Top Quark signatures of Higgsless Models

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The landscape of Higgsless models

Basic idea (Csaki et.al 03)

- W and Z bosons lightest Kaluza-Klein mode of 5D fields
- 5D gauge symmetry broken by boundary conditions: $W_\mu(y)|_{0,\pi R} = 0$
- Unitarity in $W^+W^- \to W^+W^-$ scattering restored by KK-modes instead of Higgs boson (Chivukula et.al, 02 Csaki et.al 03; Ohl CS 03)
- effective field theory with cutoff 5-10 TeV (Chivukula et.al 02, Papucci 04)

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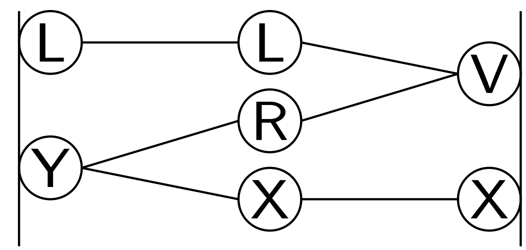
Many models:

- Warped 5D model (Csaki et.al 03)

$$SU(2)_L \times SU(2)_R \times U(1)_X \Rightarrow \begin{cases} SU(2)_L \times U(1)_X|_0 \\ SU(2)_V \times U(1)_Y|_{\pi R} \end{cases}$$



- Deconstructed 4D models $SU(2)^N \otimes U(1)^M$ (Dominici et.al, Chivukula et.al, Georgi)
- 5D continuum Theory space $SU(2) \Rightarrow U(1)|_{\pi R}$ (Foadi, Schmidt])
- 6D $SU(2) \otimes U(1)$ (Gabriel, Nandi, Seidl)

Signals in gauge boson sector

Generic signatures? (Birkedal, Matchev,Perelstein, 2004)

Use sum rules from cancellation of terms $\sim E^4$ and E^2 in $\mathcal{A}(WZ \to WZ)$:

$$g_{W^2Z^2} = g^2_{WWZ} + \sum_n g^2_{ZWW^{(n)}} \qquad g^2_{ZWW}\frac{m_Z^4}{m_W^2} = 3\sum_n g^2_{ZWW^{(n)}} m^2_{W^{(n)}}$$

$\Rightarrow$ Estimate

$$g_{ZWW^{(1)}} \lesssim \frac{g_{ZWW} m_Z^2}{\sqrt{3} m_{W^{(1)}} m_W}$$

$$\Gamma_{W^{(1)} \to WZ} \approx \frac{\alpha_{QED} m^3_{W^{(1)}}}{144 \sin^2\theta_w m_W^2} \sim \begin{cases} 13 \text{ GeV}, & m_{W^{(1)}} = 700 \text{ GeV} \\ 38 \text{ GeV}, & m_{W^{(1)}} = 1000 \text{ GeV} \end{cases}$$

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Anomalous WWZ couplings to restore E^4 SR (Csaki et.al. 03, Cacciapaglia 06)

Estimate from SRs: $\left|\dfrac{\delta g_{WWZ}}{g_{WWZ}}\right| \sim \mathcal{O}(1) \times \dfrac{m_W^2}{m^2_{W^{(1)}}}$

$SU(2)_L \times SU(2)_R$: (Chivukula et.al) $\quad \dfrac{\delta g_{WWZ}}{g_{WWZ}} = \begin{cases} \dfrac{\pi^2}{12 c^2_{\theta w}} \dfrac{m_W^2}{m^2_{W^{(1)}}} \approx 1 \times \dfrac{m_W^2}{m^2_{W^{(1)}}} & \text{(flat)} \\ \dfrac{3(2.44)^2}{16 c^2_{\theta w}} \dfrac{m_W^2}{m^2_{W^{(1)}}} \approx 1.44 \times \dfrac{m_W^2}{m^2_{W^{(1)}}} & \text{(warped)} \end{cases}$

Fermions and the top quark

Fermion sector of Higgsless models (Nomura 03; Csaki et.al,03; Foadi et.al. 04)

- 5D Fermions with brane mass and kinetic terms
- cancel S-parameter induced by gauge boson KK-modes by tuning bulk mass parameters or BKTs (Cacciapaglia et.al, Foadi et.al.)
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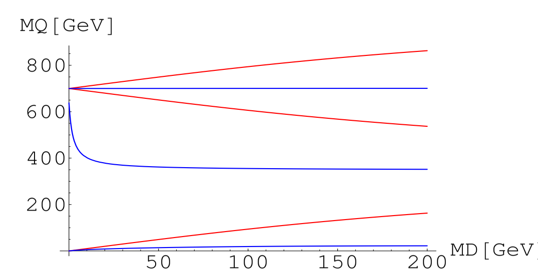
Top quark sector problematic (Cacciapaglia et.al.; Foadi, Schmidt)

- naive mass spectrum : $m_{T^{(1)}}, m_{B^{(1)}} < m_{Z^{(1)}}$
  anomalous $b_L b_L Z$ or $W t_R b_R$ couplings:
  $m_{T^{(1)}}, m_{B^{(1)}} > m_{Z^{(1)}}$



- Large mass difficult for delocalized top

Models of top sector:

- Two patches of AdS$_5$, Top Pions (Cacciapglia et.al)
- 5D Lorentz violating mass term $\kappa_t \bar{\Psi}_t \partial_5 \Psi_t$ (Foadi, Schmidt)
- More natural in theory space models (Georgi)

Unitarity sum rules for fermions

4D SM without Higgs: $\mathcal{A}(W^+W^- \to t\bar{t}) \sim E$

$\Rightarrow$ Appelquist-Chanowitz bound $\Lambda_t \approx 3.5 - 5\mathrm{TeV}$

on scale of mass generation (Appelquist, Chanowitz 87; Dicus, He, 04)

Sum rule for cancelling E growth of $\mathcal{A}(q_i\bar{q}_j \to V_a V_b)$ in Higgsless models

$$\sum_n \left(\mathrm{i}g^L_{V^5_b q_i \bar{Q}^{(n)}} g^L_{V_a Q^{(n)} \bar{q}_j} - \mathrm{i}g^R_{V^5_a q_i \bar{Q}^{(n)}} g^L_{V_b Q^{(n)} \bar{q}_j} \right) = \sum_n g^L_{V_c^{5(n)}\, q_i q_j} g_{V_a V^5_b V_c^{5(n)}}$$

coupling of V_5 : $\quad m_{V_a^{(n)}} g^L_{V_a^{5(n)}\, q_i\bar{q}_j} = \mathrm{i}(m_{q_i} g^L_{V_a^{(n)}\, q_i\bar{q}_j} - m_{q_j} g^R_{V_a^{(n)}\, q_i\bar{q}_j})$

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Satisfied for gauge invariant brane mass and kinetic terms (CS 04)

- Example: BC for 5-D fermion $\chi|_{y=0} = \frac{\mathrm{i}}{t_R^2} \sigma^\mu \partial_\mu \eta|_{y=0}$ ($\Psi = (\chi, \eta)$)

$\Rightarrow$ modifify coupling to unbroken gauge bosons to restore SR

$\Rightarrow$ Consistent BCs correspond to gauge invariant brane term:

$$\mathcal{L}_{BKT} = \frac{\mathrm{i}}{t_R} \bar{\eta}(\partial\!\!\!/ + \tau^a A\!\!\!/^a)\eta\, \delta(y)$$

Unitarity constraints on the top sector

Use unitarity sum rules for $W^+W^- \to t\bar{t}$ to constrain couplings (CS, 05)

a) Cancellation of terms $\sim E^2$

$$-(g^{L/R}_{Wtb})^2 + g_{ZWW}\, g^{L/R}_{ttZ} + g_{WW\gamma}\, g_{tt\gamma} = \sum_n \left[(g^{L/R}_{WtB^{(n)}})^2 - g_{WWZ^{(n)}}\, g^{L/R}_{ttZ^{(n)}}\right]$$

(satisfied in SM without Higgs)

b) Cancellation of terms $\sim E$:

$$(g^{L}_{Wtb})^2 + (g^{R}_{Wtb})^2 = \sum_n \left[2\frac{m_{B^{(n)}}}{m_t}\, g^{R}_{WtB^{(n)}}\, g^{L}_{WtB^{(n)}} - (g^{L}_{WtB^{(n)}})^2 - (g^{R}_{WtB^{(n)}})^2\right]$$

(Explicitly verified for 5D $SU(2)$ model in Foadi,Schmidt 05)

$\Rightarrow$ **KK-modes of b-quark** neccessary! Expect $m_{B^{(1)}} \lesssim \Lambda_t$

Constraints on anomalous couplings?

Coupling of top to $Z^{(1)}$ can cancel contribution of $B^{(1)}$ in a):

$$\Rightarrow g^{R}_{Wtb} = 0 \text{ is possible!}$$

Comparison to 5D $SU(2)$ model

Parameters and constraints of 5D $SU(2)$ model (Foadi, Schmidt)

- Top mass: $m_t = \frac{\kappa t_L t_R}{\pi R} + \mathcal{O}(t_L^2, t_R^2)$
  with boundary kinetic terms $t_{L/R}$ and 5D Lorentz violation κ.
  Flavor universal $t_L \sim \frac{\pi m_W R}{\sqrt{3}}$ tuned to cancel S parameter.

- Masses and couplings of KK modes of b quark:

$$m_B^{(n)} \approx \frac{\kappa}{R}\left(n - \frac{1}{2}\right) \quad , \quad g_{WtB^{(1)}}^{L/R} \approx \sqrt{2}(-1)^{n+1}\frac{g t_{L/R}}{\pi^2\left(n-\frac{1}{2}\right)^2}$$

- 3.6 TeV$< \kappa/R < 32$ TeV from right-handed Wtb coupling and unitarity.

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First level saturates sum rule:

$$2\frac{m_{B^{(1)}}}{m_t} g^R_{WtB^{(1)}} g^L_{WtB^{(1)}} \sim \frac{32}{\pi^3} g^2 \sim (g^L_{Wtb})^2$$

Weak bound on $g^L_{WtB^{(1)}}/g^R_{WtB^{(1)}}$:

$$\frac{g^L_{WtB^{(1)}}}{g^R_{WtB^{(1)}}} \sim \frac{t_L}{t_R} \sim \frac{\kappa\pi R m_W^2}{3 m_t} \sim 0.3 - 2 \qquad \text{(for } R^{-1} = 800 \text{ GeV)}$$

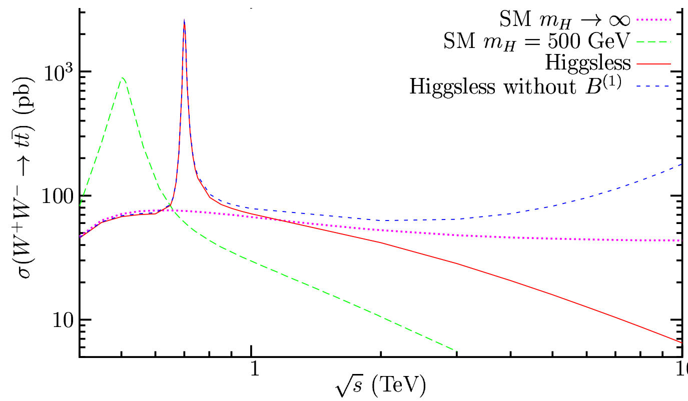
Implications for top quark physics

Toy scenario

Solve sum rules for the first KK level.

$$g_{WtB^{(1)}} \approx \frac{g}{2}\sqrt{\frac{m_t}{m_{B^{(1)}}}} \qquad g_{ttZ^{(1)}} \approx \frac{\sqrt{3}g}{4}\,\frac{m_t m_{Z^{(1)}}}{m_W m_{B^{(1)}}}$$

(vectorlike KK couplings, no anomalous couplings)



$$\Rightarrow \frac{\Gamma_{Z^{(1)}\to t\bar{t}}}{\Gamma_{Z^{(1)}\to W^+W^-}} = 27\left(\frac{m_t}{m_{B^{(1)}}}\right)^2 = 15\% \ldots 90\% \quad \text{for} \quad m_{B^{(1)}} = 2.5\text{TeV} \ldots 1\text{TeV}$$

LHC signatures of $Z^{(1)}$? (Han,Rainwater,Valencia 03, Han, Valencia, Wang 04)

- Vector boson fusion dominated by QCD background:

$$pp \to jjZ^{(1)} \to jjt\bar{t}$$

($m_{Z^{(1)}} = 1$ TeV, $\Gamma_{Z^1\to WW} = 50$ GeV, $\Gamma_{Z^1\to t\bar{t}} = 1.3$GeV)

- Associated production promising:

$$Wb \to tZ^{(1)} \to tt\bar{t} \;,\; gg \to t\bar{t}Z^{(1)} \to t\bar{t}t\bar{t}$$

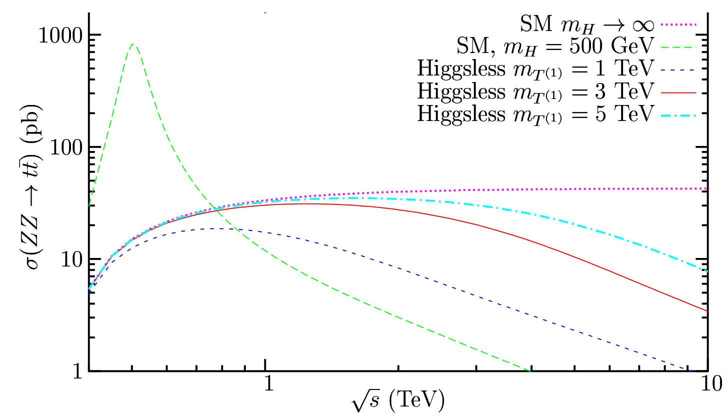
($m_{Z^{(1)}} = 1$ TeV, $\Gamma_{Z^1\to t\bar{t}+b\bar{b}} = 127$ GeV, no coupling to W^+W^-)

Implications for top quark physics

Couplings of $T^{(1)}$

(Include also $ZZ \to t\bar{t}$ and $WW \to b\bar{b}$ SRs)

$$g_{WT^{(1)}b} \approx \frac{g}{2}\sqrt{\frac{m_b}{m_{T^{(1)}}}} \quad g_{tT^{(1)}Z} \approx \sqrt{\frac{2m_t}{m_{T^{(1)}}}}\frac{g}{2c_{\theta w}}$$



Compare to heavy T in little(st) Higgs:

couplings of T suppressed by $s_L = \frac{m_t}{m_T}\frac{\lambda_1}{\lambda_2}$ (Han et.al., Perelstein, et.al. 2003)

$$\Gamma^{\text{HL}}_{T^{(1)} \to tZ} \approx 30\text{GeV} \times \left(\frac{m_{T^{(1)}}}{1\text{TeV}}\right)^2 = \frac{m_T}{4m_t}\left(\frac{\lambda_2}{\lambda_1}\right)^2 \Gamma^{\text{LH}}_T$$

Reach in single T production at LHC: $m_T = 2$ TeV for $\lambda_1 = \lambda_2$

$$\sigma_{\text{HL}}(Wb \to T^{(1)}) = \frac{m_b m_T^{(1)}}{m_t^2}\left(\frac{\lambda_2}{\lambda_1}\right)^2 \sigma_{\text{LH}}(Wb \to T) \sim 0.13\,\frac{m_T^{(1)}}{\text{TeV}}\,\sigma_{\text{LH}}(Wb \to T)$$

Conclusions

Viable Models of Higgsless symmetry breaking exist
but require tuning of fermion mass parameters and separate treatment of third generation

Tree unitarity in Higgsless Models

- Cancel unitarity violations by infinite tower of KK-modes
- Conditions for cancellations can be used to estimate couplings of KK-modes and anomalus couplings

Constraints on Top quark physics

- expect $m_{B^{(1)}}, m_{T^{(1)}} \lesssim 3.5$ TeV (but $m_{B^{(1)}} < 16$ TeV found in explicit model)
- Associated $Z^{(1)}t$ and $Z^{(1)}t\bar{t}$ production at LHC?
- Top and bottom quark KK-modes more difficult