Weak boson scattering in Gauge-Higgs Unification

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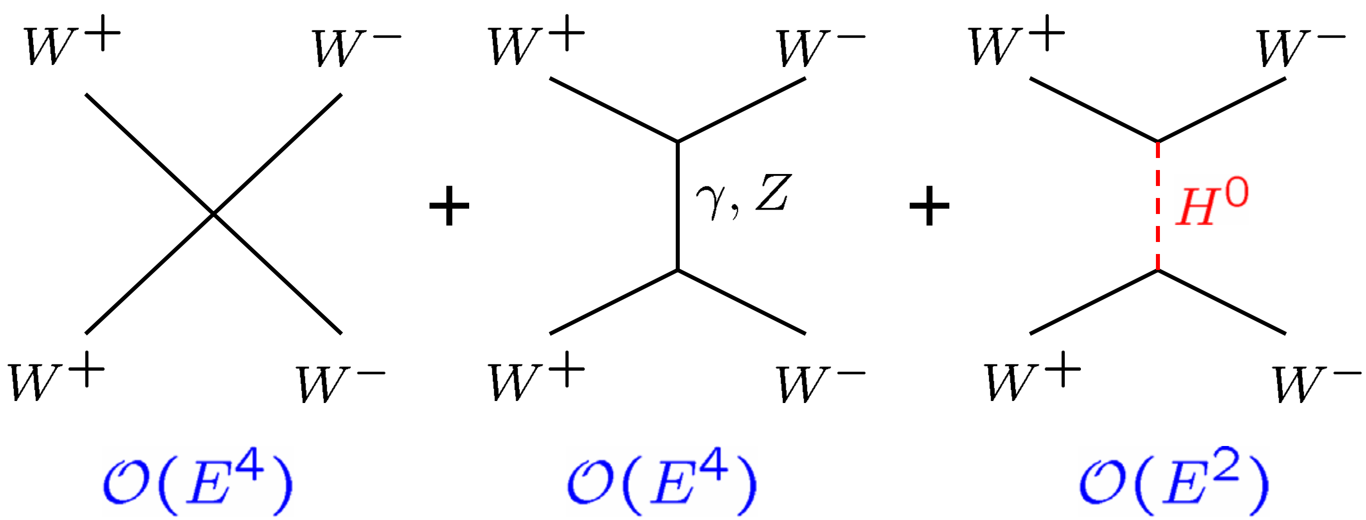
arXiv:0904.3177, 0907.xxxx

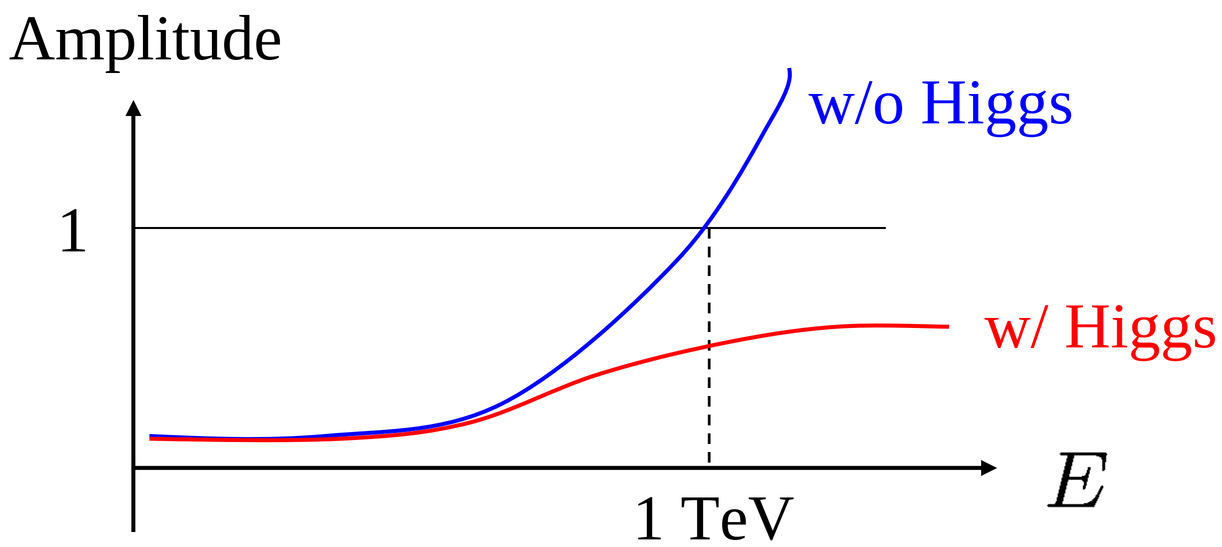
July. 7, 2009 @ PASCOS2009

Introduction

Higgs boson { Electroweak sym. breaking, (perturbative) unitarity

e.g.) $$\boldsymbol{W_L^+ + W_L^- \rightarrow W_L^+ + W_L^-}$$





If the WWH coupling vanishes, the Higgs boson cannot contribute to the unitarization.

This occurs in the **Gauge-Higgs Unification models in the warped spacetime**.

Models with extra dimension

EW breaking ⇐ **Boundary conditions** along the extra dimension

Higgsless model [Csaki, et.al, 2003]

Unitarity is recovered by KK gauge bosons

Gauge-Higgs Unification $A_M = (A_\mu, A_y)$ — A_y → Higgs

Unitarity is recovered by KK gauge bosons and zero-mode of A_y

Extra-dimensional model is non-renormalizable

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Tree-level unitarity will be violated at some scale.

Purpose

We numerically estimate

• the scattering amplitude for W, Z bosons

• a scale at which the tree-level unitarity is violated in the Gauge-Higgs Unification.

Gauge-Higgs Unification

Wilson line phase: $\theta_H \equiv g_5 \int_0^L dy\ A_y$

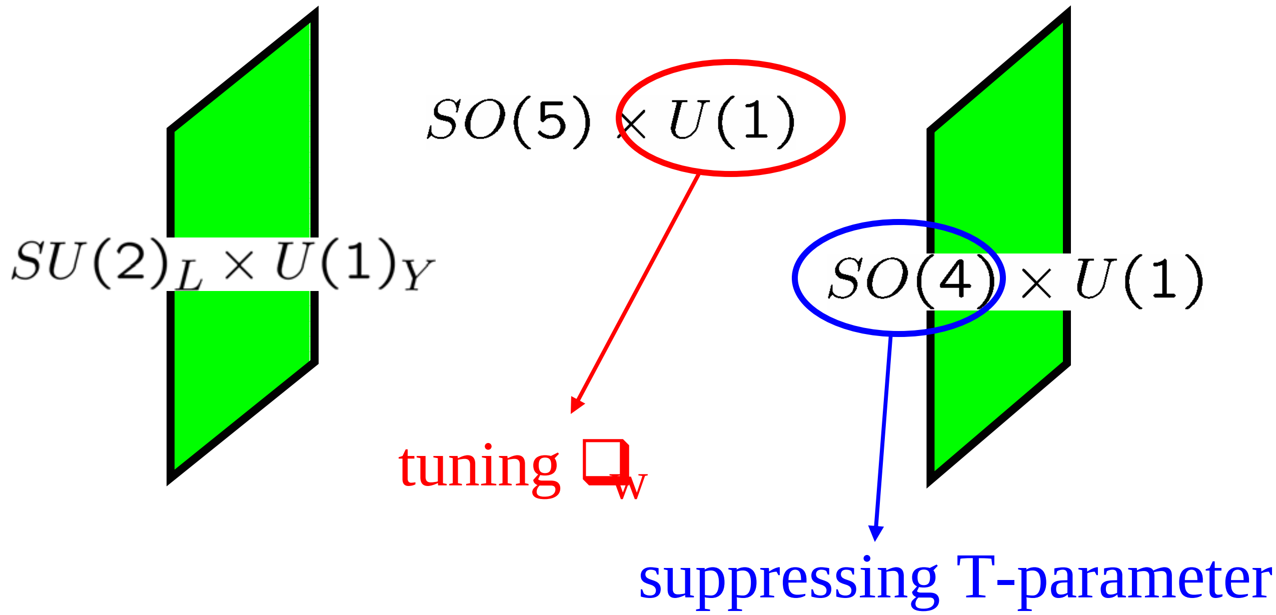
Contribution to the unitarization

	Higgs	KK modes
$\theta_H \ll 1$	main	less
$\theta_H = \mathcal{O}(1)$	less	main

[Falkowski, Pokorski, Roberts, 2007]

SO(5)xU(1) model on S^1/Z_2

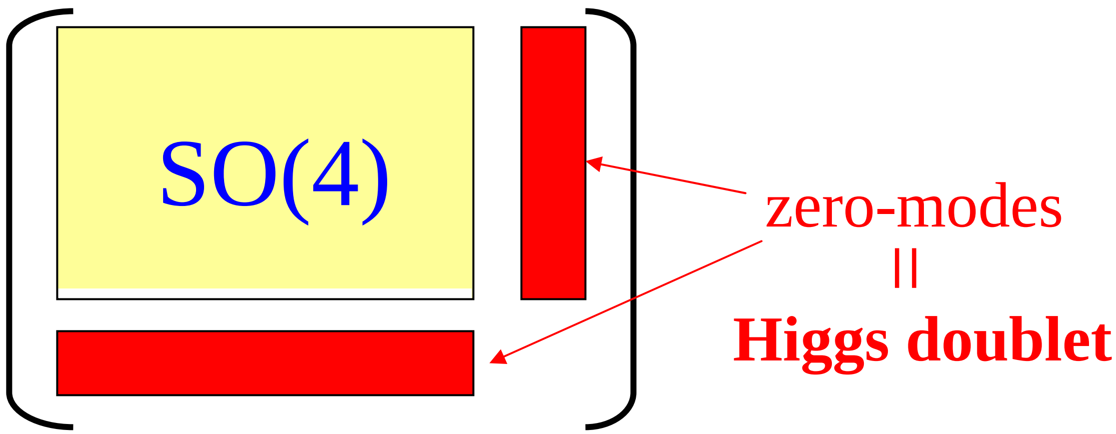
[Agashe, Contino, Pomarol, 2005]



Gauge symmetry :

$$SO(5) \times U(1) \rightarrow SU(2)_L \times U(1)_Y$$

$$\boldsymbol{A_y^{SO(5)}} =$$



Wilson line phase: $\theta_H = g_5 \int_0^L dy\ A_y \neq 0$

$\Rightarrow$ $SU(2) \times U(1) \rightarrow U(1)_{\rm EM}$

WWH, ZZH couplings

Flat case

$$\lambda_{WWH} = g_4 m_W, \quad \lambda_{ZZH} = g_4 m_Z. \quad \left(g_4 \equiv \frac{g_5}{\sqrt{L}} \right)$$

These are the same as the SM values.

Warped case [Hosotani & Y.S., 2006-2007]

$$\lambda_{WWH} = g_4 m_W \cos\theta_H, \quad \lambda_{ZZH} = g_4 m_Z \cos\theta_H.$$

When $\theta_H = \pi/2$, they vanish.

5D propagator

[Gherghetta & Pomarol, 2001]

$$i\eta_{\mu\nu} G_{\mathsf{T}}^{\alpha\beta}(p, y, y') \equiv \langle 0 | T A_\mu^\alpha(p, y) A_\nu^\beta(-p, y') | 0 \rangle$$

Advantages

We can calculate the amplitudes without

- the knowledge of the KK mass eigenvalues
- summation over infinite KK modes

In the conventional KK expansion,

$$G_{\mathsf{T}}^{\alpha\beta}(p, y, y') = -\sum_n \frac{u_n^\alpha(y) u_n^\beta(y')}{p^2 + m_n^2}$$

where $A_\mu^\alpha(p, y) = \sum_n u_n^\alpha(y) A_\mu^{(n)}(x)$

Equivalence Theorem

[Cornwall, Levin & Tiktopoulos, 1974; Lee, Quigg & Thacker, 1977]

longitudinal mode would-be NG boson

$$T(V_L^{a_1}, \cdots, V_L^{a_n}) = C_n T(\phi^{a_1}, \cdots, \phi^{a_n}) + \mathcal{O}(m_W/E)$$

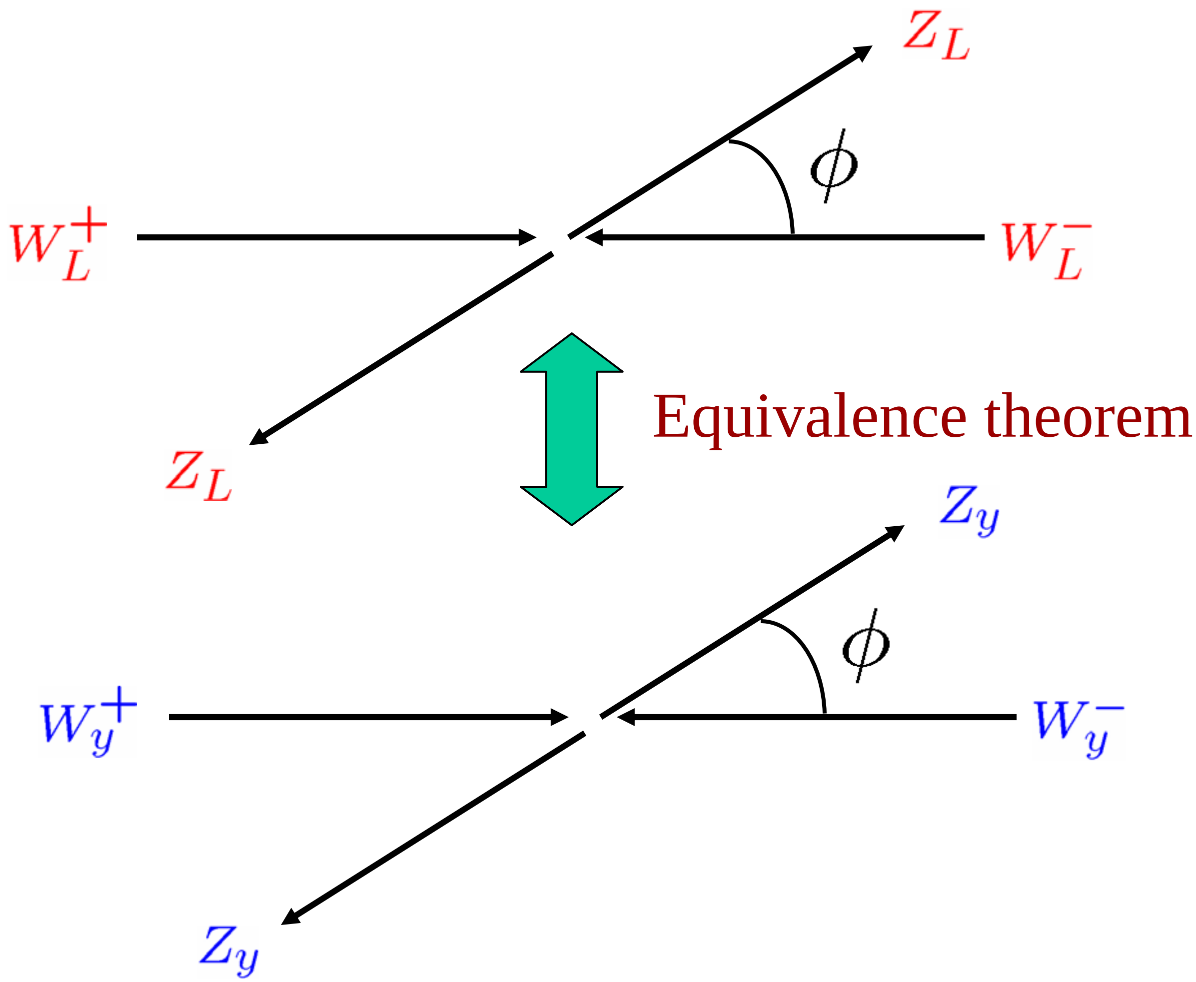
(at tree-level, $C_n = 1$)

KK equivalence theorem

[Chivukula, Dicus & He, 2002, …]

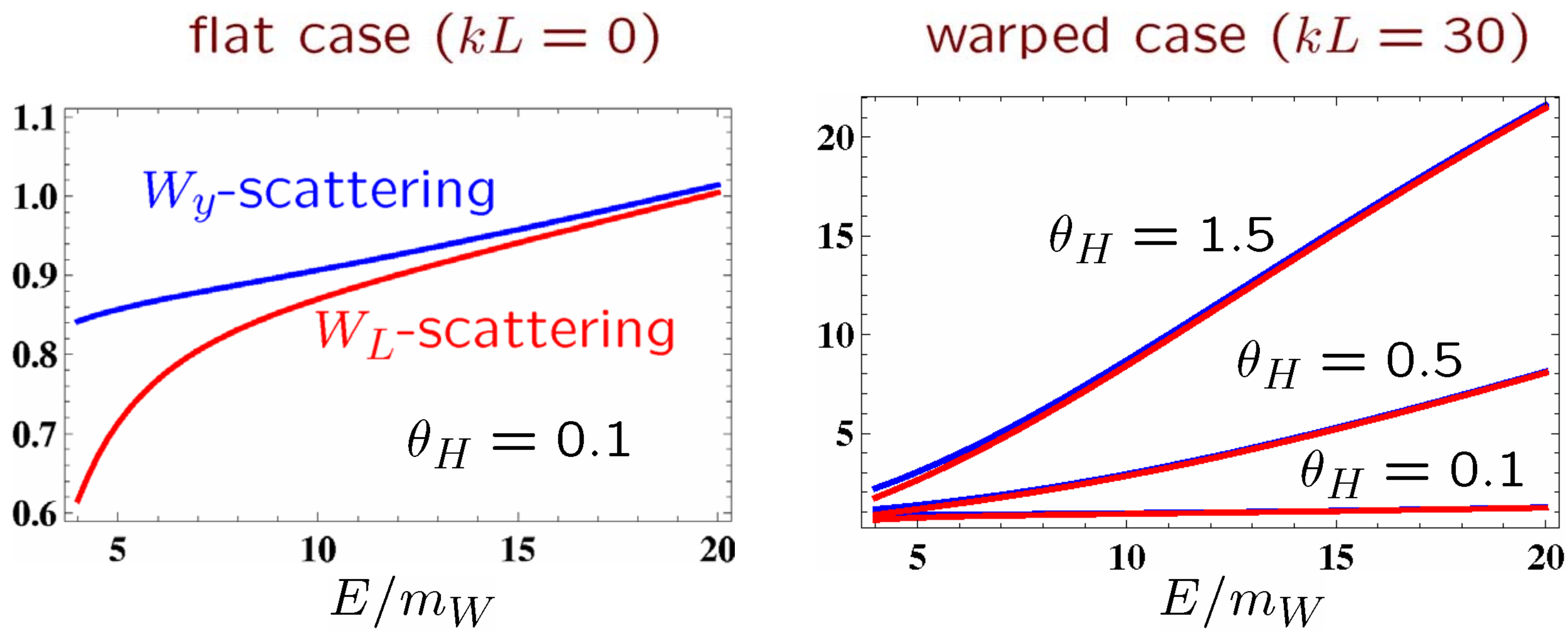
$$T(V_L^{a_1}, \cdots, V_L^{a_n}) = C_n T(V_y^{a_1}, \cdots, V_y^{a_n}) + \mathcal{O}(m_W^2/E^2)$$

In the following, we consider $\boldsymbol{W_L^+ + W_L^- \to Z_L + Z_L}$.



Scattering amplitude $\left(\phi = \frac{\pi}{3}\right)$

Metric $ds^2 = e^{ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \quad (0 \leq y \leq L)$



$$T(W_L^+ + W_L^- \to W_L^+ + W_L^-) = T(W_y^+ + W_y^- \to W_y^+ + W_y^-) + \mathcal{O}\left(\frac{m_W^2}{E^2}\right)$$

For $\theta_H = \mathcal{O}(1)$, each coupling deviates from the SM value.

[Hosotani & Y.S., 2007]

Flat case

$$g_{WWZ}, g_{WWZZ} < \text{the SM values}$$
$$\lambda_{WWH}, \lambda_{ZZH} = \text{the SM values}$$

Warped case

$$g_{WWZ}, g_{WWZZ} = \text{the SM values}$$
$$\lambda_{WWH}, \lambda_{ZZH} < \text{the SM values}$$

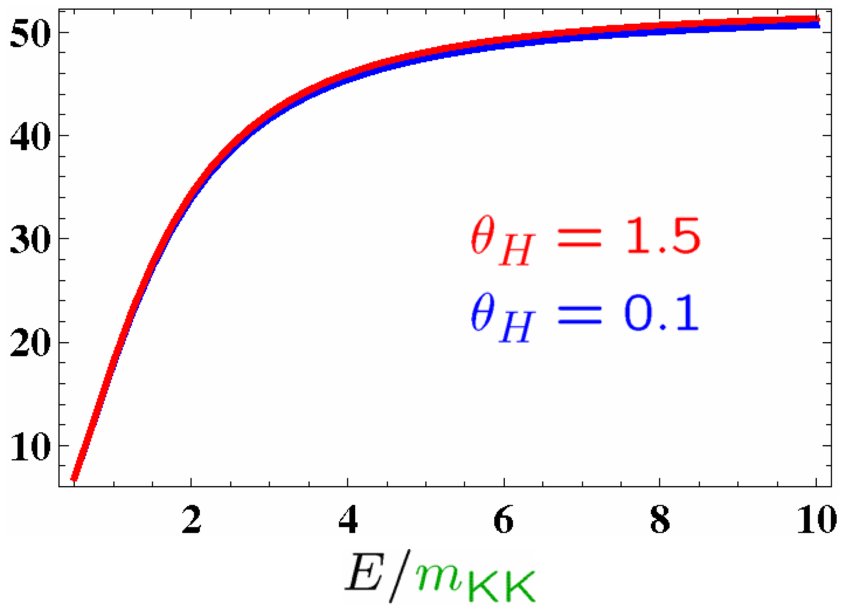
The $\mathcal{O}(E^2)$ contributions miss to be cancelled only among the light modes.

↓

cancelled by the KK modes

In the unit of the KK scale m_{KK} ,

warped case $(kL = 30)$



m_{KK} depends on θ_H when m_W is fixed.

$$\begin{pmatrix} \theta_H = 1.5 & \Rightarrow & m_{\mathrm{KK}} \simeq 17 m_W \\ \theta_H = 0.5 & \Rightarrow & m_{\mathrm{KK}} \simeq 36 m_W \\ \theta_H = 0.1 & \Rightarrow & m_{\mathrm{KK}} \simeq 172 m_W \end{pmatrix}$$

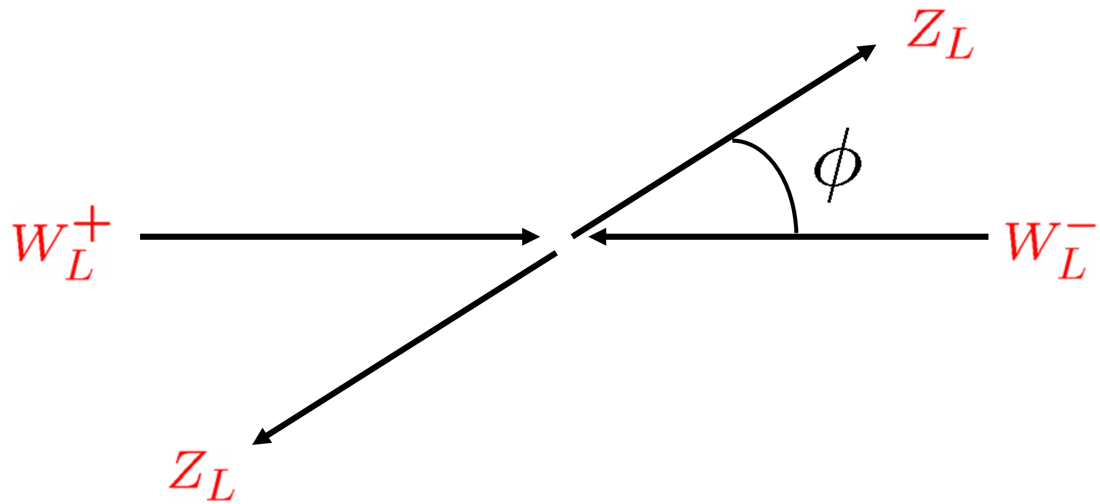
The amplitude stops growing when the KK modes start to propagate.

Unitarity condition

$$|a_0(E)|^2 \leq \frac{1}{2}$$

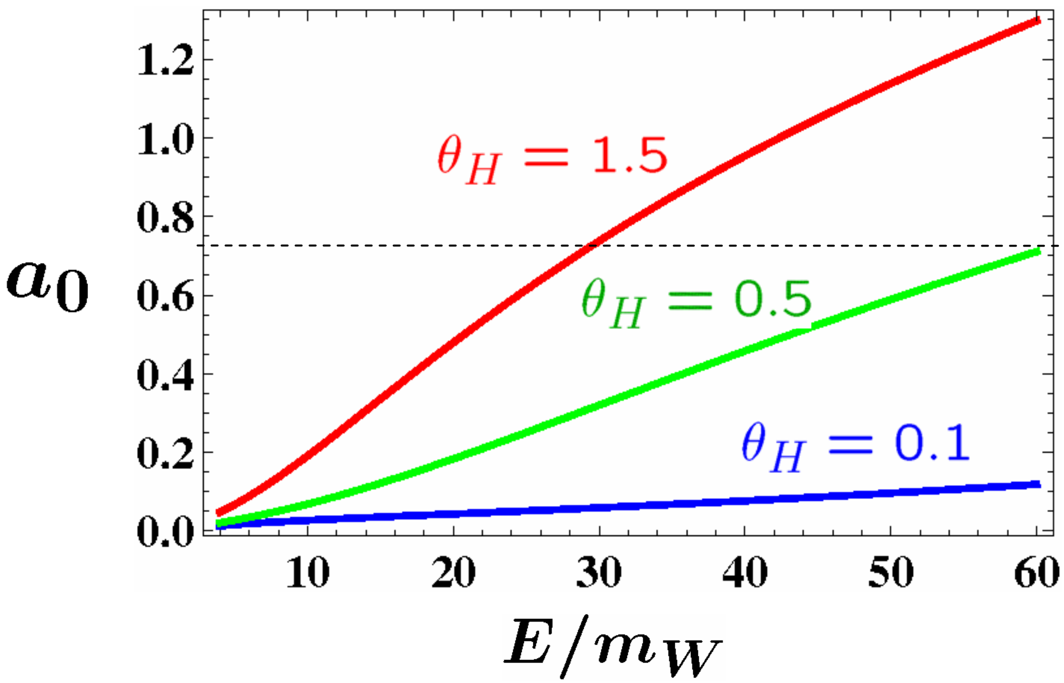
where $a_0(E) \equiv \frac{1}{32\pi}\int_{-1}^{1} d(\cos\phi) T(E,\phi)$

(S-wave amplitude)



Unitarity bound on Energy

warped case ($kL = 30$)



$\theta_H = 1.5 \Rightarrow E \leq 30 mW \simeq 2.4$ TeV

$\theta_H = 0.5 \Rightarrow E \leq 60 mW \simeq 4.8$ TeV

To obtain more stringent unitarity bound,
we should consider all possible final states.

$$W^+W^- \to W^+W^-, ZZ, W^{+(1)}W^-, \cdots$$

Unitarity condition

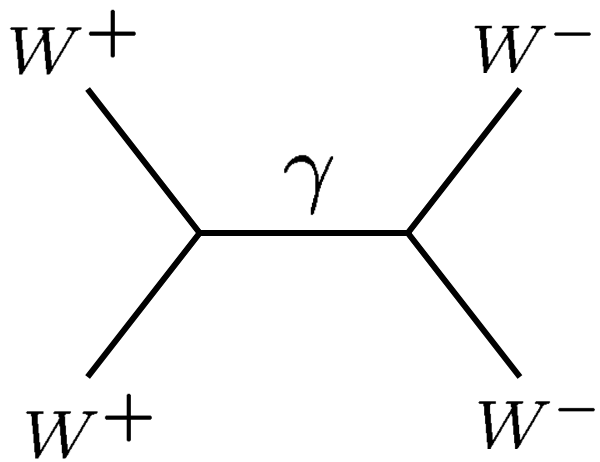
$$\underbrace{\left|a_0^{WW} - \frac{i}{2}\right|^2}_{\text{elastic scattering}} + \frac{1}{2}\left|a_0^{ZZ}\right|^2 + \cdots \leq \frac{1}{4}$$

elastic scattering — involving KK modes ($\cdots$)

expectation $E \simeq 1$ TeV for $\theta_H = 1.5$

because $\lambda_{WWH} = g_4 m_W \cos\theta_H$ vanishes.

Comment on $W^+W^- \to W^+W^-$



$$\propto \frac{1}{1-\cos\phi}$$

(ϕ: scattering angle)

Thus, $a_0(E) \equiv \frac{1}{32\pi}\int_{-1}^{1} d(\cos\phi) T(E,\phi)$ diverges.

Taking into account the width of the W boson,
the divergence at $\phi = 0$ is smeared out.

→ translated into a cut-off for ♐

Summary

- Weak boson scattering in GHU model
- Equivalence theorem holds well.
- Amplitudes have large θ_H-dependence in the warped spacetime.
- Tree-level unitarity $(WW \to ZZ)$ is violated at

$$E \simeq 2.4 \text{ TeV } (\theta_H = 1.5)$$
$$E \simeq 4.8 \text{ TeV } (\theta_H = 0.5)$$