Perturbative unitarity of Higgs derivative interactions

arXiv:1210.5674

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[5] arXiv:1210.5674 [pdf, ps, other]

Perturbative unitarity of Higgs derivative interactions

Yohei Kikuta, Yasuhiro Yamamoto

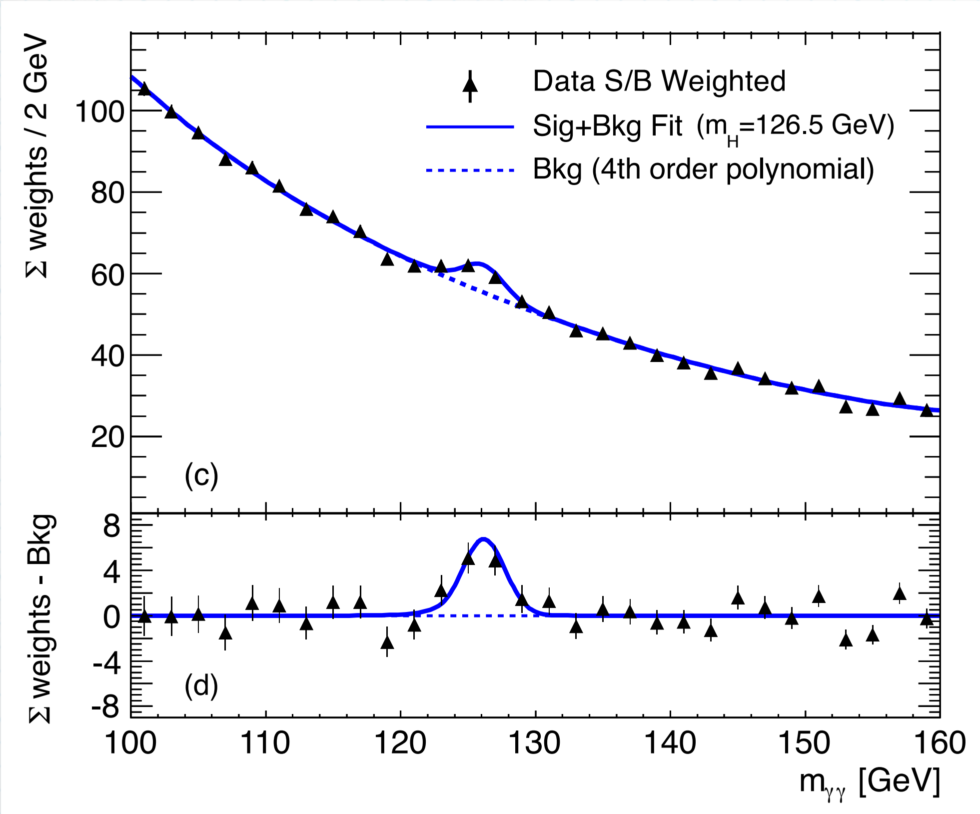
Comments: 20 pages, 6 figures

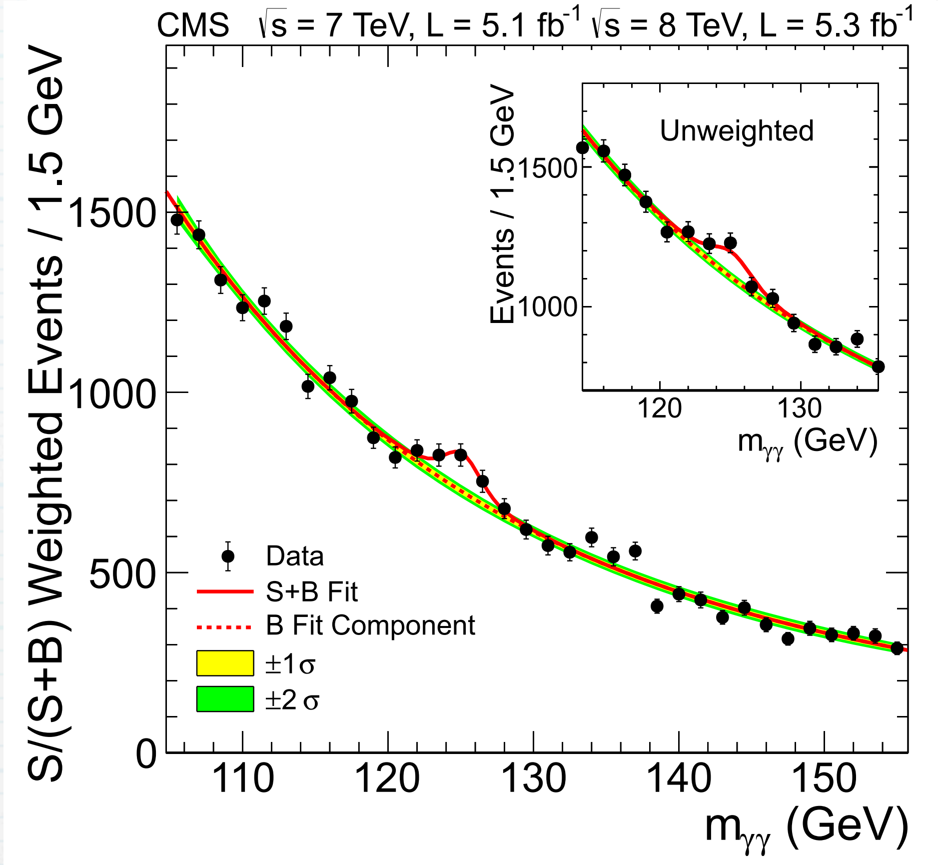
Subjects: **High Energy Physics - Phenomenology (hep-ph)**

We study the perturbative unitarity bound given by dimension six derivative interactions consisting of Higgs doublets. These operators emerge from kinetic terms of composite Higgs models or integrating out heavy particles that interact with Higgs doublets. They lead to new phenomena beyond the Standard Model. One of characteristic contributions by derivative interactions appear in vector boson scattering processes. Longitudinal modes of massive vector bosons can be regarded as Nambu Goldstone bosons eaten by each vector field with the equivalence theorem. Since their effects become larger and larger as the collision energy of vector bosons increases, vector boson scattering processes become important in a high energy region around the TeV scale. On the other hand, in such a high energy region, we have to take the unitarity of amplitudes into account. We have obtained the unitarity condition in terms of the parameter included in the effective Lagrangian for one Higgs doublet models. Applying it to some of models, we have found that contributions of derivative interactions are not so large enough to clearly discriminate them from the Standard Model ones. We also study it in two Higgs doublet models. Because they are too complex to obtain the bound in the general effective Lagrangian, we have calculated it in explicit models. These analyses tell us highly model dependence of the perturbative unitarity bounds.

Yasuhiro Yamamoto (University of Tokyo)

Observation of the (Higgs) boson

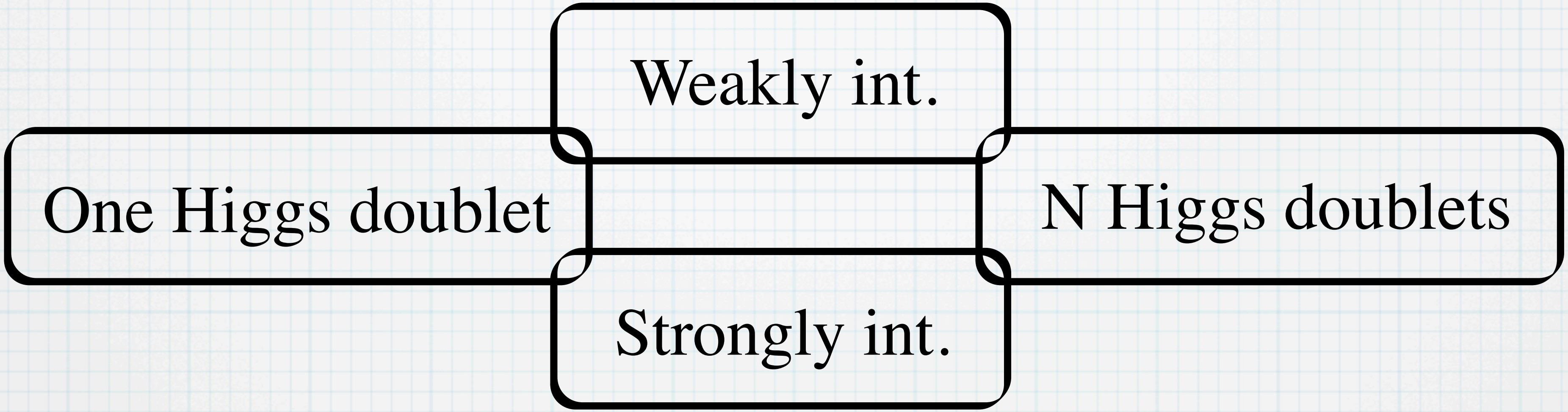




ATLAS arXiv:1207.7214v2

CMS arXiv:1207.7235v1

Possibilities of the Higgs sector



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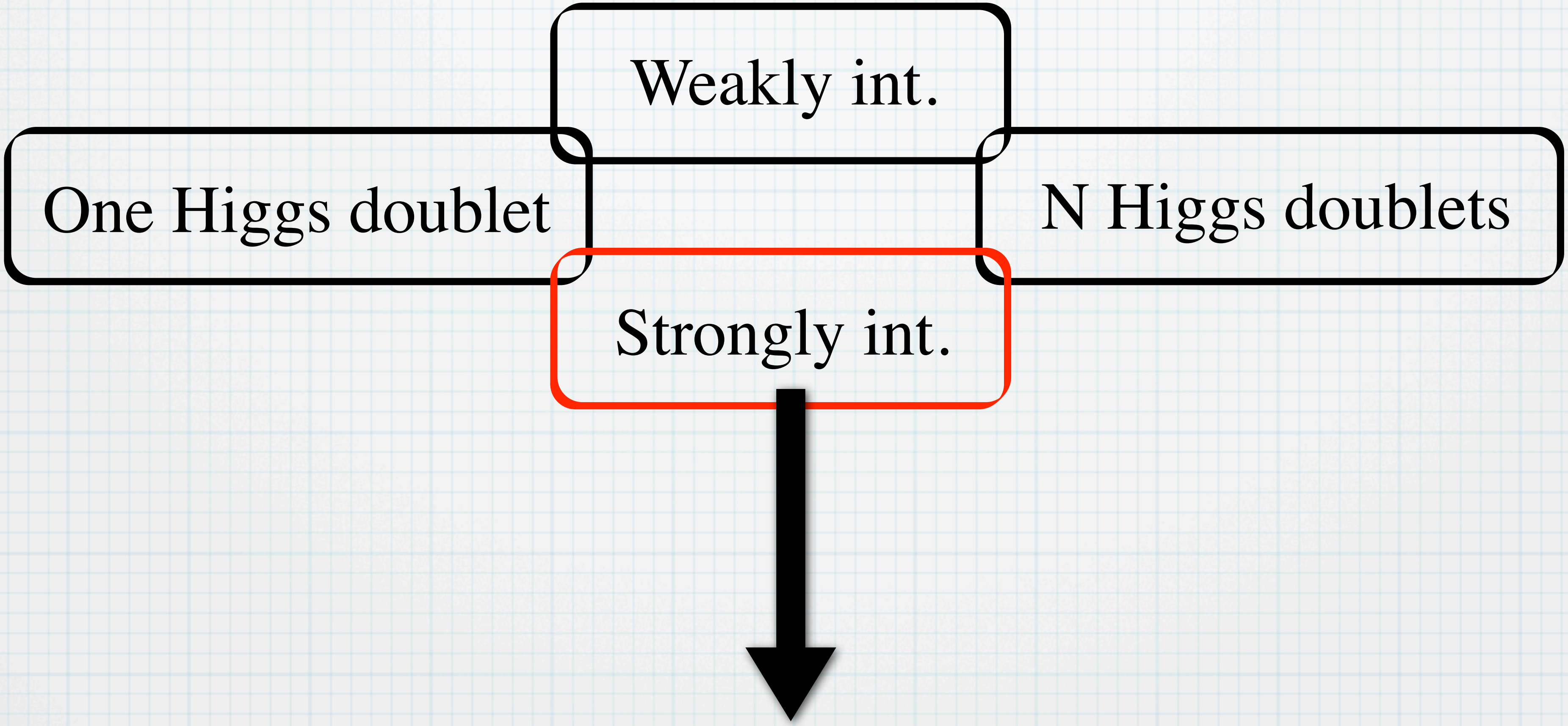


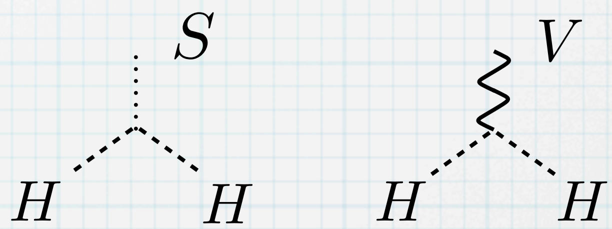
Higgs doublets arise as pseudo NG fields

Higher dimensional differential ops.

$$\mathcal{L}_{\rm eff} \supset \frac{c^H}{2f^2}\partial(H^\dagger H)\partial(H^\dagger H)$$

Kinetic terms of composite Higgs models : $\mathcal{L}_{\rm eff} = \frac{f^2}{8}{\rm tr}\left[\left(\partial e^{-2i\Pi/f}\right)\left(\partial e^{2i\Pi/f}\right)\right]$

Integrating out a heavy particle :



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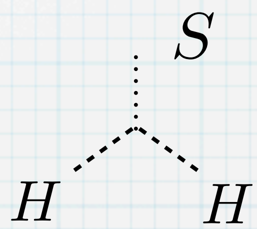
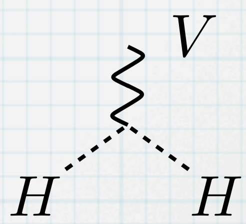
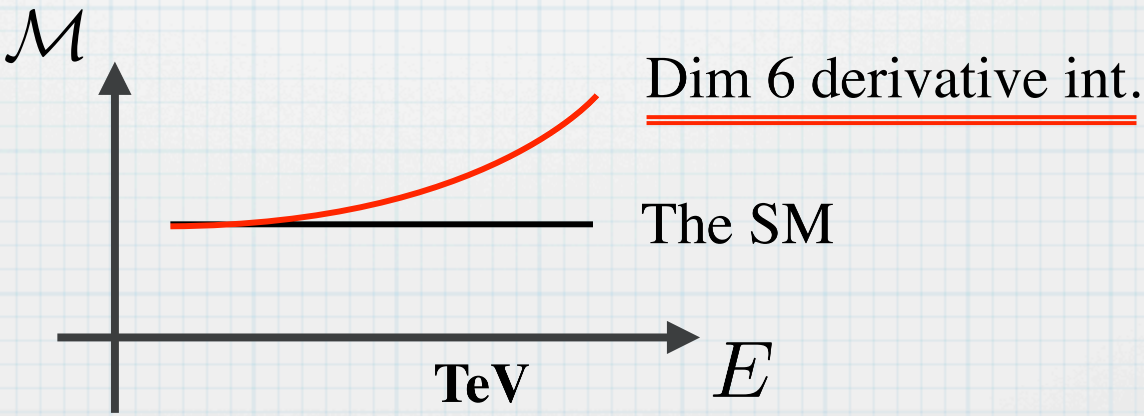
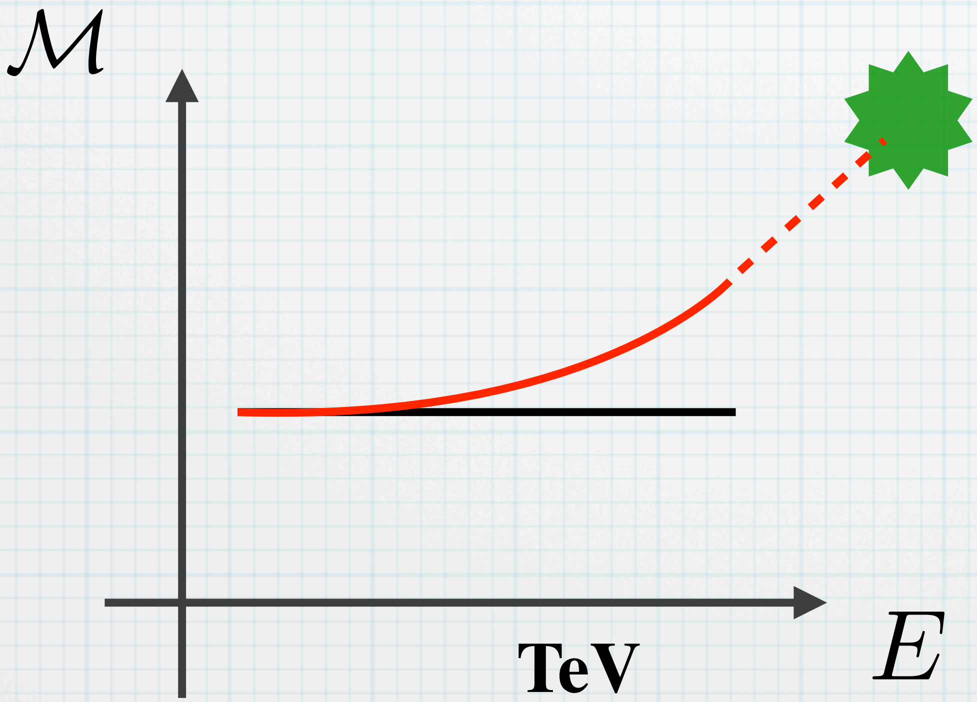






Higher dimensional differential ops.

$$\mathcal{L}_{\text{eff}} \supset \frac{c^H}{2f^2}\partial(H^\dagger H)\partial(H^\dagger H)$$



Unitarity violation

↓

New contribution appears

Where is the energy scale ?

Unitarity bound

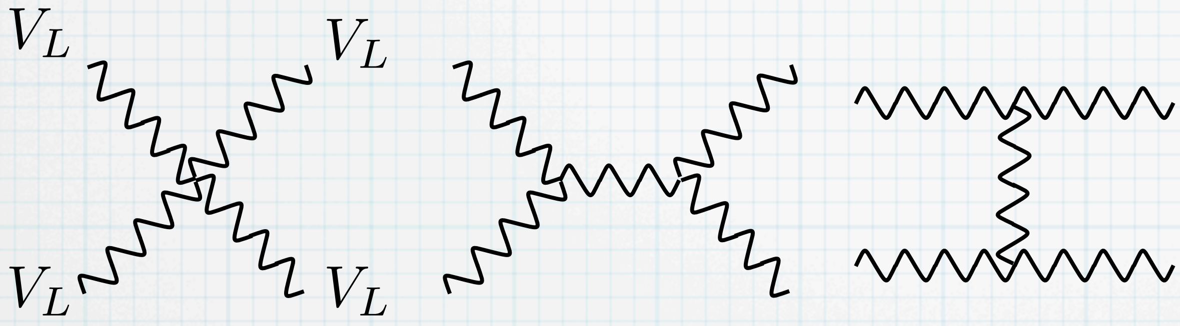
Total cross section ⟷ **Optical theorem**

+ Partial Wave Expansion

$$|\mathrm{Re}[M_l]| \leq \frac{1}{2}$$

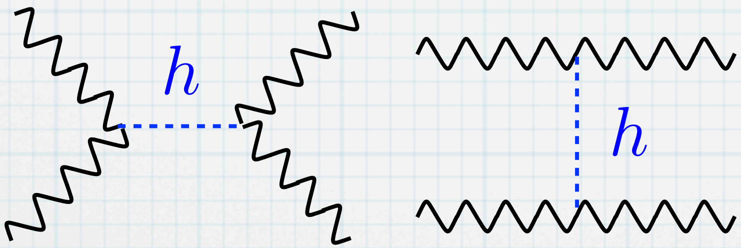
$$M_l = \frac{1}{16\pi s}\int_{-1}^{1} d\cos\theta \, P_l(\cos\theta)\, \mathcal{M}(s, \cos\theta)$$

Standard model case



Gauge symmetry **Higgs mediated**

$$= \mathcal{O}(p^4) + \mathcal{O}(p^2) + \mathcal{O}(p^0)$$



$$= \mathcal{O}(p^2) + \mathcal{O}(p^0)$$

Standard model case

Unitarity bound for charge neutral & angular momentum zeroth modes

$$
\begin{array}{c} \\ W_L^+W_L^- \\ Z_LZ_L \\ hh \\ hZ_L \end{array}
\begin{array}{c} \begin{array}{cccc} W_L^+W_L^- & Z_LZ_L & hh & hZ_L \end{array} \\
\begin{pmatrix} 1 & \frac{1}{\sqrt{8}} & \frac{1}{\sqrt{8}} & 0 \\ \frac{1}{\sqrt{8}} & \frac{3}{4} & \frac{1}{4} & 0 \\ \frac{1}{\sqrt{8}} & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 0 & 0 & \frac{1}{2} \end{pmatrix} \end{array}
\times \frac{-G_F m_H^2}{4\pi\sqrt{2}}
$$

The largest eigenvalue : $\frac{3}{2} \times \frac{-G_F m_H^2}{4\pi\sqrt{2}}$

⟶ Higgs mass upper bound

$$m_H \lesssim 1\,[\mathrm{TeV}]$$

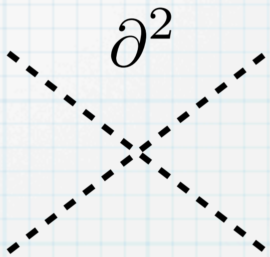
Lee, Quigg and Thacker (1977)

Derivative int. - one Higgs doublet

$$\mathcal{L}_{\rm eff} \supset \frac{c^H}{2f^2}\partial(H^\dagger H)\partial(H^\dagger H) \qquad H = \begin{pmatrix} C^+ \\ N \end{pmatrix}$$

High energy region

- Equivalence theorem
- Massless limit



Charge neutral & angular momentum zeroth modes

$$\begin{pmatrix} M_0(C^+C^- \to C^+C^-) & M_0(C^+C^- \to NN^\dagger) \\ M_0(NN^\dagger \to C^+C^-) & M_0(NN^\dagger \to NN^\dagger) \end{pmatrix} = \frac{\hat{s}}{16\pi f^2}\begin{pmatrix} c^H/2 & c^H \\ c^H & c^H/2 \end{pmatrix}$$

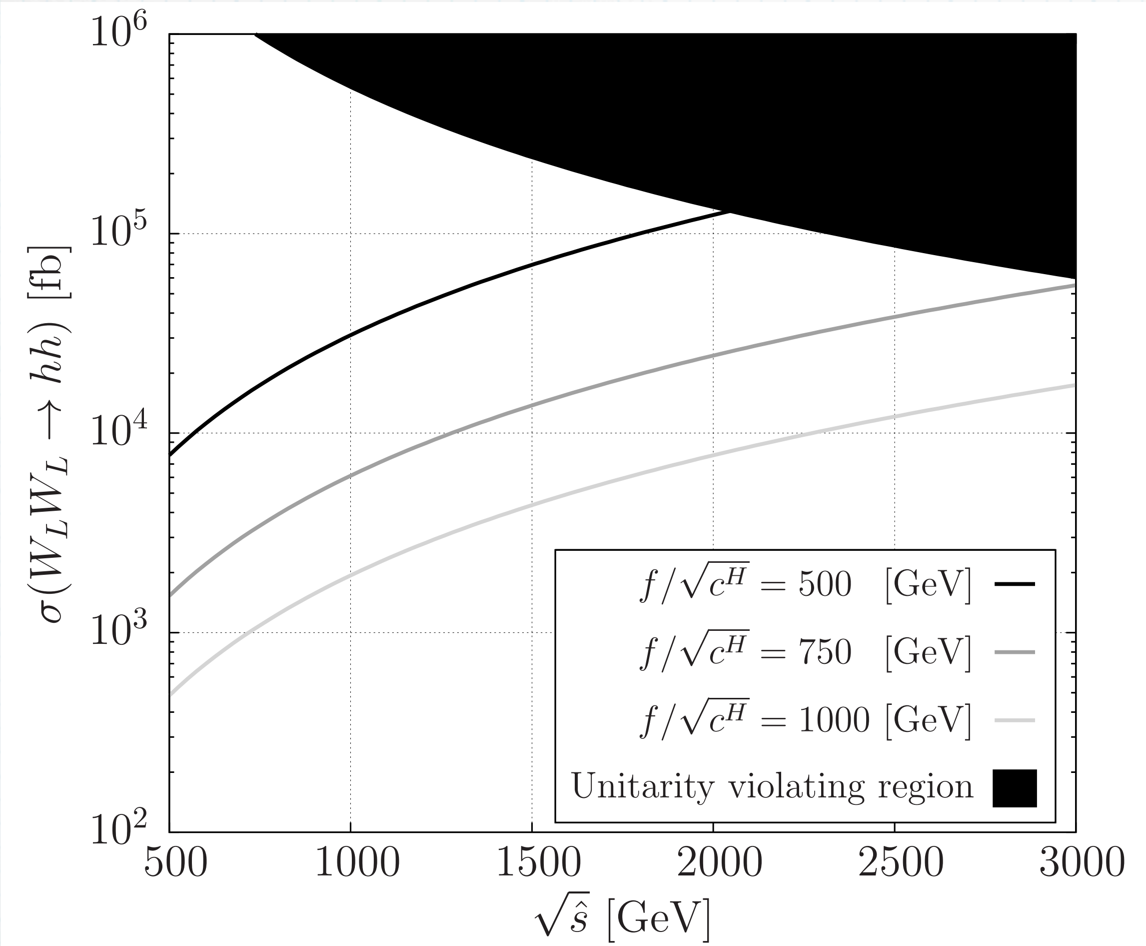
$$\downarrow$$

$$\frac{\hat{s}}{f^2} \lesssim \frac{16\pi}{3c^H}$$

Cross section

$$\frac{\hat{s}}{f^2} \lesssim \frac{16\pi}{3c^H}$$

$$\sigma(W_L^+ W_L^- \to hh) = \frac{\hat{s}}{32\pi}\left(\frac{c^H}{f^2}\right)^2 \lesssim \frac{8\pi}{9\hat{s}}$$



The MCHM : SO(5)/SO(4)

Agashe, Contino and Pomarol (2005)

$$c^H = 1$$

The LHMT : SU(5)/SO(5)

Cheng and Low (2003)

$$c^H = \frac{1}{2}$$

Comparison with the cut off scale

Naive dimensional analysis : $\Lambda \sim 4\pi f$

Unitarity violating scale : $\dfrac{\hat{s}_U}{f^2} \sim \dfrac{16\pi}{3c^H}$

$$\Rightarrow \quad \boxed{\hat{s}_U \sim \frac{\Lambda^2}{3\pi c^H}}$$

Suppose $c^H = O(1)$,

E

Λ Cut off

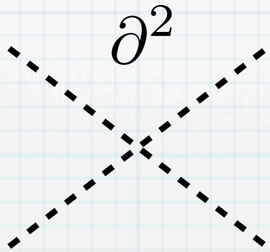
$\hat{s}_U$ Unitarity violation $\longrightarrow$ New contributions appear !!

f Decay constant

Derivative int. - two Higgs doublet

$$\mathcal{L}_{\rm eff} \supset \frac{c^H_{ijkl}}{f^2} O^H_{ijkl} + \frac{c^T_{ijkl}}{f^2} O^T_{ijkl} \qquad H_i = \begin{pmatrix} C_i^+ \\ N_i \end{pmatrix}$$

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



Charge neutral states

$$C_1^+ C_1^-, C_1^+ C_2^-, C_2^+ C_1^-, C_2^+ C_2^-, N_1 N_1^\dagger, N_1 N_2^\dagger, N_2 N_1^\dagger \text{ and } N_2 N_2^\dagger$$

8×8 matrix ↓ $|C_{\rm max}|$: The largest eigenvalue

$$\frac{\hat{s}}{f^2} \lesssim \frac{8\pi}{|C_{\rm max}|}$$

Example 1 : The bestest LH

Schmaltz, Stolarski and Thaler (2010)

Global symmetry : SO(6) × SO(6) / SO(6)

$$\mathcal{L}_{\rm eff} = \frac{f^2}{8}{\rm tr}\left[\left(\partial e^{-2i\Pi/f}\right)\left(\partial e^{2i\Pi/f}\right)\right] \quad \text{where} \quad \Pi = \frac{i}{\sqrt{2}}\begin{pmatrix} & h_1 & h_2 \\ -h_1^T & & \\ -h_2^T & & \end{pmatrix}$$

Interaction with a heavy singlet scalar

$$\mathcal{L}_\sigma = -\frac{m_\sigma^2}{2}\sigma^2 + \lambda f \sigma (H_1^\dagger H_2 + {\rm H.c.})$$

Coefficients :

$$c^H_{1111} = c^H_{2222} = \frac{1}{2},$$
$$c^H_{1221} = c^H_{1212} = \frac{1}{4} + \frac{\lambda^2 f^4}{m_\sigma^4},$$
$$c^T_{1221} = \frac{1}{4}, \quad c^T_{1212} = -\frac{1}{4}.$$

Example 1 : The bestest LH

The largest eigenvalue depends on $c^\sigma = \dfrac{\lambda^2 f^4}{m_\sigma^4}$

$$\frac{\hat{s}}{f^2} \lesssim \frac{8\pi}{|C_{\max}|}$$

$$0 \le c^\sigma < \frac{1}{8} \longrightarrow \frac{\hat{s}}{f^2} \lesssim \frac{16\pi}{2 - c^\sigma}$$

$$c^\sigma = \frac{1}{8} \longrightarrow \frac{\hat{s}}{f^2} \lesssim 8\frac{16\pi}{15}$$

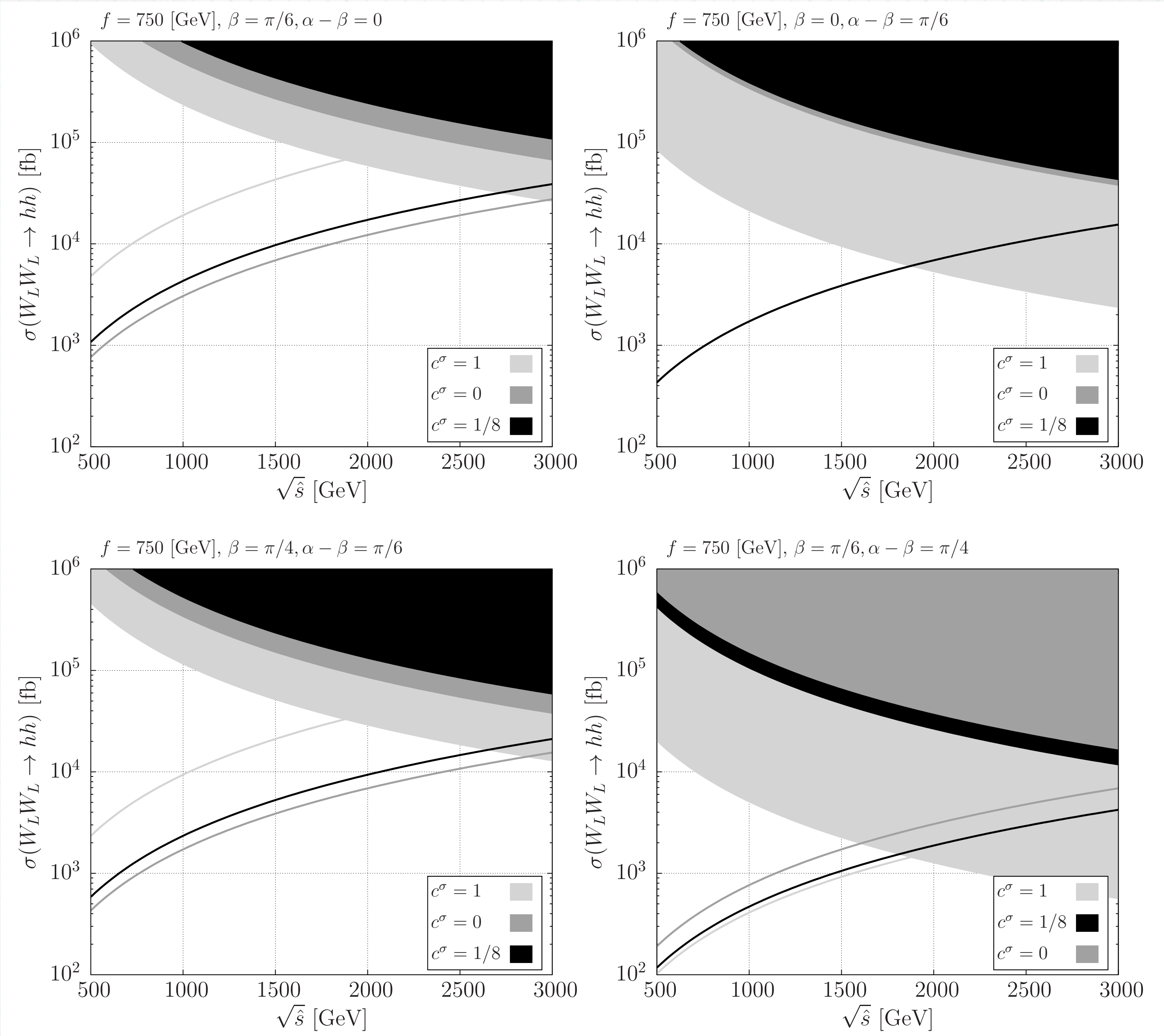
$$\frac{1}{8} < c^\sigma \longrightarrow \frac{\hat{s}}{f^2} \lesssim \frac{16\pi}{1 + 7c^\sigma}$$

Cross section :

$$\sigma(W_L^+ W_L^- \to hh) = \frac{\hat{s}}{32\pi f^4} B_h(\alpha,\beta)^2 \lesssim \frac{2\pi}{\hat{s}} \frac{B_h(\alpha,\beta)^2}{{C_{\max}}^2}$$

$$B_h(\alpha,\beta) = \frac{1}{4}\left(1 + (1 + 2c^\sigma(1 - c_{4\beta}))c_{2(\alpha-\beta)} + 2c^\sigma s_{4\beta} s_{2(\alpha-\beta)}\right)$$

Example 1 : The bestest LH



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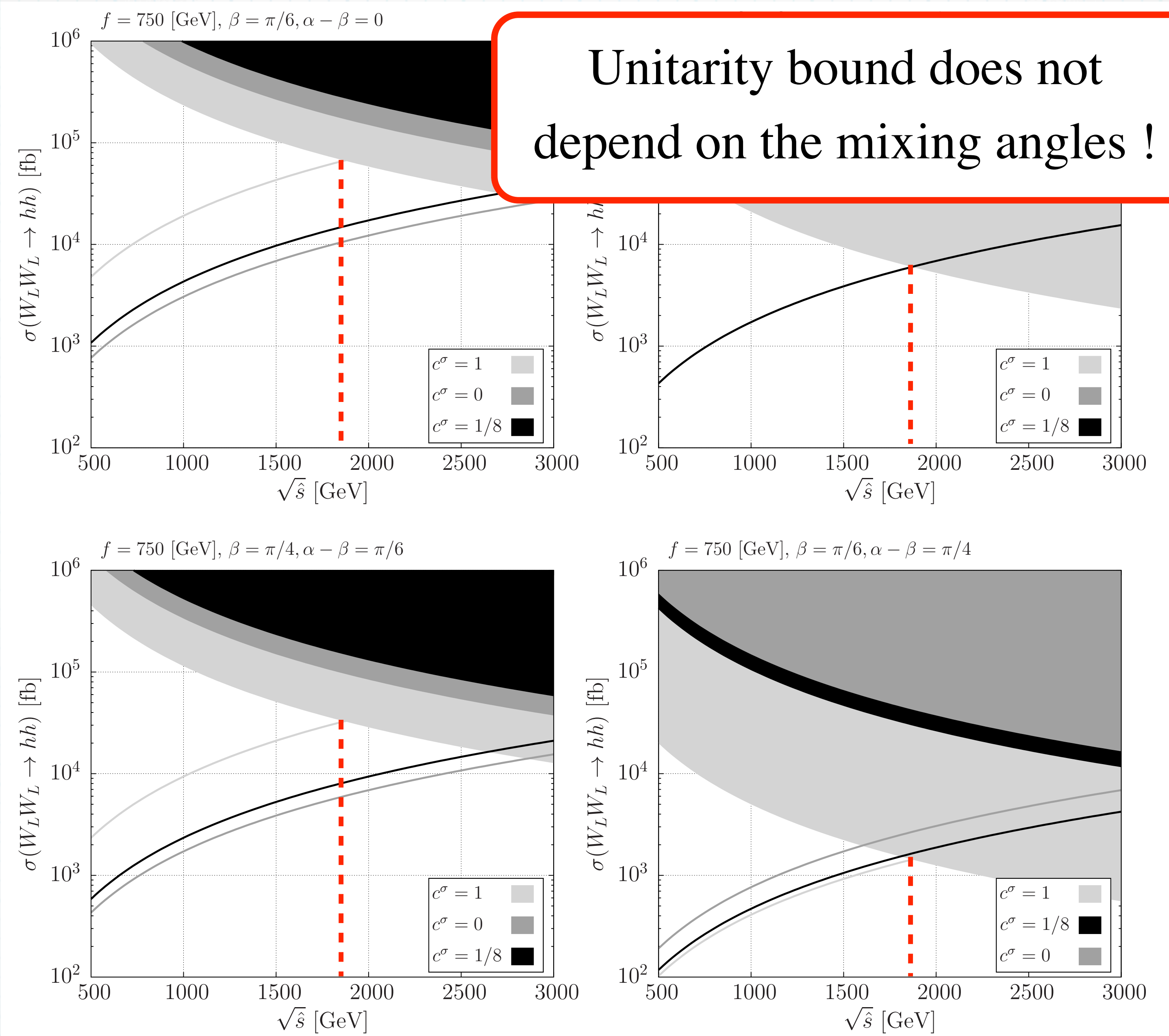


Unitarity bound does not depend on the mixing angles !

Example 2 : The UV friendly T-parity LH

Brown, Frugiuele and Gregoire (2011)

Global symmetry : SU(6) / Sp(6)

$$
\Pi = \frac{1}{2}\begin{pmatrix} & -\varepsilon(H_1 - H_2) & H_1 + H_2 & \\ \varepsilon(H_1^\dagger - H_2^\dagger) & & & -H_1^T - H_2^T \\ H_1^\dagger + H_2^\dagger & & & \varepsilon(H_1^T - H_2^T) \\ & -H_1^* - H_2^* & -\varepsilon(H_1^* - H_2^*) & \end{pmatrix}
$$

Coefficients :

$$
c^H_{1111} = c^H_{2222} = 4,
$$
$$
c^H_{1122} = 1, \quad c^H_{1212} = -3,
$$
$$
c^T_{1122} = c^T_{1212} = 1.
$$

Because of Z_2 symmetry, $\langle H_1 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ and $\langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$

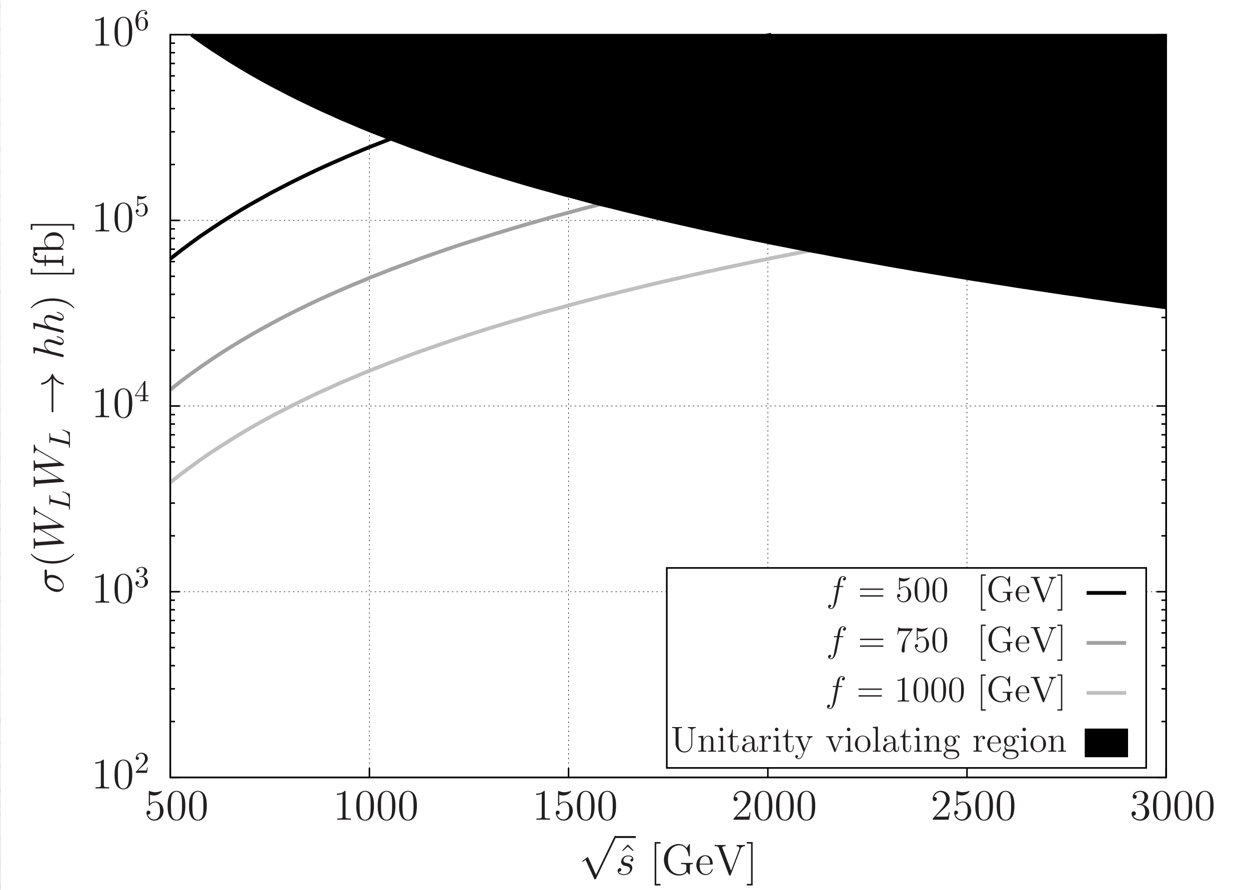
⟶ No mixing angles

Example 2 : The UV friendly LH

The largest eigenvalue : $C_{\max} = 4$

$$\frac{\hat{s}}{f^2} \lesssim \frac{8\pi}{|C_{\max}|}$$

Cross section : $\sigma(W_L^+ W_L^- \to hh) = \dfrac{\hat{s}}{2\pi f^4} \lesssim \dfrac{\pi}{2\hat{s}}$



Summary

- Unitarity bound for dim 6 derivative interactions

  - The largest eigenvalue gives the severest bound
  - One doublet & two doublets examples
  - Highly model dependence
  - Important to clarify the valid energy scale model by model

- Future directions

  - High energy linear collider study for vector boson scatterings
  - Comparison with LHC performance