Electroweak Symmetry Breaking and Collider phenomenology of Gauge-Higgs Unification Scenarios in Warped Extra Dimensions

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Geometry of Warped Extra Dimensions (RS1)

- Non-factorizable geometry with one extra dimension $y$ compactified on an orbifold $S^1/Z_2$ of radius $R$, $0 \leq y \leq \pi$.

$$ds^2 = e^{-2R\sigma} \eta_{\mu\nu} dx^\mu dx^\nu + R^2 dy^2$$

where $\sigma = k|y|$. Solution to the 5D Einstein equations. Slice of AdS_5 geometry. Mass scale at $y=0$, $M_p$ and at $y=\pi$, $M_p e^{-k\pi R}$.

- 5D Planck mass relates to $M_{pl}$:

$$M_p^3 = M_5^3 \left( 1 - e^{-2k\pi R} \right) / k$$

- Solution to the hierarchy problem: Assuming that fundamental scales are of the same order $k \sim M_5 \sim M_{pl}$, Higgs field localized near the IR brane $\rightarrow v \sim k e^{kL} \equiv k e^{kL} \sim M_{pl} e^{kL} \sim \text{TeV}$ with $kL \sim 30$, $L = \pi R$

- Geometry diagram
The Randall-Sundrum Model of Warped Space:

- elegant solution to the hierarchy problem

**RS With Bulk Fermions and Gauge bosons:**

- Higgs field must be located in the IR brane, but SM fields may live in the bulk.
- Fermions in the bulk: => suggestive theory of flavor
  - SM fermion masses related to the size of their zero mode wave function at the IR
  - Localization determined from bulk mass term: \( L_m = c_f k \bar{\Psi} \Psi \)

\[ \Psi_{L,R}(x, y) = e^{3ky} \sum_{n} \psi_{L,R}^n(x) f_{L,R}^n(y) \]

Boundary conditions for \( f(y) \) at the branes (UV, IR) = (+,+) => zero mode
- If b.c. (-,+), (+,-) or (-,-) => no zero mode
  - The KK spectrum is defined in units of \( \tilde{k} = ke^{-kL} \) of factors that depend on \( c_f \)
  - and is localized towards the IR brane
Effects of KK modes of the gauge bosons on Z pole observables

**SM in the bulk**

- Large mixing with Z and W zero modes through Higgs

![Diagram of W modes](image)

**Large corrections to the \( M_Z/M_W \) ratio (T parameter)**

\[ \downarrow \]

\[ M_{KK} \geq 5 - 10 \text{ TeV} \]

- Top and bottom zero modes localized closer to the IR brane
  - Large gauge and Yukawa couplings to Gauge Bosons and fermion KK modes

![Diagram of Z and bottom quark](image)

**Large corrections to the Zbb coupling**

\[ \downarrow \]

\[ M_{KK} \gtrsim 7 - 8 \text{ TeV} \]
How to obtain a phenomenologically interesting theory?

1) Extend SM bulk gauge symmetry to a custodial symmetry

\[ \text{SU}(2)_L \times \text{SU}(2)_R \]

\[ T \propto \begin{array}{c}
\uparrow \uparrow \\
\downarrow \downarrow
\end{array} \sim 0 \]

2) The custodial symmetry together with a discrete \( L \leftrightarrow R \) symmetry and a specific bidoublet structure of the fermions under \( \text{SU}(2)_L \times \text{SU}(2)_R \)

\[ T^3_R(b_L) = T^3_L(b_L) \]

\[ \delta g_{b_L} \propto \begin{array}{c}
\uparrow \uparrow \\
\downarrow \downarrow
\end{array} \sim 0 \]

\[ \implies \text{reduce tree level contributions to the T parameter and the Zbb coupling that allow for lightest KK gauge bosons with } M_{KK} \sim 3 \text{ TeV} \]

Alternative to the above: Large brane kinetic terms

M. Carena, A. Delgado, E. Ponton, T. Tait, C.W. ‘05,
Holographic Higgs

• Bulk gauge symm.: $\text{SU}(3)_c \times \text{SO}(5) \times \text{U}(1)_X \rightarrow \text{SO}(5) \supset \text{SU}(2)_R \times \text{SU}(2)_L$.

UV: $\text{SU}(2)_L \times \text{U}(1)_Y$ \hspace{1cm} IR: $\text{SO}(4) \times \text{U}(1)_X$.

Extra gauge bosons have the quantum numbers of the Higgs

$\text{SO}(5)/\text{SO}(4) \rightarrow A^{1 \ldots 4}_\mu (-,-) \quad A^{1 \ldots 4}_5 (+,+)$ $\leftrightarrow$ Identify with H.

No tree level Higgs potential $\rightarrow$ Induced at one-loop (calculable).

• Coleman-Weinberg Potential has been computed for the model under consideration [A.M, N. Shah and C. Wagner].
  1. EWSB minima in large regions of parameter space consistent with EWPT.
  2. Consistent with $Z, W, \text{bottom quark, top quark masses and Higgs LEP bound}$.
• EW fit easier in regions Higgs couplings are linear (similar to those of the SM).
Warped Extra Dimensions: Gauge-Higgs Unification

• The 5D action is given by,

\[ S_{5D} = \int d^4x \int_0^L dx_5 \sqrt{g} \left( -\frac{1}{4g_5^2} \text{Tr} \{ F_{MN} F^{MN} \} - \frac{1}{4g_X^2} G_{MN} G^{MN} + \bar{\psi} (i \Gamma^N D_N - M) \psi \right), \]

where \( D_N = \partial_N - iA^a_N t^a - iB_N \) and \( g_5 \) and \( g_X \) are the 5D dimensionful gauge couplings. The generators of SU(2)\( _{L,R} \) are denoted by \( T^{a}_{L,R} \), while the generator from the coset SO(5)/SO(4) are denoted by \( T^\phi \).

• Right Hypercharge \( \rightarrow \)

\[
\begin{pmatrix} A^{3R}_M \\ A^Y_M \end{pmatrix} = \begin{pmatrix} c_\phi & -s_\phi \\ s_\phi & c_\phi \end{pmatrix} \begin{pmatrix} A^3_M \\ B_M \end{pmatrix} \\

\]

\[
c_\phi \equiv \frac{g_5}{\sqrt{g_5^2 + g_X^2}}, \quad s_\phi \equiv \frac{g_X}{\sqrt{g_5^2 + g_X^2}}.
\]

• SO(5) breaking b.c.

\[
\partial_5 A^{aL,Y}_\mu = A^{aR,\hat{a}}_\mu = A^{aL,Y}_5 = 0, \quad x_5 = 0 \quad \rightarrow \quad H \propto (h^\hat{a} + ih^\hat{\alpha}, h^\hat{3} - ih^\hat{\alpha})^t,
\]

\[
\partial_5 A^{aL,aR,Y}_\mu = A^{aL,aR,Y}_5 = 0, \quad x_5 = L.
\]

• KK expansion of gauge fields

\[
A^a_\mu(x, x_5) = \sum_n f^a_n(x_5, h) A_{\mu,n}(x) \quad A^5_\mu(x, x_5) = \sum_n \frac{\partial_5 f^a_n(x_5, h)}{m_n(h)} h_n(x)
\]

\[
A^{\hat{a}}_\mu(x, x_5) = \sum_n f^{\hat{a}}_n(x_5, h) A_{\mu,n}(x) \quad A^{\hat{a}}_5(x, x_5) = \frac{C_h}{a^2(x_5)} h^{\hat{a}}(x) + \sum_n \frac{\partial_5 f^{\hat{a}}_n(x_5, h)}{m_n(h)} h_n(x)
\]

\[
A^Y_\mu(x, x_5) = \sum_n f^Y_n(x_5, h) A_{\mu,n}(x) \quad A^Y_5(x, x_5) = \sum_n \frac{\partial_5 f^Y_n(x_5, h)}{m_n(h)} h_n(x)
\]

\[
A^{3}_{\mu}(x, x_5) = \sum_n f^{3}_{n}(x_5, h) A_{\mu,n}(x) \quad A^{3}_5(x, x_5) = \sum_n \frac{\partial_5 f^{3}_{n}(x_5, h)}{m_n(h)} h_n(x)
\]

\[
A_5(x, x_5) = \sum_n \frac{\partial_5 f^Y_{n}(x_5, h)}{m_n(h)} h_n(x)
\]
Warped Extra Dimensions: Gauge-Higgs Unification

• 5D action in terms of KK tower,

\[ S_{5D} = \int d^4x \left\{ \frac{1}{2} (\partial_\mu h^\delta)^2 + \sum_n \left( -\frac{1}{4} [\partial_\mu A_{\nu,n} - \partial_\nu A_{\mu,n}]^2 + \frac{1}{2} m_n^2(h) A_{\mu,n}^2 \right) + \ldots \right\} \]

• Solving e.o.m in presence of h difficult \( \rightarrow \) gauge transformation

\[ f^\alpha(x_5,h)T^\alpha = \Omega^{-1}(x_5,h)f^\alpha(x_5,0)T^\alpha\Omega(x_5,h), \]

With

\[ \Omega(x_5,h) = \exp \left[ -iC_h hT^4 \int_0^{x_5} dy a^{-2}(y) \right]. \]

• Solutions to the e.o.m in h=0 gauge

\[
\begin{align*}
C(x_5, z) &= \frac{\pi z}{2k} a^{-1}(x_5) \left[ Y_0 \left( \frac{z}{k} \right) J_1 \left( \frac{z}{ka(x_5)} \right) - J_0 \left( \frac{z}{k} \right) Y_1 \left( \frac{z}{ka(x_5)} \right) \right] \\
S(x_5, z) &= \frac{\pi z}{2k} a^{-1}(x_5) \left[ J_1 \left( \frac{z}{k} \right) Y_1 \left( \frac{z}{ka(x_5)} \right) - Y_1 \left( \frac{z}{k} \right) J_1 \left( \frac{z}{ka(x_5)} \right) \right]
\end{align*}
\]

• UV b.c’s automatically satisfied. IR b.c’s \( \rightarrow \) system of Eqs. With non-trivial solution \( \leftrightarrow \)

\[
S(L, m_n)S'^3(L, m_n)C'(L, m_n) \left[ 2a_L^2 C'(L, m_n) S(L, m_n) + m_n \sin^2 \left( \frac{\lambda c_h}{f_h} \right) \right]^2 \times
\]
\[
\left[ 2a_L^2 C'(L, m_n) S(L, m_n) + (1 + s_0^2)m_n \sin^2 \left( \frac{\lambda c_h}{f_h} \right) \right] = 0
\]

where

\[ f_h^2 = \frac{1}{g_5^2 \int_0^L dy a^{-2}(y)} \]
Warped Extra Dimensions: Gauge-Higgs Unification

- 3 SO(5) multiplets in the quark sector,

\[
\begin{align*}
\xi_{1L} &\sim Q_{1L} = \begin{pmatrix} \lambda^u_{1L}(-,+)_{5/3} & q^u_L(+,+)_{2/3} \\ \lambda^d_{1L}(-,+)_{2/3} & q^d_L(+,+)_{1/3} \end{pmatrix} \oplus u_L(-,+)_{2/3}, \\
\xi_{2R} &\sim Q_{2R} = \begin{pmatrix} \lambda^u_{2R}(-,+)_{5/3} & q^u_R(-,+)_{2/3} \\ \lambda^d_{2R}(-,+)_{2/3} & q^d_R(-,+)_{1/3} \end{pmatrix} \oplus u_R(+,+)_{2/3}, \\
\xi_{3R} &\sim Q_{3R} = \begin{pmatrix} \lambda^u_{3R}(-,+)_{5/3} & q^u_R(-,+)_{2/3} \\ \lambda^d_{3R}(-,+)_{2/3} & q^d_R(-,+)_{1/3} \end{pmatrix}
\end{align*}
\]

\[\oplus T_1 = \begin{pmatrix} \psi_{1R}(-,+)_{5/3} \\ \overline{U}_{1R}(-,+)_{2/3} \\ \overline{D}_{1R}(-,+)_{1/3} \end{pmatrix} \oplus T_2 = \begin{pmatrix} \psi_{2R}(-,+)_{5/3} \\ \overline{U}_{2R}(-,+)_{2/3} \\ \overline{D}_{2R}(+,+)_{1/3} \end{pmatrix}.
\]

- Boundary mass mixing terms at the IR brane

\[\mathcal{L}_m = 2\delta(x_5 - L) \left[ \tilde{\nu}_L M_{B_1} u_R + \tilde{\nu}_L M_{B_2} Q_{3R} + \text{h.c.} \right].\]

- Solutions to the e.o.m in the bulk and in the h=0 gauge

\[
\begin{align*}
S_{\pm M}(x_5, z) &= e^{\pm M x_5} a^2(x_5) \frac{\tilde{S}_{\pm M}(x_5, z)}{a(x_5)}, \\
\tilde{S}_{\pm M}(x_5, z) &= e^{\pm M x_5} \frac{1}{z a(x_5)} \partial_5 \tilde{S}_{\pm M}(x_5, z),
\end{align*}
\]

with normalization

\[
\int_0^L dx_5 a(x_5)^3 f(x_5, m_n) f(x_5, m_m) = \delta_{m,n}.
\]

where

\[
\tilde{S}_M(x_5, z) = \frac{\pi z}{2k} a^{-c-\frac{1}{2}}(x_5) \left[ J_{\frac{1}{2}+c}^c \left( \frac{z}{k} \right) Y_{\frac{1}{2}+c}^c \left( \frac{z}{ka(x_5)} \right) - Y_{\frac{1}{2}+c}^c \left( \frac{z}{k} \right) J_{\frac{1}{2}+c}^c \left( \frac{z}{ka(x_5)} \right) \right].
\]
Warped Extra Dimensions: Gauge-Higgs Unification

- Vector functions for fermions in $h=0$ gauge,

\[
\begin{align*}
    f_{1,L}(x_5, 0) &= \begin{bmatrix}
        C_1 S_{M_1} \\
        C_2 S_{M_1} \\
        C_3 S_{-M_1} \\
        C_4 S_{-M_1} \\
        C_5 S_{M_1} 
    \end{bmatrix}, \\
    f_{3,R}(x_5, 0) &= \begin{bmatrix}
        C_{11} S_{-M_3} \\
        C_{12} S_{-M_3} \\
        C_{13} S_{-M_3} \\
        C_{14} S_{-M_3} \\
        C_{15} S_{-M_3} \\
        C_{16} S_{-M_3} \\
        C_{17} S_{-M_3} \\
        C_{18} S_{-M_3} \\
        C_{19} S_{-M_3} \\
        C_{20} S_{M_3} 
    \end{bmatrix}, \\
    f_{2,R}(x_5, 0) &= \begin{bmatrix}
        C_6 S_{-M_2} \\
        C_7 S_{-M_2} \\
        C_8 S_{-M_2} \\
        C_9 S_{-M_2} \\
        C_{10} S_{M_2} 
    \end{bmatrix}.
\end{align*}
\]

- Gauge transformation applied to fermions

\[
\begin{align*}
    f_{1,L}(x_5, h) &= A \Omega A^{-1} f_{1,L}(x_5, 0) \\
    f_{2,R}(x_5, h) &= A \Omega A^{-1} f_{2,R}(x_5, 0) \\
    f_{3,R}(x_5, h) &= B \Omega B^{-1} f_{3,R}(x_5, 0)
\end{align*}
\]

Where $A$ and $B$ are basis transformations from isospin to canonical base.

- IR boundary conditions,

\[
\begin{align*}
    f_{1,R}^{1,\ldots,4} + M_{B_2} f_{3,R}^{1,\ldots,4} &= 0, & f_{1,R}^5 + M_{B_1} f_{2,R}^5 &= 0, & f_{2,L}^1 &= 0, \\
    f_{3,L}^{1,\ldots,4} - M_{B_2} f_{1,L}^{1,\ldots,4} &= 0, & f_{2,L}^5 - M_{B_1} f_{1,L}^5 &= 0, & f_{3,L}^{5,\ldots,10} &= 0.
\end{align*}
\]
Warped Extra Dimensions: Gauge-Higgs Unification

• Vanishing determinant →

\[
\begin{align*}
\tilde{S}_{-M_2}'^3 &= 0 \\
\tilde{S}_{-M_3}'^5 &= 0 \\
\left[ M_{B_2}^2 \tilde{S}_{-M_1} + \frac{\alpha_2}{2} \tilde{S}_{-M_1}' \tilde{S}_{-M_3}' \right]^2 &= 0 \\
2\tilde{S}_{M_3} \left[ M_{B_2}^2 \tilde{S}_{-M_3}' S_{-M_1} + \tilde{S}_{-M_1} \tilde{S}_{-M_3}' \right] - M_{B_2}^2 \tilde{S}_{-M_1}' \sin^2 \left( \frac{\lambda_{PH}}{f_h} \right) &= 0 \\
2 M_{B_1}^2 \tilde{S}_{M_1} \left[ -1 + \tilde{S}_{M_1} \tilde{S}_{-M_2} \left( M_{B_2}^2 \tilde{S}_{-M_3}' S_{-M_1} + \tilde{S}_{-M_1} \tilde{S}_{-M_3}' \right) + \tilde{S}_{M_2} \tilde{S}_{-M_2}' \left( M_{B_2}^2 \left( -1 + \tilde{S}_{M_1} \tilde{S}_{-M_1} \tilde{S}_{-M_3}' S_{-M_1} + \tilde{S}_{-M_1} \tilde{S}_{-M_3}' \right) + \tilde{S}_{M_3}' S_{-M_3}' \right) \\
\left[ M_{B_2}^2 \tilde{S}_{M_2} \tilde{S}_{-M_3}' S_{-M_2}' + M_{B_1}^2 \left( 2 M_{B_2}^2 \tilde{S}_{M_1} \tilde{S}_{-M_3}' S_{-M_1} + \tilde{S}_{-M_3}' \right) - 2 \tilde{S}_{M_1} \tilde{S}_{-M_1} \tilde{S}_{-M_3}' - \tilde{S}_{M_2} \tilde{S}_{-M_2} \tilde{S}_{-M_3}' \right] \sin^2 \left( \frac{\lambda_{PH}}{f_h} \right) - M_{B_1}^2 \tilde{S}_{-M_3}' \sin^4 \left( \frac{\lambda_{PH}}{f_h} \right) &= 0
\end{align*}
\]

• Coleman-Weinberg Potential for the Higgs boson at one loop,

\[
V(h) = \int_0^\infty d\mu^3 \left( -\frac{12}{(4\pi)^2} \left\{ \log \left[ 1 + F_{t_1} (-\mu^2) \sin^2 \left( \frac{\lambda h}{f_h} \right) \right] + \log \left[ 1 + F_b (-\mu^2) \sin^2 \left( \frac{\lambda h}{f_h} \right) \right] \right\} + \frac{6}{(4\pi)^2} \log \left[ 1 + F_W (-\mu^2) \sin^2 \left( \frac{\lambda h}{f_h} \right) \right] + \frac{3}{(4\pi)^2} \log \left[ 1 + F_Z (-\mu^2) \sin^2 \left( \frac{\lambda h}{f_h} \right) \right] \right) 
\]
Figure 1: Higgs Mass vs top mass in GeV. Blue (dark gray) crosses represent the linear regime, green (light gray) x's the non-linear regime and black dots where a minimum for the effective potential exists.
Warped Extra Dimensions: Gauge-Higgs Unification

Figure 2: Higgs Mass vs top mass in GeV, zoomed in region. Blue (dark gray) crosses represent the linear regime, green (light gray) x's the non-linear regime.
Warped Extra Dimensions: Gauge-Higgs Unification

Figure 3: Higgs Mass (GeV) vs $\tilde{k}$ (TeV). Blue (dark gray) crosses represent the linear regime, green (light gray) x's the non-linear regime and black dots where a minimum for the effective potential exists.
Warped Extra Dimensions: Gauge-Higgs Unification

Figure 4: Minimum vs $M_{B_1}$. Blue (dark gray) crosses represent the linear regime, green (light gray) x’s the non-linear regime. The sparse region for higher values of $M_{B_1}$ is due to a coarser grid scanned in that region.
Figure 5: Minimum vs $k$ (TeV). Blue (dark gray) crosses represent the linear regime, green (light gray) x’s the non-linear regime.
Warped Extra Dimensions: Gauge-Higgs Unification

Figure 6: $c_1$ vs $c_2$. Blue (dark gray) crosses represent the linear regime, green (light gray) x’s the non-linear regime and black dots where a minimum for the effective potential exists.
Figure 7: \( e_2 \) vs. \( e_3 \). Blue (dark gray) crosses represent the linear regime, green (light gray) x’s the non-linear regime and black dots where a minimum for the effective potential exists.
Figure 8: $m_{W^1}$ vs $m_{Top^{1,2,3}}$ in TeV. Also marked is $m_{W^1}/2$ showing that only the first excited top mode can decay into gauge bosons. Blue (dark gray) crosses represent the linear regime with $c_1 > 0$, gray (light gray) crosses the linear regime with $c_1 < 0$, red x’s (dark gray) the non-linear regime with $c_1 > 0$, green x’s (light gray) the non-linear with $c_1 < 0$. 
Figure 9: $m_{W^1}$ vs $m_{E_{i}^{1,2}}$ in TeV. Also marked is $m_{W^1}/2$ showing that depending on the value of the parameters ($c_i$ and $B_i$) the first mode of the lightest exotic fermion may decay into the gauge bosons. Blue (dark gray) crosses represent the linear regime with $c_1 > 0$, gray (light gray) crosses the linear regime with $c_1 < 0$, red x’s (dark gray) the non-linear regime with $c_1 > 0$, green x’s (light gray) the non-linear with $c_1 < 0$. 
Gauge-Higgs Unification: Collider Phenomenology

• Decays of excited state of gluons $G^1$ into pairs of excited tops $t^1$, mostly singlets under SM gauge group. Improve reach to probe $t^1$-masses further than direct QCD production. The pairs of $t^1$ decay into either $W^+ b$, $H_t$ or $Z_t$.

• Example of important couplings to consider:

$$g_{G^1 t t} = g_{5s} N_{C^1} \int_0^L \left( \sum_i f_{F, t, m t}^{2/3} (x_5, h) f_{F, t, m t}^{2/3} (x_5, h) \right) C[x_5, m_{C^1}] dx_5$$
• $t^1$ decay branching ratios,

Figure 4: Branching ratios for the decay of $t^1$ vs $m_{t^1}$ (GeV). Notice that the 2:1:1 relations holds for large $m_{t^1}$.

Figure 5: Branching ratios for the decay of $G^1$ vs $m_{G^1}$ (GeV). Notice that $G^1$ decays mostly to $t^1$ pairs.
Gauge-Higgs Unification: Collider Phenomenology

- $t^1$ production cross section through QCD alone and through QCD+$G^1$ for $M_{G^1} = 4$ TeV.

Notice that for $M_{t^1} \approx 1.5$ TeV, $G^1$-induced production contributes in a significant amount to the $t^1$ production cross section.

Figure 5: Cross section for $M_{G^1} = 4.0$ TeV with couplings $g_{G^1 t^1_L t^1_L} / g_s(\bar{k}) = -5.18$ and $g_{G^1 t^1_R t^1_R} / g_s(\bar{k}) = -2.77$. 
Gauge-Higgs Unification: Collider Phenomenology

• From the Goldstone Equivalence Theorem \( \rightarrow 50 \% \) of times, \( t^1 \) decays in \( W^+b \). We shall therefore concentrate on the channel:

\[
pp \rightarrow (g + G^1) \rightarrow t^1 \bar{t}^1 \rightarrow W^+bW^b \rightarrow l^- \nu \bar{b}b j j, \quad (l = e, \mu)
\]

• Backgrounds for this signal: top quark pair production induced by \( G^1 \) in addition to QCD (main background), \( W+jets \) and \( Z+jets \) (last two backgrounds are reducible to negligible levels by requiring 2 \( b \)-tags and lepton+MET).

• Points chosen to analyze:

<table>
<thead>
<tr>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( M_{B_1} )</th>
<th>( M_{B_2} )</th>
<th>( h/(\sqrt{2}f_h) )</th>
<th>( m_{G^1} )</th>
<th>( m_{\tilde{t}_1} )</th>
<th>( g_{G^1 \tilde{t}_R} )</th>
<th>( g_{G^1 \tilde{t}_L} )</th>
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<td>0.4</td>
<td>0.278</td>
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<td>1470.2</td>
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<td>-2.28</td>
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<td>-2.12</td>
<td>-2.50</td>
<td>-2.67</td>
<td>-5.20</td>
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Table 1: Points of parameter space chosen for \( t^1 \) detection. All masses are given in GeV and the couplings are in units of \( g_s(\bar{k}) \).

• We set cone reconstruction algorithm to \( \Delta R = (\Delta \eta^2 + \Delta \phi^2)^{1/2} = 0.6 \) for \( W \) invariant mass reconstruction.
Event Selection: First selection cut on hadronized events:

1. Isolated lepton with \( p_t > 20 \text{ GeV} \) and \( |\eta| < 2.5 \) plus missing energy with \( p_t > 20 \text{ GeV} \).
2. At least three jets with \( p_t > 20 \text{ GeV} \) and \( |\eta| < 2.5 \), with exactly 2 bottom-tags.

Isolated lepton+MET reduces backgrounds from QCD jets.

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma \text{ [fb]} )</th>
<th>( N^0 \text{ Events} )</th>
<th>( N^0 \text{ after cuts} )</th>
<th>( \sigma \text{ [fb]} )</th>
<th>( N^0 \text{ Events} )</th>
<th>( N^0 \text{ after cuts} )</th>
</tr>
</thead>
<tbody>
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<td>( G^1 \rightarrow tt )</td>
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<td>1236</td>
<td>1</td>
<td>4.43</td>
<td>443</td>
<td>0</td>
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<td>( g \rightarrow t\bar{t} )</td>
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<tr>
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<td>7</td>
<td>3085</td>
<td>308509</td>
<td>6</td>
</tr>
<tr>
<td>( g + G^1 \rightarrow t\bar{t} )</td>
<td>0.88</td>
<td>266</td>
<td>24</td>
<td>2.015</td>
<td>201</td>
<td>14</td>
</tr>
</tbody>
</table>

Big top background which must be reduced to manageable levels \( \rightarrow \) Cuts \( p_{t, bottom} \) and \( H_t \).
W-mass reconstruction through two methods:

1. $W \rightarrow 2 \text{ jets}$. Works well for $t^1$ masses less than 1 TeV. Uses $\Delta R=0.4$.

2. $W \rightarrow 1 \text{ jet}$. Works well for $t^1$ masses bigger than 1 TeV. Increases signal and decreases background. Uses $\Delta R=0.6$. Figures in the case of point 1.

Figure 9: Invariant reconstructed W mass using the method of two jets. Distribution normalized to 200 events.

Figure 10: Invariant reconstructed W mass using the method of only one jet. Distribution normalized to 200 events.
Gauge-Higgs Unification: Collider Phenomenology

- Final set of cuts for reconstruction of $t^1$ mass distribution:

\[
p_t^{b,max} \geq 350 \text{ GeV}, \quad p_t^{b,max} \geq 300 \text{ GeV}, \\
H_t \geq 1900 \text{ GeV}, \quad H_t \geq 1800 \text{ GeV}, \\
p_t^{lepton} \geq 200 \text{ GeV}, \quad p_t^{lepton} \geq 150 \text{ GeV}, \\
p_t^{j,max} \geq 250 \text{ GeV}, \\
|M_W - M_W^j| \leq 20 \text{ GeV}, \\
|m_{Wb_i} - m_t| \geq 50 \text{ GeV},
\]

- Reconstructed $t^1$ invariant mass distribution choosing bottom with biggest \( \Delta R \) w.r.t $W$.
**Results**

We estimate statistical significance as $S/(S+B)^{1/2}$. With the inclusion of $K$ factors, $K \sim 1.5$, presence of these particles may be found already at 100 fb$^{-1}$ for Point 1 (60 fb$^{-1}$ point 2) and discovery at 300 fb$^{-1}$ for point 1 (200 fb$^{-1}$ for point 2).
Gauge-Higgs Unification: Collider Phenomenology

- Constant cross-section curves in \((m_{G1}, m_{t1})\) plane to estimate LHC reach at 300 fb\(^{-1}\).

Figure 20: Curves of constant cross section for QCD in addition of \(G^1\) decay, in \((m_{G1}, m_{t1})\) plane.
Conclusions

• Electroweak symmetry breaking in consistent regions given by electroweak precision tests.

• Higgs mass between 116 GeV and 160 GeV.

• First KK excitation of the top quark $t^1$ light enough to be produced from decays of first excited KK state of the gluon.

• Rich collider phenomenology: $G^1$ decays into $t^1$ expand the reach of $t^1$ detection to masses around 1.5 TeV.

• Consistent phenomenological model which will be tested at the LHC.