Higgsless Electroweak Symmetry Breaking and the LHC Signatures

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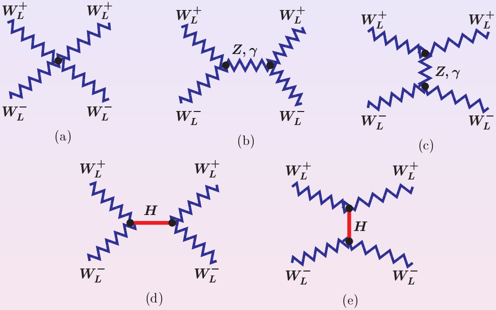
Outline

1. **Higgsless EWSB: Unitarity via Spin-1 Gauge Bosons**
2. **Geometric Higgs Mechanism and KK ET**
3. **All E-Cancellations at $O(E^{4,3,2,1,0})$ derived from ET**
4. **Effective Unitarity from Higgsless Deconstruction**
5. **Boundary Conditions from Gauge-Invariant Deconstruction**
6. **LHC Signatures of Higgsless EWSB**

- **Longitudinal Polarization**: $\epsilon_L^{\mu}(k) = \dfrac{k^{\mu}}{M_W} + \mathcal{O}\left(\dfrac{M_W}{E}\right)$



- **E-Power Counting:**

$$(a),\ (b),\ (c) \;=\; \mathcal{O}(E^4) \oplus \mathcal{O}(E^2)$$

$$(c),\ (d) \;=\; \mathcal{O}(E^2)$$

Review: Unitarity of 4d SM

▶ **E-Cancellations**: ($c = \cos\theta$)

Graphs	$g^2 \frac{E^4}{m_w^4}$	$g^2 \frac{E^2}{m_w^2}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$	$+2 - 6\cos\theta$
(b)	$-4\cos\theta$	$-\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	0	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum	**0**	**0**

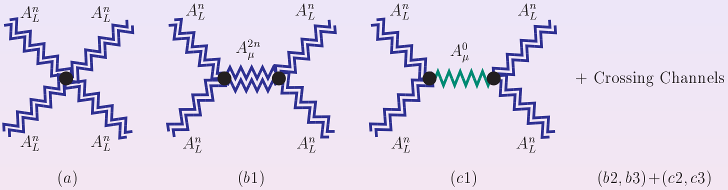
▶ **At $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound**: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0\,\text{TeV}$

▶ **If No Higgs $\Rightarrow$ Nonzero $\mathcal{O}(E^2)$** $\Rightarrow$ $E < \sqrt{8\pi}\, v \simeq 1.2\,\text{TeV}$

E-Cancellation in Longitudinal KK Scattering

RSC, DAD, HJH, hep-ph/0111016

- **Example of 5d KK Gauge Theory:**



- **E-Power Counting:**

$$
\begin{aligned}
\text{(a)} &= \mathcal{O}(E^4) \oplus \mathcal{O}(E^2) \\
\text{(b1), (b2), (b3)} &= \mathcal{O}(E^4) \oplus \mathcal{O}(E^2) \\
\text{(c1), (c2), (c3)} &= \mathcal{O}(E^4) \oplus \mathcal{O}(E^2)
\end{aligned}
$$

E-Cancellation in Longitudinal KK Scattering

RSC, DAD, HJH

▶ **E-Cancellations Due to Exchanging Spin-1 KK Modes:**
($c = \cos\theta,\ x = E/M_n$)

Graph	$g^2 C^{eab} C^{ecd}$	$g^2 C^{eac} C^{edb}$	$g^2 C^{ead} C^{ebc}$	
(a)	$6c(x^4 - x^2)$	$\frac{3}{2}(3-2c-c^2)x^4$ $-3(1-c)x^2$	$\frac{-3}{2}(3+2c-c^2)x^4$ $+3(1+c)x^2$	
$(b1)$	$-2c(x^4 - x^2)$			
$(c1)$	$-4cx^4$			
$(b2,3)$		$\frac{-1}{2}(3-2c+c^2)x^4$ $+3(1-c)x^2$	$\frac{1}{2}(3+2c-c^2)x^4$ $-3(1+c)x^2$	
$(c2,3)$		$(-3+2c+c^2)x^4$ $-8cx^2$	$(3+2c-c^2)x^4$ $-8cx^2$	
Sum	$-8cx^2$	$-8cx^2$	$-8cx^2$	$\Longrightarrow$ **0**

KK Equivalence Theorem (KK-ET)

RSC, DAD, HJH

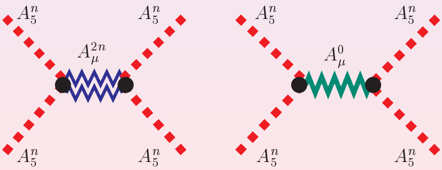
- **KK-ET results from "Geometric Higgs Mechanism":**

KK state A_μ^{an} eats KK-Goldstone A_5^{an} via compactifying x^5.

- **Formulated in R_ξ Gauge:**

$$\mathcal{T}\left[A_L^{an}, A_L^{bm}, \ldots\right] = C_{\rm mod}\, \mathcal{T}\left[A_5^{an}, A_5^{bm}, \ldots\right] + \mathcal{O}\left(\frac{M_{n,m,\ldots}}{E}\right)$$

- **KK Goldstone A_5^{an} Scattering:**



$+$ Crossing Channels

- **Power Counting** $\Longrightarrow$ $\mathcal{T}\left[A_5^{an}, A_5^{bm}, \ldots\right] \leqslant \mathcal{O}(E^0)$

KK-ET and Goldstone Boson Scattering

RSC, DAD, HJH

- **Power Counting: No E-Cancellation in A_5^{an}-Amplitude !**

$$\mathcal{T}\left[A_5^{an}, A_5^{bm}, \dots\right] \leqslant \mathcal{O}(E^0)$$

- **Explicit Calculations give,**

$$\mathcal{T}\left[A_5^{an}A_5^{an} \to A_5^{an}A_5^{an}\right] = g^2\Big[C^{abe}C^{cde}\left(-\tfrac{3}{2}c\right)$$
$$+C^{ace}C^{dbe}\left(-\frac{3(3+c)}{2(1-c)}\right) + C^{ade}C^{bce}\left(\frac{3(3-c)}{2(1+c)}\right)\Big] + \mathcal{O}\left(\frac{M_n^2}{E^2}\right)$$

- **Equal to the A_L^n-amplitude:**

$$\mathcal{T}\left[A_L^{an}A_L^{bn} \to A_L^{cn}A_L^{dn}\right] = g^2\Big[C^{abe}C^{cde}\left(\tfrac{5}{2}c\right)$$
$$+C^{ace}C^{dbe}\left(-\frac{8c^2-5c+9}{2(1-c)}\right) + C^{ade}C^{bce}\left(\frac{8c^2+5c+9}{2(1+c)}\right)\Big] + \mathcal{O}\left(\frac{M_n^2}{E^2}\right)$$

up to a Jacobi identity !

Geometric Higgs Mechanism via KK-ET

HJH, hep-ph/0412113

- **Gauge Theory on Arbitrary 5d Background:**

$$S_5 = \int d^5\widehat{x} \sqrt{-\widehat{g}}\, \widehat{g}^{IK}\widehat{g}^{JL} \frac{-1}{4\kappa^2(x^5)} \widehat{F}^a_{IJ}\widehat{F}^a_{KL}$$

defined on general 5d background,

$$ds^2 = [\kappa(x^5)h(x^5)]^2\eta_{\mu\nu}dx^\mu dx^\nu - dx^5dx^5$$

where the metric

$$\widehat{g}_{IK} = \mathrm{diag}\left(\eta_{\mu\nu}(\kappa h)^2, -1\right)$$

with 2 special cases:

$$\kappa = h = 1, \quad \Rightarrow \quad \text{Flat 5d geometry;}$$

$$\kappa = 1,\ h = \exp[-k|x^5|], \quad \Rightarrow \quad \text{Warped 5d geometry.}$$

Geometric Higgs Mechanism via KK-ET

SRC, DAD, HJH, hep-ph/0111016
HJH, hep-ph/0412113

▶ **We derive kinetic Mixing between $\widehat{A}^{a\mu}$ and $\widehat{A}^{a5}$**

$$\int_0^L dx^5 h^2(x^5)\left(-\frac{1}{2}\left[\left(\partial_5\widehat{A}^a_\mu\right)^2+\partial_\mu\widehat{A}^a_5\partial^5\widehat{A}^{a\mu}+\left(\partial_\mu\widehat{A}^a_5\right)^2\right]\right)$$

★ **Geometric Higgs Mechanism:** $A^{an}_L \Longleftrightarrow A^{an}_5$

▶ **We construct a General R_ξ Gauge:**

$$\widehat{\mathcal{L}}_{\rm gf} = -\frac{1}{2\xi}(\widehat{F}^a)^2\,, \qquad \widehat{F}^a = \kappa^{-1}\partial_\mu\widehat{A}^{a\mu}+\xi\kappa\,\partial_5(h^2\widehat{A}^{a5})$$

with corresponding FP Ghost Term: $\widehat{\mathcal{L}}_{\rm FP} = \widehat{\overline{c}}^a\widehat{s}\widehat{F}^a\,,$

and the 5d BRST transformations,

$$\widehat{s}\widehat{A}^{aJ} = D^{aJ}_b(\widehat{A})\widehat{c}^b, \quad \widehat{s}\widehat{c}^a = -\frac{1}{2}g_5C^{abc}\widehat{c}^b\widehat{c}^c, \quad \widehat{s}\,\widehat{\overline{c}}^a = -\xi^{-1}\widehat{F}^a$$

Geometric Higgs Mechanism via KK-ET

▶ **KK Expansion under Given 5d Boundary Condition (BC):**

$$\widehat{A}^{a\mu}(\widehat{x}) = \frac{1}{\sqrt{L}}\sum_n V_n^{a\mu}(x)\mathcal{X}_n(x^5)\,, \quad \widehat{A}^{a5}(\widehat{x}) = \frac{1}{\sqrt{L}}\sum_n V_n^{a5}(x)\widetilde{\mathcal{X}}_n(x^5)\,.$$

▶ **Together with 5d BRST transfs, we derive KK ET:**

$$\mathcal{T}\left[V_L^{a_1 n_1}, V_L^{a_2 n_2}, \cdots\right] = \widehat{C}_{\rm mod}^{n_1 m_1, n_2 m_2 \cdots}\,\mathcal{T}\left[V_5^{a_1 m_1}, V_5^{a_2 m_2}, \cdots\right] + O\left(\frac{M_{an}}{E_n}\right)$$

$$\widehat{C}_{\rm mod}^{n_1 m_1, n_2 m_2 \cdots} = \widehat{C}_{n_1 m_1}^{a_1} \cdots \widehat{C}_{n_\ell m_\ell}^{a_\ell} = i^\ell[(\delta_{n_1 m_1}\delta_{n_2 m_2}\cdots) + O(\text{loop})]$$

★ **KK-ET is the Manifestation of 5d Geometric Higgs Mechanism at S-matrix level, which realizes,**

$$V_5^{an} \implies V_L^{an}$$

★ **KK-ET holds for Arbitrary 5d Geometry with Any Consistent BC.**

All E-Power Cancellations from ET

RSC, HJH, MK, EHS, MT, arXiv:0806.nnnn

► **We derive general ET for 5d and deconstruction:**

$$\mathcal{T}\left[V_L^{a_1n_1},\, V_L^{a_2n_2},\cdots\right] \;=\; \widehat{C}_{\text{mod}}^{n_1m_1,n_2m_2\cdots}\,\mathcal{T}\left[V_5^{a_1m_1},\, V_5^{a_2m_2},\cdots\right] + B$$

$$=\; \widehat{C}_{\text{mod}}^{n_1m_1,n_2m_2\cdots}\,\mathcal{T}[\pi^{a_1m_1},\,\pi^{a_2m_2},\cdots] + B$$

$$B \;=\; O\left(\frac{M_{an}}{E_n}\right)-\text{suppressed}\,,$$

$$\widehat{C}_{\text{mod}}^{n_1m_1,n_2m_2\cdots} \;=\; \widehat{C}_{n_1m_1}^{a_1}\cdots\widehat{C}_{n_\ell m_\ell}^{a_\ell} \;=\; i^\ell[(\delta_{n_1m_1}\delta_{n_2m_2}\cdots) + O(\text{loop})]$$

★ **RHS of ET imposes ALL E-Cancellations at $O(E^{4,3,2,1,0})$:**

$$O(E^4): \qquad T_L(E^4) \;=\; 0\,;$$

$$O(E^3): \qquad T_L(E^3) \;=\; 0\,;$$

$$O(E^2): \qquad T_L(E^2) \;=\; T_\pi(E^2) \;\to\; 0 \quad (\text{as } N\to\infty)\,;$$

$$O(E^1): \qquad T_L(E^1) \;=\; T_\pi(E^1) \;\to\; 0 \quad (\text{as } N\to\infty)\,;$$

$$O(E^0): \qquad T_L(E^0) \;=\; T_\pi(E^0) + B(E^0)\,.$$

Summary of All E-Cancellation Conditions (1)

RSC, HJH, MK, EHS, MT, arXiv:0806.nnnn

★ **From General** $W_n^a W_n^b \to W_m^c W_m^d$ **(In)elastic Scattering, we derive Cancellation Conditions at** $O(E^{4,3,2})$**,**
$(M_\pm^2 = M_m^2 \pm M_n^2)$

$$E^{4,3}: \quad G_4^{nnmm} = \sum_k G_3^{nnk} G_3^{mmk} = \sum_k \left(G_3^{nmk}\right)^2 ,$$

$$E^2: \quad 2M_+^2 G_4^{nnmm} + \sum_k \left(G_3^{nmk}\right)^2 \left[\frac{M_-^4}{M_k^2} - 3M_k^2\right] = \frac{4M_n^2 M_m^2}{v^2} \widetilde{G}_4^{nnmm} ,$$

$$\sum_k \left[\left(G_3^{nmk}\right)^2 - G_3^{nnk} G_3^{mmk}\right] M_k^2 = \sum_k \left(G_3^{nmk}\right)^2 \frac{M_-^4}{M_k^2}$$

Summary of All E-Cancellation Conditions (2)

RSC, HJH, MK, EHS, MT, arXiv:0806.nnnn

★ **From General** $W_n^a W_n^b \to W_m^c W_m^d$ **(In)elastic Scattering, we derive Cancellation Conditions at** $O(E^{1,0})$**,**

$$E^1: \quad \widetilde{G}_{41}^{nnmm} = -\frac{2M_m}{v}\widetilde{G}_4^{nnmm} \,,$$

$$E^0: \quad \sum_k \left(G_3^{nmk}\right)^2 \left[\frac{M_k^2 - M_+^2}{M_n M_m}\right]^2 = \sum_k \left(\widetilde{G}_3^{nmk}\right)^2 \,,$$

$$G_4^{nnmm} M_-^4 + \sum_k \left[\left(G_3^{nmk}\right)^2 - G_3^{nnk} G_3^{mmk}\right] (M_k^4 - 2M_+^2 M_k^2)$$

$$= M_n^2 M_m^2 \sum_k \left[\left(\widetilde{G}_3^{nmk}\right)^2 - \widetilde{G}_3^{nnk}\widetilde{G}_3^{mmk}\right]$$

General Higgsless Deconstruction

RSC, HJH, hep-ph/0201164
RSC, et al, hep-ph/0406077
HJH, hep-ph/0412113

- **General Deconstruction Lagrangian,**

$$\mathcal{L} \;=\; \sum_j -\frac{1}{2}\mathbf{Tr}\left(F_{j\mu\nu}F_j^{\mu\nu}\right) \;+\; \sum_j \frac{f_j^2}{4}\mathbf{Tr}\left[(D_\mu U_j)^\dagger (D^\mu U_j)\right]$$

$$D^\mu U_j = \partial^\mu U_j - i g_{j-1}\mathbf{A}_{j-1}^\mu U_j + i g_j U_j \mathbf{A}_j^\mu\,, \quad U_j = \exp\left[i2\pi_j/f_j\right].$$

- **Interaction Lagrangian in Unitary Gauge,**

$$\mathcal{L}_G^{\rm int} = -\frac{G_3^{kmn}}{2} C^{abc}\overline{W}_k^{a\mu\nu} W_{m\mu}^b W_{n\nu}^c - \frac{G_4^{k\ell mn}}{4} C^{abc}C^{ade} W_k^{b\mu} W_\ell^{c\nu} W_{m\mu}^d W_{n\nu}^e$$

where $\overline{F}_j^{a\mu\nu} \equiv \partial^\mu A_j^{a\nu} - \partial^\nu A_j^{a\mu}\,, \quad \overline{W}_j^{a\mu\nu} \equiv \partial^\mu W_j^{a\nu} - \partial^\nu W_j^{a\mu}$ **.**

- **The gauge self-couplings:**

$$G_3^{kmn} \;=\; \sum_{j=0}^{N} g_j\, \mathbb{R}_{jk}^a \mathbb{R}_{jm}^b \mathbb{R}_{jn}^c\,, \qquad G_4^{k\ell mn} \;=\; \sum_{j=0}^{N} g_j^2\, \mathbb{R}_{jk}^b \mathbb{R}_{j\ell}^d \mathbb{R}_{jm}^c \mathbb{R}_{jn}^e$$

General Higgsless Deconstruction

- **Goldstone Interaction Lagrangian:**

$$\mathcal{L}_{\pi}^{\rm int} = \frac{\widetilde{G}_4^{k\ell mn}}{6v^2}\left[(\tilde{\pi}_k^a\partial_\mu\tilde{\pi}_\ell^a)(\tilde{\pi}_m^b\partial_\mu\tilde{\pi}_n^b) - (\tilde{\pi}_k^a\tilde{\pi}_\ell^a)(\partial_\mu\tilde{\pi}_m^b\partial^\mu\tilde{\pi}_n^b) + O(\tilde{\pi}_j^6)\right]$$

$$\mathcal{L}_{\pi W}^{\rm int} = \frac{\widetilde{G}_3^{mnk}}{2}\epsilon^{abc}\tilde{\pi}_m^a\partial_\mu\tilde{\pi}_n^b W_k^{c\mu} + \frac{\widetilde{G}_{41}^{nm\ell k}}{3v}\left[\tilde{\pi}_n^b\partial_\mu\tilde{\pi}_m^b\tilde{\pi}_\ell^a - \tilde{\pi}_m^b\tilde{\pi}_\ell^b\partial_\mu\tilde{\pi}_n^a\right]W_k^{a\mu} + \cdots$$

where the Goldstone couplings are:

$$\widetilde{G}_4^{k\ell mn} = \sum_{j=1}^{N+1}\frac{v^2}{f_j^2}\widetilde{\mathbb{R}}_{jk}^a\widetilde{\mathbb{R}}_{j\ell}^a\widetilde{\mathbb{R}}_{jm}^b\widetilde{\mathbb{R}}_{jn}^b\,,$$

$$\widetilde{G}_{41}^{nm\ell k} = \sum_{j=1}^{N+1}\frac{v}{f_j}\widetilde{\mathbb{R}}_{jn}^b\widetilde{\mathbb{R}}_{jm}^b\widetilde{\mathbb{R}}_{j\ell}^a\left(g_j\,\mathbb{R}_{jk}^a - g_{j-1}\mathbb{R}_{j-1,k}^a\right),$$

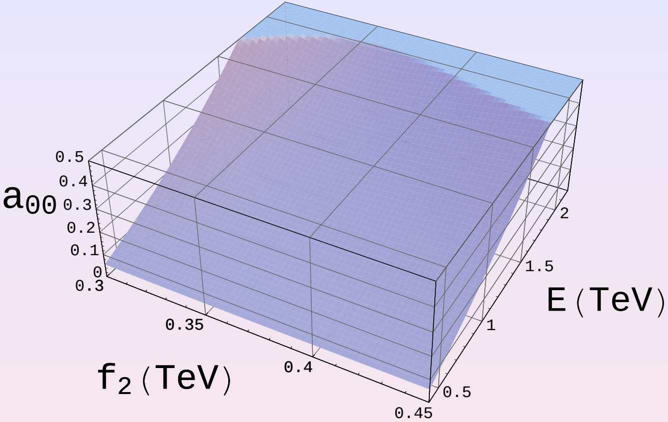
$$\widetilde{G}_3^{mnk} = \sum_{j=1}^{N+1}\widetilde{\mathbb{R}}_{jm}^a\widetilde{\mathbb{R}}_{jn}^b\left(g_j\,\mathbb{R}_{jk}^c + g_{j-1}\mathbb{R}_{j-1,k}^c\right).$$

Effective Unitarity: HJH, hep-ph/0412113

- **Delay of Unitarity Violation is essentially a Collective Effect due to participation in EWSB from Many Gauge Groups whose own symmetry breaking scales $\{f_j\}$ are higher than SM-EWSB scale $v = (\sqrt{2}G_F)^{-1/2}$.**

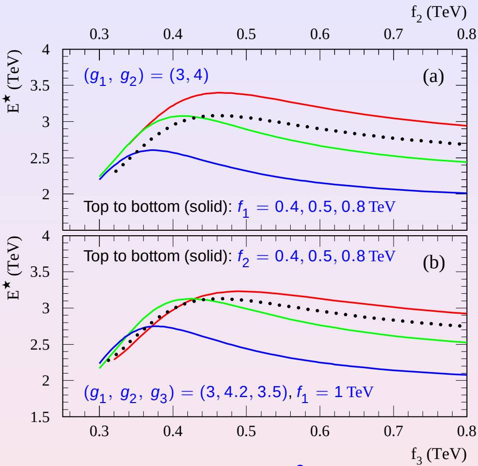
- **Such a Collective Effect does not necessarily require any exact 5D geometry, and can be realized in general non-geometric deconstruction with inputs $f_j > v$.**

Effective Unitarity in 3-Site Higgsless Model



► Unitary limit for $W_{0L}W_{0L} \to W_{0L}W_{0L}$ scattering. Input $M_1 = 0.4$ TeV. The (nearly) maximal delay of unitary violation occurs in a sizable range $f_2 \in (0.34, 0.38)\,\mathrm{TeV}$, rather than a single point at $f_1 = f_2 = \sqrt{2}v \simeq 0.35\,\mathrm{TeV}$.

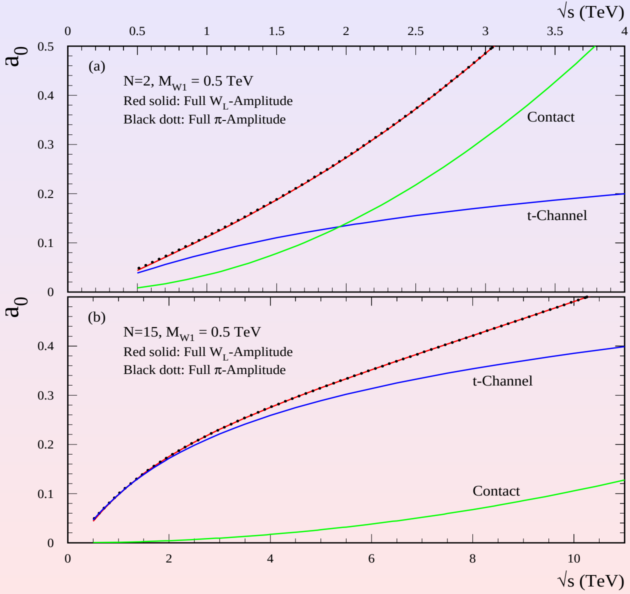
More Examples of Effective Unitarity



- Unitary limit $E^\star$ is for (a) moose $SU(2)^3 \otimes U(1)$, and for (b) moose $SU(2)^4 \otimes U(1)$. Solid curves are for 3 sets of non-geometric inputs appearing random-like. Dotted curves come from 2 sets of typical geometric inputs: $g_1 = g_2 = 4$, $f_1 = \sqrt{3}v \simeq 0.43\,\mathrm{TeV}$ in (a); and $g_1 = g_2 = g_3 = 4$, $f_1 = 1\,\mathrm{TeV}$, $f_2 = \sqrt{3}v$ in (b).

Effective Unitarity: Contact vs t/u Channel

- Scattering $W^+_{0L} W^-_{0L} \to W^+_{0L} W^-_{0L}$ ($\pi_0^+ \pi_0^- \to \pi_0^+ \pi_0^-$):



Chivukula, et al, hep-ph/0612070

Coupled Channel Analysis of Effective Unitarity

★ For $W_{nL}^{a} W_{nL}^{b} \to W_{mL}^{c} W_{mL}^{d}$ $(n, m \geqslant 0)$, Unitarity Condition is:

$$\sqrt{\left(\Re\mathfrak{e}\, \widehat{a}_{jl}^{nn}\right)^2 + \sum_{m(\neq n)} \left|\widehat{a}_{jl}^{mn}\right|^2} < \frac{1}{2}$$

which gives

$$\underline{\widehat{a}}_{jl} = \begin{pmatrix} |\widehat{a}_{jl}^{00}| & |\widehat{a}_{jl}^{01}| & \cdots\cdots & |\widehat{a}_{jl}^{0N}| \\ |\widehat{a}_{jl}^{10}| & |\widehat{a}_{jl}^{11}| & \cdots\cdots & |\widehat{a}_{jl}^{1N}| \\ \cdots & \cdots & \cdots\cdots & \cdots \\ \cdots & \cdots & \cdots\cdots & \cdots \\ |\widehat{a}_{jl}^{N0}| & |\widehat{a}_{jl}^{N1}| & \cdots\cdots & |\widehat{a}_{jl}^{NN}| \end{pmatrix} < \frac{1}{2}$$

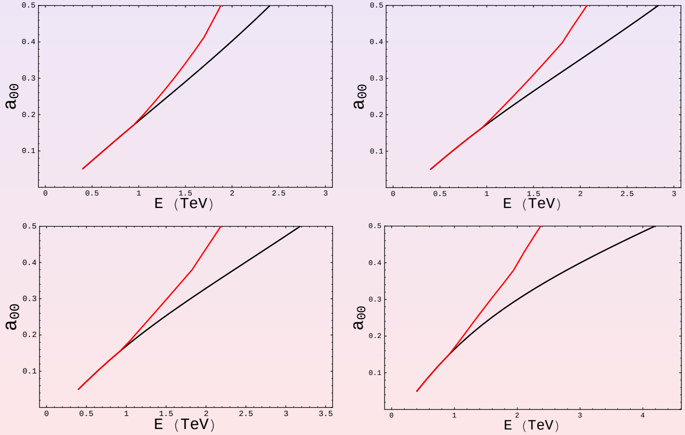
★ Optimal Unitary Condition:

$$\max \left| \left(\underline{\widehat{a}}_{jl}^{\,\mathrm{diag}}\right)_{ii} \right| < \frac{1}{2}\,, \qquad (i = 0, 1, 2, \cdots, N)$$

Effective Unitarity: Coupled Channel Analysis

RSC, HJH, MK, EHS, MT, arXiv:0807.nnnn

- Flat Models: $N+1 = 3$(upper left), 4(upper right), 5(lower left), 10(lower right)
- Elastic Unitary Bound: $E^\star = (2.4,\ 2.8,\ 3.2,\ 4.2)$ TeV. ($M_{W1} = 500$ GeV)
- Optimal Unitary Bound: $E^\star = (1.9,\ 2.1,\ 2.2,\ 2.4)$ TeV.

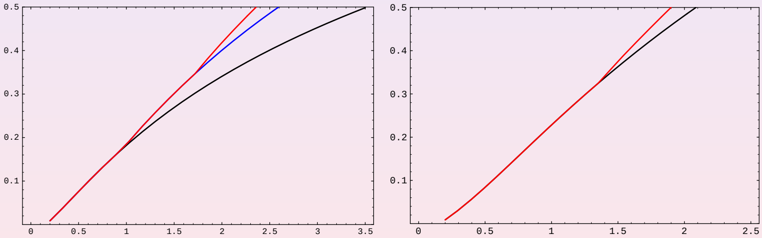


Effective Unitarity: Coupled Channel Analysis

RSC, HJH, MK, EHS, MT, arXiv:0807.nnnn

5d Warped Higgsless Models:

- **Elastic Unitary Bound**: $E^{\star} = 3.4(\text{left}),\ 2.1(\text{right})$ TeV.
- **Optimal Unitary Bound**: $E^{\star} = 2.35(\text{left}),\ 1.90(\text{right})$ TeV



- $M_{W1} = 500\,\text{GeV}$ (left-plot), $M_{W1} = 700\,\text{GeV}$ (right-plot)

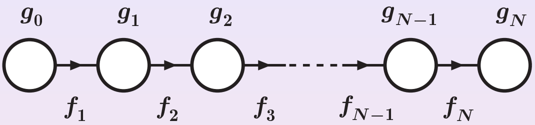
5d Gauge Symmetry Breaking from Deconstruction & Induced Boundary Conditions

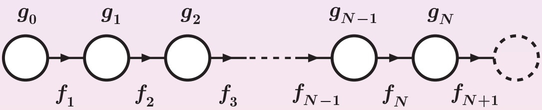
- ► **Deconstruction formulates ALL 5D gauge symmetry breakings in terms of the well-understood symmetry breaking of 4D Nonlinear Gauge Sigma Model a la CCWZ, without imposing, a priori, any Boundary Condition (which is automatically induced in the the 5D-continuum)!**

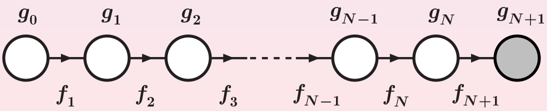
- ► **Deconstruction classifies ALL 5D gauge symmetry breaking patterns including gauge group rank-reduction.**

All 5d Higgsless Theories from Deconstruction

RSC, et al, hep-ph/0406077
HJH, hep-ph/0412113







All 5d Higgsless Theories from Deconstruction

RSC, et al, hep-ph/0406077
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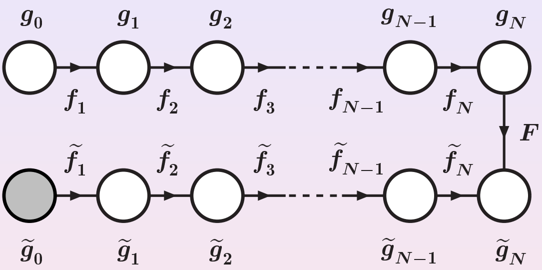
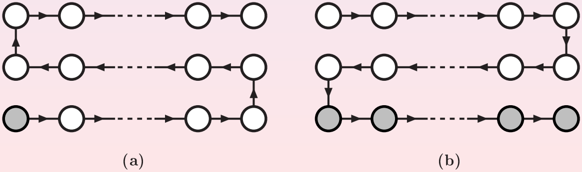
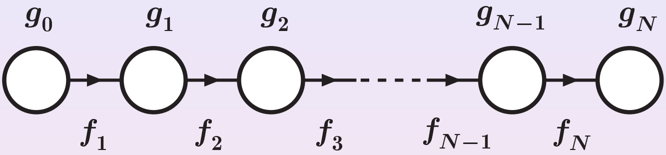




5d Gauge Symm Breaking from DC & Induced BCs

HJH, hep-ph/0412113

Deconstruction Moose-A:



► **Analyzing mass-matrix of Moose-A, we deduce Consistency Conditions on eigenvectors:**

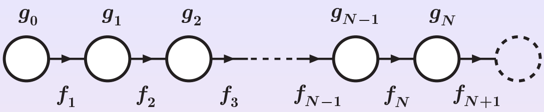
$$g_0 X_{0,n} - g_{-1} X_{-1,n} = 0 \,, \qquad g_{N+1} X_{N+1,n} - g_N X_{N,n} = 0 \,.$$

★ **We derive Induced Neumann BCs at 5d Continuum,**

$$\partial_5 \widehat{A}^a_\mu \Big|_{x^5=0} = 0 \,, \qquad \partial_5 \widehat{A}^a_\mu \Big|_{x^5=L} = 0 \,.$$

Induced BCs from Deconstruction Moose-B

HJH, hep-ph/0412113



▶ **Gauge boson mass-matrix of Moose-B:**

$$\mathbb{M}_W^2 = \frac{1}{4}\begin{pmatrix} g_0^2 f_1^2 & -g_0 g_1 f_1^2 & & & \\ -g_0 g_1 f_1^2 & g_1^2(f_1^2+f_2^2) & -g_1 g_2 f_2^2 & & \\ & -g_1 g_2 f_2^2 & g_2^2(f_2^2+f_3^2) & -g_2 g_3 f_3^2 & \\ & & \ddots & \ddots & \ddots \\ & & & -g_{N-1} g_N f_N^2 & g_N^2(f_N^2+f_{N+1}^2) \end{pmatrix},$$

▶ **Analyzing $\mathbb{M}_W^2 \Rightarrow$ Consistency Conditions on eigenvectors:**

$$g_0 X_{0,n} - g_{-1} X_{-1,n} = 0\,, \qquad X_{N+1,n} = 0\,.$$

★ **We derive Induced Neumann/Dirichlet BCs at 5d Continuum,**

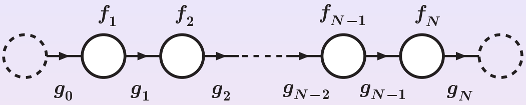
$$\partial_5 \widehat{A}^a_\mu\Big|_{x^5=0} = 0\,, \qquad \widehat{A}^a_\mu\Big|_{x^5=L} = 0\,.$$

Dual Moose and Induced BCs for $\widehat{A}_5^a$

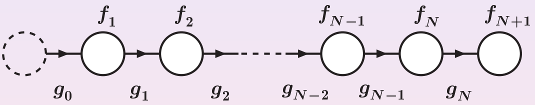
Dual Moose-$\widetilde{\rm A}$ and -$\widetilde{\rm B}$

HJH, hep-ph/0412113

(a).



(b).



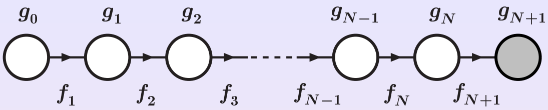
- **Dual Moose-$\widetilde{\rm A}$: Conditions for Mass-eigenvectors $\Rightarrow$ 5D BCs,**

$$\widetilde{X}_{0,n} = 0\,, \quad \widetilde{X}_{N+1,n} = 0\,; \quad \Longrightarrow \quad \widehat{A}_5^a\Big|_{x^5=0} = 0\,, \quad \widehat{A}_5^a\Big|_{x^5=L} = 0\,.$$

- **Dual Moose-$\widetilde{\rm B}$: Conditions for mass-eigenvectors $\Rightarrow$ 5D BCs,**

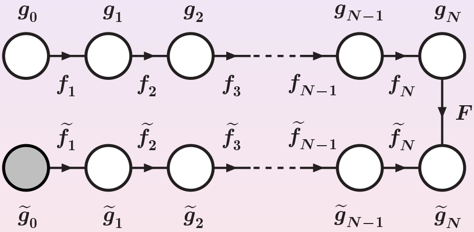
$$\widetilde{X}_{0,n} = 0\,, \; f_{N+2}\widetilde{X}_{N+2,n} - f_{N+1}\widetilde{X}_{N+1,n} = 0\,; \; \Rightarrow \; \widehat{A}_5^a\Big|_{x^5=0} = 0\,, \; \partial_5(h^2\widehat{A}_5^a)\Big|_{x^5=L} = 0$$

Induced BCs from Deconstruction Moose-C & -D



► **Analyzing its Mass-matrix, we deduce 5d BCs for Moose-C:**

$$\partial_5 \widehat{A}^{\pm}_{\mu}\Big|_{x^5=0} = 0\,, \quad \partial_5 \widehat{A}^{3}_{\mu}\Big|_{x^5=0} = 0\,; \quad \widehat{A}^{\pm}_{\mu}\Big|_{x^5=L} = 0\,, \quad \partial_5 \widehat{A}^{3}_{\mu}\Big|_{x^5=L} = 0\,.$$



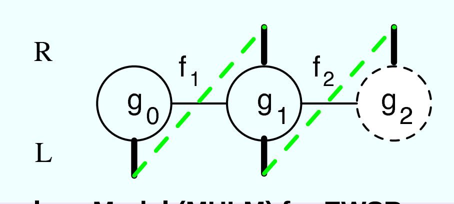
► **We further deuce 5d BCs for Moose-D:**

$$\partial_5 \widehat{A}^{a\mu}_{L}\Big|_{x^5=0} = 0\,; \quad \widehat{A}^{\pm\mu}_{R}\Big|_{x^5=0} = 0\,, \quad \partial_5 \widehat{A}^{3\mu}_{R}\Big|_{x^5=0} = 0\,;$$

$$\left(\widehat{g}_L \widehat{A}^{a\mu}_{L} - \widehat{g}_R \widehat{A}^{a\mu}_{R}\right)\Big|_{x^5=L} = 0\,, \quad \partial_5\left(\widehat{g}_R \widehat{A}^{a\mu}_{L} + \widehat{g}_L \widehat{A}^{a\mu}_{R}\right)\Big|_{x^5=L} = 0\,.$$

LHC Signatures of Minimal Higgsless EWSB

Chivukula, et al, hep-ph/0607124



▶ **Minimal Higgsless Model (MHLM) for EWSB:**

$SU(2)_0 \otimes SU(2)_1 \otimes U(1)_2 \to U(1)_{\rm em}$

$$\frac{1}{g_0^2}+\frac{1}{g_1^2}+\frac{1}{g_2^2} = \frac{1}{e^2}\,, \qquad \frac{1}{f_1^2}+\frac{1}{f_2^2} = \frac{1}{v^2}$$

Maximal delay of unitarity violation occurs around $f_1 = f_2 = \sqrt{2}v$**.**

▶ **Predictions of MHLM: New gauge bosons** (W_1, Z_1) **and new vector-like fermions** F_1 **for each family.**

▶ **Precision constraints require:**

$$M_{W_1} \geqslant 380\,{\rm GeV}\,, \qquad M_{F_1} \geqslant 1.8\,{\rm TeV}\,.$$

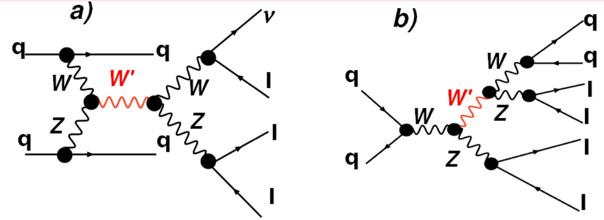
Higgsless Signatures at LHC: W_1 Boson

HJH, YPK, YHQ, BZ (Tsinghua)
AB, RSC, NDC, AP, EHS (MSU)
arXiv:0708.2588

- **Two processes for W_1 discovery at LHC:**

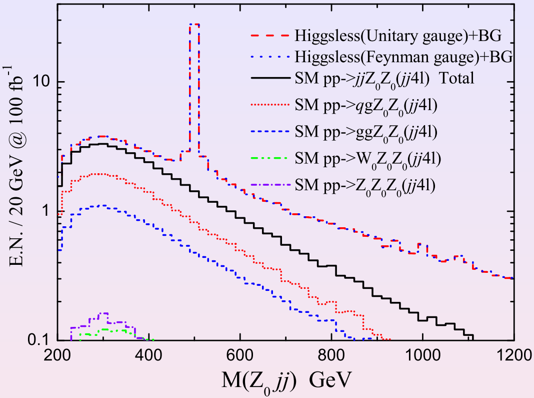
$$pp \longrightarrow W_0Z_0Z_0 \longrightarrow jj4\ell \qquad \text{(right diagram)}$$

$$pp \longrightarrow jjW_0Z_0 \longrightarrow jj\nu 3\ell \qquad \text{(left diagram)}$$



W_1 Signatures at LHC: $pp \to W_0Z_0Z_0 \to jj4\ell$

arXiv:0708.2588



- Cuts for suppressing SM backgrounds:

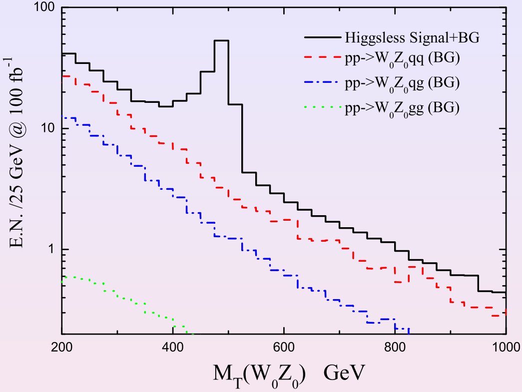
$$M_{jj} = 80 \pm 15\,\text{GeV}, \quad \Delta R(jj) < 1.5, \quad \sum_Z p_T(Z) + \sum_j p_T(j) = \pm 15\,\text{GeV}$$

- Cuts for particle identification:

$$p_{T\ell} > 10\,\text{GeV}, \quad |\eta_\ell| < 2.5, \quad p_{Tj} > 15\,\text{GeV}, \quad |\eta_j| < 4.5$$

W_1 Signatures at LHC: $pp \longrightarrow jjW_0Z_0 \longrightarrow jj\nu 3\ell$

arXiv:0708.2588



- Cuts for suppressing SM backgrounds:

$$E_j > 300\,\text{GeV}, \quad P_{Tj} > 30\,\text{GeV}, \quad |\eta_j| < 4.5, \quad |\Delta\eta_{jj}| > 4\,.$$

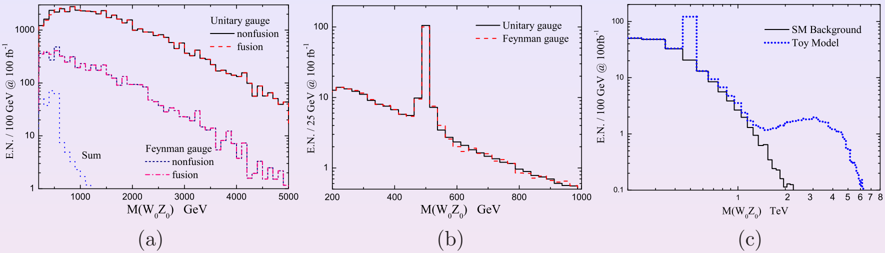
- Lepton identification cuts,

$$p_{T\ell} > 10\,\text{GeV}, \quad |\eta_\ell| < 2.5$$

Exact Gauge-Invariance vs Large Cancellation

▶ **Process** $pp \to W_0Z_0qq'$

arXiv:0708.2588



▶ **Our MHLM Lagrangian via Deconstruction is exactly gauge-invariant.**

▶ **Large cancellation between Fusion and Non-fusion Diagrams:**
E.g., at $M_{W_0Z_0} = 1$ **TeV, we find a Large Cancellation by a factor of**

$2400/2.3 \simeq 1043$ **(Unitary Gauge), and**

$195/2.3 \simeq 84.7$ **('t Hooft-Feynman Gauge).**

▶ **A 5d Toy Model via naive sum rule approach: violates gauge-invariance due to incomplete and inconsistent determinations of various gauge couplings.** $\Longrightarrow$ **destroy the Large Cancellation due to an extra faked bump around 1.5-6 TeV, as shown in Fig.(c) in unitary gauge.**

Summary of LHC Discovery Potential

arXiv:0708.2588