Signals of new fermions at large transverse momenta

J. A. Aguilar-Saavedra

Departamento de Física Teórica y del Cosmos
Universidad de Granada

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New particles, if exist, have large masses

Their signatures involve large transverse momenta in general

☞ Background evaluation must include higher orders

Two examples, with new fermion masses of 500 GeV and 150 GeV

Conclusion: Higher orders can be suppressed *a posteriori* but not *a priori*

Summary

1. Higgs discovery in $T\overline{T}$ decays
2. Heavy neutrino production

Higgs discovery in $T\overline{T}$ decays

New quarks T produced at LHC like any other quark (QCD)

Decay through electroweak interactions obtained by mixing with top

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 $\propto |V_{Tb}|^2$ → Br independent of mixing

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

$t\bar{t}H$, $H \to b\bar{b}$: proposed discovery channel
but significance for 60 fb^{-1}: 0.47 [CMS TDR]

From $T\bar{T}$ decays:

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

$\sigma = 2.14$ pb $\qquad$ $\mathrm{Br} = 0.55$

$T\bar{T}$ production greatly enhances Higgs discovery

$gg \to H$

Our analysis:

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

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

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

Fast simulation with PYTHIA + ATLFAST

Pre-selection criteria

We require a final state with:

- one isolated charged lepton with $|\eta| \leq 2.5$, $\begin{array}{l} p_t \geq 20 \text{ GeV } (\mu) \\ p_t \geq 25 \text{ GeV } (e) \end{array}$
- at least four b-tagged jets with $|\eta| \leq 2.5$, $p_t \geq 20$ GeV
- at least two non-tagged jets with $|\eta| \leq 2.5$, $p_t \geq 20$ GeV

b tagging efficiency of 60%

Event generation

$T\bar{T}$, $t\bar{t}H$, $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$ ➔ new generators developed

$t\bar{t}nj$ ➔ Generated $n = 0 \ldots 5$ with ALPGEN

Matching with PYTHIA using MLM prescription

$Wb\bar{b}4j$, $Zb\bar{b}4j$, $W6j$, $Z6j$ ➔ ALPGEN

Signals and main backgrounds

At pre-selection (relevant for $t\bar{t}H$) $\ell = e, \mu$

	σ	N	ε (%)		σ	N	ε (%)
$T\bar{T}(WH)$	173.6 fb	329.8	6.3	$t\bar{t}2j$	95.9 pb	2443	0.085
$T\bar{T}(HH)$	44.38 fb	256.5	19.3	$t\bar{t}3j$	54.0 pb	1900	0.12
$T\bar{T}(ZH)$	50.0 fb	127.4	8.5	$t\bar{t}4j$	27.4 pb	1195	0.15
$t\bar{t}H$	118.7 fb	166.0	4.6	$t\bar{t}5j$	12.8 pb	$1067^{(K)}$	0.19
$t\bar{t}$	143.2 pb	1475	0.034	$t\bar{t}b\bar{b}$	564.9 fb	1648	4.7
$t\bar{t}j$	142.7 pb	2370	0.055				

ε grows with n (larger b mistag probability)

nj by PYTHIA → $\sigma = 138.7$ fb $N = 2076$ $\varepsilon = 0.050\%$

☞ would-be $K = 5.0$

Signals and main backgrounds

At large transverse momenta (relevant for $T\bar{T}$) $\ell = e, \mu$

	N	ε' (%)		N	ε' (%)
$T\bar{T}(WH)$	253.1	4.9	$t\bar{t}2j$	254	8.8×10^{-5}
$T\bar{T}(HH)$	188.3	14.2	$t\bar{t}3j$	341	0.021%
$T\bar{T}(ZH)$	89.1	6.0	$t\bar{t}4j$	381	0.046%
$t\bar{t}$	49	0.0011	$t\bar{t}5j$	$668^{(K)}$	0.12%
$t\bar{t}j$	106	0.0024	$t\bar{t}b\bar{b}$	350	1.0%

$H_T \geq 1000$ GeV $\quad p_t^{j,\max} \geq 150$ GeV $\quad p_t^{b,\max} \geq 100$ GeV

ε' grows even more with n (larger transverse momenta)

nj by PYTHIA $\rightarrow$ $N = 220 \quad \varepsilon = 0.0052\%$

☞ would-be $K = 8.2$

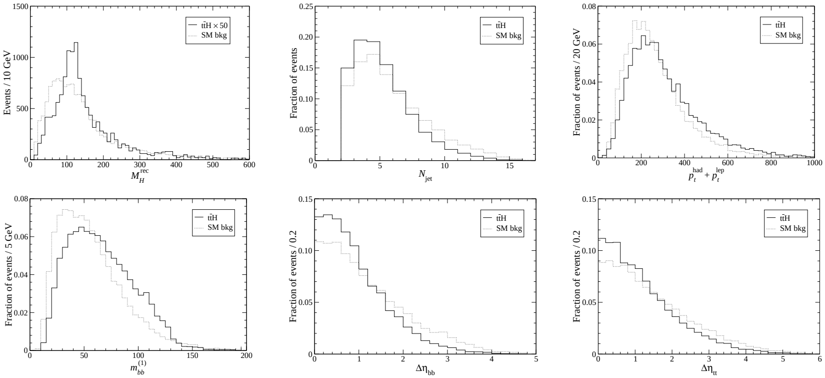
$t\bar{t}H$ search

Final state: $1\,\ell$, $4\,b$, $2\,j$

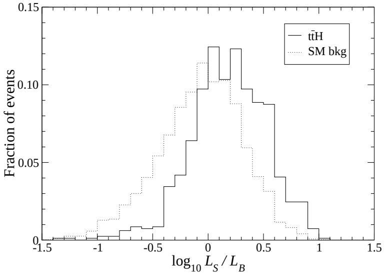
- Reconstruction done trying all pairings
- Signal likelihood function with relevant variables
- Cut on signal likelihood and reconstructed Higgs mass

$t\bar{t}H$ search

Most important variables (11 total)



$t\bar{t}H$ search — Results for 30 fb^{-1}



	$\log L_S/L_B \geq 0.75$, $100 \leq M_H^{\rm rec} \leq 140$		
$t\bar{t}H$	170.3	→	2.5
$t\bar{t}$	1498	→	0
$t\bar{t}j$	2418	→	5
$t\bar{t}2j$	2485	→	6
$t\bar{t}3j$	1948	→	4
$t\bar{t}4j$	1240	→	2
$t\bar{t}5j$	1086	→	0
$t\bar{t}b\bar{b}$	1683	→	4

Significance: 0.40σ (incl. all bkg and 20% sys)

CMS: 0.47σ (full sim, $K \simeq 1.5$, rescaled to 30 fb^{-1} and 20% sys)

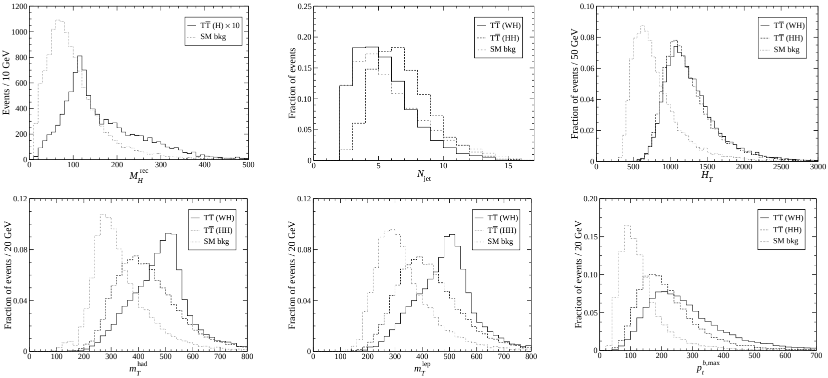
$T\bar{T} \to H$ search

Three final states: $1\,\ell$, $4/5/6\,b$, $2\,j$

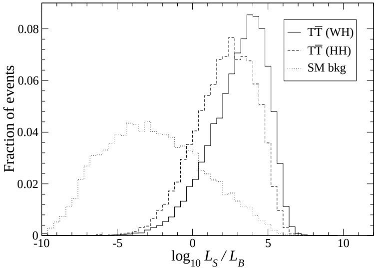
- Reconstruction for $4b$: $T\bar{T} \to W^+ bH\bar{t}/HtW^- \bar{b}$
- Reconstruction for $5b$, $6b$: $T\bar{T} \to HtH\bar{t}$
- Reconstruction done trying all pairings
- Signal likelihood function with (many) relevant variables
- Cut on signal likelihood and other variables

$T\bar{T} \longrightarrow H$ search ($4b$ final states)

Most important variables (15 total)



$T\bar{T} \to H$ search ($4b$ final states) — Results for 30 fb^{-1}



$\log L_S/L_B \geq 3.9$
$\mathcal{N}_{\text{jet}} \leq 7,\ 100 \leq M_H^{\text{rec}} \leq 140$
$350 \leq m_T^{\text{had}}, m_T^{\text{lep}} \leq 650$

$T\bar{T}(H)$	567.1	→	44.5
$t\bar{t}$	1462	→	1
$t\bar{t}j$	2346	→	0
$t\bar{t}2j$	2399	→	2
$t\bar{t}3j$	1892	→	3
$t\bar{t}4j$	1203	→	8
$t\bar{t}5j$	1018	→	2
$t\bar{t}b\bar{b}$	1477	→	3

Significance: 6.39σ (incl. all bkg and 20% sys)

Combined significance

$4b$	6.39σ
$5b$	5.93σ
$6b$	5.69σ
Total	10.41σ

Significance 25$\times$ larger than $t\bar{t}H$

Higgs discovered with 8 fb^{-1}

Heavy neutrino production

Main features

- Example in which new mass not so high: 150 GeV
- No higher order enhancement due to kinematical cuts
- No higher order enhancement due to *b* (mis)tagging

Example I

$WZnj \to \mu^\pm \mu^\pm$ and ≥ 2 jets with $p_t \geq 20$ GeV

	Generated		Pre-selection			Selection	
WZ	6437×10	→	57.7	(0.90%)	→	0.2	(0.34%)
WZj	6088×10	→	156.1	(2.56%)	→	0.9	(0.57%)
$WZ2j$	5005×10	→	244.8	(4.89%)	→	2.9	(1.18%)
$WZ3j$	$3533^{(K)} \times 10$	→	156.9	(4.44%)	→	0.8	(0.51%)
Total			615.5		→	4.8	
$WZ2j$ without matching	5005×10	→	226.0	(4.51%)	→	2.0	(0.88%)

would-be $K = 2.7\ (2.4)$

Example II

$WWnj \to \mu^\pm \mu^\pm$ and ≥ 2 jets with $p_t \geq 20$ GeV

	Pre-selection		Selection	
WW	–		–	
WWj	–		–	
$WW2j$	116.2	→	1.5	(1.29%)
$WW3j$	200.2	→	0.8	(0.40%)
Total	316.4	→	2.3	
$WW2j$ without matching	135.7	→	0.9	(0.66%)

would-be $K = 2.3\ (2.5)$

Conclusions

- Reanalysis of H discovery from $T\bar{T}$ decays
- Discovery potential for H one half as previously: 10.41σ for 30 fb^{-1}
- Significance drops in $t\bar{t}H$: 0.40σ for 30 fb^{-1}
- Higher orders are always important, but especially at large p_t
- Seen again what is well known: kinematics at large p_t must be described at generator level
- Heavy N: higher orders are not enhanced by kinematical cuts nor b tagging but still relevant
- Heavy N: lower orders also relevant due to pile-up

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, …

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

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

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

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

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

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

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

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

Indirect effects of mixing:

- 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:

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

  $X_{tt} \simeq |V_{tb}|^2$

- FCN couplings among SM quarks

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

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

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

Anomaly cancellation

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

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

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

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

Back

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

$$\mathrm{T} = -0.13 \pm 0.11 \quad (\mathrm{U\ arbitrary})$$

$$\mathrm{T} = -0.03 \pm 0.09 \quad (\mathrm{U} = 0)$$

☞ 95% bounds on $|V_{Tb}|$

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T contribution to $gg \to H$

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

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

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

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

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

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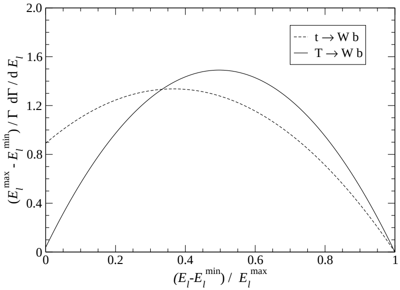
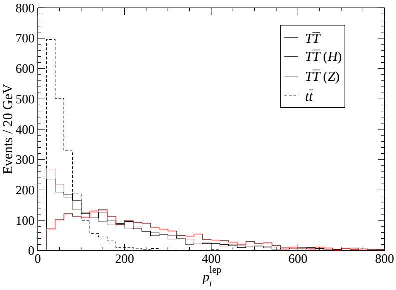
Charged lepton from t, T decays

Energy in t, T rest frame



Transverse momentum



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

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

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

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