Playing with fermion couplings in Higgsless models

Stefania De Curtis
INFN, Firenze

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- Introduction
- $SU(2)_L \times SU(2)^K \times U(1)$ linear moose
- Unitarity bounds
- Electroweak precision tests
- Delocalizing fermion interactions
- Some signatures
- Conclusions

based on:

Casalbuoni, D.C., Dominici, PRD hep-ph/0405188
Casalbuoni, D.C., Dolce, Dominici, PRD hep-ph/05022209

(Modern) Higgsless Models

- **Symmetry breaking mechanism of a gauge theory in $4+1$ dims by boundary conditions on the branes** *(Csáki, Grojean, Murayama, Pilo, Terning; Nomura)*

- **The scale at which partial wave unitarity is lost is delayed with respect to the SM without the Higgs, due the exchange of KK excitations of gauge bosons** *(Chivukula, Dicus, He; Foadi, Gopalakrishna, Schmidt)*

- **Problem: $\epsilon_3(S)$ electroweak parameter is too big if unitarity is fine** *(Barbieri, Pomarol, Rattazzi, Strumia)*

- **Solutions:**

  Brane kinetic terms *(Cacciapaglia, Csáki, Grojean, Terning; Carena, Tait, Wagner; Carena, Ponton, Tait, Wagner; Davoudiasl, Hewett, Lillie, Rizzo)*

  Fermion delocalization *(Cacciapaglia, Csáki, Grojean, Terning; Foadi, Gopalakrishna, Schmidt; Bhattacharya, Csáki, Martin, Shirman, Terning)*

Alternative approach: Dimensional Deconstruction and Moose Models *(Arkani-Hamed, Cohen, Georgi)*

Theory with gauge symmetry $[G]^{K+1}$ in $3+1$ dims:

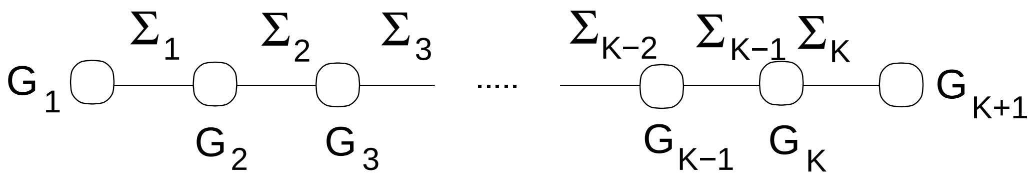
$$A^j = A^{ja} T^a, \quad j = 1, \cdots, K+1;$$

Non linear σ-model fields:

$$\Sigma_i = e^{i\pi_i^a T^a / f_c}, \quad \Sigma_i \to U_i \Sigma_i U_{i+1}^\dagger, \quad U_i \in G_i, \quad i = 1, 2, \cdots, K$$

Covariant derivatives: $D_\mu \Sigma_i = \partial_\mu \Sigma_i - i g_c A_\mu^i \Sigma_i + i g_c \Sigma_i A_\mu^{i+1}$

$$\mathcal{L}_{moose} = \sum_{i=1}^{K} f_c^2 \mathrm{Tr}[D_\mu \Sigma_i^\dagger D^\mu \Sigma_i] - \frac{1}{2} \sum_{i=1}^{K+1} \mathrm{Tr}[(F_{\mu\nu}^i)^2]$$



Mass spectrum

Mass matrix $\{A_\mu^1, A_\mu^2, \ldots, A_\mu^{K+1}\}$:

$$M^2 = g_c^2 f_c^2 \begin{pmatrix} 1 & -1 & 0 & \ldots & 0 & 0 \\ -1 & 2 & -1 & \ldots & 0 & 0 \\ 0 & -1 & 2 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & 2 & -1 \\ 0 & 0 & 0 & \ldots & -1 & 1 \end{pmatrix}$$

Mass eigenvalues:

$$M_k^2 = 4 g_c^2 f_c^2 \sin^2\left(\frac{\pi k}{2(K+1)}\right) \longrightarrow \left(\frac{k}{R}\right)^2 \quad |k| \ll K$$

For $|k| \ll K$ they reproduce the masses of KK excitations for a five dimensional theory with gauge symmetry G, compactification radius R, gauge coupling g_5, lattice spacing a:

$$\pi R = (K+1)a \qquad \frac{a}{g_5^2} = \frac{1}{g_c^2} \qquad a = \frac{1}{g_c f_c}$$

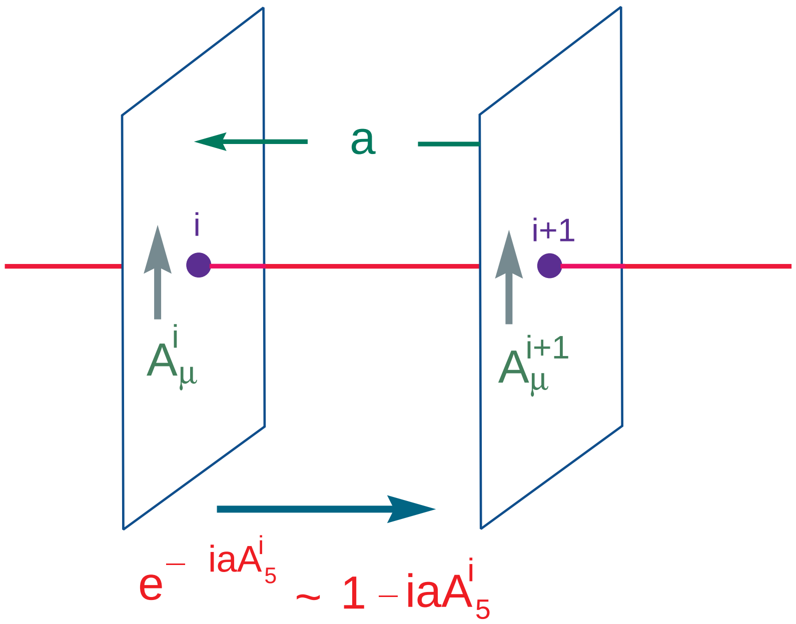
Extra dimension on a lattice

(Hill, Pokorski, Wang; Randall, Shadmi, Weiner; Abe, Kobayashi, Maru, Yoshioka)

Example: theory with abelian gauge symmetry in 5D and flat metric:

$$S = -\frac{1}{2}\int d^4x \int_0^{\pi R} dy \frac{1}{g_5^2}\left[F_{\mu\nu}F^{\mu\nu} + 2F_{\mu 5}F^{\mu 5}\right], \quad F_{\mu 5} = \partial_\mu A_5 - \partial_5 A_\mu$$

gauge transformation $\longrightarrow A_5 = 0 \longrightarrow A_\mu^{(n)}$ **acquire mass** $M_n = n/R$



Discretization of extra-dim on a lattice

The A_5 gauge field is substituted by link variables which realize the parallel transport between two lattice sites $\longrightarrow$ Wilson lines

$$\Sigma^j \sim \exp[i \int_{y_j}^{y_j+a} dz A_5(z, x_\mu)]$$

Covariant derivatives:

$$D_\mu \Sigma^j \sim a F^j_{\mu 5} = i a \partial_\mu A^j_5 - i(A^{j+1}_\mu - A^j_\mu)$$

$$S_{moose} \sim -\frac{1}{2} \int d^4x \frac{a}{g_5^2} \sum_j \left[F^j_{\mu\nu} F^{\mu\nu j} + \frac{2}{a^2} (D_\mu \Sigma^j)^\dagger (D^\mu \Sigma^j) \right]$$

Gauge theories with replicas of G $\Leftrightarrow$ compactified dimensions

$SU(2)_L \times SU(2)^K \times U(1)$ linear moose

(Casalbuoni, D.C., Dominici; see also: Foadi, Gopalakrishna, Schmidt; Hirn, Stern; Chivukula et al; Georgi)

The transformation properties of the fields are

$$\Sigma_1 \to L\Sigma_1 U_1^\dagger,$$
$$\Sigma_i \to U_{i-1}\Sigma_i U_i^\dagger\;, \quad i = 2, \cdots, K,$$
$$\Sigma_{K+1} \to U_K \Sigma_{K+1} R^\dagger,$$

$$U_i \in G_i \equiv SU(2)_i \qquad A_\mu^i = A_\mu^{ia}\tau^a/2, \quad g_i, \quad i = 1, 2, \cdots, K,$$
$$L \in G_L \equiv SU(2)_L \qquad \tilde{W}_\mu = \tilde{W}_\mu^a \tau^a/2, \quad \tilde{g},$$
$$R \in G_R \equiv SU(2)_R \supset U(1)_Y \qquad \tilde{Y}_\mu = \tilde{\mathcal{Y}}_\mu \tau^3/2, \quad \tilde{g}'$$

$$\mathcal{L} = \sum_{i=1}^{K+1} f_i^2 \mathrm{Tr}[D_\mu \Sigma_i^\dagger D^\mu \Sigma_i] - \frac{1}{2}\sum_{i=1}^{K} \mathrm{Tr}[(F_{\mu\nu}^i)^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{W}))^2] - \frac{1}{2}\mathrm{Tr}[(F_{\mu\nu}(\tilde{Y}))^2]$$

Covariant derivatives

$$D_\mu \Sigma_1 = \partial_\mu \Sigma_1 - i\tilde{g}\tilde{W}_\mu \Sigma_1 + i\Sigma_1 g_1 A_\mu^1,$$

$$D_\mu \Sigma_i = \partial_\mu \Sigma_i - i g_{i-1} A_\mu^{i-1} \Sigma_i + i\Sigma_i g_i A_\mu^i, \qquad i = 2, \cdots, K,$$

$$D_\mu \Sigma_{K+1} = \partial_\mu \Sigma_{K+1} - i g_K A_\mu^K \Sigma_{K+1} + i\tilde{g}' \Sigma_{K+1} \tilde{Y}_\mu$$

$f_i = f_c \ \forall i \Rightarrow$ flat metric in five dims; varying $f_i \Rightarrow$ warped metric

Global symmetry: $SU(2)_L \times SU(2)^K \times SU(2)_R$

$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2}\sum_{i,j=0}^{K+1} (M_2)_{ij} A_\mu^i A^{\mu j}$$

with $A_\mu^0 = \tilde{W}^\mu$, $A_\mu^{K+1} = \tilde{Y}^\mu$, and

$$(M_2)_{ij} = g_i^2 (f_i^2 + f_{i+1}^2)\delta_{i,j} - g_i g_{i+1} f_{i+1}^2 \delta_{i,j-1} - g_j g_{j+1} f_{j+1}^2 \delta_{i,j+1}$$

where $g_0 = \tilde{g}$, $g_{K+1} = \tilde{g}'$, $f_0 = f_{K+2} = 0$

Calling $\tilde{A}_\mu^n$, $n = 1, \cdots, K$ the mass eigenstates, and m_n^2 the squared mass eigenvalues,

$$A_\mu^i = \sum_{n=0}^{K+1} S_n^i \tilde{A}_\mu^n,$$

$$S_m^i (M_2)_{ij} S_n^j = m_n^2 \delta_{m,n}.$$

Besides the massless photon, the lowest eigenvalues are (at the leading order in $O((\tilde{g}/g_i)^2)$)

$$\tilde{M}_W^2 = \frac{v^2}{4}\tilde{g}^2 \,, \quad \tilde{M}_Z^2 = \tilde{M}_W^2/\tilde{c}_\theta^2 \,, \quad \tan\tilde{\theta} = \frac{\tilde{g}}{\tilde{g}'}$$

where we have identified

$$\frac{4}{v^2} \equiv \frac{1}{f^2} = \sum_{i=1}^{K+1} \frac{1}{{f_i}^2} \qquad v = \text{EW scale} = 246 \text{ GeV}$$

We assume standard fermionic couplings w.r.t. $SU(2)_L \otimes U(1)_Y \longrightarrow$ Fermions are located at the end of the moose: ψ_L to the left end, ψ_R to the right end

Partial wave unitarity bounds

(see also: Chivukula, He; Papucci; Mück, Nilse, Pilaftis, Rückl)

Unitary gauge for $A^i_\mu \quad \Rightarrow \quad \Sigma_i = \exp\left(i f \vec{\pi} \cdot \vec{\tau} / 2 f_i^2\right) \quad \Rightarrow \quad \mathcal{L}(\pi, A^i_\mu)$

Equivalence theorem: $\mathcal{A}_{W_L^+ W_L^- \to W_L^+ W_L^-} \sim \mathcal{A}_{\pi^+\pi^- \to \pi^+\pi^-} \; (\sqrt{s} >> M_W)$

$$\mathcal{A}_{\pi^+\pi^- \to \pi^+\pi^-} \sim -\frac{1}{4} f^4 \sum_{i=1}^{K+1} \frac{u}{f_i^6} + \frac{1}{4} f^4 \sum_{i,j=1}^{K+1} L_{ij} \left(\frac{u-t}{(s-M^2)_{ij}} + \frac{u-s}{(t-M^2)_{ij}} \right)$$

where $$L_{ij} = g_i g_j \left(\frac{1}{f_i^2} + \frac{1}{f_{i+1}^2} \right) \left(\frac{1}{f_j^2} + \frac{1}{f_{j+1}^2} \right)$$

High energy limit: $$\mathcal{A}_{\pi^+\pi^- \to \pi^+\pi^-} \quad \to \quad -\frac{1}{4} f^4 \sum_{i=1}^{K+1} \frac{u}{f_i^6}$$

minimized by $f_i = f_c \quad \forall i$ $$\to \quad -\frac{u}{(K+1)^2 v^2}$$

Unitarity condition from $J = 0$ partial wave $|a_0| < 1/2$:
Single channel $\pi^+\pi^- \longrightarrow \pi^+\pi^-$ contribution: $\Lambda_{\rm moose} = (K+1)\Lambda_{\rm HSM}$

But the deconstructed theory has many other longitudinal vector bosons,
considering all channels $(\Sigma_i = \exp(i\vec{\pi}_i \cdot \vec{\tau}/2f_i))$ and using the
Equivalence Theorem: $\mathcal{A}_{A_L^i A_L^i \to A_L^i A_L^i} \sim \mathcal{A}_{\pi^i\pi^i \to \pi^i\pi^i}$ $(\sqrt{s} >> M_{A^i})$

$$\mathcal{A}_{\pi_i\pi_i \to \pi_i\pi_i} \to -\frac{1}{4}\frac{u}{f_i^2}$$

The unitarity limit is determined by the smallest f_i. Taking all equal:

$$\boxed{\Lambda_{\rm moose}^{TOT} = \sqrt{K+1}\,\Lambda_{\rm HSM}}$$

Higgs bosons are not necessary up to $\sqrt{K+1}$ times the scale of unitarity
violation in the Higgsless SM (see NDA analysis: $\Lambda_5 = \sqrt{K}\Lambda_4$)

Approximately, by imposing $M_A^{(K+1)} < \Lambda_{moose}^{TOT}$, with $\Lambda_{\rm HSM} = 2\sqrt{2}\pi v$ we
get the bound $g_c < 5$ $\longrightarrow$ Electroweak corrections too large

Electroweak Precision Tests

Custodial symmetry: $\epsilon_1 = \epsilon_2 = 0$ to $\mathcal{O}((\tilde{g}/g_i)^2)$

Dispersive representation in terms of current-current correlators:

$$\epsilon_3 \left(= \frac{\tilde{g}^2 S}{16\pi} \right) = -\frac{\tilde{g}^2}{4\pi} \int_0^\infty \frac{ds}{s^2} Im[\Pi_{VV}(s) - \Pi_{AA}(s)]$$

Use vector meson dominance to saturate $Im\Pi_{VV(AA)}$ with vector boson exchanges (to $\mathcal{O}((\tilde{g}/g_i)^2)$):

$$\epsilon_3 = \frac{\tilde{g}^2}{4} \sum_n \left(\frac{g_{nV}^2}{m_n^4} - \frac{g_{nA}^2}{m_n^4} \right) = \tilde{g}^2 g_1 g_K f_1^2 f_{K+1}^2 (M_2^{-2})_{1K} = \tilde{g}^2 \sum_{i=1}^{K} \frac{(1-y_i)y_i}{g_i^2}$$

where g_{nV}, g_{nA} are vector decay constants, M_2 is the gauge boson squared mass matrix with eigenvalues m_n^2, and $y_i = \sum_{j=1}^{i} f^2/f_j^2$

Since $0 \leq y_i \leq 1 \Rightarrow \epsilon_3 > 0$, whatever the metric

For $f_i = f_c$, $g_i = g_c \longrightarrow \epsilon_3 = \frac{K(K+2)}{6(K+1)} \frac{\tilde{g}^2}{g_c^2}$

$\epsilon_3^{exp} \sim 10^{-3}$. For $K = 1 \Rightarrow g_c \sim 16\tilde{g} \sim 10$. For large $K \Rightarrow g_c \sim 10\sqrt{K}$

$\Rightarrow$ strongly interacting gauge bosons, unitarity violation

For increasing K and reasonable values of $g_c \Rightarrow \epsilon_3$ too large

Delocalizing fermion interactions

(Casalbuoni, D.C., Dolce, Dominici; see also: Chivukula, Simmons, He, Kurachi)

Let us build

$$\chi_L^i = \Sigma_i^\dagger \Sigma_{i-1}^\dagger \cdots \Sigma_1^\dagger \psi_L, \qquad \chi_L^i \to U_i \chi_L^i\,, \quad U_i \in SU(2)_i \quad i = 1, \ldots, K$$

New terms describing direct left-handed fermion couplings to A_μ^i, invariant under the $SU(2)_L \times SU(2)^K \times U(1)$ symmetry:

$$\sum_{i=1}^{K} b_i \bar{\chi}_L^i i\gamma^\mu (\partial_\mu + i g_i A_\mu^i + \frac{i}{2}\tilde{g}'(B-L)\tilde{\mathcal{Y}}_\mu)\chi_L^i$$

b_i dimensionless parameters.

In the unitary gauge ($\Sigma_i \equiv I$) and after a rescaling $\psi_L \to \frac{1}{\sqrt{1+\sum_i b_i}}\psi_L$:

$$\mathcal{L}_{fermions}^{tot} = \bar{\psi}_R i\gamma^\mu \left[\partial_\mu + i\tilde{g}'\frac{\tau^3}{2}\tilde{\mathcal{Y}}_\mu + \frac{i}{2}\tilde{g}'(B-L)\tilde{\mathcal{Y}}_\mu\right]\psi_R$$

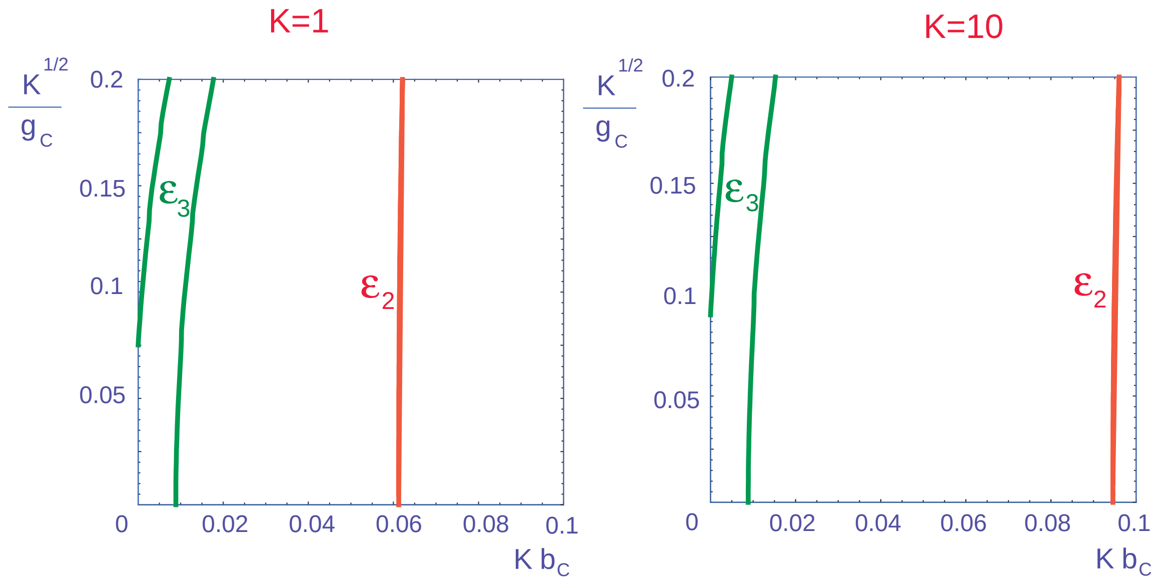
$$+\bar{\psi}_L i\gamma^\mu \left[\partial_\mu + \frac{1}{1+\sum_{i=1}^K b_i}\left(i\tilde{g}\tilde{W}_\mu + i\sum_{i=1}^{K} b_i g_i A_\mu^i\right) + \frac{i}{2}\tilde{g}'(B-L)\tilde{\mathcal{Y}}_\mu\right]\psi_L$$

Bounds from ϵ_i parameters

Take the low-energy limit by eliminating the A_i fields with their e.o.m.
Evaluate the corrections to the relevant physical quantities to $\mathcal{O}(\tilde{g}/g_i)^2$, $\mathcal{O}(b_i)$ and neglect $\mathcal{O}(b_i/g_i^2)$:

$$\epsilon_1 \simeq 0, \quad \epsilon_2 \simeq 0 \quad \epsilon_3 \simeq \sum_{i=1}^{K} y_i\left(\frac{\tilde{g}^2}{g_i^2}(1-y_i) - b_i\right) \qquad \left(y_i = \sum_{j=1}^{i} \frac{f^2}{f_j^2}\right)$$

Simplest model: $g_i \equiv g_c,\ b_i \equiv b_c,\ f_i \equiv f_c,\ \ \forall i$

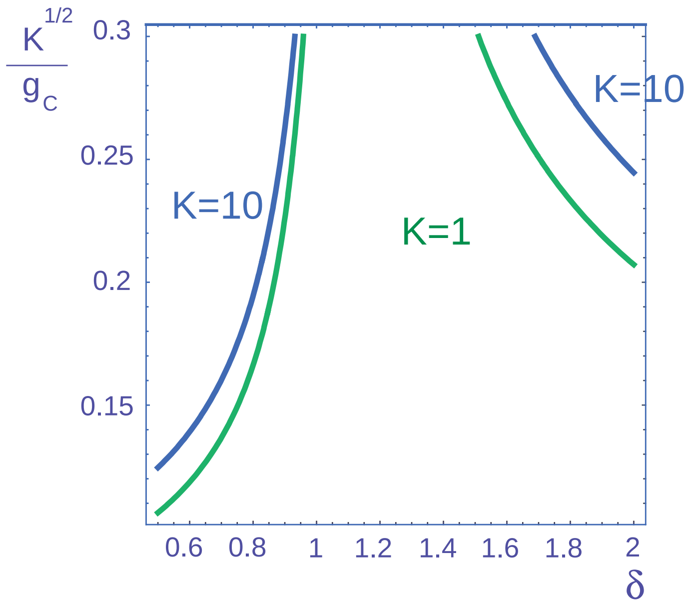


95%CL bound from ϵ_1: $b_c < 0.14 \ \ (0.025)$ for $K = 1 \ (10)$, independent on g_c

Local cancellation: $b_i = \delta \frac{\tilde{g}^2}{g_i^2}(1 - y_i)$

for $\delta = 1$ there is no contribution to ϵ_3 from new physics

Take: $g_i \equiv g_c, f_i \equiv f_c, \quad \forall i$



95% CL bounds on the parameter space $(\delta, \sqrt{K}/g_c)$ *from the experimental value of* ϵ_3*. The allowed region is between the corresponding lines.* ϵ_1, ϵ_2 *give very loose bounds.*

By fine-tuning every direct fermion coupling in each site to compensate the gauge bosons contribution to ϵ_3, a sizeable region of the parameter space is left.

Continuum limit ($K \to \infty$)

Let $K \to \infty$ with $Ka \to \pi R$, πR is the length of the extra-dim

$$\lim_{a\to 0} a f_i^2 = f^2(y), \quad \lim_{a\to 0} a g_i^2 = g_5^2(y), \quad \lim_{a\to 0} \frac{b_i}{a} = b(y)$$

Assuming: $g_5(y) = g_5$, and $f(y) = \bar{f} \quad \to$ flat metric

$$S = -\frac{1}{4}\int d^4x \int_0^{\pi R} dy \Big\{ \frac{1}{g_5^2}(F_{MN}^a)^2 + \frac{1}{g_0^2}(F_{\mu\nu}^a)^2 \delta(y) + \frac{1}{g_0'^2}(F_{\mu\nu}^3)^2 \delta(y - \pi R) \Big\} + S^{ferm} + \mathrm{BC's}$$

- **Non-local fermion interaction in terms of $\Sigma_1 \Sigma_2 \cdots \Sigma_i$:**

$$\Sigma^j \to \exp(i \int_{y_i}^{y_j + a} dz A_5(z, x_\mu)), \qquad \Sigma_1 \Sigma_2 \cdots \Sigma_i \to P\Big[\exp(i \int_0^y dz A_5(z, x_\mu))\Big]$$

$$\chi_L^i(x_\mu) = \Sigma_i^\dagger \Sigma_{i-1}^\dagger \cdots \Sigma_1^\dagger \psi_L(x_\mu) \quad \to \chi_L(y, x_\mu) = P\Big[\exp(i \int_0^y dz A_5(z, x_\mu))\Big]^\dagger \psi_L(x_\mu)$$

Left-handed fermions interact with gauge bosons in the bulk via Wilson lines

- **Mass term for the fermions:**

$$\lambda^{ij} \bar{\psi}_L^i \Sigma_1 \Sigma_2 \cdots \Sigma_{K+1} \psi_R^j \to \lambda^{ij} \bar{\psi}_L^i P\Big[(\exp(i \int_0^{\pi R} dz A_5(z, x_\mu))\Big] \psi_R^j$$

Stefania De Curtis
INFN, Firenze

What is the continuum limit for the direct fermionic couplings when local cancellation is required?

Assuming $g_5(y) = g_5$

$$\epsilon_3 \equiv 0 \rightarrow \quad b(y) = \frac{\tilde{g}^2}{g_5^2} \int_y^{\pi R} dt \frac{f^2}{f^2(t)}, \qquad \frac{1}{f^2} = \int_0^{\pi R} \frac{dy}{f^2(y)}$$

In general $b(y)$ **decreases along the fifth dim:** $b(0) = \frac{\tilde{g}^2}{g_5^2}, \quad b(\pi R) = 0$

Flat metric: $f(y) = \bar{f}$

$$b(y) = \frac{\tilde{g}^2}{g_5^2} \left(1 - \frac{y}{\pi R}\right)$$

Randall-Sundrum metric: $f(y) = \bar{f} e^{ky}$

$$b(y) = \frac{\tilde{g}^2}{g_5^2} \frac{e^{-2\pi kR} - e^{-2ky}}{e^{-2\pi kR} - 1}$$

Signatures: Triple-gauge-boson vertices

(Chivukula, Simmons, He, Kurachi, Tanabashi)

5-dim $SU(2)_A \otimes SU(2)_B$ gauge theory broken to the $U(1)_{em}$ by BC's.

The fermion probability distribution is related to the W boson wave function to minimize the deviations in EW parameters (*ideal delocalization*)

The main characteristics are contained in our deconstructed moose model:
important property $\rightarrow$ the KK resonances of the $W^{\pm}, Z$ gauge bosons are fermiophobic

Consequences:

- very narrow KK resonances ($\Gamma/M \sim 10^{-4}, 10^{-3}$)
- loose constraints by direct collider search for new gauge bosons

measurements of triple-gauge-boson vertices can provide bounds on KK masses

The actual lower bound on Δg_1^Z from LEPII leads $M_W^1 > 500\ GeV$ for the *ideal delocalized* model in flat metric *(Chivukula et al.)*

@LHC with 30 fb^{-1} from WZ production $\Delta g_1^Z < 0.11$ *(Dobbs)* $\rightarrow$ $M_W^1 > 800\ GeV$ *(Chivukula et al.)*

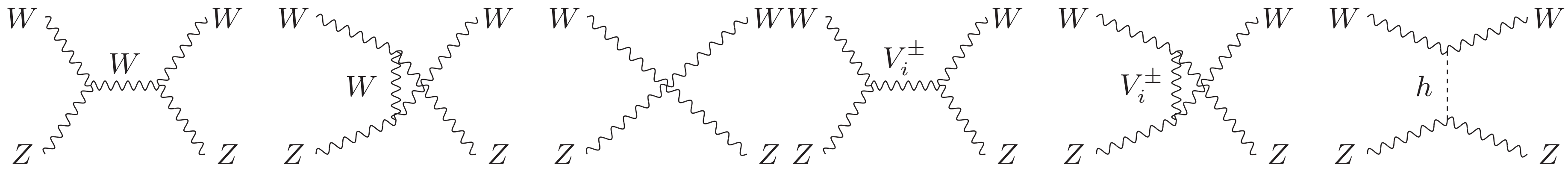
@ 500(800)GeV LC with polarized beams $\Delta g_1^Z < 0.0048(0.0027)$ and $\Delta k_Z < 9.8(4.2)10^{-4}$ *(Menges)* $\rightarrow$ $M_W^1 > 2.6(4.0) TeV$ *(Chivukula et al.)*

Collider Phenomenology

(Birkedal, Matchev, Perelstein)

Common feature of the Higgless models: the scale of perturbative unitarity violation is raised by new massive vector bosons whose masses and couplings are constrained by *unitarity sum rules*.

Example: $W_L Z_L$ elastic scattering



A good test → analysis of the vector boson fusion at future colliders

(the most promising channel for Higgsless models with fermion delocalization since the KK resonances are fermiophobic)

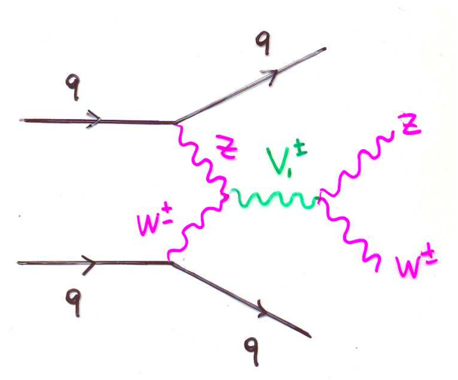
Birkedal, Matchev, Perelstein: simplifying assumption that the sum rules are saturated by the first KK resonance V^1

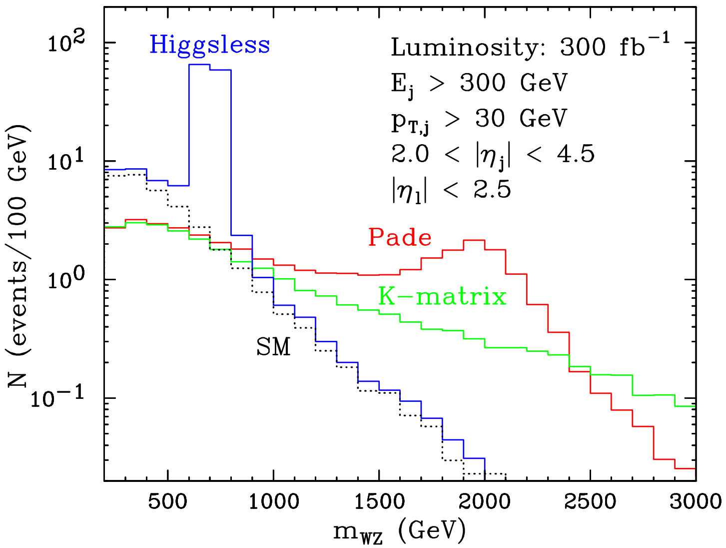
$$g_{WV^1Z} < \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_V^1 M_W}, \quad \Gamma(V^1) = \frac{\alpha (M_V^1)^3}{144 s_W^2 M_W^2}$$

a very narrow and light resonance in WZ scattering

Higgsless Models @ the LHC

(Birkedal, Matchev, Perelstein)





Typical final state includes two forward jets + a pair of vector bosons

Cuts to suppress the SM BCKGND and possible signal from Drell-Yan:

$$2 < |\eta| \leq 4.5,\ E > 300GeV,\ p_T > 30GeV$$

The gold-plated final state is $2j + 3l$+missing E_T

Discovery reach @ LHC (10 events)

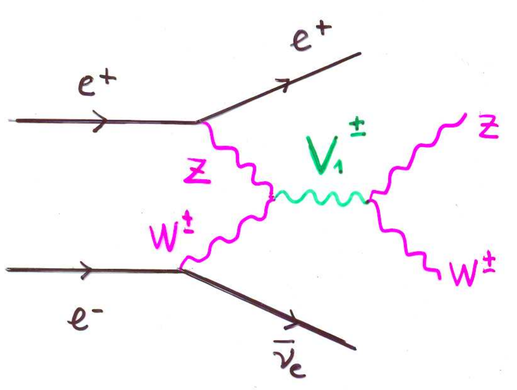
$M_V^1 \leq 550(1000)\ GeV$ with 10(60) fb^{-1}

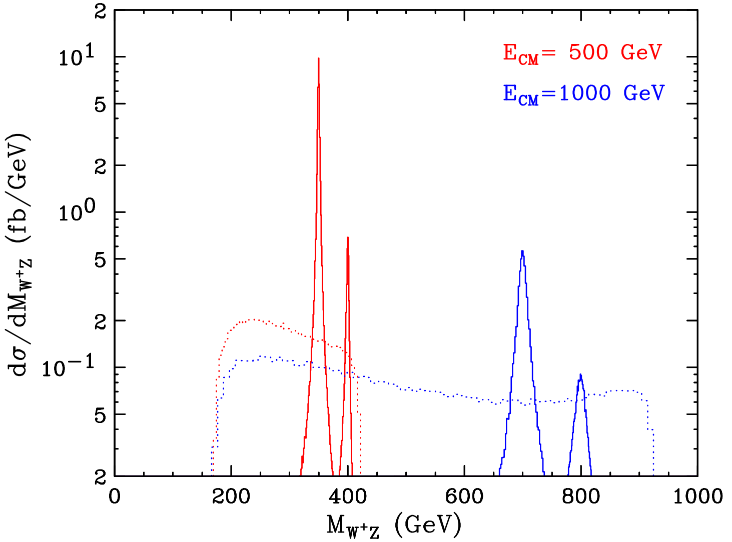
To identify the resonance as a part of a Higgsless model $\longrightarrow$ test the *unitarity sum rules*: **measure of the mass and couplings $\longrightarrow$ a task for the ILC**

Higgsless Models @ the ILC

(Birkedal, Matchev, Perelstein)

The first KK excitations of the Higgsless models are expected to be below 1 TeV and can be produced @ the ILC by bremsstrahlung of W and Z off the initial state e^+ and e^-.





The ILC searches appear promising.

Further studies to be done, for example: study of the W^+W^- channel, include the electron beam polarization, consider the production of longitudinally polarized gauge bosons, consider the beam energy spread issues.

Conclusions

- **Moose models appear deconstructing Higgsless models from five to four dimensions**

- **Hope: the scale where partial wave unitarity is violated is higher w.r.t. the Higgsless SM due to the exchange of KK excitations in the four gauge boson amplitude scattering**

- **Problem: compatibility between precision electroweak data and unitarity requirement**

- **Possible solution with fine-tuning: delocalize the fermion interactions**

- **Signatures: deviations in the multi-gauge-boson vertices** *(Chivukula, Simmons, He, Kurachi, Tanabashi)*, **new gauge bosons as resonances in the WZ channel at the LHC and the ILC** *(Birkedal, Matchev, Perelstein)*

Low-energy limit

Eliminating the A_μ^i fields when $(\tilde{g}/g_i)^2 \ll 1, \ \ \forall i$ and after a field redefinition:

$$
\begin{aligned}
\mathcal{L}_{eff}^{charg} &= \frac{-\tilde{e}}{\sqrt{2}\tilde{s}_\theta}\left(1-\frac{b}{2}-\frac{z_w}{2}\right)\overline{\psi}\gamma^\mu\frac{1-\gamma_5}{2}\psi W_\mu^- + \ h.c.,\\
\mathcal{L}_{eff}^{neutr} &= \frac{-\tilde{e}}{\tilde{s}_\theta\tilde{c}_\theta}\left(1-\frac{b}{2}-\frac{z_z}{2}\right)\overline{\psi}\gamma^\mu\left[T_L^3\frac{1-\gamma_5}{2}-Q\tilde{s}_\theta^2\frac{1-\frac{\tilde{c}_\theta}{\tilde{s}_\theta}z_{z\gamma}}{1-\frac{b}{2}}\right]\psi Z_\mu,\\
&- \tilde{e}\left(1-\frac{z_\gamma}{2}\right)\overline{\psi}\gamma^\mu Q\psi A_\mu\,.
\end{aligned}
$$

where

$$
\begin{aligned}
z_\gamma &= \tilde{s}_\theta^2\sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2, \qquad z_w = \sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2(1-y_i)^2,\\
z_z &= \frac{1}{\tilde{c}_\theta^2}\sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2\left(\tilde{c}_\theta^2-y_i\right)^2, \qquad z_{z\gamma} = -\frac{\tilde{s}_\theta}{\tilde{c}_\theta}\sum_{i=1}^{K}\left(\frac{\tilde{g}}{g_i}\right)^2\left(\tilde{c}_\theta^2-y_i\right),\\
b &= \frac{2\sum_{i=1}^{K} y_i b_i}{1+\sum_{j=1}^{K} b_j}
\end{aligned}
$$

Current-current interaction terms are also generated

$$\mathcal{L}_{eff}^{quart} = \beta \sum_{a=1}^{3} \left(\bar{\psi}_L \gamma^\mu \frac{\tau^a}{2} \psi_L \right)^2$$

with

$$\beta = \frac{1}{8f^2} \left(\bar{b}_K - b \right)^2 - \frac{1}{8f^2} \sum_{i=1}^{K} x_{i+1} \bar{b}_i^2$$

$x_i = f^2/f_i^2$ and

$$\bar{b}_i = 2 \frac{\sum_{j=1}^{i} b_j}{1 + \sum_{j=1}^{K} b_j} \quad (i = 1, \cdots, K) \, .$$

Physical quantities:

$$M_Z^2 = \tilde{M}_Z^2 (1 - z_z), \;\; M_W^2 = \tilde{M}_W^2 (1 - z_w),$$

$$e = \tilde{e} (1 - \frac{z_\gamma}{2}), \;\; \frac{G_F}{\sqrt{2}} = \frac{1}{8} \tilde{g}^2 \left(1 - \frac{b}{2} \right)^2 \frac{1 - z_w}{M_W^2} + \frac{1}{4\beta}.$$