Vector-like quark multiplets, mixings and bounds

Aldo Deandrea
IPNL, Université Lyon 1 &
Institut Universitaire de France

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Outline

- Motivations
- Mixing structures
- Bounds (tree and loop level)
- Model independent framework
- Conclusions

Based on :
ArXiv:1007.2933 JHEP1011 (2010) 159
ArXiv:1108.6329 JHEP 1203 (2012) 070
ArXiv:1305.4172 Nucl. Phys. B876 (2013) 376
ArXiv: in preparation

Thanks to all my collaborators on this topic:
M.Buchkremer, G.Cacciapaglia, N.Gaur,
D.Harada, Y.Okada, L.Panizzi.

What is a vector-like fermion?

- VL currents are vectorial (like in QED), so left and right chiralities couple with the same strength

$$J^\mu = \bar{\Psi}\gamma^\mu\Psi = \bar{\Psi}_L\gamma^\mu\Psi_L + \bar{\Psi}_R\gamma^\mu\Psi_R = J^\mu_L + J^\mu_R$$

- gauge invariant mass terms independent of the Higgs mechanism are allowed and give a new scale M (L and R are in the same representation)

$$M\bar{\Psi}\Psi = M(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L)$$

- Coupling to SM fermions and Higgs via Yukawa-type interactions

Where and why (VL quarks)?

- top partners are expected in many extensions of the SM (composite/Little higgs models, Xdim models)
- they come in complete multiplets (not just singlets)
- theoretical expectation is a not too heavy mass scale M ($\sim$TeV) and mainly coupling to the 3rd generation
- Present LHC mass bounds $\sim$ 700 GeV
- Mixings bounded by EWPT, flavour…(more on this later)

Simplest multiplets (and SM quantum numbers)

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}\begin{pmatrix}t\\b\end{pmatrix}$	(t') (b')	$\begin{pmatrix}X\\t'\end{pmatrix}$ $\begin{pmatrix}t'\\b'\end{pmatrix}$ $\begin{pmatrix}b'\\Y\end{pmatrix}$	$\begin{pmatrix}X\\t'\\b'\end{pmatrix}$ $\begin{pmatrix}t'\\b'\\Y\end{pmatrix}$
$SU(2)_L$	2	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}}\bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}}\bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}}\bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

Embeddings in $SU(2)_L \times U(1)_Y$

Complete list of vector-like multiplets forming mixed Yukawa terms with the SM quark representations and a SM or SM-like Higgs boson doublet

ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}
U	$(\mathbf{1}, 2/3)$	0	$+2/3$
D	$(\mathbf{1}, -1/3)$	0	-1/3
$X^{8/3}$ $X^{5/3}$ U	$(\mathbf{3}, 5/3)$	$+2$ $+1$ 0	$+8/3$ $+5/3$ $+2/3$
$X^{5/3}$ U D	$(\mathbf{3}, 2/3)$	$+1$ 0 -1	$+5/3$ $+2/3$ $-1/3$
U D $Y^{-4/3}$	$(\mathbf{3}, -1/3)$	$+1$ 0 -1	$+2/3$ $-1/3$ $-4/3$

ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}
U D	$(\mathbf{2}, 1/6)$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
$X^{5/3}$ U	$(\mathbf{2}, 7/6)$	$+1/2$ $-1/2$	$+5/3$ $+2/3$
D $Y^{-4/3}$	$(\mathbf{2}, -5/6)$	$+1/2$ $-1/2$	$-1/3$ $-4/3$
$X^{8/3}$ $X^{5/3}$ U D	$(\mathbf{4}, 7/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+8/3$ $+5/3$ $+2/3$ $-1/3$
$X^{5/3}$ U D $Y^{-4/3}$	$(\mathbf{4}, 1/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+5/3$ $+2/3$ $-1/3$ $-4/3$
U D $Y^{-4/3}$ $Y^{-7/3}$	$(\mathbf{4}, -5/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+2/3$ $-1/3$ $-4/3$ $-7/3$

Sample effective Lagrangian

Lagrangian with the extra vector-like fermion $\psi = (X\ U)$

$$\mathcal{L}_m = -\left(\bar{Q}_L^1\ \bar{Q}_L^2\ \bar{Q}_L^3\right) \tilde{V}_{CKM} \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix} H \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}$$

SM Yukawa for down-type quarks
$\tilde{V}_{CKM}$ is the modified V_{CKM}
due to the presence of ψ

$$-\left(\bar{Q}_L^1\ \bar{Q}_L^2\ \bar{Q}_L^3\right) \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} H^c \begin{pmatrix} u_r \\ c_R \\ t_R \end{pmatrix}$$

SM Yukawa for up-type quarks

$$-\left(\lambda_1\ \lambda_2\ \lambda_3\right) \bar{\psi}_L H \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} - M(\bar{U}_L U_R + \bar{X}_L X_R)$$

ψ mass
and mixing with SM quarks

Mass matrices after the Higgs develops a VEV

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

down-type quark masses
$\tilde{m}_i \equiv \frac{y_i v}{\sqrt{2}} = m_i^{SM}$

$$-\left(\bar{u}_L\ \bar{c}_L\ \bar{t}_L\ \bar{U}_L\right) \begin{pmatrix} \tilde{m}_u & & & \\ & \tilde{m}_c & & \\ & & \tilde{m}_t & \\ x_1 & x_2 & x_3 & M \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \end{pmatrix}$$

mass matrix for up-type quarks
the heavy U induces the mixing
$x_i = \frac{\lambda^i v}{\sqrt{2}}$

$$-M\,\bar{X}_L\,X_R$$

X mass

Simplified Mixing effects (t-T sector only)

- Yukawa coupling generates a mixing between the new state(s) and the SM ones

- Type 1 : singlet and triplets couple to SM L-doublet

  - Singlet ψ = (1, 2/3) = U : only a top partner is present

  - triplet ψ = (3, 2/3) = {X, U, D} , the new fermion contains a partner for both top and bottom, plus X with charge 5/3

  - triplet ψ = (3, −1/3) = {U, D, Y} , the new fermions are a partner for both top and bottom, plus Y with charge −4/3

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

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & x \\ 0 & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Simplified Mixing effects (t-T sector only)

- Type 2 : new doublets couple to SM R-singlet
- SM doublet case ψ = (2, 1/6) = {U, D} , the vector-like fermions are a top and bottom partners
- non-SM doublets ψ = (2, 7/ 6) = {X, U} , the vector-like fermions are a top partner and a fermion X with charge 5/3
- non-SM doublets ψ = (2, -5/ 6) = {D,Y} , the vector-like fermions are a bottom partner and a fermion Y with charge -4/3

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

$$\begin{pmatrix} \cos\theta_u^L & -\sin\theta_u^L \\ \sin\theta_u^L & \cos\theta_u^L \end{pmatrix} \begin{pmatrix} \frac{y_u v}{\sqrt{2}} & 0 \\ x & M \end{pmatrix} \begin{pmatrix} \cos\theta_u^R & \sin\theta_u^R \\ -\sin\theta_u^R & \cos\theta_u^R \end{pmatrix}$$

Mixing 1VLQ (doublet) with the 3 SM generations

$$M_u = \begin{pmatrix} \tilde{m}_u & & & \\ & \tilde{m}_c & & \\ & & \tilde{m}_t & \\ x_1 & x_2 & x_3 & M \end{pmatrix} = V_L \cdot \begin{pmatrix} m_u & & & \\ & m_c & & \\ & & m_t & \\ & & & M \end{pmatrix} \cdot V_R^\dagger$$

$$V_L \implies M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & & & x_1^* \tilde{m}_u^2 \\ & \tilde{m}_c^2 & & x_2^* \tilde{m}_c^2 \\ & & \tilde{m}_t^2 & x_3 \tilde{m}_t^2 \\ x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t & |x_1|^2 + |x_2|^2 + x_3^2 + M^2 \end{pmatrix}$$

$m_q \propto \tilde{m}_q$

mixing is suppressed by quark masses

$$V_R \implies M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde{m}_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix}$$

mixing in the right sector present also for $\tilde{m}_q \to 0$

flavour constraints for q_R are relevant

Mixing expansion in x/M

$$V_R^{ij} = \begin{pmatrix} 1-\frac{|x_1|^2}{2m_X^2} & -\frac{x_1^* x_2 m_c^2}{(m_c^2-m_u^2)m_X^2} & -\frac{x_1^*\sin\theta_R}{m_X} & V_R^{14} \\ \frac{x_1 x_2^* m_u^2}{(m_c^2-m_u^2)m_X^2} & 1-\frac{|x_2|^2}{2m_X^2} & -\frac{x_2^*\sin\theta_R}{m_X} & V_R^{24} \\ 0 & 0 & \cos\theta_R+\frac{(m_{t'}^2+m_t^2)(|x_1|^2+|x_2|^2)\cos\theta_R\sin^2\theta_R}{2(m_{t'}^2-m_t^2)m_X^2} & V_R^{34} \\ V_R^{41} & V_R^{42} & V_R^{43} & V_R^{44} \end{pmatrix}$$

with:

$$V_R^{ut'} = \frac{x_1^*\cos\theta_R}{m_X}, \quad V_R^{ct'} = \frac{x_2^*\cos\theta_R}{m_X}, \quad V_R^{tt'} = \sin\theta_R - \frac{(m_{t'}^2+m_t^2)(|x_1|^2+|x_2|^2)\cos^2\theta_R\sin\theta_R}{2(m_{t'}^2-m_t^2)m_X^2},$$

$$V_R^{t'u} = -\frac{x_1}{m_X}, \quad V_R^{t'c} = -\frac{x_2}{m_X}, \quad V_R^{t't} = -\sin\theta_R + \frac{(|x_1|^2+|x_2|^2)(3m_{t'}^2-m_t^2+(m_{t'}^2+m_t^2)\cos 2\theta_R)\sin\theta_R}{4(m_{t'}^2-m_t^2)m_X^2},$$

$$V_R^{t't'} = \cos\theta_R - \frac{(|x_1|^2+|x_2|^2)(m_{t'}^2-3m_t^2-(m_{t'}^2+m_t^2)\cos 2\theta_R)\sin\theta_R}{4(m_{t'}^2-m_t^2)m_X^2}.$$

Mixing with more VL multiplets

integer isospin multiplets

$$
\mathcal{L}_{\text{mass}} = \bar{q}_L \cdot \left(\begin{array}{ccc|ccc|ccc}
\mu_1 & 0 & 0 & 0 & \dots & 0 & x_{1,n_d+4} & \dots & x_{1,N} \\
0 & \mu_2 & 0 & 0 & \dots & 0 & x_{2,n_d+4} & \dots & x_{2,N} \\
0 & 0 & \mu_3 & 0 & \dots & 0 & x_{3,n_d+4} & \dots & x_{3,N} \\
\hline
y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 & & & \\
\vdots & \vdots & \vdots & 0 & \ddots & 0 & & \omega_{\alpha\beta} & \\
y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} & & & \\
\hline
0 & 0 & 0 & & & & M_{n_d+4} & 0 & 0 \\
\vdots & \vdots & \vdots & & \omega'_{\alpha\beta} & & 0 & \ddots & 0 \\
0 & 0 & 0 & & & & 0 & 0 & M_N
\end{array} \right) \cdot q_R + h.c.
$$

semi-integer isospin multiplets

Mixing structure

- $n_d \times 3$ matrix y of the Yukawa couplings of the VL doublets (semi-integer isospin)
- $3 \times n_s$ matrix x of the Yukawa couplings of the VL singlets/triplets (integer isospin)
- M_α are the VL masses of the new representations
- $n_d \times n_s$ matrix ω and $n_s \times n_d$ matrix ω' contain the Yukawa couplings among VL representations
- ω' couplings correspond to the “wrong” (opposite) chirality configuration with respect to SM Yukawa couplings

Bounds

- Tree-level bounds
  - FCNC effects at tree level due to mixing
  - W → t b, ~ +/-20% variation still allowed (TeVatron data)
  - Z → b b +1% → -0.2% in the left coupling and +20% → -5% in the right coupling (L and R are correlated)
  - Atomic parity violation (weak charge affected by FCNC of Z → light quarks)
- Loop level bounds
  - new particles are expected in the loops (not only the new heavy fermions)
  - FCNC effects at loop level
  - Precision EW tests with the T-parameter, but other new particle may affect the result

Tree level bounds

- Rare top decays (induced by mixing)

$$\frac{\Gamma(t \to Zu) + \Gamma(t \to Zc)}{\Gamma(t \to Wb)} < 0.34\%$$

measured at CMS @ $4.6\, fb^{-1}$

implies :

$$|V_R^{t't}| \sqrt{|V_R^{t'u}|^2 + |V_R^{t'c}|^2} < 0.08 |V_{tb}|$$

- Z → cc coupling from LEP

$$g_{ZL}^c = 0.3453 \pm 0.0036$$
$$g_{ZR}^c = -0.1580 \pm 0.0051$$

implies :

$$|V_R^{t'c}| < 0.2$$

Weak charge of nuclei

- Atomic parity violation, weak charge :

$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL}+g^u_{ZR})+(Z+2N)(g^d_{ZL}+g^d_{ZR})\right]$$

for Cesium:

$$Q_W(^{133}\mathrm{Cs})|_{exp} = -73.20 \pm 0.35 \qquad Q_W(^{133}\mathrm{Cs})|_{SM} = -73.15 \pm 0.02$$

- at 3 sigmas this implies :

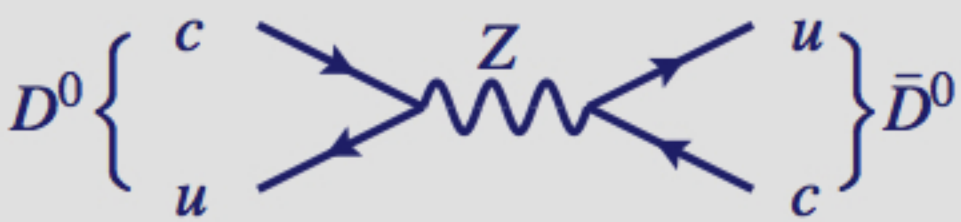
$$\delta Q_W = -(2Z+N)|V_R^{t'u}|^2 \qquad |V_R^{t'u}| < 7.8 \times 10^{-2}$$

FCNC tree level (if no b')

- D-Dbar mixing and D → l+l- :

Contribution of the right-handed couplings in the vector-like scenario

Mixing ($\Delta C = 2$):



$$\delta x_D = f(m_D, \Gamma_D, m_c, m_Z)(g_{ZR}^{uc})^2$$

Decay ($\Delta C = 1$):

$$\delta BR = g(m_D, \Gamma_D, m_l, m_Z)(g_{ZR}^{uc})^2$$

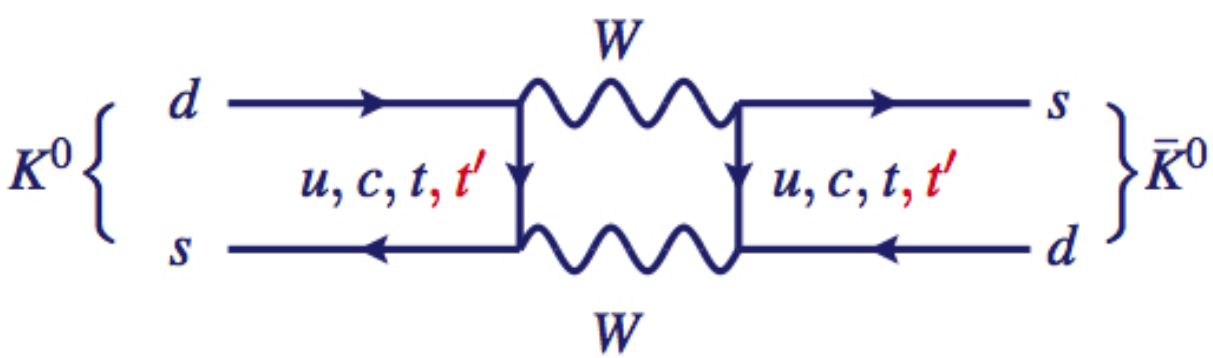
- strongest bound from xD :

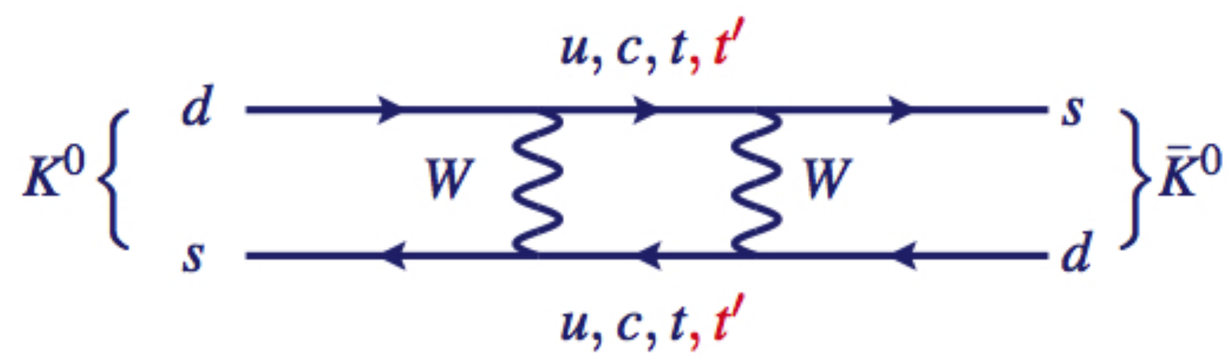
$$x_D = \frac{\Delta m_D}{\Gamma_D} = 0.0100^{+0.0024}_{-0.0026}$$

$$(g_{ZR}^{uc})^2 = \frac{\pi\alpha}{c_W^2 s_W^2} |V_R^{t'u}|^2 |V_R^{t'c}|^2 \quad \Longrightarrow \quad |V_R^{t'u}||V_R^{t'c}| < 3.2 \times 10^{-4} \quad @3\sigma$$

Kaons

- t' in the loop :





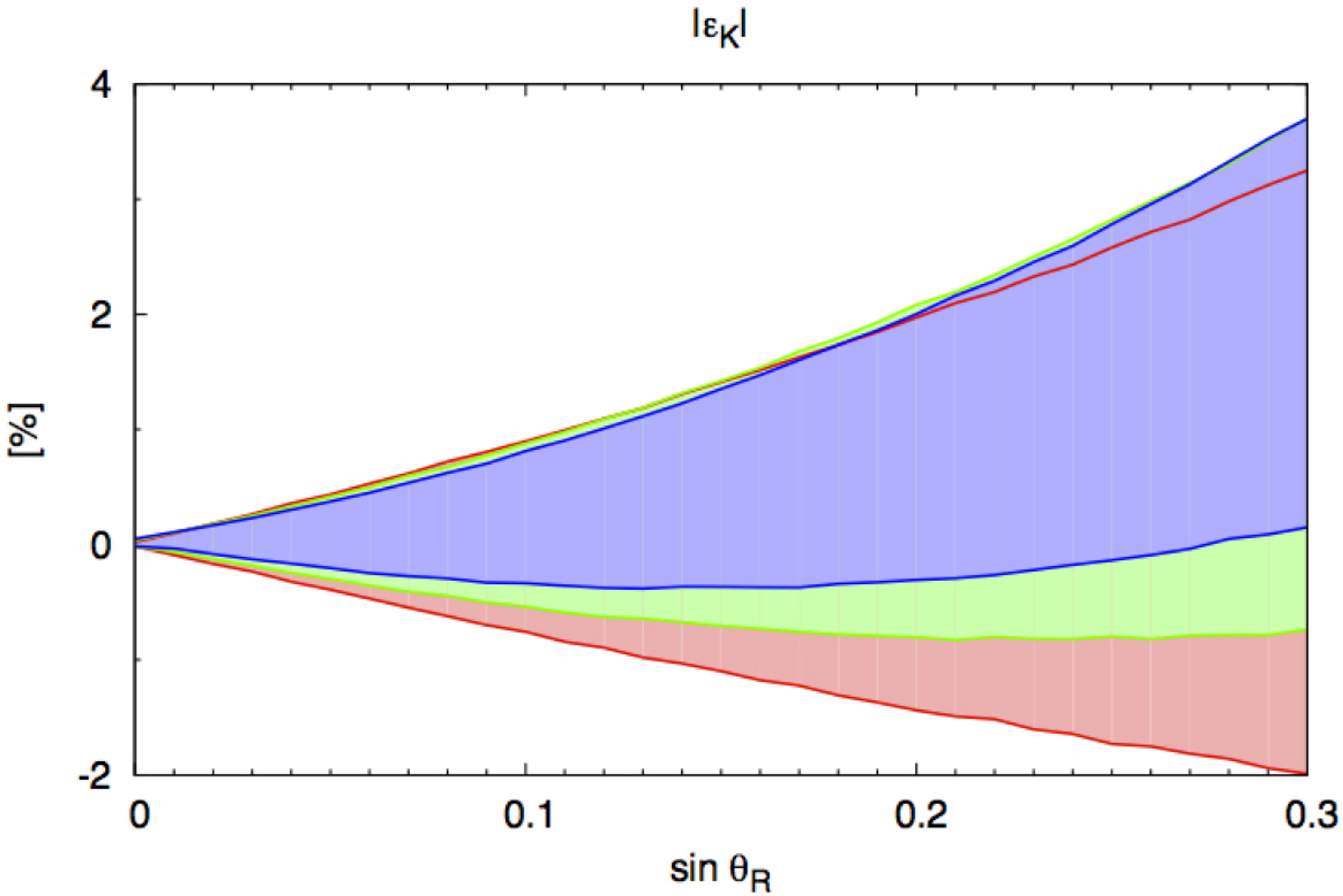
$$\Delta m_K \equiv m_{K_L} - m_{K_S} = 2Re\, M_{12} \simeq 2|M_{12}|$$

$$\epsilon_K \simeq \frac{e^{i\pi/4}}{\sqrt{2}\Delta m_K} Im\, M_{12}$$

$$\Delta m_K|_{exp} = (3.483 \pm 0.006) \times 10^{-15}\ GeV \quad |\epsilon_K|_{exp} = (2.233 \pm 0.015) \times 10^{-3}$$

corrections to ϵ_K in the 4% range

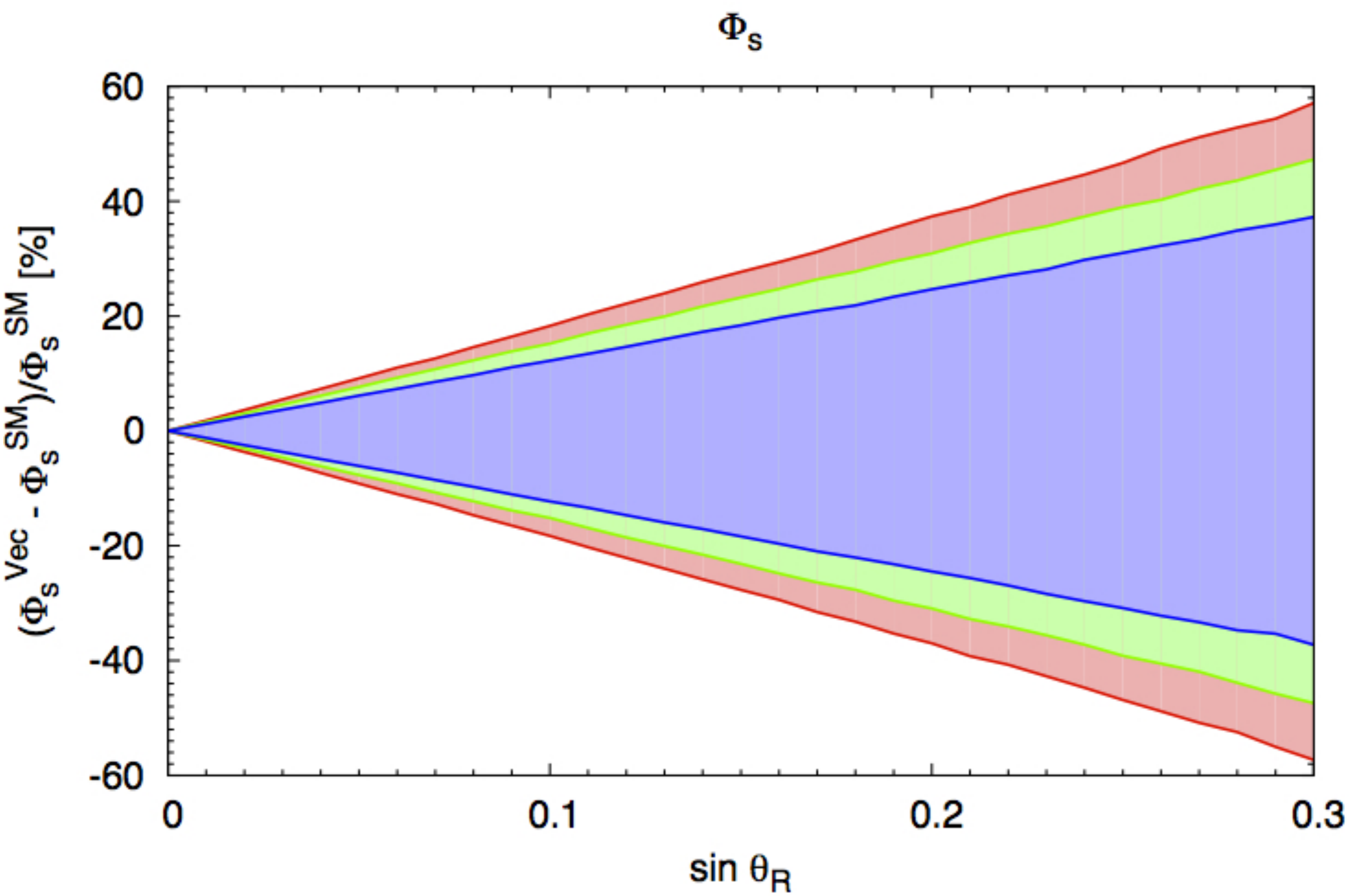
Kaons



Parameters: $|V_R^{t'u}| \leq 0.078 \qquad |V_R^{t'c}| \leq 0.2 \qquad |V_R^{t'u}||V_R^{t'c}| \leq 3.2 \times 10^{-4}$

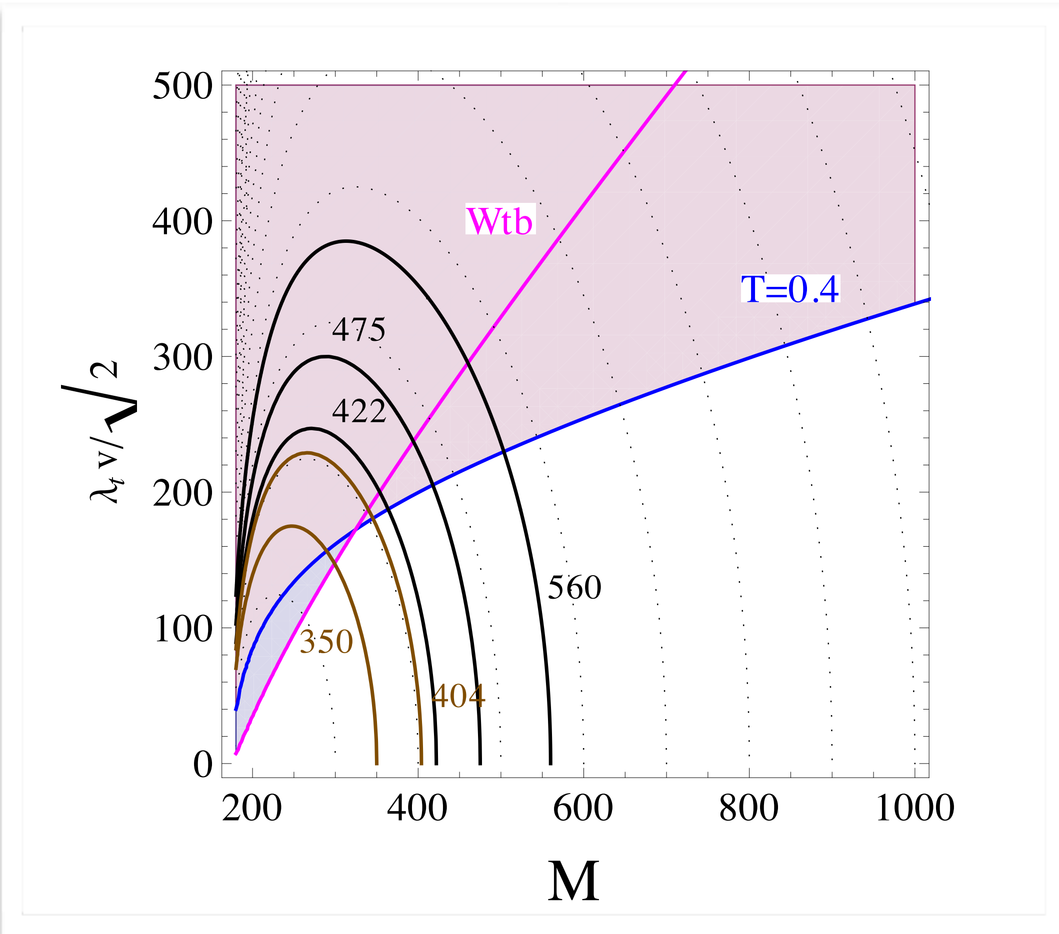
Mt' = 350, 500, 1000 GeV

Bs-mesons

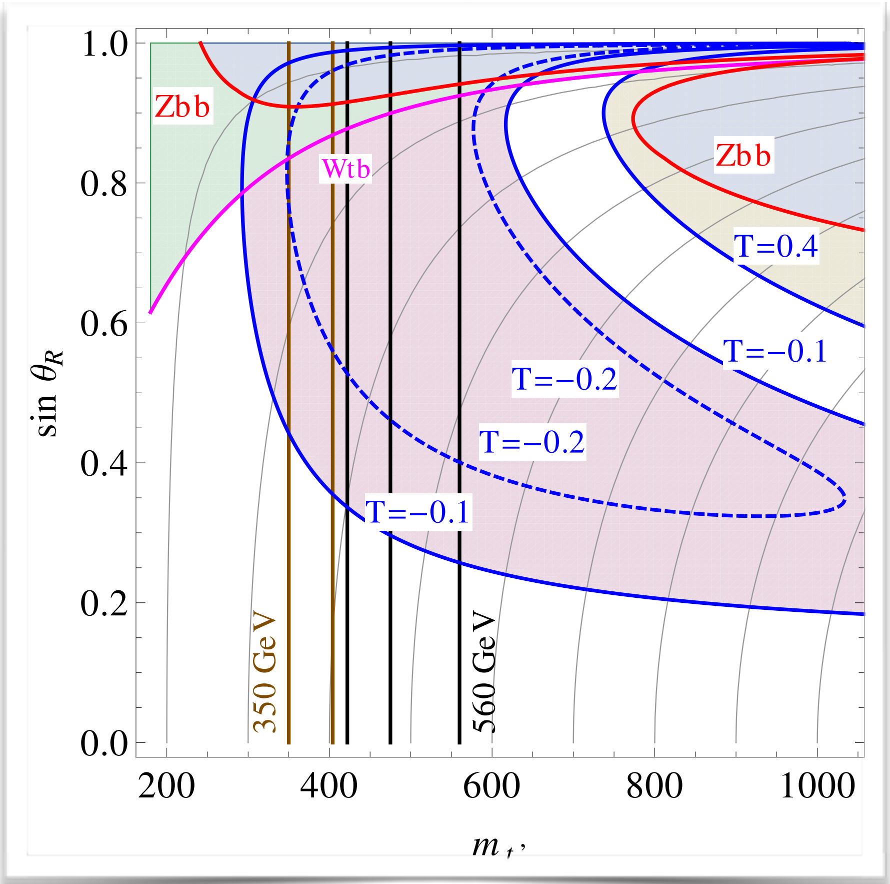


Effect on phase up to 60% as in many BSM models. To be checked with CPV in $B_s \to J/\Psi\ \phi$.

EW precision tests

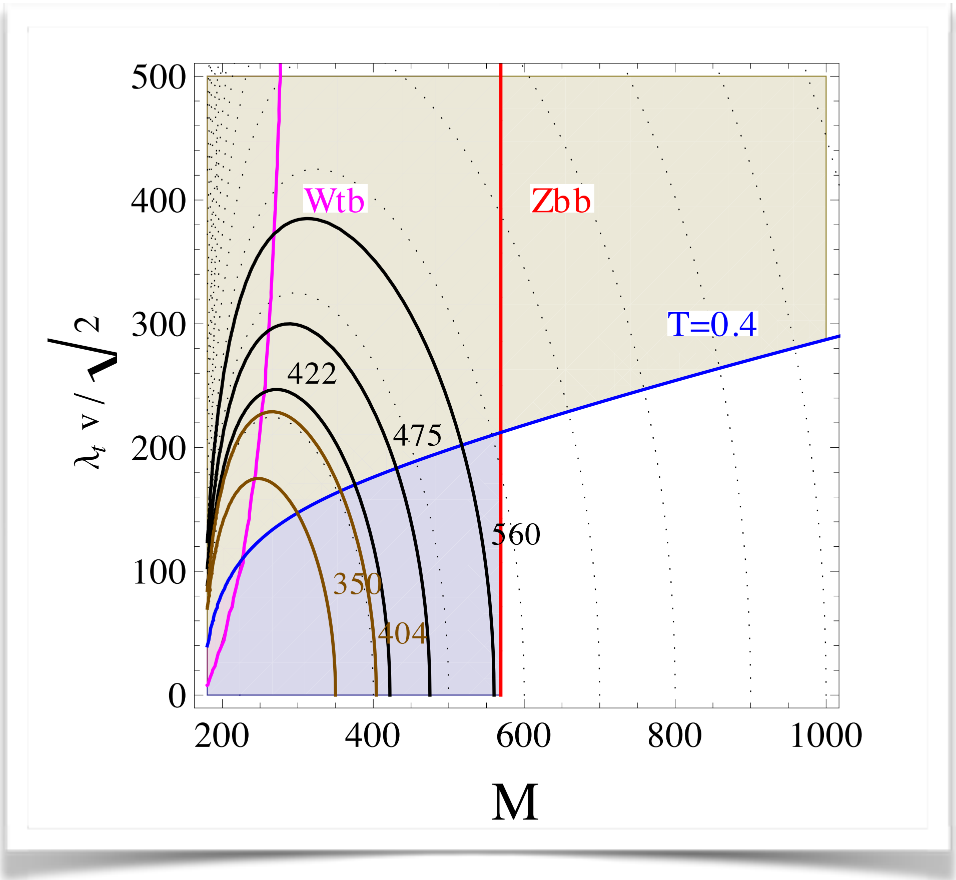


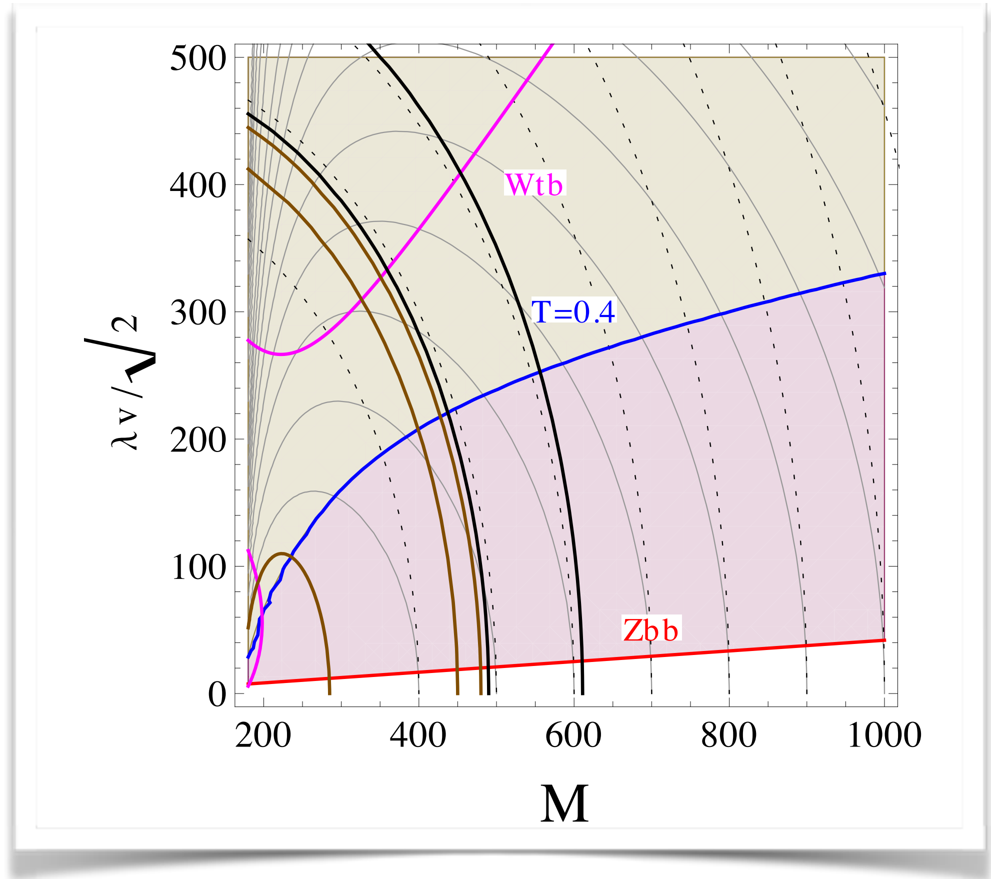
Singlet



non-SM doublet

EW precision tests

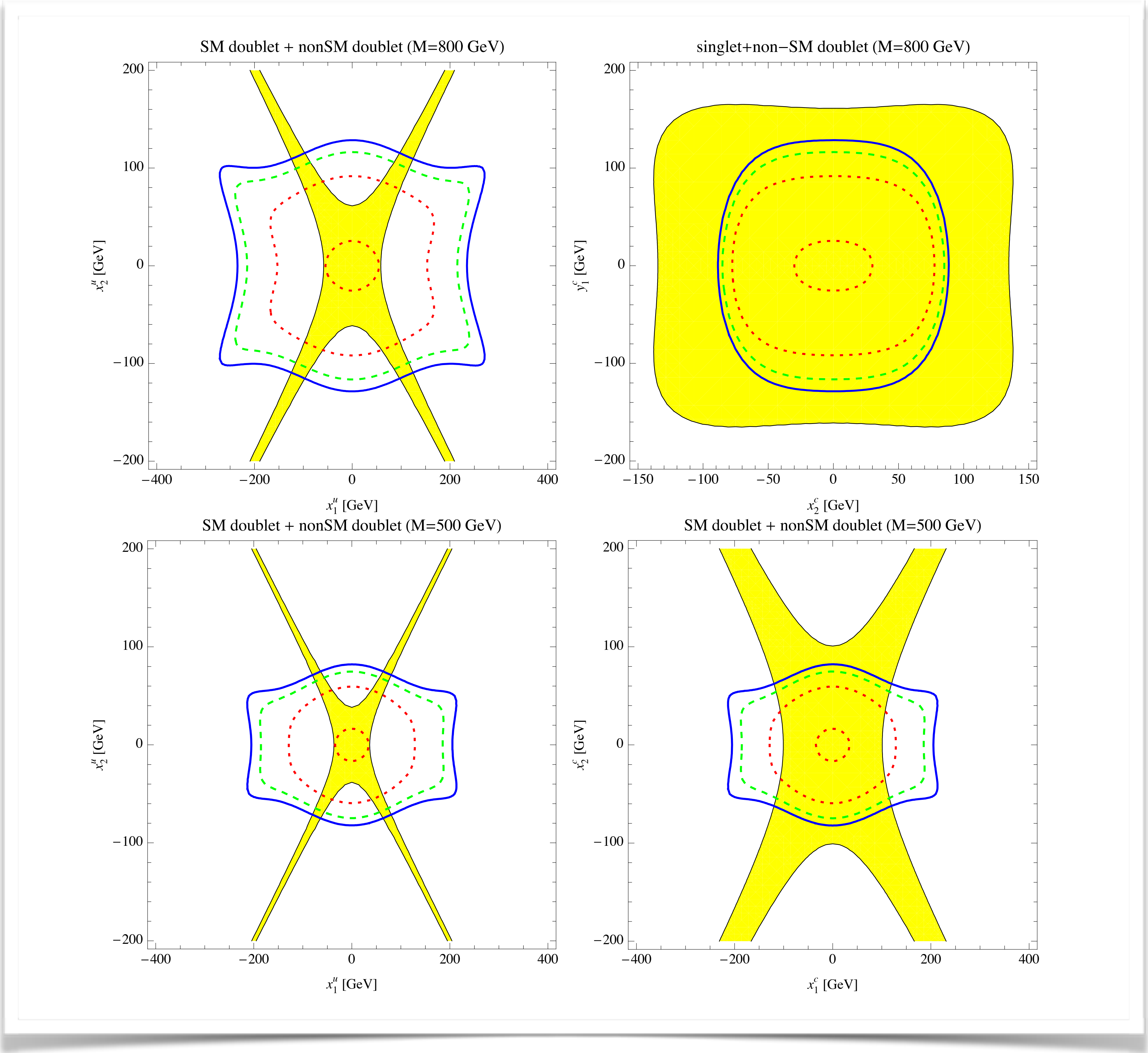




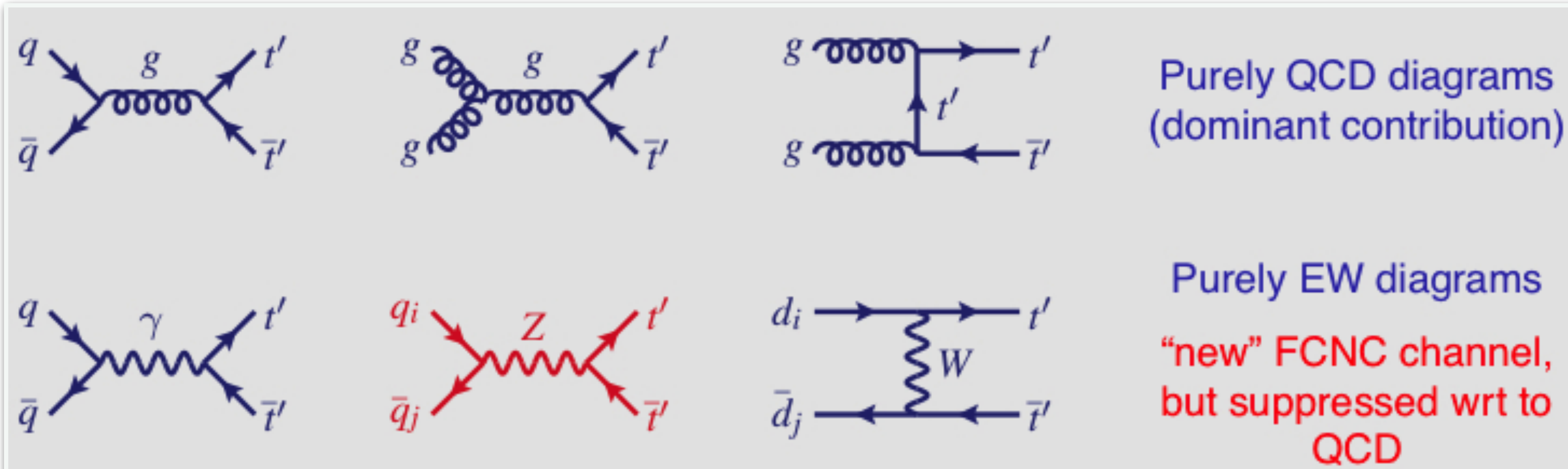
SM-like doublet

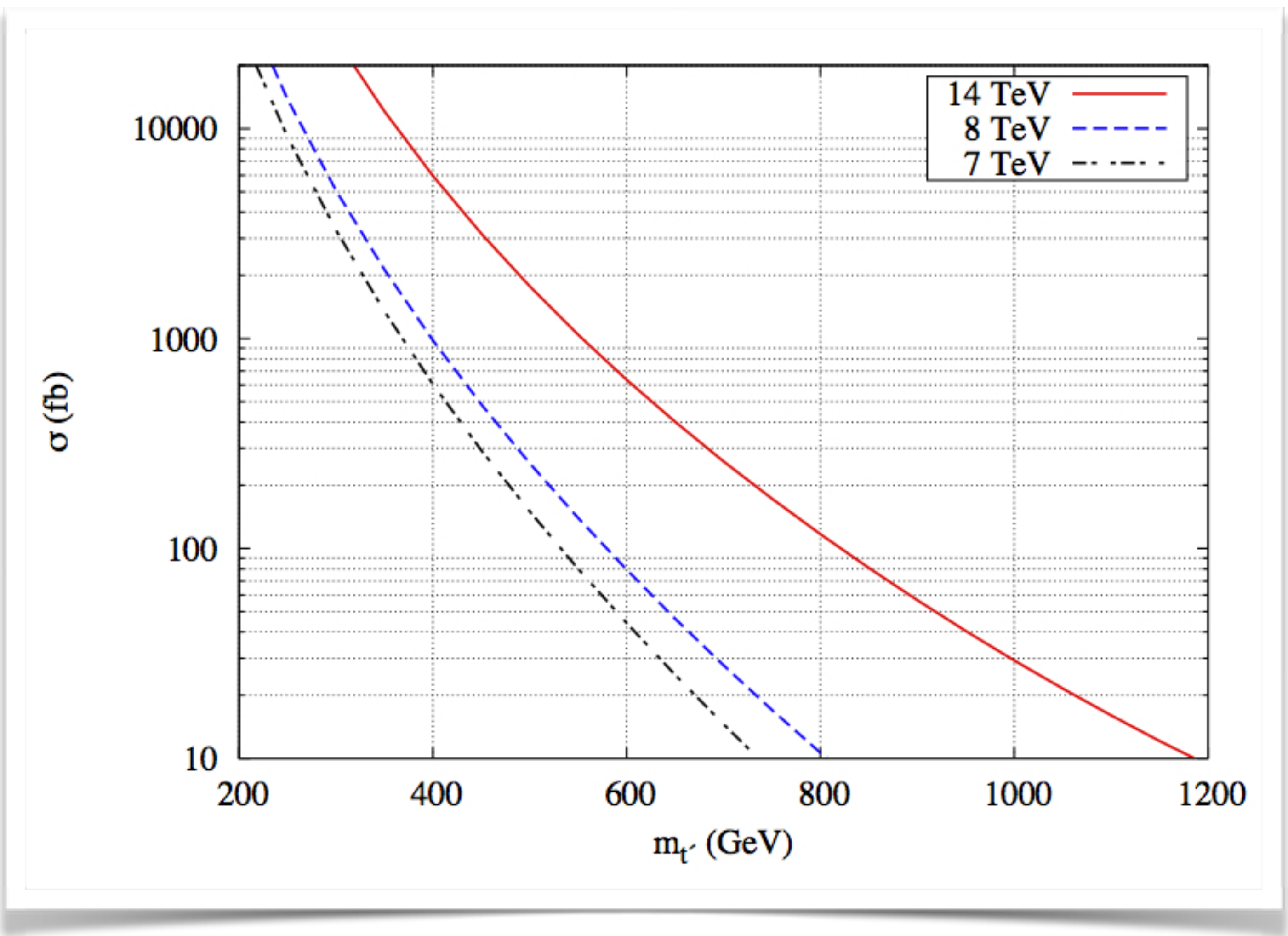
Triplet

EW bounds (2 VL multiplets)



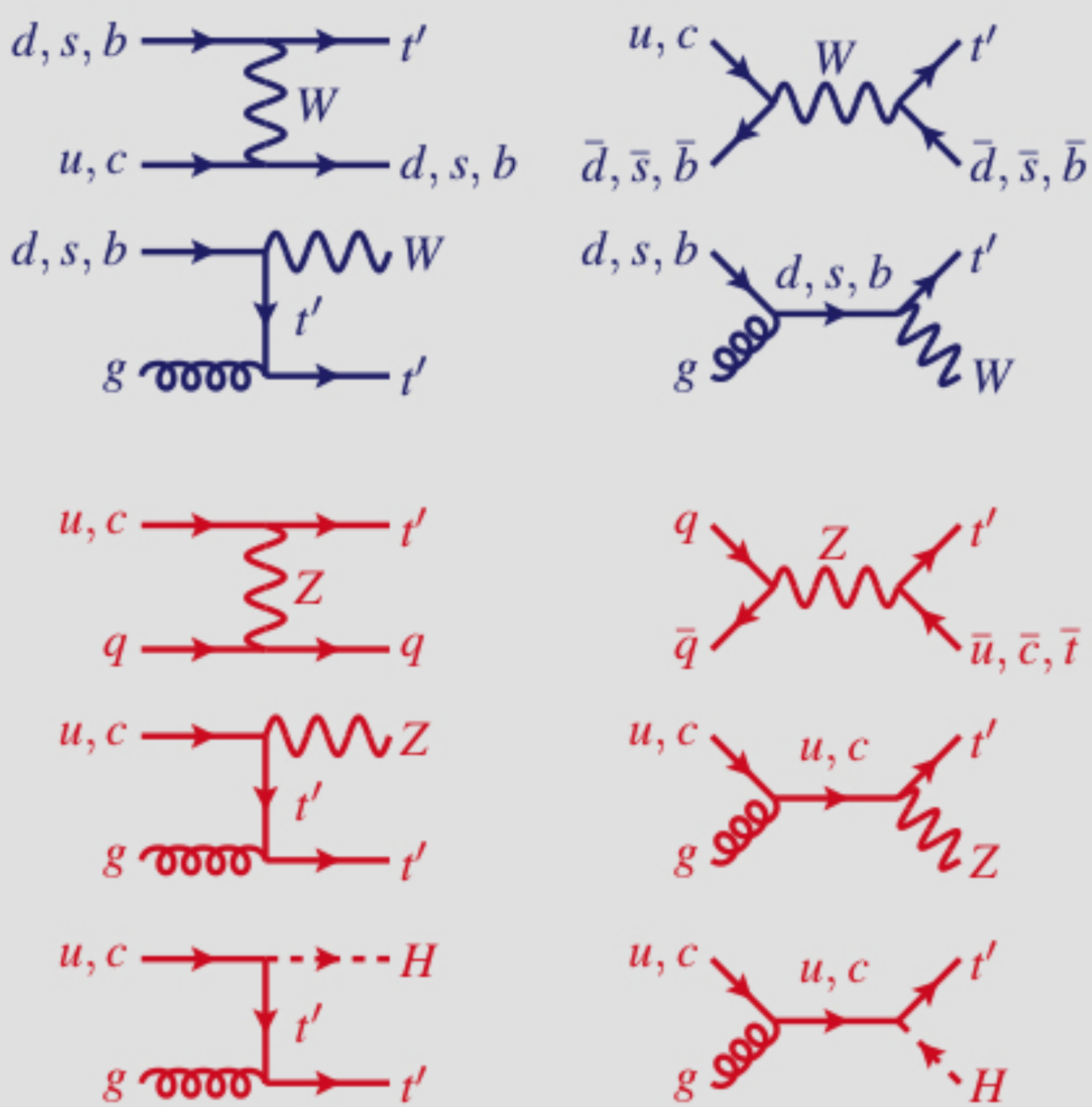
Pair production





Pair production for t'
of the non-SM doublet
pp → t' t @ LHC

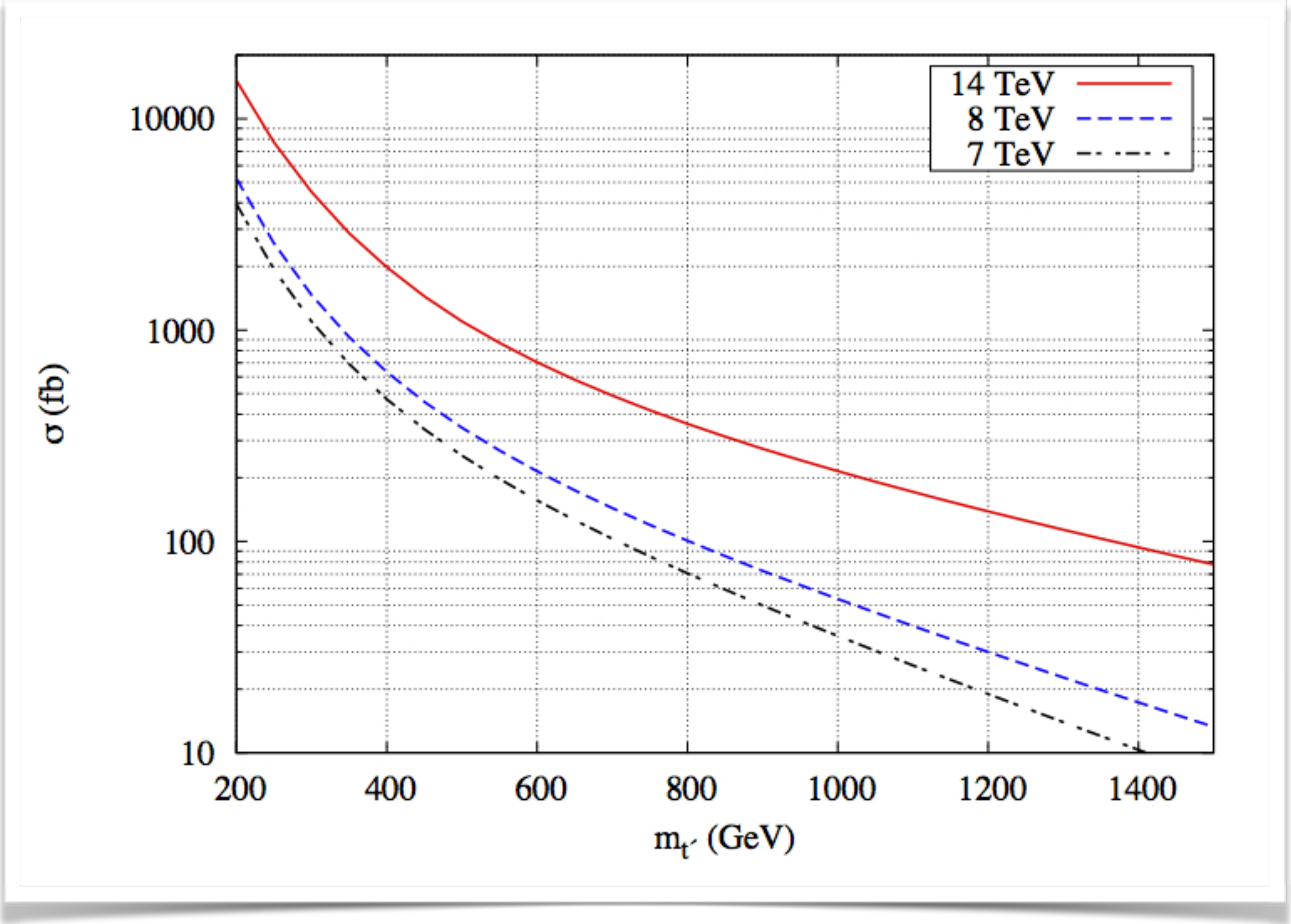
Single production



Charged current channels are suppressed in $(X \;\; t')$ doublet, non-suppressed in singlet and triplets

FCNCs channels can be relevant in single production especially in the singlet t' and $(X \;\; t')$ doublet

Single production



Non-SM doublet single t' production cross section
as function of the t' mass

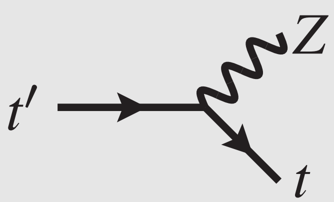
t’ decays

Decay modes never 100% in one channel, in the limit of the equivalence theorem, dictated by the multiplet representation :

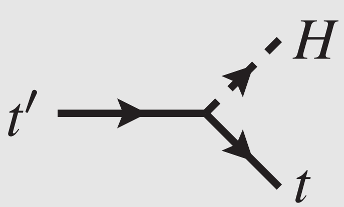
t’	Wb	Zt	ht
Singlet, Triplet Y=2/3	50%	25%	25%
Doublet, Triplet Y=-1/3	~0%	50%	50%

T’ decays

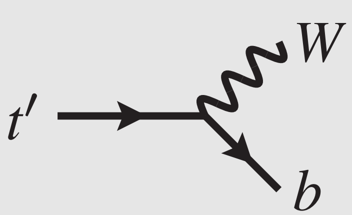
Different possibilities for t' decay ($\sin\theta_R = 0.3$, i.e. mixing with top dominates)



$$pp \to j\,(t' \to t\,Z) \to j\,(t \to b\,l^+\,\nu)\,(Z \to \nu\,\bar{\nu}) \to j\,b\,l^+\,\not{E}_T$$
$$\to j\,(t \to b\,l^+\,\nu)\,(Z \to l^+\,l^-) \to j\,b\,l^+\,l^+\,l^-\,\not{E}_T$$
$$\to j\,(t \to b\,l^+\,\nu)\,(Z \to j\,j) \to j\,j\,j\,b\,l^+\,\not{E}_T$$



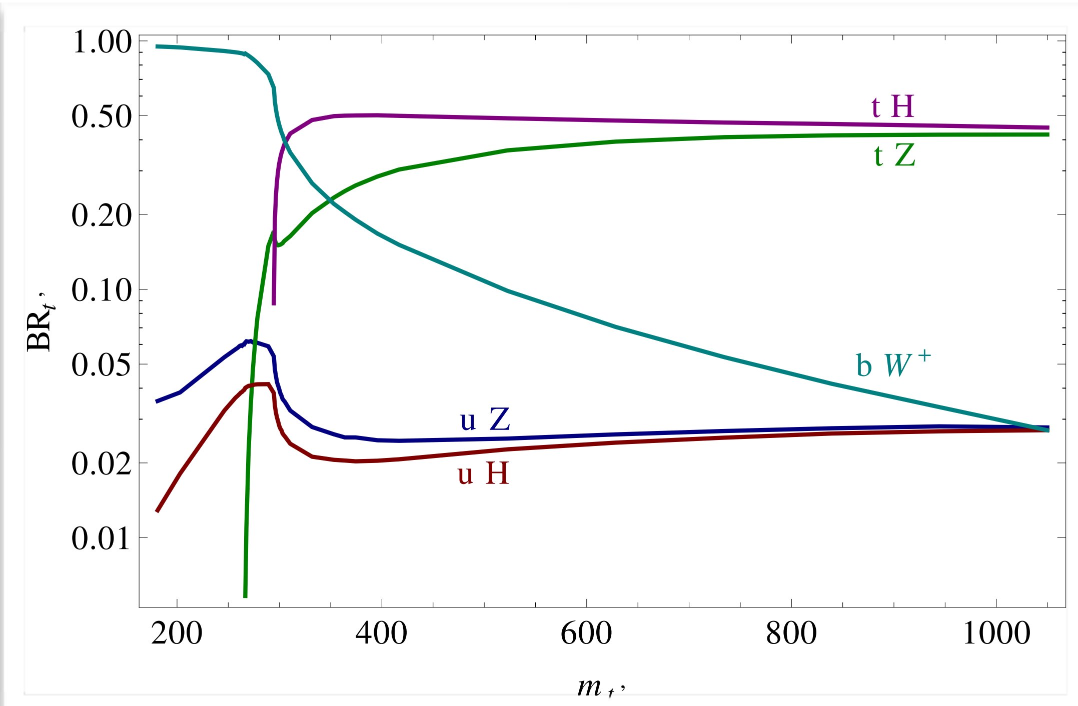
$$pp \to j\,(t' \to t\,H) \to j\,(t \to b\,l^+\,\nu)\,(H \to b\,\bar{b}) \to b\,\bar{b}\,b\,l^+\,\not{E}_T$$



$$pp \to j\,(t' \to b\,W) \to j\,b\,(W \to l^+\,\nu) \to j\,b\,l^+\,\not{E}_T$$

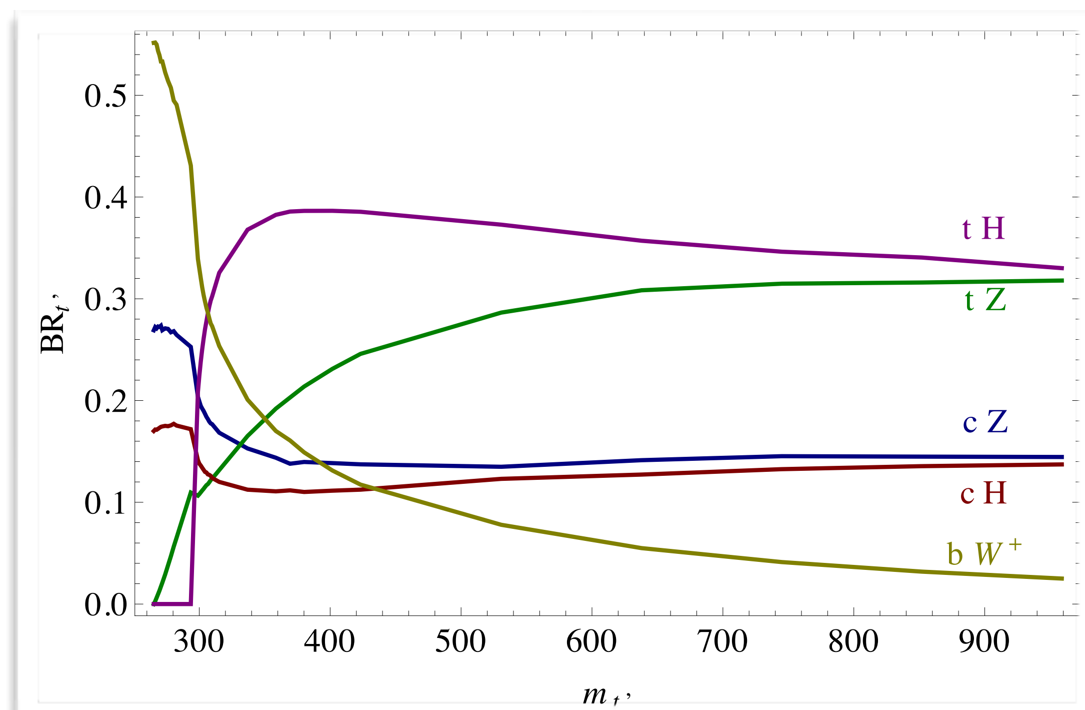
Assuming for example κ = 0.1 and RL =50% cross-sections are
~500 fb for t' in singlet or non-standard doublet and
~200 fb for t' in standard doublet
Production in association with light quarks is ~ 90%
See table 8 of ArXiv:1305.4172

T’ decays ($X^{5/3}$,T’) multiplet



Mixing mostly with top
V_R^{41} maximal

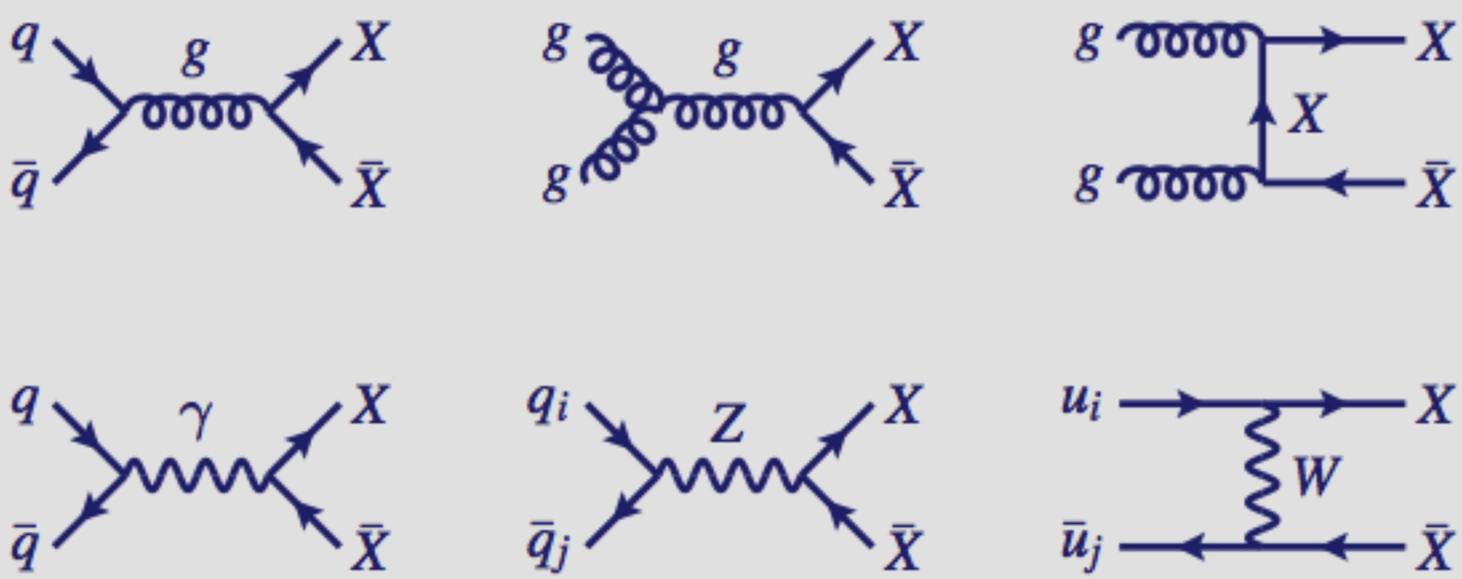
Mixing mostly with top
V_R^{42} maximal



In all cases T' → bW
NOT dominant for allowed masses

$X^{5/3}$ production

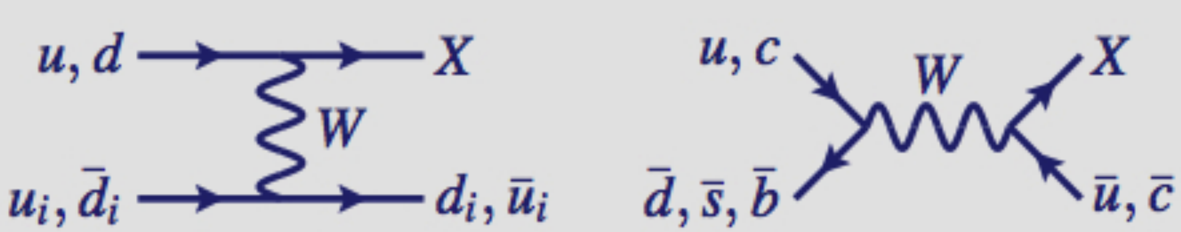
Pair production



Purely QCD diagrams (dominant contribution)

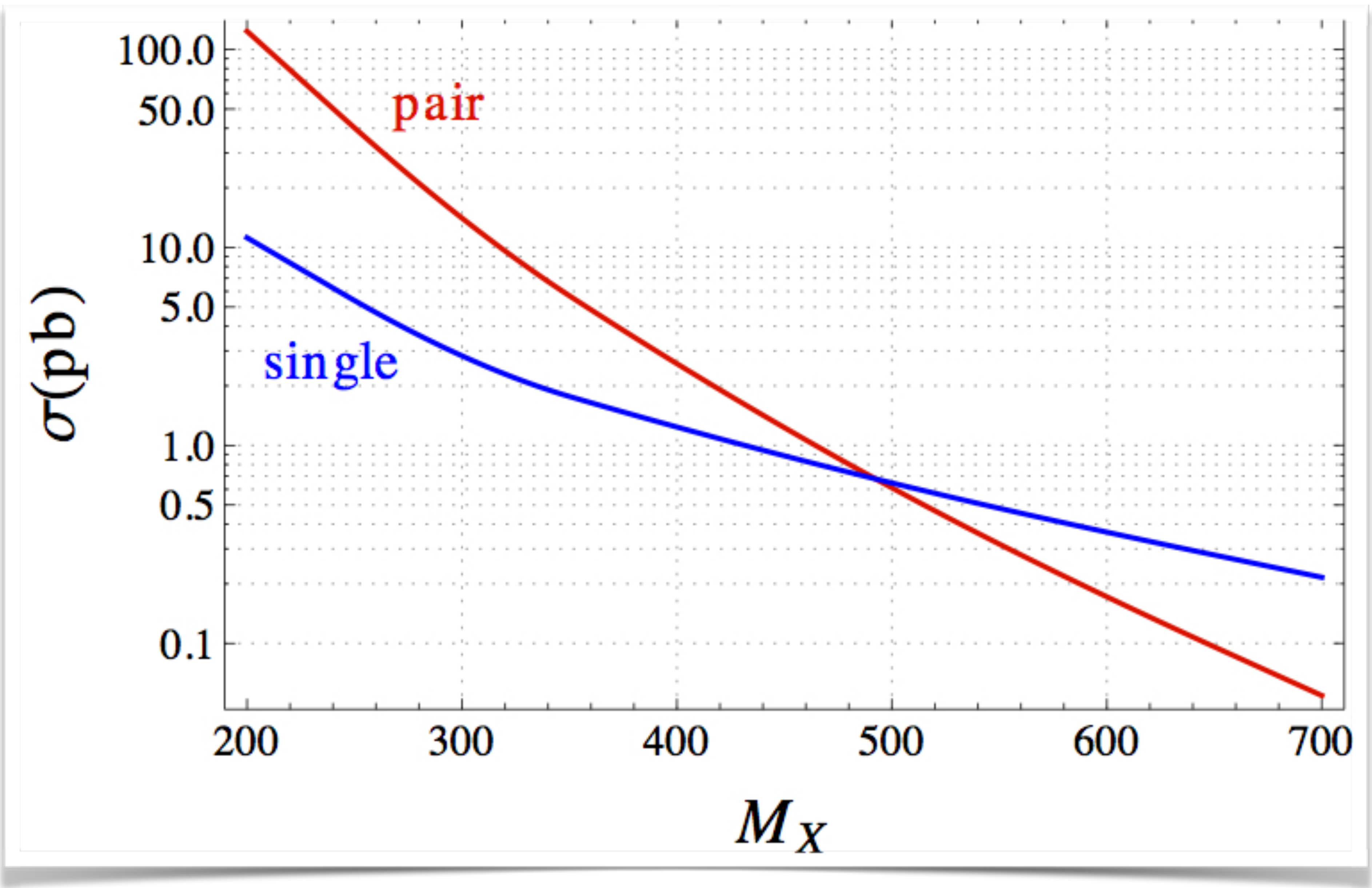
Purely EW diagrams

Single production

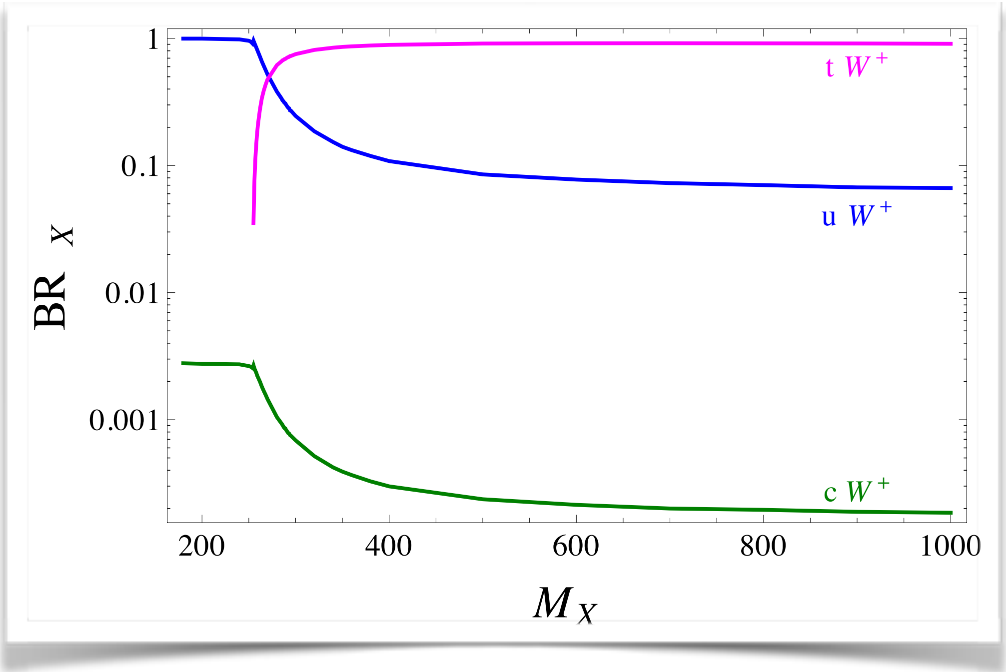


Charged current channels are suppressed in doublets, non-suppressed in singlet and triplets

$X^{5/3}$ production

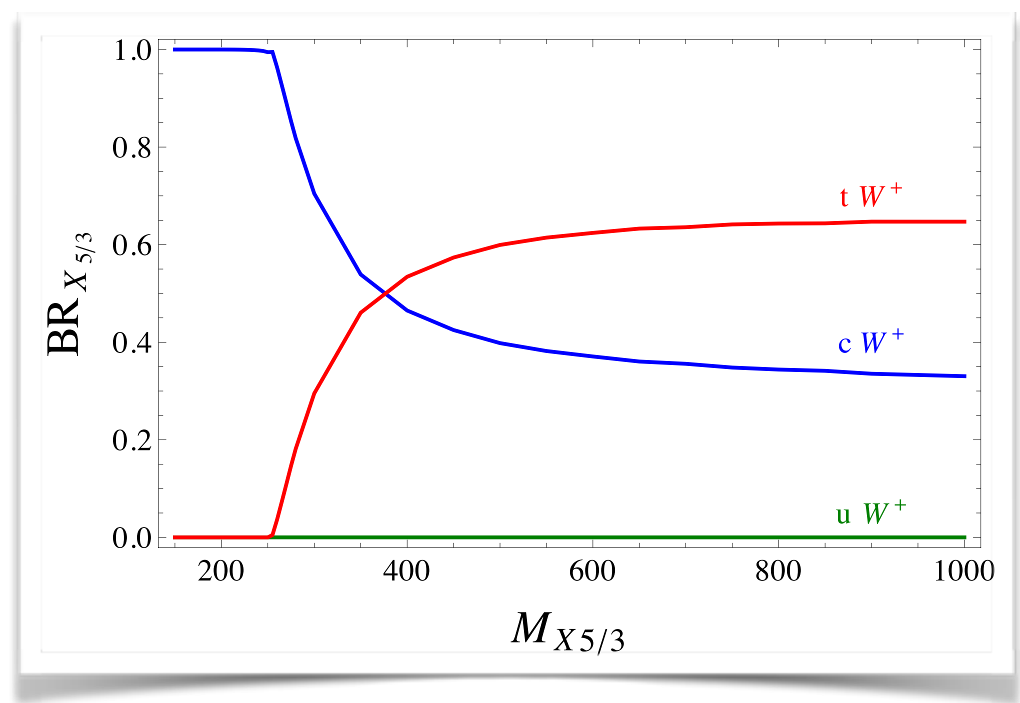


$X^{5/3}$decays ($X^{5/3}$,T') multiplet



Mixing mostly with top
V_R^{41} maximal

Mixing mostly with top
V_R^{42} maximal



General parameterisation (example with a t')

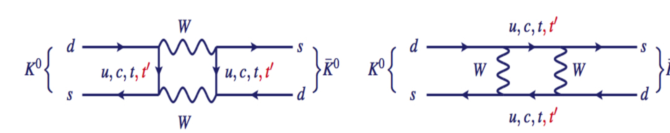
- T' will in general couple with Wq, Zq, hq
- it is more physical to consider observables (BRs, cross-sections) rather than Lagrangian parameters
- Neglect SM quark masses here (full case in the paper)

$$BR(T \to V q_i) = \frac{\kappa_V^2 |V_{L/R}^{4i}|^2 \Gamma_V^0}{\left(\sum_{j=1}^3 |V_{L/R}^{4j}|^2\right)\left(\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0\right)}$$

$$\zeta_i = \frac{|V_{L/R}^{4i}|^2}{\sum_{j=1}^3 |V_{L/R}^{4j}|^2}, \quad \sum_{i=1}^3 \zeta_i = 1,$$

$$\xi_V = \frac{\kappa_V^2 \Gamma_V^0}{\sum_{V'=W,Z,H} \kappa_{V'}^2 \Gamma_{V'}^0}, \quad \sum_{V=W,Z,H} \xi_V = 1;$$

$$BR(T \to V q_i) = \zeta_i \xi_V$$



- Only 5 independent parameters, M, ξ_W, ξ_Z, ζjet , κ
- Choosing multiplet fixes ξ_W, ξ_Z

General parameterisation

- Complete Lagrangian

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} \, [\bar{T}_L Z_\mu \gamma^\mu u_L^i] \right.$$
$$\left. - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} \, [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} \, [\bar{T}_L H t_R] \right\}$$
$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} \, [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} \, [\bar{B}_R H d_L^i] \right\}$$
$$+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + h.c. \, ,$$

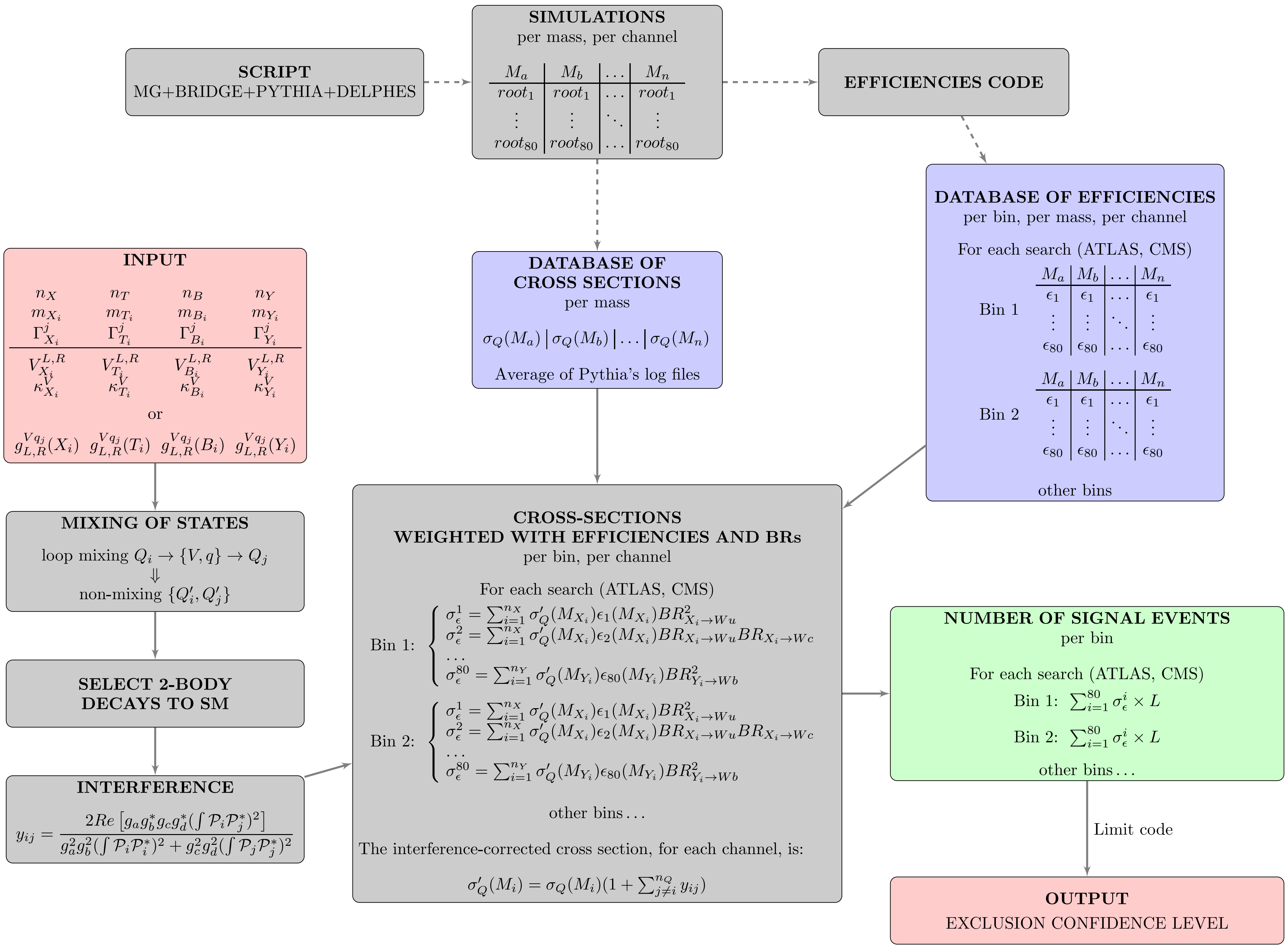
- Parameters: Mass + 4 (for T and B) or + 2 (for X and Y)

Parameterisation: Montecarlo simulations

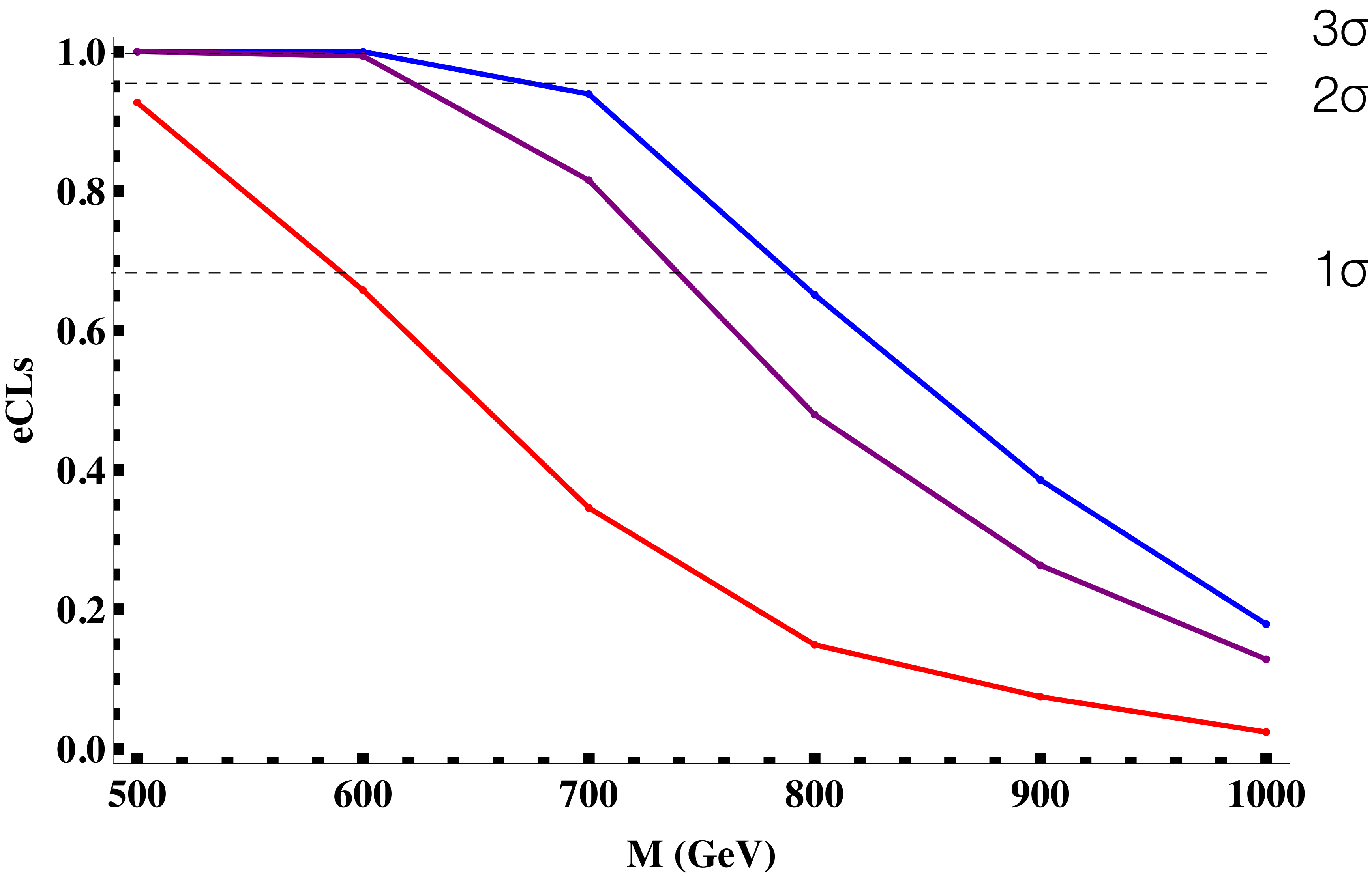
- General FeynRules model and MadGraph/CalcHep implementation:
- http://feynrules.irmp.ucl.ac.be/wiki/VLQ
- Specific multiplets (3 parameters)
- http://feynrules.irmp.ucl.ac.be/wiki/VLQ_tsingletvl
- http://feynrules.irmp.ucl.ac.be/wiki/VLQ_tbdoubletvl
- http://feynrules.irmp.ucl.ac.be/wiki/VLQ_xtdoubletvl
- M mass of the VL quarks in the multiplet, g* coupling strength for single production, R_L fraction of decay to light quarks

Analysis tool (data recasting)

- Tool to recast LHC analyses for vector-like quarks (still private as under development)



Analysis tool example



Blue, purple, red correspond to $R_L = 0, 0.5, \infty$ respectively. Obtained combining SUSY CMS searches (α_T, monolepton, OS dileptons, SS dileptons)

Conclusions

- Heavy vector-like fermions are present in many extensions of the SM
- Present constraints can be improved, especially for realistic cases, beyond too simplified assumptions
- Flavour results are helpful to establish the allowed range of mixings
- LHC can produce or bound these particles to a level giving a real feedback on new physics scenarios to theorists
- Present bounds just start probing the interesting mass range for VL relevant in BSM model building
- A general parameterisation, useful for LHC searches is available and an analysis tool is in preparation