Structure of dim-6 derivative interactions in *N* pseudo Nambu-Goldstone-Higgs doublet models

Osaka U @ 12 Mar. 2012

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Collaborators:
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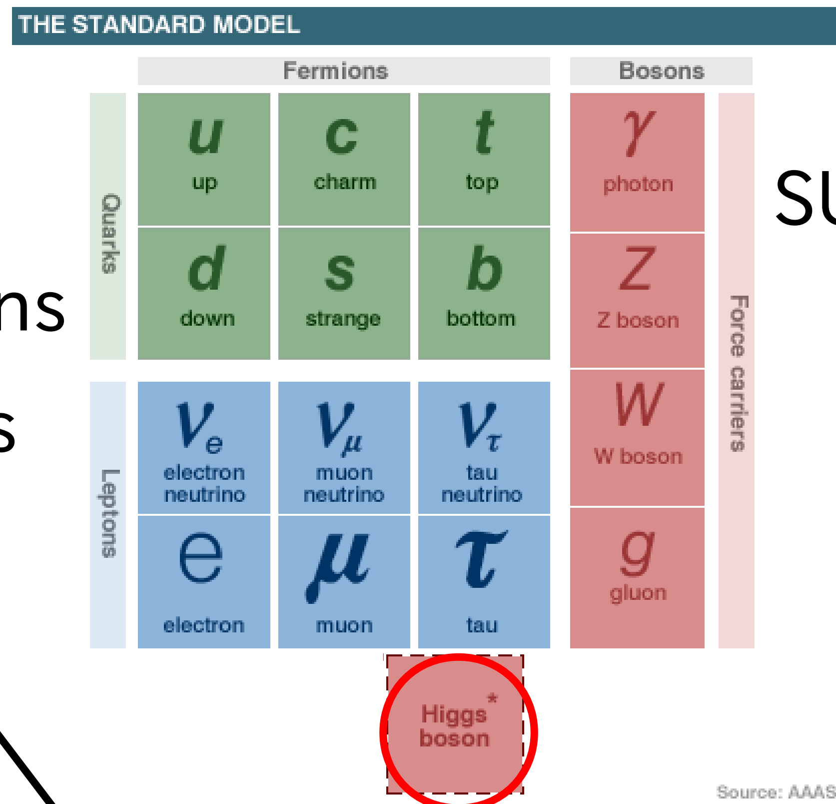
(Sokendai/KEK)

Based on arXiv:**1111.2120** [hep-ph]

The Standard Model

19 parameters manage the universe!!



Quarks, Leptons

3 generations

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

⇩

$SU(3)_C \times U(1)_{EM}$

mass

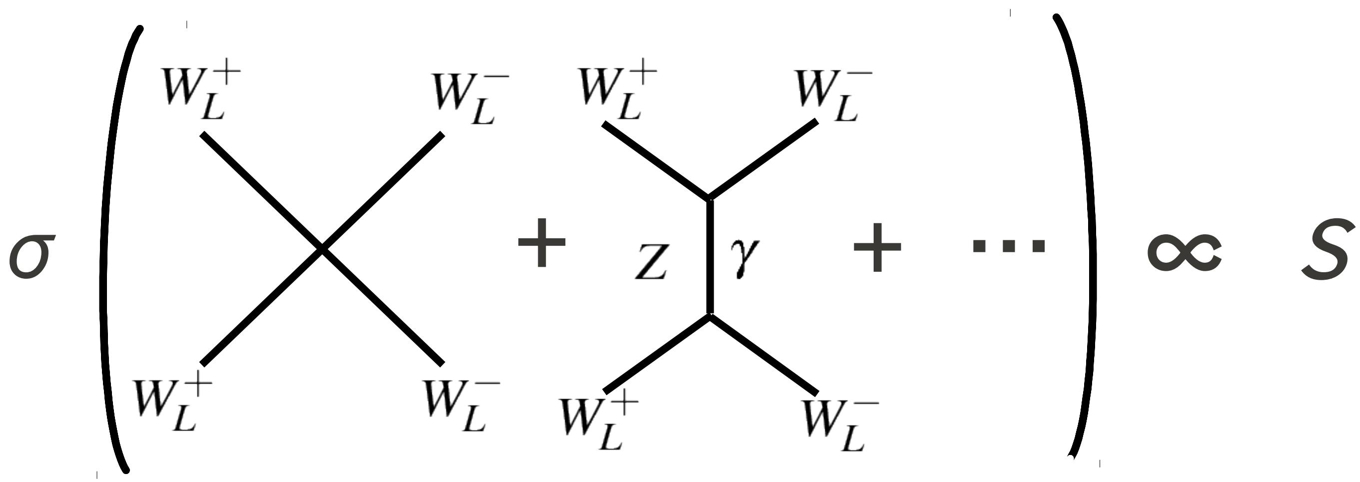
mass

Spontaneous sym. breaking

Who have seen the Higgs?

What we know about the Higgs boson

- Unitarity → Higgs Physics $\lesssim$ 1 TeV
- EWPM → $M_h \sim$ 100 GeV
- Recent LHC results → $M_h \sim$ 125 GeV (?)
- Vacuum stability → Meta stable (?)
- Structure of the Higgs sector is add-hook.



'77 Lee, Quigg and Thacker

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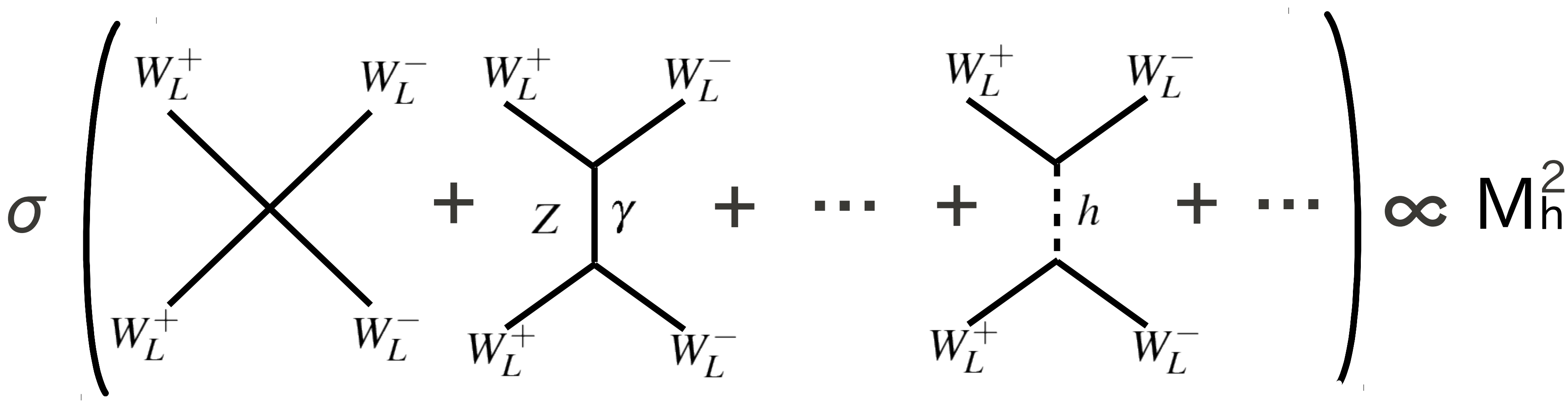

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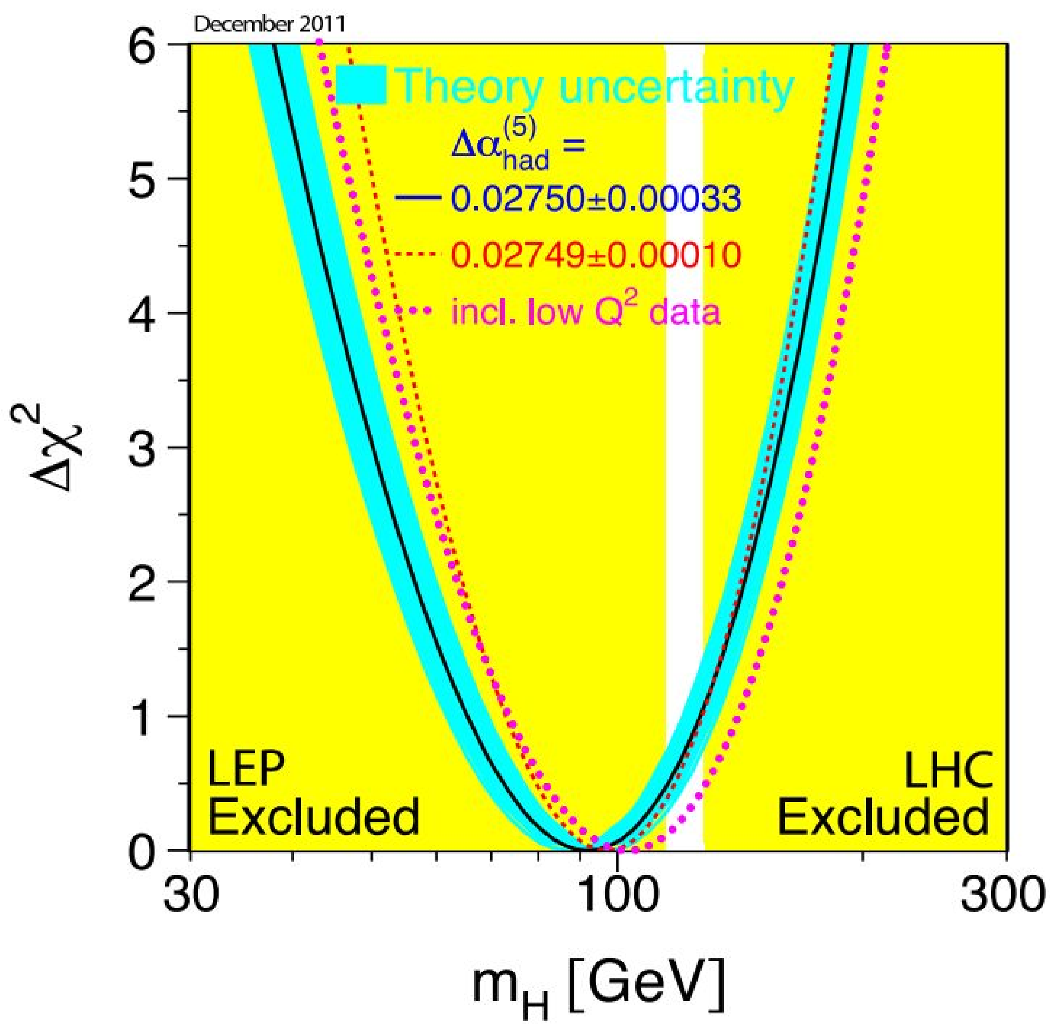

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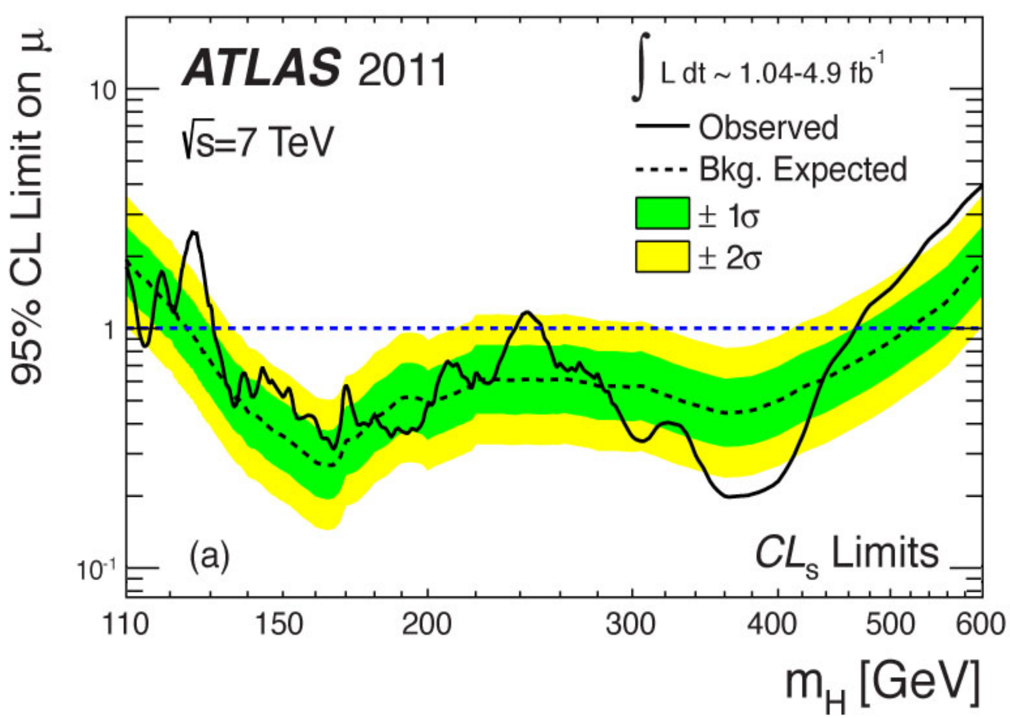

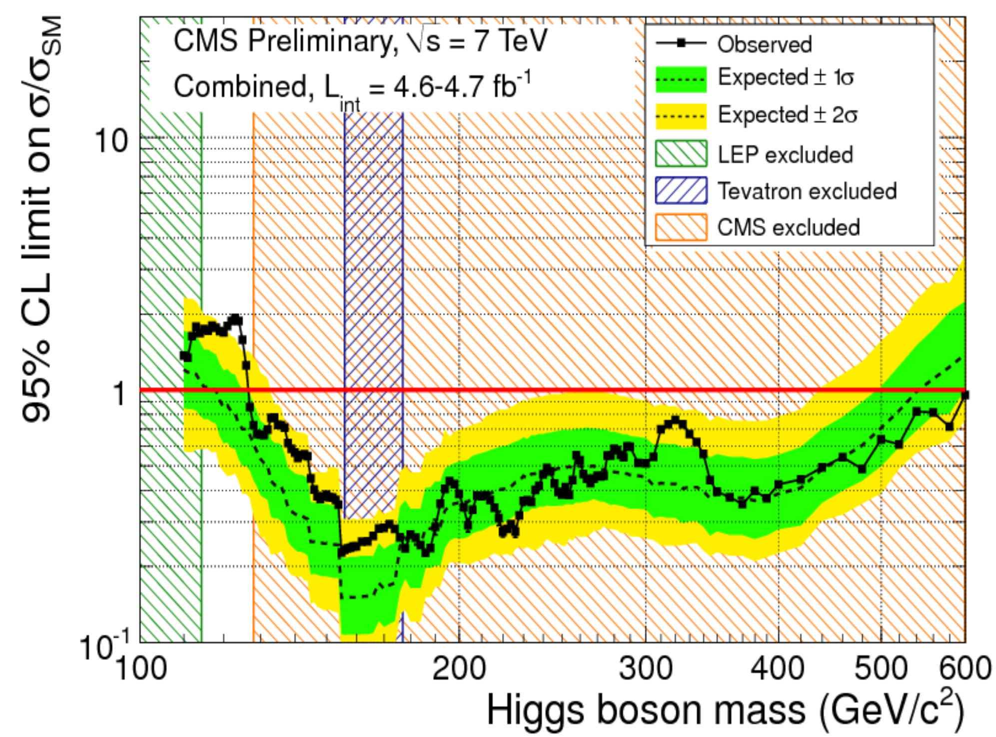

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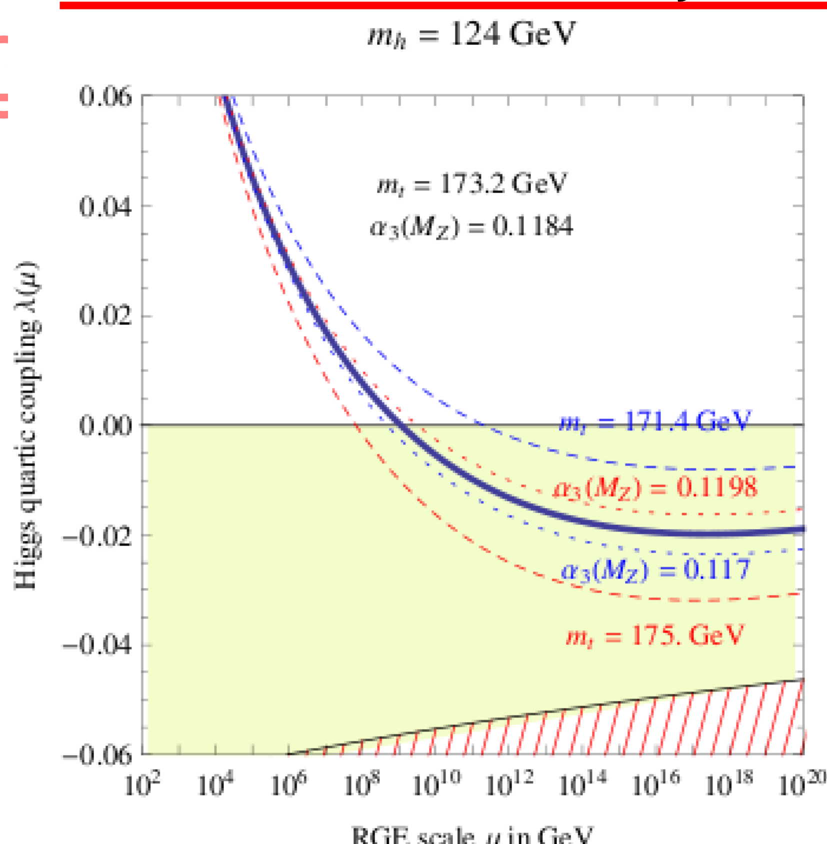

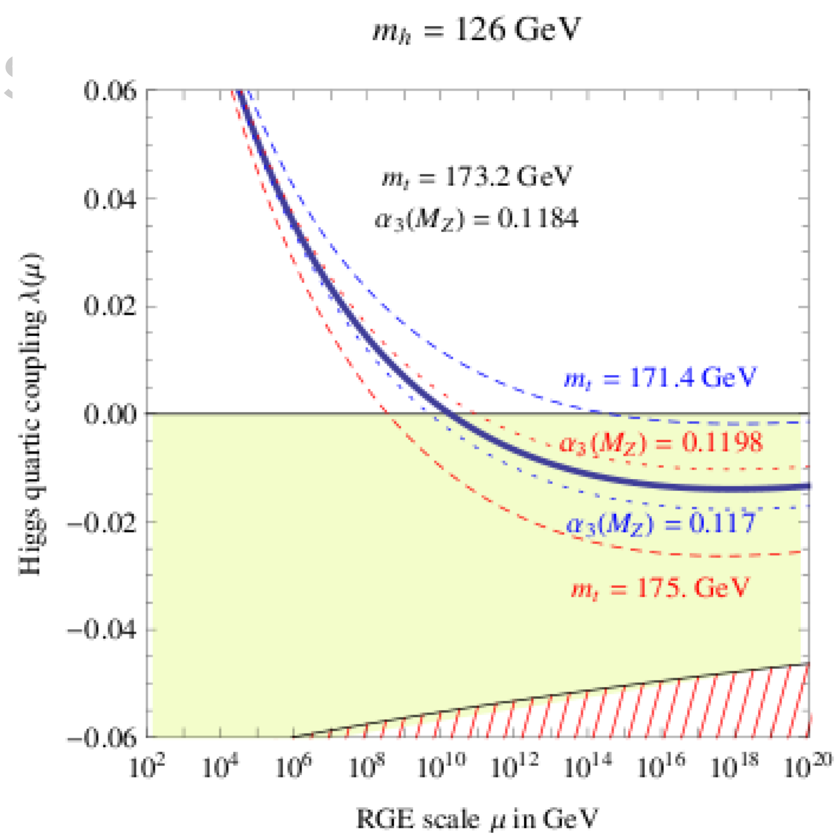

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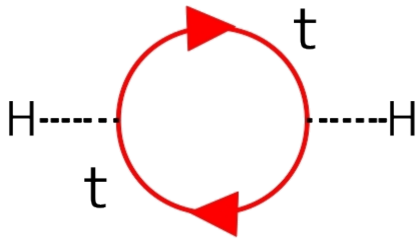
$$V_h = -\mu^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2$$

Electroweak symmetry is broken by hand.

The hierarchy problem

Huge Hierarchy

EW ⟵ - - - - - - - - ⟶ M_P



$$\sim \frac{\Delta m_h^2}{m_h^2} \sim \left(0.3\frac{M_P}{100\mathrm{GeV}}\right)^2 > 10^{33}$$

$$\Lambda_{\mathrm{SM}} \sim 1\,\mathrm{TeV} \Rightarrow \frac{\Delta m_h^2}{m_h^2} \sim 10$$

New physics appears @ TeV !?

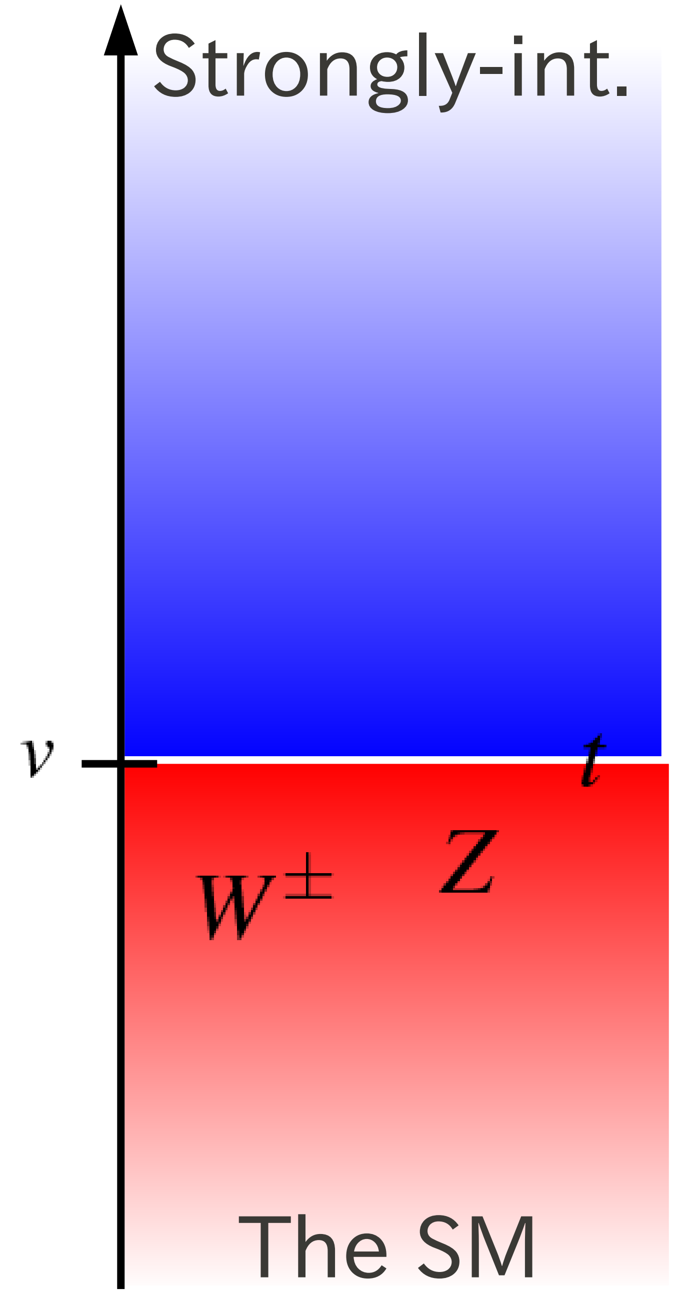
(屮°д°)屮 Come on!!

	1 Higgs	2Higgs	3Higgs	......
Weakly-Int.	SM...	SUSY ...	......	......
Strongly-Int.	Composite Higgs models			

Composite Higgs models

Electroweak sym. breaking
↓
Dynamical sym. breaking

- QCD-like technicolor
  - → Large S parameter.
  - → Dificulties of strong dynamics.
    - Lattice calculation.



Composite Higgs models

Electroweak sym. breaking
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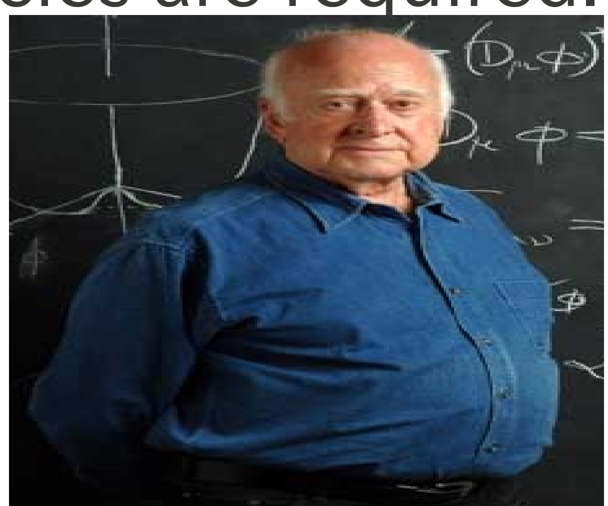
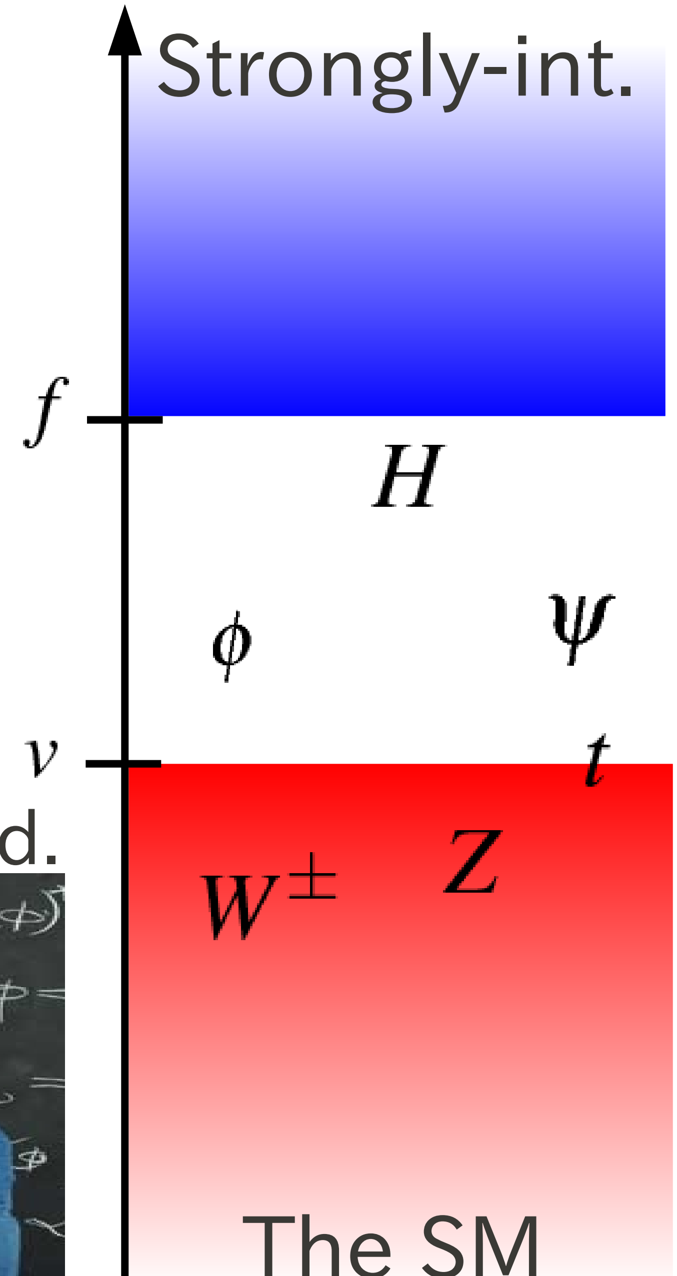
Dynamical sym. breaking

- The Higgs doublet is embedded in pseudo NG fields.
  → Large Higgs mass ($m_h \sim f$).
  → Light new particles are required.





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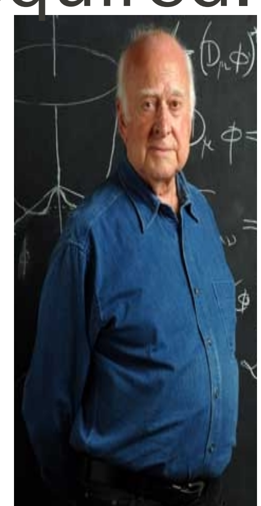
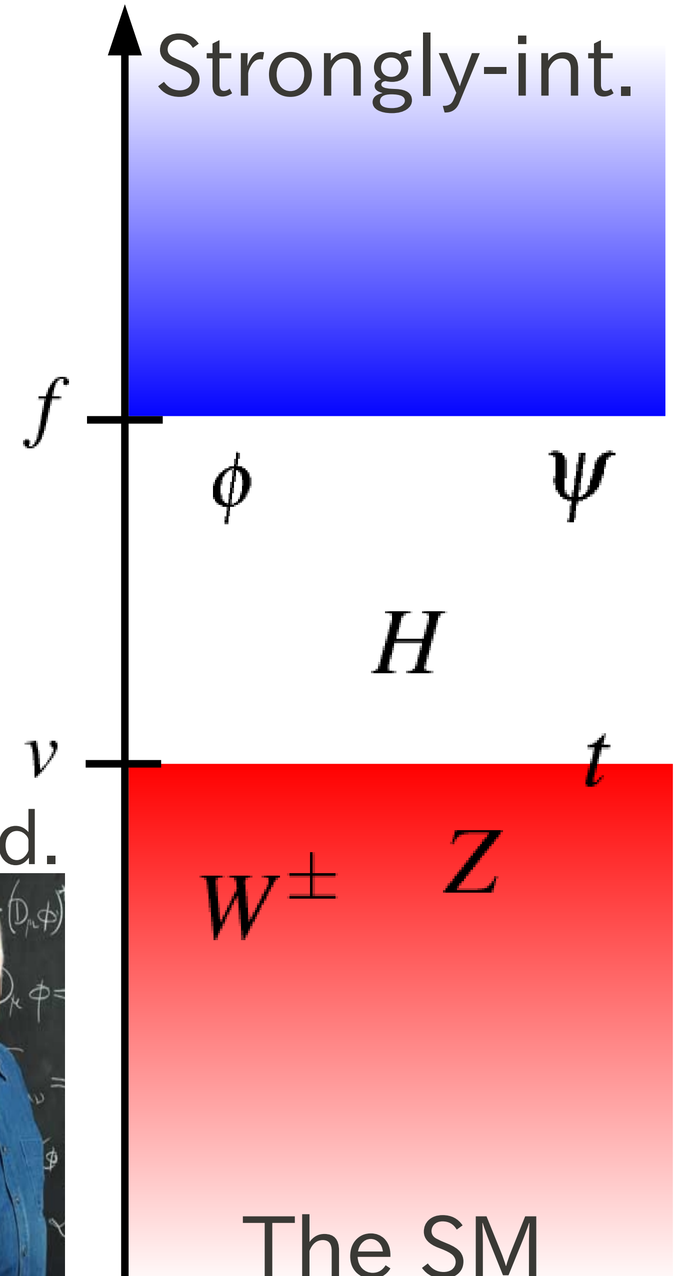


- New mech. for light Higgs.
  - → Little Higgs models
    Minimal comp. Higgs



Composite Higgs models

Electroweak sym. breaking
↓
Dynamical sym. breaking

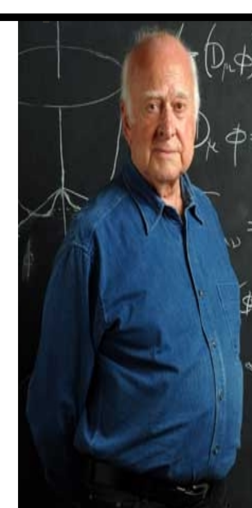
Strongly-interacting light Higgs

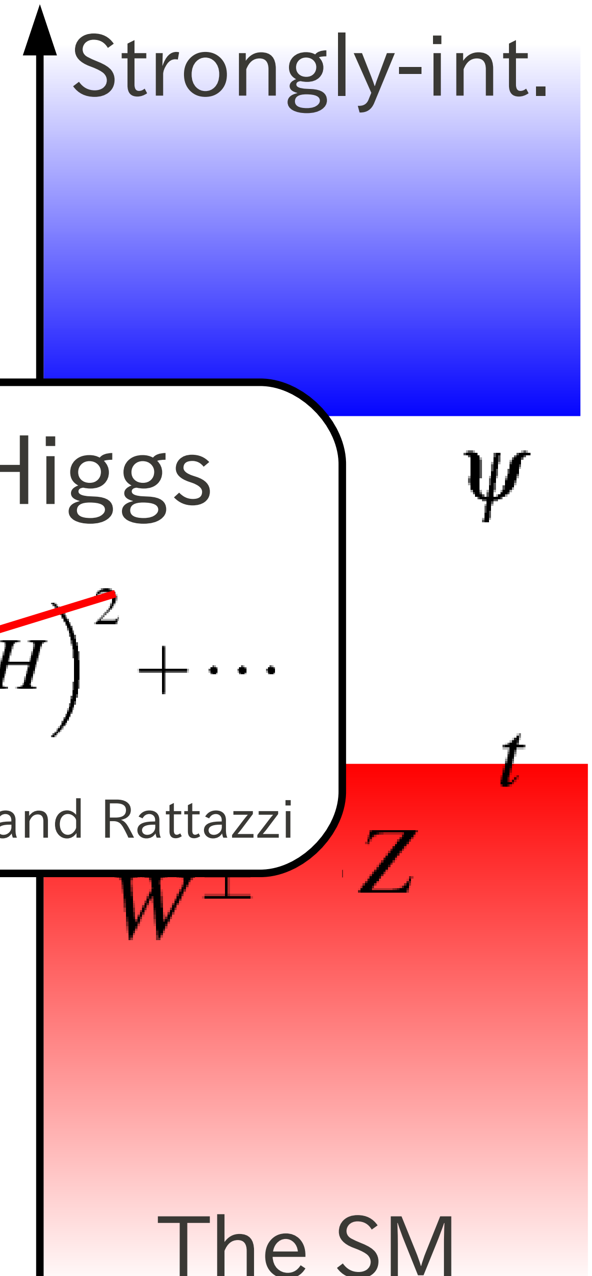
$$\mathscr{L}_{\rm SILH} = \frac{c^H}{2f^2}\left(\partial\left(H^\dagger H\right)\right)^2 + \frac{c^T}{2f^2}\left(H^\dagger \overleftrightarrow{D} H\right)^2 + \cdots$$

'07 Giudice, Grojean, Pomarol and Rattazzi

◆ New mech. for light Higgs

→ Little Higgs models
Minimal comp. Higgs





Derivative interactions of the Higgs

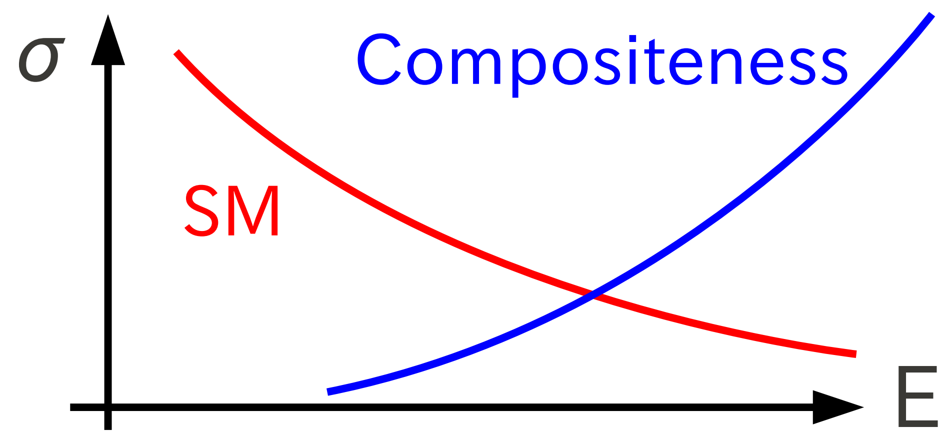
$$\frac{c^H}{f^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H)$$

- Any interactions with the Higgs are changed.

$$\Rightarrow \frac{1}{2}\left(1+c^H\frac{v^2}{f^2}\right)(\partial h)^2 \qquad \Rightarrow h \to \frac{h}{\sqrt{\left(1+c^H\frac{v^2}{f^2}\right)}}$$

- Cross sections of VBF grow @ high energy region.

$$\Rightarrow \frac{c^H}{f^2}h(\partial h)\phi(\partial\phi)$$



Derivative int. and nonlinear rep.

$$\mathcal{L}_{\rm NG} = \frac{f^2}{2}{\rm tr}\left[(\partial e^{-i\pi/f})(\partial e^{i\pi/f})\right]$$

$$\Rightarrow \frac{1}{2}\partial h \partial h - \frac{1}{24 f^2}\left(4 f^{aci} f^{bdi} + f^{ace} f^{bde}\right) h^a h^b (\partial h^c)(\partial h^d) + \cdots$$

4N real scalars

Antisymmetric under (a,c) and (b,d).

Derivative interactions are constrained.

Extend the analysis to the *N* Higgs doublet model.

(Application to the 2HDM.)

Y. Kikuta, Y. Okada and YY
arXiv: 1111.2120

Contents

- Introduction
- Derivative int and nonlinear rep.
  - The case of one Higgs doublet.
  - The case of *N* Higgs doublets.
- Application to the 2HDM
  - Notation
  - Cross sections
- Conclusion

The case of one Higgs

'09 Low, Rattazzi and Vichi

$$\mathscr{L}_{\rm NG} = \frac{f^2}{2}\mathrm{tr}\left[(\partial e^{-i\pi/f})(\partial e^{i\pi/f})\right]$$

4 real scalars

$$\Rightarrow \frac{1}{2}\partial h \partial h - \frac{1}{24 f^2}\left(4 f^{aci} f^{bdi} + f^{ace} f^{bde}\right) h^a h^b (\partial h^c)(\partial h^d) + \cdots$$

Antisymmetric under (a,c) or (b,d).

$$\longrightarrow h T^{so(4)} \partial h \quad (T^{so(4)} \in \{T^{L\alpha}, T^{R\beta}\})$$

$$\Rightarrow a_L (h T^{L\alpha} \partial h)(h T^{L\alpha} \partial h) + a_R (h T^{R\beta} \partial h)(h T^{R\beta} \partial h)$$

$$+ a_Y (h T^{R3} \partial h)(h T^{R3} \partial h)$$

$$\begin{cases} h T^{L\alpha} \partial h \propto \mathrm{Tr}\left[\Phi^\dagger \sigma^\alpha \overleftrightarrow{\partial} \Phi\right] \\ h T^{R\beta} \partial h \propto \mathrm{Tr}\left[\Phi \sigma^\beta \overleftrightarrow{\partial} \Phi^\dagger\right] \end{cases}$$

$$\Phi = (i\sigma^2 H^* \; H)$$

$$\Phi \to L \Phi R^\dagger$$

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Antisymmetric under (a,c) or (b,d).

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$$\Rightarrow a_L (h T^{L\alpha}\partial h)(h T^{L\alpha}\partial h) + a_R (h T^{R\beta}\partial h)(h T^{R\beta}\partial h)$$

$$+ a_Y (h T^{R3}\partial h)(h T^{R3}\partial h)$$

$$= \frac{a^L + a^R}{4 f^2}(O^H - 4 O^r) + \frac{a^Y}{4 f^2} O^T$$

	Re	Im
General	3	1
Nonlinear	2	0

$$O^H = (\partial H^\dagger H)(\partial H^\dagger H)$$

$$O^T = (H^\dagger \overleftrightarrow{\partial} H)(H^\dagger \overleftrightarrow{\partial} H)$$

$$O^r = (H^\dagger H)(\partial H^\dagger \partial H)$$

$$O^{HT} = (\partial H^\dagger H)(H^\dagger \overleftrightarrow{\partial} H)$$

The case of one Higgs

'09 Low, Rattazzi and Vichi

$$\mathscr{L}_{6\mathrm{NL}} = \frac{a^L + a^R}{4f^2}(O^H - 4O^r) + \frac{a^Y}{4f^2}O^T$$

$$H \to H + \frac{a}{f^2}(H^\dagger H)H$$

$$(\partial H)^\dagger(\partial H) \to (\partial H)^\dagger(\partial H) + \frac{a}{f^2}O^H + \frac{2a}{f^2}O^r$$

$$\Rightarrow \frac{3(a^L + a^R)}{4f^2}O^H + \frac{a^Y}{4f^2}O^T$$

This Lagrangian is general for O^H and O^T.

	Re	Im
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$$O^H = (\partial H^\dagger H)(\partial H^\dagger H)$$

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VBF is described by one parameter.

$$O^H = (\partial H^\dagger H)(\partial H^\dagger H)$$

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	Re	Im
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The case of *N* Higgs

$$\mathscr{L}_{\mathrm{NG}} = \frac{f^2}{2}\mathrm{tr}\left[(\partial e^{-i\pi/f})(\partial e^{i\pi/f})\right]$$

4N real scalars

$$\Rightarrow \frac{1}{2}\partial h \partial h - \frac{1}{24 f^2}\underline{\left(4 f^{aci} f^{bdi} + f^{ace} f^{bde}\right)} h^a h^b (\partial h^c)(\partial h^d) + \cdots$$

$$h T^{so(4N)} \partial h \quad (T^{so(4N)} \in \{T^{L\alpha}_{(i,j)}, T^{R\beta}_{(i,j)}, S^{\alpha\beta}_{(i,j)}, U_{(i,j)}\})$$

$$SU(2)_L \times SU(2)_R : (\mathbf{3},\mathbf{1}),\ (\mathbf{1},\mathbf{3}),\ (\mathbf{3},\mathbf{3}),\ (\mathbf{1},\mathbf{1})$$

$$\begin{cases} h T^{L\alpha}_{(i,j)} \partial h \propto \mathrm{Tr}\left[\Phi^\dagger_{ii} \sigma^\alpha \overleftrightarrow{\partial} \Phi_{jj} + \Phi^\dagger_{jj} \sigma^\alpha \overleftrightarrow{\partial} \Phi_{ii}\right] \\ h T^{R\beta}_{(i,j)} \partial h \propto \mathrm{Tr}\left[\Phi_{ii} \sigma^\beta \overleftrightarrow{\partial} \Phi^\dagger_{jj} + \Phi_{jj} \sigma^\beta \overleftrightarrow{\partial} \Phi^\dagger_{ii}\right] \\ h S^{\alpha\beta}_{(i,j)} \partial h \propto i\mathrm{Tr}\left[\Phi^\dagger_{ii} \sigma^\alpha \overleftrightarrow{\partial} \Phi_{jj} \sigma^\beta + \Phi_{ii} \sigma^\beta \overleftrightarrow{\partial} \Phi^\dagger_{jj} \sigma^\alpha\right] \\ h U_{(i,j)} \partial h \propto i\mathrm{Tr}\left[\Phi^\dagger_{jj} \overleftrightarrow{\partial} \Phi_{ii} + \Phi_{jj} \overleftrightarrow{\partial} \Phi^\dagger_{ii}\right] \end{cases}$$

$$\Phi_{ii} = (i\sigma^2 H_i^* \, H_i)$$

$$\Phi_{ii} \to L \Phi_{ii} R^\dagger$$

The case of *N* Higgs

$$\mathcal{L}^{6\mathrm{NL}}_{\mathrm{NHD}} = \frac{1}{f^2}\underline{\mathcal{T}^{\mathrm{NHD}}_{abcd}} h^a h^b \partial h^c \partial h^d$$

$$\left(T^{L\alpha}_{(i,j)}\right)_{ac}\left(T^{L\alpha}_{(k,l)}\right)_{bd} \quad \left(T^{R\beta}_{(i,j)}\right)_{ac}\left(T^{R\beta}_{(k,l)}\right)_{bd} \quad \left(T^{R3}_{(i,j)}\right)_{ac}\left(T^{R3}_{(k,l)}\right)_{bd}$$

$$\left(S^{\alpha\beta}_{(i,j)}\right)_{ac}\left(S^{\alpha\beta}_{(k,l)}\right)_{bd} \quad \left(S^{\alpha 3}_{(i,j)}\right)_{ac}\left(S^{\alpha 3}_{(k,l)}\right)_{bd} \quad \left(T^{L\alpha}_{(i,j)}\right)_{ac}\left(S^{\alpha 3}_{(k,l)}\right)_{bd}$$

$$\left(U_{(i,j)}\right)_{ac}\left(U_{(k,l)}\right)_{bd} \quad \left(T^{R3}_{(i,j)}\right)_{ac}\left(U_{(k,l)}\right)_{bd}$$

- Translate derivative interactions with doublets.

$$O^H_{ijkl} = (\partial H_i^\dagger H_j)(\partial H_k^\dagger H_l) \qquad O^r_{ijkl} = (H_i^\dagger H_j)(\partial H_k^\dagger \partial H_l)$$

$$O^T_{ijkl} = (H_i^\dagger \overleftrightarrow{\partial} H_j)(H_k^\dagger \overleftrightarrow{\partial} H_l) \quad O^{HT}_{ijkl} = (\partial H_i^\dagger H_j)(H_k^\dagger \overleftrightarrow{\partial} H_l)$$

N Higgs の場合 (まとめ)

	Re	Im
General	$(3/2)N^2(N^2+1)$	$(1/2)N^2(3N^2-1)$
O^H	$(1/4)N^2(N^2+3)$	$(1/4)N^2(N^2-1)$
O^T	$(1/4)N^2(N^2+3)$	$(1/4)N^2(N^2-1)$
O^r	$(1/2)N^2(N^2+1)$	$(1/2)N^2(N^2-1)$
O^{HT}	$(1/2)N^2(N^2-1)$	$(1/2)N^2(N^2+1)$
Nonlinear	$(1/2)N^2(N^2+3)$	$(1/2)N^2(N^2-1)$

1/3

- O^{HT} do not appear.
- Lagrangian of NG-Higgs is given with only O^H and O^T.

The case of *N* Higgs (summary)

<u>Field redefinition</u>

$$H_i \to H_i + \frac{a_{ijkl}}{f^2}(H_j^\dagger H_k)H_l$$

$$\frac{a_{kijl}+a^*_{ljik}}{2f^2}(O^H_{ijkl}+2O^r_{ijkl}) + \frac{-a_{kijl}+a^*_{ljik}}{2f^2}O^{HT}_{ijkl}$$

/3

O^{HT}	$(1/2)N^2(N^2-1)$	$(1/2)N^2(N^2+1)$
Nonlinear	$(1/2)N^2(N^2+3)$	$(1/2)N^2(N^2-1)$

- O^{HT} do not appear.
- Lagrangian of NG-Higgs is given with only O^H and O^T.

Contents

2 Higgs doublet model

- The model including two (**2**, **½**) scalar bosons.

$$H_1 = \begin{pmatrix} h_1 + ih_2 \\ v\cos\beta + h_3 + ih_4 \end{pmatrix}, \quad H_2 = \begin{pmatrix} h_5 + ih_6 \\ v\sin\beta + h_7 + ih_8 \end{pmatrix}$$

- Mass eigenstates are given by mixing.

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_3 \\ h_7 \end{pmatrix},$$

$$\begin{pmatrix} G^+ & G^0 \\ H^+ & A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} h_1 + ih_2 & h_4 \\ h_5 + ih_6 & h_8 \end{pmatrix}$$

- Only the Higgs derivative interactions are considered.

The case of 2 Higgs

$$\mathscr{L}^{6\mathrm{NL}}_{2\mathrm{HD}} = \frac{1}{f^2}\mathscr{T}^{2\mathrm{HD}}_{abcd}\, h^a h^b \partial h^c \partial h^d$$

$$\begin{aligned}
\mathcal{T}^{abcd}_{2\mathrm{HDM}} = {} & a^L_{1111}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(1,1)}\right)_{bd} + 2a^L_{1112}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(1,2)}\right)_{bd} + 2a^L_{1122}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(2,2)}\right)_{bd} \\
& + a^L_{1212}\left(T^{L\alpha}_{(1,2)}\right)_{ac}\left(T^{L\alpha}_{(1,2)}\right)_{bd} + 2a^L_{2221}\left(T^{L\alpha}_{(2,2)}\right)_{ac}\left(T^{L\alpha}_{(2,1)}\right)_{bd} + a^L_{2222}\left(T^{L\alpha}_{(2,2)}\right)_{ac}\left(T^{L\alpha}_{(2,2)}\right)_{bd} \\
& + a^R_{1111}\left(T^{R\alpha}_{(1,1)}\right)_{ac}\left(T^{R\alpha}_{(1,1)}\right)_{bd} + 2a^R_{1112}\left(T^{R\alpha}_{(1,1)}\right)_{ac}\left(T^{R\alpha}_{(1,2)}\right)_{bd} + 2a^R_{1122}\left(T^{R\alpha}_{(1,1)}\right)_{ac}\left(T^{R\alpha}_{(2,2)}\right)_{bd} \\
& + a^R_{1212}\left(T^{R\alpha}_{(1,2)}\right)_{ac}\left(T^{R\alpha}_{(1,2)}\right)_{bd} + 2a^R_{2221}\left(T^{R\alpha}_{(2,2)}\right)_{ac}\left(T^{R\alpha}_{(2,1)}\right)_{bd} + a^R_{2222}\left(T^{R\alpha}_{(2,2)}\right)_{ac}\left(T^{R\alpha}_{(2,2)}\right)_{bd} \\
& + a^S_{1212}\left(S^{\alpha 3}_{(1,2)}\right)_{ac}\left(S^{\alpha 3}_{(1,2)}\right)_{bd} + a^{SS}_{1212}\left(S^{\alpha\beta}_{(1,2)}\right)_{ac}\left(S^{\alpha\beta}_{(1,2)}\right)_{bd} + 2a^{LS}_{1112}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(S^{\alpha 3}_{(1,2)}\right)_{bd} \\
& + a^{LS}_{1212}\left(T^{L\alpha}_{(1,2)}\right)_{ac}\left(S^{\alpha 3}_{(1,2)}\right)_{bd} + 2a^{LS}_{2221}\left(T^{L\alpha}_{(2,2)}\right)_{ac}\left(S^{\alpha 3}_{(2,1)}\right)_{bd} + 2a^Y_{1111}\left(T^{R3}_{(1,1)}\right)_{ac}\left(T^{R3}_{(1,1)}\right)_{bd} \\
& + 4a^Y_{1112}\left(T^{R3}_{(1,1)}\right)_{ac}\left(T^{R3}_{(1,2)}\right)_{bd} + 2a^Y_{1122}\left(T^{R3}_{(1,1)}\right)_{ac}\left(T^{R3}_{(2,2)}\right)_{bd} + a^Y_{1212}\left(T^{R3}_{(1,2)}\right)_{ac}\left(T^{R3}_{(1,2)}\right)_{bd} \\
& + 4a^Y_{2212}\left(T^{R3}_{(2,2)}\right)_{ac}\left(T^{R3}_{(1,2)}\right)_{bd} + 2a^Y_{2222}\left(T^{R3}_{(2,2)}\right)_{ac}\left(T^{R3}_{(2,2)}\right)_{bd} + a^U_{1212}\left(U_{(1,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd} \\
& + 4a^{YU}_{1112}\left(T^{R3}_{(1,1)}\right)_{ac}\left(U_{(1,2)}\right)_{bd} + a^{YU}_{1212}\left(T^{R3}_{(1,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd} + 4a^{YU}_{2212}\left(T^{R3}_{(2,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd}.
\end{aligned}$$

The case of 2 Higgs

$$\mathscr{L}^{6\mathrm{NL}}_{2\mathrm{HD}} = \frac{1}{f^2}\mathscr{T}^{2\mathrm{HD}}_{abcd} h^a h^b \partial h^c \partial h^d$$

$$\mathcal{T}^{abcd}_{2\mathrm{HDM}} = a^L_{1111}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(1,1)}\right)_{bd} + 2a^L_{1112}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(1,2)}\right)_{bd} + 2a^L_{1122}\left(T^{L\alpha}_{(1,1)}\right)_{ac}\left(T^{L\alpha}_{(2,2)}\right)_{bd}$$

$$\cdots$$

$$+ 4a^Y_{2212}\left(T^{R3}_{(2,2)}\right)_{ac}\left(T^{R3}_{(1,2)}\right)_{bd} + 2a^Y_{2222}\left(T^{R3}_{(2,2)}\right)_{ac}\left(T^{R3}_{(2,2)}\right)_{bd} + a^U_{1212}\left(U_{(1,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd}$$

$$+ 4a^{YU}_{1112}\left(T^{R3}_{(1,1)}\right)_{ac}\left(U_{(1,2)}\right)_{bd} + a^{YU}_{1212}\left(T^{R3}_{(1,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd} + 4a^{YU}_{2212}\left(T^{R3}_{(2,2)}\right)_{ac}\left(U_{(1,2)}\right)_{bd}.$$

General
Re: 30; Im: 22 →

Nonlinear
Re: 14; Im: 6 ↓

CP sym.
Re: 14; Im: 0 ←

O(4) sym.
Re: 8; Im: 0

The case of 2 Higgs

- O(4) symmetric Lagrangean

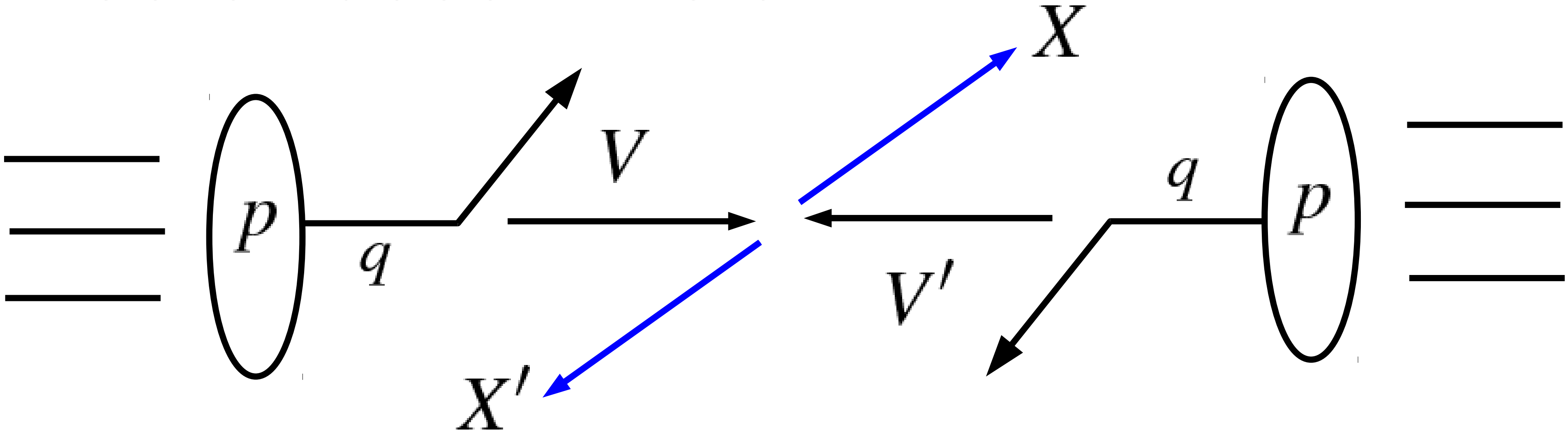
$$
\begin{aligned}
\mathscr{L}_{\text{2HDM}} = {} & \frac{c^H_{1111}}{2f^2} O^H_{1111} + \frac{c^H_{1112}}{f^2} (O^H_{1112} + O^H_{1121}) + \frac{c^H_{1122}}{f^2} O^H_{1122} \\
& + \frac{c^H_{1221}}{f^2} O^H_{1221} + \frac{c^H_{1212}}{2f^2} (O^H_{1212} + O^H_{2121}) \\
& + \frac{c^H_{2221}}{f^2} (O^H_{2212} + O^H_{2221}) + \frac{c^H_{2222}}{2f^2} O^H_{2222} \\
& + \frac{c^T_{1122}}{f^2} O^T_{1122} + \frac{c^T_{1221}}{f^2} O^T_{1221} + \frac{c^T_{1212}}{2f^2} (O^T_{1212} + O^T_{2121})
\end{aligned}
$$

where $c^T_{1122} = -(c^T_{1221} + c^T_{1212}) = -\frac{1}{3}(c^H_{1221} - c^H_{1212})$

$$
O^H_{ijkl} = (\partial H_i^\dagger H_j)(\partial H_k^\dagger H_l), \; O^T_{ijkl} = (H_i^\dagger \overleftrightarrow{\partial} H_j)(H_k^\dagger \overleftrightarrow{\partial} H_l)
$$

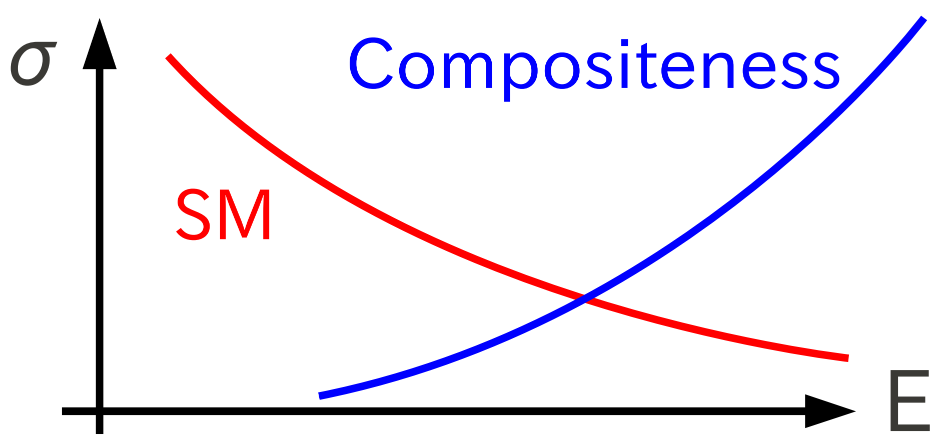
→ Contributions to VBF are studied.

Vector boson fusion



$$V, V' \in \{W_L^{\pm}, Z_L\}$$

$$X, X' \in \{W_L^{\pm}, Z_L, h, H^{\pm}, A, H\}$$



Cross sections

$VV' \to LL'$

$$\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{2}{3}C_1(\beta)^2,$$

$$\sigma(W_L^+W_L^- \to hh)_{\text{cust}} = \frac{s}{32\pi f^4}C_2(\alpha,\beta)^2,$$

$$\sigma(W_L^+W_L^- \to Z_LZ_L)_{\text{cust}} = \frac{3}{2}\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to W_L^+W_L^-)_{\text{cust}} = 3\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to hh)_{\text{cust}} = \sigma(W_L^+W_L^- \to hh)_{\text{cust}},$$

$$\sigma(W_L^+Z_L \to W_L^+Z_L)_{\text{cust}} = \sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\text{cust}},$$

$$\sigma(W_L^+W_L^+ \to W_L^+W_L^+)_{\text{cust}} = \frac{3}{2}\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\text{cust}},$$

$VV' \to LH$

$$\sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{2}{3}C_3(\beta)^2,$$

$$\sigma(W_L^+W_L^- \to hH)_{\text{cust}} = \frac{s}{32\pi f^4}2C_4(\alpha,\beta)^2,$$

$$\sigma(W_L^+W_L^- \to hA)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{2}{27}\sin^2(\alpha-\beta)(c^H_{1221}-c^H_{1212})^2,$$

$$\sigma(W_L^+W_L^- \to Z_LA)_{\text{cust}} = 3\sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to W_L^+H^-)_{\text{cust}} = 3\sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to hH)_{\text{cust}} = \sigma(W_L^+W_L^- \to hH)_{\text{cust}},$$

$$\sigma(W_L^+Z_L \to H^+h)_{\text{cust}} = \sigma(W_L^+W_L^- \to hA)_{\text{cust}},$$

$$\sigma(W_L^+Z_L \to W_L^+A)_{\text{cust}} = \sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}},$$

$$\sigma(W_L^+Z_L \to H^+Z_L)_{\text{cust}} = \sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}},$$

$$\sigma(W_L^+W_L^+ \to W_L^+H^+)_{\text{cust}} = 3\sigma(W_L^+W_L^- \to W_L^+H^-)_{\text{cust}},$$

$VV' \to HH'$

$$\sigma(W_L^+W_L^- \to H^+H^-)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{2}{3}(C_5(\beta)^2 - C_5(\beta)(c^H_{1221}-c^H_{1122}) + (c^H_{1221}-c^H_{1122})^2),$$

$$\sigma(W_L^+W_L^- \to HH)_{\text{cust}} = \frac{s}{32\pi f^4}C_6(\alpha,\beta)^2,$$

$$\sigma(W_L^+W_L^- \to AA)_{\text{cust}} = \frac{s}{32\pi f^4}C_5(\beta)^2,$$

$$\sigma(W_L^+W_L^- \to HA)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{2}{27}\cos^2(\alpha-\beta)(c^H_{1221}-c^H_{1212})^2,$$

$$\sigma(Z_LZ_L \to H^+H^-)_{\text{cust}} = 2\sigma(W_L^+W_L^- \to AA)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to HH)_{\text{cust}} = \sigma(W_L^+W_L^- \to HH)_{\text{cust}},$$

$$\sigma(Z_LZ_L \to AA)_{\text{cust}} = \frac{s}{32\pi f^4}(c^H_{1122}-3c^T_{1221})^2,$$

$$\sigma(W_L^+Z_L \to H^+H)_{\text{cust}} = \sigma(W_L^+W_L^- \to HA)_{\text{cust}},$$

$$\sigma(W_L^+Z_L \to H^+A)_{\text{cust}} = \frac{s}{32\pi f^4}\frac{1}{2}\Big((C_5(\beta) - c^H_{1122} + c^H_{1221} - 3c^T_{1221})^2 + \frac{1}{3}\left(C_5(\beta) + \frac{c^H_{1221}+2c^H_{1212}}{3} - c^H_{1122} + c^T_{1221}\right)^2\Big),$$

$$\sigma(W_L^+W_L^+ \to H^+H^+)_{\text{cust}} = \sigma(W_L^+W_L^- \to AA)_{\text{cust}}.$$

Characters of cross sections

$$VV' \to LL'$$

$$\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\rm cust} = \frac{s}{32\pi f^4}\frac{2}{3}C_1(\beta)^2,$$
$$\sigma(W_L^+W_L^- \to hh)_{\rm cust} = \frac{s}{32\pi f^4}C_2(\alpha,\beta)^2,$$
$$\sigma(W_L^+W_L^- \to Z_LZ_L)_{\rm cust} = \frac{3}{2}\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\rm cust},$$
$$\sigma(Z_LZ_L \to W_L^+W_L^-)_{\rm cust} = 3\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\rm cust},$$
$$\sigma(Z_LZ_L \to hh)_{\rm cust} = \sigma(W_L^+W_L^- \to hh)_{\rm cust},$$
$$\sigma(W_L^+Z_L \to W_L^+Z_L)_{\rm cust} = \sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\rm cust},$$
$$\sigma(W_L^+W_L^+ \to W_L^+W_L^+)_{\rm cust} = \frac{3}{2}\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\rm cust},$$

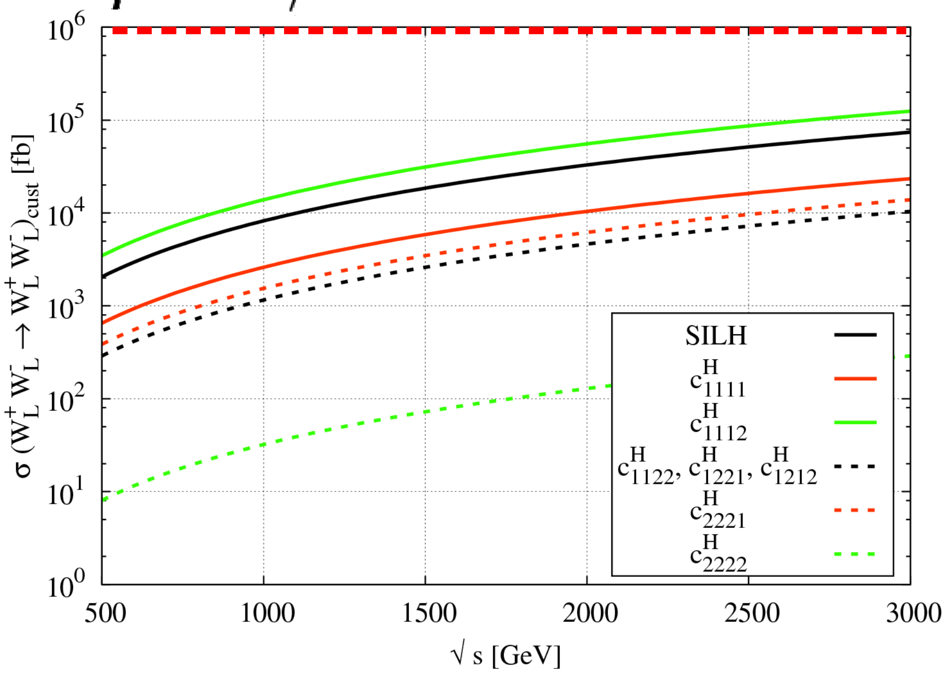
- 8 coeffs. ($c^{H,T}/f^2$) and 2 angles (α, β) can be fixed.

Numerical results

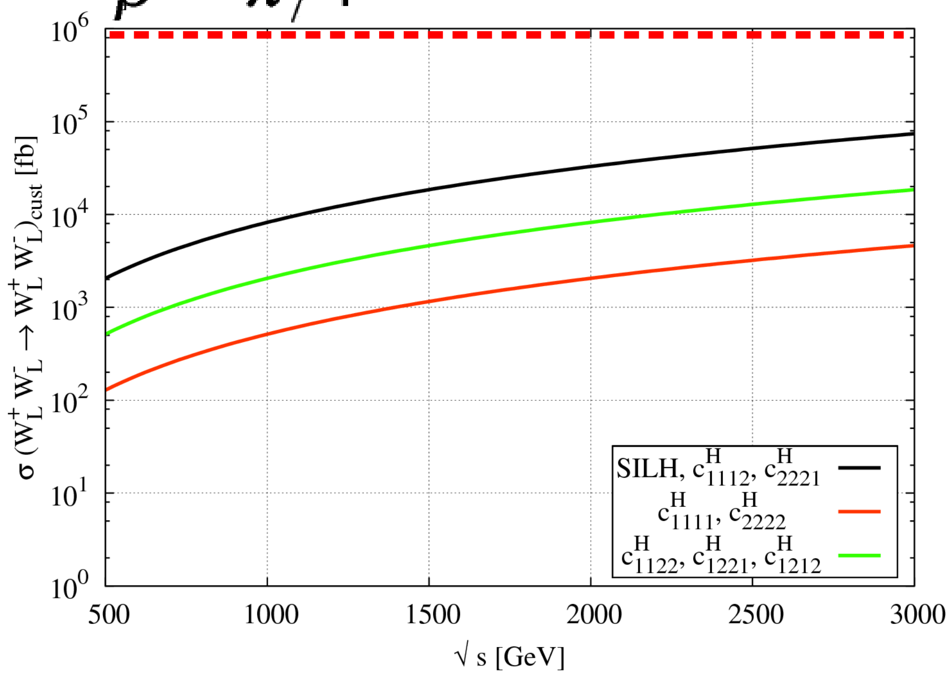
- $W_L^{\pm}$ cross sections given by a coefficient.

$$c^{H,T}/f^2 = 1/(750\text{GeV})^2$$

$\beta = \pi/6$



$\beta = \pi/4$



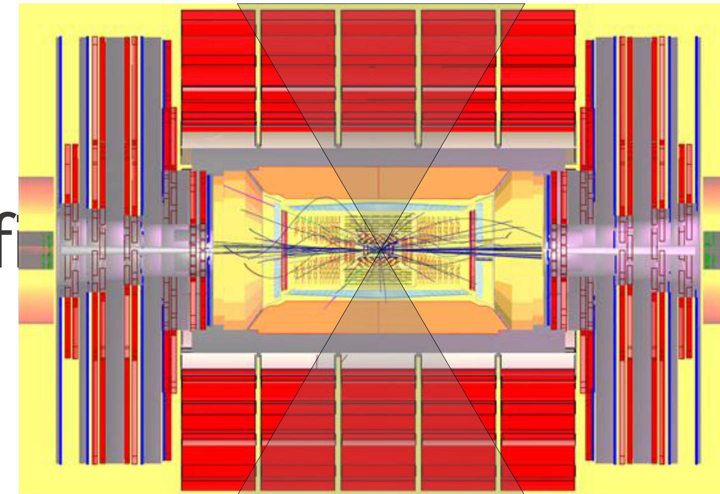
$$\sigma(W_L^+ W_L^- \to W_L^+ W_L^-)_{\text{SILH}} \sim 10^{3\sim5}\,\text{fb}$$

$$\sigma(W^+ W^- \to W^+ W^-)_{\text{SM}} \sim 2 \times 10^6\,\text{fb}$$

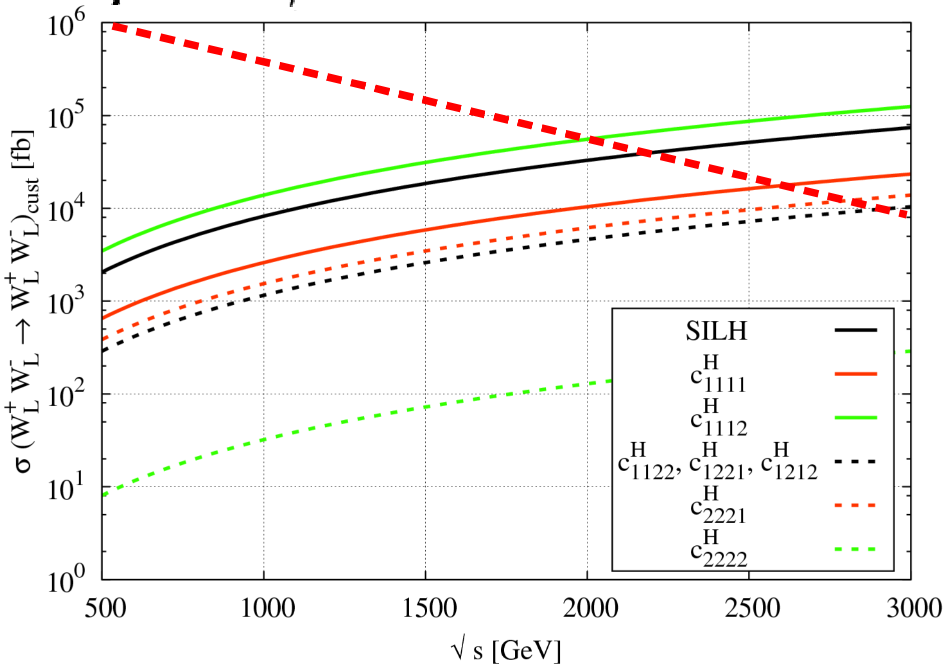
Numerical results

- $W_L^{\pm}$ cross sections given by a coeffi

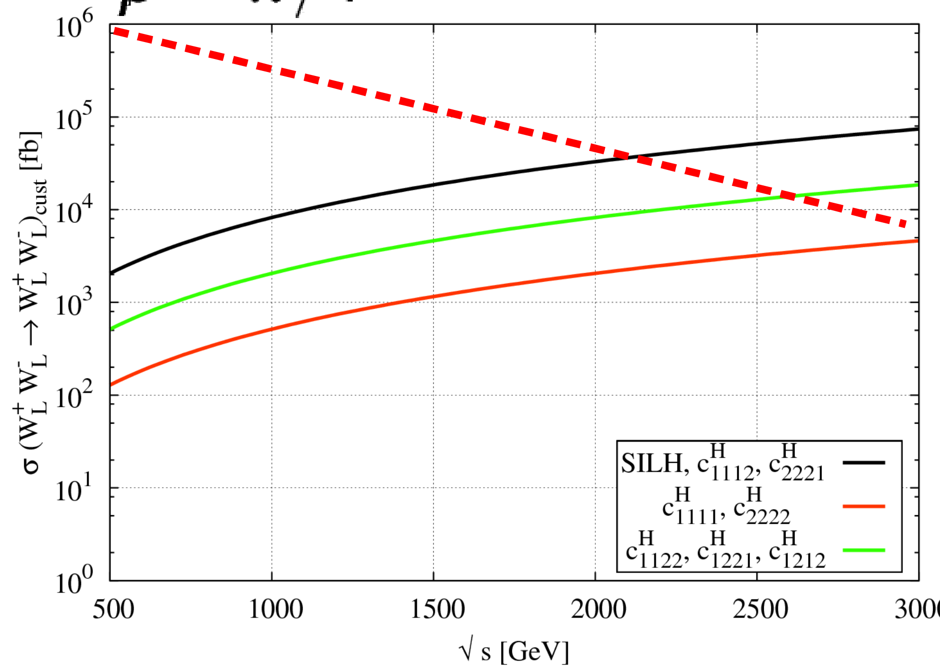
$$c^{H,T}/f^2 = 1/(750\mathrm{GeV})^2$$



$\beta = \pi/6$



$\beta = \pi/4$

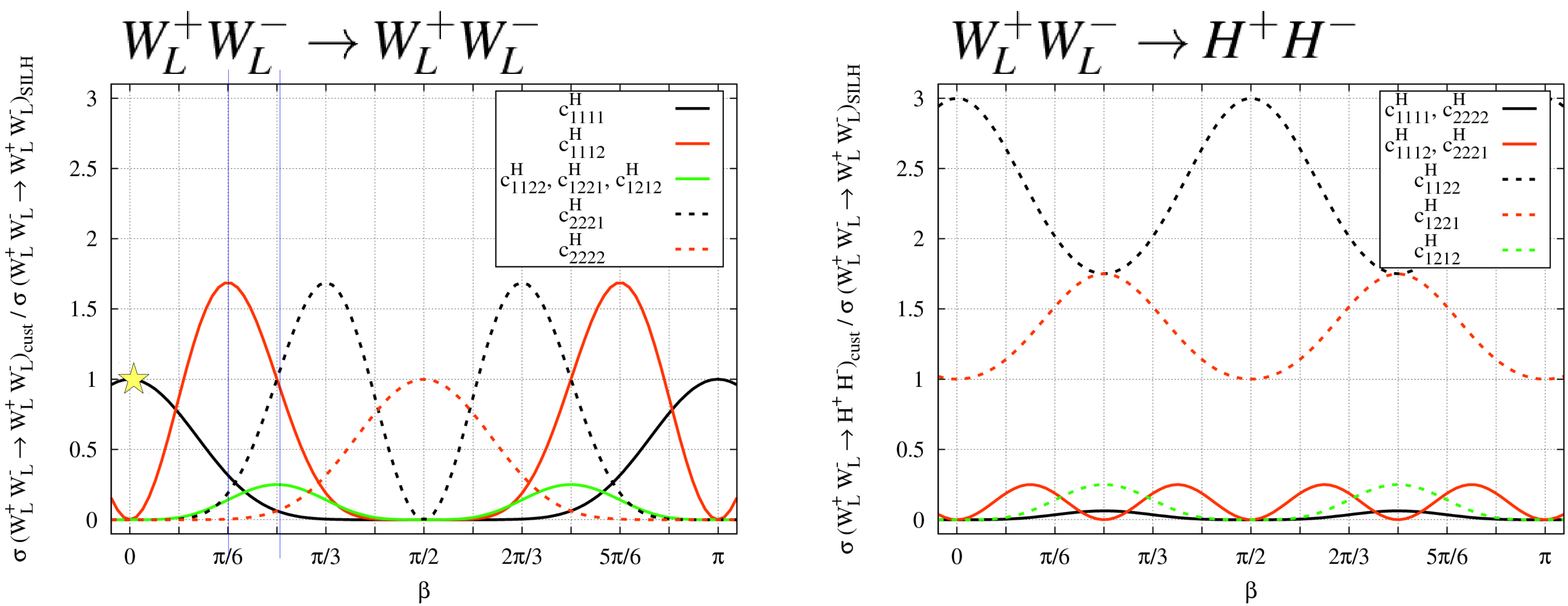


$$\sigma(W_L^+W_L^- \to W_L^+W_L^-)_{\mathrm{SILH}} \sim 10^{3\sim5}\,\mathrm{fb}$$

$$\sigma(W^+W^- \to W^+W^-)_{\mathrm{SM}} \sim 2\times10^{6}\,\mathrm{fb}$$

Numerical results

- β dependences of cross sections in the unit of the SILH W boson scattering.

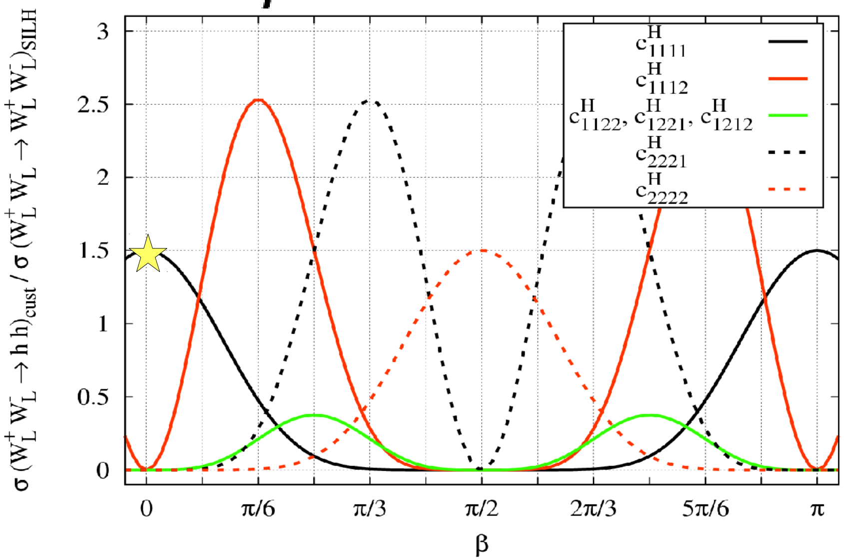


- $c^H_{1122,1221}$ generate non-zero σ to the $H^\pm$ production, while contributions to the $W_L^\pm$ production are small.

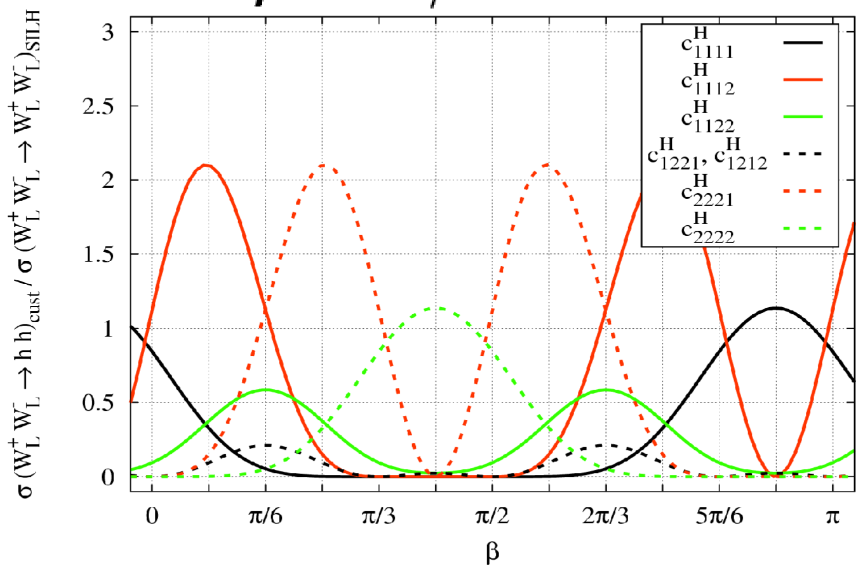
Numerical results

- α, β dependence of the *h* pair production.

$\alpha - \beta = 0$



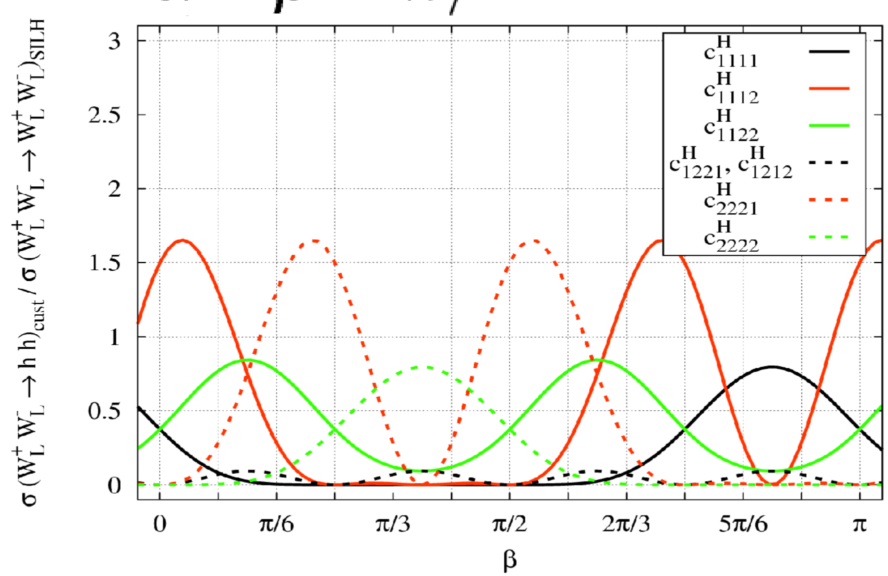
$\alpha - \beta = \pi/6$



$$\sigma(W_L^+ W_L^- \to W_L^+ W_L^-)_{\mathrm{SILH}} \sim 10^{3\sim5}\,\mathrm{fb}$$

$$\sigma(W^+ W^- \to hh)_{\mathrm{SM}} \sim 5 \times 10^4\,\mathrm{fb}$$

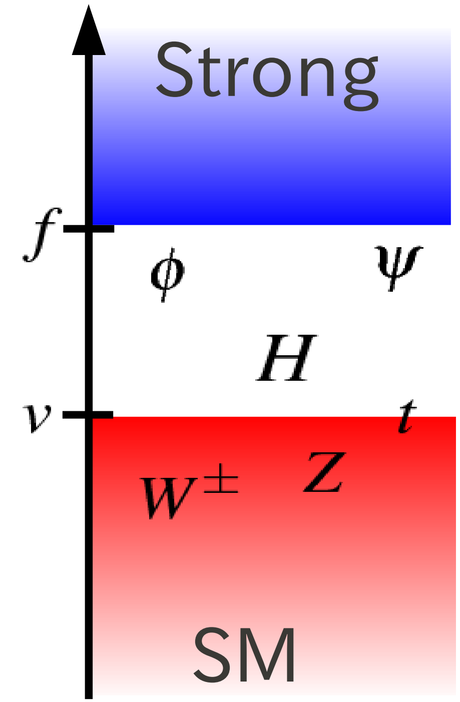
$\alpha - \beta = \pi/4$



- SILH can be distinguished from the others.

Conclusion

	1Higgs	2Higgs	3Higgs	......
Weak	SM...	SUSY ...	......	......
Strong	Composite Higgs models			



$$\mathscr{L}_{\rm NG} = \frac{f^2}{2}\mathrm{tr}\left[(\partial e^{-i\pi/f})(\partial e^{i\pi/f})\right]$$

$$= \frac{1}{2}\partial h \partial h - \frac{1}{24 f^2}\left(4 f^{aci} f^{bdi} + f^{ace} f^{bde}\right) h^a h^b (\partial h^c)(\partial h^d) + \cdots$$

4N real scalars

$$h T^{so(4N)} \partial h \quad (T^{so(4N)} \in \{T^{L\alpha}_{(i,j)}, T^{R\beta}_{(i,j)}, S^{\alpha\beta}_{(i,j)}, U_{(i,j)}\})$$

$$SU(2)_L \times SU(2)_R : (\mathbf{3},\mathbf{1}),\ (\mathbf{1},\mathbf{3}),\ (\mathbf{3},\mathbf{3}),\ (\mathbf{1},\mathbf{1})$$

	Re	Im
General	$(3/2)N^2(N^2+1)$	$(1/2)N^2(3N^2-1)$
Nonlinear	$(1/2)N^2(N^2+3)$	$(1/2)N^2(N^2-1)$

1/3

- Lagrangian is given using only O^H and O^T.