Scalar and fermion on-shell amplitudes in generalized HEFT

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In collaboration with

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Based on arXiv:2102.08519

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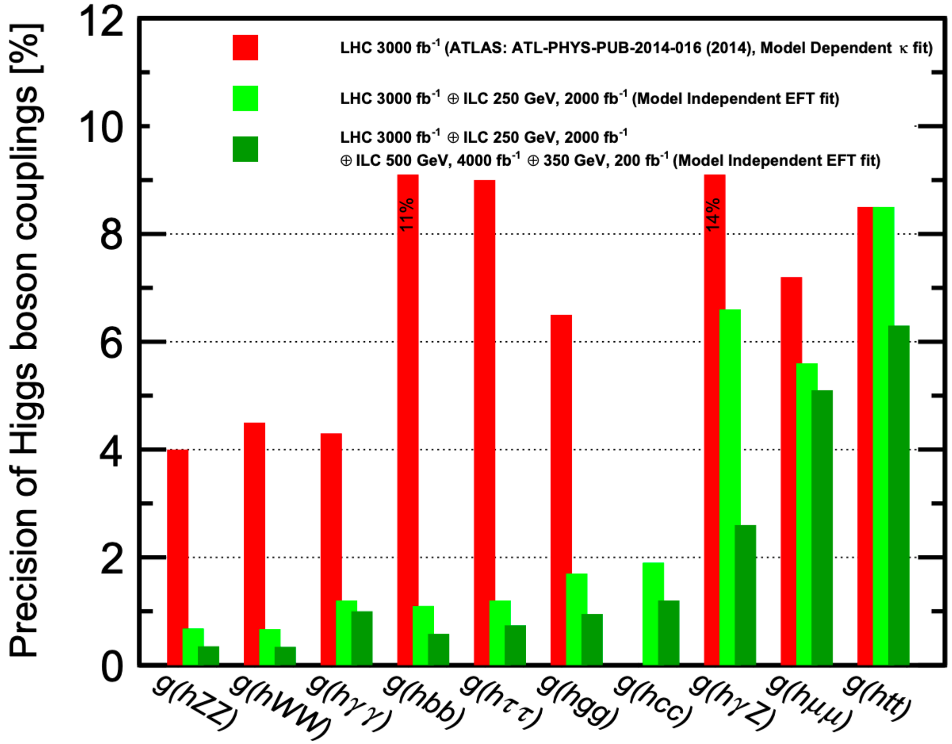
ONLINE

Introduction

Overview

Linear collider experiments will enable us to test the SM precisely



K. Fujii, et. al., arXiv:1710.07621

Question : "if we find the deviations from the SM in the future, can we extract the new physics properties from the deviation patterns?"

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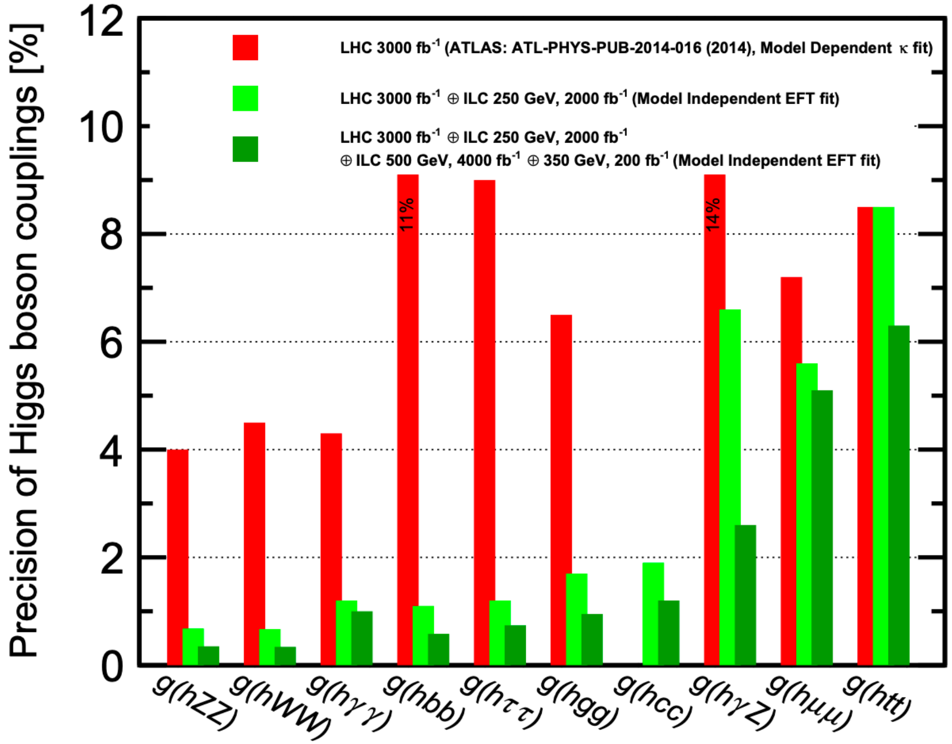

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Question : “if we find the deviations from the SM in the future, can we extract the new physics properties from the deviation patterns?”

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production cross sections of new particles

Goal

extract the new particles' production cross sections from the deviation patterns

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EFT approach is useful

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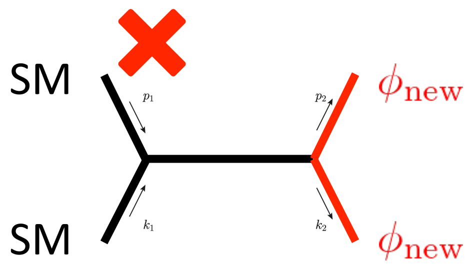
extract the new particles' production cross sections from the deviation patterns

Heavy new particles are integrated out in EFT framework

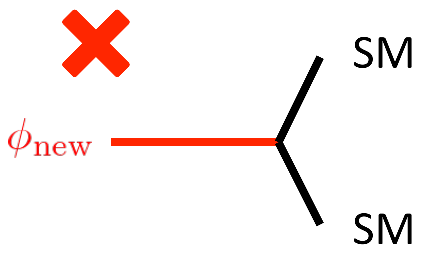
EFT approach is useful

EFT approach cannot deal with …

・ production process



・ decay process



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extract the new particles' production cross sections from the deviation patterns

Heavy new particles are integrated out in EFT framework

EFT approach is useful

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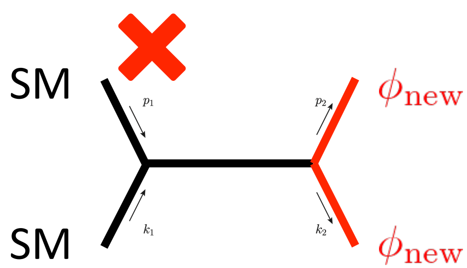
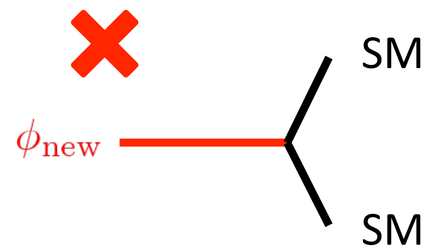
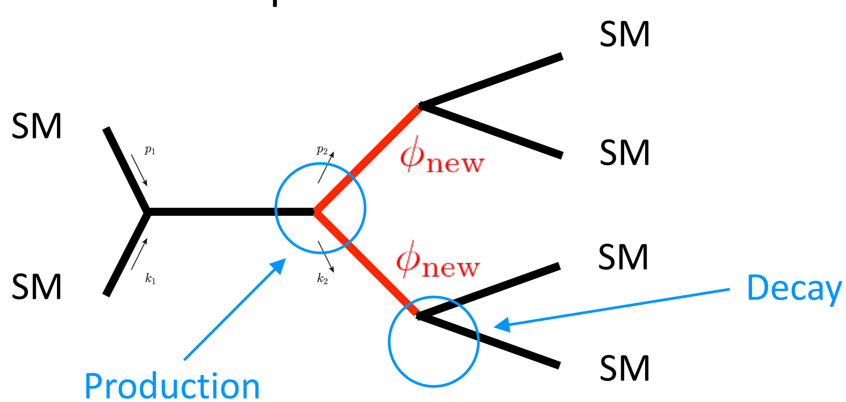
- production process



- decay process



These are essential quantities for direct search



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extract the new particles' production cross sections from the deviation patterns

Heavy new particles are integrated out in EFT framework

EFT approach is useful

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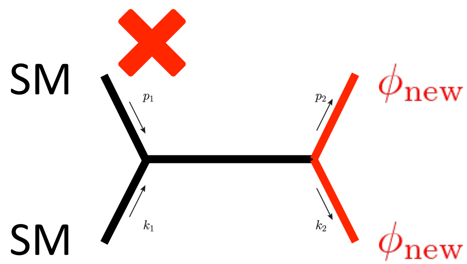

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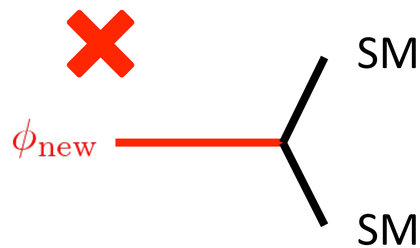

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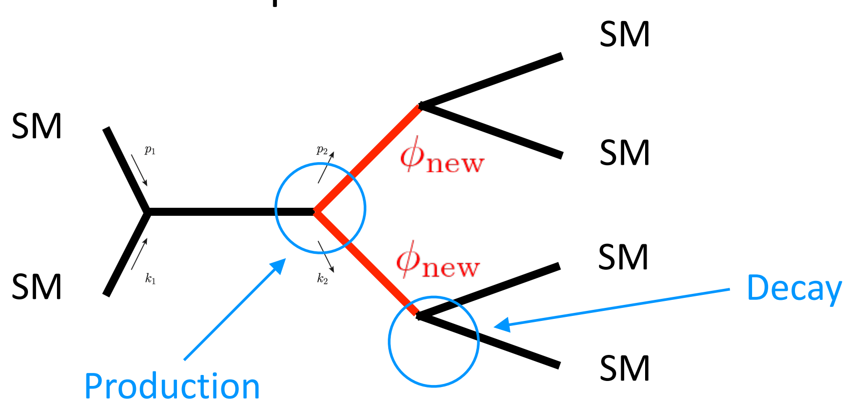


To achieve **Goal**, we must extend EFT framework so that it includes new particles

Strategy

Add new particles to the HEFT in a consistent manner with (nonlinear) $SU(2)_L \times U(1)_Y$

HEFT : Higgs Effective Field Theory

$$\mathcal{L}_{\rm HEFT} = \frac{v^2}{4} F(h) {\rm Tr}[(D_\mu U)^\dagger D^\mu U] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \cdots$$

$$F(h) = 1 + \kappa_1 \frac{h}{v} + \kappa_2 \left(\frac{h}{v}\right)^2 + \cdots \qquad U = \exp\left(\frac{i\pi^a \tau^a}{v}\right)$$

$$V(h) = m_h^2 h^2 + \lambda_3 h^3 + \cdots$$

- Symmetry : $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Matter contents : $h,\ Z_\mu,\ W_\mu^\pm\ \cdots$ classified under $U(1)_{\rm em}$
- 125 GeV scalar h is not necessarily included in H

Strategy

Add new particles to the HEFT in a consistent manner with (nonlinear) $SU(2)_L \times U(1)_Y$

→ *We can make model-independent prediction on new particles*

	Matter Contents
HEFT : Higgs Effective Field Theory	SM
1409.1709 R. Nagai, M. Tanabashi, K. Tsumura	SM + neutral scalar
1904.07618 R. Nagai, M. Tanabashi, K. Tsumura, Y.U.	SM + charged scalar
✔ 2102.08519 R. Nagai, M. Tanabashi, K. Tsumura, Y.U.	SM + charged scalar + Weyl fermion

Today's talk

Extension of HEFT

Extension of the HEFT

Generalized HEFT (GHEFT)

Symmetry : $SU(3)_C \times SU(2)_L \times U(1)_Y$

Matter contents :

$w^{\pm},\ z\ =$ would-be Goldstone bosons

$\phi^I = (h,\ H^+,\ H^-,\ \cdots)$ ← New scalars

$\psi^{\hat{i}} = (q_L,\ u_R,\ d_R,\ \cdots,\ \Psi_{\rm new},\ \cdots)$ ← New fermions

$$\begin{aligned}
\mathcal{L}_{\rm GHEFT} = &\ \frac{1}{2} G_{ab}(\phi)\, \alpha^a_{\perp\mu}\, \alpha^{a\mu}_{\perp} \\
&+ G_{aI}(\phi)\, \alpha^a_{\perp\mu}\, (\mathcal{D}^\mu \phi^I) \\
&+ \frac{1}{2} G_{IJ}(\phi) (\mathcal{D}^\mu \phi^I)(\mathcal{D}_\mu \phi^J) - V(\phi) \\
&+ \frac{i}{2} G_{\hat{i}\hat{j}^*}(\phi) \left(\psi^{\dagger \hat{j}^*}\, \bar{\sigma}^\mu\, (\mathcal{D}_\mu \psi^{\hat{i}}) - (\mathcal{D}_\mu \psi^{\dagger \hat{j}^*})\, \bar{\sigma}^\mu\, \psi^{\hat{i}} \right) \\
&+ V_{\hat{i}\hat{j}^* a}(\phi)\, \psi^{\dagger \hat{j}^*}\, \bar{\sigma}^\mu\, \psi^{\hat{i}}\, \alpha^a_{\perp\mu} \\
&+ V_{\hat{i}\hat{j}^* I}(\phi)\, \psi^{\dagger \hat{j}^*}\, \bar{\sigma}^\mu\, \psi^{\hat{i}}\, (\mathcal{D}_\mu \phi^I) \\
&- \frac{1}{2} M_{\hat{i}\hat{j}}(\phi)\, \psi^{\hat{i}} \psi^{\hat{j}} - \frac{1}{2} M_{\hat{i}^*\hat{j}^*}(\phi)\, \psi^{\dagger \hat{i}^*} \psi^{\dagger \hat{j}^*} \\
&+ \frac{1}{8} S_{\hat{i}\hat{j}\hat{k}\hat{l}}(\phi) (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\hat{k}} \psi^{\hat{l}}) \\
&+ \frac{1}{8} S_{\hat{i}^*\hat{j}^*\hat{k}^*\hat{l}^*}(\phi) (\psi^{\dagger \hat{i}^*} \psi^{\dagger \hat{j}^*})(\psi^{\dagger \hat{k}^*} \psi^{\dagger \hat{l}^*}) \\
&+ \frac{1}{4} S_{\hat{i}\hat{j}\hat{k}^*\hat{l}^*}(\phi) (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\dagger \hat{k}^*} \psi^{\dagger \hat{l}^*}) \,,
\end{aligned}$$

- $\alpha^a_{\perp\mu} = {\rm tr}\left[\frac{1}{i} \xi^\dagger_W (\partial_\mu \xi_W) \tau^a\right]$, $\quad (a = 1, 2)$

  $\alpha^3_{\perp\mu} = {\rm tr}\left[\frac{1}{i} \xi^\dagger_W (\partial_\mu \xi_W) \tau^3\right] + {\rm tr}\left[\frac{1}{i} (\partial_\mu \xi_Y) \xi^\dagger_Y \tau^3\right]$

  ξ_W and ξ_Y are defined as

  $\xi_W := \exp\left(\frac{i}{2v} \sum_{\alpha=1,2} w^\alpha \tau^\alpha\right)$, $\quad \xi_Y := \exp\left(\frac{i}{2v_Z} z \tau^3\right)$

- $(\mathcal{D}_\mu \phi)^I = \partial_\mu \phi^I + i \mathcal{V}^3_\mu\, [Q_\phi]^I{}_J\, \phi^J$

  with $\mathcal{V}^3_\mu$ defined by $\mathcal{V}^3_\mu = -{\rm tr}\left[\frac{1}{i} (\partial_\mu \xi_Y) \xi^\dagger_Y \tau^3\right] + c\alpha^3_{\perp\mu}$

  Q_ϕ : charged matrix

$$Q_\phi = \begin{pmatrix} \overbrace{\begin{matrix} -q_1\sigma_2 & & \\ & \ddots & \\ & & -q_{n_C}\sigma_2 \end{matrix}}^{\text{charged}} & \\ & \underbrace{\begin{matrix} 0 & & \\ & \ddots & \\ & & 0 \end{matrix}}_{\text{neutral}} \end{pmatrix}$$

Please visit 2102.08519

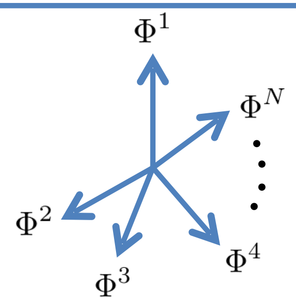
Difficulties in EFT analysis

Difficulty : non-uniqueness of parametrization methods

⇨ Difficult to compare results computed in different field basis

Solution : Focus on target space of the scalar Lagrangian

Alonso et.al., 1511.00724 and 1605.03602



$$\mathcal{L}_{\mathrm{GHEFT}} = \frac{1}{2} g_{ij}(\Phi) \partial_\mu \Phi^i \partial^\mu \Phi^j - V$$

⇨ Amplitudes can be expressed by covariant tensors in field space

ex.) $\phi^1\phi^2 \to \phi^3\phi^4$

$$\simeq \quad s\, R_{1423} + s(1+\cos\theta)\, R_{1234}$$

1904.07618

Application to GHEFT

Symmetry : $SU(3)_C \times SU(2)_L \times U(1)_Y$

Matter contents : SM + new scalars + new Weyl fermions

ϕ^i : scalar (SM + NP) , $\psi^{\hat{i}}$: Weyl fermion (SM + NP)

$$
\begin{aligned}
\mathcal{L}_{\mathrm{GHEFT}} = & \frac{1}{2} g_{ij}(\phi)(\partial_\mu \phi^i)(\partial^\mu \phi^j) - V(\phi) \\
& + \frac{i}{2} g_{\hat{i}\hat{j}^*}(\phi)\left(\psi^{\dagger\hat{j}^*}\bar{\sigma}^\mu(\partial_\mu \psi^{\hat{i}}) - (\partial_\mu \psi^{\dagger\hat{j}^*})\bar{\sigma}^\mu \psi^{\hat{i}}\right) \\
& + v_{\hat{i}\hat{j}^* i}(\phi)\, \psi^{\dagger\hat{j}^*}\bar{\sigma}^\mu \psi^{\hat{i}}(\partial_\mu \phi^i) \\
& - \frac{1}{2} M_{\hat{i}\hat{j}}(\phi)\, \psi^{\hat{i}}\psi^{\hat{j}} \quad + \mathrm{h.c.} \\
& + \frac{1}{8} S_{\hat{i}\hat{j}\hat{k}\hat{l}}(\phi)(\psi^{\hat{i}}\psi^{\hat{j}})(\psi^{\hat{k}}\psi^{\hat{l}}) \quad + \mathrm{h.c.} \\
& + \frac{1}{4} S_{\hat{i}\hat{j}\hat{k}^*\hat{l}^*}(\phi)(\psi^{\hat{i}}\psi^{\hat{j}})(\psi^{\dagger\hat{k}^*}\psi^{\dagger\hat{l}^*})
\end{aligned}
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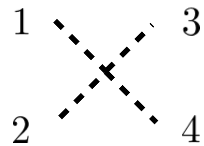
\mathcal{L}_{\mathrm{GHEFT}} = &\frac{1}{2} g_{ij}(\phi)(\partial_\mu \phi^i)(\partial^\mu \phi^j) - V(\phi) \\
&+ \frac{i}{2} g_{\hat{i}\hat{j}^*}(\phi)\left(\psi^{\dagger \hat{j}^*} \bar{\sigma}^\mu (\partial_\mu \psi^{\hat{i}}) - (\partial_\mu \psi^{\dagger \hat{j}^*})\bar{\sigma}^\mu \psi^{\hat{i}}\right) \\
&+ \boxed{v_{\hat{i}\hat{j}^* i}(\phi)}\, \psi^{\dagger \hat{j}^*} \bar{\sigma}^\mu \psi^{\hat{i}} (\partial_\mu \phi^i) \quad \longrightarrow \quad \boxed{v_{\hat{i}\hat{j}^* i}(\phi)} = \frac{i}{2}\left(g_{i\hat{j}^*,\hat{i}}(\phi) - g_{i\hat{i},\hat{j}^*}(\phi)\right) \\
&- \frac{1}{2} M_{\hat{i}\hat{j}}(\phi)\, \psi^{\hat{i}} \psi^{\hat{j}} \quad + \mathrm{h.c.} \\
&+ \frac{1}{8} S_{\hat{i}\hat{j}\hat{k}\hat{l}}(\phi)(\psi^{\hat{i}}\psi^{\hat{j}})(\psi^{\hat{k}}\psi^{\hat{l}}) \quad + \mathrm{h.c.} \\
&+ \frac{1}{4} S_{\hat{i}\hat{j}\hat{k}^*\hat{l}^*}(\phi)(\psi^{\hat{i}}\psi^{\hat{j}})(\psi^{\dagger \hat{k}^*}\psi^{\dagger \hat{l}^*})
\end{aligned}
$$

We define Affine connection: $\Gamma^{\hat{i}}_{j\hat{k}} := \frac{1}{2} g^{\hat{i}\hat{l}^*}\left[g_{\hat{k}\hat{l}^*,j} + g_{j\hat{l}^*,\hat{k}} - g_{j\hat{k},\hat{l}^*} \right]$

High Energy Behavior

$\phi^1\phi^2 \to \phi^3\phi^4$



$$\simeq \quad s\ R_{1423} + s(1+\cos\theta)\ R_{1234}$$

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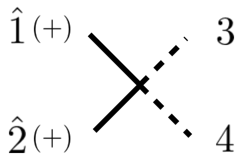
$\psi^{\hat{1}}\psi^{\hat{2}} \to \phi^3\phi^4$



$$\simeq \quad \sqrt{s}\ \left(\mathcal{D}_4\mathcal{D}_3 M_{\hat{1}\hat{2}}\right) - \sqrt{s}\cos\theta\ \left(M_{\hat{2}}R_{\hat{1}\hat{2}34} + M_{\hat{1}}R_{\hat{1}\hat{2}34}\right)$$

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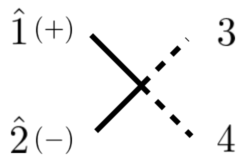
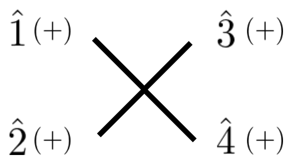


$$\simeq \quad s\sin\theta\ R_{\hat{1}\hat{2}34}$$

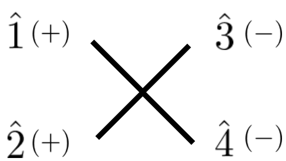
$\hat{i}$: flavor index of Weyl fermion

i : flavor index of scalar

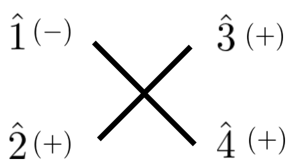
$\psi^{\hat{1}}\psi^{\hat{2}} \to \psi^{\hat{3}}\psi^{\hat{4}}$



$$\simeq \quad s\ R_{\hat{1}\hat{4}\hat{2}\hat{3}} + s(1+\cos\theta)\ R_{\hat{1}\hat{2}\hat{3}\hat{4}}$$



$$\simeq \quad s\ R_{\hat{1}\hat{3}\hat{2}\hat{4}}$$



$$\simeq \quad \sqrt{s}\sin\theta\ \left(M_{\hat{1}}R_{\hat{1}\hat{3}\hat{2}\hat{4}} - M_{\hat{3}}R_{\hat{2}\hat{1}\hat{4}\hat{3}} + M_{\hat{4}}R_{\hat{2}\hat{1}\hat{3}\hat{4}}\right)$$

Take Home Massage & Summary

- We construct the generalized HEFT incorporating the new scalars and Weyl fermions.

- We find that the cancellation of the energy growing term in the scalar fermion scattering amplitudes require the flatness of the Riemann curvature tensors evaluated at the vacuum.

$$R_{1234}\Big|_0 = R_{\hat{1}\hat{2}^*34}\Big|_0 = R_{\hat{1}\hat{2}\hat{3}\hat{4}}\Big|_0$$
$$= R_{\hat{1}^*\hat{2}^*\hat{3}^*\hat{4}^*}\Big|_0 = R_{\hat{1}\hat{2}^*\hat{3}\hat{4}^*}\Big|_0 = 0$$