Flavor-Changing Top Decays at the LHC

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Based on work with C. Kao

Flavor Changing Neutral Currents

The Standard Model conserves flavor in neutral current vertices: γ, g,Z, and h.
Beginning with general Yukawa couplings:

$$\mathscr{L} = Y_u^{ij} Q_i \phi u_j^c + Y_d^{ij} Q_i \phi^* d_j^c + Y_e^{ij} L_i \phi^* e_j^c + h.c.$$

Generations are redefined by unitary rotations:

$$u^c \rightarrow U_{uR} u^c, \quad d^c \rightarrow U_{dR} d^c,$$

$$U_{uL}^{\dagger} Y_u U_{uR} = M_u(diag)$$

$$u_c^{\dagger} \not{D} u_c \rightarrow u_c^{\dagger} U_{uR}^{\dagger} \quad \not{D} \quad U_{uR} u_c \qquad = u_c^{\dagger} \not{D} u_c$$

$$Q^{\dagger} \not{D} Q \rightarrow u^{\dagger} U_{uL}^{\dagger} \quad W^+ \quad U_{dL} d \qquad = u^{\dagger} V_{CKM} d \quad W^+$$

-Only charged currents show flavor changing due to misaligned unitary

Two Higgs Doublet Models

Natural to extend Standard Model with additional Higgs doublets.
Required in Supersymmetry, $SO(10)$ Unification, etc.
Generically, all doublets couple to all SM fermions.

$$\mathscr{L} = Y_{u1} Q \phi_1 u^c + Y_{d1} Q \phi_1^* d^c + Y_{e1} L \phi_1^* e^c$$
$$+ Y_{u2} Q \phi_2 u^c + Y_{d2} Q \phi_2^* d^c + Y_{e2} L \phi_2^* e^c$$

$$M_u = U_{uL}^\dagger (Y_{u1} v_1 + Y_{u2} v_2) U_{uR}$$
$$u U_{uL}^\dagger Y_{u1} U_{uR} u^c (\cos(\beta) h^0 + \sin(\beta) H^0) \neq u M_u u^c h$$

FCNCs arise *unless* each Higgs doublet couples to only one charge-type of quark or only one Higgs couples to fermions.

Models with FCNCs

- MSSM requires two doublets but with separate ”up-type" and ”down-type" couplings. However, SUSY-breaking effects and loops will induce FCNCs.
- All Multi-Doublet Models will generically have FCNCs unless controlled by symmetries.
- Flavor-changing effects from light-quarks are strongly constrained from measurements of $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$, $D^0 - \overline{D}^0$ masses and kaon CP violation. (Atwood, Reina and Soni, 1997)
- *However*, currents involving the top quark may be much larger. Experimental constraints are weak for t.

Moreover, large m_t may indicate a special role for the top. e.g.-

It may be the only fermion coupled to one doublet with a large vev in a 2HDM. (Kao and Das, 1996)

Top Quarks with FCNCs

For a general effective model with FCNCs, we can write the top quark coupling:

$$\mathscr{L} = \frac{g_W}{2\sqrt{2}} g_{tq} \overline{q} (c_v + c_a \gamma_5) t h^0 + h.c.$$

$$g_W = \frac{e^2}{\sin\theta_W}, \quad |c_v|^2 + |c_a|^2 = 1$$

SM: $g_{tc} \sim 10^{-6}$ (Mele, Petrarca and Soddu, 1998)

MSSM: $g_{tc} \sim 0.04$ (Gausch and Sola, 1999)

2HDM: $g_{tc} \simeq \frac{\sqrt{2 m_t m_c}}{m_W} \sim 0.27$

g_{tu} also possible but typically much smaller.

Top Quark Decays

For non-SM models, g_{tc} may be detected in rare top decays $t \to ch^0$, involving the lightest neutral Higgs. (Branco and Aguilar-Saavedra, 2000)

For $g_{tc} = \frac{\sqrt{2 m_t m_c}}{m_W}$ and $m_h = 120$ GeV :

$$BF(t \to ch^0) = 2.62 \times 10^{-3}$$

$g_{hbb} \propto m_b(m_h)$.

Typically at 120 GeV:

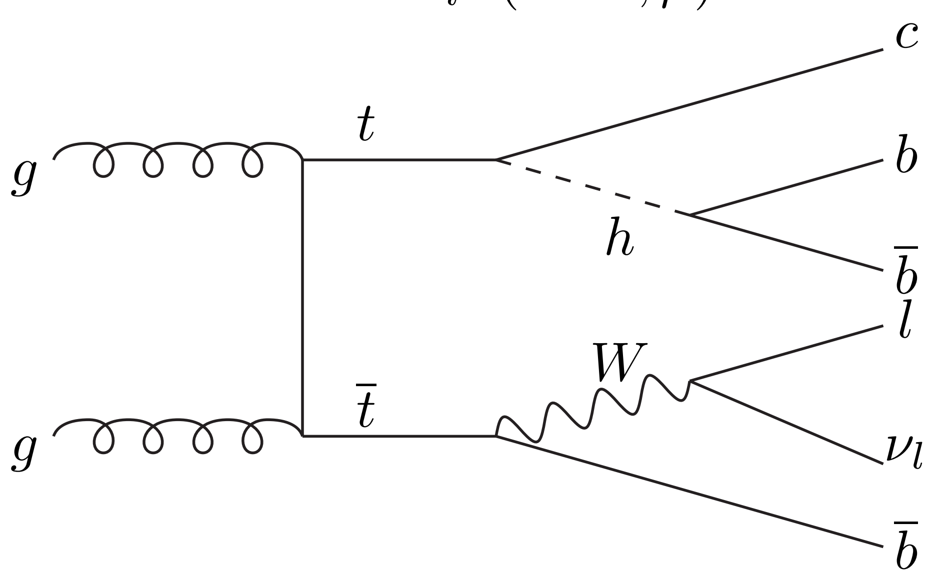
$$BF(h \to b\bar{b}) \simeq 0.7$$

Enhanced for $\tan(\beta) > 1$.

- Search for $t \to ch^0 \to cb\bar{b}$ is best channel for light Higgs.

Search Channel

We consider $PP \to t\bar{t} \to cb\bar{b}\bar{b}l^-\nu_l$. $(l = e, \mu)$

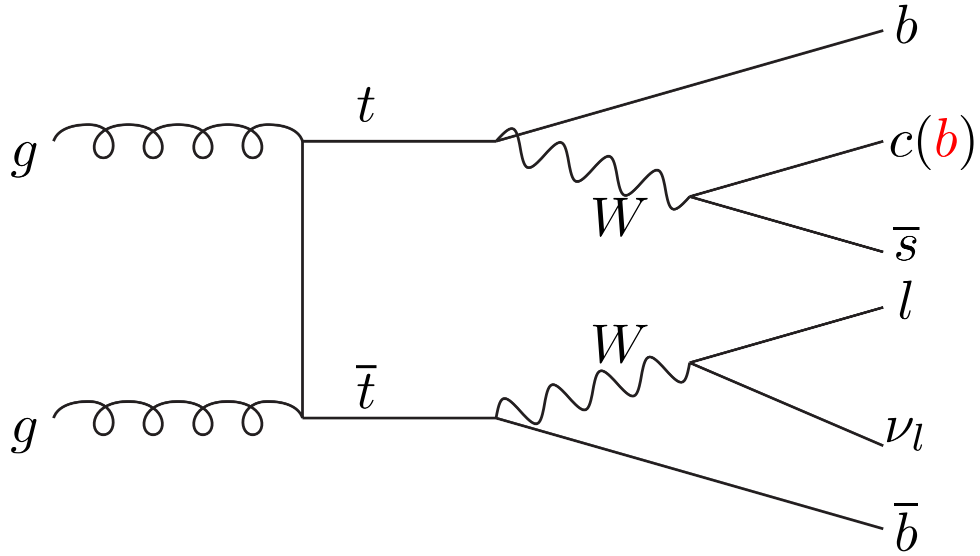


Plus crossings, gluon fusion and $q - \bar{q}$ fusion.
Signature:

- 4 jets
- 3 b-tagged jets
- 1 charged lepton
- Missing E_T

Backgrounds

Primary background is $PP \to t\bar{t} \to cb\bar{s}\bar{b}l^-\nu_l$ with c mis-tagged as a b.



Other backgrounds found to be negligible after cuts/tagging:

- $pp \to (t \to cb\bar{s})\bar{b}l^-\nu_l$
- $pp \to no\,t \to cb\bar{s}\bar{b}l^-\nu_l$
- $pp \to b\bar{b}b\bar{b}l^-\nu_l$
- $pp \to c\bar{c}b\bar{b}l^-\nu_l$

Top Reconstruction

We look for one leptonicly decaying top, but lose information due to neutrino.

Assume MET comes primarily from neutrino but must estimate k_L^ν.

Technically two unknown variables, but since we assume it is a neutrino, E^ν is determined.

$\rightarrow$ Require that k_L^ν satisfy

$$(k^\nu + p^l)^2 = m_W^2$$

Top Reconstruction II

Assuming an on-shell W, k_L can be solved for:

$$k_L = \frac{p_L(2p_T.k_T + m_W^2 - m_l^2) \pm p_0\sqrt{(2p_T.k_T + m_W^2 - m_l^2)^2 - 4k - T^2(m_l^2 + p_T^2)}}{m_l^2 + p_T^2}$$

where $p_T.k_T = p_x k_x + p_y k_y$.
Quadratic equation leaves a choice of sign, we select whichever leads to a better reconstruction of the top-quark mass.

$$\text{min}[m_t^2 - (k^\nu + p^l + p^b)^2]$$

Event Reconstruction

Begin with 3 b-tagged jets + 1 untagged jet + 1 charged lepton + MET.
Apply basic cuts:

- $p_T(b_1, b_2, b_3) > 50, 35, 20$ GeV
- $p_T(j) > 20$ GeV
- $p_T(l) > 20$ GeV
- $MET > 20$ GeV
- $\Delta_R(jj, jl) > 0.5$
- $|\eta(j, l)| > 2.5$

Reconstruction cuts:

- Search over three possible bb pairs.
- Require $|m_{bb} - m_h| < 0.2 * m_h$
- Require $|m_{bbj} - m_t| < 0.2 * m_t$
- Estimate k^ν as above. Use remaining b to reconstruct $\bar{t}$
- Require $|m_{bl\nu} - m_t| < 0.2 * m_t$

W-veto

The cuts listed above do a good job of selecting out background *except* for $t\bar{t} \to cb\bar{s}\bar{b}l^-\nu_l$.

Both signal and background have $m_{bbj} \sim m_t$, $m_{l,\nu} \sim m_W$, $m_{bl\nu} \sim m_t$.

Only $m_{bb} \sim m_h$ peak is effective discriminant.
Narrower t windows will improve signal vs. other backgrounds but tend to limit significance against $t\bar{t}$.

$\to$ Make use of second W in background.

- $c\bar{s}$, tagged as bj should have a peak near m_W
- Check both bj combinations in $bbj \sim t$ and $bb \sim h$
- Select min$[|m_{bj} - m_W|]$
- Require $|m_{bj} - m_W| > 5$ GeV

Implementation

We add the flavor changing vertex to MadGraph4 to generate parton-level results.

We choose $\mu_F = \mu_R = \sqrt{\hat{s}}$, applying a K-factor of 2.

α_s is calculated at LO and we use CTEQ6L1 PDFs.

For results below, we set $g_t c = \frac{\sqrt{2 m_t m_c}}{m_W} \simeq 0.27$ and use $BF(h \to b\bar{b})$ for a SM-like higgs.

Generated events can be passed to Pythia 6.4, then PGS4.
(Cone algorithm with $R_{cone} = 0.5$.)

Tagging efficiencies

Quark-type	(Mis)tag rate
b	60%
c	10%
u, d, s	1%

Predicted Detection Rates

(Work in progress.)
At the LHC, assuming $\sqrt{s} = 14$ TeV.

Higgs mass	$N_S(30\,\text{fb}^-1)$	$N_B(30\,\text{fb}^-1)$	$N_S/\sqrt{N_B}$	Detection Luminosity
120	171	4263	2.65	107
$120^\star$	63	687	2.4	130
130	85	3882	1.36	405
$130^\dagger$	41	1083	1.23	495

$\star$- We require a more aggressive W-veto, reject events if $65 < m_{bj} < 100$ GeV. We also require a tighter t window: $150 < m_{bbj} < 190$ GeV.

$\dagger$- $70 < m_{bj} < 95$ GeV and $150 < m_{bbj} < 190$ GeV

Summary

- Flavor Changing Neutral Currents may arise in many models with additional Higgs.
- In particular, the top quark may have relatively large FCNC couplings.
- If so, the top can decay to a Higgs plus charm.
- We make use of several kinematic features to reconstruct the event and discriminate against background.
- Detecting such a decay will require a large amount of data. Improvements can be made with excellent b-tagging and jet reconstruction.