Signals of new fermions at large transverse momenta

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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 \textit{a posteriori} but not \textit{a priori}
Summary

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

Signals of new fermions at large transverse momenta
New quarks $T$ produced at LHC like any other quark (QCD)
Decay through electroweak interactions obtained by mixing with top

<table>
<thead>
<tr>
<th>Decays of $T$</th>
<th>$(M_H = 115$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T$</td>
<td>500 GeV 1 TeV</td>
</tr>
<tr>
<td>$\text{Br}(T \to W^+ b)$</td>
<td>0.50 0.50</td>
</tr>
<tr>
<td>$\text{Br}(T \to Z t)$</td>
<td>0.16 0.23</td>
</tr>
<tr>
<td>$\text{Br}(T \to H t)$</td>
<td>0.34 0.27</td>
</tr>
</tbody>
</table>

All three partial widths $\propto |V_{Tb}|^2 \quad \Rightarrow \quad \text{Br independent of mixing}$
SM Higgs detection more difficult for $M_H \lesssim 130$ GeV

$t\bar{t}H, H \rightarrow b\bar{b}$: proposed discovery channel

but significance for 60 fb$^{-1}$: 0.47

[CMS TDR]

From $T\bar{T}$ decays:

\[ gg, qq \rightarrow T\bar{T} \rightarrow \begin{cases} 
W^+ bHt + \text{CC} & \text{Br} = 0.33 \\
HtH\bar{t} & \text{Br} = 0.11 \\
ZtH\bar{t} + \text{CC} & \text{Br} = 0.10 
\end{cases} \]

$\sigma = 2.14$ pb $\quad \text{Br} = 0.55$

$T\bar{T}$ production greatly enhances Higgs discovery
Our analysis:

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

$$\begin{align*}
\text{SM} & \quad \rightarrow \quad t\bar{t}H \rightarrow W^+bW^+bH \\
\text{With } T & \quad \rightarrow \quad t\bar{t}H + T\bar{T} \rightarrow \\
& \quad \begin{cases} 
W^+bHt + CC \rightarrow W^+bW^-bH \\
HtHt \rightarrow W^+bW^-bHH \\
ZtHt + CC \rightarrow W^+bW^-bHZ
\end{cases}
\end{align*}$$

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

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 $|\eta| \leq 2.5$, $p_t \geq 20$ GeV ($\mu$) $p_t \geq 25$ GeV ($e$)
- 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%
Higgs discovery in $T\bar{T}$ decays
Heavy neutrino production

Event generation

$T\bar{T}, \bar{t}H, \bar{t}t\bar{b}\bar{b}, \bar{t}t\bar{c}\bar{c} \quad \longrightarrow \quad \text{new generators developed}$

$\bar{t}\bar{t}n j \quad \longrightarrow \quad \text{Generated } n = 0 \ldots 5 \text{ with ALPGEN}$

Matching with PYTHIA using MLM prescription

$Wb\bar{b}4j, Zb\bar{b}4j, W6j, Z6j \quad \longrightarrow \quad \text{ALPGEN}$

J. A. Aguilar-Saavedra
Signals of new fermions at large transverse momenta
Signals and main backgrounds

<table>
<thead>
<tr>
<th>At pre-selection (relevant for $\bar{t}\bar{t}H$)</th>
<th>$\ell = e, \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>$N$</td>
</tr>
<tr>
<td>$T\bar{T}(WH)$</td>
<td>173.6 fb</td>
</tr>
<tr>
<td>$T\bar{T}(HH)$</td>
<td>44.38 fb</td>
</tr>
<tr>
<td>$T\bar{T}(ZH)$</td>
<td>50.0 fb</td>
</tr>
<tr>
<td>$\bar{t}tH$</td>
<td>118.7 fb</td>
</tr>
<tr>
<td>$\bar{t}\bar{t}$</td>
<td>143.2 pb</td>
</tr>
<tr>
<td>$\bar{t}tj$</td>
<td>142.7 pb</td>
</tr>
</tbody>
</table>

$\varepsilon$ grows with $n$ (larger $b$ mistag probability)

$nj$ by PYTHIA $\quad \Rightarrow \quad \sigma = 138.7 \text{ fb} \quad N = 2076 \quad \varepsilon = 0.050\%$

would-be $K = 5.0$
Signals and main backgrounds

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

<table>
<thead>
<tr>
<th>Process</th>
<th>$N$</th>
<th>$\varepsilon'$ (%)</th>
<th>$N$</th>
<th>$\varepsilon'$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T\bar{T}(WH)$</td>
<td>253.1</td>
<td>4.9</td>
<td>$\bar{t}t2j$</td>
<td>254</td>
</tr>
<tr>
<td>$T\bar{T}(HH)$</td>
<td>188.3</td>
<td>14.2</td>
<td>$\bar{t}t3j$</td>
<td>341</td>
</tr>
<tr>
<td>$T\bar{T}(ZH)$</td>
<td>89.1</td>
<td>6.0</td>
<td>$\bar{t}t4j$</td>
<td>381</td>
</tr>
<tr>
<td>$\bar{t}t$</td>
<td>49</td>
<td>0.0011</td>
<td>$\bar{t}t5j$</td>
<td>668(\text{K})</td>
</tr>
<tr>
<td>$\bar{t}tj$</td>
<td>106</td>
<td>0.0024</td>
<td>$\bar{t}t\bar{b}\bar{b}$</td>
<td>350</td>
</tr>
</tbody>
</table>

$H_T \geq 1000$ GeV  \( p_{t}^{j,\text{max}} \geq 150 $ GeV  \( p_{t}^{b,\text{max}} \geq 100 $ GeV

$\varepsilon'$ grows even more with $n$ (larger transverse momenta)

nj by PYTHIA  \( \Rightarrow \)  $N = 220$  \( \varepsilon = 0.0052\% $

\( \Rightarrow \) would-be  \( K = 8.2 $
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
Most important variables (11 total)
$\bar{t}tH$ search

Results for 30 fb$^{-1}$

<table>
<thead>
<tr>
<th>$\log L_S/L_B$</th>
<th>$100 \leq M^\text{rec}_H \leq 140$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}tH$</td>
<td>170.3</td>
</tr>
<tr>
<td>$\bar{t}t$</td>
<td>1498</td>
</tr>
<tr>
<td>$\bar{t}tj$</td>
<td>2418</td>
</tr>
<tr>
<td>$\bar{t}t2j$</td>
<td>2485</td>
</tr>
<tr>
<td>$\bar{t}t3j$</td>
<td>1948</td>
</tr>
<tr>
<td>$\bar{t}t4j$</td>
<td>1240</td>
</tr>
<tr>
<td>$\bar{t}t5j$</td>
<td>1086</td>
</tr>
<tr>
<td>$\bar{t}t\bar{b}b$</td>
<td>1683</td>
</tr>
</tbody>
</table>

Significance: 0.40$\sigma$ (incl. all bkg and 20% sys)

CMS: 0.47$\sigma$ (full sim, $K \simeq 1.5$, rescaled to 30 fb$^{-1}$ and 20% sys)
$T\bar{T} \rightarrow H$ search

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

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

Most important variables (15 total)
$T\bar{T} \rightarrow H$ search ($4b$ final states)

Results for $30 \text{ fb}^{-1}$

Significance: 6.39$\sigma$ (incl. all bkg and 20% sys)

$\log L_S/L_B \geq 3.9$

$N_{\text{jet}} \leq 7$, $100 \leq M_H^{\text{rec}} \leq 140$
$350 \leq m_T^{\text{had}}, m_T^{\text{lep}} \leq 650$

<table>
<thead>
<tr>
<th>$TT(H)$</th>
<th>567.1</th>
<th>$\rightarrow$</th>
<th>44.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>1462</td>
<td>$\uparrow$</td>
<td>1</td>
</tr>
<tr>
<td>$t\bar{t}j$</td>
<td>2346</td>
<td>$\uparrow$</td>
<td>0</td>
</tr>
<tr>
<td>$t\bar{t}2j$</td>
<td>2399</td>
<td>$\uparrow$</td>
<td>2</td>
</tr>
<tr>
<td>$t\bar{t}3j$</td>
<td>1892</td>
<td>$\uparrow$</td>
<td>3</td>
</tr>
<tr>
<td>$t\bar{t}4j$</td>
<td>1203</td>
<td>$\uparrow$</td>
<td>8</td>
</tr>
<tr>
<td>$t\bar{t}5j$</td>
<td>1018</td>
<td>$\uparrow$</td>
<td>2</td>
</tr>
<tr>
<td>$t\bar{t}b\bar{b}$</td>
<td>1477</td>
<td>$\uparrow$</td>
<td>3</td>
</tr>
</tbody>
</table>
Combined significance

\begin{align*}
4b & \quad 6.39\sigma \\
5b & \quad 5.93\sigma \\
6b & \quad 5.69\sigma \\
\hline
\text{Total} & \quad 10.41\sigma
\end{align*}

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

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 kinemetical cuts
- No higher order enhancement due to $b$ (mis)tagging
### Example I

\[ WZnj \rightarrow \mu^\pm \mu^\pm \text{ and } \geq 2 \text{ jets with } p_t \geq 20 \text{ GeV} \]

<table>
<thead>
<tr>
<th></th>
<th>Generated</th>
<th>Pre-selection</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>6437 × 10</td>
<td>57.7 (0.90%)</td>
<td>0.2 (0.34%)</td>
</tr>
<tr>
<td>WZj</td>
<td>6088 × 10</td>
<td>156.1 (2.56%)</td>
<td>0.9 (0.57%)</td>
</tr>
<tr>
<td>WZ2j</td>
<td>5005 × 10</td>
<td>244.8 (4.89%)</td>
<td>2.9 (1.18%)</td>
</tr>
<tr>
<td>WZ3j</td>
<td>3533(^K)× 10</td>
<td>156.9 (4.44%)</td>
<td>0.8 (0.51%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>615.5</strong></td>
<td></td>
<td><strong>4.8</strong></td>
</tr>
</tbody>
</table>

\[ WZ2j \text{ without matching} \]

<table>
<thead>
<tr>
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<th>Generated</th>
<th>Pre-selection</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ2j</td>
<td>5005 × 10</td>
<td>226.0 (4.51%)</td>
<td>2.0 (0.88%)</td>
</tr>
</tbody>
</table>

would-be \[ K = 2.7 (2.4) \]
**Example II**

**$WWnj \rightarrow \mu^\pm \mu^\pm$ and $\geq 2$ jets with $p_t \geq 20$ GeV**

<table>
<thead>
<tr>
<th></th>
<th>Pre-selection</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$WWj$</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$WW2j$</td>
<td>116.2</td>
<td>1.5 (1.29%)</td>
</tr>
<tr>
<td>$WW3j$</td>
<td>200.2</td>
<td>0.8 (0.40%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>316.4</td>
<td>2.3</td>
</tr>
<tr>
<td>$WW2j$ without matching</td>
<td>135.7</td>
<td>0.9 (0.66%)</td>
</tr>
</tbody>
</table>

**$K = 2.3 (2.5)$**
Conclusions

- Reanalysis of $H$ discovery from $T\bar{T}$ decays
- Discovery potential for $H$ one half as previously: $10.41\sigma$ for 30 fb$^{-1}$
- Significance drops in $t\bar{t}H$: $0.40\sigma$ 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?

- SU(2)_L singlets $T$ with charge $Q = 2/3$ appear in several SM extensions
  - Extra dimensions, little Higgs models, GUTs

- They provide a consistent way of breaking $3 \times 3$ 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

$$M_u = \frac{\nu}{\sqrt{2}} Y_u, \ B^u \text{ bare mass term (or from Higgs singlet)}$$

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

Mixing with singlet modifies interactions with $W$, $Z$ and $H$
does not affect interactions with $\gamma$, $g$

\[
\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[ \bar{u} \gamma^\mu V P_L d W^\mu_\mu + \bar{d} \gamma^\mu V^\dagger P_L u W^-_\mu \right] \\
\mathcal{L}_Z = -\frac{g}{2c_W} \bar{u} \gamma^\mu \left[ P_L - \frac{4}{3} s_W^2 4 \times 4 \right] u Z^\mu \\
\mathcal{L}_H = \frac{g}{2M_W} \bar{u} \left[ \mathcal{M}^u P_L + \mathcal{M}^u P_R \right] u H
\]
Overview of the model

Mixing with singlet modifies interactions with $W$, $Z$ and $H$
does not affect interactions with $\gamma$, $g$

\[
\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left[ \bar{u} \gamma^\mu V_{4 \times 3} P_L d W^\mu_\mu + \bar{d} \gamma^\mu V^\dagger_{4 \times 3} P_L u W^-_\mu \right]
\]

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

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

\[
X = VV^\dagger
\]
Main features:

- New quark $T$ has a CC coupling to the $b$ quark
  \[- \frac{g}{\sqrt{2}} \bar{T} \gamma^\mu V_{Tb} P_L b W^+_\mu + \text{h.c.} \quad (V_{Td}, V_{Ts} \text{ much smaller})\]

- FCN coupling to the top and $Z$ boson
  \[- \frac{g}{2c_W} \bar{t} \gamma^\mu X_{tT} P_L T Z_\mu + \text{h.c.} \quad (X_{uT}, X_{cT} \text{ much smaller})\]
  \[|X_{tT}|^2 \simeq |V_{Tb}|^2 (1 - |V_{Tb}|^2)\]

- FCN coupling to the top and Higgs
  \[\frac{g}{2M_W} \bar{t} X_{tT} (m_t P_L + m_T P_R) T H + \text{h.c.}\]
  \[|X_{tT}| \simeq |V_{Tb}|^2\]

- and a small Yukawa coupling
  \[\frac{g}{2M_W} \bar{T} X_{TT} m_T T H\]
  \[|X_{TT}| \simeq |V_{Tb}|^2\]

$\begin{align*}
  m_T &= 500 \\
  V_{Tb} &= 0.2 \\
  X_{tT} &= 0.196 \\
  X_{TT} &= 0.04
\end{align*}$
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:
  
  $$- \frac{g}{2c_W} \bar{t} \gamma^\mu (1 - \frac{4}{3} s_W^2) P_L t Z_\mu \rightarrow - \frac{g}{2c_W} \bar{t} \gamma^\mu (X_{tt} - \frac{4}{3} s_W^2) P_L t Z_\mu$$
  
  $$X_{tt} \simeq |V_{tb}|^2$$

- FCN couplings among SM quarks
  
  $$- \frac{g}{2c_W} \bar{q} \gamma^\mu X_{qt} P_L t Z_\mu + \text{h.c.} \quad q = u, c$$
  
  $$- \frac{g}{2c_W} \bar{u} \gamma^\mu X_{uc} P_L c Z_\mu + \text{h.c.}$$
Anomaly cancellation

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

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

\[ \text{tr}[Y^3] = \sum_f Y_f^3 \rightarrow \Delta = \left( -\frac{2}{3} \right)^3 + \left( \frac{2}{3} \right)^3 = 0 \]

\[ \text{tr}[Y] = \sum_f Y_f \rightarrow \Delta = \left( -\frac{2}{3} \right) + \frac{2}{3} = 0 \]
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

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

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

95% bounds on $|V_{Tb}|$
Model description
Constraints on $V_{Tb}$
$T$ contribution to $gg \rightarrow H$

$T$ contribution to $gg \rightarrow H$

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

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

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

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

$X_{tt} \simeq 0.96$ $\Rightarrow$ top contribution reduced
Charged lepton from $t, T$ decays

Energy in $t, T$ rest frame

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

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

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