Vector-like quark phenomenology

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Orsay - November 8th 2016

Top quark is special for BSM

- Composite models (technicolor, effective lagrangians like little Higgs, topcolor...):
  - top effective 4 fermion operators
  - vector-like top partners → see Giacomo's talk
  - new coloured scalars
- Extra-dimensional models:
  - KK-modes of top and gluons
  - Xdim realisations of composite models

why vector-like quarks?

- top partners are expected in many extensions of the SM (composite/Little higgs models, Xdim models)
- they come in complete multiplets (not only singlets)
- in some specific models not too heavy mass scale M ($\sim$TeV) and mainly coupling to the 3rd generation
- Present LHC mass bounds $\sim$ 800 GeV
- Mixings bounded by EWPT, flavour…
- In realistic composite models also scalars and vectors are expected.

Example: SU(4)xSU(6) → Sp(4)xSO(6)

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$	σ
			$(\mathbf{5},\mathbf{1})$	π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$	σ_c
			$(\mathbf{1},\mathbf{20})$	π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$	ψ_1^1
			$(\mathbf{5},\mathbf{6})$	ψ_1^5
$\chi\bar{Q}\bar{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$	ψ_2^1
			$(\mathbf{5},\mathbf{6})$	ψ_2^5
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$	ψ_4^5
			$(\mathbf{10},\mathbf{6})$	ψ_4^{10}
$\bar{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	a
			$(\mathbf{10},\mathbf{1})$	ρ
$\bar{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$	a_c
			$(\mathbf{1},\mathbf{15})$	ρ_c

spin 0

VLQs

Spin 1

from 1507.02283

Embeddings in SU(2)$_L$ × U(1)$_Y$

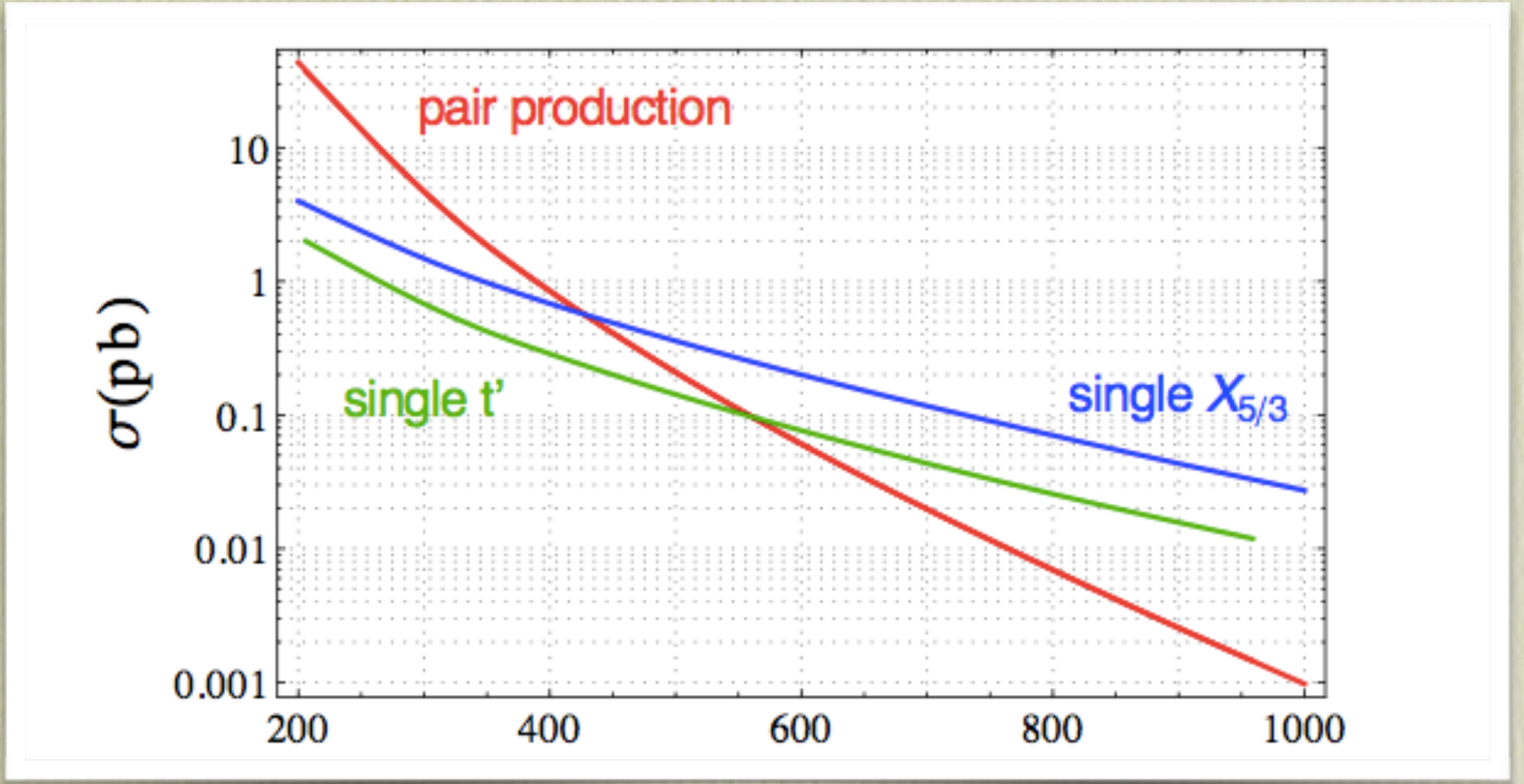
Vector-like multiplets forming mixed Yukawa terms with the SM quark representations and a SM or SM-like Higgs boson doublet

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	$+2/3$ $-1/3$ $-4/3$

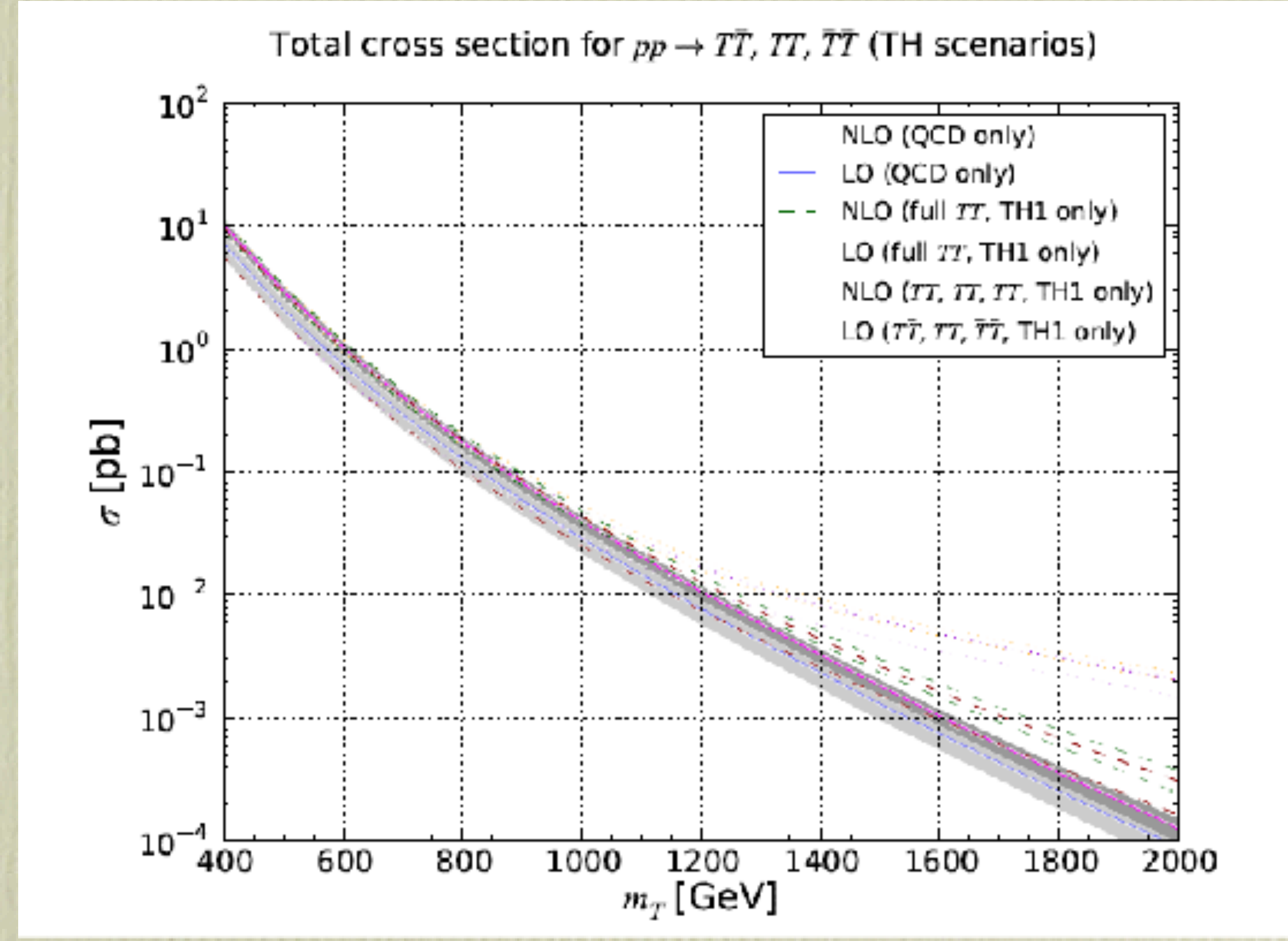
ψ	$(SU(2)_L, U(1)_Y)$	T_3	Q_{EM}
U D	$(\mathbf{2}, 1/6)$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
$X^{5/3}$ U	$(\mathbf{2}, 7/6)$	$+1/2$ $-1/2$	$+5/3$ $+2/3$
D $Y^{-4/3}$	$(\mathbf{2}, -5/6)$	$+1/2$ $-1/2$	$-1/3$ $-4/3$
$X^{8/3}$ $X^{5/3}$ U D	$(\mathbf{4}, 7/6)$	$+3/2$ $+1/2$ $-1/2$ $-3/2$	$+8/3$ $+5/3$ $+2/3$ $-1/3$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

Single vs pair cross-sections

- Reach at LHC substantial and only partially exploited
- Mixings with all the 3 SM generations important (production/decay)
- Single production important with present mass bound at LHC (~800 GeV)



NLO tools and calculations



hep-ph/1610.04622 B.Fuks & H.-S. Shao

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 $M + 3 \times \lambda^i$

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 with more VL multiplets

ArXiv:1305.4172 M.Buchkremer et al.

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

Bounds: weak charge

- 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 :

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

Bounds

- Rare top decays (induced by mixing)

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

- Z → cc coupling from LEP

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

implies :

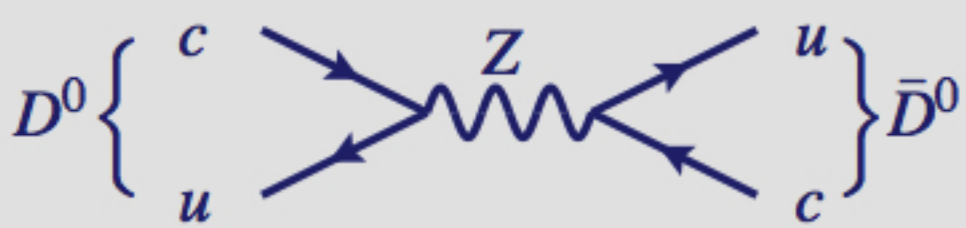
$$|V_R^{t'c}| < 0.2$$

Bounds: FCNC (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 ($\Delta C = 1$):

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

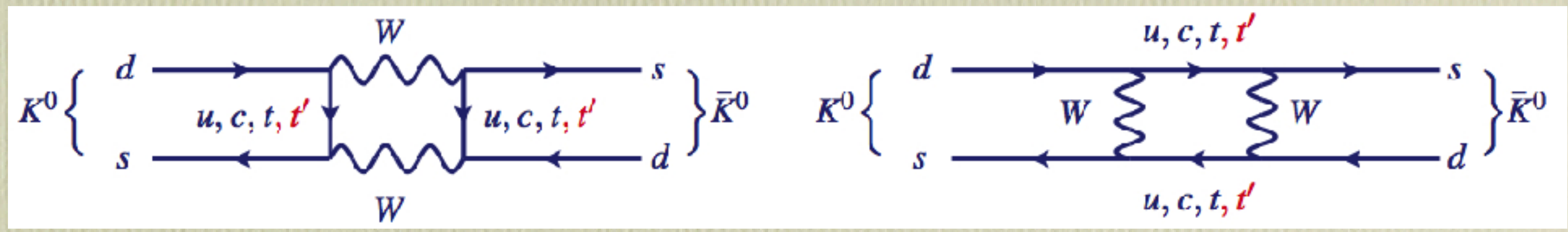
- strongest bound from xD :

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

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

Kaons (and similar for Bs)

- t' in the loop :



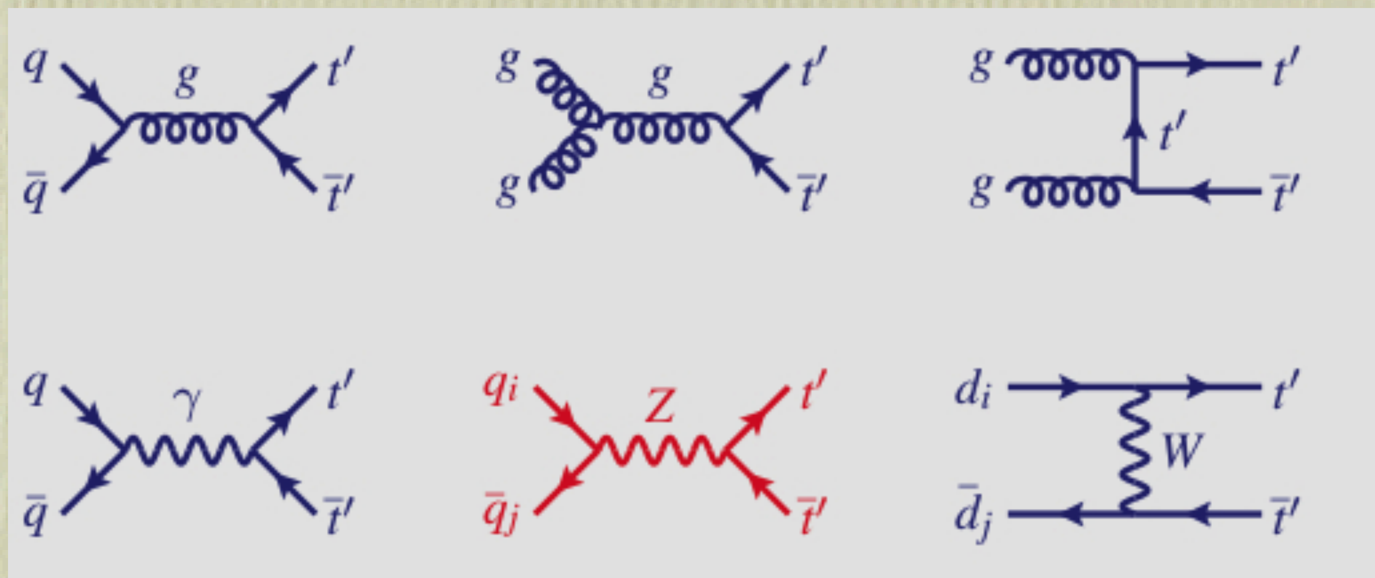
$$\Delta m_K \equiv m_{K_L} - m_{K_S} = 2Re\, M_{12} \simeq 2|M_{12}|$$

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

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

corrections to ϵ_K in the 4% range

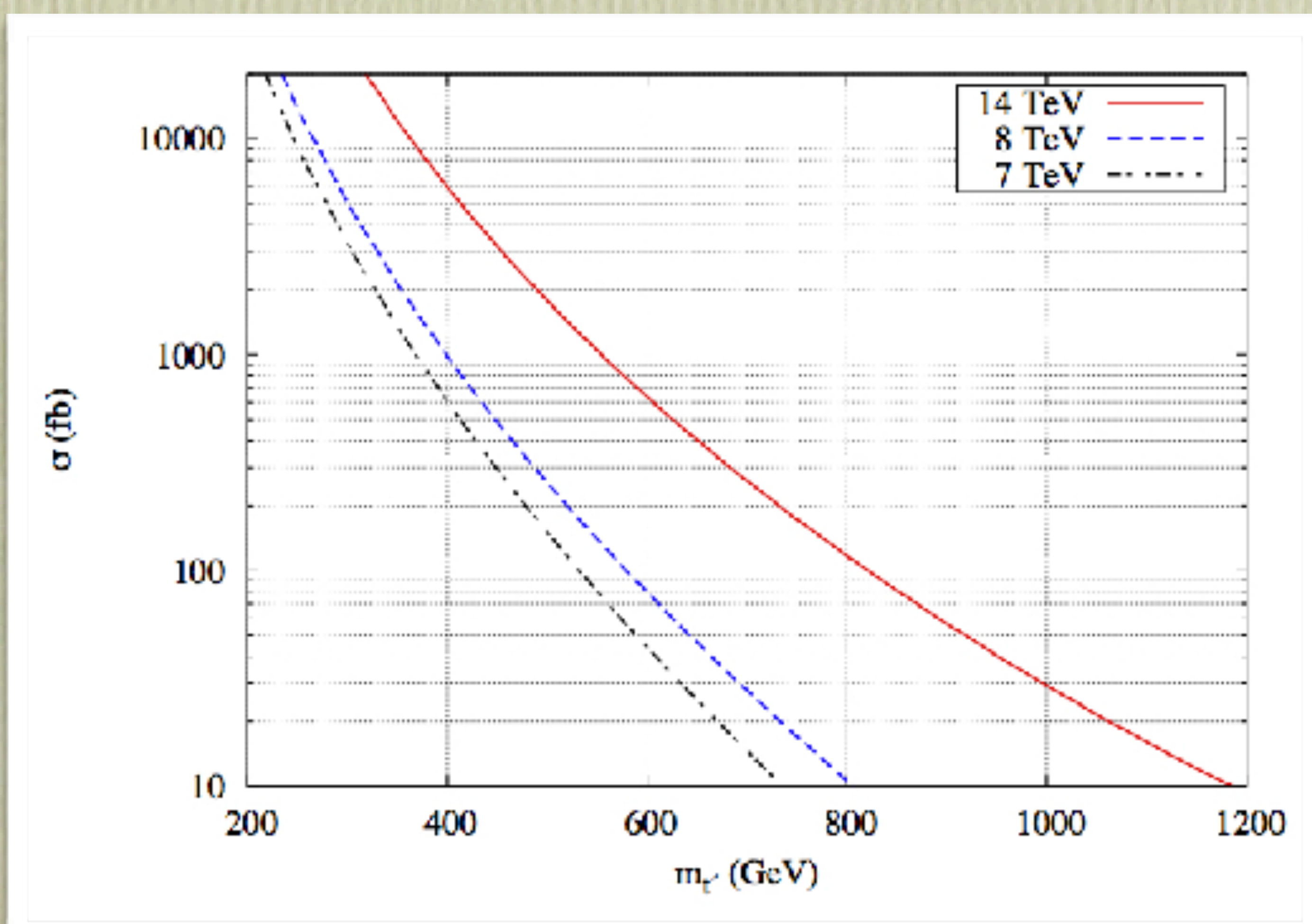
Pair production



Purely QCD diagrams (dominant contribution)

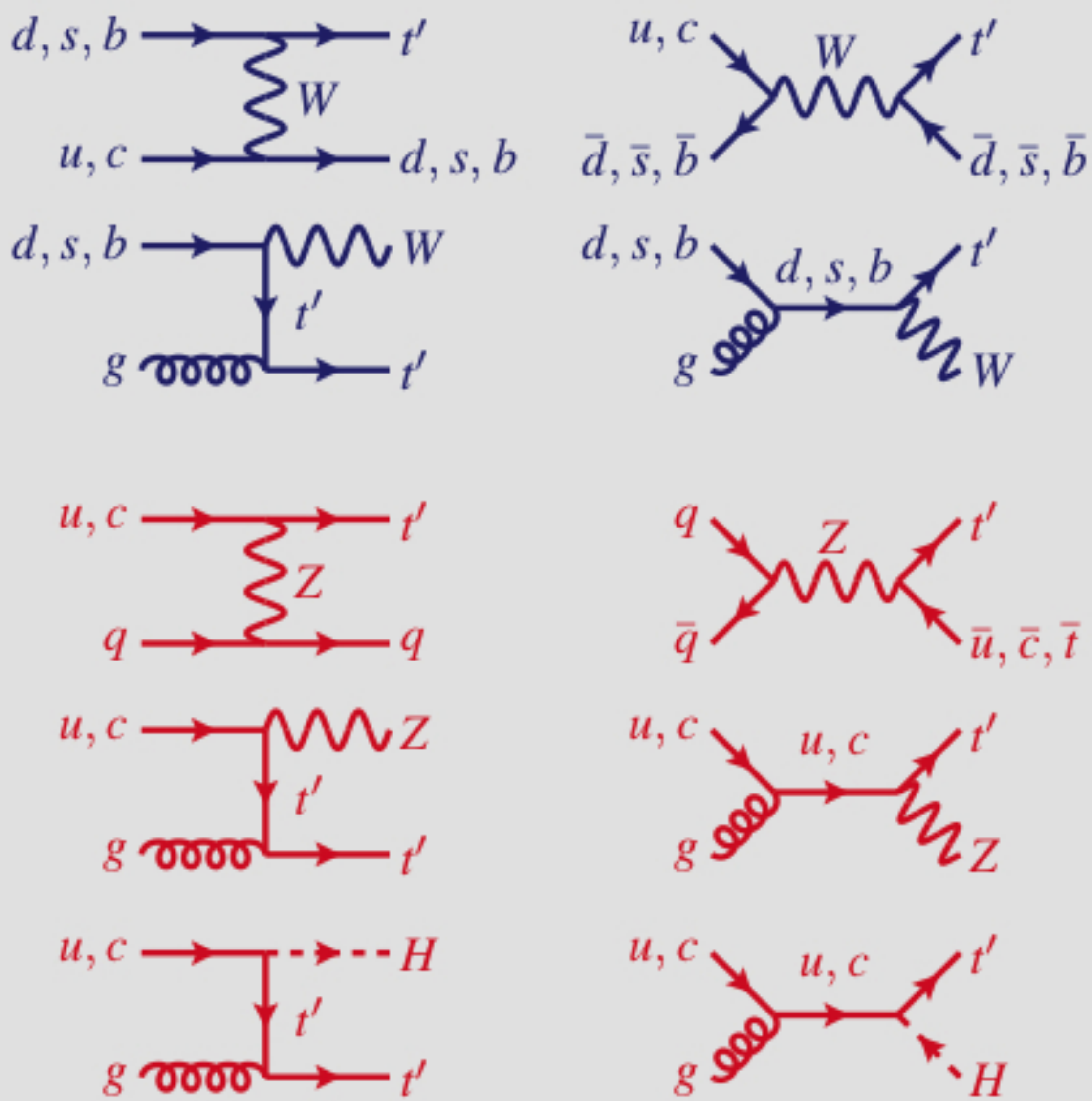
Purely EW diagrams

"new" FCNC channel, but suppressed wrt to QCD



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

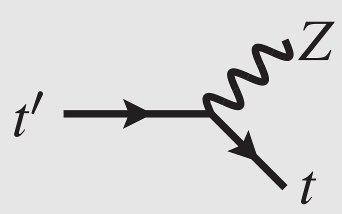
T' decays

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

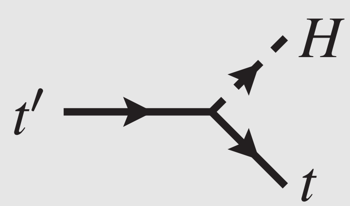
t'	Wb	Zt	ht
Singlet, Triplet Y=2/3	50%	25%	25%
Doublet, Triplet Y=-1/3	0%	50%	50%

T’ decays

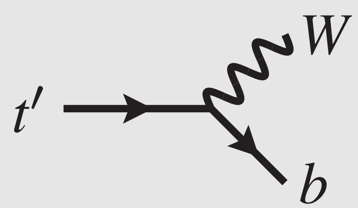
Different possibilities for t' decay ($\sin\theta_R = 0.3$, i.e. mixing with top dominates)



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



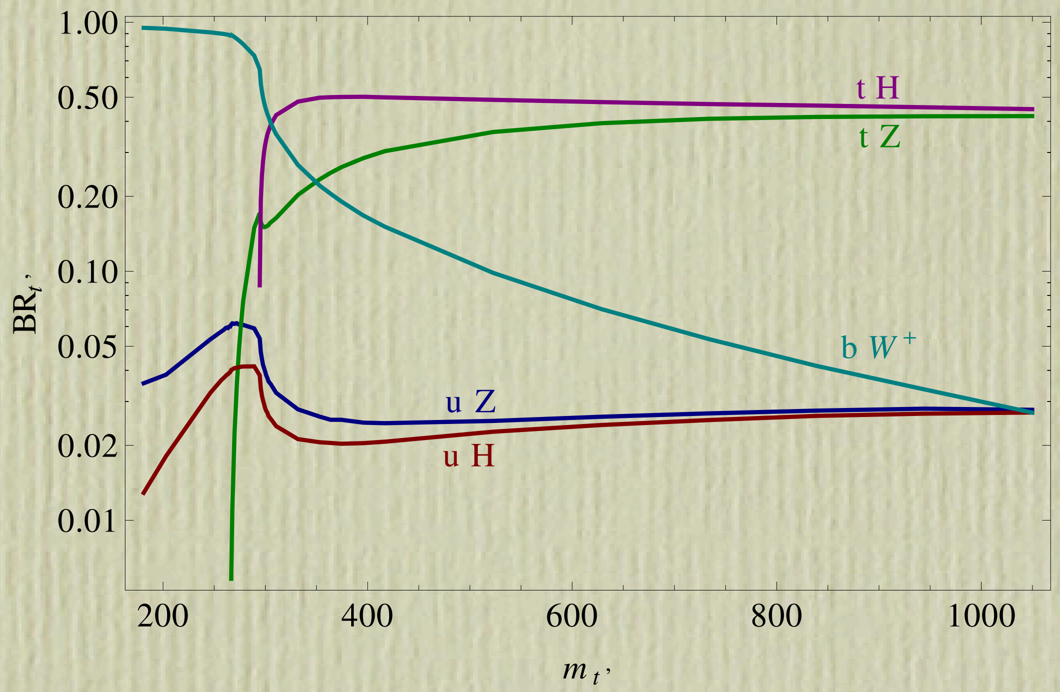
$$pp \to j\,(t' \to t\,H) \to j\,(t \to b\,l^+\,\nu)\,(H \to b\,\bar{b}) \to b\,\bar{b}\,b\,l^+\,\not{E}_T$$



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

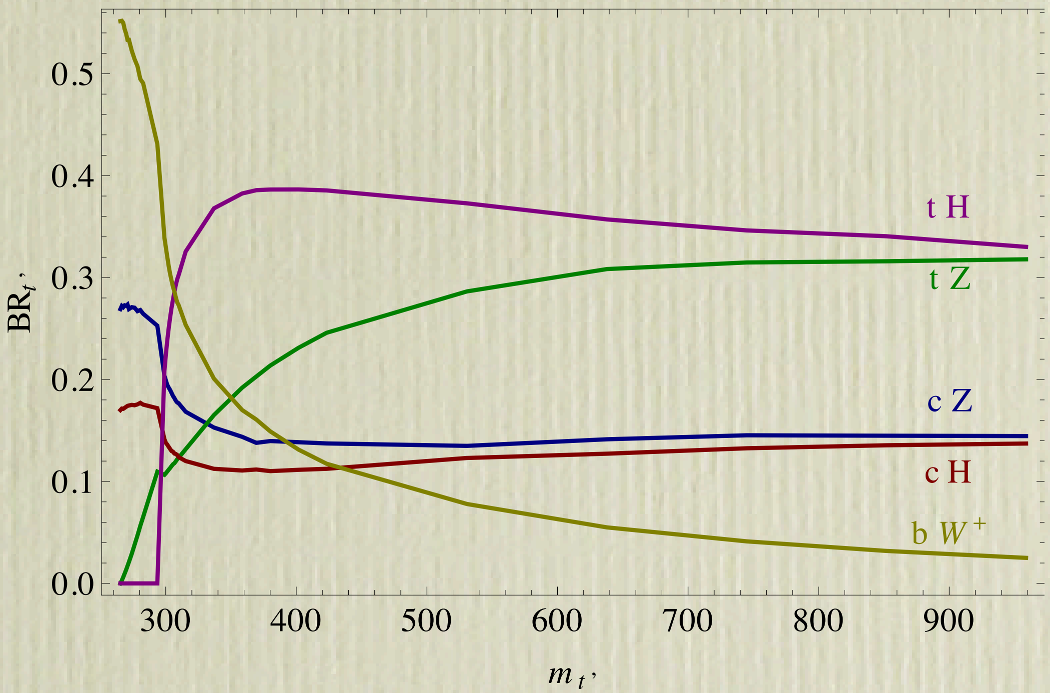
Assuming for example κ = 0.1 and RL =50% cross-sections are
~500 fb for t' in singlet or non-standard doublet and
~200 fb for t' in standard doublet
Production in association with light quarks is ~ 90%
See table 8 of Buchkremer et al.1305.4172

T’ decays ($X^{5/3}$,T’) multiplet



Mixing mostly with top
V_R^{41} maximal

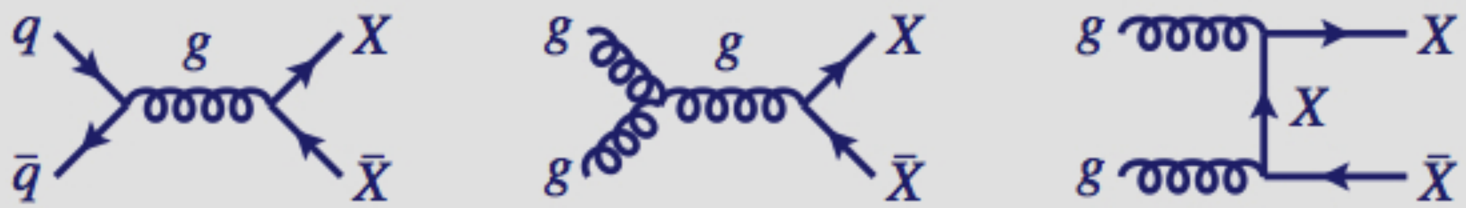
Mixing mostly with top
V_R^{42} maximal



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

$X^{5/3}$ production

Pair production



Purely QCD diagrams (dominant contribution)

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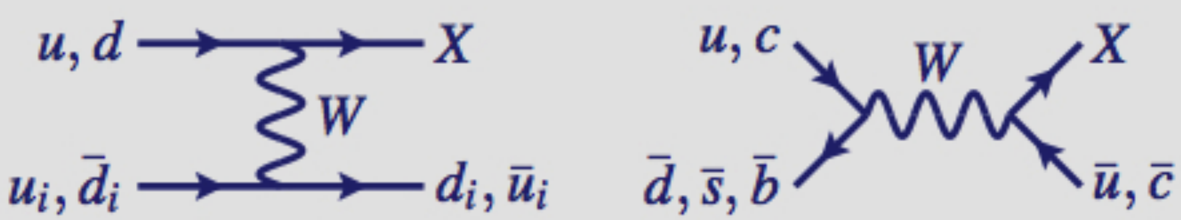
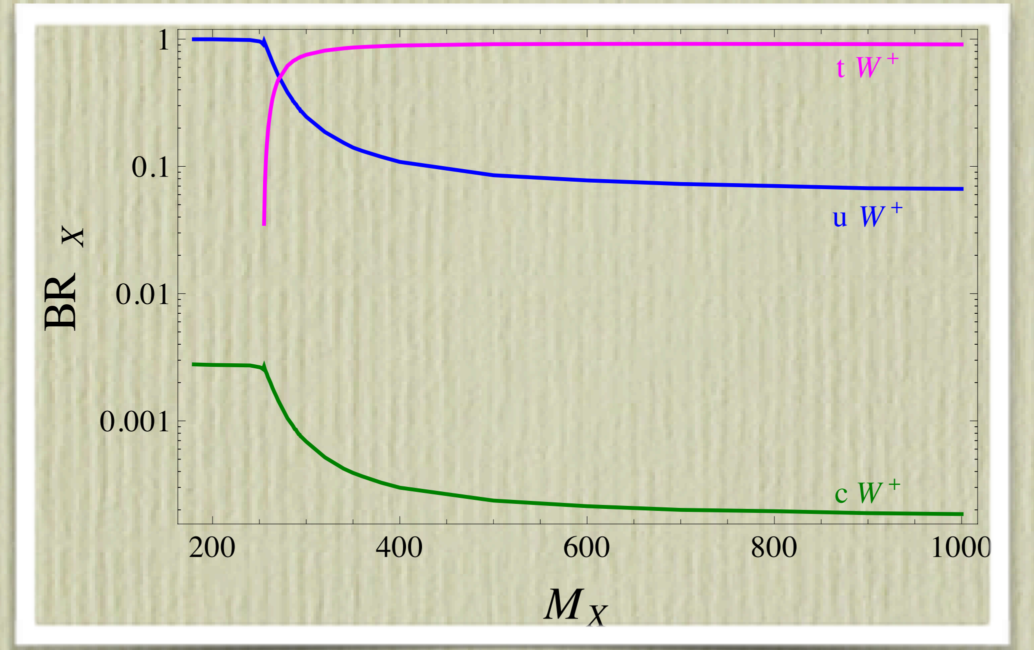
Single production



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

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



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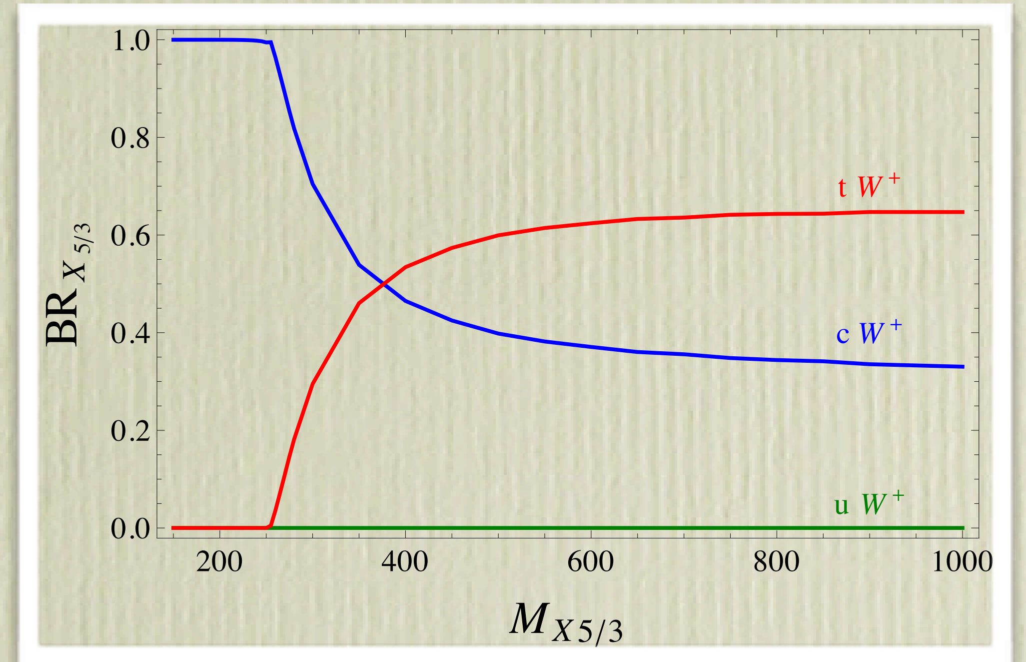

General parameterisation (example with a t')

- 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)

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

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

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

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

$$\zeta_{jet} = \zeta_1 + \zeta_2 = 1 - \zeta_3$$

- @ NLO all the couplings of the vector-like quarks to a gauge or a Higgs boson are free parameters
- @ LO only 5 independent parameters, M, ξ_W , ξ_Z , ζjet , κ
- Choosing multiplet selects ξ_W , ξ_Z

Perspectives @LHC 13 TeV

- Current limits with the 7 and 8 TeV data span up to 800-900 GeV in mass for vector like quarks.
- perspectives with 100 fb-1 I.L. at 13 TeV are roughly discovery if σ~ 100 fb for a 1 TeV T' and exclusion with σ~45 fb (see Backovic et al. 1507.06568)
- Search strategy change towards boosted object techniques

Conclusions

- top quark plays a special role in SM and BSM
- top partners are a rich sector to explore to discover or constrain BSM physics, but not only them as VLQ come in multiplets, sometimes with exotic states.
- mixing with the light generations should not be neglected
- NLO calculation are now available and allow more precise study