Model Independent Search of Vector-like Quarks,

aka Top-partners

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IPN Lyon

Top-LHC France 2013
22 mars

BSM: beyond supersymmetry

The most common new particle is a new coloured quark:

A.Falkowski's talk!

C.Delaunay's talk!

- 4th generation: excluded by Higgs discovery!
- Little Higgs: massive top partners responsible for the cancellation of quadratic divergences in the Higgs mass.
- Extra dimensions: recurrences of SM quarks, propagating in the bulk.
- Composite Higgs: massive top arises as a composite state, accompanied by heavier resonances.
- Extended gauge symmetries: new fermions needed to complete SM quark representations.

What is a VL quark?

- They have a Dirac mass without the Higgs.

$$\mathcal{L}_{\text{mass}} \sim -M\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

- They couple to SM quarks via Yukawa-type interactions.

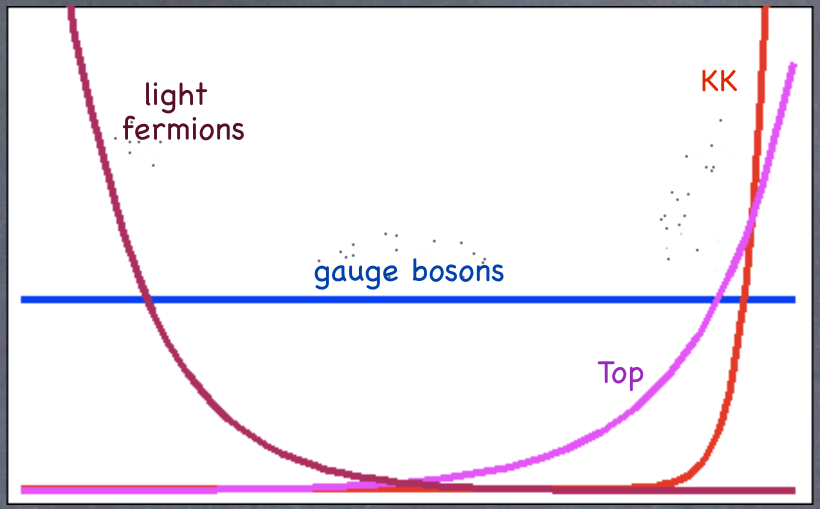
$$\mathcal{L}_{\text{Yuk}} \sim -\frac{\lambda v}{\sqrt{2}}\left(\bar{q}_L \psi_R + \bar{\psi}_R q_L\right) \quad \underline{\text{or}} \quad \left(\bar{\psi}_L q_R + \bar{q}_R \psi_L\right)$$

- The couplings depend on the representation of SU(2) - few possible choices!

$$\mathcal{L}_{\text{singlet}} \sim \frac{g}{\sqrt{2}} V_L^{4i}\, W_\mu^+\, \bar{t}'_L \gamma^\mu d_L^i + \frac{g}{2\cos\theta_W} V_L^{4i}\, Z_\mu\, \bar{t}'_L \gamma^\mu u_L^i + h.c.$$

$$\mathcal{L}_{\text{doublets}} \sim \pm \frac{g}{2\cos\theta_W} V_R^{4i}\, Z_\mu\, \bar{t}'_R \gamma^\mu u_R^i + h.c.$$

Models: composite Higgs

UV  IR

- Composite top implies large corrections to the Z couplings of the left-handed b, which are constrained at the 0.1% level!
- Solution:

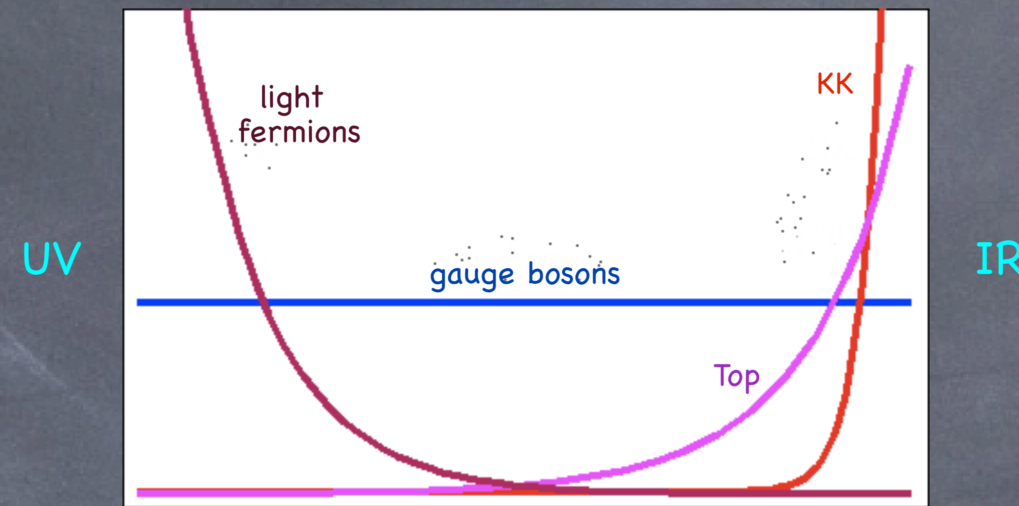
(2,2)$_{2/3}$ $$Q_L = \begin{pmatrix} t_L & X \\ b_L & T \end{pmatrix}$$

(1,1)$_{2/3}$ $$Q_R = t_R$$

(2,2)$_0$ $$H = \begin{pmatrix} \phi_0^* & \phi^+ \\ -\phi^- & \phi_0 \end{pmatrix}$$

$$\mathcal{L}_{\rm Yukawa} = y_t \, {\rm Tr}\,(\bar{Q}_L \cdot H) t_R = y_t \, \left(\phi_0^* \bar{t}_L t_R + \phi_0 \bar{T} t_R + \ldots\right)$$

Models: composite Higgs



Different BC's on the UV brane

$$Q_L = \left(\begin{matrix} t_L \\ b_L \end{matrix} \quad \begin{matrix} X \\ T \end{matrix} \right)$$

Zero mode

$$Y = T_R^3 + (B-L) = \frac{1}{2} + \frac{2}{3} = \frac{7}{6}$$

the

$(2,2)_{2/3}$

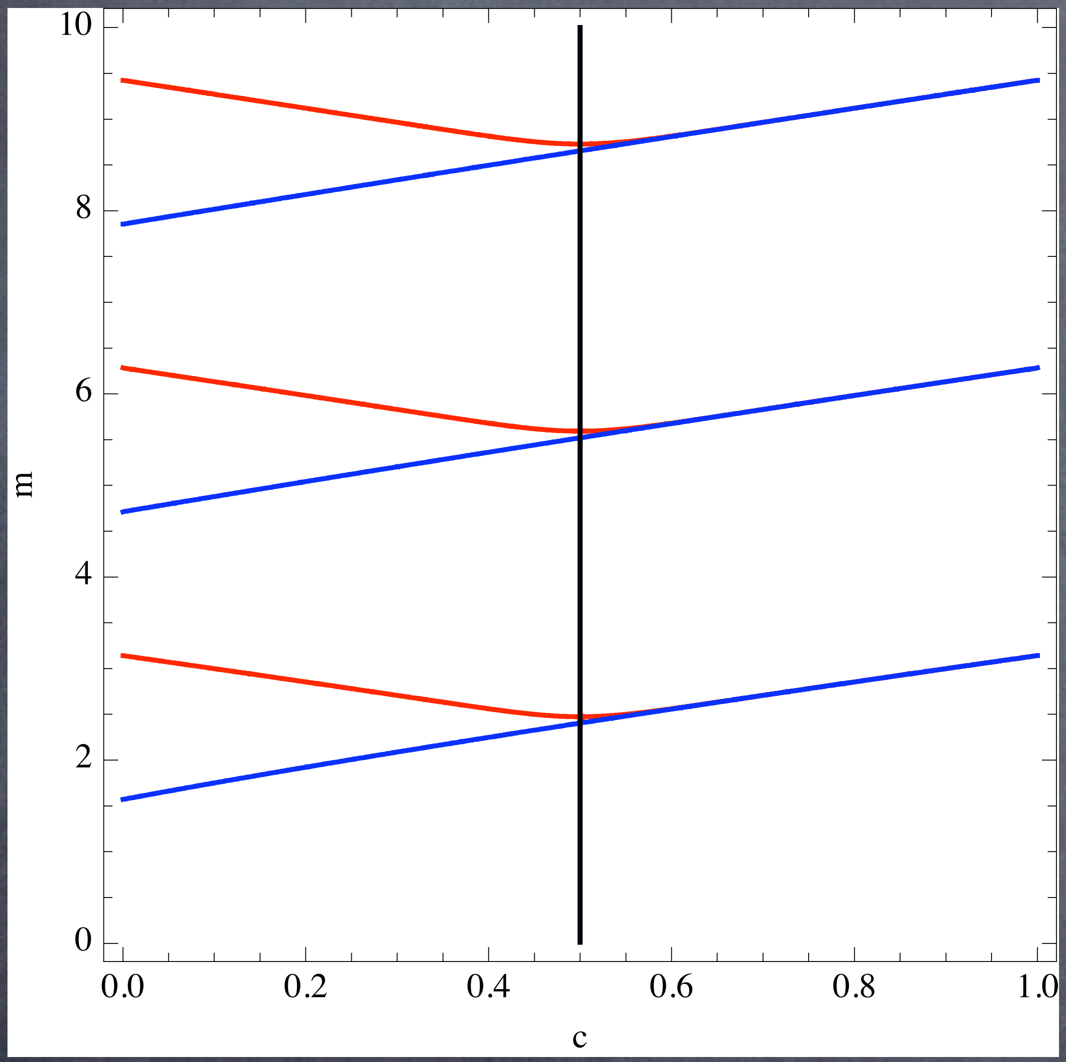
$R =$

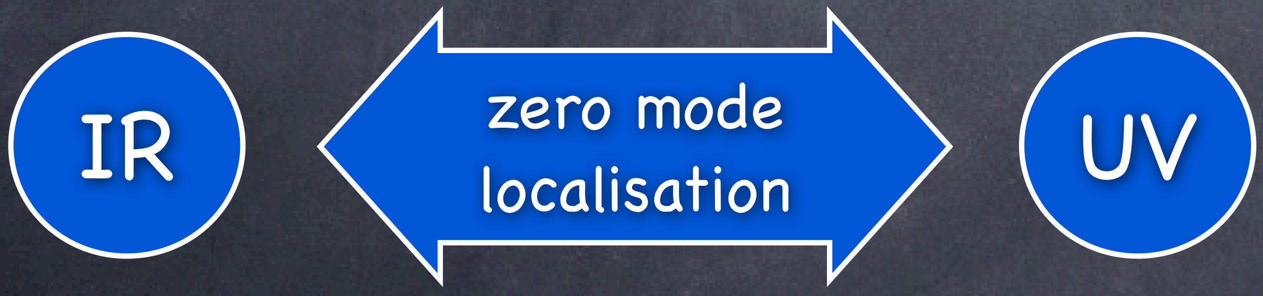
$(1,1)_{2/3}$

$\dots)$

$(2,2)_0$

Models: composite Higgs





- with zero mode (SM)

- without zero mode

For strongly IR localised fields (top and partners) there are light states appearing in the spectrum!

Lightest states are a $SU(2)_L$ doublet with hypercharge 7/6!

Thus, many theorists have appetite for VL quarks...

CMS Menu, 7 TeV

	Prices (GeV)
b' pair, 100% Wt	
$l^{\pm}l^{\pm} + \geq 4$ jets	611
$l(\text{high } p_T) + \geq 4$ jets$(1b)$ + kin cuts	675
b' pair, 100% Zb	
$l^{+}l^{-}(Z) + \geq 2$ jets$(2b)$	550
t' pair, 100% Wb	
$l^{+}l^{-} + \geq 2$ jets$(2b)$	557
$l(\text{high } p_T) + \geq 4$ jets$(1b)$ + kin cuts	560
X pair, 100% Wt	
$l^{\pm}l^{\pm} + \geq 4$ jets + H_T	645

ATLAS Menu, 7 TeV

Prices (GeV)

- *b', X pair, 100% Wt*

  $l^{\pm}l^{\pm} + \geq 2\,\text{jets}\,(1b) + H_T + MET$ — 670

- *t' pair, 100% Wb* — 656

  $l\ (\text{high}\ p_T) + \geq 3\,\text{jets} + MET$

- *t' pair, 50% Wb* — 500

- *single q' jet, 100% W q*

  $l\,\nu\ (W) + 2\,\text{jets}(1\ \text{forward})$ — b': 1120, X: 1420

- *single q' jet, 100% Z q*

  $l^{+}l^{-}\ (Z) + 2\,\text{jets}(1\ \text{forward})$ — t': 1080

G.C., A.Deandrea, N.Gaur,
D.Harada, Y.Okada, L.Panizzi
1007.2933, 1108.6329, ...

Top partner t′:

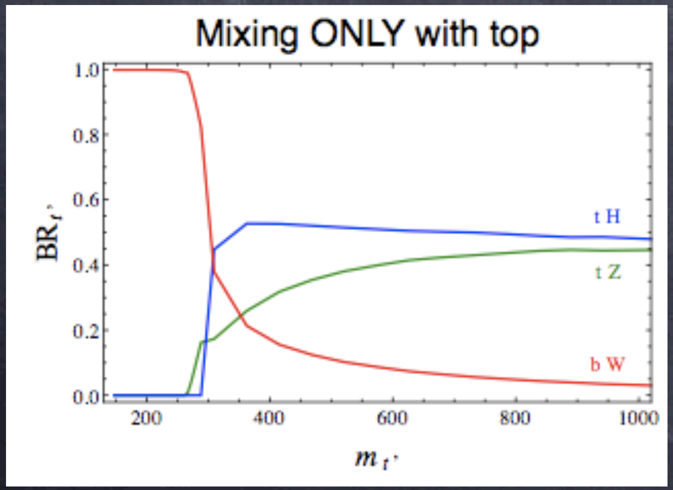
➤ branchings are never 100% in one channel!

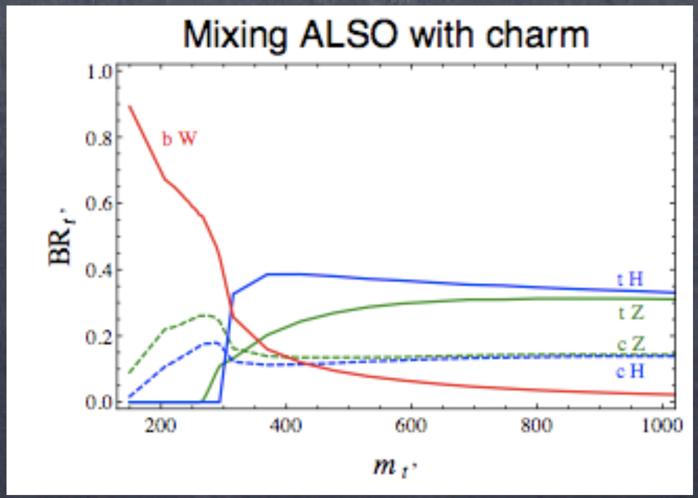
t′	Wb	Zt	ht
Single, Triplet Y=2/3	50%	25%	25%
Doublets, Triplet Y=-1/3	~ 0%	50%	50%

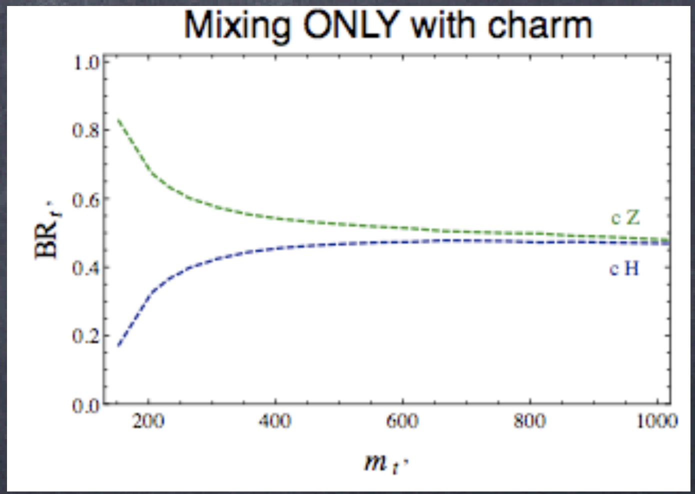
EQUIVALENCE THEOREM: at large VL masses, BR(Zt) = BR(ht)!!!

➤ decays into light quarks may not be negligible!

Flavour bounds: however, BRs are NOT proportional to the mixing matrices nor to the Yukawa couplings!







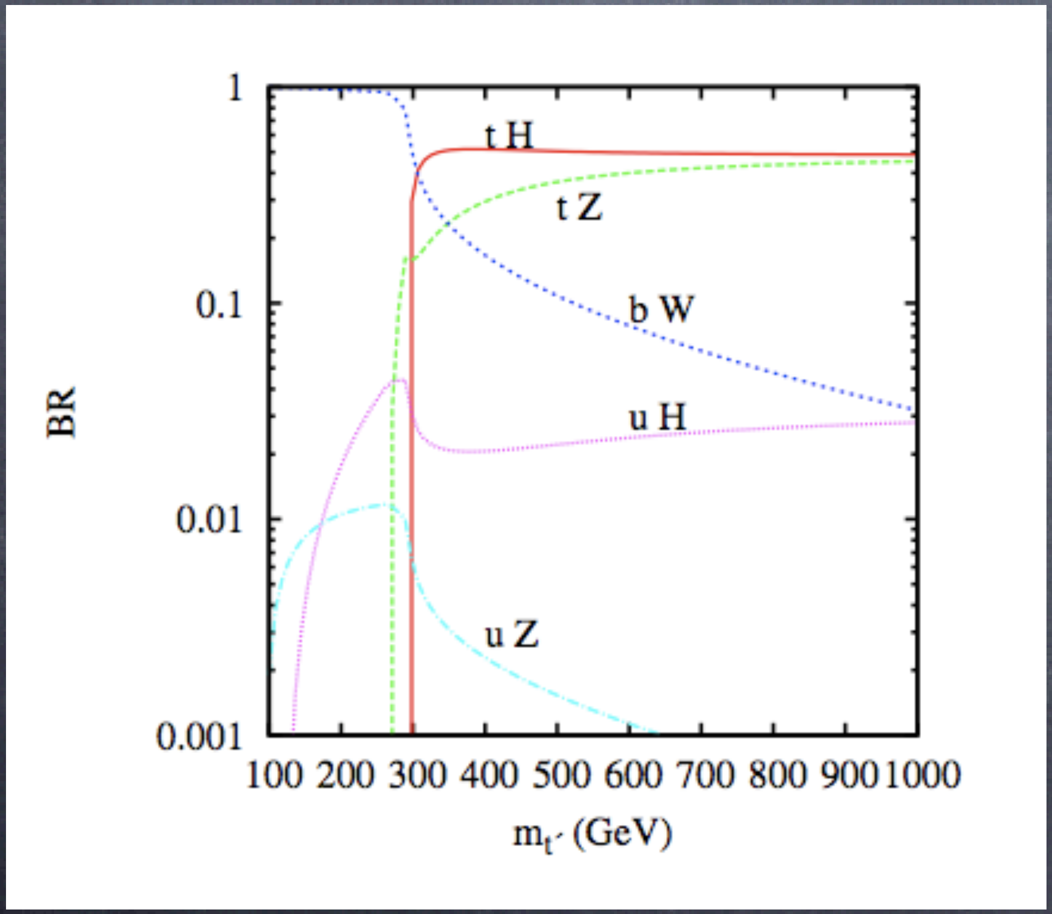
LHC bounds on the t'

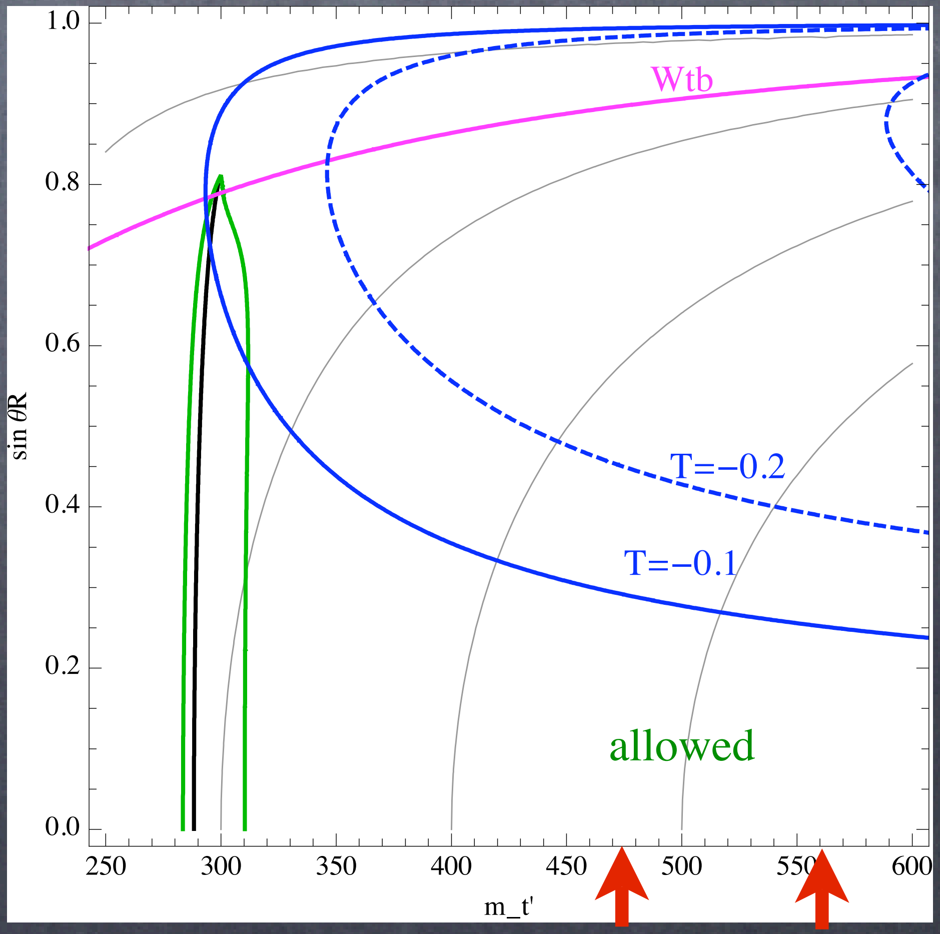
$$t'\bar{t}' \to W^+ b\, W^- \bar{b} \to b\,\bar{b}\, l\, \nu\, j\, j$$

Nominal bounds: 560 (CMS 5/fb)
(assuming 100% Branching Ratio)

$$t'\bar{t}' \to Zt\, Z\bar{t} \to l^+ l^- t\, X$$

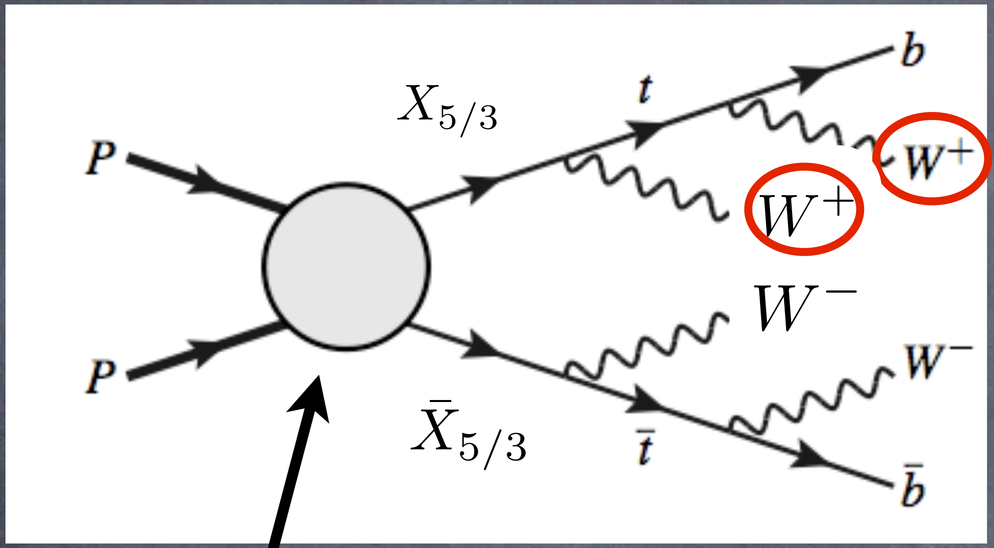
Nominal bounds: 475 (CMS 1/fb)
(assuming 100% Branching Ratio)





Exotic $X_{5/3}$:

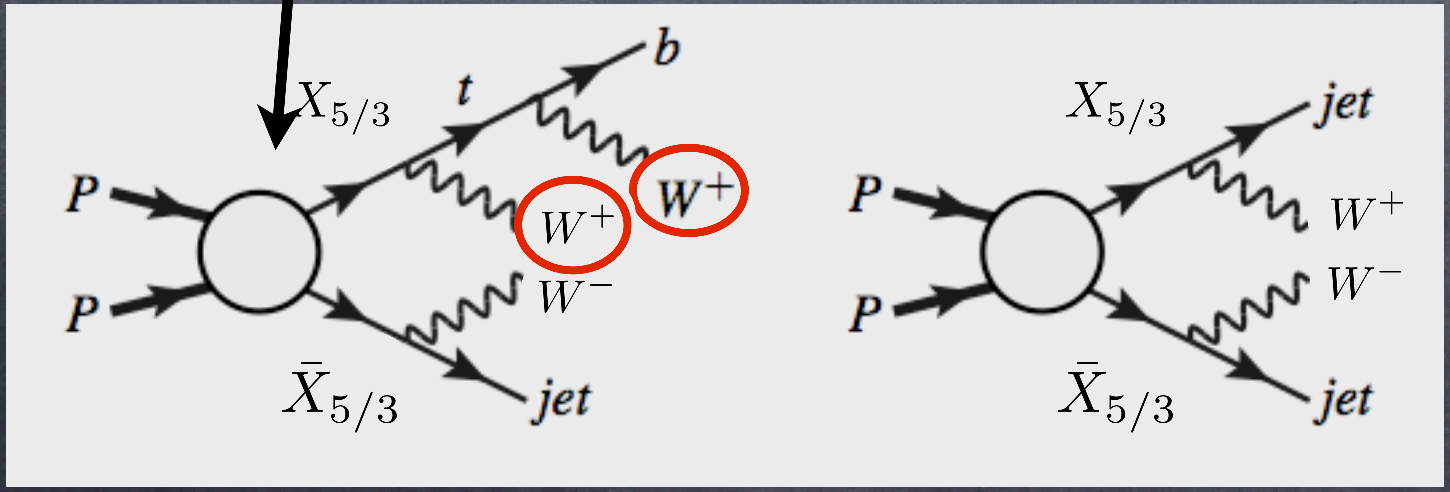
Example: same sign dilepton in X decays



Assuming 100% decays into Wt

ss dilepton from W's
large number of jets (4+)

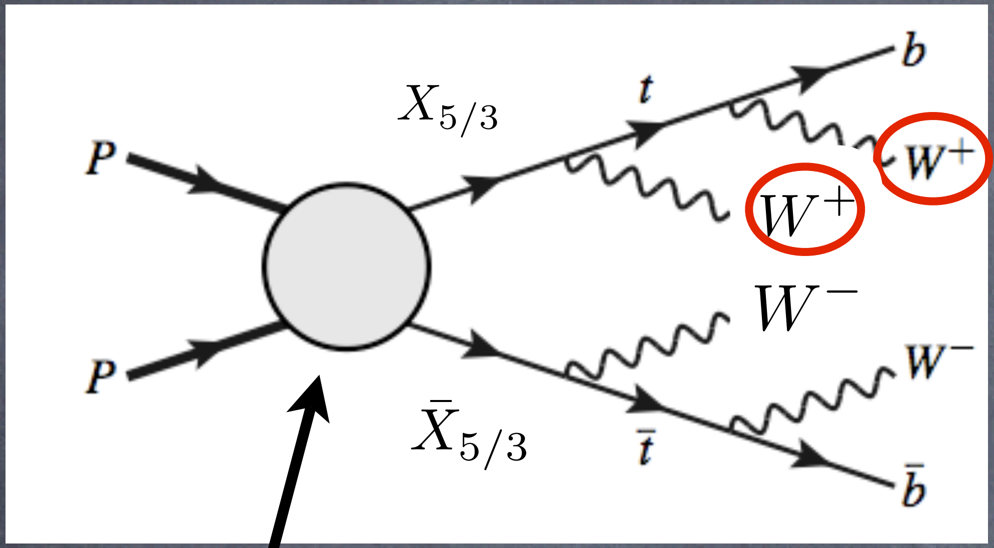
Different efficiencies!!!!



Decays in W q
should also be included
in the same search!

Exotic $X_{5/3}$:

Example: same sign dilepton in X decays



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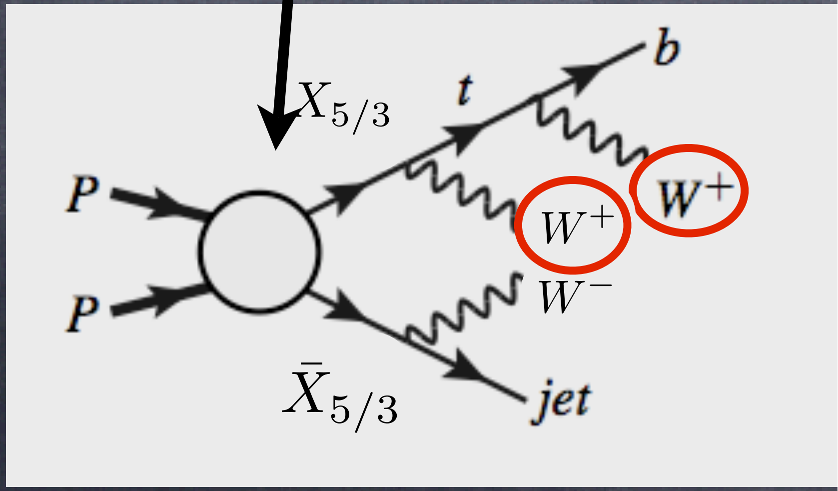
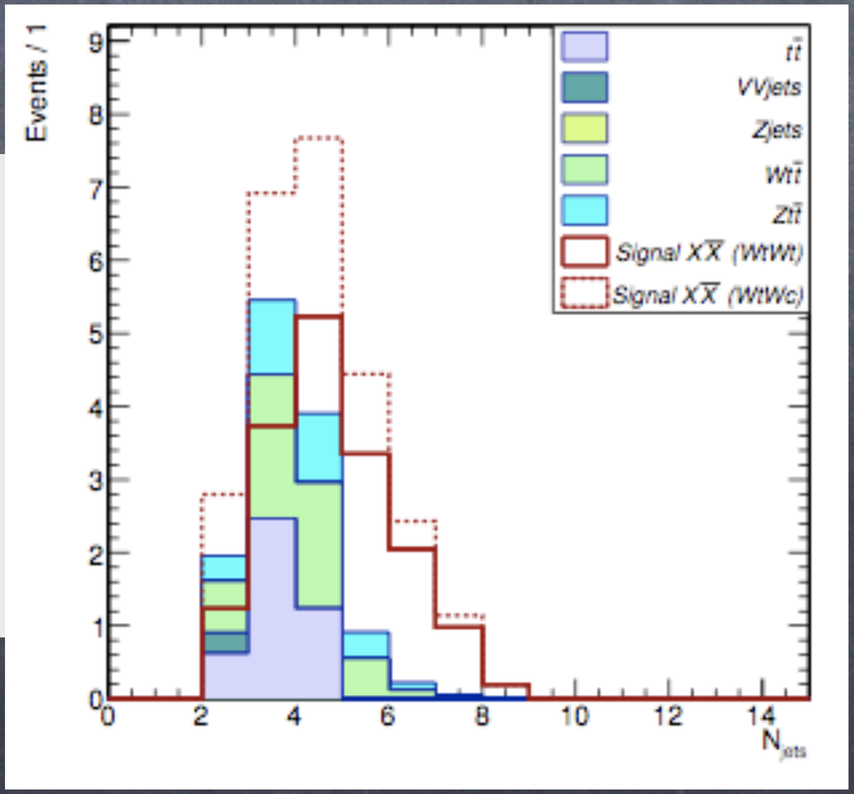


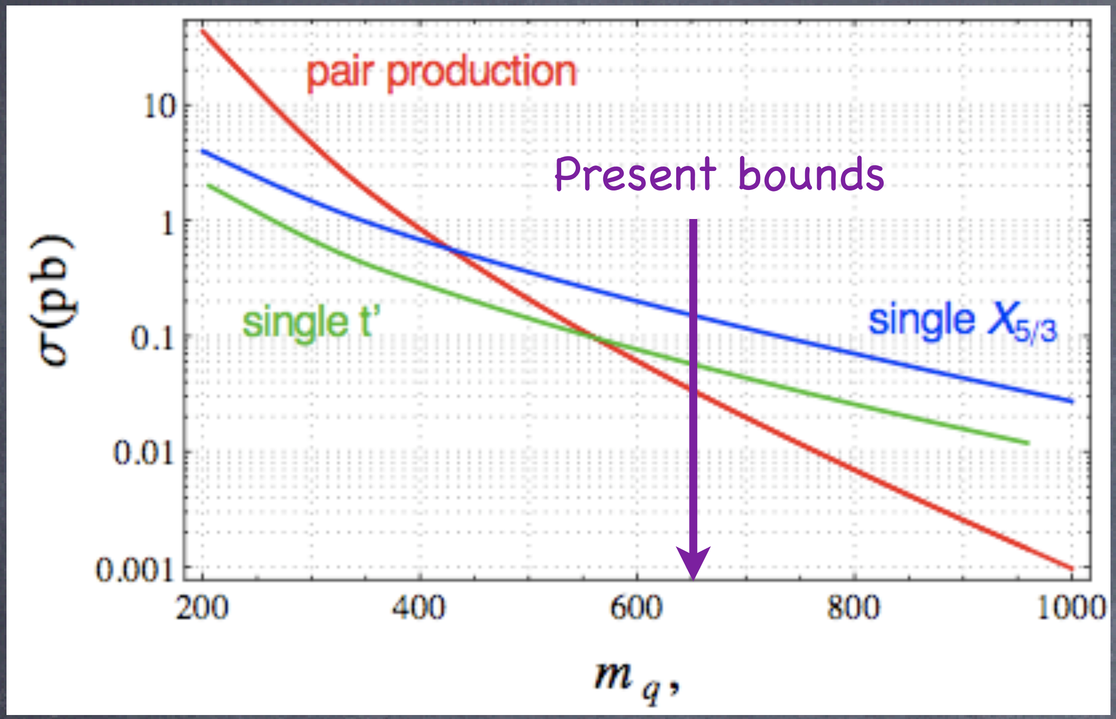


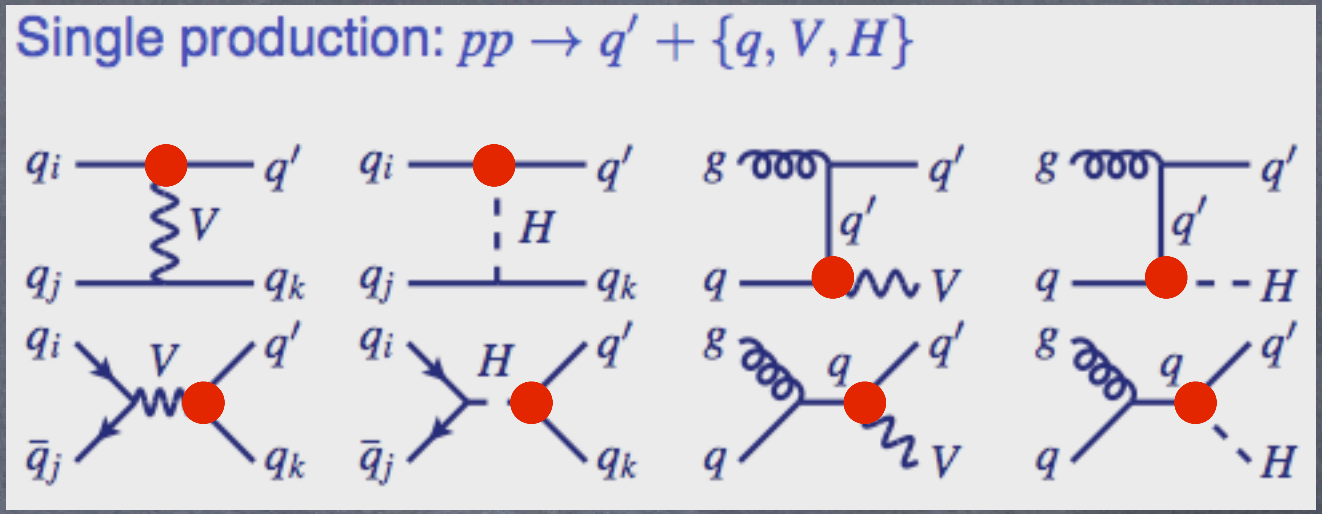
We propose an alternative cut on HT!

G.C., A.Deandrea, L.Panizzi, S.Perries, V.Sordini
1211.4034

Relevance of Single Production!

Pair production is "model independent", being dominated by QCD!





Couplings proportional to the mixing
i.e. sensitive to the Yukawa couplings!

- Potential window to size of Yukawa couplings/mixing!
- Potentially relevant at high masses.
- It needs to be included in a consistent way (flavour bounds!!!)

Exotic $X_{5/3}$:

Model independent, complete parametrisation of the couplings:

$$\mathcal{L} = \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma^0_W}} \frac{g}{\sqrt{2}} \, [\bar{X}_{L/R} W^+_\mu \gamma^\mu u^i_{L/R}] \right\} + h.c.\,.$$

G.C., M.Buchkremer, A.Deandrea, L.Panizzi
in preparation

$$BR(X \to W^+ u/c) = \frac{(1-\zeta_3)}{1-\zeta_3 \delta^t_W}\,, \qquad BR(X \to W^+ t) = \frac{\zeta_3 (1-\delta^t_W)}{1-\zeta_3 \delta^t_W}\,.$$

Single production can be correlated to Branching ratios:

$$\begin{aligned} \sigma(X\bar{t}) &= \kappa_X^2 \left(\sum_{i=1}^{2} \zeta_i \, \bar{\sigma}_i^{X\bar{t}} \right), \\ \sigma(Xjet) &= \kappa_X^2 \left(\sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_i^{Xjet} \right), \\ \sigma(XW^-) &= \kappa_X^2 \left(\sum_{i=1}^{2} \zeta_i \, \bar{\sigma}_i^{XW} \right). \end{aligned}$$

	X				$\bar{X}$		
	$i=1$	$i=2$	$i=3$		$i=1$	$i=2$	$i=3$
$X\bar{t}$	3,630 fb	52.8 fb	9.7 fb	$\bar{X}t$	181 fb	52.8 fb	3.4 fb
$Xt\bar{t}$	-	-	1.3 fb	$\bar{X}tt$	-	-	1.3 fb
$Xjet$	94,350 fb	4,060 fb	-	$\bar{X}jet$	4,600 fb	1,780 fb	-
XW^-	4,430 fb	74.6 fb	-	$\bar{X}W^+$	241 fb	74.6 fb	-

Pair: 170 fb

Outlook

- VL quark pheno can be described in terms of a few parameters: t′, b′, X(5/3), Y(-4/3)...
- Many neglected final states need to be analysed.
- Tool to extract reliable bounds: G.C., M.Buchkremer, A.Deandrea, L.Panizzi (F.Maltoni) in preparation

Experimentalists needed!

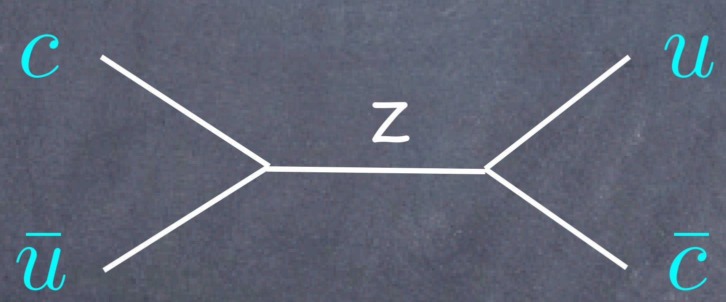
- identify un-equivalent channels (production+decay modes).
- calculate experimental efficiency per channel.
- input parameters: mass, BR, coupling (single prod.)

Bounds: D0-antiD0 mixing

$$D_0 = c\bar{u} \qquad \bar{D}_0 = \bar{c}u$$

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

In the SM, determined by long distance therefore, not calculable!



Conservative bound if exp value saturated by
new physics contribution!

$$x_D = \frac{f_D^2 m_D B_D}{2 m_Z^2 \Gamma_D} \frac{2}{3} r(m_c, m_Z) (g_{ZR}^{uc})^2$$

$$|V_R^{41}| \, |V_R^{42}| < 3.2 \times 10^{-4} \, .$$

Bound on product: VR41 or VR42 can be large!

Bounds:

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

Lesson to take away:

- Strong bound on product VR41*VR42!
- Mild bounds on individual couplings: mixing to either charm or up can be sizeable!
- Possible large Branching in light quarks and/or large single production cross section!

t':

Model independent parametrisation of the couplings:

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d^i_{L/R}] + \sqrt{\frac{\zeta_i \xi_Z}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^\mu u^i_{L/R}] - \sqrt{\frac{\zeta_i \xi_H}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_{R/L} h u^i_{L/R}] \right\} + h.c.\,.$$

$$BR(T \to Zu/c) = \frac{(1-\zeta_3)\xi_Z}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)}, \quad BR(T \to Zt) = \frac{\zeta_3\xi_Z(1-\delta^t_Z)}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)}, \quad (21)$$

$$BR(T \to hu/c) = \frac{(1-\zeta_3)\xi_H}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)}, \quad BR(T \to ht) = \frac{\zeta_3\xi_H(1-\delta^t_H)}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)}, \quad (22)$$

$$BR(T \to W^+d/s) = \frac{(1-\zeta_3)(1-\xi_Z-\xi_H)}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)}, \quad BR(T \to W^+b) = \frac{\zeta_3(1-\xi_Z-\xi_H)}{1-\zeta_3(\sum_{V=Z,H}\xi_V\delta^t_V)} \quad (23)$$

t':

Model independent parametrisation of the couplings:

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \left[\bar{T}_{L/R} W_\mu^+ \gamma^\mu d_{L/R}^i\right] + \sqrt{\frac{\zeta_i \xi_Z}{\Gamma_Z^0}} \frac{g}{2c_W} \left[\bar{T}_{L/R} Z_\mu \gamma^\mu u_{L/R}^i\right] - \sqrt{\frac{\zeta_i \xi_H}{\Gamma_H^0}} \frac{M}{v} \left[\bar{T}_{R/L} h u_{L/R}^i\right] \right\} + h.c..$$

Pair: 170 fb

$$\sigma(Tjet) = \kappa_T^2 \left(\xi_Z \sum_{i=1}^{2} \zeta_i \, \bar{\sigma}_{Zi}^{Tjet} + \xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_{Wi}^{Tjet} + \sqrt{\xi_Z \xi_W} \sum_{ij} \sqrt{\zeta_i \zeta_j} \bar{\sigma}_{WZij}^{Tjet} \right),$$

	$T\bar{t}$ $i=1$	$i=2$	$i=3$	$\bar{T}t$ $i=1$	$i=2$	$i=3$
$\bar{\sigma}_{Zi}^{T}$	-	-	6.6 fb	-	-	6.6 fb
$\bar{\sigma}_{Wi}^{T}$	1,470 fb	113 fb	33.4 fb	226 fb	113 fb	33.5 fb
$\bar{\sigma}_{ZWi}^{T}$	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb

	T $i=1$	$i=2$	$i=3$	$\bar{T}$ $i=1$	$i=2$	$i=3$
$\bar{\sigma}_{Zi}^{Tjet}$	63,400 fb	2,430 fb	-	5,700 fb	2,300 fb	-
$\bar{\sigma}_{Wi}^{Tjet}$	45,600 fb	6,830 fb	2,680 fb	5,840 fb	3,160 fb	1,165 fb
$\bar{\sigma}_{ZWii}^{Tjet}$	$-1,900$ fb	~ 0 fb	-	~ 0 fb	~ 0 fb	-
$\bar{\sigma}_{ZWlk}^{Tjet}$	12: ~ 0 fb	13: ~ 0 fb	23: ~ 0 fb	12: ~ 0 fb	13: ~ 0 fb	23: ~ 0 fb

t':

Model independent parametrisation of the couplings:

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z}{\Gamma_Z^0}} \frac{g}{2 c_W} \, [\bar{T}_{L/R} Z_\mu \gamma^\mu u_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H}{\Gamma_H^0}} \frac{M}{v} \, [\bar{T}_{R/L} h u_{L/R}^i] \right\} + h.c. \, .$$

	$T\bar{t}$			$\bar{T}t$		
	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
$\bar{\sigma}_{Zi}^T$	-	-	6.6 fb	-	-	6.6 fb
$\bar{\sigma}_{Wi}^T$	1,470 fb	113 fb	33.4 fb	226 fb	113 fb	33.5 fb
$\bar{\sigma}_{ZWi}^T$	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb	~ 0 fb

	T			$\bar{T}$		
	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
$\bar{\sigma}_{Zi}^{Tjet}$	63,400 fb	2,430 fb	-	5,700 fb	2,300 fb	-
$\bar{\sigma}_{Wi}^{Tjet}$	45,600 fb	6,830 fb	2,680 fb	5,840 fb	3,160 fb	1,165 fb
$\bar{\sigma}_{ZWii}^{Tjet}$	$-1,900$ fb	~ 0 fb	-	~ 0 fb	~ 0 fb	-
$\bar{\sigma}_{ZWlk}^{Tjet}$	12: ~ 0 fb	13: ~ 0 fb	23: ~ 0 fb	12: ~ 0 fb	13: ~ 0 fb	23: ~ 0 fb

$$\sigma(TZ) = \kappa_T^2 \left(\xi_Z \sum_{i=1}^{2} \zeta_i \, \bar{\sigma}_i^{TZ} \right) ,$$

$$\sigma(Th) = \kappa_T^2 \left(\xi_H \sum_{i=1}^{2} \zeta_i \, \bar{\sigma}_i^{Th} \right) ,$$

$$\sigma(TW) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}_i^{TW} \right) .$$

Pair: 170 fb

	T			$\bar{T}$		
	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
$\bar{\sigma}_i^{TZ}$	4,560 fb	77 fb	-	285 fb	124 fb	-
$\bar{\sigma}_i^{Th}$	7,820 fb	189 fb	-	438 fb	189 fb	-
$\bar{\sigma}_i^{TW^\pm}$	1,840 fb	154 fb	48 fb	303 fb	154 fb	48 fb

Catalogue:

Singlets $\psi_{1a} = \mathbf{1}_{\frac{2}{3}} = U$ $\psi_{1b} = \mathbf{1}_{-\frac{1}{3}} = D$

SM doublet $\psi_2 = \mathbf{2}_{\frac{1}{6}} = \begin{pmatrix} U \\ D \end{pmatrix}$

Doublets $\psi_{3a} = \mathbf{2}_{\frac{7}{6}} = \begin{pmatrix} X \\ U \end{pmatrix}$ $\psi_{3b} = \mathbf{2}_{-\frac{5}{6}} = \begin{pmatrix} D \\ X \end{pmatrix}$

Triplets $\psi_{4a} = \mathbf{3}_{\frac{2}{3}} = \begin{pmatrix} X \\ U \\ D \end{pmatrix}$ $\psi_{4b} = \mathbf{3}_{-\frac{1}{3}} = \begin{pmatrix} U \\ D \\ X \end{pmatrix}$

Two fermion mixing: singlets/triplets vs doublets

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

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

3 parameters
top mass fixed

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

2 free parameters
mt' - x or M - x

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

$$\sin\theta_u^L \gg \sin\theta_u^R$$

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

$$\sin\theta_u^R \gg \sin\theta_u^L$$

Stronger bounds from left-handed couplings!

Flavour mixing

$$\mathcal{L}_{\rm yuk} = -y_u^{i,j}\, Q_L^i H^c u_R^j - y_d^{i,j}\, Q_L^i H d_R^j - \lambda^j\, \psi_L H u_R^j\,.$$

Diagonalising yu and yd, the mass matrix reads:

$$-\,(u_L, c_L, t_L, U_L)\cdot \begin{pmatrix} \tilde m_u & & & 0 \\ & \tilde m_c & & 0 \\ & & \tilde m_t & 0 \\ x_1 & x_2 & x_3 & M \end{pmatrix} \cdot \begin{pmatrix} u_R \\ c_R \\ t_R \\ U_R \end{pmatrix} - M\, X_L X_R + h.c.$$

lh mixing (VL) given by:

$$M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde m_u^2 & 0 & 0 & x_1^* \tilde m_u \\ 0 & \tilde m_c^2 & 0 & x_2^* \tilde m_c \\ 0 & 0 & \tilde m_t^2 & x_3 \tilde m_t \\ x_1 \tilde m_u & x_2 \tilde m_c & x_3 \tilde m_t & M^2 + |x_1|^2 + |x_2|^2 + x_3^2 \end{pmatrix}.$$

lh mixing angles suppressed by light quark masses!!!!!!

rh mixing (VR) given by:

$$M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde m_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde m_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3 x_1 & x_3 x_2 & \tilde m_t^2 + x_3^2 & x_3 M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix}.$$

Possibly large mixing!
Suppressed only by small x1, x2

Flavour mixing

Couplings of U to the Z are different from up quark couplings:

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

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

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

Large Flavour violating couplings only in the right handed Z sector. No large left handed couplings to Z and W!!!!

This leads to milder flavour constraints!!!