Discovering the Higgs boson in heavy singlet decays

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Summary

Why quark singlets?

- $\mathrm{SU}(2)_L$ singlets T with charge $Q = 2/3$ appear in several SM extensions

  ▸ Anomalies

  ☞ extra dimensions, little Higgs models, GUTs

- They provide a consistent way of breaking 3×3 CKM unitarity leading to many observable effects

  ☞ FCNC, effects in meson physics, ...

- Among new effects → Higgs discovery from fermion mixing

Overview of the model

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)

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

Overview of the model

Mixing with singlet ☞ $\left[\begin{array}{l}\text{modifies interactions with } W, Z \text{ and } H \\ \text{does not affect interactions with } \gamma, \text{g}\end{array}\right.$

$$\begin{aligned}
\mathcal{L}_W &= -\frac{g}{\sqrt{2}}\left[\bar{u}\gamma^\mu\ V\ P_L\ \ d\ W_\mu^+ + \bar{d}\gamma^\mu\ V^\dagger\ P_L\ u\ W_\mu^-\right] \\
\mathcal{L}_Z &= -\frac{g}{2c_W}\bar{u}\gamma^\mu\left[P_L\ \ -\frac{4}{3}s_W^2\mathbb{1}_{4\times4}\right]u\ Z_\mu \\
\mathcal{L}_H &= \frac{g}{2M_W}\bar{u}\left[\ \mathcal{M}^u\ P_L + \ \mathcal{M}^u\ P_R\right]u\ H
\end{aligned}$$

Overview of the model

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

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

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

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

$X = VV^\dagger$

Main features:

- New quark T has a CC coupling to the b quark

  More

  $-\frac{g}{\sqrt{2}}\bar{T}\gamma^\mu V_{Tb} P_L b\, W^+_\mu + \text{h.c.}$ (V_{Td}, V_{Ts} much smaller)

- FCN coupling to the top and Z boson

  $-\frac{g}{2c_W}\bar{t}\,\gamma^\mu X_{tT} P_L T\, Z_\mu + \text{h.c.}$ (X_{uT}, X_{cT} much smaller)

  $|X_{tT}|^2 \simeq |V_{Tb}|^2(1-|V_{Tb}|^2)$

- FCN coupling to the top and Higgs

  $\frac{g}{2M_W}\bar{t}\, X_{tT}(m_t P_L + m_T P_R) T\, H + \text{h.c.}$

- and a small Yukawa coupling

  $\frac{g}{2M_W}\bar{T}\, X_{TT} m_T T\, H$

  $|X_{TT}| \simeq |V_{Tb}|^2$

$m_T = 500$
$V_{Tb} = 0.2$
$X_{tT} = 0.196$
$X_{TT} = 0.04$

Main features:

- V_{tb} smaller than unity

  $|V_{tb}|^2 = 1 - |V_{ub}|^2 - |V_{cb}|^2 - |V_{Tb}|^2 \simeq 1 - |V_{Tb}|^2$ ▸ More

- $Z\, t_L t_L$ coupling also smaller:

  $-\frac{g}{2c_W}\bar{t}\gamma^\mu(1 - \frac{4}{3}s_W^2)P_L t\, Z_\mu \quad \rightarrow \quad -\frac{g}{2c_W}\bar{t}\gamma^\mu(X_{tt} - \frac{4}{3}s_W^2)P_L t\, Z_\mu$

  $X_{tt} \simeq |V_{tb}|^2$ ▸ More

- FCN couplings among SM quarks

  $-\frac{g}{2c_W}\bar{q}\gamma^\mu X_{qt} P_L t\, Z_\mu + \text{h.c.} \quad q = u, c$

  $-\frac{g}{2c_W}\bar{u}\gamma^\mu X_{uc} P_L c\, Z_\mu + \text{h.c.}$

$m_T = 500$
$V_{Tb} = 0.2$
$V_{tb} = 0.98$
$X_{tt} = 0.96$

Signals from the new quark:

- 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 $gq \to Zt$, $gq \to Ht$

- Various effects in meson physics [JAAS, PRD '03]

Signals from the new quark:

- 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]

- 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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Signals from the new quark:

- 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

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  ☞ $\left[\begin{array}{l} X_{ut} \gtrsim 0.01 \text{ or} \\ X_{ct} \gtrsim 0.01 \end{array} \right.$

- Various effects in meson physics [JAAS, PRD '03]

Signals from the new quark:

- Production of the new quark T

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

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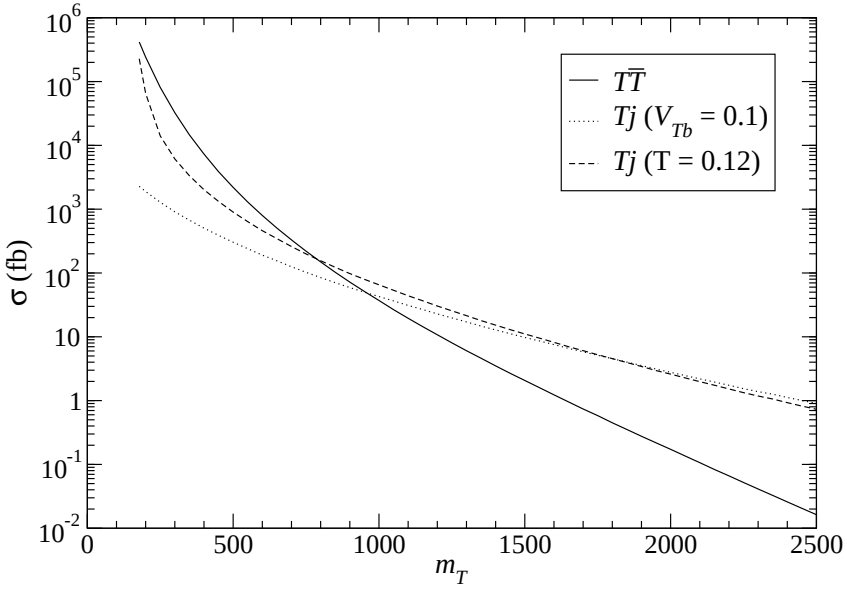
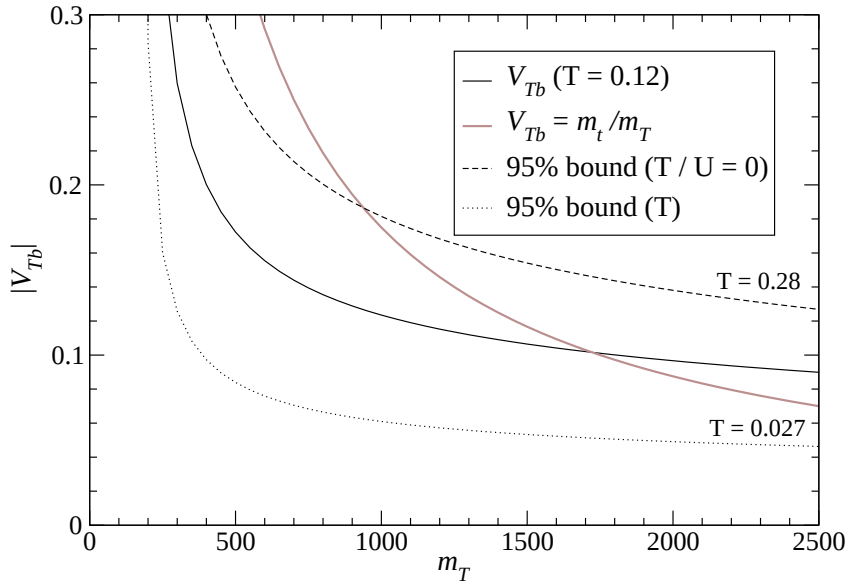
  Rare top decays $t \to Zq$, $t \to Hq$ $(q = u, c)$
  Single top production $gq \to Zt$, $gq \to Ht$

- Various effects in meson physics ☞ $V_{Tb} \gtrsim 0.2$, $V_{Ts} \gtrsim 0.03$ and new CP phases

Direct $T\overline{T}$, 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

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

All three partial widths $\propto |V_{Tb}|^2$

$T\bar{T} \to W^+ b W^- \bar{b}$ better to discover heavier T [JAAS, POS '06]

$T\bar{T} \to W^+ b H \bar{t}, H t W^- \bar{b}$ better for $m_T \sim 500$ GeV

it produces Higgs bosons ☞ could it help discover the Higgs?

▸ $gg \to H$

SM Higgs discovery at LHC

$M_H \lesssim 130$ GeV

- $gg, q\bar{q} \to t\bar{t}H, H \to b\bar{b}$ (Br $\simeq 0.8$) → $\mathcal{L} = 100$ fb^{-1} ($M_H = 120$ GeV)
- $gg \to H +$ others, $H \to \gamma\gamma$ (Br $\simeq 0.2\%$) → $\mathcal{L} = 60$ fb^{-1} ($M_H = 120$ GeV)
- $qq \to q'q'H$ (VBF), $H \to W^+W^- \to \ell\nu\ell'\nu$ (Br $\simeq 0.12$) → $\mathcal{L} = 57$ fb^{-1} ($M_H = 120$ GeV)

130 GeV $\lesssim M_H \lesssim 2M_W$

- $gg \to H \to ZZ^* \to 4\ell$ (Br $\simeq 0.04$) → $\mathcal{L} = 15$ fb^{-1} ($M_H = 130$ GeV)
- VBF, $H \to W^+W^-$ (Br $\simeq 0.3$) → $\mathcal{L} = 13$ fb^{-1} ($M_H = 130$ GeV)

SM Higgs discovery at LHC

$2M_W \lesssim M_H < 2M_Z$

- $gg \to H \to W^+W^-$ (Br $\simeq 0.97$) → $\mathcal{L} = 4$ fb^{-1} ($M_H = 170$ GeV)
- VBF, $H \to W^+W^-$ (Br $\simeq 0.97$) → $\mathcal{L} = 2$ fb^{-1} ($M_H = 170$ GeV)

$2M_Z < M_H$

- $gg \to H \to ZZ \to 4\ell$ (Br $\simeq 0.25$) → $\mathcal{L} = 2.6 - 32$ fb^{-1} ($M_H = 200 - 600$ GeV)

Good news from ($Q = 2/3$) quark singlets

Higgs expected to be light:

$M_H = 91^{+45}_{-32}$ GeV in the SM (fit)
$M_H > 114.4$ GeV, 90% CL (LEP)

SM Higgs detection more difficult for $M_H \lesssim 130$ GeV 😟

Higgs production from T decays most relevant in this mass range 🙂

Process: $gg, qq \to T\bar{T} \to \begin{cases} W^+ bH\bar{t} + \text{CC} & \text{Br} = 0.33 \\ HtH\bar{t} & \text{Br} = 0.11 \\ ZtH\bar{t} + \text{CC} & \text{Br} = 0.10 \end{cases}$

$\sigma = 2.14$ pb $\qquad\qquad$ Br $= 0.55$

Our aim:

Study Higgs discovery in the final state $\ell\nu bbbbjj$ [JAAS, '06]

$$\left[\begin{array}{lll} \text{SM} & \rightarrow & t\bar{t}H \to W^+bW^-bH \\ \text{With } T & \rightarrow & t\bar{t}H + T\bar{T} \to \left[\begin{array}{lll} W^+bH\bar{t} + \text{CC} & \to & W^+bW^-\bar{b}H \\ HtH\bar{t} & \to & W^+bW^-\bar{b}HH \\ ZtH\bar{t} + \text{CC} & \to & W^+bW^-\bar{b}HZ \end{array}\right. \end{array}\right.$$

with semileptonic decay of W^+W^-, $H \to b\bar{b}/c\bar{c}$, $Z \to q\bar{q}/\nu\bar{\nu}$

We consider $m_T = 500$ GeV

Event generation done with newly developed MC generators ($t\bar{t}H$, $T\bar{T}$, $t\bar{t}$, $t\bar{t}b\bar{b}$, ...) and ALPGEN ($W/Z+$ jets)

Analysis done with PYTHIA + ATLFAST

Pre-selection criteria

We require a final state with:

- one isolated charged lepton with $|\eta| \leq 2.5$, $p_t \geq 6$ GeV (μ), $p_t \geq 20$ GeV (e)
- four b-tagged jets with $|\eta| \leq 2.5$, $p_t \geq 15$ GeV
- at least two additional jets with $|\eta| \leq 2.5$, $p_t \geq 15$ GeV

b tagging efficiency of 60%

Main signals and backgrounds ($\ell = e, \mu$)

Process	$\sigma \times$ eff	Process	$\sigma \times$ eff
$T\bar{T}\,(WH)$	12.25 fb	$t\bar{t}H$	6.50 fb
$T\bar{T}\,(HH)$	9.26 fb	$t\bar{t}jj$	64.20 fb
$T\bar{T}\,(ZH)$	4.44 fb	$t\bar{t}b\bar{b}$ (QCD)	25.99 fb
		$t\bar{t}c\bar{c}$ (QCD)	4.04 fb
		$t\bar{t}b\bar{b}$ (EW)	2.89 fb
		$Wb\bar{b}jjjj$	3.11 fb

▸ More

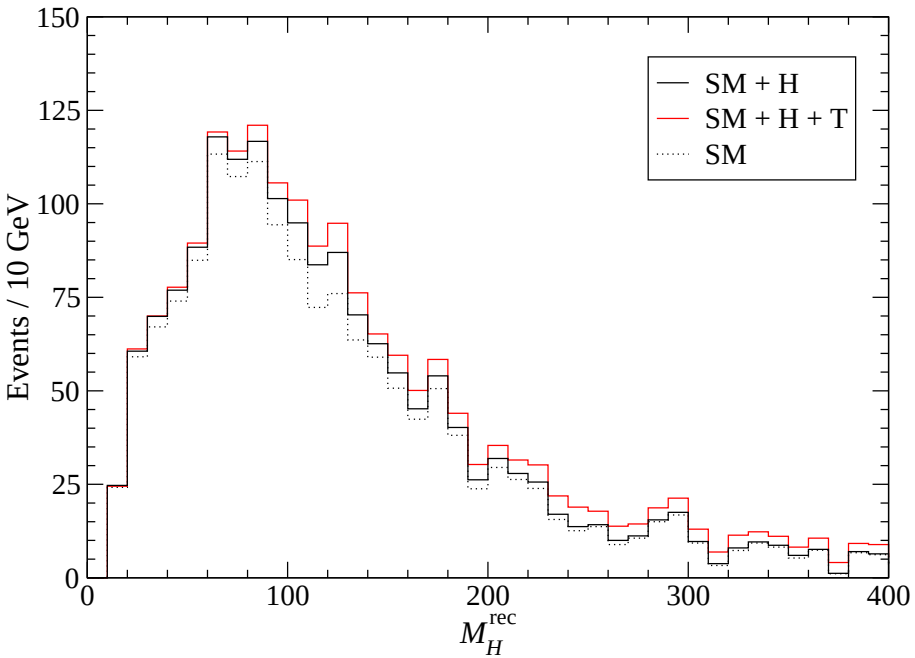
"Standard" Higgs search ($t\bar{t}H$ reconstruction)

Final state: $\ell\nu bbbbjj$ ☞ from $t\bar{t}H$

- Hadronic W from two jets (rescaled)
- Leptonic W from ℓ and $\not{p}_t$ (2 choices)
- Assign the 2 b from $t\bar{t}$: minimum $(m_t^{\text{had}} - m_t)^2 + (m_t^{\text{lep}} - m_t)^2$ (12 choices)
- The 2 remaining b correspond to the Higgs ☞ peak See
- "Quality" cuts: $M_W^{\text{had}} = M_W \pm 30$ GeV
  $m_t^{\text{had}}, m_t^{\text{lep}} = m_t \pm 30$ GeV See

"Standard" Higgs search ($t\bar{t}H$ reconstruction)

Results for $\mathcal{L} = 30$ fb^{-1}



Peak	$95 \leq M_H^{\text{rec}} \leq 135$
$t\bar{t}H$	39.7
$T\bar{T}\,(H)$	28.3
SM bkg	311.9

▸ Details

Signal significance	
$t\bar{t}H$	2.25σ
$t\bar{t}H + T\bar{T}$	3.71σ
5σ (SM) →	150 fb^{-1}

"New" Higgs search ($T\overline{T} \to W^+ bH\bar{t}$ reconstruction)

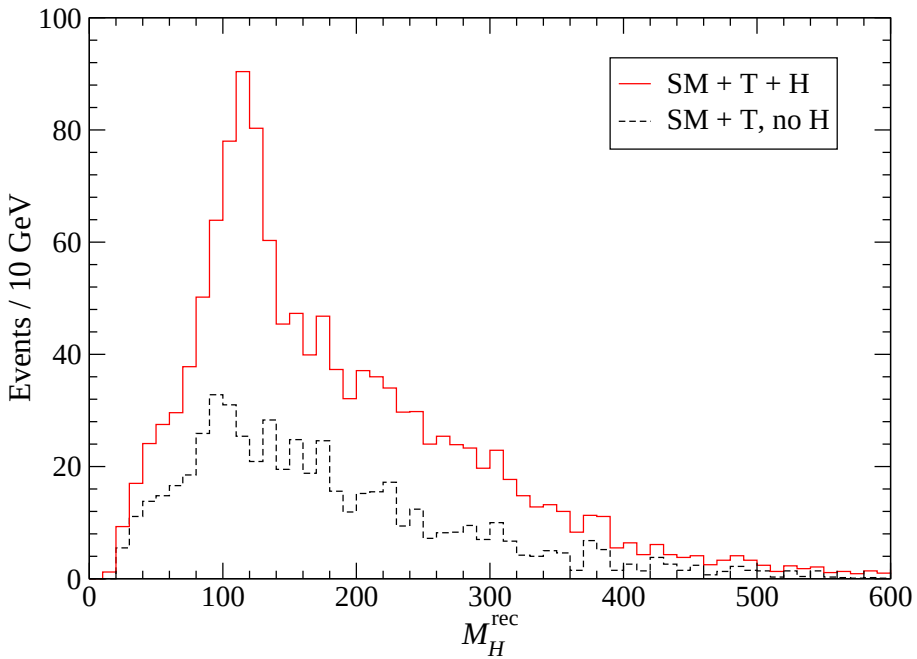
Final state: $\ell\nu bbbbjj$ ☞ from $T\overline{T} \to W^+ bH\bar{t} + \text{CC}$

- Hadronic W from two jets
- Leptonic W from ℓ and $\not{p}_t$ (2 choices)
- Assign 3 b to one W and 1 b to other: minimum $|m_T^{\text{had}} - m_T^{\text{lep}}|$ (8 choices)
- Assign 1 b of the three to top quark minimum $|m_t^{\text{rec}} - m_t|$ (3 choices)
- The 2 remaining b correspond to the Higgs ☞ peak See
- "High p_t" cuts: $H_t \geq 1000$ GeV $\quad p_t^{j,\text{max}} \geq 150$ GeV $\quad p_t^{b,\text{max}} \geq 100$ GeV $\quad p_t^{b,T} \geq 50$ GeV See

"New" Higgs search

($T\bar{T} \to W^+ bH\bar{t}$ reconstruction)

Results for $\mathcal{L} = 30$ fb^{-1}



Peak $80 \leq M_H^{\text{rec}} \leq 140$

$T\bar{T}\,(H)$	262.3
$\Delta T\bar{T}\,(\not{H})$	-17.3
$t\bar{t}H$	13.8
SM bkg	132.4
$T\bar{T}$ bkg	31.9

▸ Details

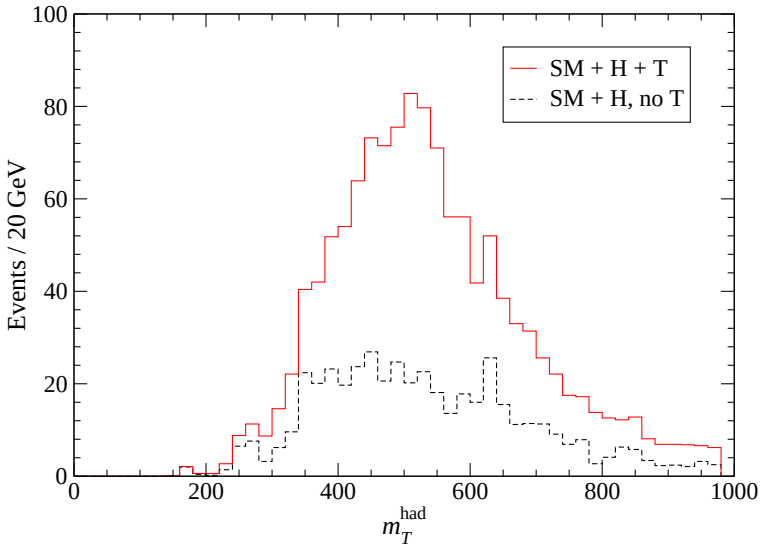
Signal significance

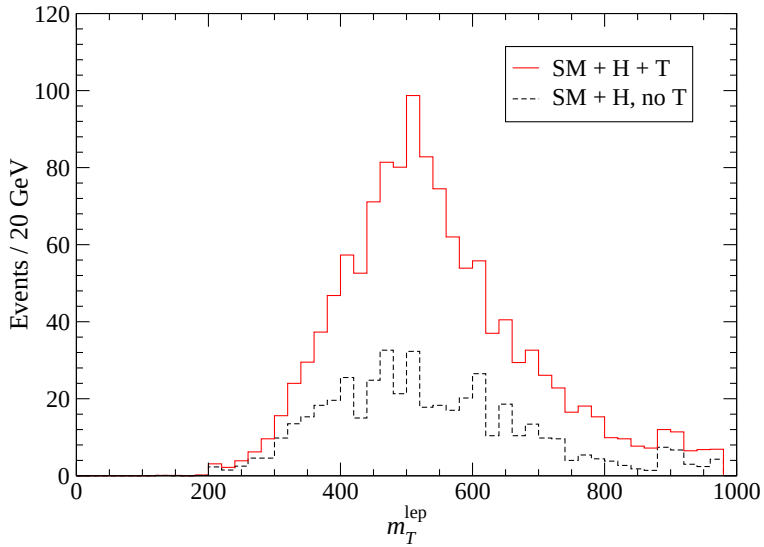
H (all)		20.19σ
5σ	→	1.9 fb^{-1}

T singlet search ($T\overline{T} \to W^+bH\bar{t}$ reconstruction)

Results for $\mathcal{L} = 30$ fb^{-1}

Details





Peak $350 \leq m_T^{had}, m_T^{lep} \leq 650$

$T\overline{T}$ (all)	533.1
SM bkg	255.0

Details

Signal significance

$T\overline{T}$ (all)		34.04σ
5σ	→	0.7 fb^{-1}

Comparison with $T\bar{T} \to W^+bW^-\bar{b}$

$m_T = 500$ GeV — $10\ \text{fb}^{-1}$

$$T\bar{T} \to \left[\begin{array}{l} W^+bW^-\bar{b} \\ + \text{extra modes} \end{array}\right] \to \ell\nu bbjj \qquad S/\sqrt{B} = 10.94$$

$$T\bar{T} \to \left[\begin{array}{l} W^+bH\bar{t} + \text{CC} \\ + \text{extra modes} \end{array}\right] \to \ell\nu bbbbjj \qquad S/\sqrt{B} = 19.65$$

$m_T = 1$ TeV — $300\ \text{fb}^{-1}$

$$T\bar{T} \to \left[\begin{array}{l} W^+bW^-\bar{b} \\ + \text{extra modes} \end{array}\right] \to \ell\nu bbjj \qquad S/\sqrt{B} = 9.1$$

$$T\bar{T} \to \left[\begin{array}{l} W^+bH\bar{t} + \text{CC} \\ + \text{extra modes} \end{array}\right] \to \ell\nu bbbbjj \qquad S/\sqrt{B} \lesssim 4$$

▸ More

Conclusions

Is this the most interesting effect of $Q = 2/3$ singlets?

- No need to worry about T mixing with u, c, d, s

  T produced by QCD interactions, decays even for small V_{Tb}

  ☞ As long as T decays (in the detector), it decays to Ht

  No need of "large" V_{Td}, V_{Ts}, V_{Tb} or phases to see effect

- It can be seen very quickly (1.9 fb^{-1}) at LHC

- Allows to discover the most hunted particle

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

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

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

plus other model-dependent new physics contributions (ignored)

Experimentally

$$\mathrm{T} = -0.17 \pm 0.12 \quad (\mathrm{U\ arbitrary})$$
$$\mathrm{T} = 0.12 \pm 0.10 \quad (\mathrm{U} = 0)$$

☞ 95% bounds on $|V_{Tb}|$

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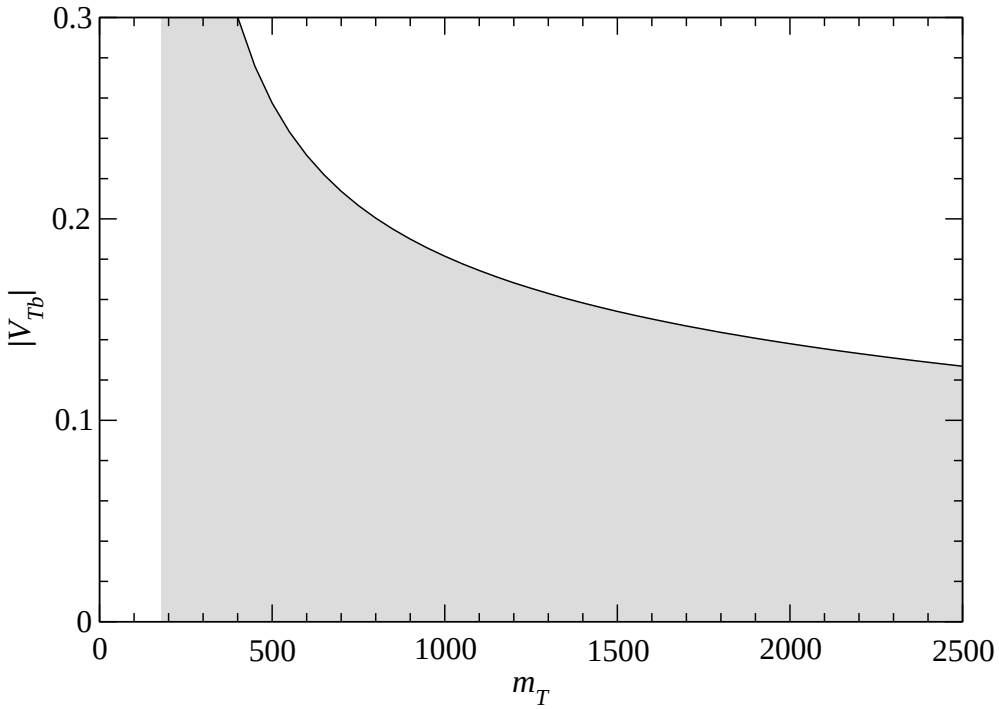
Indirect constraints on V_{Tb}



Stronger constraints for larger m_T

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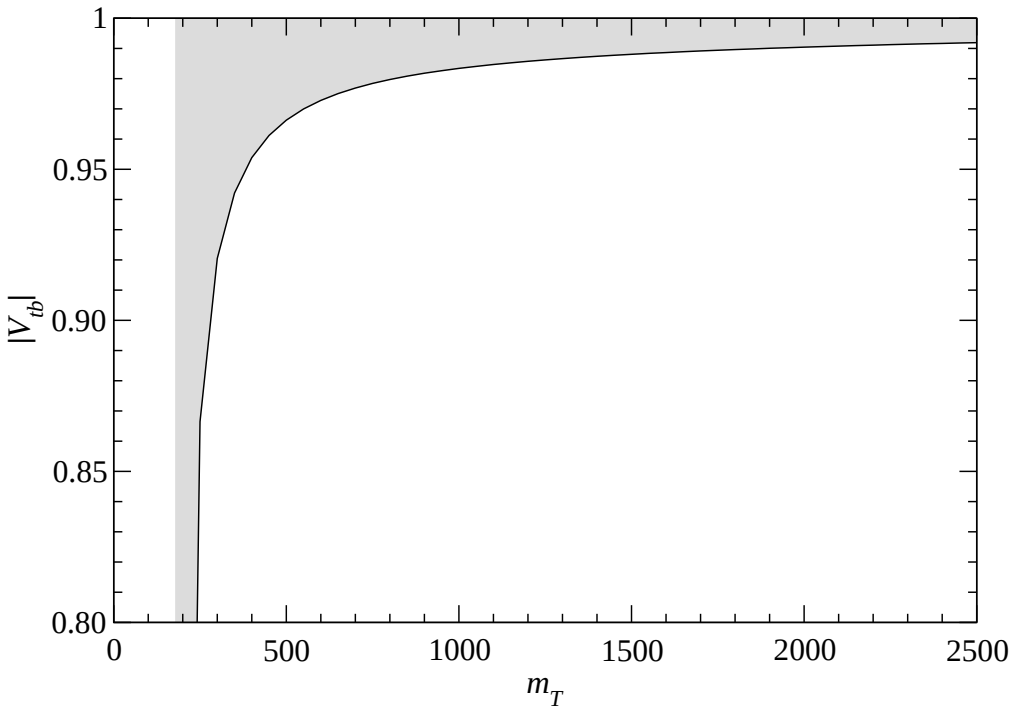
Allowed range for V_{tb}



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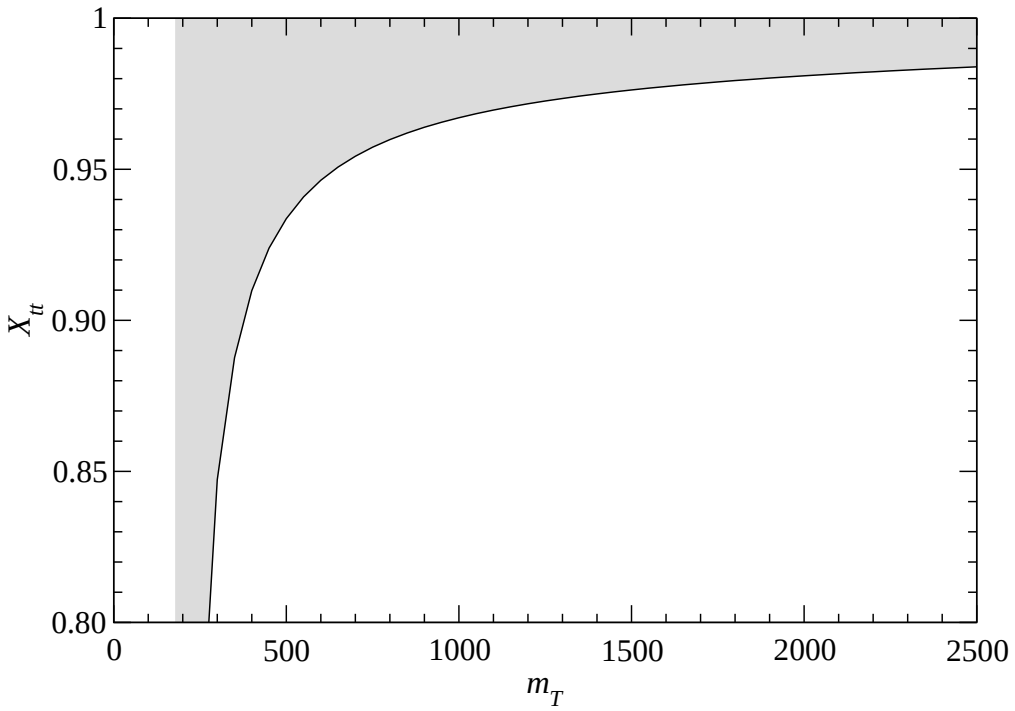
Allowed range for X_{tt}



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T contribution to $gg \to H$

$$\frac{A(T)}{A(t)_{\rm SM}} = \frac{y_{HTT}}{y_{Htt}|_{\rm SM}} \left[\frac{I(m_T^2/M_H^2)}{I(m_t^2/M_H^2)}\right] = \frac{m_T X_{TT}}{m_t} \left[\frac{I(m_T^2/M_H^2)}{I(m_t^2/M_H^2)}\right]$$

$$\frac{A(t)}{A(t)_{\rm SM}} = \frac{y_{Htt}}{y_{Htt}|_{\rm SM}} = X_{tt}$$

$I(x) \simeq 1 + \frac{7}{120x} \simeq 1$

$X_{TT} \simeq 0.04 \rightarrow A(T) \simeq 0.11 A(t)_{\rm SM}$

$X_{tt} \simeq 0.96 \rightarrow$ top contribution reduced

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Signals and backgrounds ($\ell = e, \mu$)

Process	$\sigma \times$ eff	Process	$\sigma \times$ eff
$T\bar{T}\,(WH)$	12.25 fb	$t\bar{t}H$	6.50 fb
$T\bar{T}\,(HH)$	9.26 fb	$t\bar{t}jj$	64.20 fb
$T\bar{T}\,(ZH)$	4.44 fb	$t\bar{t}b\bar{b}$ (QCD)	25.99 fb
$T\bar{T}\,(WZ)$	1.25 fb	$t\bar{t}c\bar{c}$ (QCD)	4.04 fb
$T\bar{T}\,(ZZ)$	0.351 fb	$t\bar{t}b\bar{b}$ (EW)	2.89 fb
$T\bar{T}b\bar{b}$	0.041 fb	$t\bar{t}c\bar{c}$ (EW)	0.128 fb
$Zjjjjj$	0.021 fb	$Wjjjjj$	0.328 fb
$Zb\bar{b}jjj$	0.470 fb	$Wb\bar{b}jjj$	3.11 fb
$Zc\bar{c}jjj$	0.133 fb	$Wc\bar{c}jjj$	0.361 fb
		$Wb\bar{b}b\bar{b}jj$	0.028 fb

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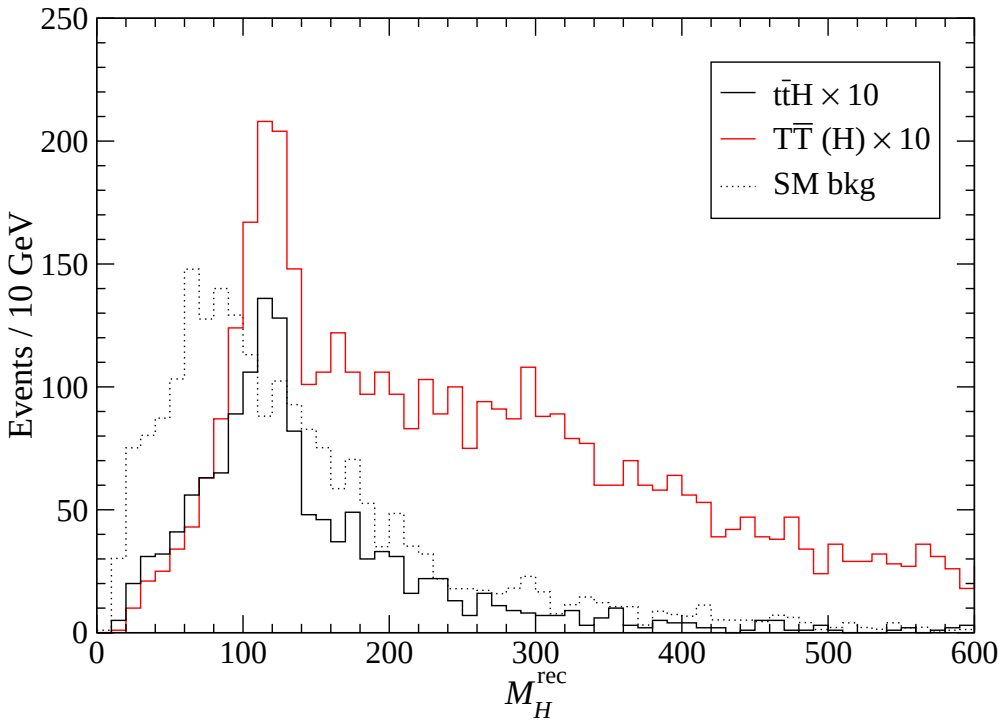
Reconstructed Higgs mass ($t\bar{t}H$ reconstruction)



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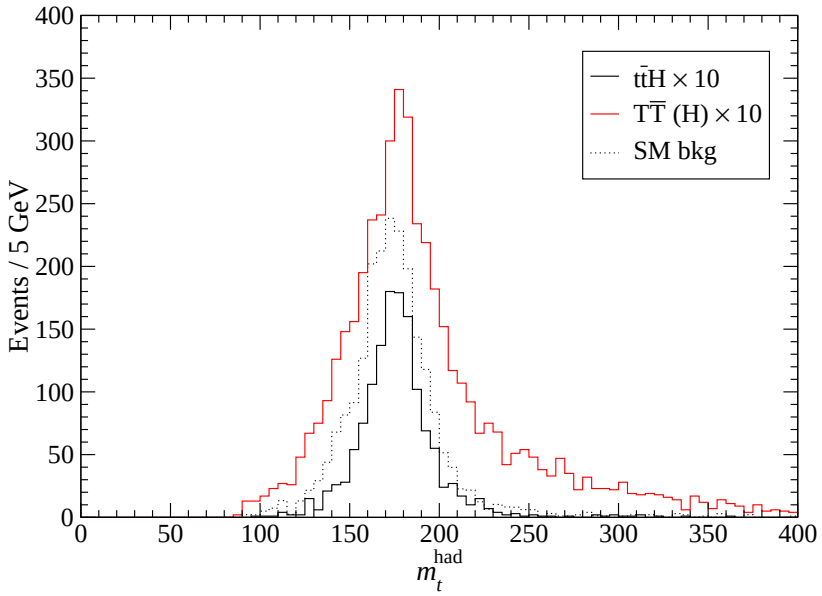
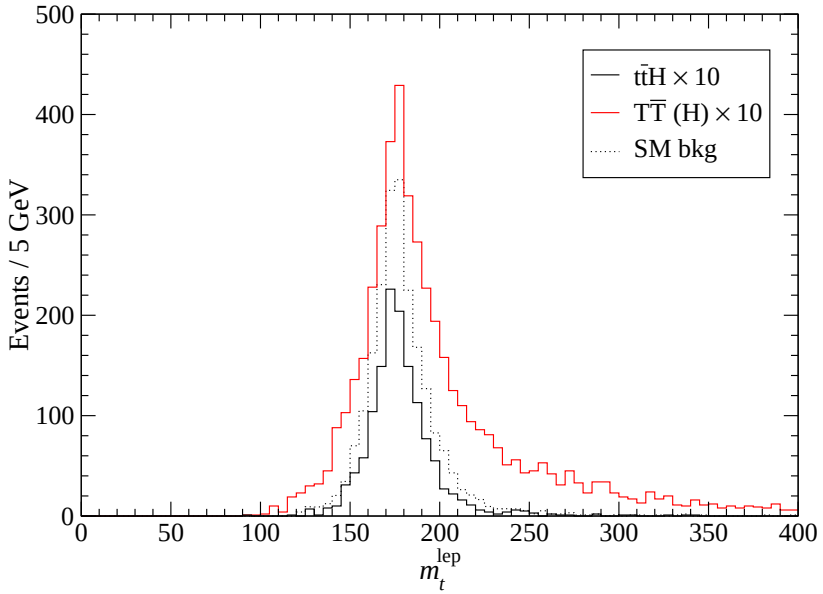
Reconstructed top masses ($t\bar{t}H$ reconstruction)

Hadronic



Leptonic



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Signals and backgrounds ($\ell = e, \mu$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	7.3	$t\bar{t}H$	38.2 / 35.9
$T\bar{T}\,(HH)$	10.8	$t\bar{t}jj$	188
$T\bar{T}\,(ZH)$	9.7	$t\bar{t}b\bar{b}$ (QCD)	77
$T\bar{T}\,(WZ)$	0.4	$t\bar{t}c\bar{c}$ (QCD)	14
$T\bar{T}\,(ZZ)$	0.4	$t\bar{t}b\bar{b}$ (EW)	13.1 / 11.8
$T\bar{T}b\bar{b}$	0.0	$t\bar{t}c\bar{c}$ (EW)	0.4 / 0.2
$Zjjjjj$	1	$Wjjjjj$	1
$Zb\bar{b}jjj$	3	$Wb\bar{b}jjj$	7
$Zc\bar{c}jjj$	0	$Wc\bar{c}jjj$	1
		$Wb\bar{b}b\bar{b}jj$	0.2

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Signals and backgrounds ($\ell = \tau$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	0.2	$t\bar{t}H$	1.5 / 1.4
$T\bar{T}\,(HH)$	0.3	$t\bar{t}jj$	6
$T\bar{T}\,(ZH)$	0.0	$t\bar{t}b\bar{b}$ (QCD)	0
$T\bar{T}\,(WZ)$	0.0	$t\bar{t}c\bar{c}$ (QCD)	0
$T\bar{T}\,(ZZ)$	0.1	$t\bar{t}b\bar{b}$ (EW)	0.2 / 0.2
$T\bar{T}b\bar{b}$	0.0	$t\bar{t}c\bar{c}$ (EW)	0.0 / 0.0
$Zjjjjj$	0	$Wjjjjj$	0
$Zb\bar{b}jjj$	0	$Wb\bar{b}jjj$	0
$Zc\bar{c}jjj$	0	$Wc\bar{c}jjj$	0
		$Wb\bar{b}b\bar{b}jj$	0.0

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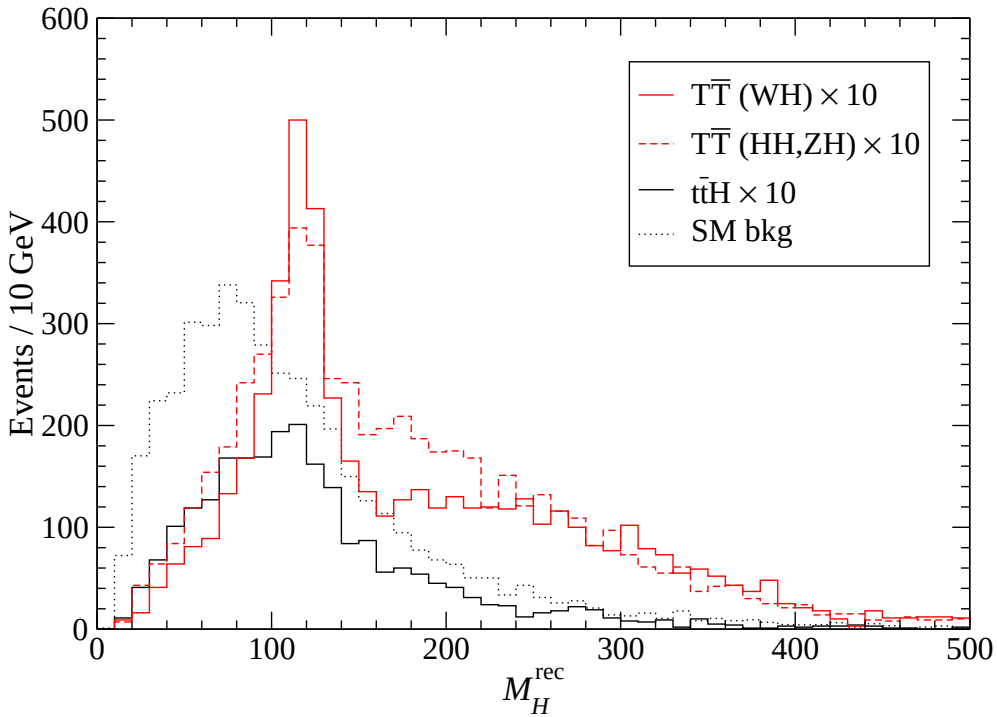
Reconstructed Higgs mass ($T\overline{T} \to W^+bH\bar{t}$ reconstruction)



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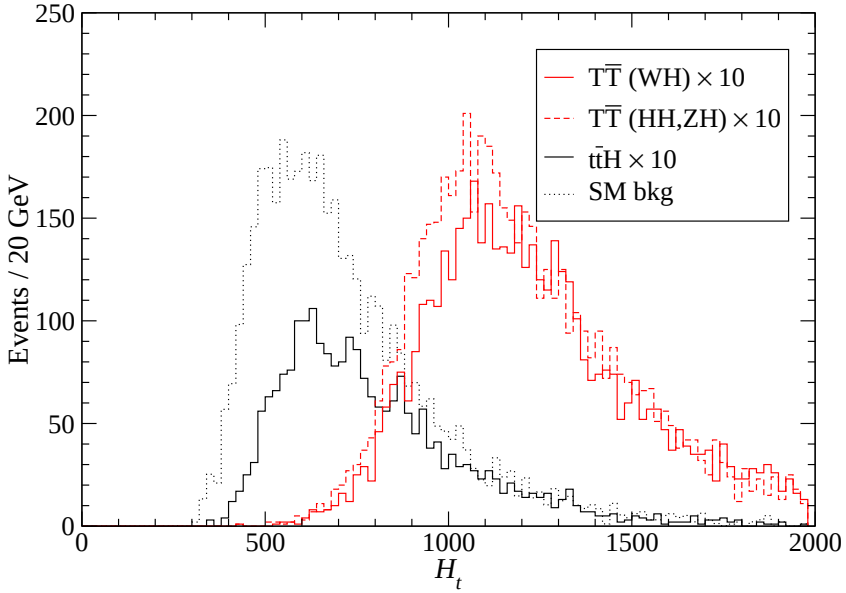
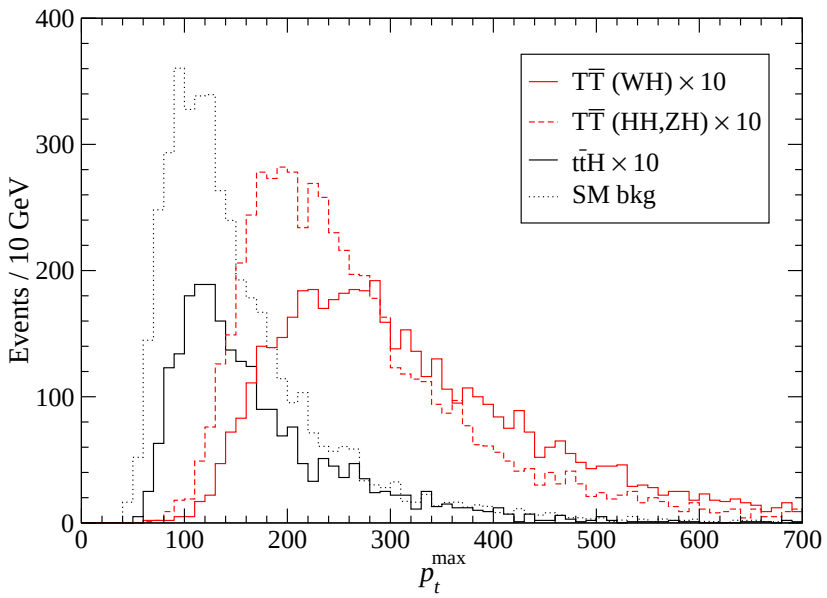
Transverse momenta ($T\overline{T} \to W^+ bH\bar{t}$ reconstruction)

Total



Fastest jet



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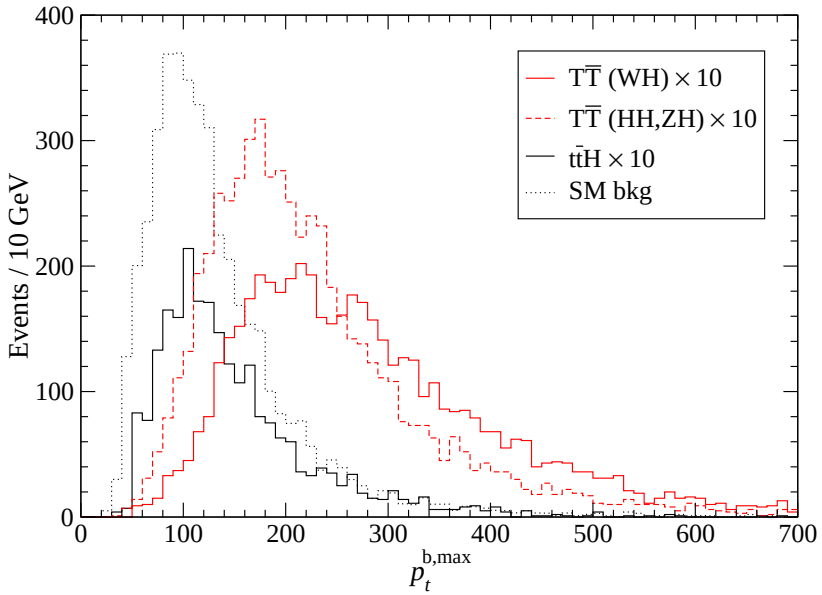
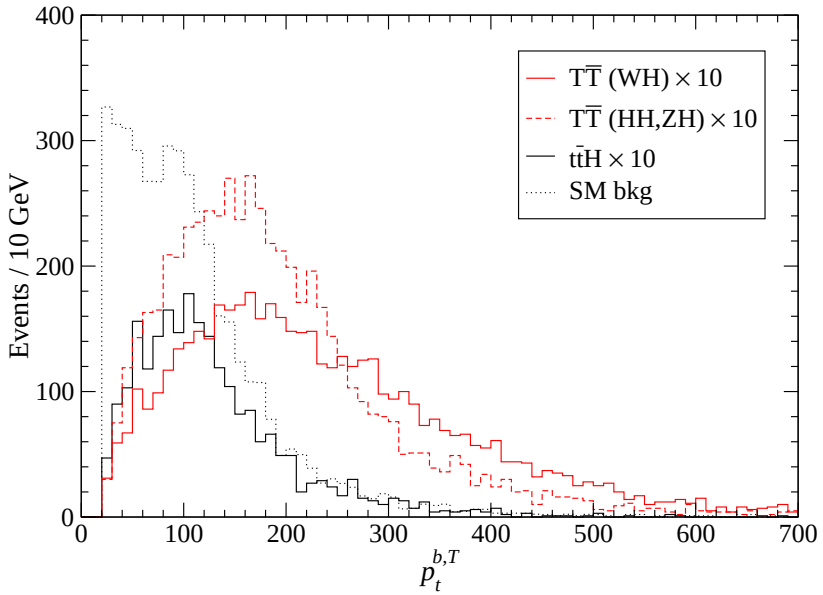
Transverse momenta ($T\overline{T} \to W^+ bH\bar{t}$ reconstruction)

Fastest b jet



b jet from $T \to Wb$



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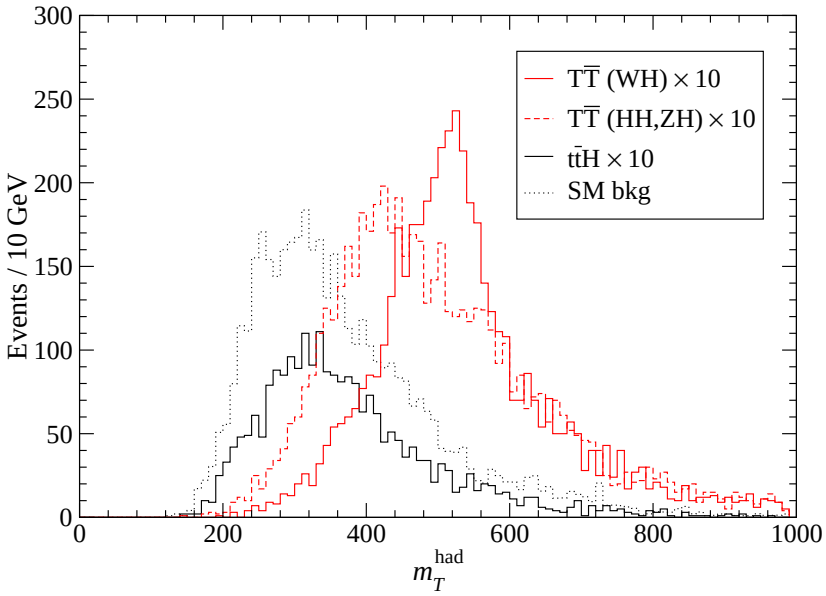
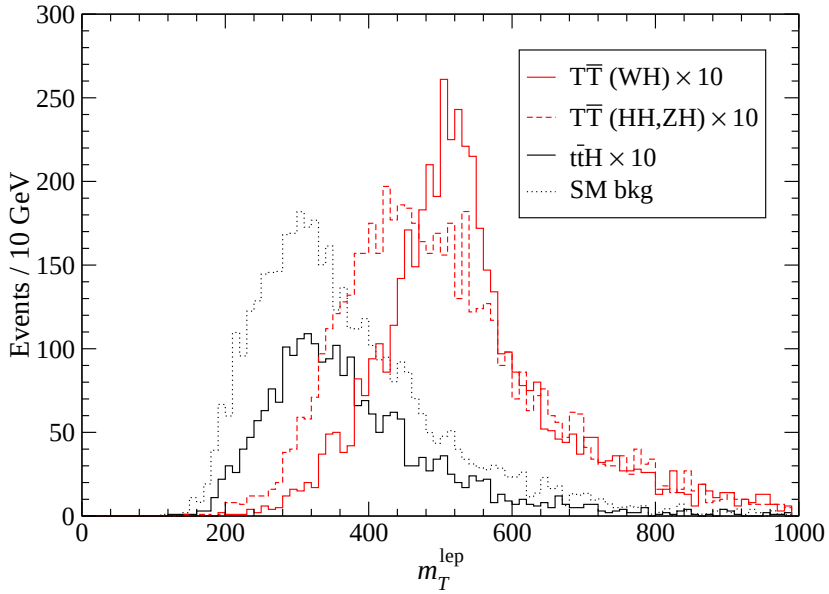
Reconstructed T masses ($T\overline{T} \to W^+bH\bar{t}$ reconstruction)

Hadronic



Leptonic



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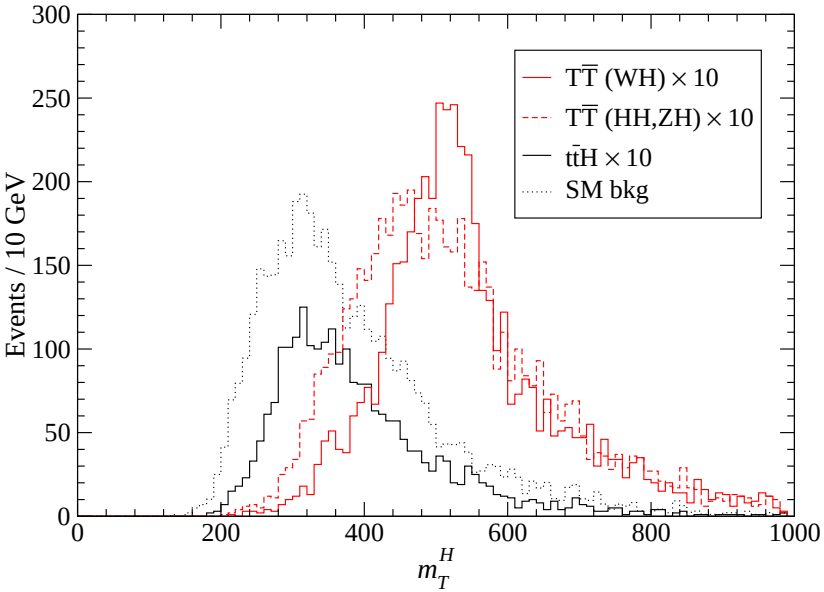
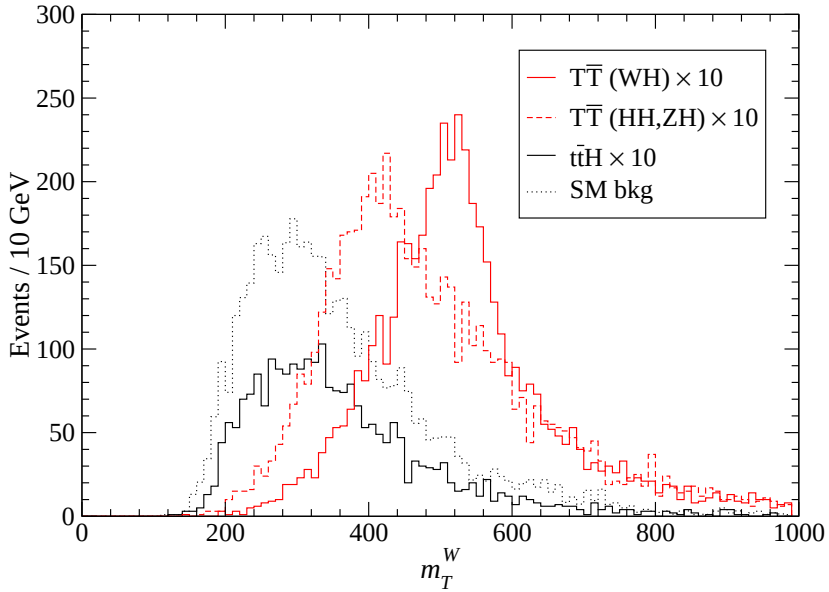
Reconstructed T masses ($T\overline{T} \to W^+bH\bar{t}$ reconstruction)

$T \to Ht$



$T \to Wb$



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Signals and backgrounds ($\ell = e, \mu$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	137.6	$t\bar{t}H$	13.6
$T\bar{T}\,(HH)$	78.8	$t\bar{t}jj$	42
$T\bar{T}\,(ZH)$	37.2	$t\bar{t}b\bar{b}$ (QCD)	59
$T\bar{T}\,(WZ)$	24.6 / 11.8	$t\bar{t}c\bar{c}$ (QCD)	8
$T\bar{T}\,(ZZ)$	5.6 / 2.3	$t\bar{t}b\bar{b}$ (EW)	4.7
$T\bar{T}b\bar{b}$	0.6 / 0.1	$t\bar{t}c\bar{c}$ (EW)	0.6
$Zjjjjj$	0	$Wjjjjj$	1
$Zb\bar{b}jjj$	3	$Wb\bar{b}jjj$	8
$Zc\bar{c}jjj$	2	$Wc\bar{c}jjj$	1
		$Wb\bar{b}b\bar{b}jj$	0.0

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Signals and backgrounds ($\ell = \tau$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	4.1	$t\bar{t}H$	0.2
$T\bar{T}\,(HH)$	3.3	$t\bar{t}jj$	0
$T\bar{T}\,(ZH)$	1.3	$t\bar{t}b\bar{b}$ (QCD)	1
$T\bar{T}\,(WZ)$	0.9 / 0.4	$t\bar{t}c\bar{c}$ (QCD)	1
$T\bar{T}\,(ZZ)$	0.1 / 0.0	$t\bar{t}b\bar{b}$ (EW)	0.1
$T\bar{T}b\bar{b}$	0.1 / 0.0	$t\bar{t}c\bar{c}$ (EW)	0.0
$Zjjjjj$	0	$Wjjjjj$	0
$Zb\bar{b}jjj$	0	$Wb\bar{b}jjj$	1
$Zc\bar{c}jjj$	0	$Wc\bar{c}jjj$	0
		$Wb\bar{b}b\bar{b}jj$	0.0

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Signals and backgrounds ($\ell = e, \mu$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	253.9	$t\bar{t}H$	24.3
$T\bar{T}\,(HH)$	156.0	$t\bar{t}jj$	66
$T\bar{T}\,(ZH)$	73.2	$t\bar{t}b\bar{b}$ (QCD)	113
$T\bar{T}\,(WZ)$	26.8	$t\bar{t}c\bar{c}$ (QCD)	10
$T\bar{T}\,(ZZ)$	5.4	$t\bar{t}b\bar{b}$ (EW)	8.7
$T\bar{T}b\bar{b}$	0.7	$t\bar{t}c\bar{c}$ (EW)	0.8
$Zjjjjj$	0	$Wjjjjj$	1
$Zb\bar{b}jjj$	5	$Wb\bar{b}jjj$	17
$Zc\bar{c}jjj$	2	$Wc\bar{c}jjj$	1
		$Wb\bar{b}b\bar{b}jj$	0.0

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Signals and backgrounds ($\ell = \tau$)

Process	Events	Process	Events
$T\bar{T}\,(WH)$	8.6	$t\bar{t}H$	0.9
$T\bar{T}\,(HH)$	5.4	$t\bar{t}jj$	0
$T\bar{T}\,(ZH)$	2.2	$t\bar{t}b\bar{b}$ (QCD)	4
$T\bar{T}\,(WZ)$	0.0	$t\bar{t}c\bar{c}$ (QCD)	1
$T\bar{T}\,(ZZ)$	0.0	$t\bar{t}b\bar{b}$ (EW)	0.3
$T\bar{T}b\bar{b}$	0.0	$t\bar{t}c\bar{c}$ (EW)	0.0
$Zjjjjj$	0	$Wjjjjj$	0
$Zb\bar{b}jjj$	0	$Wb\bar{b}jjj$	0
$Zc\bar{c}jjj$	0	$Wc\bar{c}jjj$	0
		$Wb\bar{b}b\bar{b}jj$	0.0

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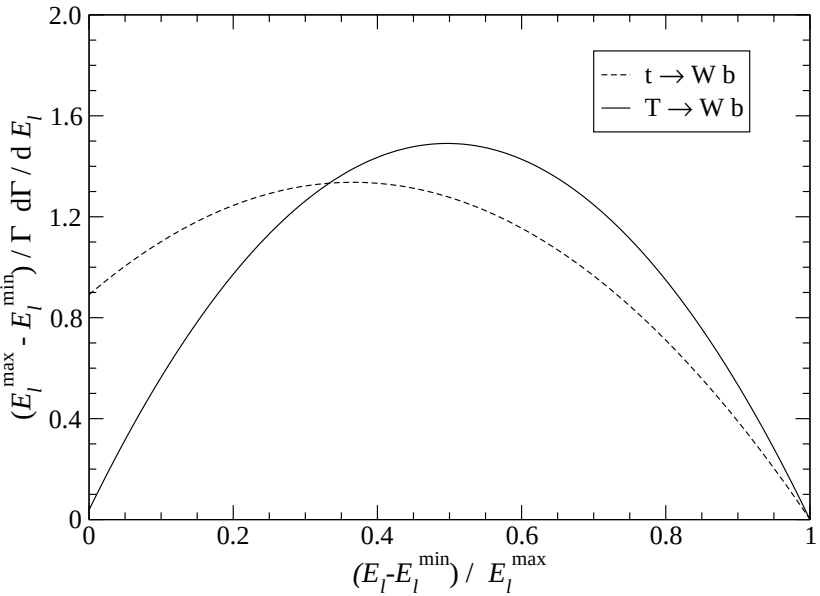
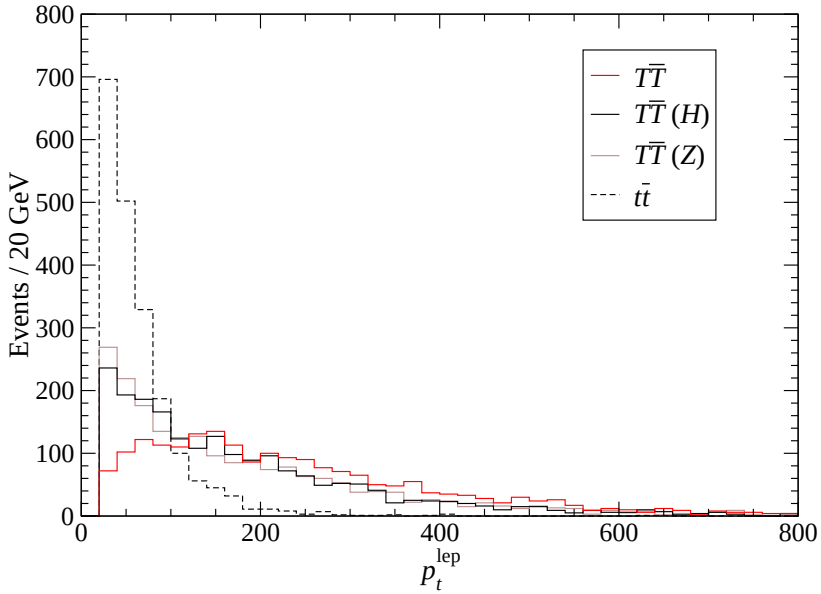
Charged lepton from t, T decays

Energy in t, T rest frame



Transverse momentum



$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_\ell} = \frac{1}{(E_\ell^{max} - E_\ell^{min})^3}\left[3(E_\ell - E_\ell^{min})^2 F_R + 3(E_\ell^{max} - E_\ell)^2 F_L + 6(E_\ell^{max} - E_\ell)(E_\ell - E_\ell^{min}) F_0\right]$$

t : $E_\ell^{max} = 87.4$ GeV $E_\ell^{min} = 18.5$ GeV

T : $E_\ell^{max} = 500$ GeV $E_\ell^{min} = 3.2$ GeV

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