New Approaches to ElectroWeak Symmetry Breaking

Part Three

Higgsless Theories

- Gauge Symmetry Breaking by Boundary Conditions.
- Higgs Mechanism on the Brane. Higgs Decoupling.
- AdS/CFT and the Custodial Symmetry

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Higgsless Approach

In the gauge-Higgs unification models, we have been breaking bigger gauge groups down to SU(2)×U(1) by orbifold.

Why can’t we break directly SU(2)×U(1) to U(1)_{em} by orbifold?

Let us try...
First Obstacles

- **Rank Reduction**
  
  \[ SU(2) \times U(1) \rightarrow U(1) \]  
  the rank is reduced by one

  \[ A_\mu(-y) = U A_\mu(y) U^\dagger \]  
  \( U \) has to be an automorphism of the algebra

  - inner automorphism (\( U \) belongs to the gauge group): no rank reduction
  - outer automorphism: a rank reduction is possible but few breaking patterns allowed

- **Non Rational Mass Ratios**

  Kaluza-Klein spectrum is dictated by geometry: typically \( M_n = n/R \)

  How can we generate gauge boson masses that depends on the gauge couplings?

- **How is Unitarity Restored?**

  If \( W^\pm \) and \( Z \) acquire a KK mass without a Higgs, what ensures the unitarity of \( W \) scattering above 1.2 TeV?
A SM-like Example

**SU(2) → U(1)**

Bulk EOM

\[ A_\mu^a - \partial^2 A_\mu^a = 0 \]

**KK decomposition**

\[ A_\mu(x, y) = \sum_n f_n(y) A_n^\mu(x) \]

**Boundary Conditions**

\[ f_n(y) = -m_n^2 f_n(y) \]

\[ f = 0 \text{ or } f' = 0 \text{ at } y = 0, \pi R \]

**Masses**

\[ \begin{align*}
M_\gamma &= 0 \\
M_{W^\pm} &= \frac{1}{2R} \\
M_Z &= \frac{1}{R} 
\end{align*} \]
Dynamical Origin of the BCs

\[ S = \int d^4x \int_0^{\pi R} dy \left( \frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right) - \int_{y=0,\pi R} d^4x \frac{1}{2} M_0,\pi R \phi^2 \]

integration by part

\[ \delta S = \int_{y=0,\pi R} d^4x \delta \phi \left( \partial_5 \phi + M_0^2,\pi R \phi \right) \]

Bulk Part

bulk eq. of motion

\[ \Box_5 \phi = -V'(\phi) \]

BC's

\[ \delta \phi \left( \partial_5 \phi + M_0^2,\pi R \phi \right) = 0 \]

Dirichlet BC: \( \phi = \text{cst.} \)

Mixed BC: \( \partial_5 \phi_{0,\pi R} = -M_0^2,\pi R \phi_{0,\pi R} \)

\[ \begin{align*}
M^2 & \to \infty & \phi_{0,\pi R} &= 0 & \text{Dirichlet BC} \\
M^2 & \to 0 & \partial_5 \phi_{0,\pi R} &= 0 & \text{Neumann BC}
\end{align*} \]
Unitarization of (Elastic) Scattering Amplitude

\[ A = A^{(4)} \left( \frac{E}{M} \right)^4 + A^{(2)} \left( \frac{E}{M} \right)^2 + \ldots \]

Same KK mode 'in' and 'out'

\[ \epsilon_{\perp}^{\mu} = \left( \frac{E}{M} \frac{p}{M} \right) \]

Center Grojean

Unitarization of (Elastic) Scattering Amplitude

New approaches to ElectroWeak Symmetry Breaking

\[ A^{(4)} = i \left( g_{nnnn} - \sum_k g_{nnk}^2 \right) \left( f^{abe} f^{cde} (3 + 6c_\theta - c_\theta^2) + 2(3 - c_\theta^2) f^{ace} f^{bdde} \right) \]

\[ A^{(2)} = i \left( 4g_{nnnn}^2 - 3 \sum_k g_{nnk}^2 \frac{M_k^2}{M_n^2} \right) \left( f^{ace} f^{bdde} - s_\theta^2/2 f^{abe} f^{cde} \right) \]
In a KK theory, the effective couplings are given by overlap integrals of the wavefunctions

\[
\mathcal{A}^{(4)} \propto g_{n n n n}^2 - \sum_k g_{n n k}^2 \\
\mathcal{A}^{(2)} \propto 4g_{n n n n}^2 - 3 \sum_k g_{n n k}^2 \frac{M_k^2}{M_n^2}
\]

**E⁴ Sum Rule**

\[
g_{n n n n}^2 - \sum_k g_{n n k}^2 = g_{5D}^2 \int_0^{\pi R} dy f_n^4(y) - g_{5D}^2 \int_0^{\pi R} dy \int_0^{\pi R} dz f_n^2(y) f_n^2(z) \sum_k f_k(y) f_k(z) = 0
\]

\[
\sum_k f_k(y) f_k(z) = \delta(y - z)
\]

Completeness of KK modes

\[
\mathcal{A}^{(4)} = 0
\]
**KK Sum Rules**

\[ A^{(4)} \propto g_{nnnn}^2 - \sum_k g_{nnk}^2 \]

**E^2 Sum Rule**

\[ 4g_{nnnn}^2 M_n^2 - 3 \sum_k g_{nnk}^2 M_k^2 = 4g_{5D}^2 M_n^2 \int_0^\pi dy f_n^4(y) - 3g_{5D}^2 \int_0^\pi dy dz f_n^2(y) f_n^2(z) \sum_k f_k(y) f_k(z) M_k^2 \]

\[ \int dz f_n^2(z) f''_k(z) = -2 \int dz f_n(z) f'_n(z) f'_k(z) \]

\[ = 2 \int dz f_n(z) f''_n(z) f_k(z) + 2 \int dz f''_n(z) f_k(z) \]

\[ \sum_k f_k(y) f_k(z) = \delta(y - z) \]

\[ \mathcal{A}^{(2)} = 0 \]

\[ \int dy f_n^2(y) f''_n(y) = -2 \int dy f_n^2(y) f''_n(y) - \int dy f_n^3(y) f''_n(y) \]

\[ = \frac{1}{3} M_n^2 \int dy f_n^4(y) \]

up to boundary terms...
KK Sum Rules with Boundary Terms

Keeping track of the boundary terms in the integrations by part, we get

\[ A^{(2)} \propto g_5^2 D \left( \frac{-2}{3} \left[ f_n^3 f'_n \right] - \sum_k \left[ f_n^2 f'_k \right] \int dy f_n^2(y) f_k(y) + 2 \sum_k \left[ f_n f'_n f_k \right] \int dy f_n^2(y) f_k(y) \right) \]

The boundary terms cancel for Dirichlet or Neumann BCs.

For mixed BCs \((f'=af)\), there is a residual \(E^2\) growing term in the scattering amplitude.

The mixed BCs correspond to an explicit breaking on the brane.

We need to add new degrees of freedom on the brane to restore unitarity.
Explicit Example of KK Sum Rules

\[ A^3_\mu(x, y) = \sum_{k=0}^{\infty} \sqrt{2} \delta_{k,0} \pi R \cos \frac{ky}{R} \gamma^{(k)}_\mu(x) \]

\[ A^1_\mu(x, y) = \sum_{k=0}^{\infty} \frac{1}{\sqrt{\pi R}} \sin \frac{(2k + 1)y}{2R} \left( W^{+(k)}_\mu(x) + W^{-(k)}_\mu(x) \right) \]

\[ A^2_\mu(x, y) = \sum_{k=0}^{\infty} \frac{1}{\sqrt{\pi R}} \sin \frac{(2k + 1)y}{2R} \left( W^{+(k)}_\mu(x) - W^{-(k)}_\mu(x) \right) \]

\[ g_{W^{(n)}W^{(n)}\gamma^{(k)}} = \frac{g_{5D}}{2\sqrt{\pi R}} \left( \delta_{k,0} - \frac{1}{\sqrt{2}} \delta_{k,2n+1} \right) \]

\[ g_{W^{(n)}W^{(n)}W^{(n)}W^{(n)}} = \frac{3g_{5D}^2}{8\pi R} \]

up to a sign, the momentum is conserved at the boundaries

thus the selection rule

The two sum rules are trivially satisfied

\[ M_{W^{(k)}} = \frac{2k+1}{2R} \]

\[ M_{\gamma^{(k)}} = \frac{k}{R} \]

\[ M_{W^{(k)}} = 2k+1 \]

\[ M_{\gamma^{(k)}} = k \]
Let us consider a Higgs mechanism localized on a brane.

\[ \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \]

**SU(2)**

\[ \partial_5 A_\mu^a(0) = 0 \]

\[ \partial_5 A_\mu^a(\pi R) = -\frac{1}{4} g_5^2 v^2 A_\mu^a(\pi R) \]

**BCs give**

\[ m_k \tan(m_k \pi R) = \frac{1}{4} g_5^2 v^2 \]

Need the exchange of the brane degrees of freedom to cancel the growing piece of the amplitude.

the Higgs being localized at \( \pi R \) its coupling to the gauge bosons is proportional to \( f_k^2(\pi R) \)

**Higgs decoupling**

\[ v \rightarrow \infty \]

\[ A^{(2)} \propto 1/(Rv)^6 \]

Unlike in the SM, the masses of the gauge bosons are not proportional to the Higgs vev.

The gauge bosons that would couple to the Higgs on the brane have a wavefunction that actually vanishes on the brane.

Nomura, Smith, Weiner '01

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New approaches to ElectroWeak Symmetry Breaking

3\textsuperscript{rd} Lecture
Is it a counter-example of the theorem by Cornwall et al.? i.e. can we unitarize the theory without scalar field?

No!

\[ g_{nnnn}^2 = \sum_k g_{nnk}^2 = \sum_k g_{nnk}^2 \frac{3M_k^2}{4M_n^2} \]

the sum rules cannot be satisfied with a finite number of KK modes
(to unitarize the scattering of massive KK modes, you always need heavier KK states)

Pushing the need for a scalar to higher scale

With a finite number of KK modes

New Physics
(Higgs/strongly coupled theory?)

4\pi M_W(n) / g_4

5D cutoff

not directly set by the weak scale
flat space

\[ \Lambda_{5D} = \frac{24\pi^3}{g_4^2} = \frac{12\pi^2 M_W}{g_4^2} \]

already a factor 10 higher than the naive cutoff

weakly coupled states observable
at low energy

\[ \{ \text{weakly coupled states} \} \]

4\pi M_W / g_4

Naive cutoff

\[ \text{(Higgs/strongly coupled theory?)} \]

5D cutoff

4\pi M_W(n) / g_4

\[ \text{5D cutoff} \]

\[ \text{Naive cutoff} \]

\[ \text{New Physics} \]

\[ \text{(Higgs/strongly coupled theory?)} \]
A Flat Higgsless Model

\[ \begin{align*}
    &\text{SU(2)}_R \times \text{U(1)}_{B-L} \\
    \quad \Rightarrow \quad &\text{U(1)}_Y
    \\
    &A_{\mu}^{R \pm} = 0 \\
    &g' B_{\mu} - g A_{\mu}^{R 3} = 0 \\
    &\partial_5 (g B_{\mu} + g' A_{\mu}^{R 3}) = 0
\end{align*} \]

\[ \begin{align*}
    &\text{SU(2)}_L \times \text{SU(2)}_R \\
    \quad \times \quad &\text{U(1)}_{B-L}
    \\
    &\pi R
\end{align*} \]

\[ \begin{align*}
    &\text{SU(2)}_D \\
    \quad \Rightarrow \quad &\text{U(1)}_{\text{em}}
\end{align*} \]

\[ \begin{align*}
    B_{\mu}(x, y) &= g a_0 \gamma_{\mu}(x) + g' \sum_{k=1}^{\infty} b_k \cos(M_k^Z y) Z_{\mu}^{(k)}(x) \\
    A_{\mu}^{L 3}(x, y) &= g' a_0 \gamma_{\mu}(x) - g \sum_{k=1}^{\infty} b_k \frac{\cos(M_k^Z (y - \pi R))}{2 \cos(M_k^Z \pi R)} Z_{\mu}^{(k)}(x) \\
    A_{\mu}^{R 3}(x, y) &= g' a_0 \gamma_{\mu}(x) - g \sum_{k=1}^{\infty} b_k \frac{\cos(M_k^Z (y + \pi R))}{2 \cos(M_k^Z \pi R)} Z_{\mu}^{(k)}(x)
\end{align*} \]

\[ \begin{align*}
    A_{\mu}^{L \pm}(x, y) &= \sum_{k=1}^{\infty} c_k \cos(M_k^W (y - \pi R)) W_{\mu}^{(k) \pm}(x) \\
    A_{\mu}^{R \pm}(x, y) &= \sum_{k=1}^{\infty} c_k \cos(M_k^W (y + \pi R)) W_{\mu}^{(k) \pm}(x)
\end{align*} \]

\[ \begin{align*}
    \tan^2 M_k^Z \pi R &= \frac{g^2 + 2g'^2}{g^2} \\
    \cotan^2 M_k^W \pi R &= 0
\end{align*} \]
**Phenomenological Issues**

- **Light \( W \) and \( Z \) resonances**
  
  These resonances will have a coupling to fermions of the same strength as the SM couplings.

- **Rho parameter**
  
  The gauge bosons masses have a dependence on the gauge couplings, but this dependence is different from the SM one.

\[
M_Z = \frac{1}{\pi R} \arctan \sqrt{\frac{g^2 + 2g'^2}{g^2}}
\]

\[\rho \approx 1.10\]

*experimentally excluded*
Warped Space and Localization of Gauge Fields

Why is rho different from 1 while we started with an SU(2) \(_R\) symmetry in the bulk?

the SU(2) \(_R\) symmetry is broken on the \(y=0\) brane

we should engineer a set-up such that the wavefunctions are localized on the other side

Go to a Warped Space

\[
\Omega = \frac{R_{IR}}{R_{UV}} \approx 10^{16} \text{ GeV}
\]

Wavefunction of massive gauge field

\[
f_m(z) = z \left( a J_1(mz) + b Y_1(mz) \right)
\]

(generically) peaked on the IR brane
AdS/CFT and the Custodial Symmetry

CFT picture

- gauge symmetry $H$
- global symmetry $G/H$ (KK spectrum is $G/H$ degenerate)
- gauge symmetry $H$ is spontaneously broken to $H_0$ in the IR
- UV matter = fundamental particles of the CFT
- IR matter = composites particles of the CFT

The Higgsless model should inherit from a global symmetry that will protect the rho parameter

Agashe, Delgado, May, Sundrum ‘03
Csaki, Grojean, Pilo, Terning ‘03

Maldacena ‘97
Arkani-Hamed, Porrati, Randall ‘01
Rattazzi, Zaffaroni ‘01
Warped Higgsless Model

\[ \psi_A (z) = z \left( a_{k}^{(A)} J_1(q_k z) + b_{k}^{(A)} Y_1(q_k z) \right) \]

\[ B_{\mu}(x, z) = g_5 a_0 \gamma_{\mu}(x) + \sum_{k=1}^{\infty} \psi_k^{(B)}(z) Z_{\mu}^{(k)}(x) \]

\[ A_{\mu}^{L3}(x, z) = g_5 a_0 \gamma_{\mu}(x) + \sum_{k=1}^{\infty} \psi_k^{(L3)}(z) Z_{\mu}^{(k)}(x) \]

\[ A_{\mu}^{R3}(x, z) = g_5 a_0 \gamma_{\mu}(x) + \sum_{k=1}^{\infty} \psi_k^{(R3)}(z) Z_{\mu}^{(k)}(x) \]

\[ A_{\mu}^{L\pm}(x, z) = \sum_{k=1}^{\infty} \psi_k^{(L\pm)}(z) W_{\mu}^{(k)} \pm(x) \]

\[ A_{\mu}^{R\pm}(x, z) = \sum_{k=1}^{\infty} \psi_k^{(R\pm)}(z) W_{\mu}^{(k)}(x) \]

\[ R_i^{UV} \equiv \frac{Y_i(M R^{UV})}{J_i(M R^{UV})}, \quad R_i^{IR} \equiv \frac{Y_i(M R^{IR})}{J_i(M R^{IR})} \]

\[ 2 g_5^2 (R_0^{UV} - R_1^{IR})(R_0^{IR} - R_1^{UV}) = g_5^2 \left( (R_0^{UV} - R_0^{IR})(R_1^{UV} - R_1^{IR}) + (R_1^{IR} - R_0^{UV})(R_0^{IR} - R_1^{UV}) \right) \]

\[ (R_0^{UV} - R_1^{IR})(R_1^{UV} - R_1^{IR}) + (R_1^{IR} - R_0^{UV})(R_0^{IR} - R_1^{UV}) = 0 \]
Warped Higgsless Model: Spectrum

\[(R_0^{UV} - R_0^{IR})(R_1^{UV} - R_1^{IR}) + (R_1^{IR} - R_0^{UV})(R_0^{IR} - R_1^{UV}) = 0\]

expansion of the Bessel functions around the origin...

\[Y_0(z) \sim \frac{2 \log z}{\pi} + \ldots \quad Y_1(z) \sim -\frac{2}{\pi z} + \ldots\]

\[J_0(z) \sim 1 + \ldots \quad J_1(z) \sim \frac{z}{2} + \ldots\]

“light” mode:

\[M_W^2 = \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}\]

\[M_Z^2 \sim \frac{g_5^2 + 2 g_5' g_4}{g_5^2 + g_4^2} \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}\]

KK tower:

\[M_{KK}^2 = \text{cst of order unity} \frac{1}{R_{IR}^2}\]

W around 80 GeV, KK around 1.2 TeV

Why a log? AdS/CFT

spontaneous breaking at IR scale

\[\frac{1}{g_4^2} = \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} = \frac{R_{UV} \log(R_{IR}/R_{UV})}{g_5^2} \quad \text{and} \quad g_5^2 \sim R_{UV}\]

\[M_W^2 \sim g_4^2 \left(\frac{1}{R_{IR}^2}\right) \sim \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}\]
SM Fermions in Higgsless Models

- The fermions have to live in the bulk

**Vector-like brane**
- Isospin invariant mass only
- (Same mass for the top and bottom or electron and neutrino)

**Chiral brane**
- No possible mass term

\[ SU(2)_L \times U(1)_y \times SU(2)_R \times U(1)_{B-L} \]
\[ SU(2)_D \times U(1)_{B-L} \]
Fermion Boundary Conditions

\[ \Psi = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix} \]

5D spinor = 4D Dirac spinor = 2 vector-like 2-components spinors

Flat space...

\[ S = \int d^5 x \left( -i \bar{\chi} \sigma^\mu \partial_\mu \chi - i \psi \sigma^\mu \partial_\mu \bar{\psi} + \frac{1}{2} (\psi \bar{\partial}_5 \chi - \bar{\chi} \bar{\partial}_5 \bar{\psi}) + m(\psi \chi + \bar{\chi} \bar{\psi}) \right) \]

variation of the action

\[ -i \bar{\sigma}^\mu \partial_\mu \chi - \partial_5 \bar{\psi} + m \bar{\psi} = 0 \]
\[ -i \sigma^\mu \partial_\mu \bar{\psi} + \partial_5 \chi + m \chi = 0 \]

Boundary conditions:

the bulk eq. evaluated at the boundary coupled the two fields:

need to impose BCs only on one field

\[ \psi \big| = 0 \quad \Leftrightarrow \quad (\partial_5 \chi + m \chi) \big| = 0 \]

different BCs also means chiral spectrum and there should exist a massless mode

massless mode

\[ \psi = 0 \quad \chi = e^{-my} \tilde{\chi}(x) \quad \text{with} \quad -i \bar{\sigma}^\mu \partial_\mu \tilde{\chi} = 0 \]
AdS Fermions

in these coordinates, the spin connection will drop off

\[ S = \int d^5 x \frac{R^4}{z^4} \left( -i \bar{\chi} \sigma^\mu \partial_\mu \chi - i \psi \sigma^\mu \partial_\mu \bar{\psi} + \frac{1}{2} \left( \psi \overleftrightarrow{\partial_5} \chi - \bar{\chi} \overleftrightarrow{\partial_5} \bar{\psi} \right) + \frac{c}{z} (\psi \chi + \bar{\chi} \bar{\psi}) \right) \]

bulk eqs of motion:

\[-i \bar{\sigma}^\mu \partial_\mu \chi - \partial_5 \bar{\psi} + \frac{c + 2}{z} \bar{\psi} = 0\]
\[-i \sigma^\mu \partial_\mu \bar{\psi} + \partial_5 \chi + \frac{c - 2}{z} \chi = 0\]

wavefunctions

\[ \chi = (mz)^{5/2} \left( a_n J_{1/2 + c}(mz) + b_n J_{-1/2 - c}(mz) \right) \]
\[ \psi = (mz)^{5/2} \left( a_n J_{-1/2 + c}(mz) - b_n J_{1/2 + c}(mz) \right) \]

Boundary conditions:

the bulk eq. evaluated at the boundary coupled the two fields:

need to impose BCs only on one field

\[ \psi|_{R^{UV},R^{IR}} = 0 \iff (\partial_5 \chi + \frac{c - 2}{z} \chi)|_{R^{UV},R^{IR}} = 0 \]

massless mode

\[ \psi = 0 \quad \chi = a_0 \left( \frac{z}{R} \right)^{2-c} \tilde{\chi}(x) \text{ with } -i \bar{\sigma}^\mu \partial_\mu \tilde{\chi} = 0 \]

the bulk mass, c, controls the localization of the fermion zero mode

normalization

\[ \int_{R^{UV}} d\mathcal{R} a_0^2 \left( \frac{z}{R} \right)^{-2c} = 1 \]

\[ c > 1/2: \text{the zero is normalizable when } R^{IR} \text{ is sent to infinity (no IR brane): UV localized} \]
\[ c < 1/2: \text{the zero is normalizable when } R^{UV} \text{ is sent to 0 (no UV brane): IR localized} \]
Fermion Masses

SU(2)_L x U(1)_y

isospin splitting

\[ -i\kappa \psi_{dR} \sigma^\mu \partial_\mu \bar{\psi}_{dR} \]

SU(2)_D x U(1)_{B-L}

vector-like mass

\[ R_{IR} M_D (\chi_u \psi_u + \chi_d \psi_d + h.c.) \]

brane operators will modify the BCs

\[ \chi_L + \psi_L \]
\[ \psi_L |_{TeV} = 0 \]
\[ \chi_R - \psi_R \]
\[ \chi_R |_{TeV} = 0 \]

\[ \chi_u R - \psi_u R \]
\[ \psi_u R |_{UV} = 0 \]

Vector like mass

\[ M_D \]

discontinuities

\[ \psi_L |_{TeV} = -M_D R_{IR} \psi_R |_{TeV} \]
\[ \chi_R |_{TeV} = M_D R_{IR} \chi_L |_{TeV} \]

Isospin splitting

\[ \kappa \]

discontinuities in

\[ \psi_u R \]

\[ \chi_u R |_{UV} = \kappa m \psi_u R |_{UV} \]

\[ m \approx \frac{\sqrt{2c_L - 1}}{\sqrt{\kappa^2 - 1/(2c_R + 1)}} M_D \left( \frac{R_{UV}}{R_{IR}} \right)^{c_L - c_R - 1} \]
EW Precisions Tests in Higgsless Models

At the lowest order in the $\log(R_{IR}/R_{UV})$ expansion: $S=T=Y=W=0$

At next order \[ S = \frac{6\pi}{g^2 \log(R_{IR}/R_{UV})} \approx 1.15 \] ...like in technicolor models

Add brane operators to modify $S$

S can be made small but at the same time the mass of the KK gauge bosons increase and are not that efficient to restore unitarity. Thus we enter a strongly coupled regime.

need to find another way to suppress $S$

Barbieri, Pomarol, Ratazzi ‘03
Cacciapaglia, Csaki, Grojean, Terning ‘04
EWPT with Delocalized Fermions

Couplings gauge bosons/fermions = overlap integrals of the wavefunctions

\( S, T, Y, W \) will depend on the localization of the fermions, which is controlled by the bulk mass parameters.

Oblique corrections

\[ \text{UV scale} \]
\[ \text{(controls the} \]
\[ \text{\( W' \) and \( Z' \) masses)} \]
\[ \log_{10} R \text{[GeV}^{-1}] \]

\[ \text{IR fermion} \quad \text{UV fermion} \]

\[ \text{fermion localization parameter} \]

\[ \text{Cacciapaglia, Csaki, Grojean, Terning '04} \]
a 500 GeV Z' allows to postpone the unitarity breakdown up to around 10 TeV
Some Signatures

- Deviations in the gauge bosons self-couplings
  - in usual gauge theories: $g_4^2 = g_3^2$
  - in higgsless theories, this relation is modified to take into account the exchange of KK excitations of $W$ and $Z$
  - typically 1%-5% deviations compare to the SM self-couplings

- Non-universality of the couplings gauge boson/fermions
  - fermion mass $\Leftrightarrow$ wavefunction profile in the bulk
  - couplings $\Leftrightarrow$ wavefunction overlap
  - different masses $\Leftrightarrow$ different couplings to $W$ and $Z$

First two generations

$$
\frac{\delta g_{SM}}{g_{SM}} \approx \mathcal{O} \left( \frac{m}{\text{TeV}} \right) \approx 0.1\% \text{ at most}
$$

Third generation

$Z_{b_L\bar{b}_L}$ deviations

difficult to get a small deviation in the perturbative regime

severe constraints
Collider Signatures

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

\[ g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \quad \Gamma(W' \rightarrow WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2} \]

a narrow and light resonance

W' production

discovery reach @ LHC (10 events)

550 GeV \rightarrow 10 \, fb^{-1}

1 \, TeV \rightarrow 60 \, fb^{-1}

should be seen within one/two years
Conclusions

LHC will tell us how EW symmetry is broken
we might see a Higgs
there is room for more interesting/exciting possibilities

We are lucky to live in this wonderfull time

So let us enjoy life ... with or without a Higgs