Pair production of heavy $Q = 2/3$ singlets at LHC

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Summary

Overview of the model

Addition of one $\mathrm{SU}(2)_L$ singlet T with charge $Q = 2/3$

☞ extra dimensions, little Higgs models, GUTs

▸ Anomalies

Mass matrix of $Q = 2/3$ quarks with seesaw structure

$M^u = \frac{v}{\sqrt{2}} Y^u$, B^u bare mass term or from Higgs singlet

$$\mathcal{M}^u = \begin{pmatrix} M^u \\ B^u \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ B_1 & B_2 & B_3 & B_4 \end{pmatrix}$$

Mixing with singlet ☞ [modifies interactions with W, Z and H
does not affect interactions with γ, g

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[\bar{u}\gamma^\mu \; V \, P_L \;\; d \, W_\mu^+ + \bar{d}\gamma^\mu \, V^\dagger \, P_L \; u \, W_\mu^- \right]$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \bar{u}\gamma^\mu \left[P_L \;\; - \frac{4}{3} s_W^2 1\!\!1_{4\times 4} \right] u \, Z_\mu$$

$$\mathcal{L}_H = \frac{g}{2M_W} \, \bar{u} \left[\; \mathcal{M}^u \; P_L + \; \mathcal{M}^u \; P_R \right] u \, H$$

Mixing with singlet ☞ [modifies interactions with W, Z and H
does not affect interactions with γ, g

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\left[\bar{u}\gamma^\mu\, V_{4\times 3} P_L d\, W_\mu^+ + \bar{d}\gamma^\mu V_{4\times 3}^\dagger P_L u\, W_\mu^-\right]$$

$$\mathcal{L}_Z = -\frac{g}{2c_W}\bar{u}\gamma^\mu\left[X\, P_L - \frac{4}{3}s_W^2 \mathbb{1}_{4\times 4}\right] u\, Z_\mu$$

$$\mathcal{L}_H = \frac{g}{2M_W}\,\bar{u}\left[\mathcal{M}^u\, X P_L + X\, \mathcal{M}^u P_R\right] u\, H$$

$X = VV^\dagger$

In particular:

- New quark T has a CC coupling V_{Tb} to the b quark (V_{Td}, V_{Ts} much smaller)

  See more

- T has a FCN coupling to the top and Z boson
  $|X_{tT}|^2 \simeq |V_{Tb}|^2(1 - |V_{Tb}|^2)$

- V_{tb} smaller than unity:
  $|V_{tb}|^2 = 1 - |V_{ub}|^2 - |V_{cb}|^2 - |V_{Tb}|^2 \simeq 1 - |V_{Tb}|^2$

- $Z\, t_L t_L$ coupling also smaller:
  $c_L = 1 - \frac{4}{3}s_W^2 \quad \longrightarrow \quad c_L = X_{tt} - \frac{4}{3}s_W^2, \quad \text{with } X_{tt} \simeq |V_{tb}|^2$

Signals at LHC

- Production of the new quark T

  QCD pair production $pp \to T\overline{T}$ [Aguila et al., NPB '90]

  EW single production $pp \to Tj$ [Han et al., PRD '03]

- FCN processes involving the top quark [JAAS, APPB '04]

  Rare top decays $t \to Zq$, $t \to Hq$ $(q = u, c)$

  Single top production $gq \to Zt$, $gq \to Ht$

Signals at LHC

- Production of the new quark T

  QCD pair production $pp \to T\overline{T}$ ☞ [larger σ for moderate m_T / σ independent of V_{Tb}]

  EW single production $pp \to Tj$ [Han et al., PRD '03]

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Signals at LHC

- Production of the new quark T

  QCD pair production $pp \to T\overline{T}$ [Aguila et al., NPB '90]

  EW single production $pp \to Tj$ ☞ [$\sigma \propto |V_{Tb}|^2$; larger* σ for $m_T \gtrsim 1$ TeV

- FCN processes involving the top quark [JAAS, APPB '04]

  Rare top decays $t \to Zq$, $t \to Hq$ ($q = u, c$)

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Decays of T ($M_H = 115$ GeV)

m_T	500 GeV	1 TeV
$\mathrm{Br}(T \to W^+ b)$	0.50	0.50
$\mathrm{Br}(T \to Zt)$	0.16	0.23
$\mathrm{Br}(T \to Ht)$	0.34	0.27

Decay $T \to W^+ b$: the same final states as for a top quark
(4^{th} generation T may have decays $T \to W^+ B$ with $B \to W^- t$)

Additional decays $T \to Zt$, $T \to Ht$ establish that T is a singlet

$T \to Ht$ discovery channel for a light Higgs boson

$T\overline{T}$ production at LHC

We study $T\overline{T}$ production in the channel $T\overline{T} \to W^+ b W^- \bar{b}$
with one W decaying leptonically and the other one hadronically

[JAAS, PLB '05]

We consider $m_T = 500$ GeV, $m_T = 1$ TeV

Event generation done with our own MC generators ($T\overline{T}$, $t\bar{t}$, $t\bar{b}j$) and ALPGEN ($Wb\bar{b}jj$, $Zb\bar{b}jj$)

Analysis done with PYTHIA + ATLFAST

b tagging efficiency of 60% (50%) for low (high) luminosity phase

We require a final state with:

- one isolated charged lepton
- two b-tagged jets
- at least two additional jets

] with $|\eta| \leq 2.5$, $p_t \geq 20$ GeV

☞ Additional signal contributions from $T \to Zt$, $T \to Ht$ decays:

$$T\overline{T} \to W^+ b\, H \bar t\,,\ Ht\, W^- \bar b \to W^+ b\, W^- \bar b\, H \quad (H \to b\bar b, c\bar c)$$

$$T\overline{T} \to W^+ b\, Z \bar t\,,\ Zt\, W^- \bar b \to W^+ b\, W^- \bar b\, Z \quad (Z \to jj, b\bar b, \nu\bar\nu)$$

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Signal and background cross sections

Process		$\sigma \times$ eff	Process	$\sigma \times$ eff
$T\bar{T}$ (500)		37.3 fb	$t\bar{t}$	18.8 pb
	+	46.5 fb (H)	$Wb\bar{b}jj$	1.23 pb
	+	19.8 fb (Z)	$Zb\bar{b}jj$	246 fb
$T\bar{T}$ (1000)		0.618 fb	$t\bar{b}j$	710 fb
	+	0.638 fb (H)		
	+	0.481 fb (Z)		

We require high transverse momentum for the charged lepton and jets

$m_T = 500$ GeV

$$p_t^{\text{lep}} \geq 50 \text{ GeV}$$
$$p_t^{j,\text{max}} \geq 250 \text{ GeV}$$
$$p_t^{b,\text{max}} \geq 150 \text{ GeV}$$
$$H_T \geq 1000 \text{ GeV}$$
$$50 \text{ GeV} \leq \not{p}_t \leq 600 \text{ GeV}$$

$m_T = 1$ TeV

$$p_t^{\text{lep}} \geq 200 \text{ GeV}$$
$$p_t^{j,\text{max}} \geq 400 \text{ GeV}$$
$$p_t^{b,\text{max}} \geq 300 \text{ GeV}$$
$$H_T \geq 1800 \text{ GeV}$$
$$50 \text{ GeV} \leq \not{p}_t \leq 400 \text{ GeV}$$

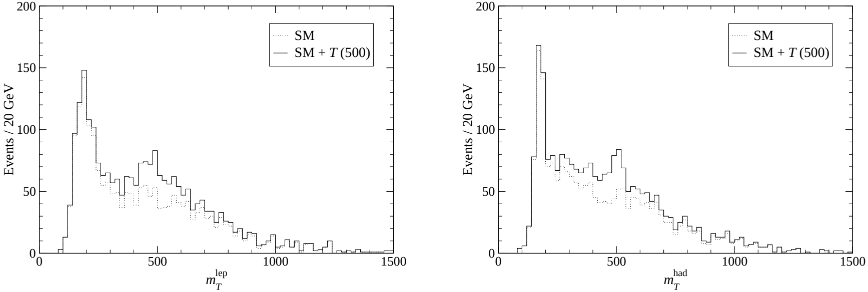
Reconstruction done looking for two particles of equal mass

$$m(\ell\,\nu\,b_1) = m(j_1\,j_2\,b_2)$$

Signals and backgrounds after cuts ($m_T = 500$ GeV)

Process		$N_{\rm cut}$	$N_{\rm peak}$	
$T\bar{T}$		201.7	125.8	
	$+$	139.4	45.4	(H)
	$+$	58.5	20.9	(Z)
$t\bar{t}$		1609	240	
$Wb\bar{b}jj$		287	65	
$Zb\bar{b}jj$		39	10	
$t\bar{b}j$		70	11	

$m_T = 500$ GeV, 10 fb^{-1} $\longrightarrow$ 10.9 σ evidence (300 – 660 GeV)



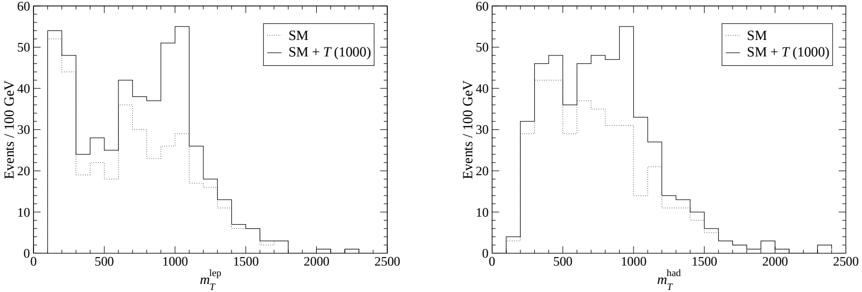
$$\text{`SM'} = t\bar{t}\,,\ Wb\bar{b}jj\,,\ Zb\bar{b}jj\,,\ t\bar{b}j$$

$$\text{`}T\text{'} = T\overline{T} \to W^+b\,W^-\bar{b} \to \ell^\pm \nu b\bar{b}jj \quad + H, Z \text{ contributions}$$

Signals and backgrounds after cuts ($m_T = 1$ TeV)

Process		N_{cut}	N_{peak}	
$T\bar{T}$		58.2	33.5	
	$+$	39.6	7.8	(H)
	$+$	21.0	5.1	(Z)
$t\bar{t}$		208	10	
$Wb\bar{b}jj$		132	15	
$Zb\bar{b}jj$		19	1	
$t\bar{b}j$		3	0	

$$m_T = 1 \text{ TeV}, 300 \text{ fb}^{-1} \longrightarrow 9.1\ \sigma \text{ evidence} \quad (800 - 1200 \text{ GeV})$$



$$\text{‘SM’} = t\bar{t}\,,\ Wb\bar{b}jj\,,\ Zb\bar{b}jj\,,\ t\bar{b}j$$

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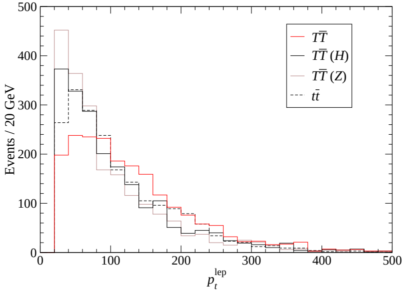
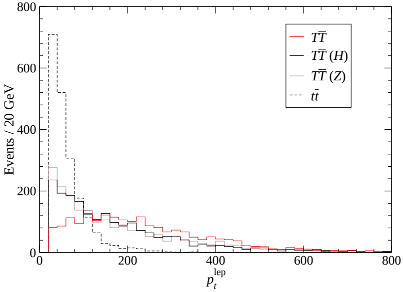
More details . . .

p_t^{lep} cut substantially reduces the $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals

(Cut required to reduce backgrounds)

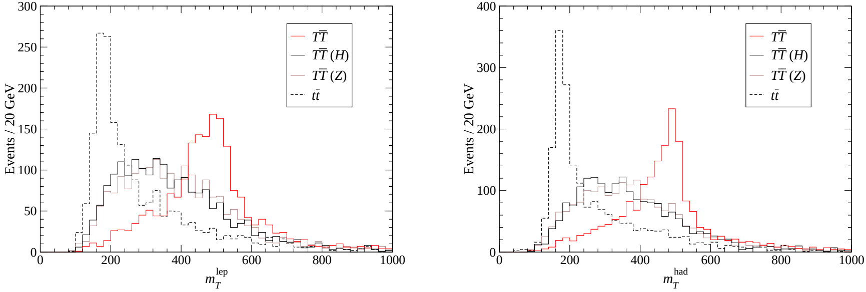




Distributions for 2000 events, without cuts

More details . . .

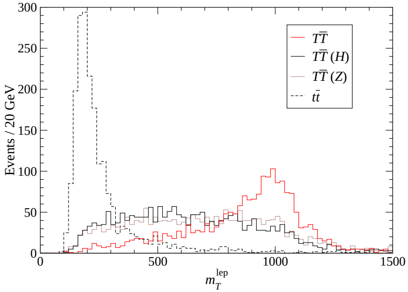
For $m_T = 500$ GeV, $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals have a sizeable contribution around the m_T peak

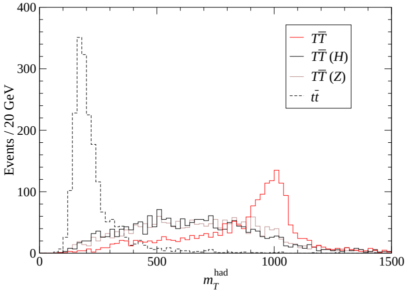


Distributions for 2000 events, without cuts

More details . . .

For $m_T = 1$ TeV, $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals are widely distributed across the m_T^{lep} and m_T^{had} range



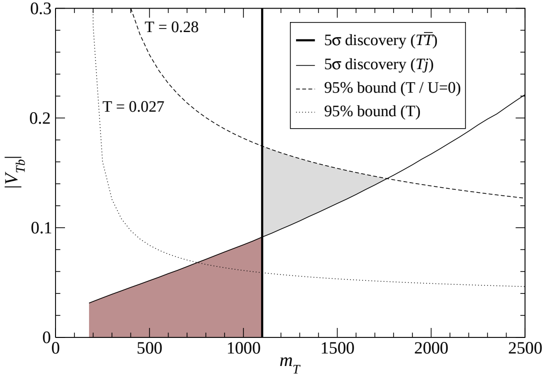


Distributions for 2000 events, without cuts

LHC reach for $Q = 2/3$ singlets

For $m_T = 500$ GeV, 5 σ evidence achieved with 2.1 fb^{-1}

Eventually, $m_T \simeq 1.1$ TeV can be reached with 300 fb^{-1}



Tj scaled

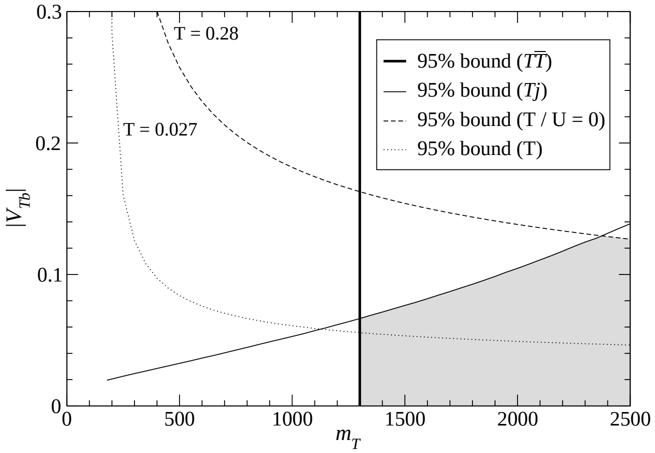
from ATLAS result

[Azuelos et al., EPJC '05]

More details

LHC reach for $Q = 2/3$ singlets

If $Q = 2/3$ singlets not observed at LHC ☞ limits on m_T, $|V_{Tb}|$



Conclusions

New T singlets with a mass up to ~ 1 TeV can be observed at LHC

(with a mass around 500 GeV they will be quickly discovered)

In addition to direct observation, $Q = 2/3$ singlets may give indirect effects in low energy physics:

- CP asymmetries in B decays
- δm_{B_s}, δm_D
- Rare kaon decays

as well as in top physics:

- top FCN decays $t \to qZ$
- $e^+e^- \to t\bar{t}$ (ILC)

Anomaly cancellation

$$\mathrm{tr}[t^a t^b Y] = \frac{1}{2}\delta^{ab}\sum_q Y_q \quad \longrightarrow \quad \Delta = \left(-\frac{2}{3}\right) + \frac{2}{3} = 0$$

$$\mathrm{tr}[\tau^a \tau^b Y] = \frac{1}{2}\delta^{ab}\sum_{f,d} Y_f \quad \longrightarrow \quad \Delta = 0$$

$$\mathrm{tr}[Y^3] = \sum_f Y_f^3 \quad \longrightarrow \quad \Delta = \left(-\frac{2}{3}\right)^3 + \left(\frac{2}{3}\right)^3 = 0$$

$$\mathrm{tr}[Y] = \sum_f Y_f \quad \longrightarrow \quad \Delta = \left(-\frac{2}{3}\right) + \frac{2}{3} = 0$$

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Indirect constraints on V_{Tb}

V_{Tb} constrained by the T parameter

$$T = \frac{N_c}{16\pi s_W^2 c_W^2} \left\{ |V_{Tb}|^2 \left[\theta_+(y_T, y_b) - \theta_+(y_t, y_b) \right] - |X_{tT}|^2 \theta_+(y_T, y_t) \right\}$$

[Lavoura, Silva, PRD '93]
[JAAS, PRD '03]

plus other model-dependent new physics contributions (ignored)

Experimentally

$$T = -0.17 \pm 0.12 \quad \text{(U arbitrary)}$$

$$T = 0.12 \pm 0.10 \quad (U = 0)$$

☞ 95% bounds on $|V_{Tb}|$

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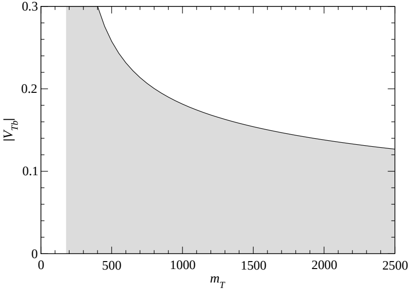
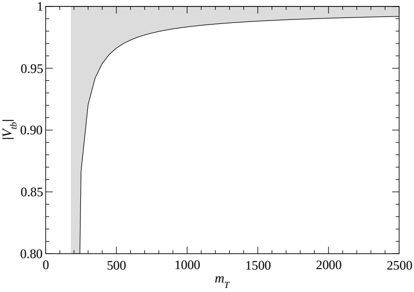
Indirect constraints on V_{Tb}

Allowed range for V_{Tb}, V_{tb}





Stronger constraints for larger m_T

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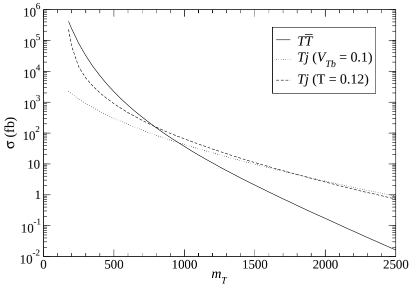
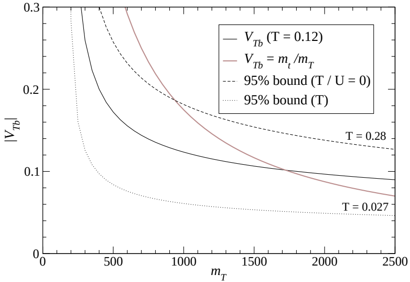
More

m_T dependence of $T\overline{T}$, Tj production

$V_{Tb} \sim m_t/m_T$ expected from mass matrix diagonalisation

…but $V_{Tb} = m_t/m_T$ too large for $m_T \lesssim 900$ GeV





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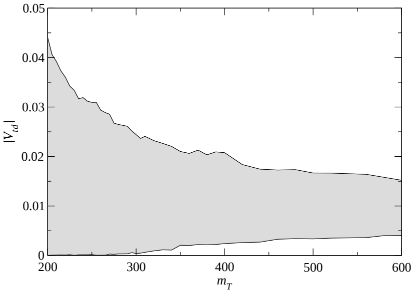
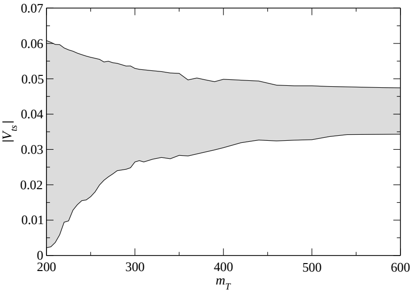
Allowed range for V_{td}, V_{ts}

Experimental data from K, B physics $\longrightarrow$ constraints on V_{td}, V_{ts}





Stronger constraints for larger m_T

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Allowed range for X_{tt}