

Overview of Higgsless Electroweak Symmetry Breaking and LHC Signatures

Hong-Jian He

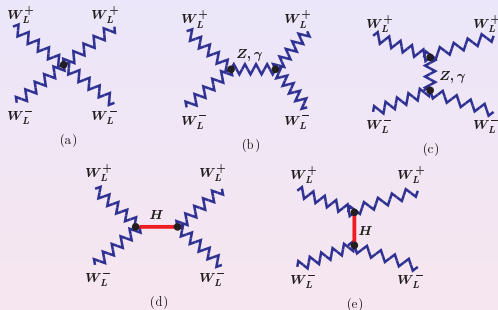
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- 1 Higgsless EWSB: Unitarity via Spin-1 Gauge Bosons
- 2 Geometric Higgs Mechanism and KK ET
- 3 All E -Cancellations at $O(E^{4,3,2,1,0})$ derived from ET
- 4 Effective Unitarity from Higgsless Deconstruction
- 5 Boundary Conditions from Gauge-Invariant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

Review: Unitarity of 4d SM

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



► **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

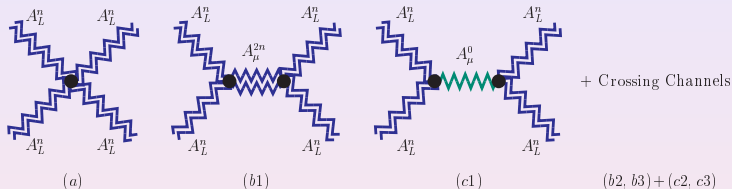
► **At $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound:** $m_H < \sqrt{16\pi/3} v \simeq 1.0 \text{ TeV}$

► **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

Chivukula, Dicus, He
hep-ph/0111016

► Example of 5d KK Gauge Theory:



► E-Power Counting:

$$(a) = \mathcal{O}(E^4) \oplus \mathcal{O}(E^2)$$

$$(b1), (b2), (b3) = \mathcal{O}(E^4) \oplus \mathcal{O}(E^2)$$

$$(c1), (c2), (c3) = \mathcal{O}(E^4) \oplus \mathcal{O}(E^2)$$

E-Cancellation in Longitudinal KK Scattering

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► 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	$-8cx^2$	$-8cx^2$	$-8cx^2$	$\implies \mathbf{0}$

KK Equivalence Theorem (KK-ET)

Chivukula, Dicus, He

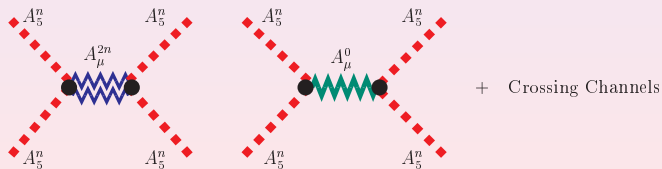
► KK-ET results from “**Geometric Higgs Mechanism**”:

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

► Formulated in R_ξ Gauge: $[C_{\text{mod}} = 1 + O(\text{loop})]$

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

► KK Goldstone A_5^{an} Scattering:



► Power Counting $\Rightarrow \mathcal{T}[A_5^{an}, A_5^{bm}, \dots] \leq \mathcal{O}(E^0)$

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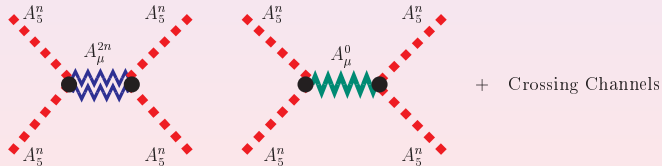
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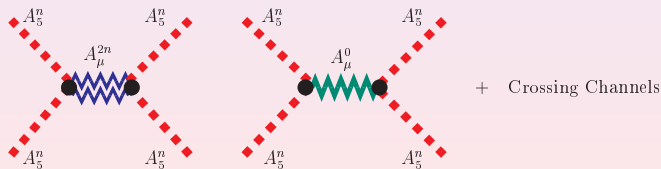
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KK-ET and Goldstone Boson Scattering

Chivukula, Dicus, He

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

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

- ▶ **Explicit Calculations give,**

$$\begin{aligned} \mathcal{T} [A_5^{an} A_5^{an} \rightarrow A_5^{an} A_5^{an}] &= g^2 [C^{abe} C^{cde} \left(-\frac{3}{2}c\right) \\ &+ C^{ace} C^{dbe} \left(-\frac{3(3+c)}{2(1-c)}\right) + C^{ade} C^{bce} \left(\frac{3(3-c)}{2(1+c)}\right)] + \mathcal{O}\left(\frac{M_h^2}{E^2}\right) \end{aligned}$$

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

$$\begin{aligned} \mathcal{T} [A_L^{an} A_L^{bn} \rightarrow A_L^{cn} A_L^{dn}] &= g^2 [C^{abe} C^{cde} \left(\frac{5}{2}c\right) \\ &+ C^{ace} C^{dbe} \left(-\frac{8c^2-5c+9}{2(1-c)}\right) + C^{ade} C^{bce} \left(\frac{8c^2+5c+9}{2(1+c)}\right)] + \mathcal{O}\left(\frac{M_h^2}{E^2}\right) \end{aligned}$$

up to a Jacobi identity!

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up to a **Jacobi identity!**

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

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

defined on general 5d background,

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

where the metric

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

with 2 special cases:

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

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

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}

$$\int_0^L dx^5 h^2(x^5) \left(-\frac{1}{2} \left[\left(\partial_5 \widehat{A}_\mu^a \right)^2 + \partial_\mu \widehat{A}_5^a \partial^5 \widehat{A}^{a\mu} + \left(\partial_\mu \widehat{A}_5^a \right)^2 \right] \right)$$

★ Geometric Higgs Mechanism: $A_L^{an} \longleftrightarrow A_5^{an}$

- ▶ We construct a General R_ξ Gauge:

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

with corresponding FP Ghost Term: $\widehat{\mathcal{L}}_{\text{FP}} = \widehat{\bar{c}}^a \widehat{S} \widehat{F}^a$,

and the 5d BRST transformations,

$$\widehat{S} \widehat{A}^{aJ} = D_b^{aJ}(\widehat{A}) \widehat{c}^b, \quad \widehat{S} \widehat{c}^a = -\frac{1}{2} g_5 C^{abc} \widehat{c}^b \widehat{c}^c, \quad \widehat{S} \widehat{\bar{c}}^a = -\xi^{-1} \widehat{F}^a$$

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Geometric Higgs Mechanism via KK-ET

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

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

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

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

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★ 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** under **Any Consistent BC**.

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All E-Power Cancellations from ET

RSC, HJH, MK, EHS, MT, arXiv:0808.1682

► We derive general ET for 5d and deconstruction:

$$\begin{aligned} \mathcal{T} \left[V_L^{a_1 n_1}, V_L^{a_2 n_2}, \dots \right] &= \widehat{\mathcal{C}}_{\text{mod}}^{n_1 m_1, n_2 m_2 \dots} \mathcal{T} \left[V_5^{a_1 m_1}, V_5^{a_2 m_2}, \dots \right] + B \\ &= \widehat{\mathcal{C}}_{\text{mod}}^{n_1 m_1, n_2 m_2 \dots} \mathcal{T} \left[\pi^{a_1 m_1}, \pi^{a_2 m_2}, \dots \right] + B \end{aligned}$$

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

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

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

$$\mathcal{O}(E^4): \quad T_L(E^4) = 0;$$

$$\mathcal{O}(E^3): \quad T_L(E^3) = 0;$$

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

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

$$\mathcal{O}(E^0): \quad T_L(E^0) = T_\pi(E^0) + B(E^0).$$

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

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

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

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All E-Power Cancellations from ET

RSC, HJH, MK, EHS, MT, arXiv:0808.1682

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Summary of All E-Cancellation Conditions (1)

RSC, HJH, MK, EHS, MT, arXiv:0808.1682

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

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

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

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

Summary of All E-Cancellation Conditions (2)

RSC, HJH, MK, EHS, MT, 0808.1682

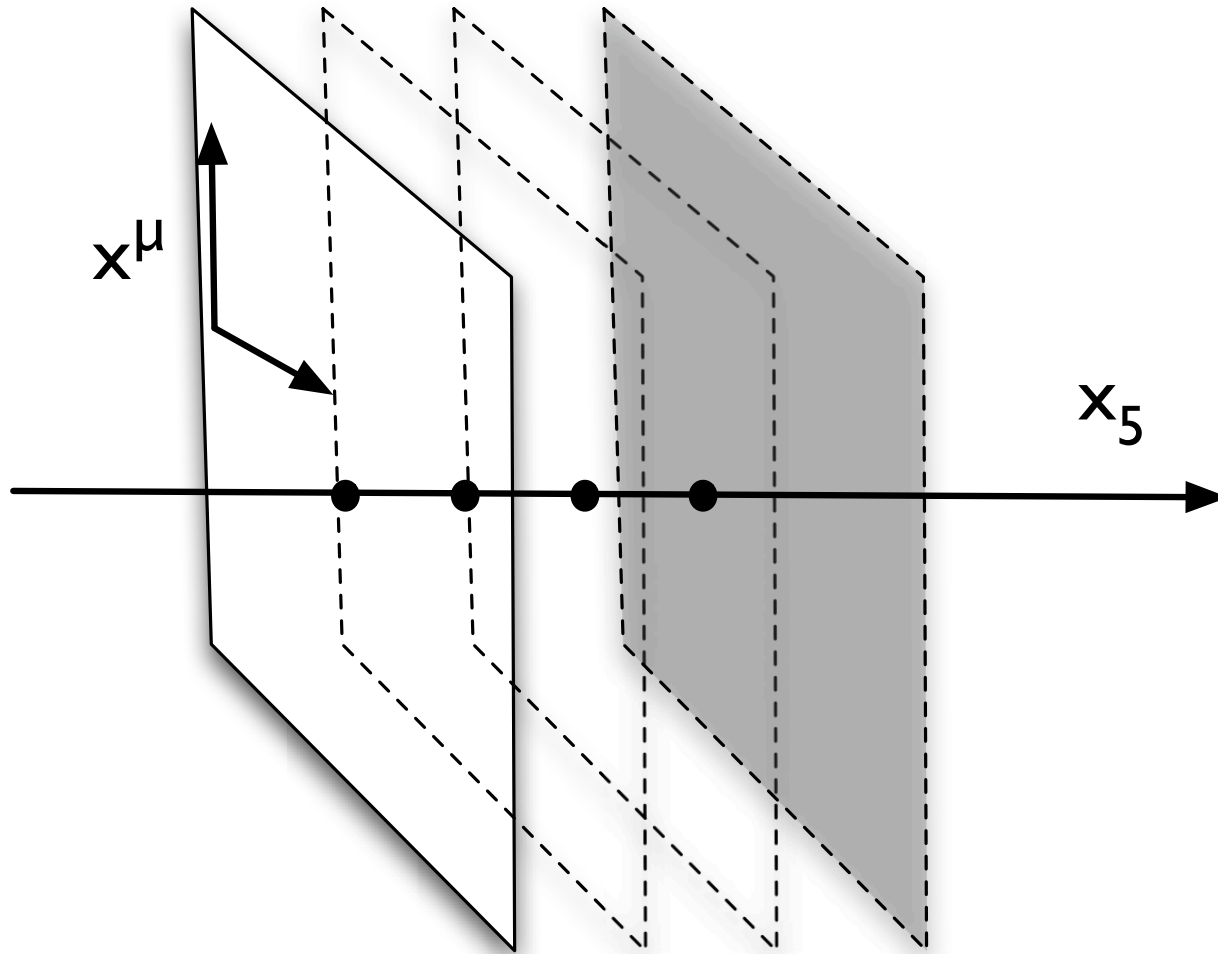
★ From General $W_n^a W_n^b \rightarrow W_m^c W_m^d$ (In)elastic Scattering, we derive **Cancellation Conditions** at $O(E^{1,0})$,

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

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

$$\begin{aligned} & G_4^{nnmm} M_-^4 + \sum_k \left[\left(G_3^{nmk} \right)^2 - G_3^{nnk} G_3^{mkm} \right] \left(M_k^4 - 2M_+^2 M_k^2 \right) \\ &= M_n^2 M_m^2 \sum_k \left[\left(\tilde{G}_3^{nmk} \right)^2 - \tilde{G}_3^{nnk} \tilde{G}_3^{mkm} \right], \end{aligned}$$

Latticize Fifth Dimension



► **General Deconstruction Lagrangian,**

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

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

► **Interaction Lagrangian in Unitary Gauge,**

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

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

► **The gauge self-couplings:**

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

General Higgsless Deconstruction

► Goldstone Interaction Lagrangian:

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

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

where the Goldstone couplings are:

$$\tilde{G}_4^{klmn} = \sum_{j=1}^{N+1} \frac{V^2}{f_j^2} \tilde{R}_{jk}^a \tilde{R}_{j\ell}^a \tilde{R}_{jm}^b \tilde{R}_{jn}^b,$$

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

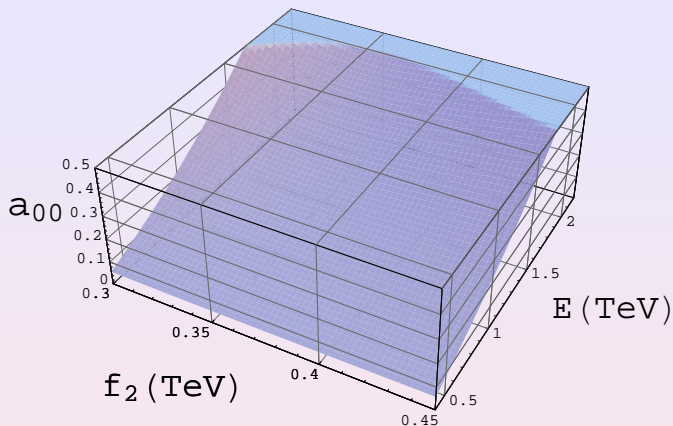
$$\tilde{G}_3^{mnk} = \sum_{j=1}^{N+1} \tilde{R}_{jm}^a \tilde{R}_{jn}^b \left(g_j \mathbb{R}_{jk}^c + g_{j-1} \mathbb{R}_{j-1,k}^c \right).$$

Effective Unitarity

HJH, hep-ph/0412113

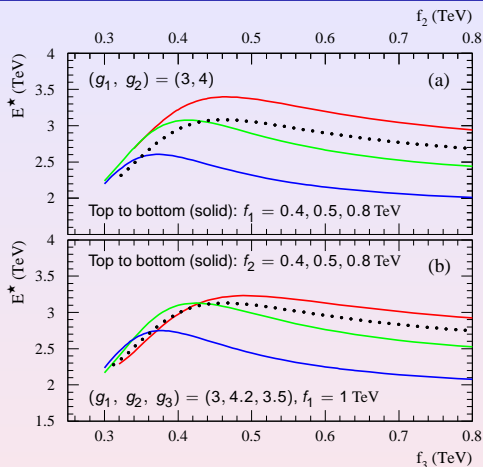
- ▶ **Delay of Unitarity Violation** is essentially a **Collective Effect** due to participation in EWSB from **Many Gauge Groups** whose own symmetry breaking scales $\{f_j\}$ are higher than SM-EWSB scale $v = (\sqrt{2}G_F)^{-1/2}$.
- ▶ Such a **Collective Effect** does not necessarily require any 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 $W_{0L}W_{0L} \rightarrow W_{0L}W_{0L}$ scattering. Input $M_{W_1} = 400 \text{ GeV}$. The (nearly) maximal delay of unitary violation occurs in a sizable range $f_2 \in (0.34, 0.38) \text{ TeV}$, rather than a single point at $f_1 = f_2 = \sqrt{2}v \simeq 0.35 \text{ TeV}$.

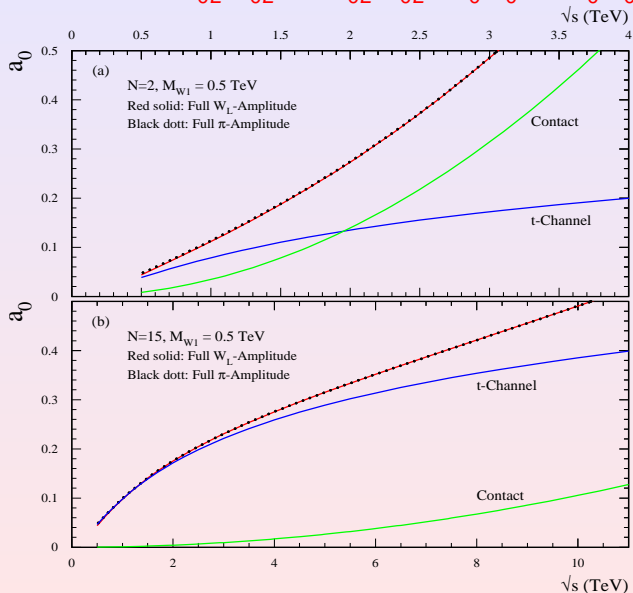
More Examples of Effective Unitarity



► **Unitary limit E^*** for: (a) moose $SU(2)^3 \otimes U(1)$, and (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 typical Flat Geometry Inputs: $g_1 = g_2 = 4$, $f_1 = \sqrt{3}v \simeq 0.43$ TeV in (a); and $g_1 = g_2 = g_3 = 4$, $f_1 = 1$ TeV, $f_2 = \sqrt{3}v$ in (b).

Effective Unitarity: Contact vs t/u Channel

► Scattering $W_{OL}^+ W_{OL}^- \rightarrow W_{OL}^+ W_{OL}^-$ ($\pi_0^+ \pi_0^- \rightarrow \pi_0^+ \pi_0^-$):



Chivukula, et al,
hep-ph/0612070

Coupled Channel Analysis of Effective Unitarity

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

$$\sqrt{\left(\operatorname{Re} \hat{a}_{jI}^{nn}\right)^2 + \sum_{m(\neq n)} \left|\hat{a}_{jI}^{mn}\right|^2} < \frac{1}{2}$$

which gives

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

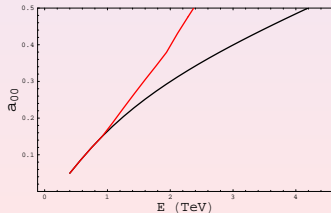
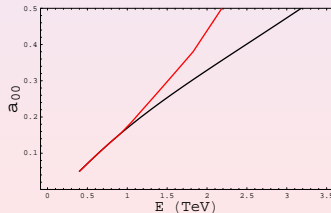
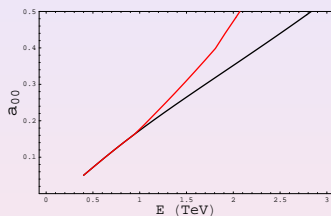
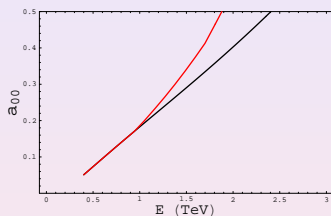
★ Optimal Unitarity Condition:

$$\max \left| \left(\hat{\underline{a}}_{jI}^{\text{diag}} \right)_{ii} \right| < \frac{1}{2}, \quad (i = 0, 1, 2, \dots, N)$$

Effective Unitarity: Coupled Channel Analysis

RSC, HJH, MK, EHS, MT, arXiv:0904.nnnn

- ▶ **Flat Models:** $N+1 = 3$ (upper left), 4 (upper right), 5 (lower left), 10 (lower right)
- ▶ Elastic Unitary Bound: $E^* = (2.4, 2.8, 3.2, 4.2)$ TeV. ($M_{W_1} = 500$ GeV)
- ▶ Optimal Unitary Bound: $E^* = (1.9, 2.1, 2.2, 2.4)$ TeV.

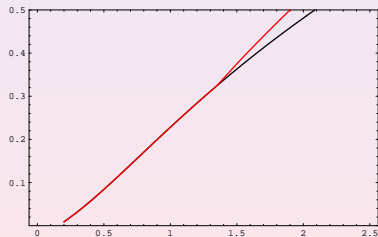
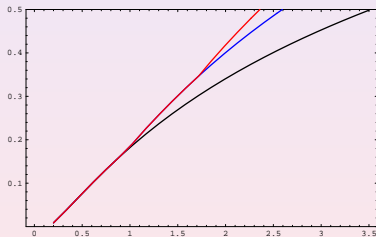


Effective Unitarity: Coupled Channel Analysis

RSC, HJH, MK, EHS, MT, arXiv:0904.nnnn

5d Warped Higgsless Models

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



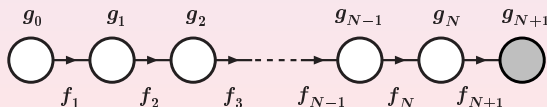
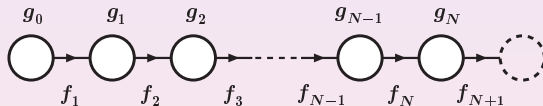
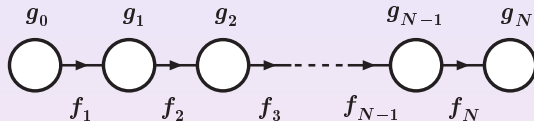
- ▶ $M_{W1} = 500 \text{ GeV}$ (left-plot), $M_{W1} = 700 \text{ GeV}$ (right-plot)

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 Gauged Sigma Model** a la CCWZ, **without** invoking, a priori, any **Boundary Condition** (which is automatically **induced** in the 5D-continuum)!
- ▶ **Deconstruction** classifies **ALL 5D gauge symmetry breaking patterns** including gauge group rank-reduction.

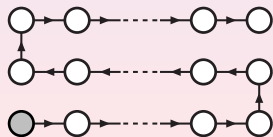
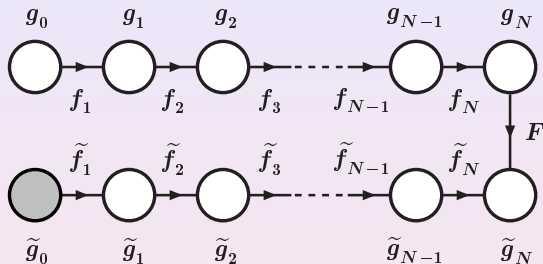
All 5d Higgsless Theories from Deconstruction

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

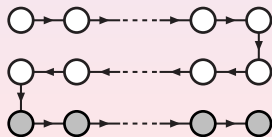


All 5d Higgsless Theories from Deconstruction

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



(a)

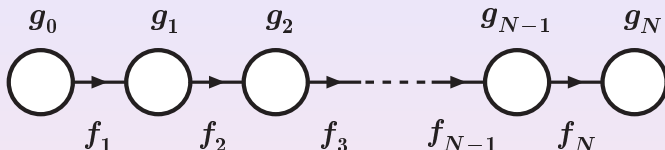


(b)

5d Gauge Symm Breaking from DC & Induced BCs

HJH, hep-ph/0412113

Deconstruction Moose-A:

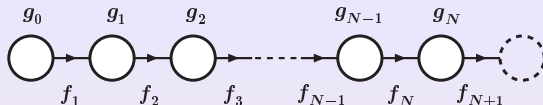


- Analyzing mass-matrix of Moose-A, we deduce **Consistency Conditions** on eigenvectors:

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

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

$$\partial_5 \hat{A}_\mu^a \Big|_{x^5=0} = 0, \quad \partial_5 \hat{A}_\mu^a \Big|_{x^5=L} = 0.$$



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

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

► Analyzing $M_W^2 \Rightarrow$ **Consistency Conditions** on eigenvectors:

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

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

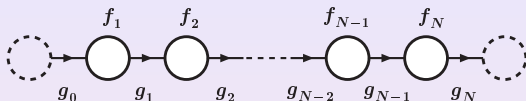
$$\partial_5 \widehat{A}_\mu^a \Big|_{x^5=0} = 0, \quad \widehat{A}_\mu^a \Big|_{x^5=L} = 0.$$

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

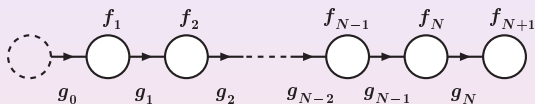
Dual Moose- \widetilde{A} and \widetilde{B}

HJH, hep-ph/0412113

(a).



(b).



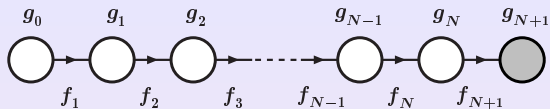
► **Dual Moose- \widetilde{A}** : Conditions for Mass-eigenvectors \Rightarrow 5D BCs,

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

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

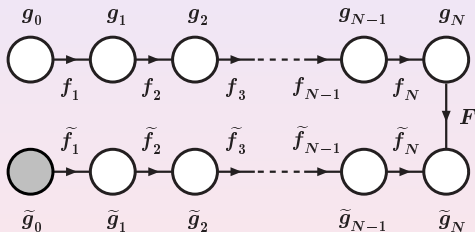
$$\widetilde{X}_{0,n} = 0, \quad f_{N+2} \widetilde{X}_{N+2,n} - f_{N+1} \widetilde{X}_{N+1,n} = 0; \quad \Rightarrow \quad \widehat{A}_5^a \Big|_{x^5=0} = 0, \quad \partial_5 (h^2 \widehat{A}_5^a) \Big|_{x^5=L} = 0$$

Induced BCs from Deconstruction Moose-C & -D



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

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



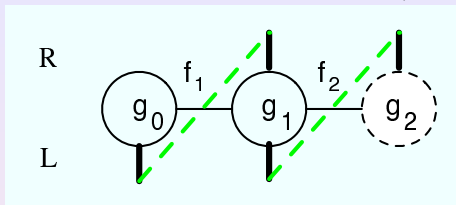
► We further deduce **5d BCs for Moose-D**:

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

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

LHC Signatures of Minimal Higgsless EWSB

Chivukula, et al, hep-ph/0607124



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

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

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

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:**

$$M_{W_1} \geq 380 \text{ GeV}, \quad M_{F_1} \geq 1.8 \text{ TeV}.$$

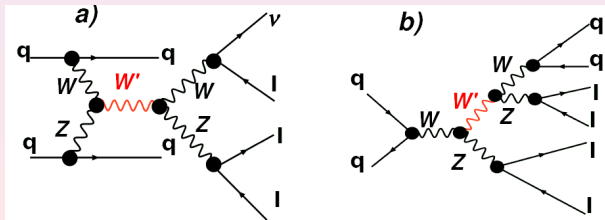
Higgsless Signatures at LHC: W_1 Boson

HJH, YPK, YHQ, BZ (Tsinghua)
AB, RSC, NDC, AP, EHS (MSU)
PRD78(2008)031701(R)

► Two processes for W_1 discovery at LHC:

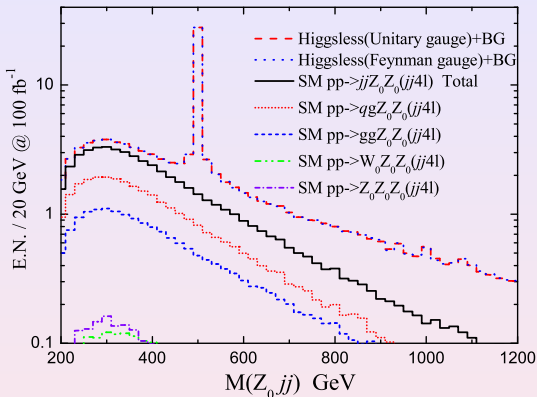
$$pp \rightarrow W_0 Z_0 Z_0 \rightarrow jj4\ell \quad (\text{right diagram})$$

$$pp \rightarrow jjW_0 Z_0 \rightarrow jj\nu 3\ell \quad (\text{left diagram})$$



W_1 Signatures at LHC: $pp \rightarrow W_0 Z_0 Z_0 \rightarrow jj4\ell$

PRD78(2008)031701(R)

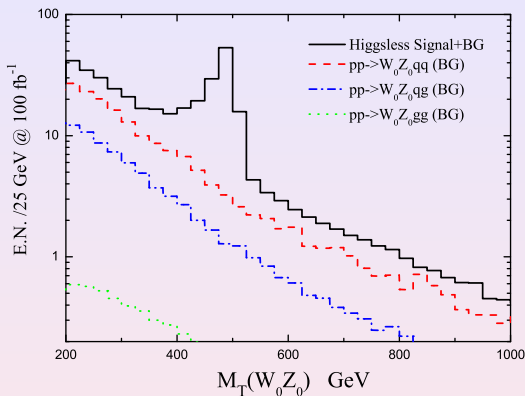


- ▶ Cuts for suppressing SM backgrounds:

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

- ▶ Cuts for particle identification:

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



- ▶ Cuts for suppressing SM backgrounds:

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

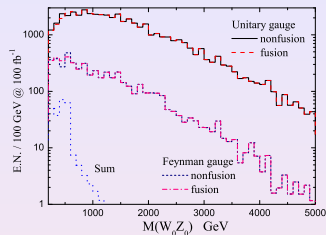
- ▶ Lepton identification cuts,

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

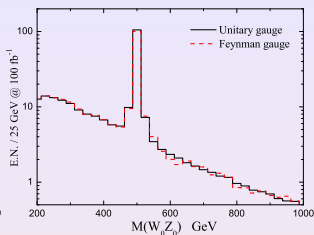
Exact Gauge-Invariance vs Large Cancellation

► Process $pp \rightarrow W_0 Z_0 qq'$

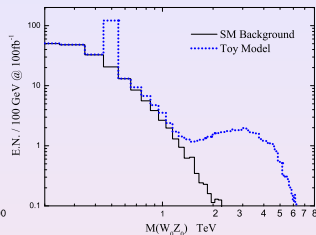
PRD78(2008)031701(R)



(a)



(b)



(c)

► Our MHLM Lagrangian via **Deconstruction** is **Exactly Gauge-Invariant**.

► Large cancellation between Fusion and Non-fusion Diagrams:

E.g., at $M_{W_0 Z_0} = 1$ TeV, we find a Large Cancellation by a factor of

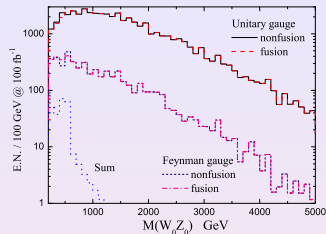
$2400/2.3 \simeq 1043$ (Unitary Gauge), and $195/2.3 \simeq 84.7$ (Feynman Gauge)

► A “5d Toy Model” via naive sum rule approach: violates gauge-invariance due to incomplete/inconsistent determinations of various gauge couplings. \implies **destroy the Large Cancellation** due to an extra **faked bump** around 1.5-6 TeV, as shown in Fig.(c) in Unitary Gauge.

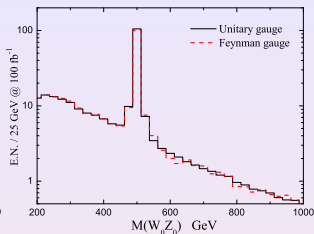
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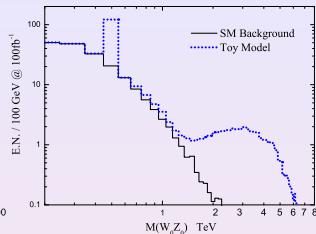
PRD78(2008)031701(R)



(a)



(b)



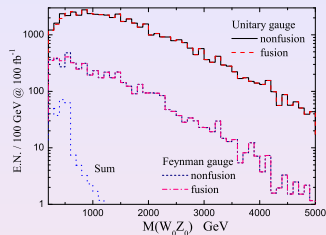
(c)

- Our MHLM Lagrangian via **Deconstruction** is **Exactly Gauge-Invariant**.
- **Large cancellation** between Fusion and Non-fusion Diagrams:
E.g., at $M_{W_0 Z_0} = 1$ TeV, we find a Large Cancellation by a factor of $2400/2.3 \simeq 1043$ (**Unitary Gauge**), and $195/2.3 \simeq 84.7$ (**Feynman Gauge**)
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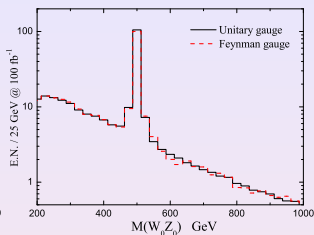
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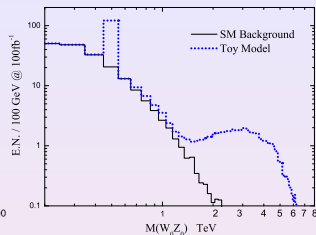
PRD78(2008)031701(R)



(a)



(b)

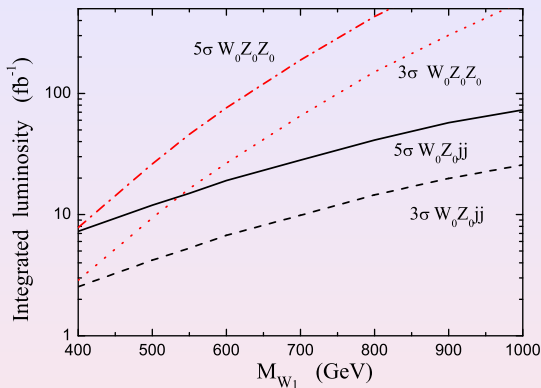


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Summary of LHC Discovery Potential

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5 σ Discovery: $pp \rightarrow W_0Z_0Z_0 \rightarrow jj4\ell$ $pp \rightarrow W_0Z_0jj \rightarrow \nu 3ljj$

$M_{W_1} = 400$ GeV: 7.8 fb $^{-1}$ 7 fb $^{-1}$

$M_{W_1} = 500$ GeV: 26 fb $^{-1}$ 12 fb $^{-1}$

Final Summary

- ▶ **Spin-1 Gauge Boson** (rather than Spin-0 Scalar) is the **key** for **Higgsless EWSB**, which exhibits **Effective Unitarity (Delayed Unitarity Violation)** in longitudinal gauge boson scattering.
- ▶ We demonstrate that the **E-Cancellation** and **Effective Unitarity** are ensured by the **Geometric Higgs Mechanism a la KK ET**.
- ▶ We demonstrate that All **E-Cancellations** at $O(E^{4,3,2,1,0})$ are generally guaranteed by **KK ET**, **independent** of any detail of the 5d Boundary Conditions (BCs).
- ▶ We demonstrate **Effective Unitarity** in general **Higgsless Deconstruction** for arbitrary 5d geometry or without any geometry (when only a few 4d Gauge Groups are invoked).
- ▶ We prove that all 5d BCs can be **automatically induced** from **Gauge-Invariant 4d Deconstruction** in continuum limit.
- ▶ We demonstrate the generic **LHC Discovery Signatures** of **Spin-1 New Gauge Bosons** from **Minimal Higgsless EWSB**.

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