Signals of quark singlets at large colliders and B factories

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Summary

1. Overview of the model
2. Signals at LHC
3. Signals at B factories

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

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

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$m_T = B\,, \qquad V_{Tb} \sim \frac{m_t}{m_T}$ [Aguila, Bowick '83]

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

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

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

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

Mixing with singlet ☞ [modifies interactions with W, Z and H
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$$\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}}\left[\bar{u}\gamma^\mu\, V_{4\times 3} P_L d\; W_\mu^+ + \bar{d}\gamma^\mu V_{4\times 3}^\dagger P_L u\; W_\mu^-\right] \\
\mathcal{L}_Z &= -\frac{g}{2c_W}\bar{u}\gamma^\mu\left[X\, P_L - \frac{4}{3}s_W^2 \mathbb{1}_{4\times 4}\right] u\; Z_\mu \\
\mathcal{L}_H &= \frac{g}{2M_W}\,\bar{u}\left[\mathcal{M}^u\, X P_L + X\,\mathcal{M}^u P_R\right] u\; H
\end{aligned}$$

$X = VV^\dagger$

In particular:

- New quark T has a CC coupling V_{Tb} to the b quark (V_{Td}, V_{Ts} much smaller)
- T has a FCN coupling to the top and Z boson
  $X_{tT} \simeq |V_{Tb}|^2 (1 - |V_{Tb}|^2)$
- 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 $t \to Zq$, $t \to Hq$ $(q = u, c)$

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

Decays of T ($M_H = 115$ GeV)		
m_T	500 GeV	1 TeV
$\text{Br}(T \to W^+ b)$	0.50	0.50
$\text{Br}(T \to Zt)$	0.16	0.23
$\text{Br}(T \to Ht)$	0.34	0.27

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 ($T\bar{T}$, $t\bar{t}$, $t\bar{b}j$) and ALPGEN ($Wb\bar{b}jj$, $Zb\bar{b}jj$)

Analysis done with PYTHIA + ATLFAST

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

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

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

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

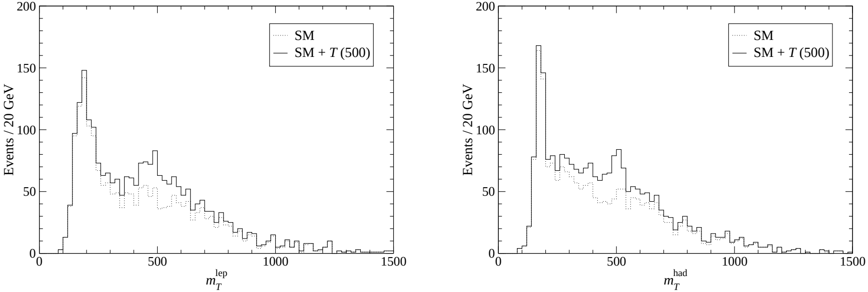
$m_T = 1$ TeV

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

Reconstruction done looking for two particles of equal mass

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

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



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

$$\text{‘T’} = T\overline{T} \to W^+b\,W^-\bar{b} \to \ell^\pm \nu b\bar{b}jj$$

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

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

See details

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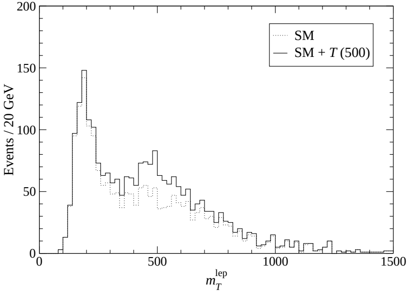

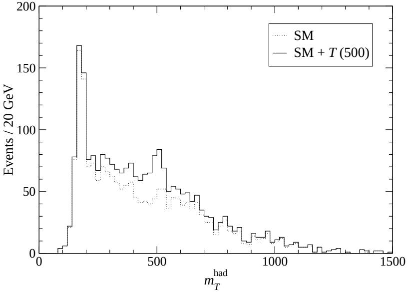

$$\text{`SM'} = t\bar{t}\,,\ Wb\bar{b}jj\,,\ Zb\bar{b}jj\,,\ t\bar{b}j$$

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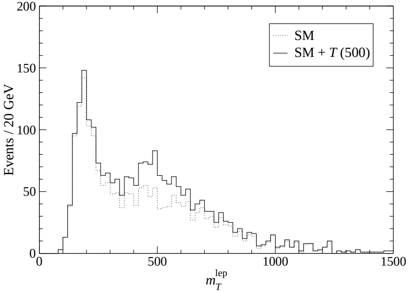

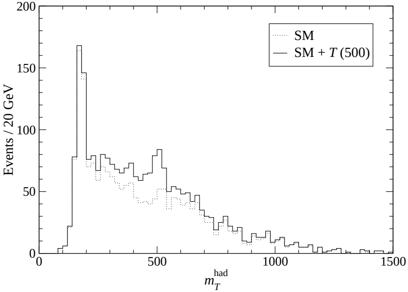

$$
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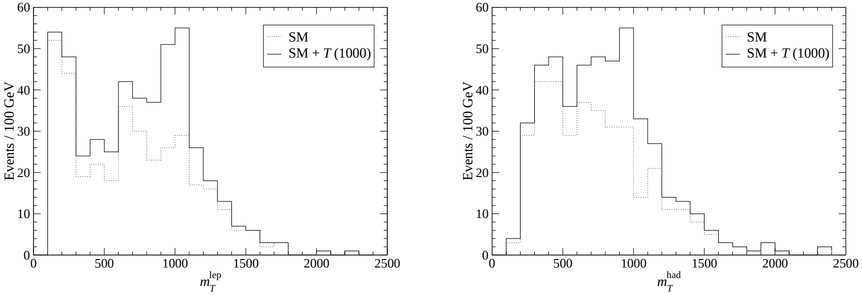
&+ T\overline{T} \to W^+b\,Z\bar{t}\,,\ Zt\,W^-\bar{b} \to W^+b\,W^-\bar{b}\,Z \quad (Z \to jj, b\bar{b}, \nu\bar{\nu})
\end{aligned}
$$

See details

$m_T = 1000$ GeV, 300 fb^{-1} $\longrightarrow$ 9.1 σ evidence (800 – 1200 GeV)

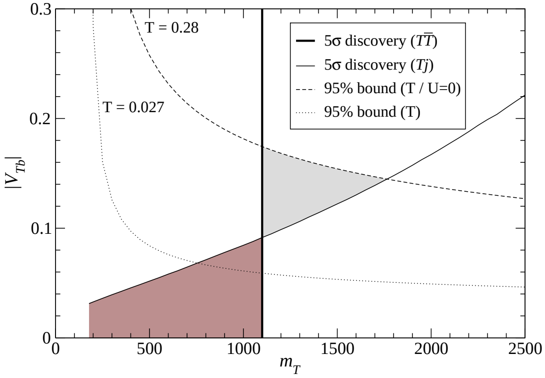


See details

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

Signals at B factories

New effects in low energy physics given by:

- Loss of unitarity of the 3×3 CKM matrix
- Contribution of the new quark to loop observables

[Barger, Berger, Phillips, PRD '95]

"Screening" property:

for $m_T = m_t$ both contributions cancel

for $m_T > m_t$, new quark can enhance or screen CKM breaking effects

[JAAS, Botella, Branco, Nebot, NPB '05]

We do not consider other (model-dependent) contributions from new bosons, etc.

3×3 unitarity breaking ☞ different ranges for $|V_{td}|$, $|V_{ts}|$, $|V_{tb}|$

$$|V| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| & \cdots \\ |V_{cd}| & |V_{cs}| & |V_{cb}| & \cdots \\ |V_{td}| & |V_{ts}| & |V_{tb}| & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$m_T = 500$ GeV $\Rightarrow$ $|V_{td}|$, $|V_{ts}|$ with their SM values ☹ More

important deviations allowed in $|V_{tb}|$ ☺ More

3×3 unitarity breaking ☞ different ranges for the phases

$$\arg V = \begin{pmatrix} 0 & \chi' & -\gamma & \cdots \\ \pi & 0 & 0 & \cdots \\ -\beta & \pi + \chi & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$m_T = 500$ GeV $\Rightarrow$ $|\chi'| \lesssim 0.06$ (general)
but $|\chi| \simeq 0.3$ is possible

The phase χ

- β, γ appear in standard unitarity triangle while χ, χ' do not
- $0.015 \leq \chi \leq 0.022$ at 90% CL in the SM
- With $Q = 2/3$ singlets $\chi \sim \pm 0.3$ is possible while having β, γ very close to the SM prediction
- χ is involved in B_s mixing and $b \longrightarrow s\bar{s}s$ decays

Back

Some effects in B physics

Analysis done taking experimental constraints into account:

R_b, R_c, FB asymmetries, oblique parameters, ε, ε', δm_{B_d}, δm_{B_s}, δm_D, $a(B \to \psi K_S)$, $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \mu^+ \mu^-$, $b \to s\gamma$, $b \to s \ell^+ \ell^-$ and more

[JAAS, PRD '03]

Recent measurements also OK:

$\mathcal{A}_{\rm SL}$, $a(b \to s\gamma)$, $a(B \to DK)$, $a(B \to \rho\rho)$

SM predictions		with an extra quark
$\delta m_{B_s} / \delta m_{B_d} \sim 35$	$\longrightarrow$	between 26 and 77
$a(B \to \psi\phi) \sim \lambda^2$	$\longrightarrow$	between -0.4 and 0.4 (More)
$a(B \to \phi K_S) = a(B \to \psi K_S)$	$\longrightarrow$	difference $O(\lambda)$ (More)

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Other effects in low energy physics

$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \simeq 2.4 \times 10^{-11}$ $\longrightarrow$ up to 4.4×10^{-10}

$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq 6.4 \times 10^{-11}$ $\longrightarrow$ can accomodate larger values

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Signals correlated with a large χ

$$\sin\chi = \frac{\mathrm{Im}\, X_{ct}}{|V_{cs}||V_{ts}|} + O(\lambda^2) \quad \longrightarrow \quad \chi \sim \lambda \text{ requires } X_{ct} \sim \lambda^3$$

$$|X_{ct}|^2 \leq (1 - X_{cc})(1 - X_{tt}) \quad \longrightarrow \quad X_{ct} \sim \lambda^3 \text{ requires } X_{tt} \simeq 0.96$$

More

$$X_{tt} \simeq 1 - |V_{Tb}|^2 \quad \longrightarrow \quad X_{tt} \simeq 0.96 \text{ for } m_T \lesssim 800 \text{ GeV}$$

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More

$\longrightarrow$ Observable at LHC

Conclusions

$Q = 2/3$ singlets with a mass up to ~ 1 TeV can be observed at LHC

If they exist, they may give new effects in low energy physics

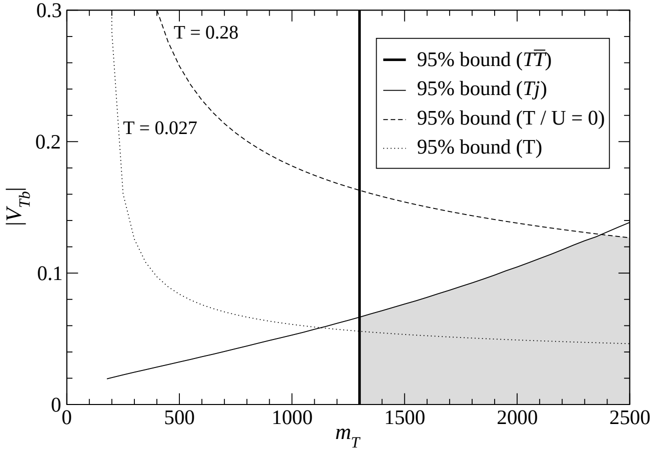
- CP asymmetries in B decays
- δm_{B_s}, δm_D
- Rare kaon decays

as well as in top physics

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

Conclusions

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



More details

Anomaly cancellation

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

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

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

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

Back

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

Process		N_{cut}	N_{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	

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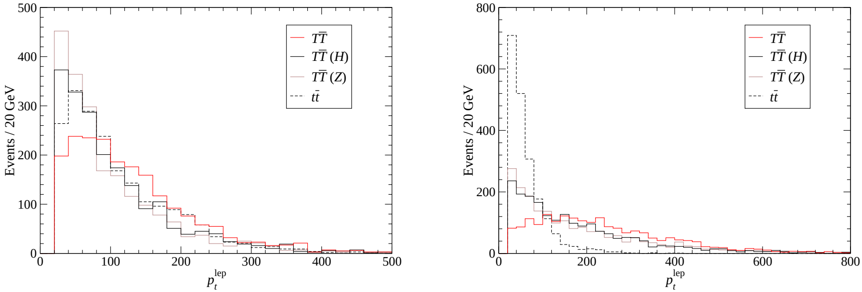
$p_t^{\rm lep}$ cut substantially reduces the $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals

Cut required to reduce backgrounds



Distributions for 2000 events, without cuts

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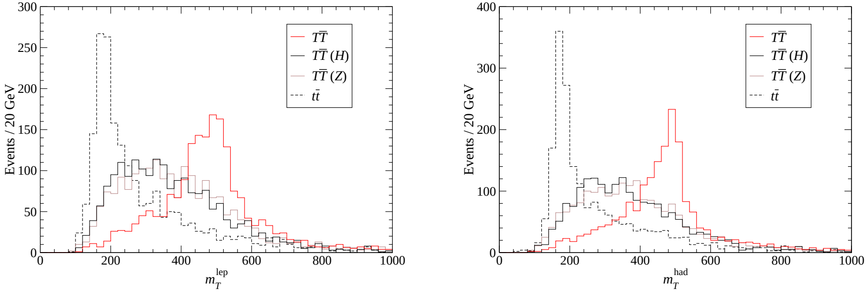
For $m_T = 500$ GeV, $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals have a sizeable contribution around the m_T peak



Distributions for 2000 events, without cuts

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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	

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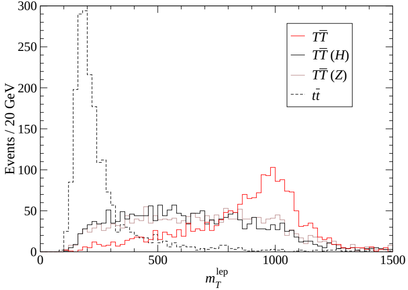
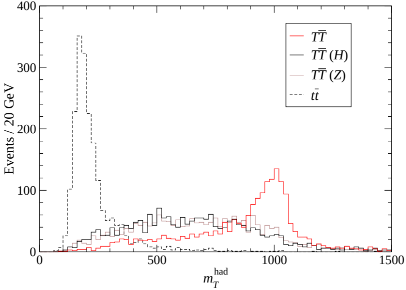
For $m_T = 100$ TeV, $T\bar{T}$ (H) and $T\bar{T}$ (Z) signals are widely distributed across the $m_T^{\rm lep}$ and $m_T^{\rm had}$ range





Distributions for 2000 events, without cuts

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Indirect constraints on V_{Tb}

V_{Tb} constrained by the T parameter

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

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

plus other model-dependent new physics contributions (ignored)

Experimentally

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

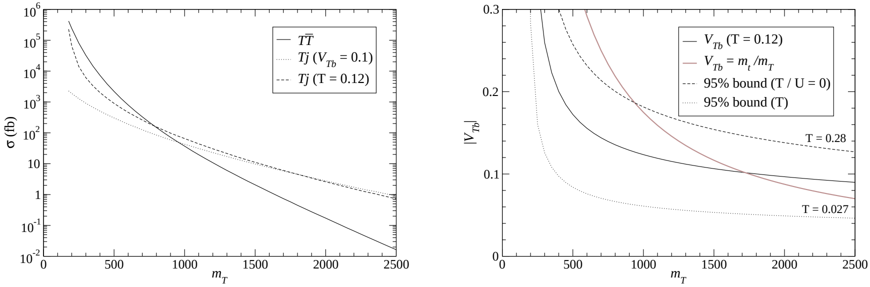
$\mathrm{T} = 0.12 \pm 0.10$ $(\mathrm{U} = 0)$

☞ 95% bounds on $|V_{Tb}|$

Back Conclusions More

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

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



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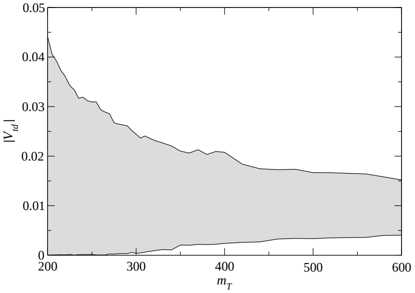
Conclusions

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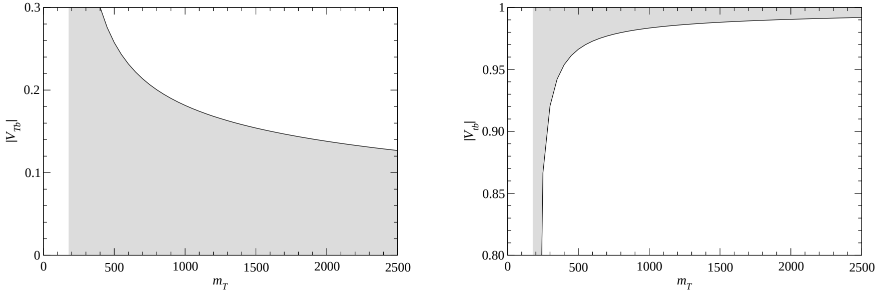
Allowed range for V_{Tb}, V_{tb}

T parameter $\longrightarrow$ constraints on V_{Tb}, V_{tb}



Stronger constraints for larger m_T

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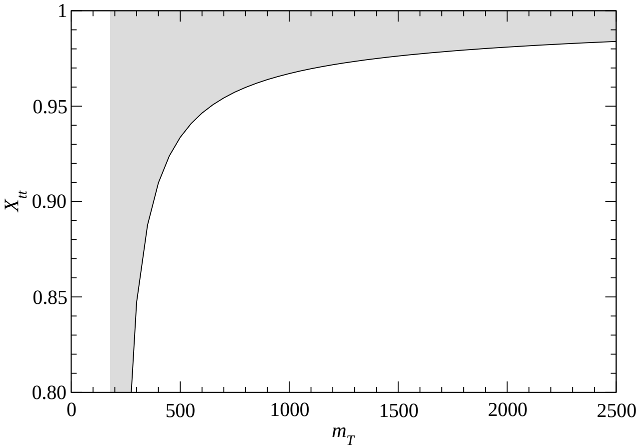
Allowed range for X_{tt}



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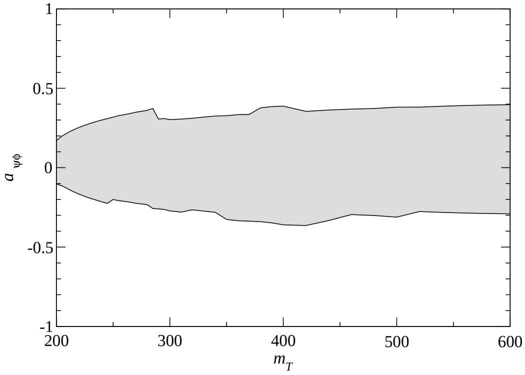
Allowed range for $a_{\psi\phi}$



Measured at LHCb with a precision of ± 0.03

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New physics in $a_{\phi K_S}$, $a_{\psi\phi}$

$Q = 2/3$ singlets:

- $a(B \to \phi K_S) = a(B \to \psi K_S)$ violated $O(\lambda)$:
  $0.57 \leq a(B \to \phi K_S) \leq 0.93$
- $a(B \to \psi\phi) \lesssim 0.4$

[JAAS, Botella, Branco, Nebot, NPB '05]

$Q = -1/3$ singlets:

- $a(B \to \phi K_S) = a(B \to \psi K_S)$ largely violated [Hiller, PRD '02]
- $0 \lesssim a(B \to \psi\phi) \lesssim 0.11$ [JAAS, PRD '03]

Other SM extensions: possibly larger effects ...

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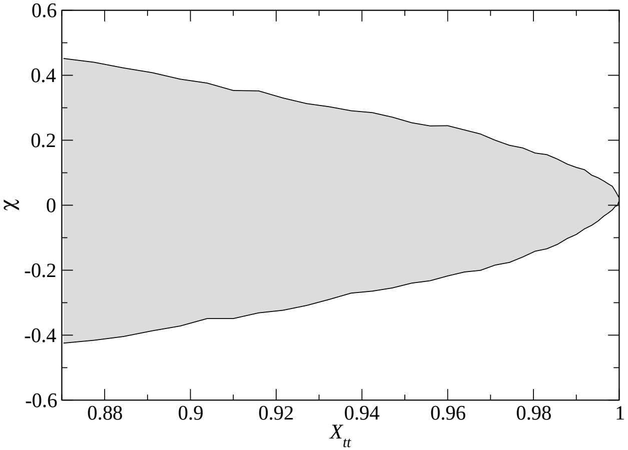
Dependence of χ on X_{tt}



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