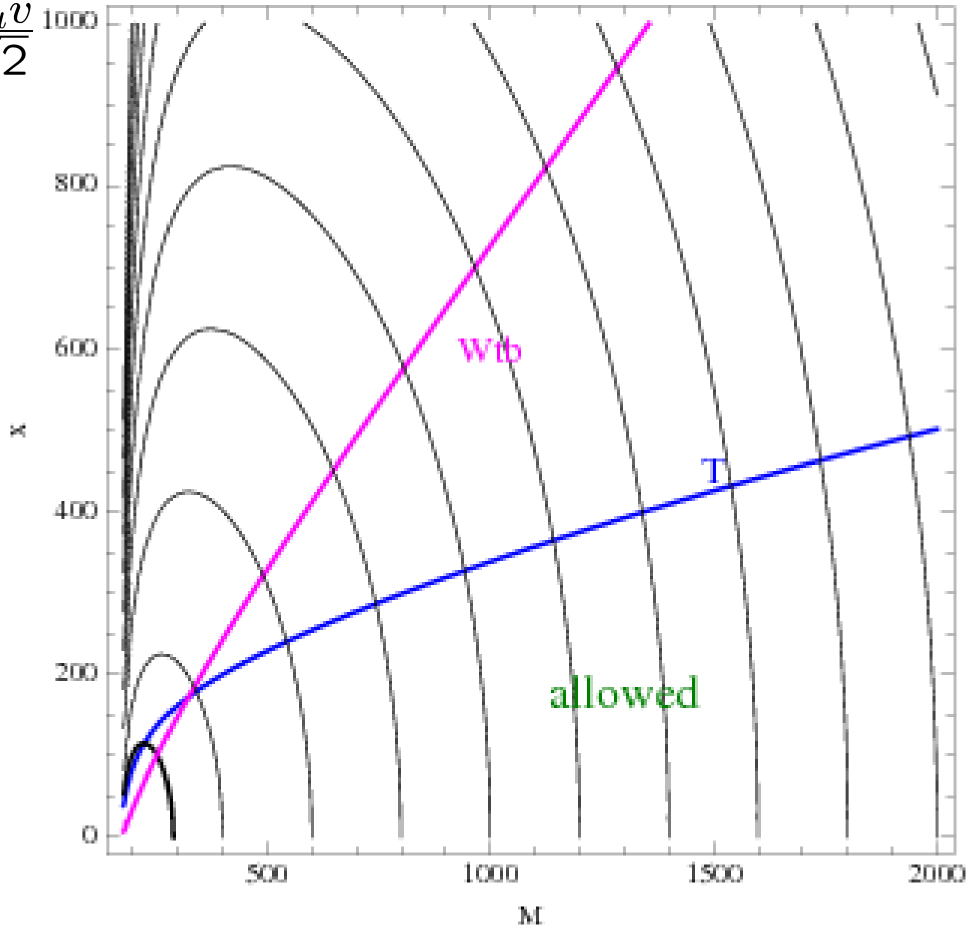
$$m_{t'}^2 = M^2\left(1+\frac{x^2}{M^2-m_t^2}\right) \qquad x = \frac{\lambda v}{\sqrt{2}}$$

Bounds of t' in Singlet model

$$-\Delta\mathcal{L} = \lambda_u \bar{q}_L \tilde{\Phi} U_R + M \bar{U}_L U_R + \text{h.c.}$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

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



T parameter

$$-0.2 < T < 0.4$$

Wtb coupling

$$\frac{\delta g_W}{g_W^{SM}} = \cos\theta_u^L - 1 \sim -\frac{1}{2}\frac{x^2}{M^2}$$

$$\frac{\delta g_W}{g_W^{SM}} = \pm 20\ \%$$

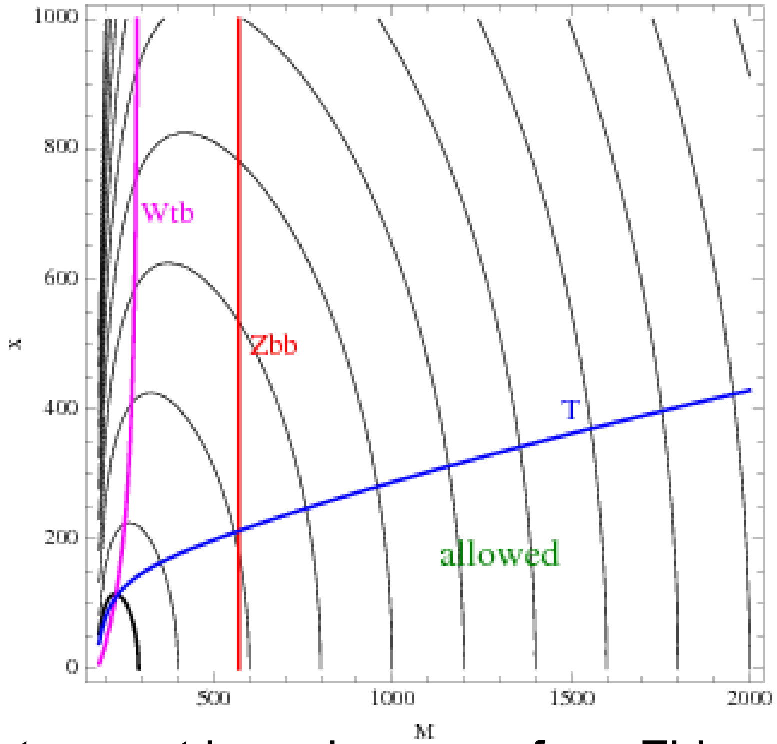
In this model right-handed angle is smaller

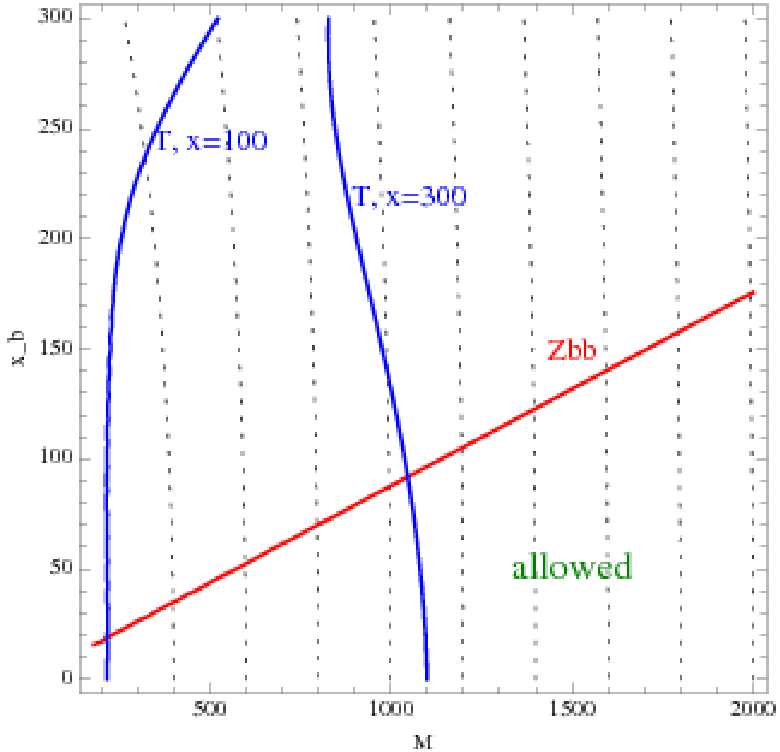
As the bottom sector is unaffected, the only tree level bounds comes from Wtb.

Bounds of t' in SM doublet model

$$-\Delta\mathcal{L} = \lambda_u \bar{\psi}_L \tilde{\Phi} u_R + \lambda_d \bar{\psi}_L \Phi d_R + M\bar{\psi}_L \psi_R + \text{h.c.} \qquad \psi = \begin{pmatrix} U \\ D \end{pmatrix}$$

$x = \frac{\lambda_u v}{\sqrt{2}}$ $\quad x_b = 50$ $\qquad x_b = \frac{\lambda_d v}{\sqrt{2}}$





The strongest bounds comes from Zbb coupling.

$$-5\ \% < \frac{\delta g_{ZbbR}}{g^{SM}_{ZbbR}} < 20\ \%$$

negative

$$\frac{\delta g_{ZbbR}}{g^{SM}_{ZbbR}} = -\frac{3\sin^2\theta^R_d}{2\sin^2\theta_W} \sim -\frac{3}{2\sin^2\theta_W}\frac{x_b^2}{M^2}$$

left-handed angle is smaller

Wtb coupling $\quad \frac{\delta g_W}{g^{SM}_W} \sim -\frac{1}{2}\frac{x^2 m_t^2}{M^4}$

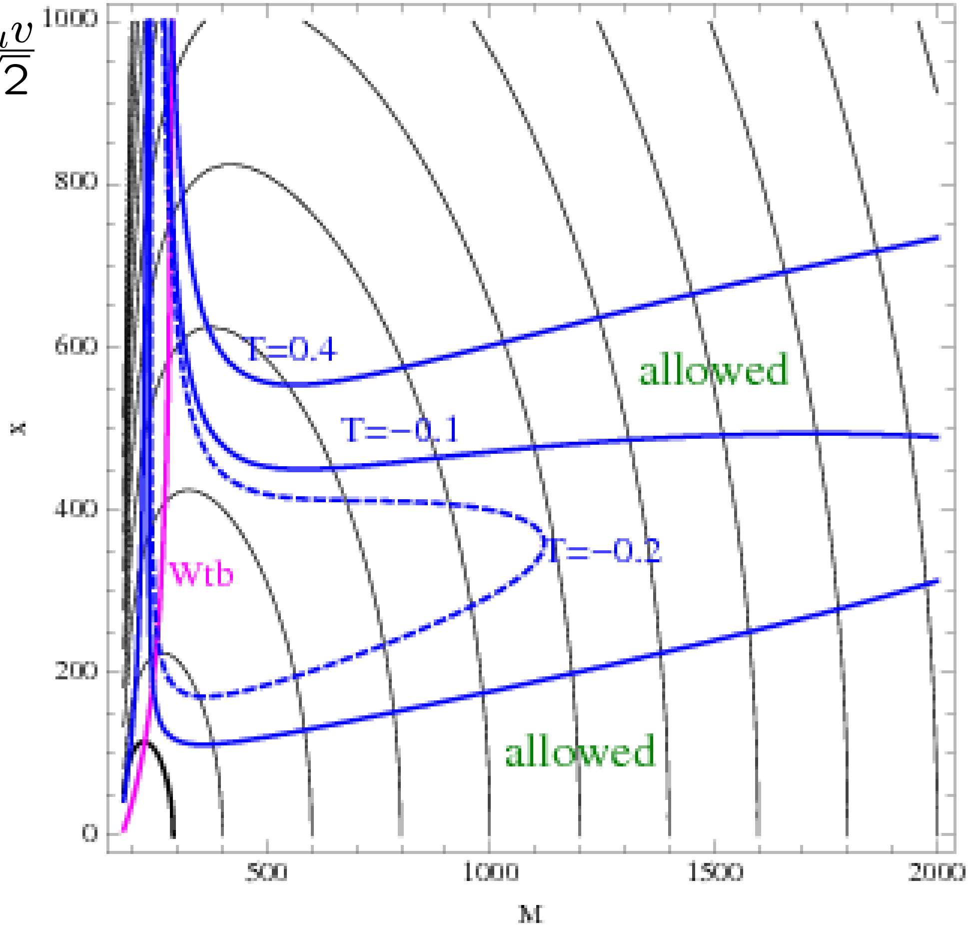
D has the same coupling as the left-handed SM down quark

Bounds of t' in Non-SM doublet model

$$-\Delta\mathcal{L} = \lambda_u \bar{\psi}_L \Phi u_R + M \bar{\psi}_L \psi_R$$

$$\psi = \begin{pmatrix} X \\ U \end{pmatrix}$$ X with charge 5/3

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



T parameter

$$-0.2 < T < 0.4$$

Wtb coupling

$$\frac{\delta g_W}{g_W^{SM}} = \cos\theta_u^L - 1 \sim -\frac{1}{2}\frac{x^2 m_t^2}{M^4}$$

$$\frac{\delta g_W}{g_W^{SM}} = \pm 20\ \%$$

In this model left-handed angle is smaller

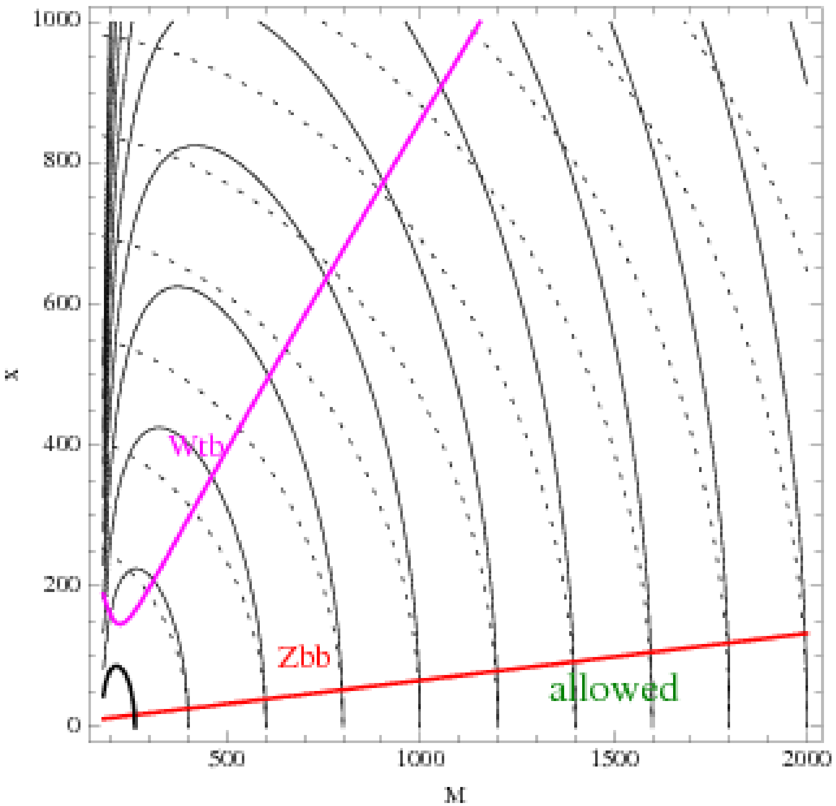
Bounds of t' in Triplet 1 model

$$-\Delta\mathcal{L} = \sum_{a=1}^{3} \lambda \bar{q}_L (\psi_R^a \tau^a)\tilde{\Phi} + M\bar{\psi}_L^a \psi_R^a + \text{h.c.}$$

$$= \frac{\lambda v}{\sqrt{2}} \bar{u}_L U_R + \lambda v \bar{d}_L D_R$$

$$+ M(\bar{U}_L U_R + \bar{D}_L D_R + \bar{X}_L X_R) + \text{h.c.}$$

$$\psi = \begin{pmatrix} X \\ U \\ D \end{pmatrix}$$ X with charge 5/3



Zbb coupling

$$\frac{\delta g_{ZbbL}}{g_{ZbbL}^{SM}} = \frac{1}{1-\frac{2}{3}\sin^2\theta_W} \sin^2\theta_d^L$$

$$\sim \frac{2}{1-2/3\sin^2\theta_W} \frac{x^2}{M^2}$$

positive

$$-0.2\ \% < \frac{\delta g_{ZbbL}}{g_{ZbbL}^{SM}} < 1\ \%$$

$$\frac{\delta g_{ZbbR}}{g_{ZbbR}^{SM}} = -\frac{3\sin^2\theta_d^R}{\sin^2\theta_W}$$

$$\sim -\frac{6}{\sin^2\theta_W} \frac{x^2 m_b^2}{M^4}$$

negative

$$-5\ \% < \frac{\delta g_{ZbbR}}{g_{ZbbR}^{SM}} < 20\ \%$$

In this model right-handed angle is smaller

The strongest bounds comes from the positive deviation to the left-handed Zbb coupling.

Bounds of t' in Triplet 2 model

$$-\Delta\mathcal{L} = \sum_{a=1}^{3} \lambda \bar{q}_L(\psi_R^a \tau^a)\Phi + M\bar{\psi}_L^a \psi_R^a + \text{h.c.}$$
$$= \lambda v \bar{u}_L U_R - \frac{\lambda v}{\sqrt{2}} \bar{d}_L D_R$$
$$+ M(\bar{U}_L U_R + \bar{D}_L D_R + \bar{Y}_L Y_R) + \text{h.c.}$$

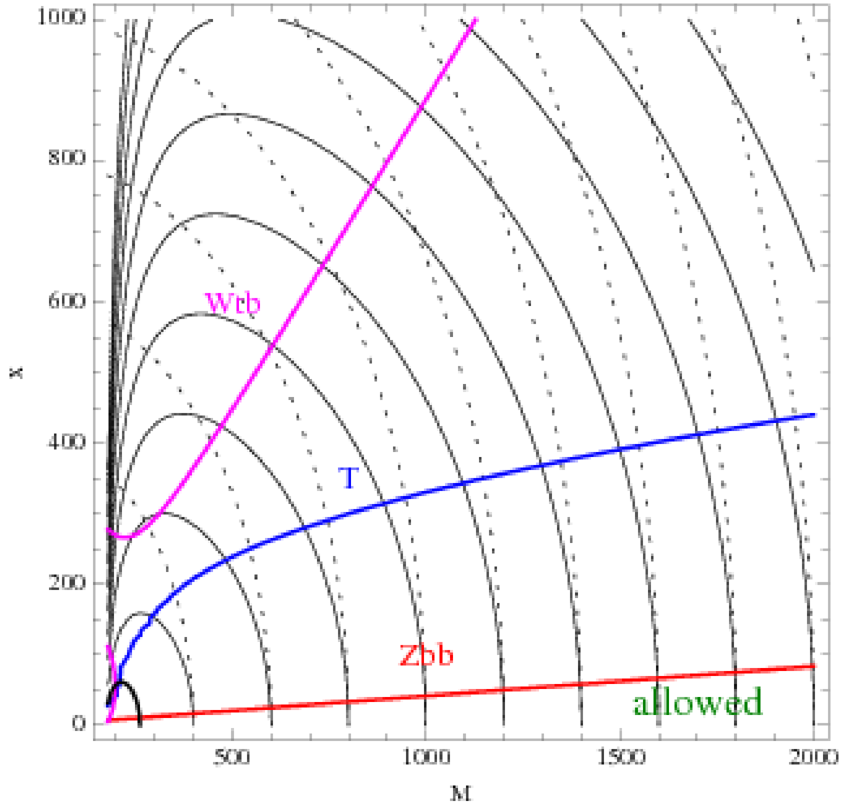
$$\psi_2 = \begin{pmatrix} U \\ D \\ Y \end{pmatrix}$$ Y with charge -4/3

Zbb coupling

$$\frac{\delta g_{ZbbL}}{g_{ZbbL}^{SM}} = -\frac{1}{1-\frac{2}{3}\sin^2\theta_W}\sin^2\theta_d^L$$
$$\sim -\frac{1}{1-2/3\sin^2\theta_W}\frac{x^2}{M^2}$$

negative

$$-0.2\ \% < \frac{\delta g_{ZbbL}}{g_{ZbbL}^{SM}} < 1\ \%$$

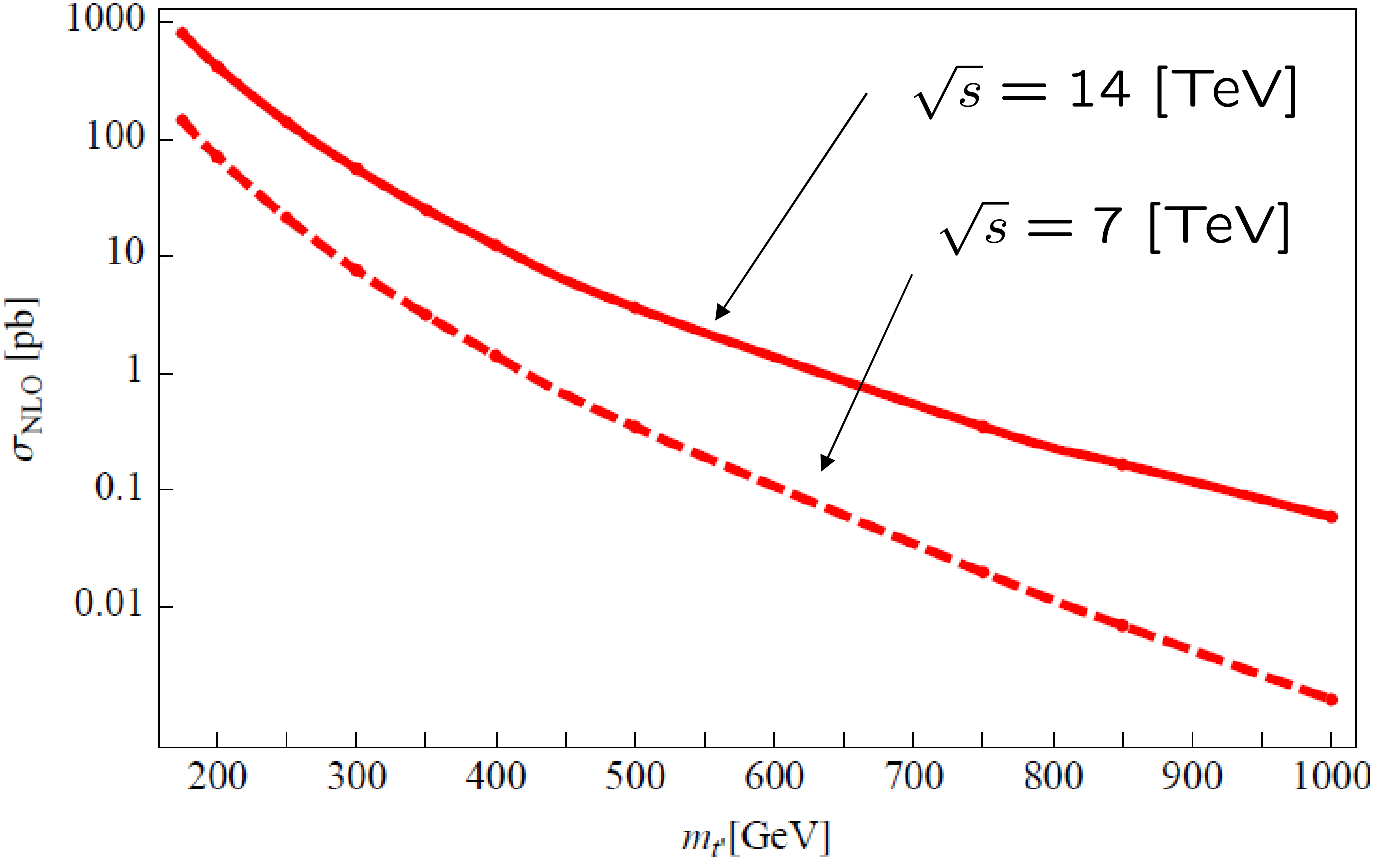


In this model
right-handed angle is smaller

The strongest bounds comes from the negative deviation to the left-handed Zbb coupling.

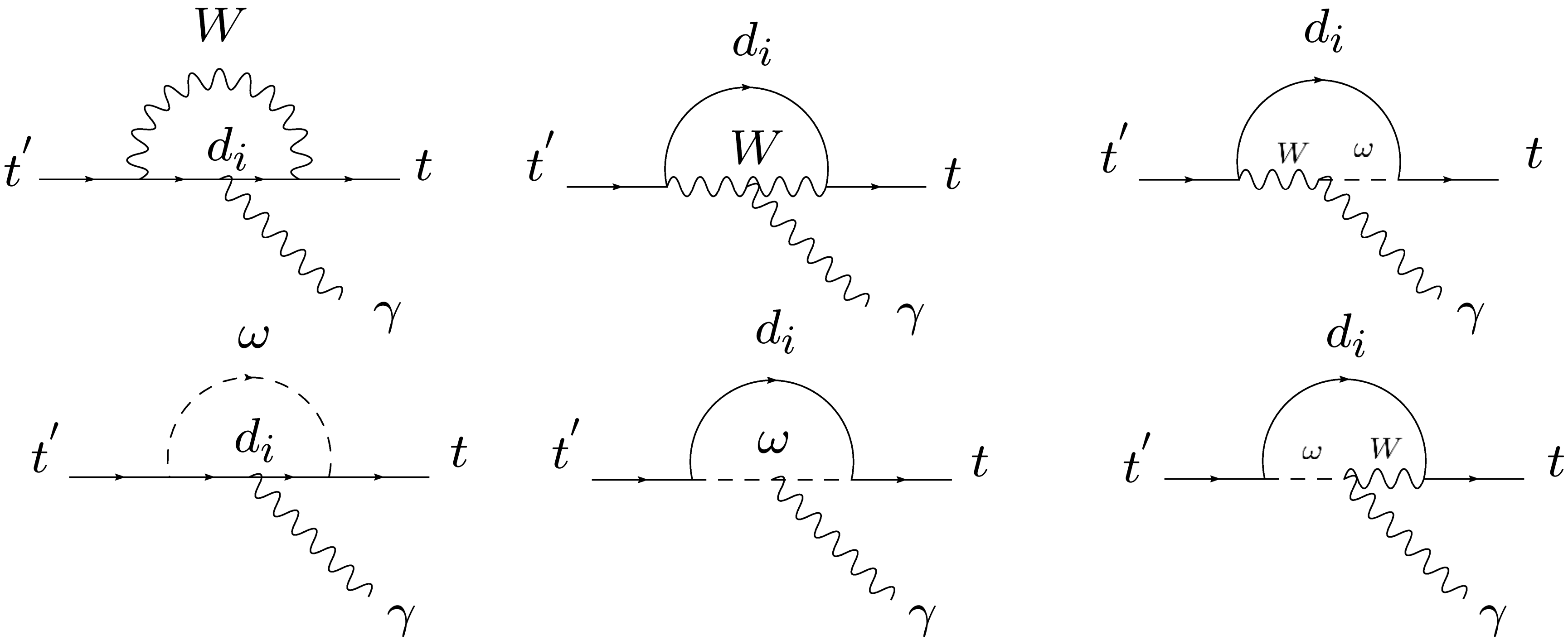
Heavy quarks pair production at LHC

$pp \to gg \to t'\overline{t}'$



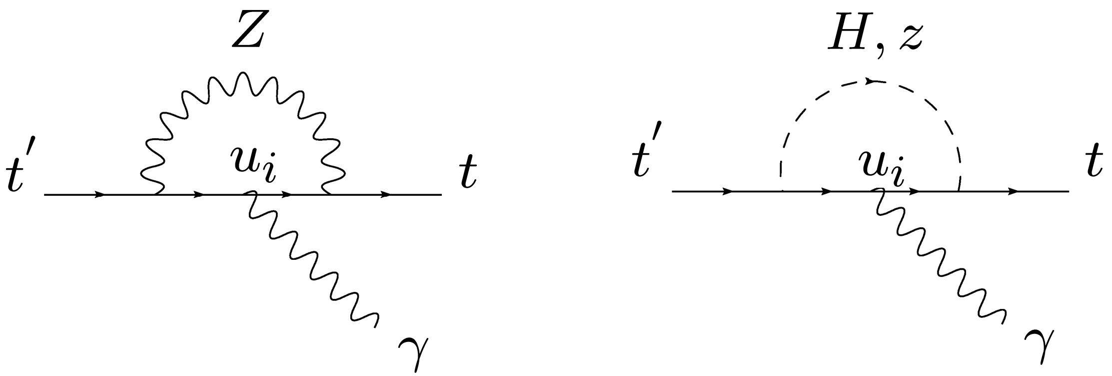
For $m_{t'} < 1$ [TeV] $\sigma(pp \to t'\overline{t}') > 100$ [fb]

$t^{'} \to t\gamma$ process



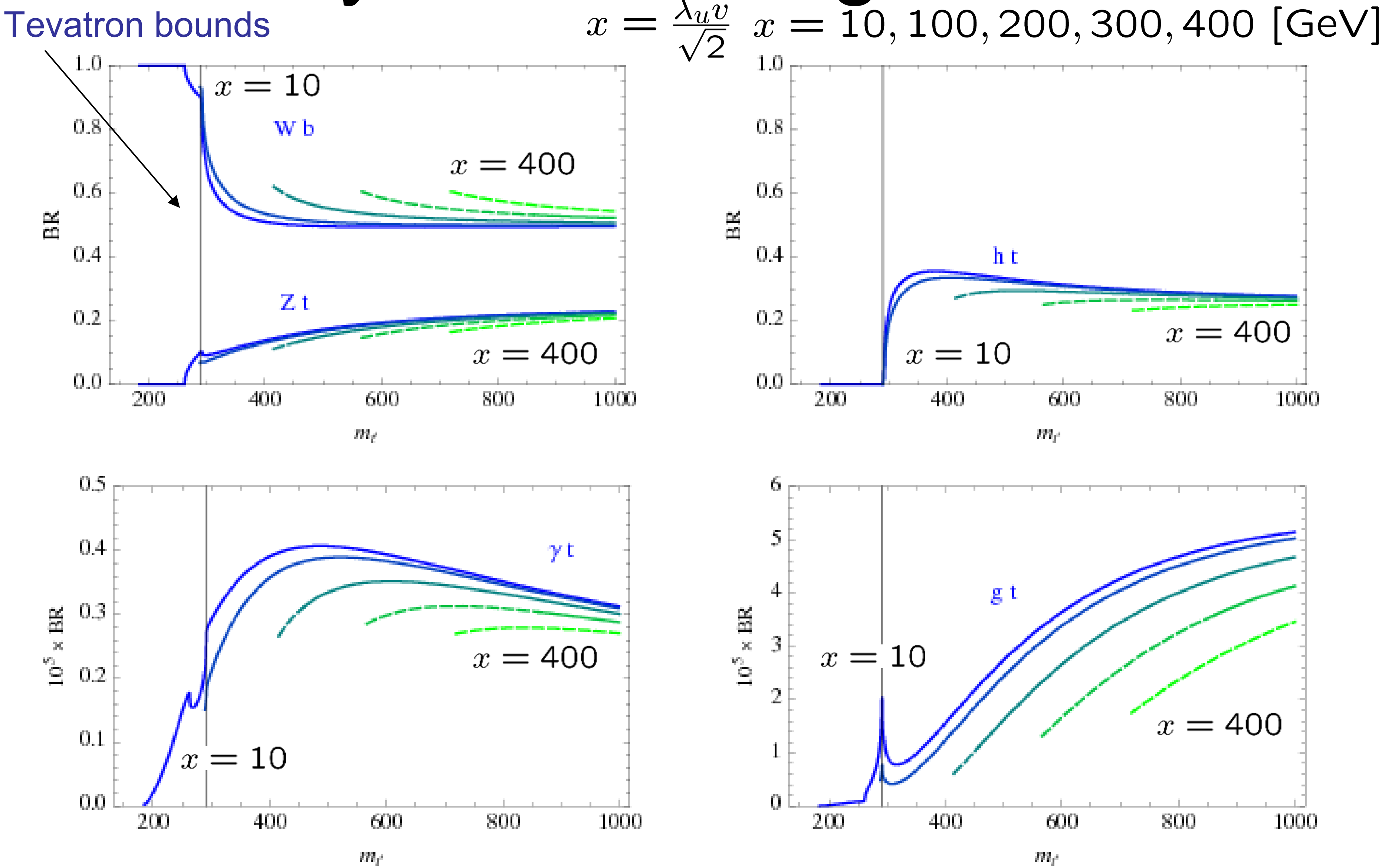
$(d_i = b, b^{'})$

Additional Feynman diagrams



$(u_i = t, t^{'})$

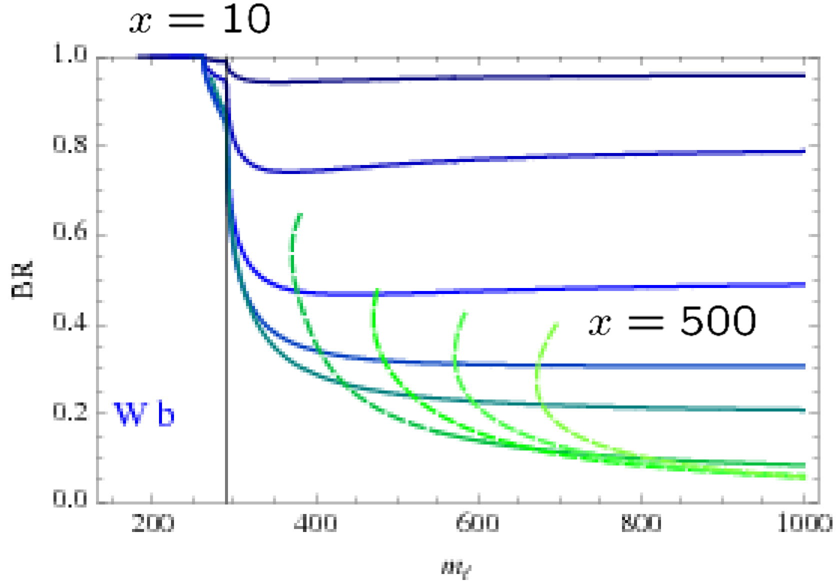
Decays of t' in Singlet model

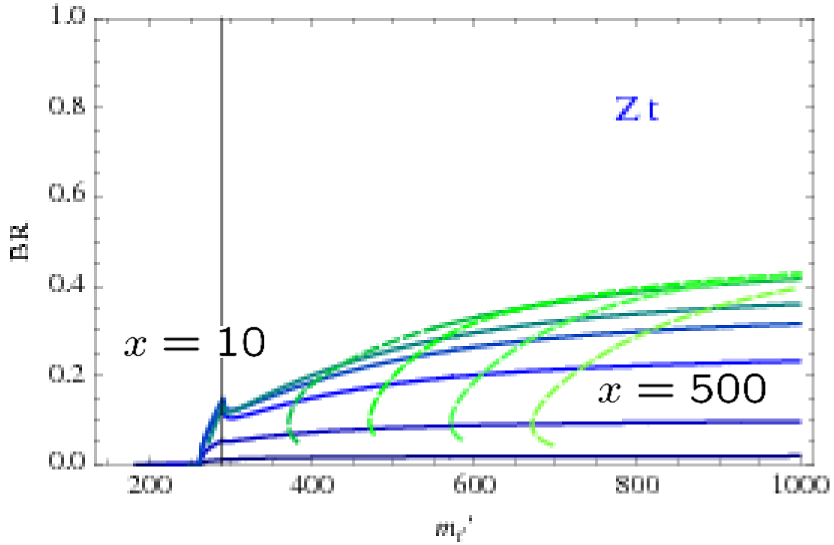


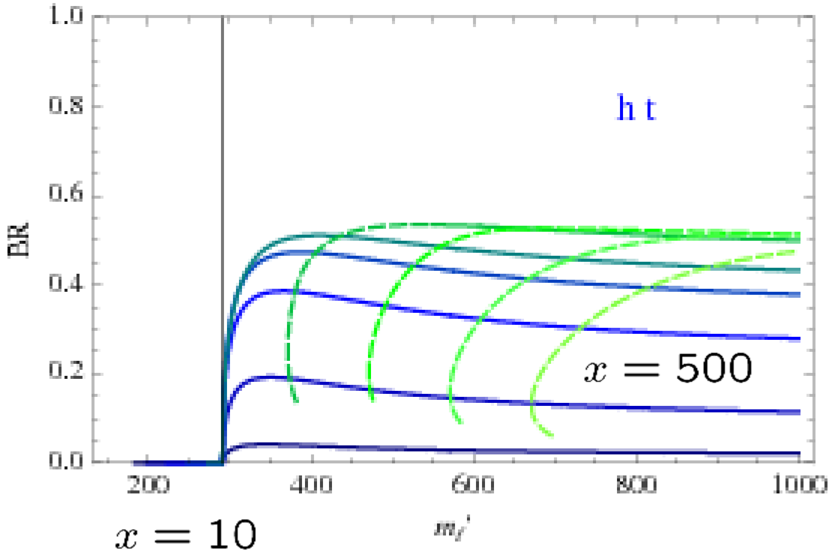
$\text{Br}(t\gamma) \sim 10^{-6}$ $\text{Br}(tg) \sim 10^{-5}$ $\text{Br}(Wb) \sim 50$ % $\text{Br}(Zt) \sim 25$ % $\text{Br}(ht) \sim 25$ %

Decays of t' in SM doublet model

$x_b = 50$ [GeV] $\quad x = 10, 25, 50, 75, 100, 200, 300, 400, 500$ [GeV]







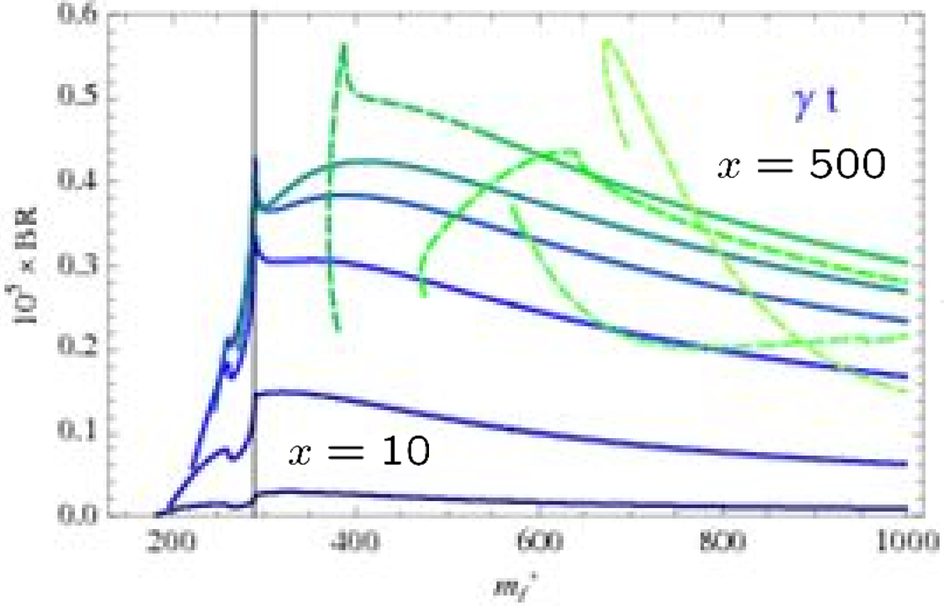
$$\Gamma(t' \to bW)/\Gamma(t' \to tZ) = 2\left(\frac{x_b}{x}\right)^2$$

$$\Gamma(t' \to th)/\Gamma(t' \to tZ) = 1$$

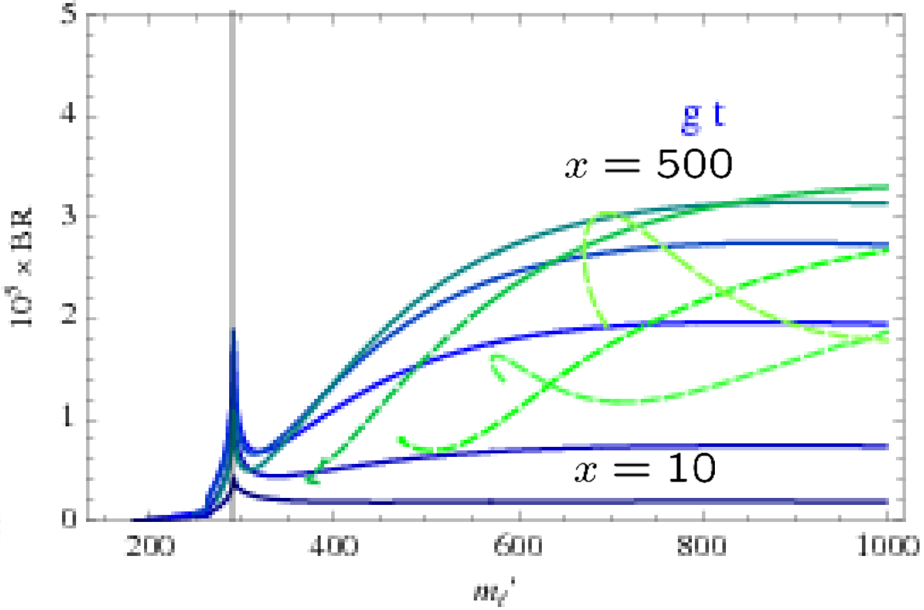
$$x = \frac{\lambda_u v}{\sqrt{2}} \quad x_b = \frac{\lambda_d v}{\sqrt{2}}$$

Decays of t' in SM doublet model

$x_b = 50$ [GeV] $\quad x = 10, 25, 50, 75, 100, 200, 300, 400, 500$ [GeV]



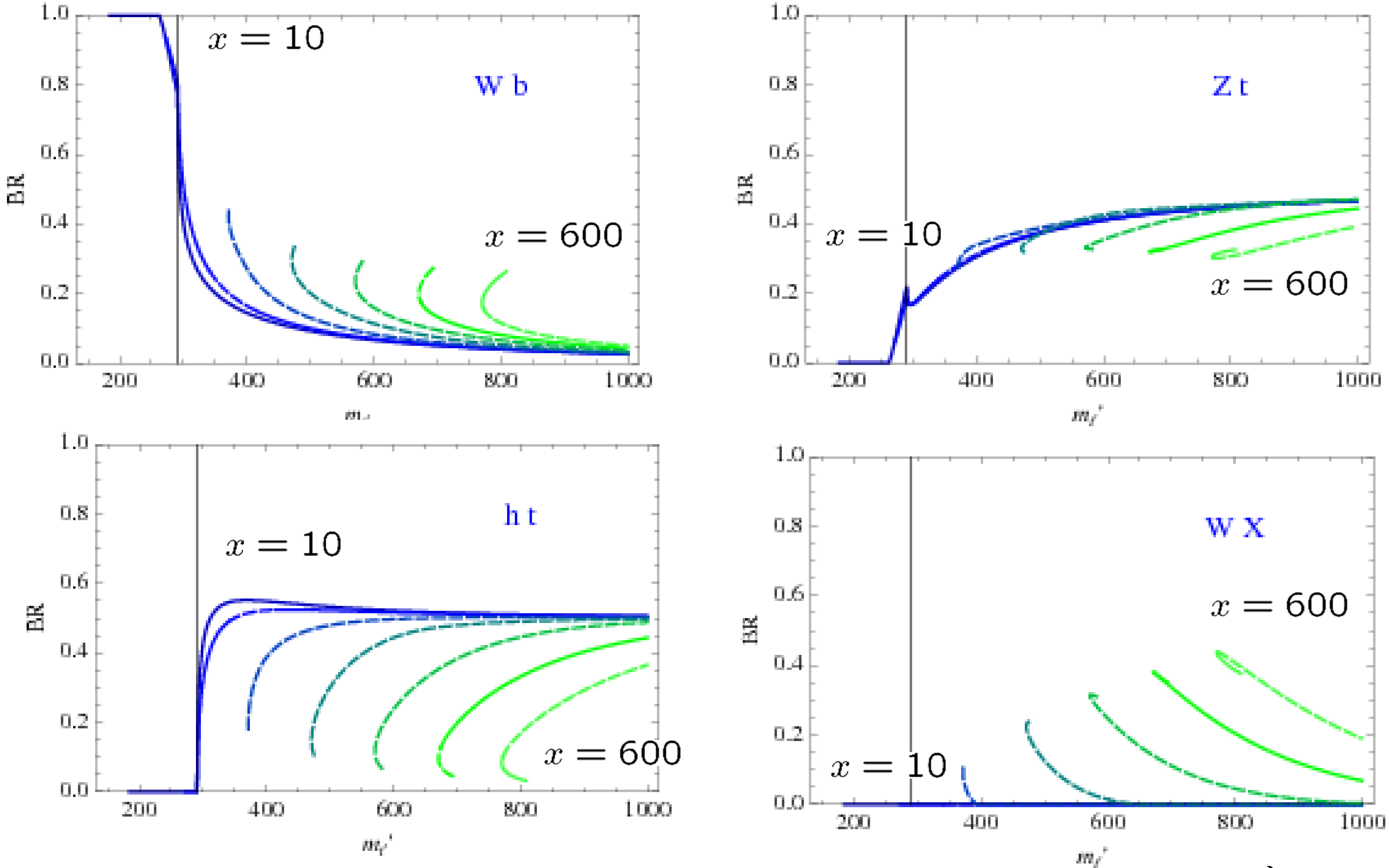
$\mathrm{Br}(t\gamma) \sim 10^{-6}$



$\mathrm{Br}(tg) \sim 10^{-5}$

Decays of t' in Non-SM doublet model

$x = 10, 100, 200, 300, 400, 500, 600$ [GeV]

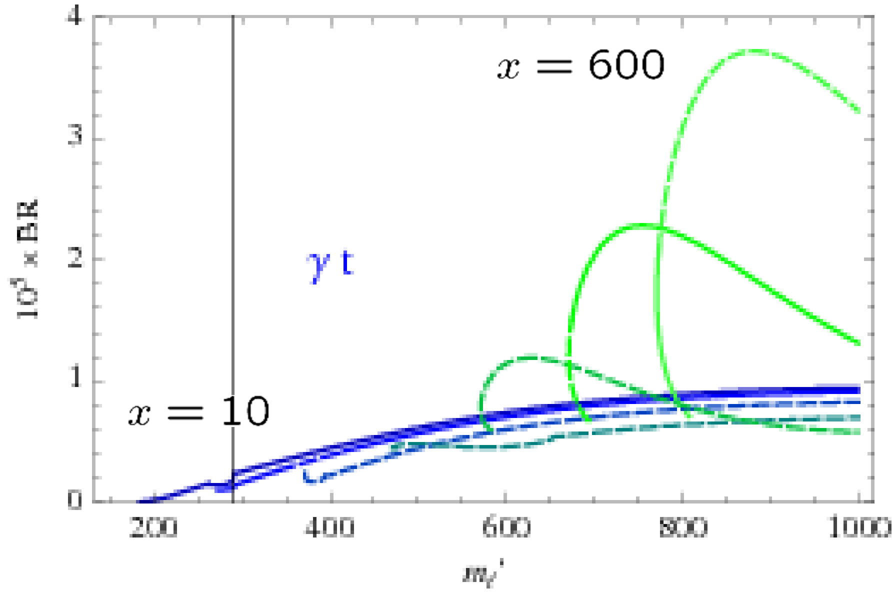


Br(Zt) ~ Br(ht) ~ 50 %

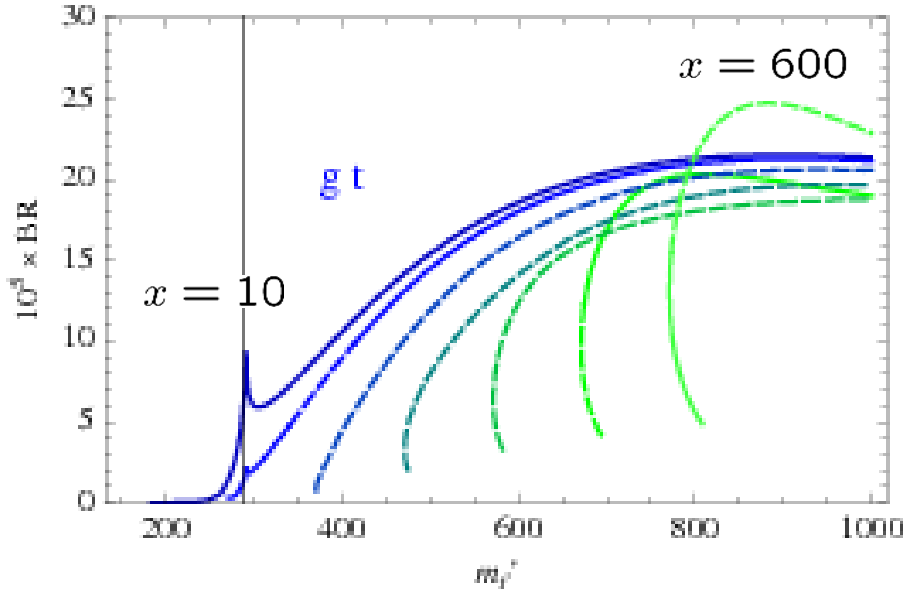
$x = \frac{\lambda_u v}{\sqrt{2}}$

Decays of t' in Non-SM doublet model

$x = 10, 100, 200, 300, 400, 500, 600$ [GeV]



$\mathrm{Br}(t\gamma) \sim 10^{-5}$



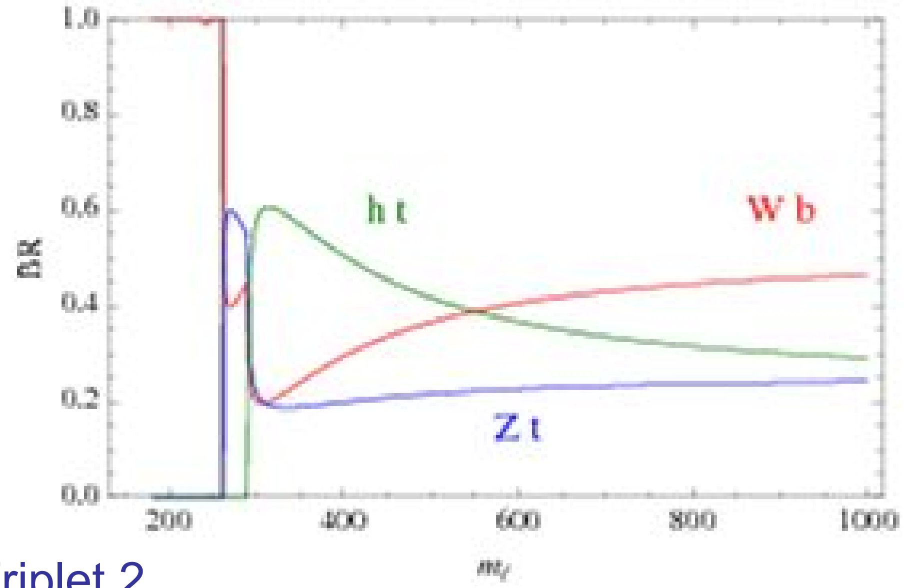
$\mathrm{Br}(tg) \sim 10^{-4}$

Decays of t’ in Triplet model

Triplet 1

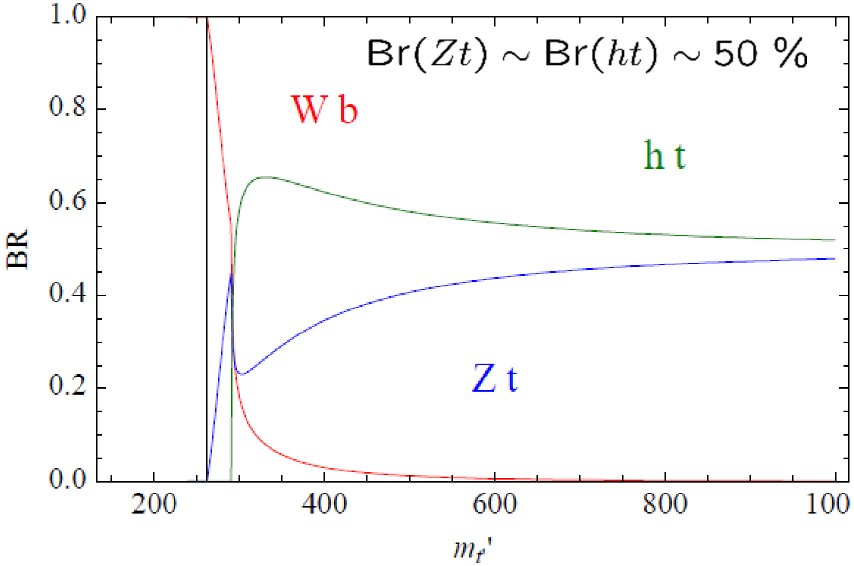
$\text{Br}(Wb) \sim 50\ \%$ $\text{Br}(Zt) \sim \text{Br}(ht) \sim 25\ \%$

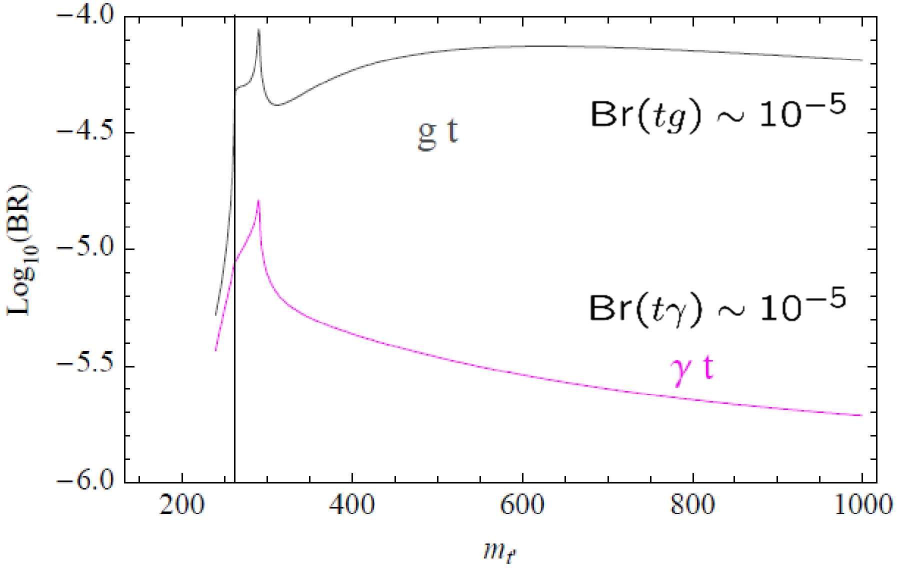
$x = 10$ [GeV] $x = \frac{\lambda v}{\sqrt{2}}$



$\text{Br}(t\gamma) \sim \text{Br}(tg) \sim 10^{-5}$

Triplet 2





Summary

We studied decay of heavy fermion in vector-like 4th generation model.

$t' \to t\gamma$ process would be detectable at the LHC (SLHC).

For $m_{t'} = 500$ [GeV]

Cross section $\sigma(pp \to t'\bar{t}') \sim 5$ [pb]

Branching ration

$x = 10$	Wb	Zt	ht	γt	gt
Singlet	0.50	0.17	0.33	4×10^{-6}	2.7×10^{-5}
SM doublet	0.95	0.017	0.03	0.21×10^{-6}	0.2×10^{-5}
Non-SM doublet	0.09	0.37	0.61	6×10^{-6}	15×10^{-5}
Triplet 1	0.36	0.22	0.42	7.2×10^{-6}	2.4×10^{-5}
Triplet 2	0.01	0.41	0.58	3.5×10^{-6}	7.1×10^{-5}

Summary

Measuring the loop decay may help to determine the size of the Yukawa interaction, and discriminate between weakly interacting models and decays of excited states of the SM fermions.

cf. Excited quark

$$\mathrm{Br}(q^* \to qg) \sim 80\ \% \qquad \mathrm{Br}(q^* \to q\gamma) \sim \text{a few}\ \%$$

Double Higgs production process is useful to distinguish 4^{th} generation quark is whether chiral or vector-like model.

In the vector-like 4^{th} generation model, a non-decoupling limit cannot be taken due to the severe experimental constraints

Backup Slide

Chiral 4th generation model

The Z branching ratio for invisible decay is

$$\mathrm{BR}(Z \to \mathrm{inv}) = 20.00 \pm 0.06\ \%$$

$$\mathrm{BR}(Z \to \nu_e \bar{\nu}_e,\ \nu_\mu \bar{\nu}_\mu,\ \nu_\tau \bar{\nu}_\tau) = 6.7\ \%$$

$\Rightarrow$ $N_\nu \sim 3$

This suggests that 3rd generation model.

However, $m_{\nu'} > \frac{m_Z}{2}$ is not excluded by LEP.

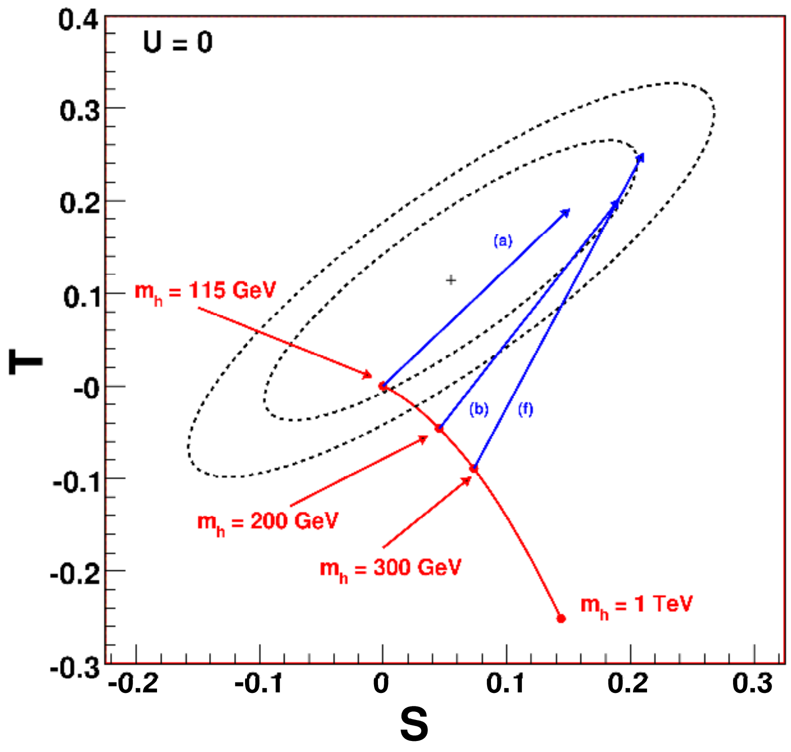
Chiral 4th generation model

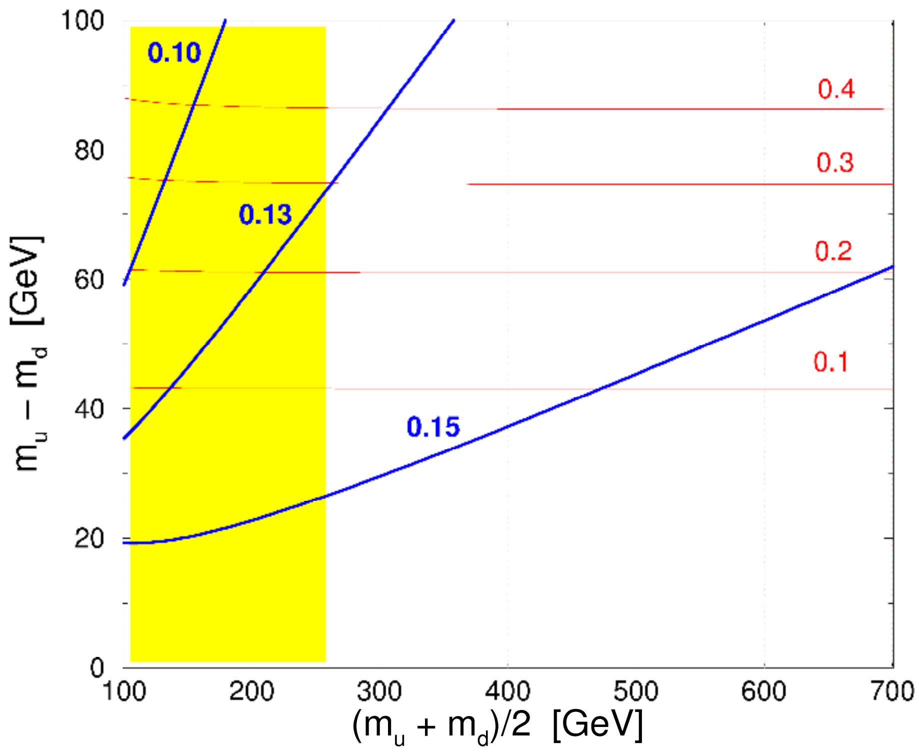
The chiral 4th generation quark t' and b'

Yukawa coupling

$$\mathcal{L}_{\rm Yuk} = -y_{t'}\bar{Q}_L t'_R\tilde{\Phi} - y_{b'}\bar{Q}_L b_R\Phi + \text{h.c.} \qquad Q_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$$

(a) $m_{t'} = 310,\ m_{b'} = 260$ [GeV]



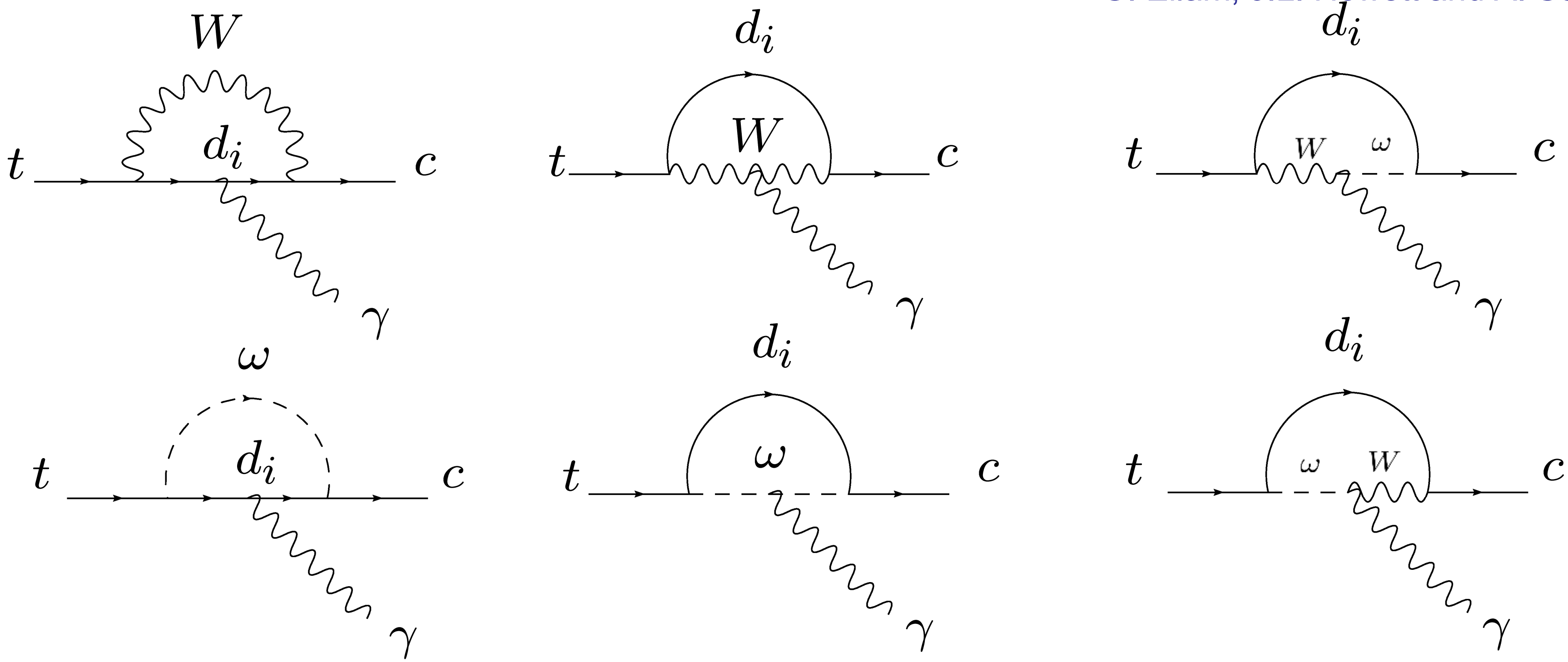


$$\Delta S = \frac{N_c}{6\pi}\left(1 - 2Y \ln \frac{m_{t'}^2}{m_{b'}^2}\right)$$

G. Kribs, T. Plehn, M. Spanowsky and T. Tait

$t \to c\gamma$ process in the SM

G. Eilam, J.L. Hewett and A. Soni



$(d_i = d, s, b)$

SM

$$Br(t \to c\gamma) \sim 4.6 \times 10^{-13}$$
$$Br(t \to cZ) \sim 10^{-13}$$
$$Br(t \to cg) \sim 4.6 \times 10^{-11}$$

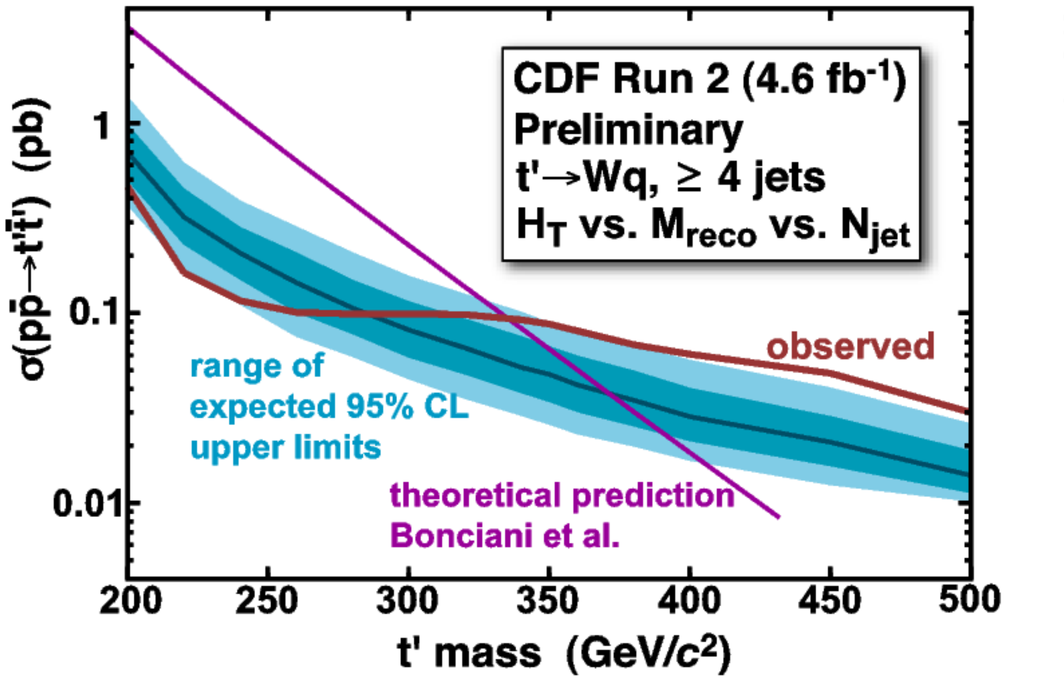
LHC Integrated luminosity $\mathcal{L} = 1\ \text{fb}^{-1}$

$$Br(t \to q\gamma) < 10^{-3}$$
$$Br(t \to qZ) < 10^{-3}$$
$$Br(t \to qg) < 10^{-2}$$

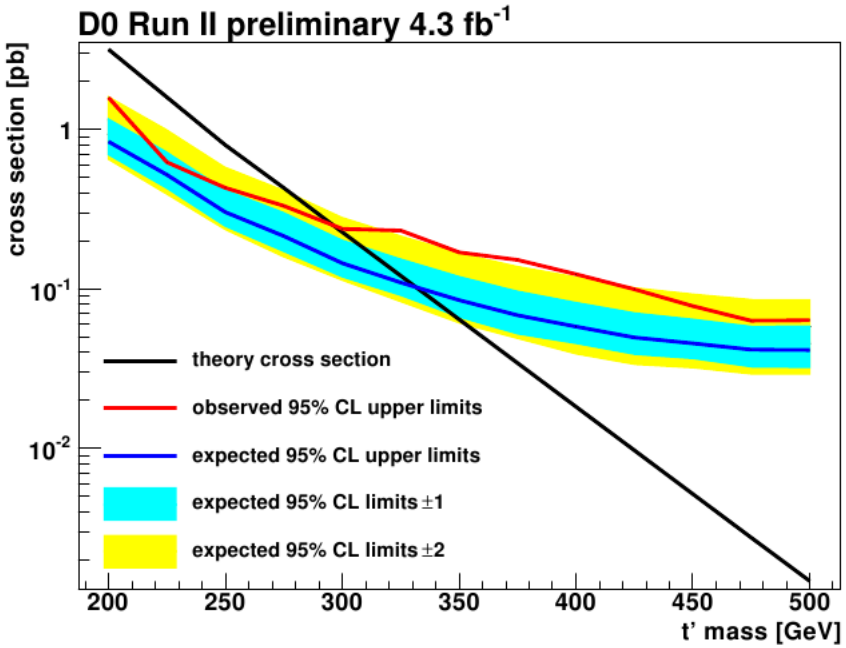
Heavy t' searches at Tevatron

$p\bar{p} \to t'\bar{t}'$

$m_{t'} - m_{b'} < m_W$ $\quad$ $\mathrm{Br}(t' \to Wq) = 100\ \%$ $\quad$ $(q = d, s, b)$



$m_{t'} < 335$ GeV (CDF2010)



$m_{t'} < 296$ GeV (D02010)