Higgsless Electroweak Symmetry Breaking

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Introduction

Physical Higgs boson not discovered (yet)

In Standard Model (SM): Higgs unitarizes

$$\mathcal{A}(W_L\ W_L \to W_L\ W_L)$$

Is it possible that there is no (physical) Higgs?

If yes, what unitarizes $\mathcal{A}$?

Clue: Good Unitary prop of Extra dimensional th.

Extra Z',W' unitarize $\mathcal{A}$ [Chivukula,Dicus,He]

Boundary Conditions break EW symmetry

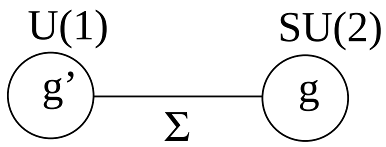
[Csaki,Grojean,Murayama,Pilo,Terning]

"(De)Construction" will aid analysis

[Arkani-Hamed,Cohen,Georgi]

Higgsless Models

SM w/o Higgs: $U(1) \times SU(2)$



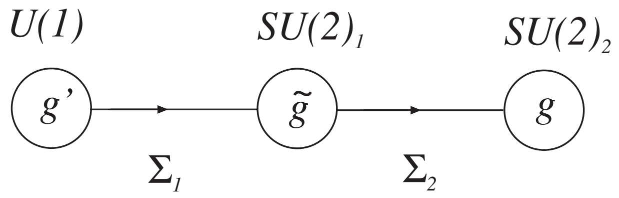
$$\Sigma \;=\; e^{2i\pi^a T^a/v}$$

$$\mathcal{L} = -\tfrac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tfrac{1}{4} W^{a\,\mu\nu} W^a_{\mu\nu} + \frac{v^2}{4} \mathrm{tr}\left[D^\mu \Sigma (D_\mu \Sigma)^\dagger \right]$$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g' T^3 B_\mu \Sigma + i g \Sigma T^a W^a_\mu$$

[Foadi,S.G,Schmidt]

Beyond SM: $U(1) \times SU(2)_1 \times SU(2)_2$



$$\Sigma_1 \;=\; e^{2i\pi_1^a T^a/f_1}\;, \qquad \Sigma_2 \;=\; e^{2i\pi_2^a T^a/f_2}$$

$$\mathcal{L} = -\tfrac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tfrac{1}{4} W_1^{a\,\mu\nu} W^a_{1\,\mu\nu} - \tfrac{1}{4} W_2^{a\,\mu\nu} W^a_{2\,\mu\nu} + \\ + \frac{f_1^2}{4} \mathrm{tr}\left[D^\mu \Sigma_1 (D_\mu \Sigma_1)^\dagger \right] + \frac{f_2^2}{4} \mathrm{tr}\left[D^\mu \Sigma_2 (D_\mu \Sigma_2)^\dagger \right]$$

$$D_\mu \Sigma_1 = \partial_\mu \Sigma_1 - i g' T^3 B_\mu \Sigma_1 + i \tilde{g} \Sigma_1 T^a W^a_{1\mu}$$

$$D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - i \tilde{g} T^a W^a_{1\mu} \Sigma_2 + i g \Sigma_2 T^a W^a_{2\mu}$$

$U(1) \times SU(2)_1 \times SU(2)_2$ **contd...**

Charged Sector

$$W_1^{\pm} = a_{11}\, W'^{\pm} + a_{12}\, W^{\pm}$$

$$W_2^{\pm} = a_{21}\, W'^{\pm} + a_{22}\, W^{\pm}$$

Neutral Sector

$$B = b_{00}\, A + b_{01}\, Z' + b_{02}\, Z$$

$$W_1^3 = b_{10}\, A + b_{11}\, Z' + b_{12}\, Z$$

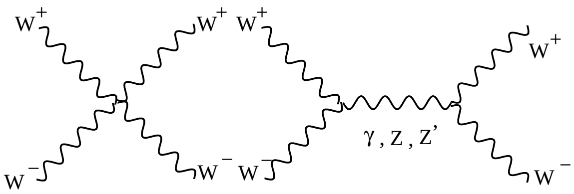
$$W_2^3 = b_{20}\, A + b_{21}\, Z' + b_{22}\, Z$$

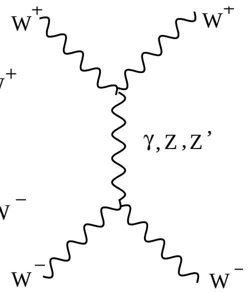
Parameters

$$\{g', \tilde{g}, g, f_1, f_2\} \to \{e, m_W, m_Z, m_{W'}, m_{Z'}\}$$

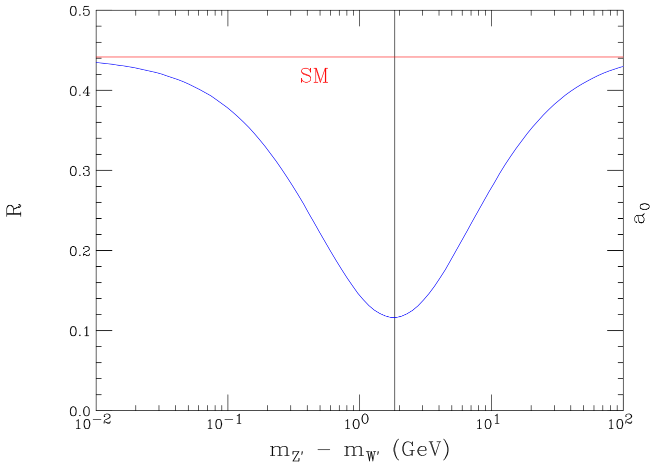
Delayed unitarity violation in

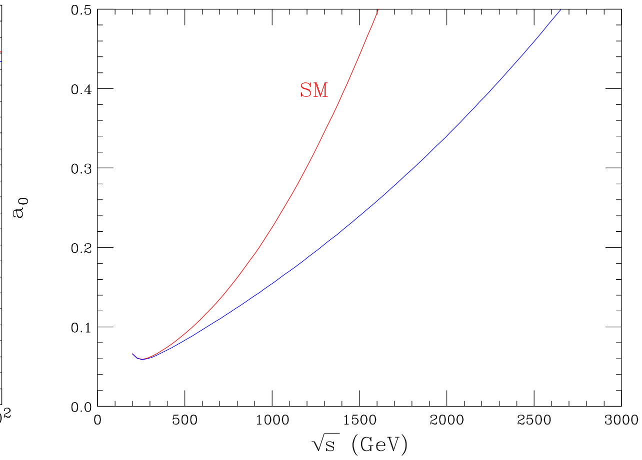
$$W_L^+ \; W_L^- \to W_L^+ \; W_L^-$$





$$\mathcal{A} \;=\; \frac{E^2}{m_W^2}\,\frac{(1+\cos\theta)}{2}\,R + \mathcal{O}\left(\left(\frac{m_W^2}{E^2}\right)^0\right)$$





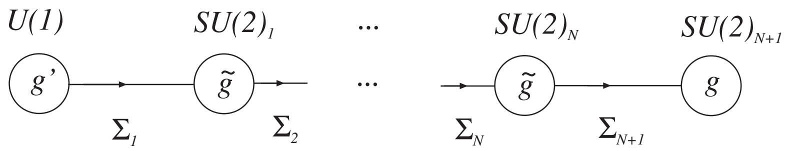
$$m_{Z'}^2 - m_{W'}^2 = m_Z^2 - m_W^2$$

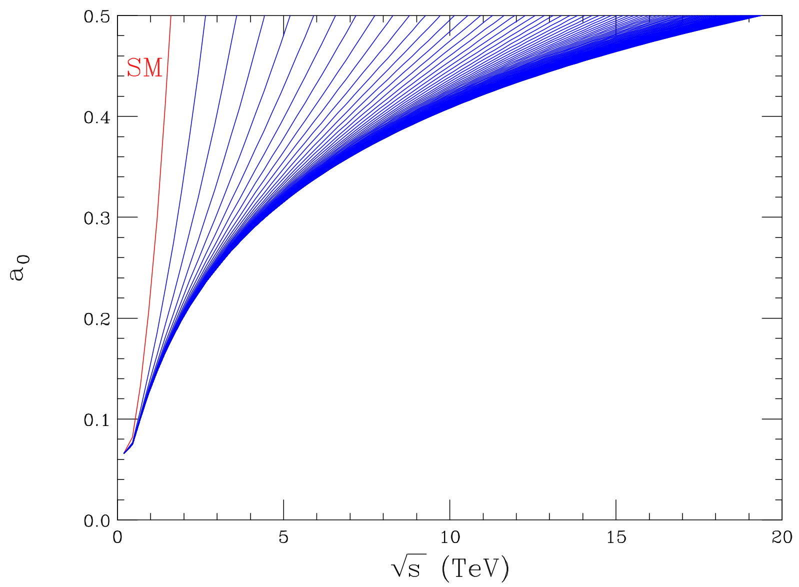
$$f_1 = f_2$$

$$\tilde{g} >> g, g'$$

$$m_{W'} = 500 \text{ GeV}$$

$U(1) \times [SU(2)]^N \times SU(2)_{N+1}$





Continuous (extra dimension) limit: $(N+1 \to \infty)$

Line segment $[0, \pi R]$

$$\pi R = (N+1)a = \frac{2(N+1)}{\tilde{g} f}$$

$$g_5^2 = a\tilde{g}^2$$

$$\frac{\tilde{g}^2}{N+1} = \frac{g_5^2}{\pi R}$$

Extra dimension

$$\mathcal{S} = \int_0^{\pi R} dy \int d^4x \left[-\frac{1}{4g_5^2} W^{a\,MN} W^a_{MN} - \delta(y) \frac{1}{4g'^2} W^{3\,\mu\nu} W^3_{\mu\nu} \right.$$
$$\left. -\delta(y-\pi R) \frac{1}{4g^2} W^{a\,\mu\nu} W^a_{\mu\nu} \right]$$

$\delta\mathcal{S} = 0$ implies:

Bulk EOM $\quad \partial_\mu W^{\mu\nu} = \partial_5 \partial_5 W^\nu$

At $y = 0$
$$\left(\frac{1}{g_5^2} W^{3,\,5\nu} + \frac{1}{g'^2} \partial_\mu W^{3,\,\mu\nu} \right) \delta W^3_\nu = 0$$
$$\left(\frac{1}{g_5^2} W^{\pm\,5\nu} \right) \delta W^\pm_\nu = 0$$

At $y = \pi R$
$$\left(-\frac{1}{g_5^2} W^{5\nu} + \frac{1}{g^2} \partial_\mu W^{\mu\nu} \right) \delta W_\nu = 0$$

Impose boundary conditions:

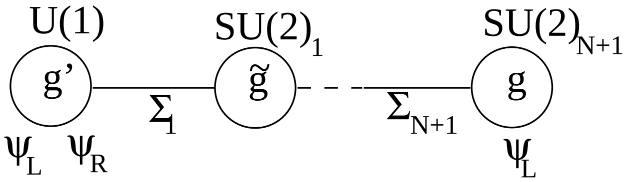
$W^\pm_\mu|_0 = 0 \qquad (\ldots) = 0$ **for others**

Results in:

$$m_W^2 = \frac{1}{\pi R} \frac{g^2}{g_5^2} \qquad m_{W'_n} \sim \frac{n}{R}$$
$$m_Z^2 = \frac{1}{\pi R} \frac{g^2 + g'^2}{g_5^2} \qquad m_{Z'_n} \sim \frac{n}{R}$$

Fermions

Simplest scheme:



$$\mathcal{L}_{Int} = g' \; \bar{\psi}\gamma_\mu (Y_L P_L + Y_R P_R)\, \psi \;\; B^\mu + g \;\; \bar{\psi}\gamma_\mu T^a P_L \psi \;\; W^{a\,\mu}_{N+1}$$

More clever ways are possible

Experimental Constraints

Direct

CDF **from** $\frac{\sigma(qq' \to W_1' \to \ell\nu)}{\sigma(qq' \to W \to \ell\nu)}$

$m_{W'} \gtrsim 500$ GeV

LEP II **from** $\sigma(e^+ e^- \to f\bar{f})$

(limit on 4-fermion contact intr)

$m_{Z'} \gtrsim 500$ GeV

Indirect

$$\alpha S = \frac{2\pi^2}{3} \frac{m_W^2}{m_{W'}^2} \sin^2\theta_W$$

$$T \approx 0$$

$$U \approx 0$$

Best fit to data: $S \lesssim 0.14$

(w/ Heavy Higgs $m_H \approx 600$ GeV**)**

$m_{W'} \gtrsim 3$ TeV

Conclusions

We considered theories w/o a physical Higgs

Only Goldstone bosons present

Unitarity violation delayed by Z', W' states

$N + 1 \to \infty$: **continuous extra dimension**

For this, need $m_{Z'}$,$m_{W'} \sim 500$ GeV

Challenge is to avoid violation of S parameter

Larger gauge group?

Bulk fermions?