COMPOSITE HIGGS BOSON THEORIES

Roberto Contino

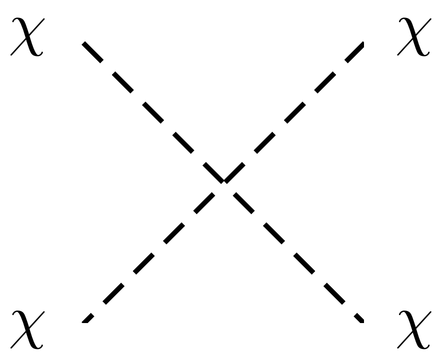
EPFL, Lausanne & CERN

Based on: RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

CLIC Detector and Physics Collaboration Meeting, CERN 1-2 October 2013

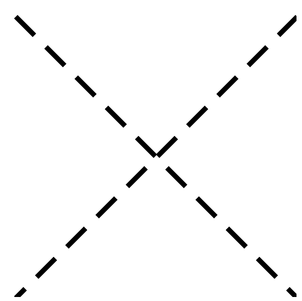
Strong vs Weak EWSB

In the {SM-H}

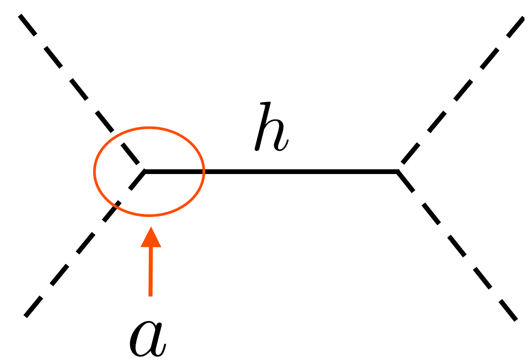


$$A(W_L W_L \to W_L W_L) = A(\chi\chi \to \chi\chi) \sim \frac{E^2}{v^2} \equiv g^2(E)$$

In the {SM-H} + H

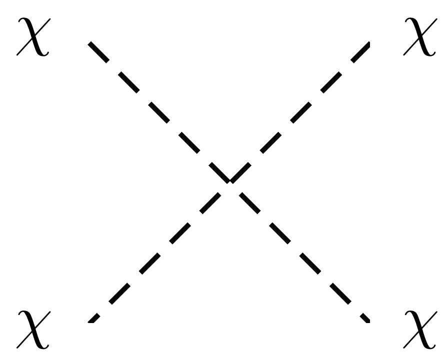


+



$$A \sim \frac{E^2}{v^2}(1 - a^2) - a^2\, \frac{m_h^2}{v^2}\, \frac{s}{s - m_h^2}$$

In the {SM-H}



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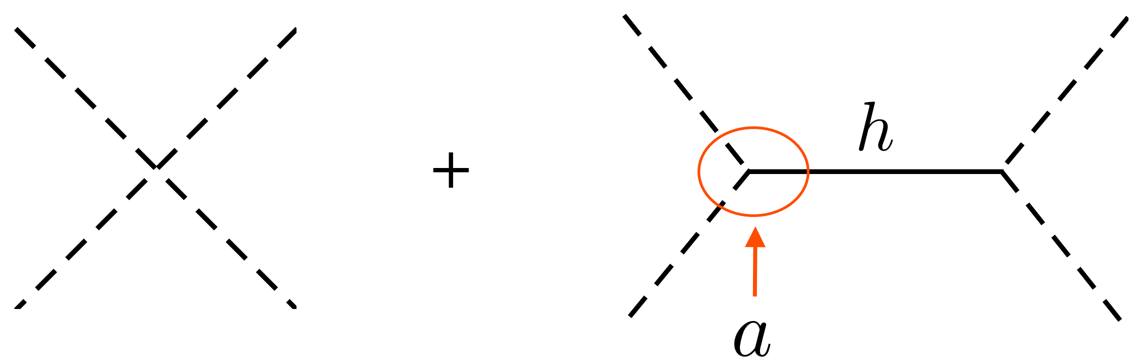
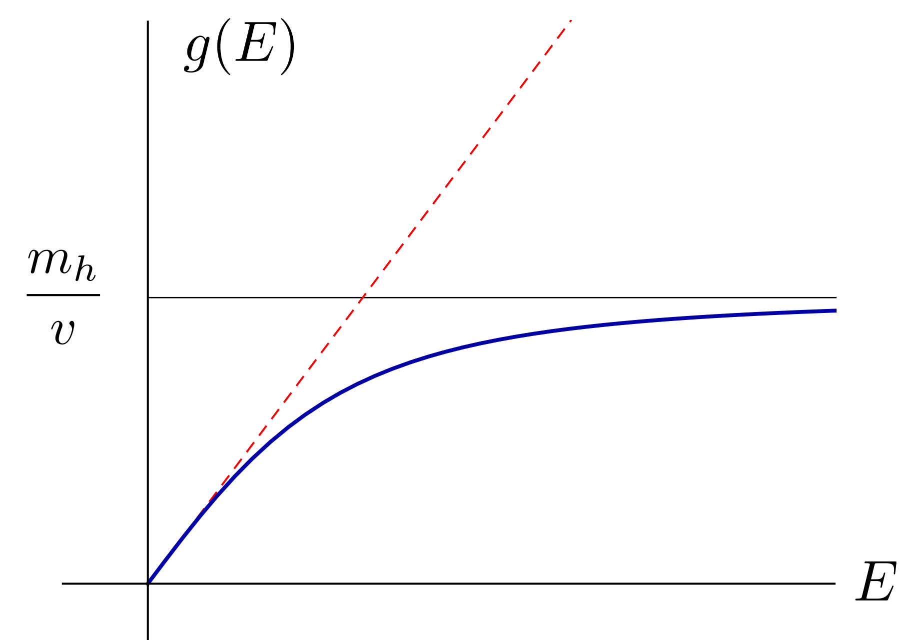


$$A \sim \underbrace{\frac{E^2}{v^2}(1-a^2)}_{=\,0} - a^2\,\frac{m_h^2}{v^2}\,\frac{s}{s-m_h^2}$$

Elementary Higgs: $a = 1$

weak →



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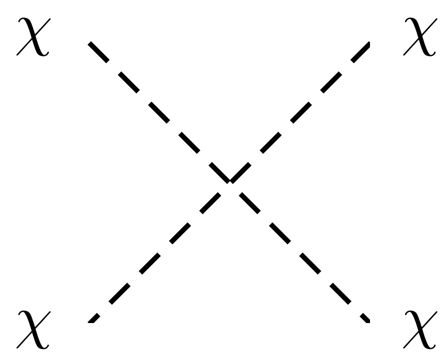

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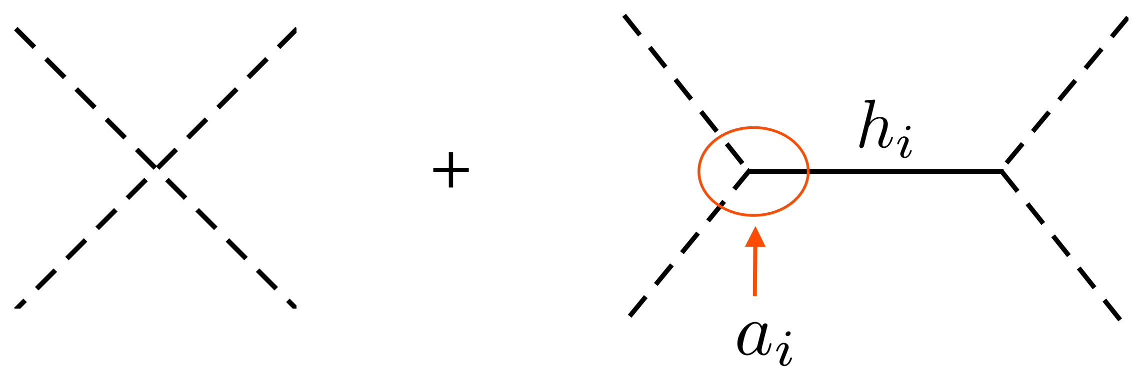


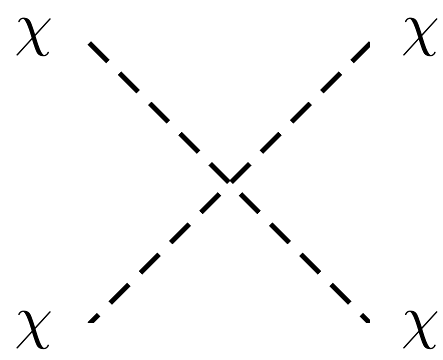
$$A \sim \frac{E^2}{v^2}\left(1 - \sum_i a_i^2\right) + \dots$$

$= 0$

Elementary Higgses:
(more than one)

- $\delta a_i \sim O(1)$ possible
- sum rule: $\sum_i a_i = 1$

In the {SM-H}



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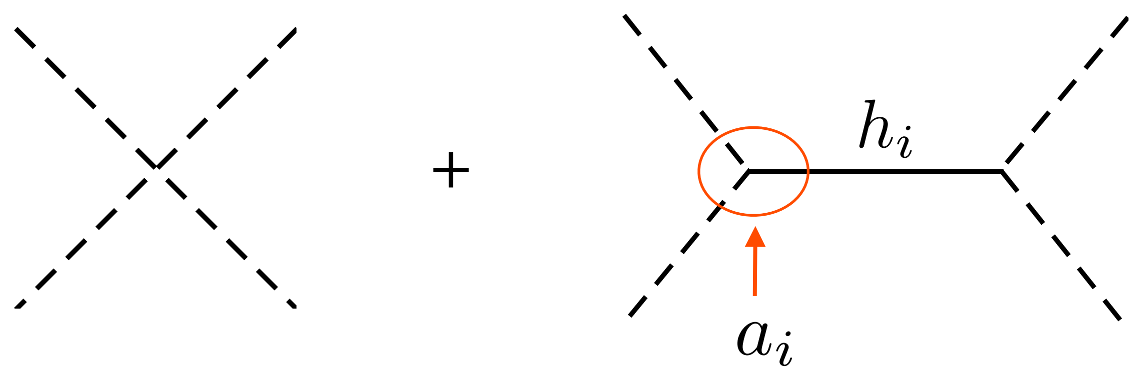
In the {SM-H} + H



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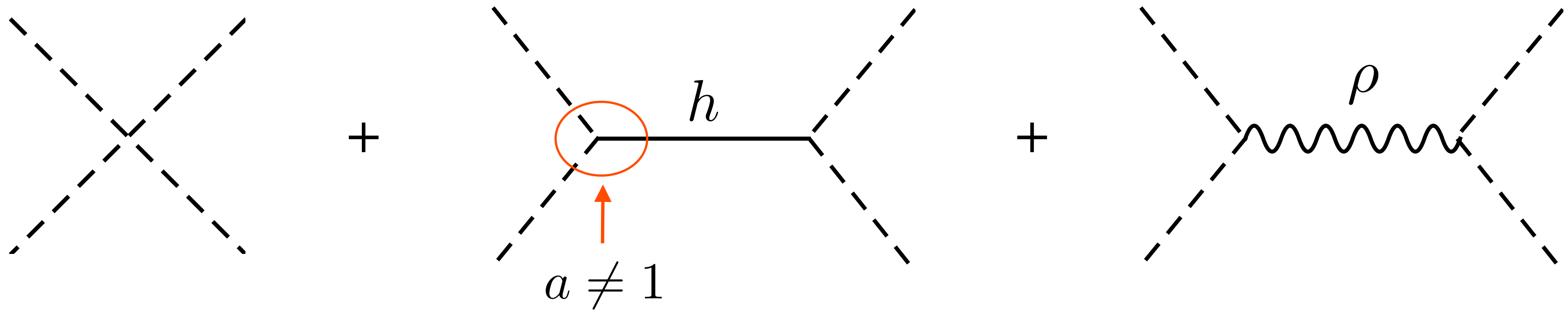
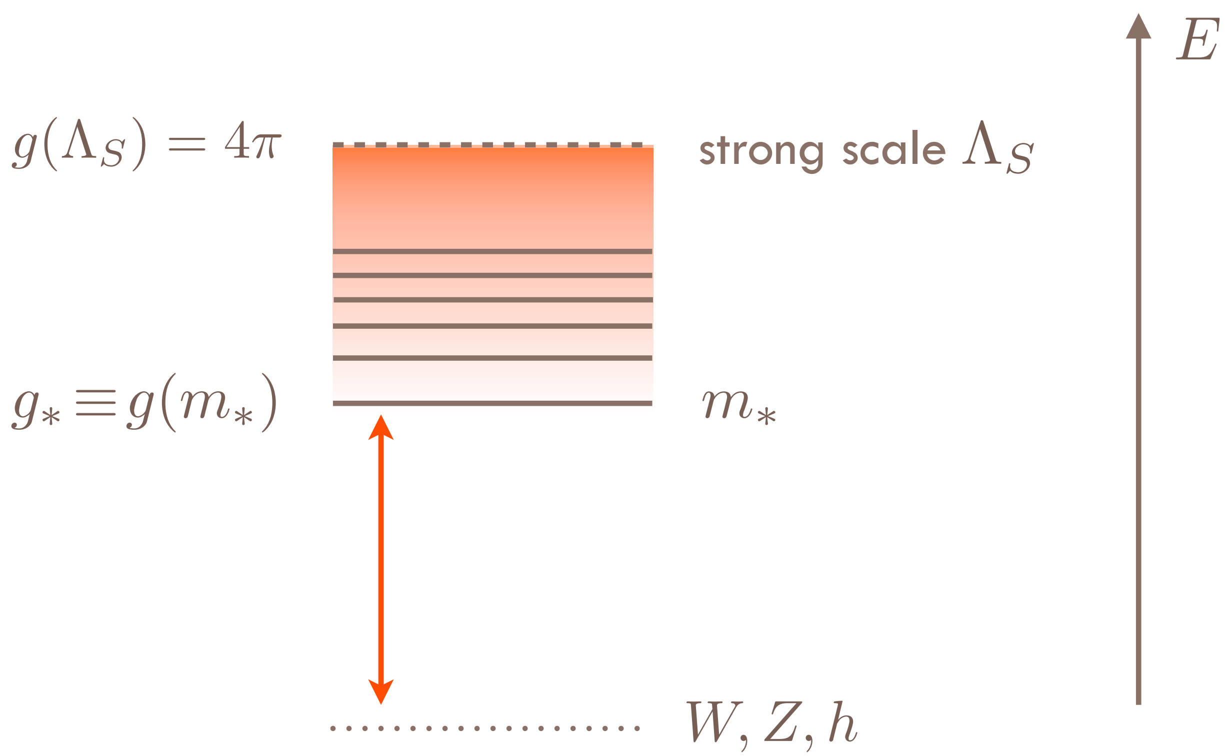
Composite Higgs:



coupling strength grows with energy and saturates at $g_* \lesssim 4\pi$

Energy cartoon:



Analogy with $\pi\pi$ scattering in QCD: $h \leftrightarrow \sigma$

↓

Q: why light and narrow ?

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A: the Higgs is itself a (pseudo) NG boson [Georgi & Kaplan, '80]

ex: $\frac{SO(5)}{SO(4)} \longrightarrow$ 4 NGBs transforming as a (2,2) of SO(4) [Agashe, RC, Pomarol NPB 719 (2005) 165]

$$f^2 \left| \partial_\mu \, e^{i\pi/f} \right|^2 = (\partial\pi)^2 + \frac{(\pi\partial\pi)^2}{f^2} + \frac{\pi^2(\pi\partial\pi)^2}{f^4} + \dots$$

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[Giudice et al. JHEP 0706 (2007) 045]

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1. $O(v^2/f^2)$ shifts in tree-level Higgs couplings. Ex: $a = 1 - c_H \left(\frac{v}{f} \right)^2 + \dots$

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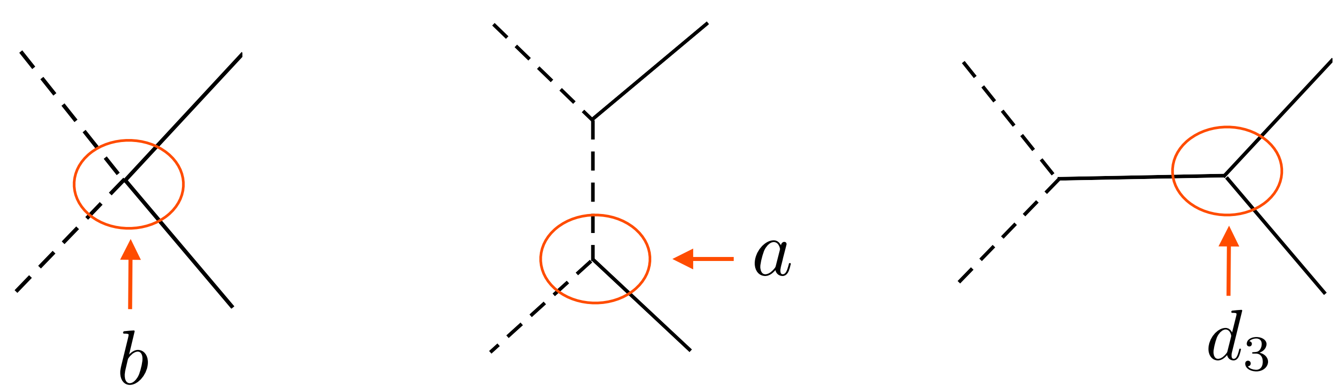
2. Scatterings involving the Higgs also grow with energy

$$A(WW \to hh) \sim \frac{s}{v^2}(a^2 - b)$$



How to test Higgs compositeness

1. Direct: Reach energy threshold for direct production of new resonances

2. Indirect: Precision measurement of low-energy quantities

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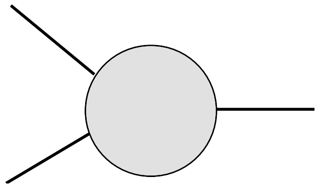

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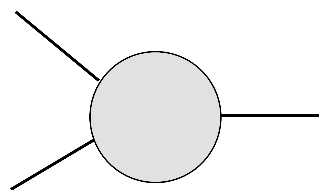
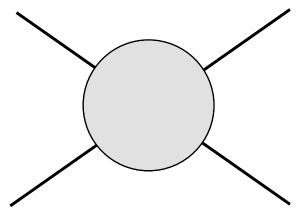
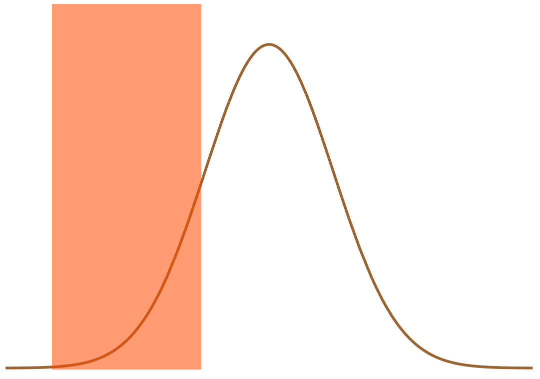


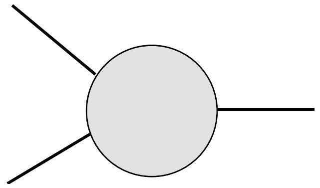
   ii) tails in scattering amplitudes

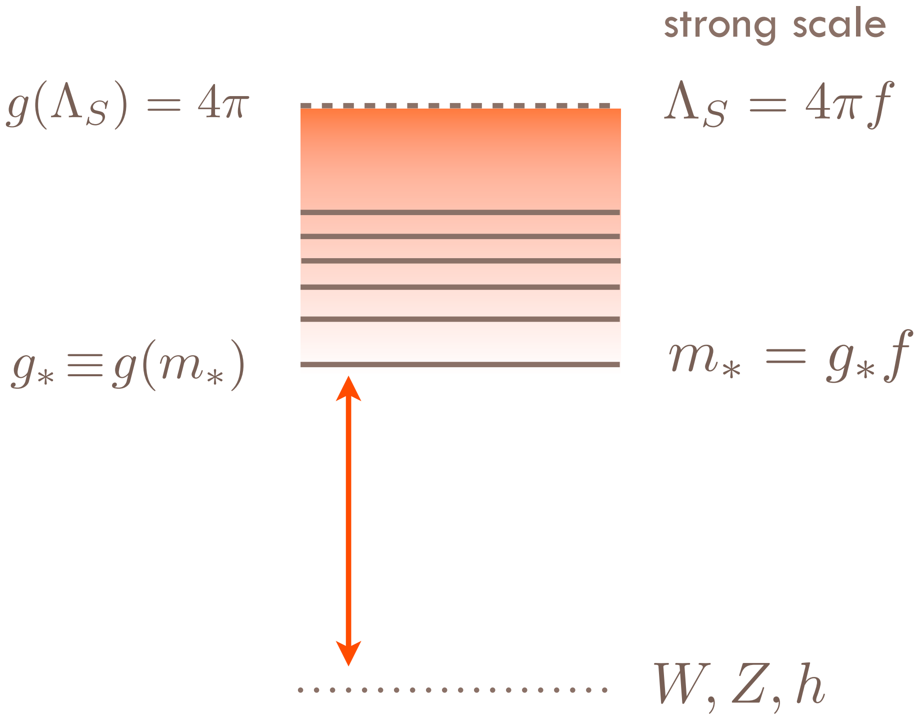




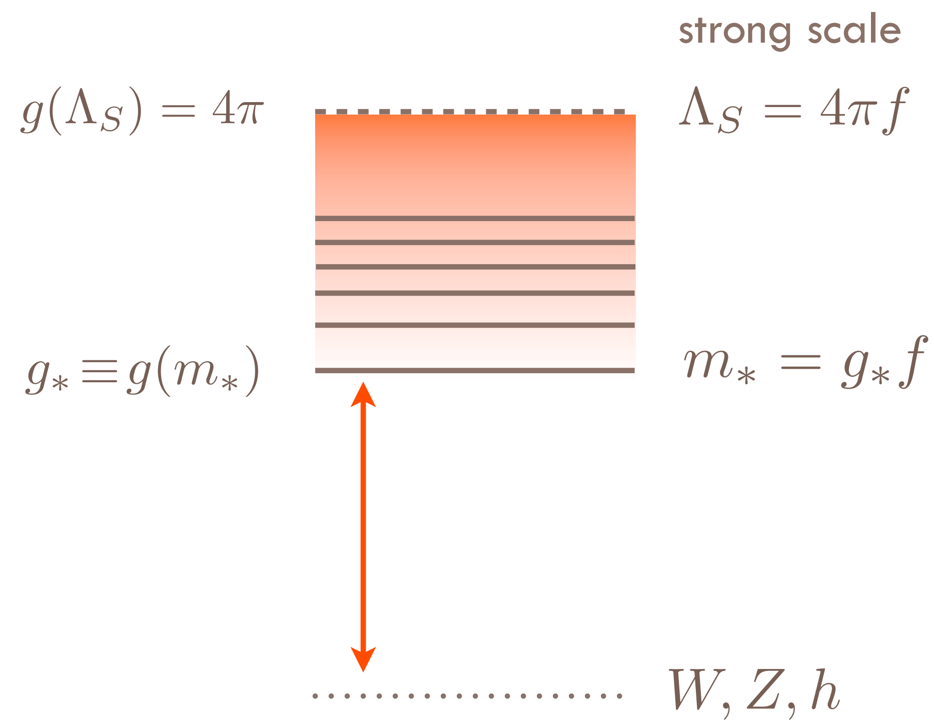
Corrections to Higgs couplings

Precision measurement of Higgs couplings can give an appraisal of the strength of the underlying interactions





$$\frac{\delta \mathcal{O}}{\mathcal{O}} \sim \frac{v^2}{f^2} + \frac{g_*^2 v^2}{m_*^2}$$



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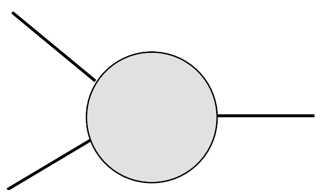

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from NL sigma model

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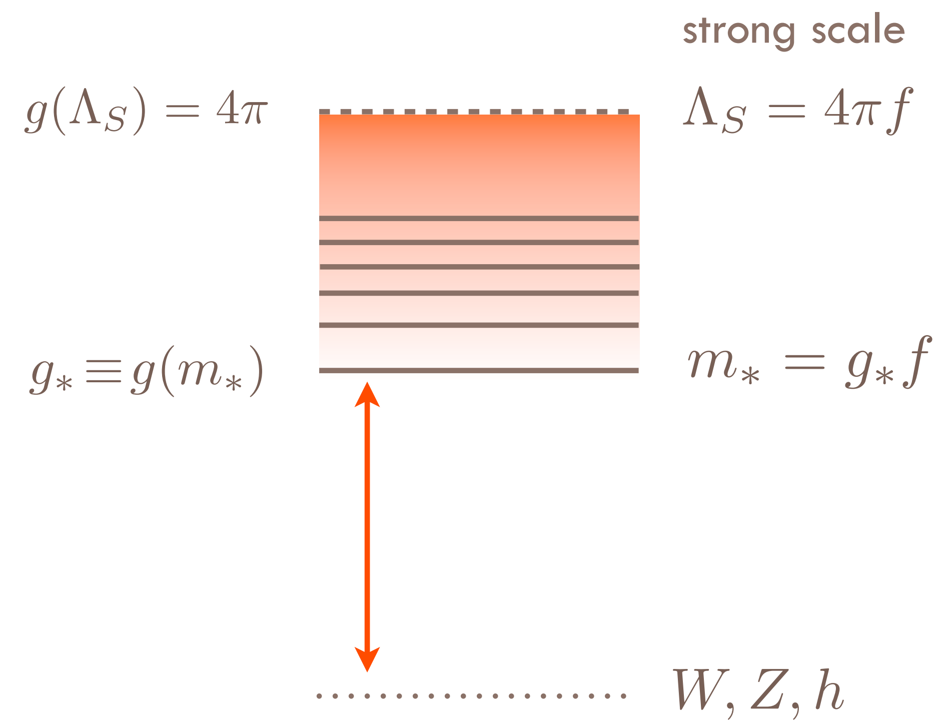

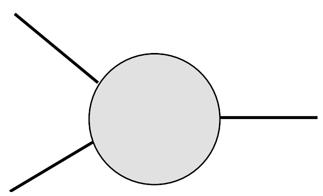

contribution of resonances

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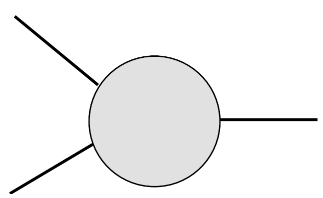

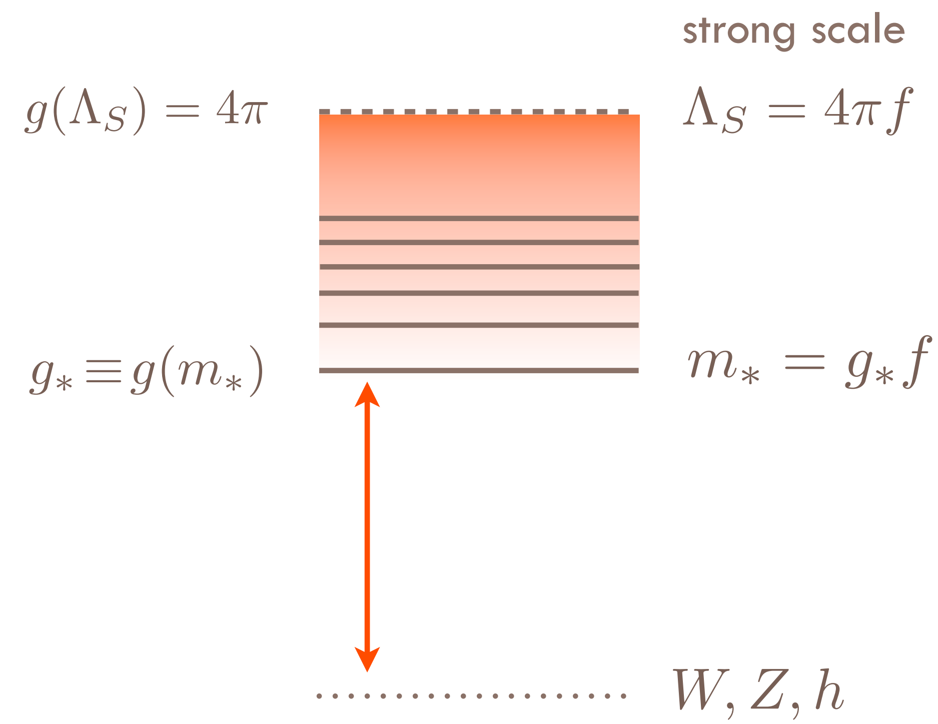

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Suppose we find:

$$\left.\frac{\delta\mathcal{O}}{\mathcal{O}}\right|_{exp} = \delta_{\mathcal{O}}^{exp}$$

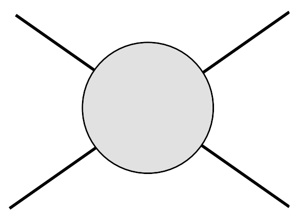
$$m_* > M$$

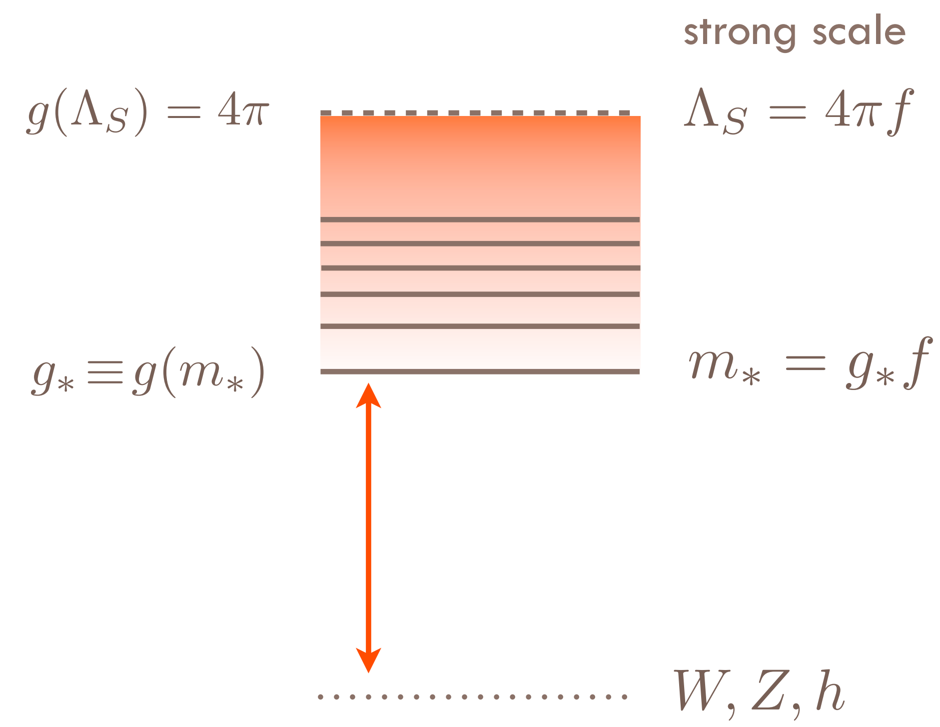
(from direct searches)

$$g_* > \sqrt{\delta_{\mathcal{O}}^{exp}}\,\frac{M}{v}$$

Tails in scattering amplitudes

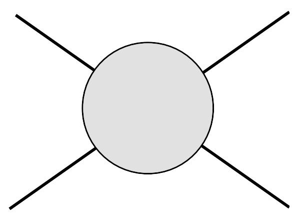
Precision measurement of scattering amplitudes can give an appraisal of the strength of the underlying interactions

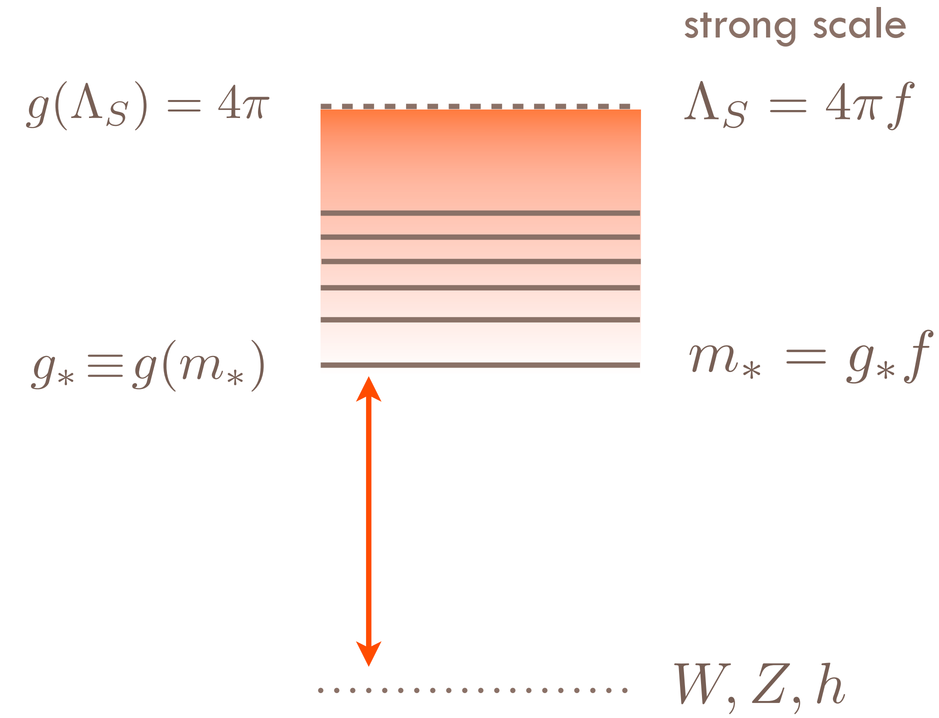




$$\mathcal{A}(2 \to 2) = \delta_{hh} \frac{E^2}{v^2} \left(1 + O\left(\frac{E^2}{m_*^2}\right)\right)$$

Precision measurement of scattering amplitudes can give an appraisal of the strength of the underlying interactions





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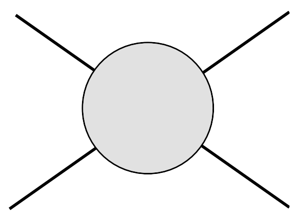

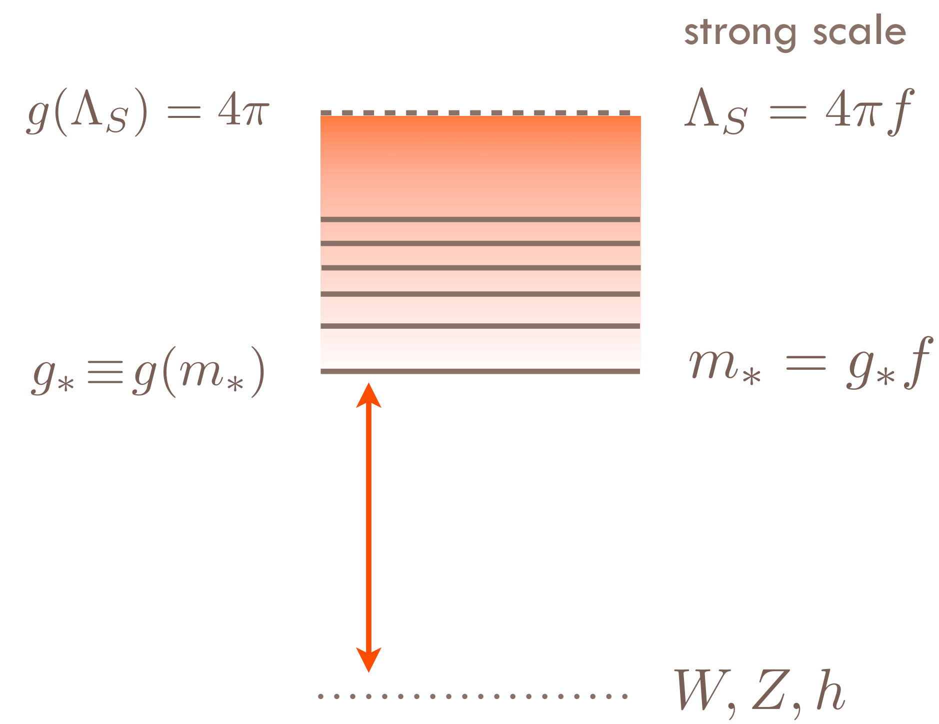

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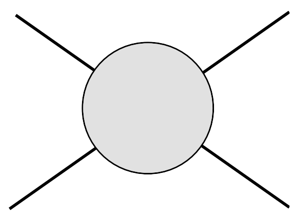
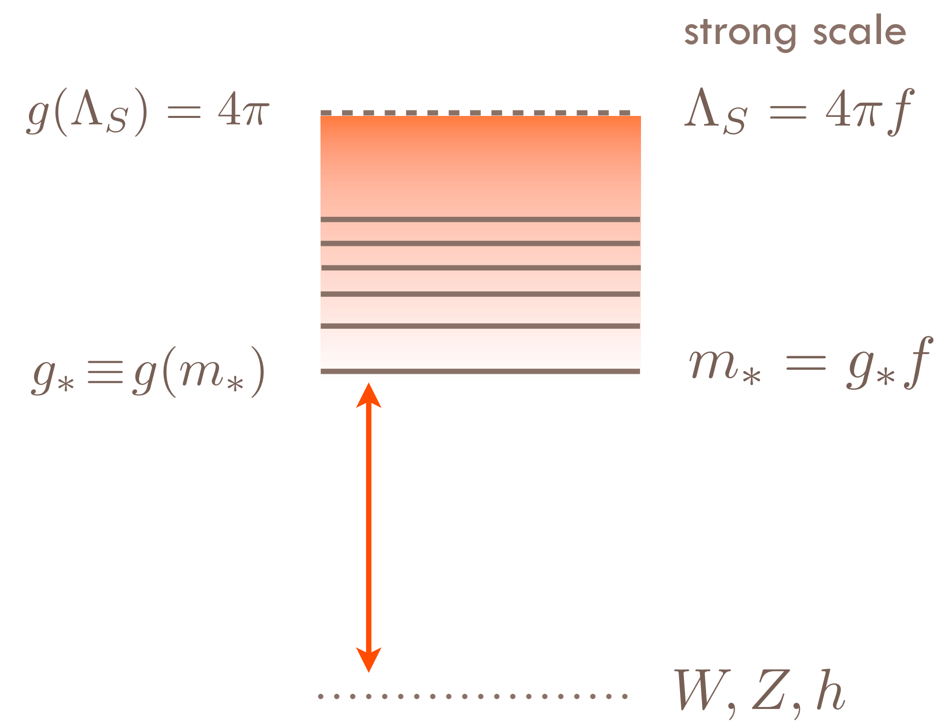
Suppose we find:

$$\delta_{hh}^{exp} \neq 0$$

$$g_* > g(E) = \sqrt{\delta_{hh}^{exp}} \, \frac{E}{v}$$

Precision measurement of scattering amplitudes can give an appraisal of the strength of the underlying interactions





Suppose we can bound $\frac{E^2}{m_*^2} < \epsilon_{hh}$ hence $m_* > \frac{E}{\sqrt{\epsilon_{hh}}} \equiv M$

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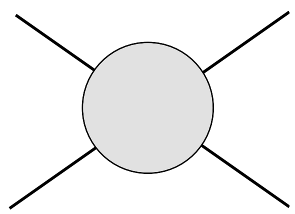

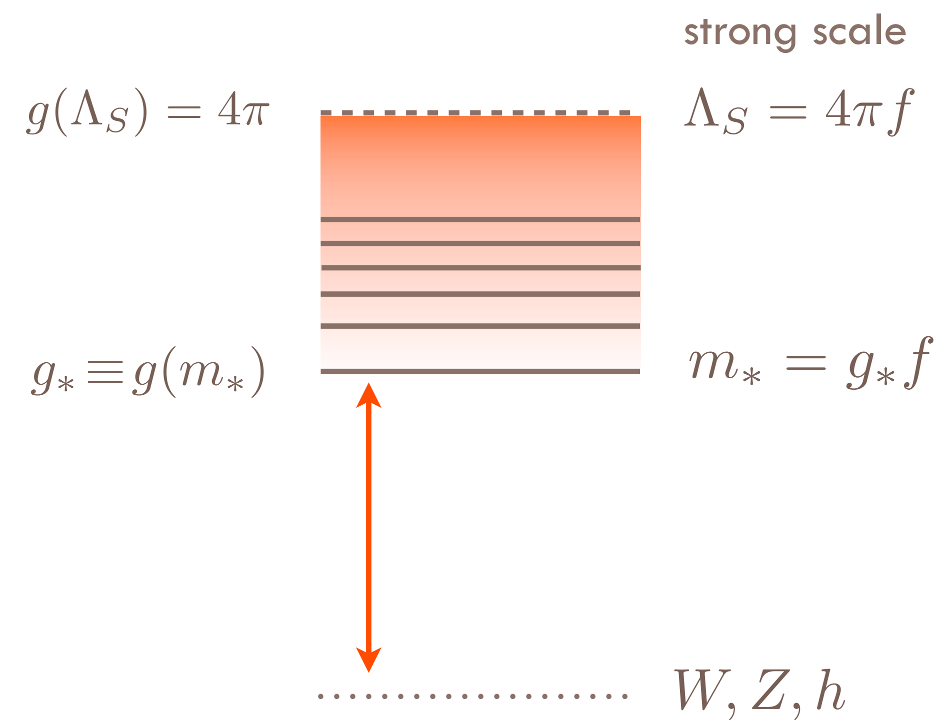

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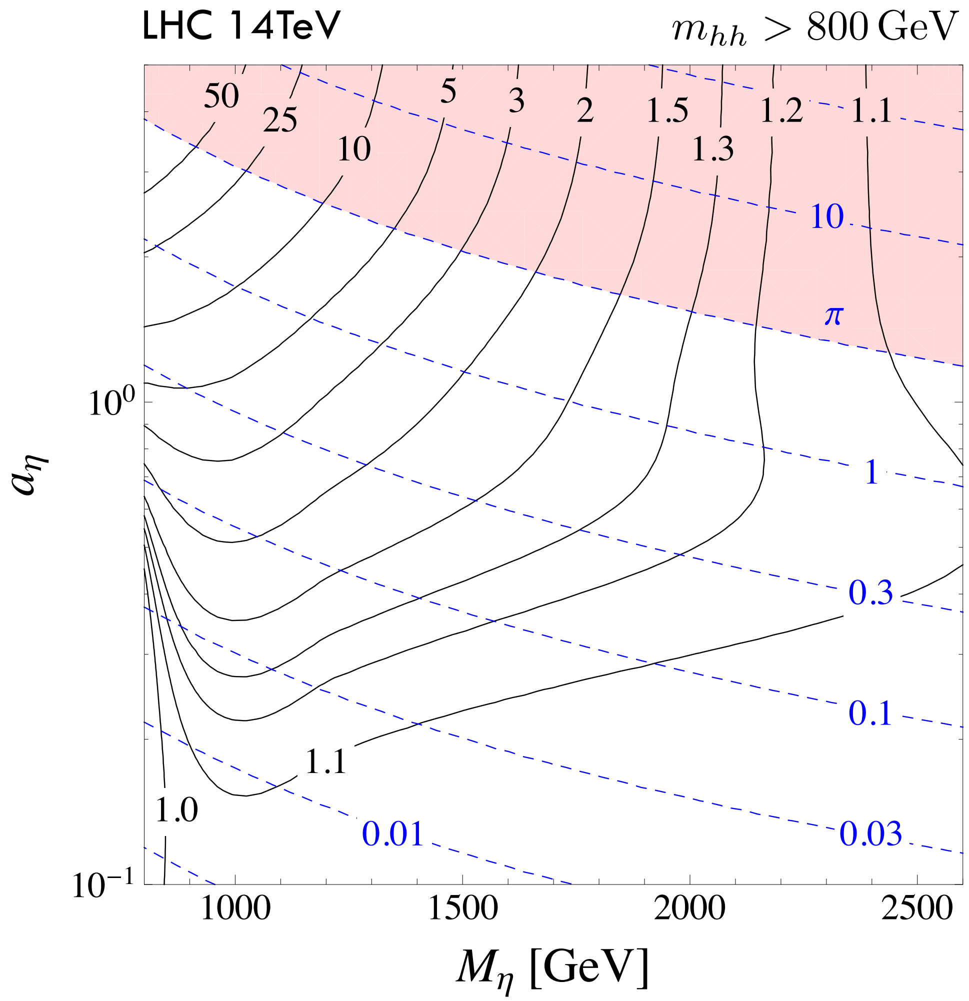
$$g_* > g(E) = \sqrt{\delta_{hh}^{exp}} \frac{E}{v}$$

then we get the stronger limit

$$g_* > g(M) = \sqrt{\frac{\delta_{hh}^{exp}}{\epsilon_{hh}}} \frac{E}{v}$$



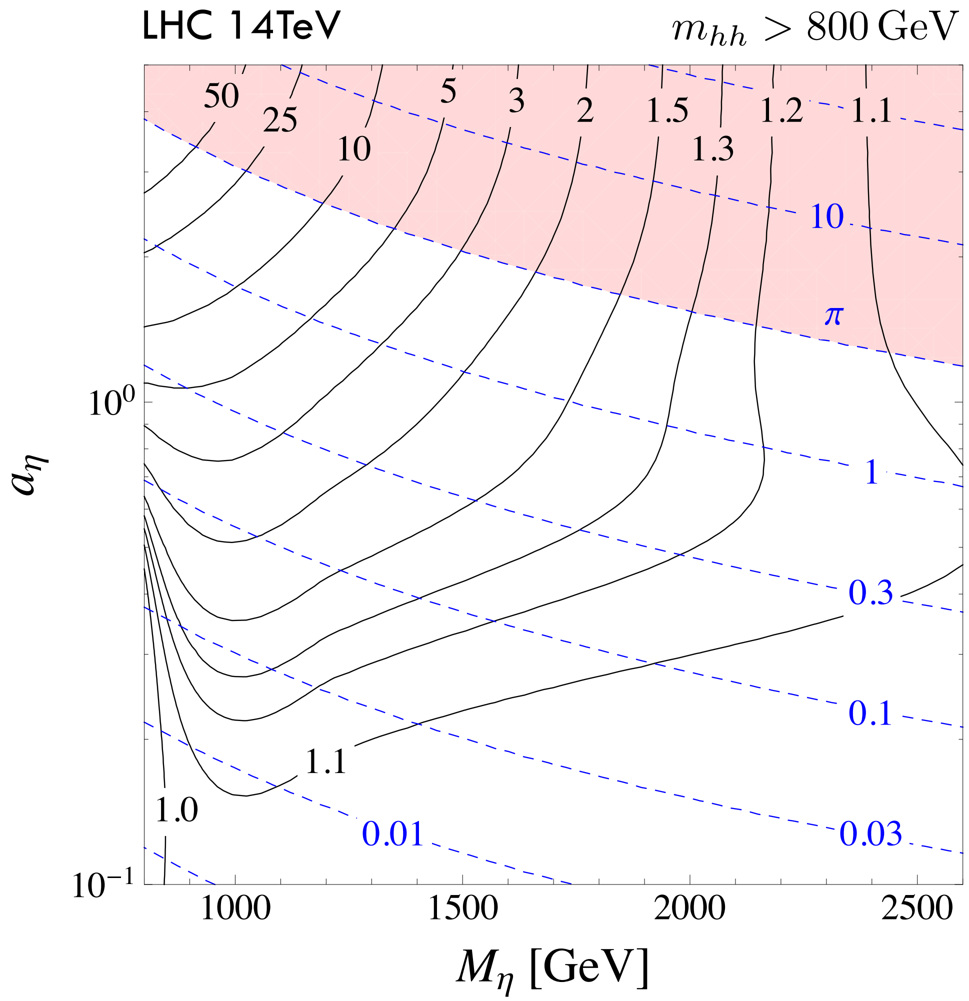
$$R = \frac{\sigma(pp \to hhjj)}{\sigma(pp \to hhjj)|_{LET}}$$

$$\mathcal{L} = \frac{a_\eta}{2f}\,\eta(\partial_\mu \pi)^2 + \ldots$$

[RC, Marzocca, Pappadopulo, Rattazzi, JHEP 1110 (2011) 081]

$$\mathcal{A}(2 \to 2) = \delta_{hh}\frac{E^2}{v^2}\left(1 + O\left(\frac{E^2}{m_*^2}\right)\right)$$

measurement of resonance effects
gives direct access to strong dynamics



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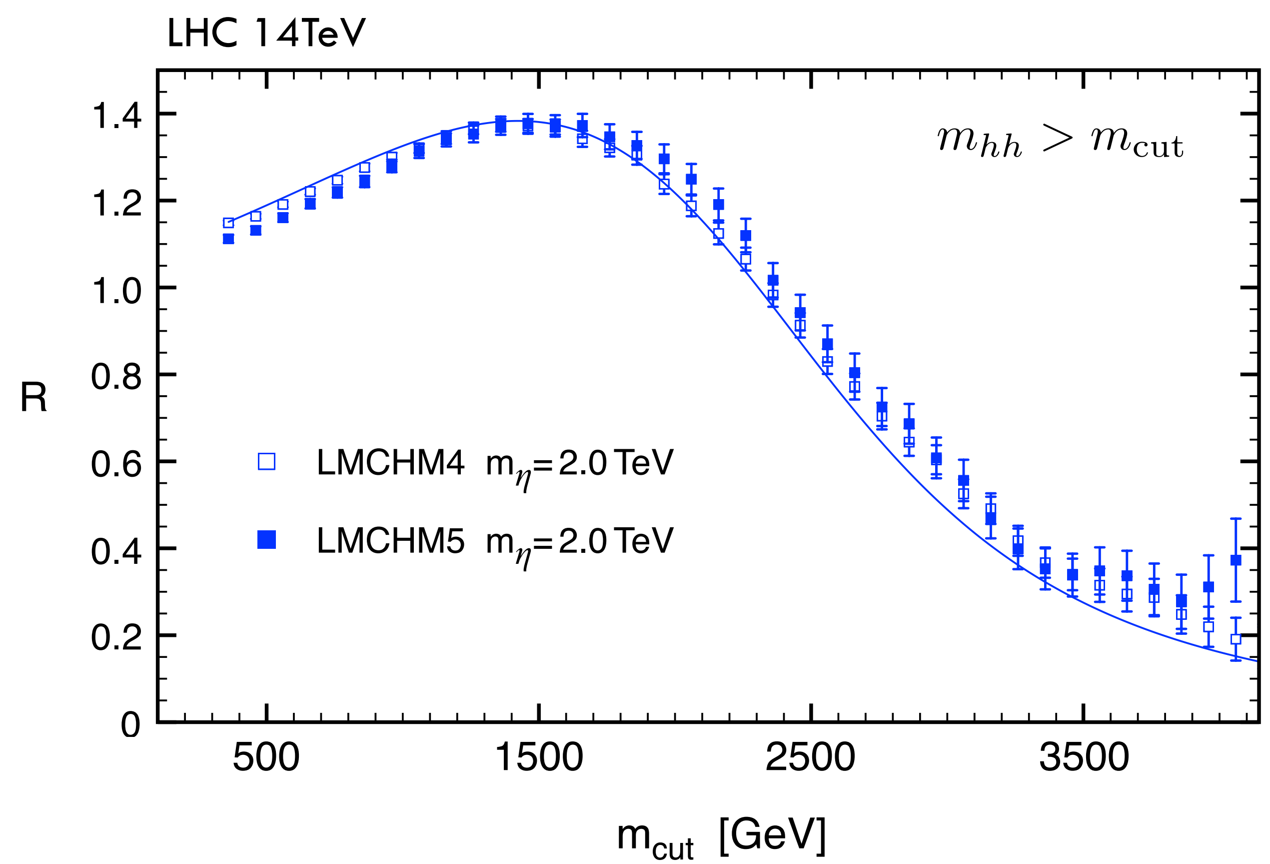
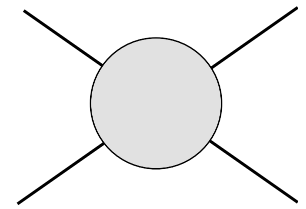


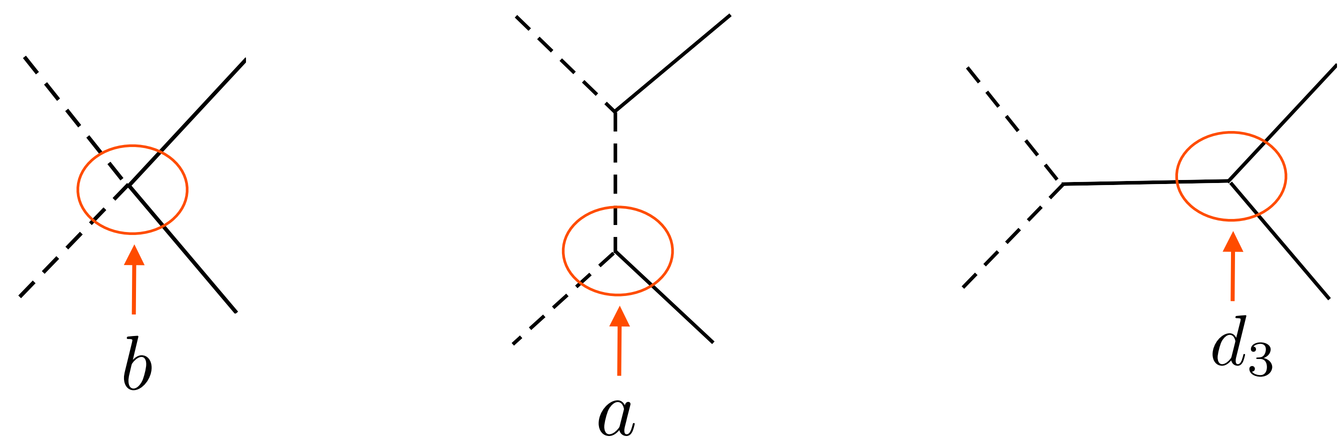
A high-energy e^+e^- collider (such as CLIC 3TeV) can provide a clean environment to make precision studies of scattering amplitudes



[RC, Grojean, Pappadopulo, Rattazzi, Thamm, arXiv:1309.7038]

Example: $WW \to hh$

$$A(WW \to hh) \sim \frac{s}{v^2}(a^2 - b)$$



dim 6: $$O_H = \frac{c_H}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

dim 8: $$O'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu |H|^2 \partial^\mu |H|^2$$

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

$$b = 1 - 2c_H\frac{v^2}{f^2} + \left(3c_H^2 - \frac{3c'_H}{2}\right)\frac{v^4}{f^4}$$

[Higgs Effective Lagrangian (SILH basis)]

Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be re-summed:

$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

$$\Delta b \equiv 1 - b$$

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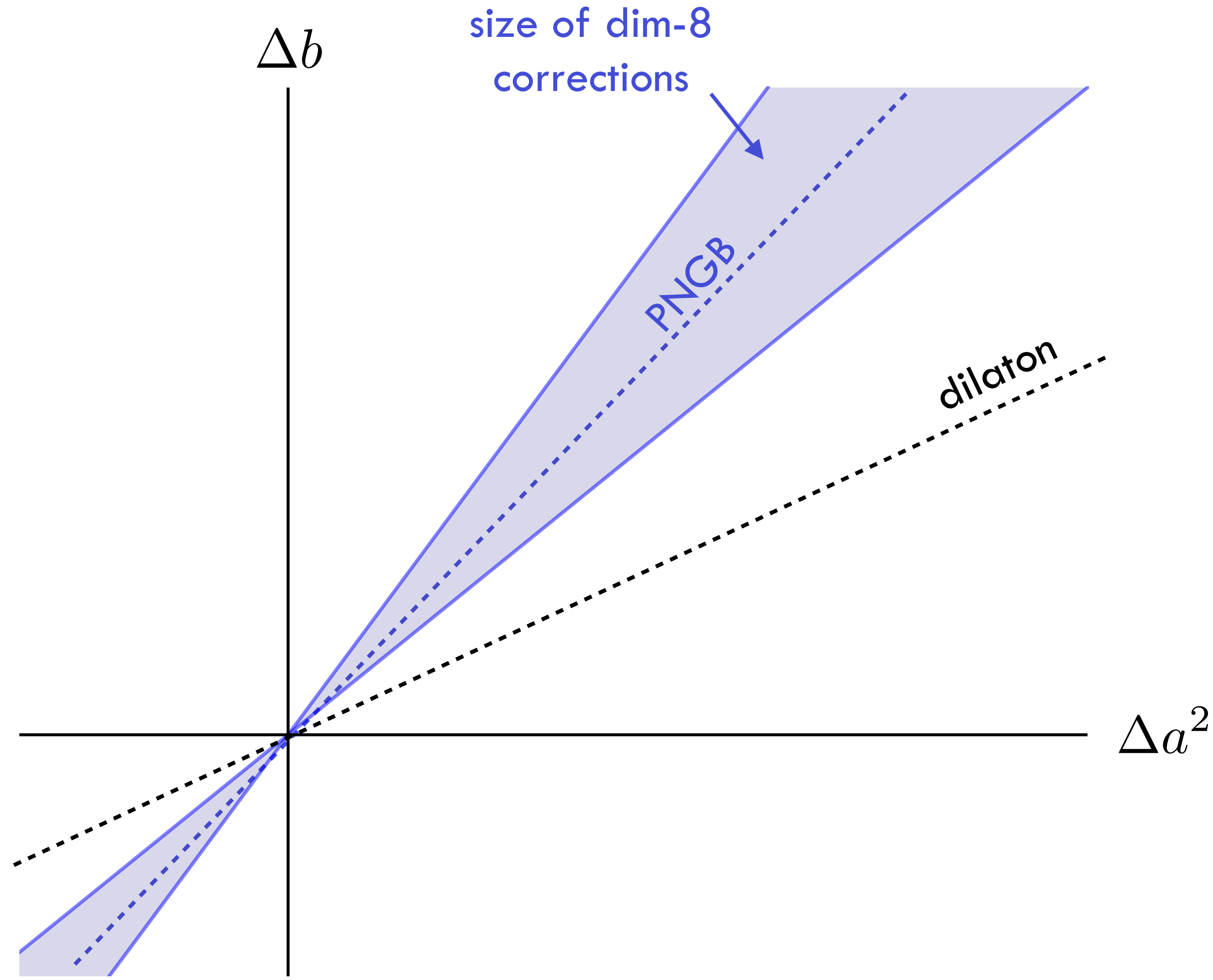
Scenario 1:

$\Delta a^2 \sim \Delta b \sim 10\%$

Exp. precision $\sim 1\%$

→ Test dim-8 operators



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$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

$$\Delta b \equiv 1 - b$$
$$\Delta a^2 \equiv 1 - a^2$$

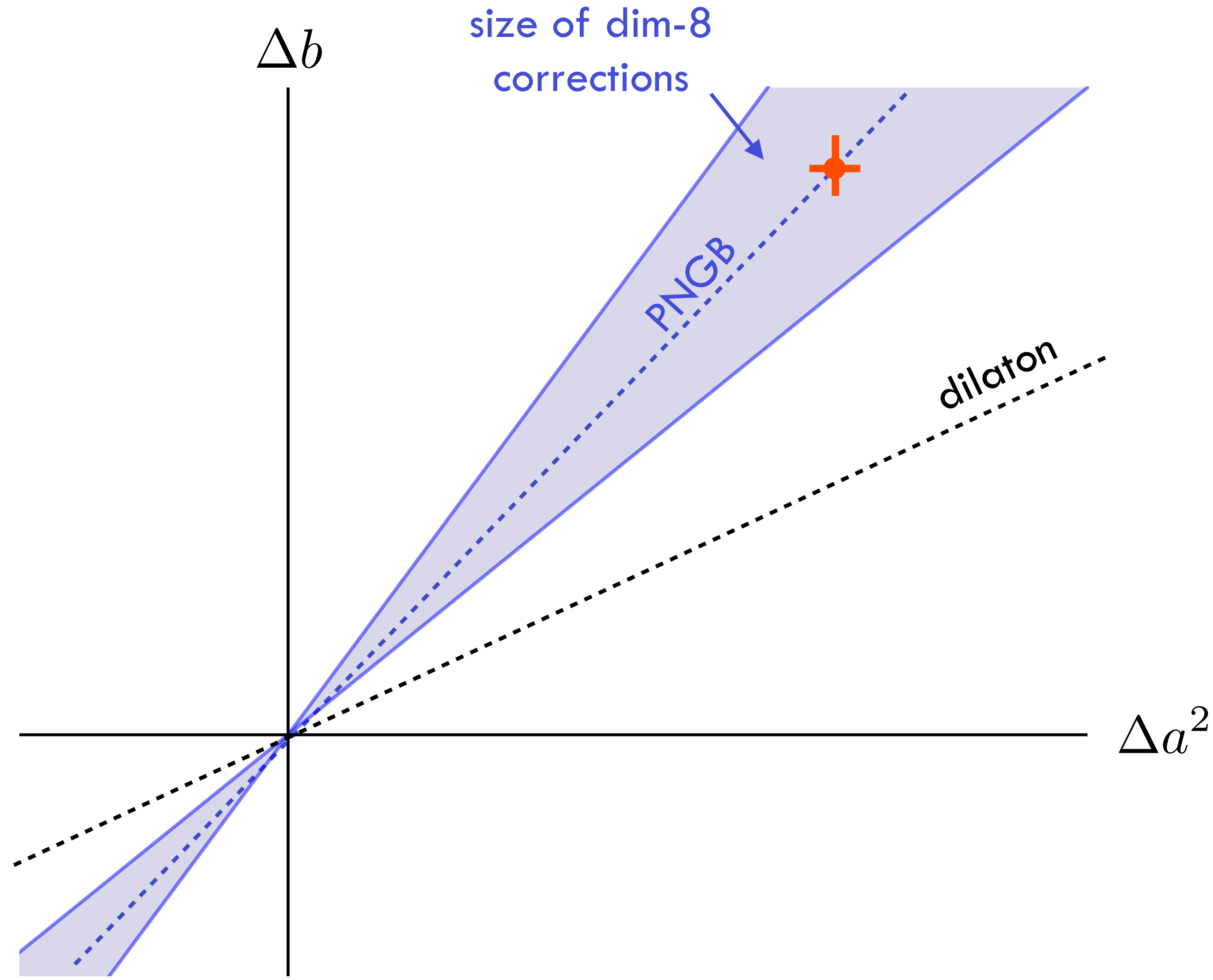
Scenario 1:

$$\Delta a^2 \sim \Delta b \sim 10\%$$

$$\text{Exp. precision} \sim 1\%$$

→ Test dim-8 operators

1. PNGB (and specific coset) proved



Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be re-summed:

$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

$$\Delta b \equiv 1 - b$$

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Scenario 1:

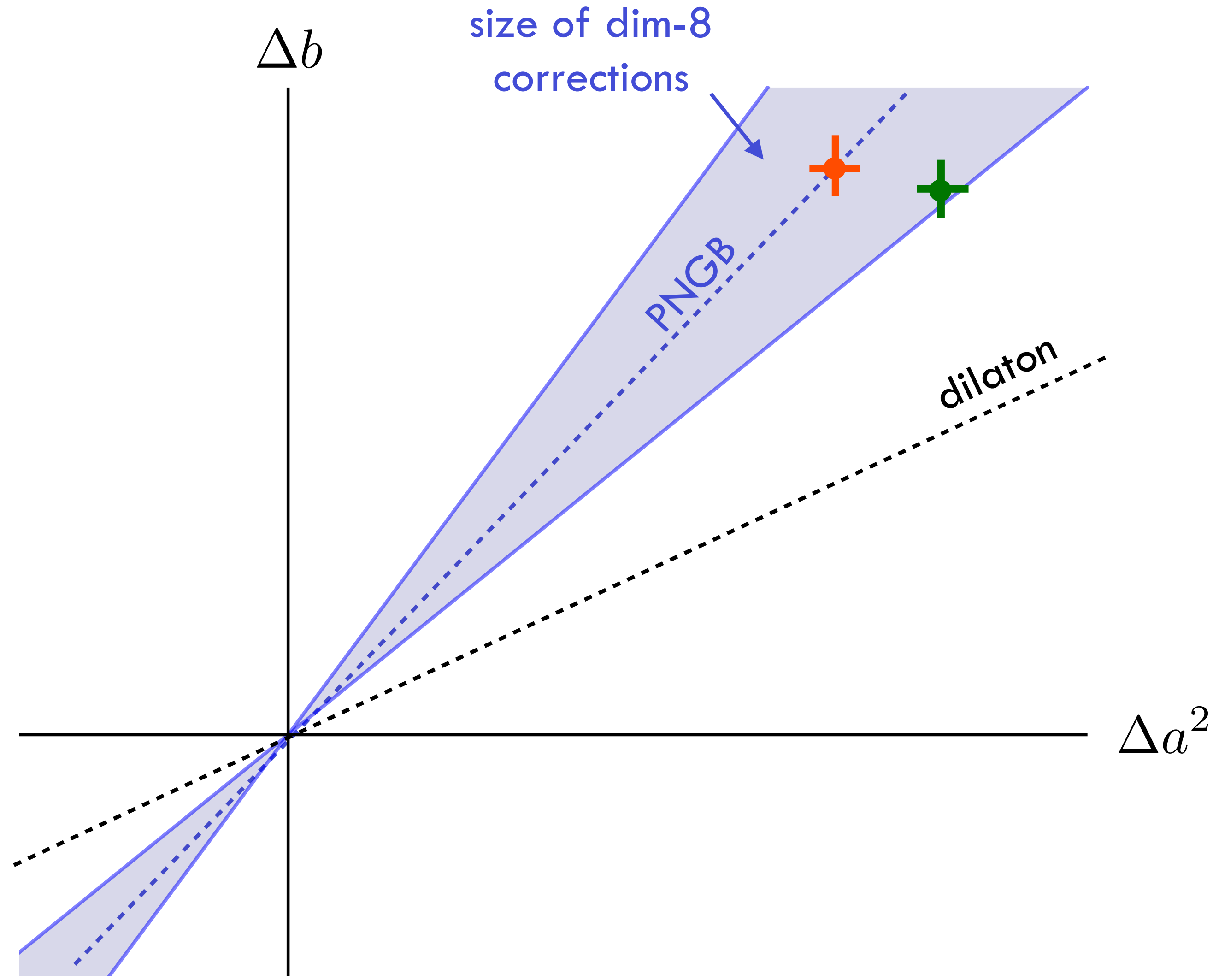
$$\Delta a^2 \sim \Delta b \sim 10\%$$

$$\text{Exp. precision} \sim 1\%$$

→ Test dim-8 operators

1. PNGB (and specific coset) proved

2. SILH proved, PNGB disproved



Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be re-summed:

$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

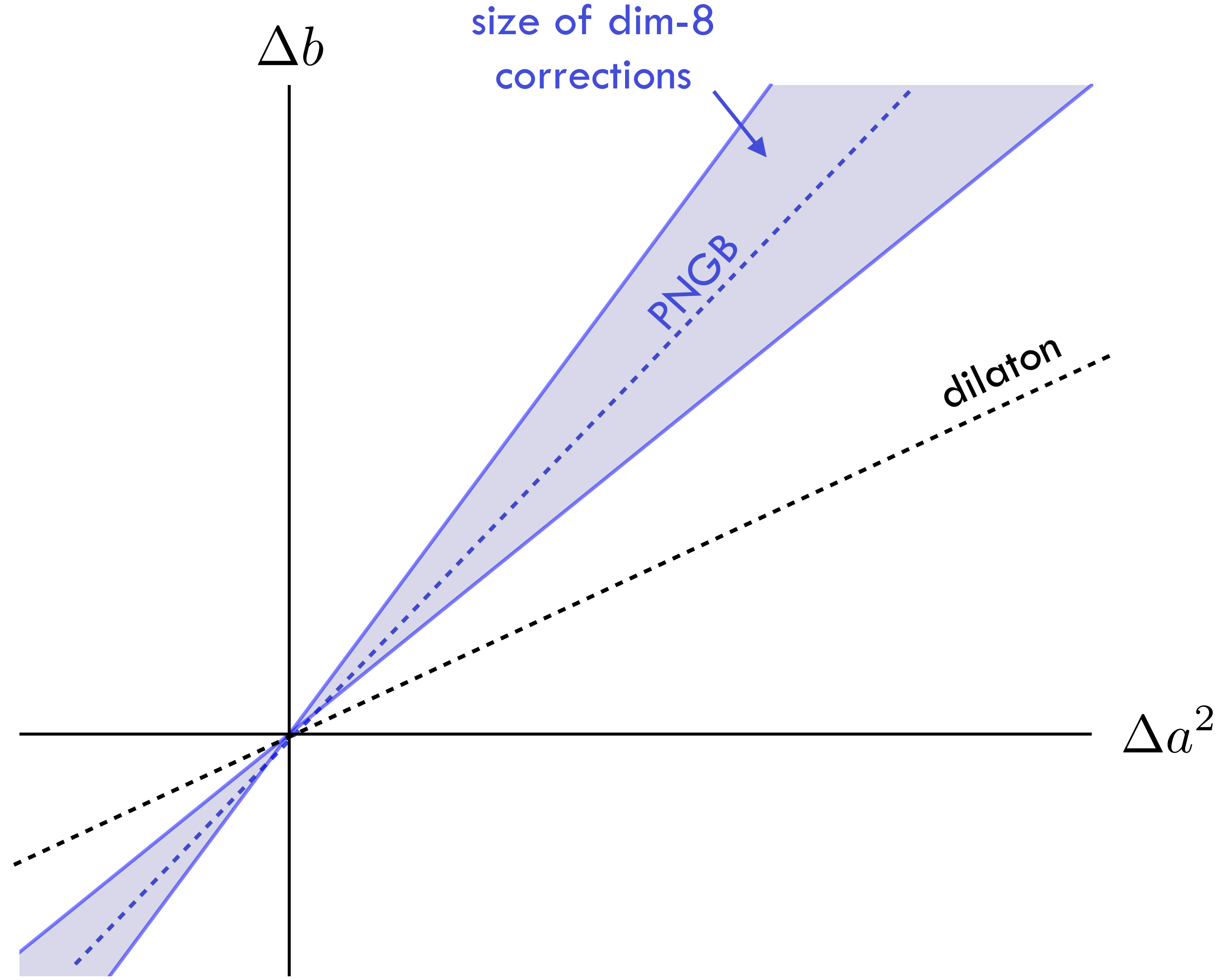
$$\Delta b \equiv 1 - b$$

$$\Delta a^2 \equiv 1 - a^2$$

Scenario 2:

$$\Delta a^2 \sim \Delta b \sim 1\%$$

$$\text{Exp. precision} \sim 1\%$$



Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be re-summed:

$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$\xi = \frac{v^2}{f^2}$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

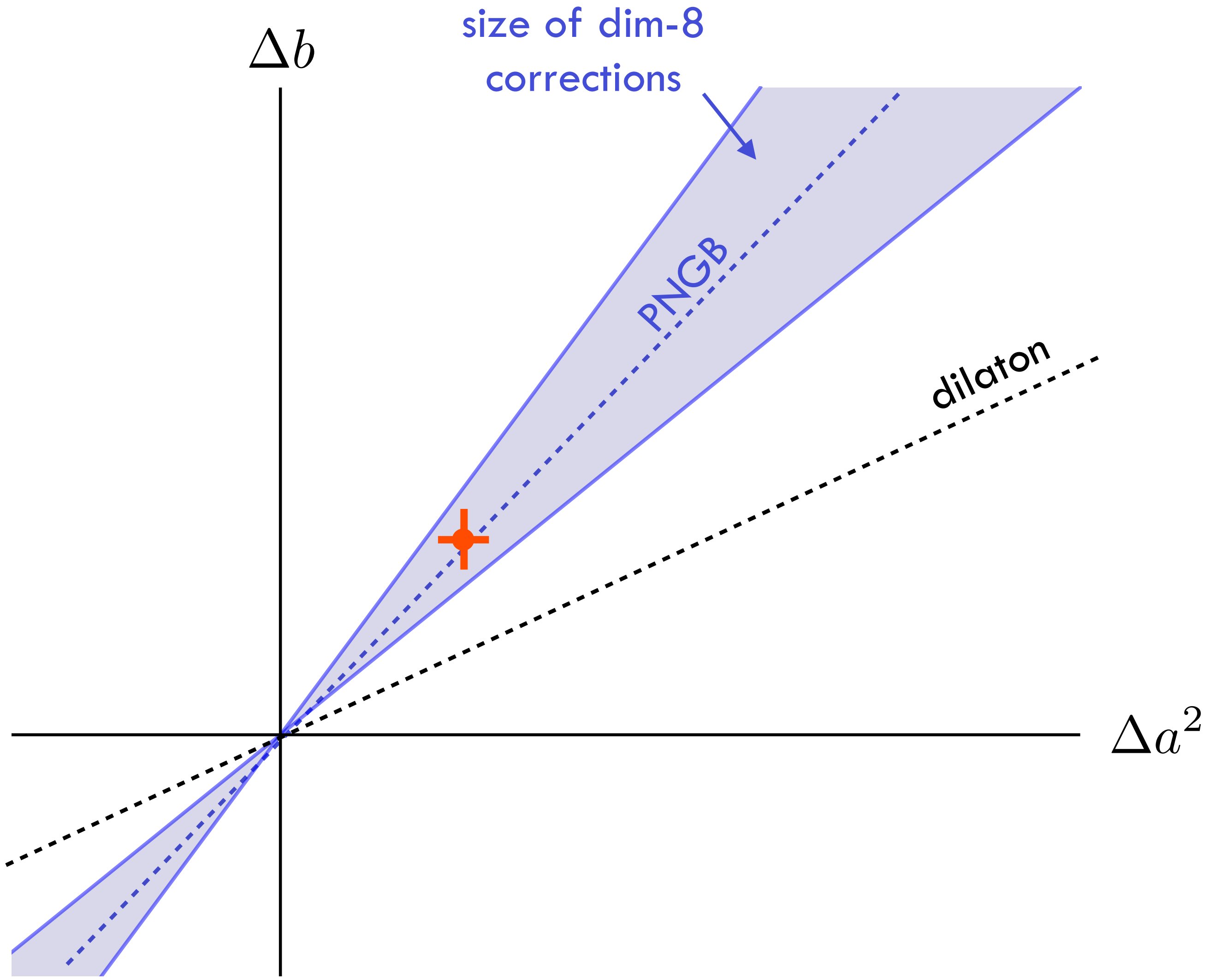
$$\Delta b \equiv 1 - b$$
$$\Delta a^2 \equiv 1 - a^2$$

Scenario 2:

$$\Delta a^2 \sim \Delta b \sim 1\%$$

$$\text{Exp. precision} \sim 1\%$$

1. SILH proved



Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be re-summed:

$$a = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

$$b = 1 - 2\xi$$

At dimension-6 level:

$$\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$$

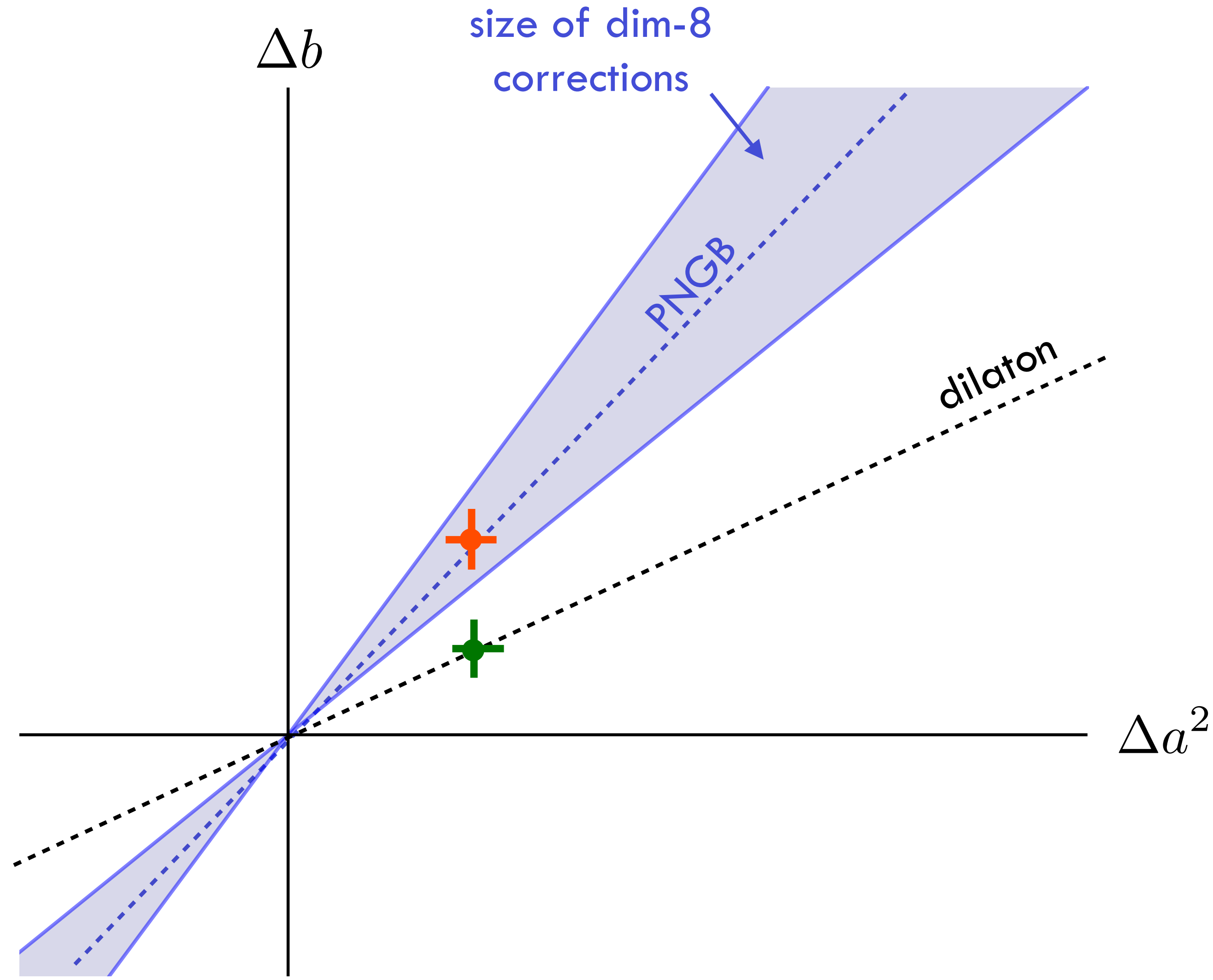
$$\Delta b \equiv 1 - b$$
$$\Delta a^2 \equiv 1 - a^2$$

Scenario 2:

$$\Delta a^2 \sim \Delta b \sim 1\%$$

$$\text{Exp. precision} \sim 1\%$$

1. SILH proved
2. SILH (i.e. Higgs doublet) disproved



Extracting $b\,,d_3$ at CLIC with $\sqrt{s}=3\,\mathrm{TeV}$ through $e^+e^-\to\nu\bar{\nu}\,hh\to\nu\bar{\nu}\,b\bar{b}b\bar{b}$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Extracting $b\,, d_3$ at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

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$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

The analysis in a nutshell

Parton level + Gaussian smearing of jet energy $\Delta E/E = 5\%$

Selected events with: 4 jets

Basic acceptance cuts: $E_j > 20\,\mathrm{GeV}$ $|\eta_j| < 2$ $\Delta R_{jj} > 0.4$

$E_l > 5\,\mathrm{GeV}$ $|\eta_l| < 2$ $\Delta R_{jl} > 0.4$

Higgs reconstruction:

1) choose pairing $(j_1 j_2, j_3 j_4)$ that minimizes $\chi^2 = (m_{j_1 j_2} - m_h)^2 + (m_{j_3 j_4} - m_h)^2$

2) each candidate must satisfy $|m_{jj} - m_h| < 15\,\mathrm{GeV}$

3) keep events with at least 3 b-tags

Extracting b, d_3 at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

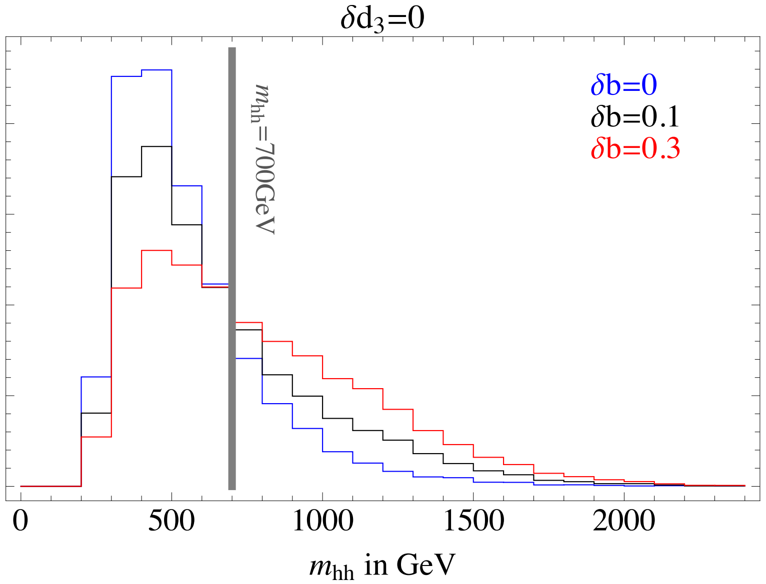
RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$
$$\delta_{d_3} = 1 - d_3/a$$

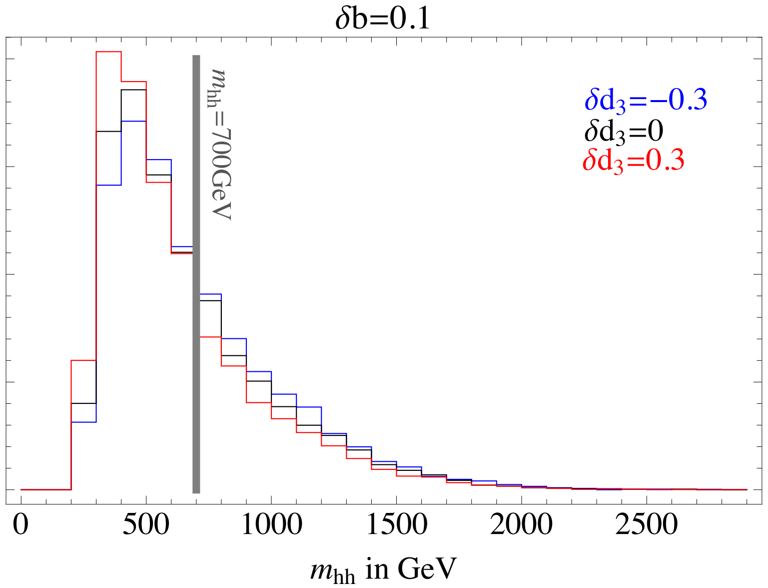
Background negligible (requires good mass resolution h vs Z)

(largest processes: $hZ\nu\bar{\nu}$, $ZZ\nu\bar{\nu}$, ZZe^+e^-)



Signal analyzed in 4 kinematic regions to enhance sensitivity on Higgs couplings:

$$\mathrm{I}: \quad m_{hh} > 700\,\mathrm{GeV}\ \text{and}\ H_T > 400\,\mathrm{GeV}$$
$$\mathrm{II}: \quad m_{hh} > 700\,\mathrm{GeV}\ \text{and}\ H_T < 400\,\mathrm{GeV}$$
$$\mathrm{III}: \quad m_{hh} < 700\,\mathrm{GeV}\ \text{and}\ H_T > 400\,\mathrm{GeV}$$
$$\mathrm{IV}: \quad m_{hh} < 700\,\mathrm{GeV}\ \text{and}\ H_T < 400\,\mathrm{GeV}$$



Extracting $b\,,d_3$ at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Expected precision on δ_b with $L = 1\,\mathrm{ab}^{-1}/(a^2 BR(b\bar{b})/BR(b\bar{b})_{SM})^2$

	measured δ_b	$\bar{\delta}_{d_3}$ -0.5	-0.3	-0.1	0	0.1	0.3	0.5
	0	$-0.045^{+0.060}_{-0.025}$	$0.015^{+0.020}_{-0.040}$	$0.010^{+0.070}_{-0.045}$	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.03}$	$0.00^{+0.03}_{-0.03}$	$0.00^{+0.03}_{-0.03}$
	0.01	$-0.055^{+0.070}_{-0.020}$	$0.030^{+0.030}_{-0.045}$	$0.020^{+0.080}_{-0.035}$	$0.015^{+0.030}_{-0.035}$	$0.010^{+0.020}_{-0.030}$	$0.010^{+0.025}_{-0.025}$	$0.010^{+0.025}_{-0.025}$
$\bar{\delta}_b$	0.02	$0.02^{+0.030}_{-0.035}$	$0.040^{+0.040}_{-0.050}$	$0.025^{+0.075}_{-0.020}$	$0.020^{+0.030}_{-0.035}$	$0.020^{+0.025}_{-0.025}$	$0.020^{+0.025}_{-0.025}$	$0.020^{+0.025}_{-0.025}$
	0.03	$0.03^{+0.030}_{-0.035}$	$0.050^{+0.040}_{-0.050}$	$0.035^{+0.030}_{-0.020}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.020}_{-0.020}$
	0.05	$0.05^{+0.030}_{-0.035}$	$0.080^{+0.020}_{-0.040}$	$0.055^{+0.025}_{-0.020}$	$0.050^{+0.025}_{-0.020}$	$0.050^{+0.025}_{-0.025}$	$0.050^{+0.025}_{-0.025}$	$0.050^{+0.020}_{-0.020}$
	0.1	$0.12^{+0.025}_{-0.030}$	$0.10^{+0.03}_{-0.02}$	$0.10^{+0.03}_{-0.03}$	$0.10^{+0.02}_{-0.03}$	$0.10^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$
	0.3	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$
	0.5	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$

Extracting $b\,, d_3$ at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Expected precision on δ_b with $L = 1\,\mathrm{ab}^{-1}/(a^2 BR(b\bar{b})/BR(b\bar{b})_{SM})^2$

	measured δ_b	$\bar{\delta}_{d_3}$ = -0.5	-0.3	-0.1	0	0.1	0.3	0.5
$\bar{\delta}_b$	0	$-0.045^{+0.060}_{-0.025}$	$0.015^{+0.020}_{-0.040}$	$0.010^{+0.070}_{-0.045}$	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.03}$	$0.00^{+0.03}_{-0.03}$	$0.00^{+0.03}_{-0.03}$
	0.01	$-0.055^{+0.070}_{-0.020}$	$0.030^{+0.030}_{-0.045}$	$0.020^{+0.080}_{-0.035}$	$0.015^{+0.030}_{-0.035}$	$0.010^{+0.020}_{-0.030}$	$0.010^{+0.025}_{-0.025}$	$0.010^{+0.025}_{-0.025}$
	0.02	$0.02^{+0.030}_{-0.035}$	$0.040^{+0.040}_{-0.050}$	$0.025^{+0.075}_{-0.020}$	$0.020^{+0.030}_{-0.035}$	$0.020^{+0.025}_{-0.025}$	$0.020^{+0.025}_{-0.025}$	$0.020^{+0.025}_{-0.025}$
	0.03	$0.03^{+0.030}_{-0.035}$	$0.050^{+0.040}_{-0.050}$	$0.035^{+0.030}_{-0.020}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.025}_{-0.025}$	$0.030^{+0.020}_{-0.020}$
	0.05	$0.05^{+0.030}_{-0.035}$	$0.080^{+0.020}_{-0.040}$	$0.055^{+0.025}_{-0.020}$	$0.050^{+0.025}_{-0.020}$	$0.050^{+0.025}_{-0.025}$	$0.050^{+0.025}_{-0.025}$	$0.050^{+0.020}_{-0.020}$
	0.1	$0.12^{+0.025}_{-0.030}$	$0.10^{+0.03}_{-0.02}$	$0.10^{+0.03}_{-0.03}$	$0.10^{+0.02}_{-0.03}$	$0.10^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$
	0.3	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.30^{+0.02}_{-0.02}$
	0.5	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$	$0.50^{+0.02}_{-0.02}$

For injected SM: precision on δ_b is 5%

Extracting $b\,,d_3$ at CLIC with $\sqrt{s}=3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar\nu\, hh \to \nu\bar\nu\, b\bar b b\bar b$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Expected precision on δ_{d_3} with $L = 1\,\mathrm{ab}^{-1}/(a^2 BR(b\bar b)/BR(b\bar b)_{SM})^2$

	measured δ_{d_3}	$\bar\delta_{d_3}$ -0.5	-0.3	-0.1	0	0.1	0.3	0.5
$\bar\delta_b$	0	$-0.50^{+0.35}_{-0.25}$	$-0.25^{+0.20}_{-0.50}$	$0.00^{+0.25}_{-0.40}$	$0.05^{+0.30}_{-0.30}$	$0.10^{+0.25}_{-0.20}$	$0.30^{+0.20}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.01	$-0.45^{+0.35}_{-0.30}$	$-0.20^{+0.30}_{-0.55}$	$-0.05^{+0.30}_{-0.30}$	$0.00^{+0.25}_{-0.25}$	$0.10^{+0.20}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.02	$-0.35^{+0.30}_{-0.35}$	$-0.25^{+0.25}_{-0.60}$	$-0.10^{+0.25}_{-0.30}$	$0.00^{+0.20}_{-0.25}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.03	$-0.40^{+0.30}_{-0.35}$	$-0.25^{+0.20}_{-0.70}$	$-0.10^{+0.20}_{-0.25}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.05	$-0.55^{+0.30}_{-0.40}$	$-0.30^{+0.20}_{-0.30}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.10}_{-0.10}$
	0.1	$-0.50^{+0.15}_{-0.25}$	$-0.30^{+0.15}_{-0.20}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.15}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.3	$-0.50^{+0.15}_{-0.15}$	$-0.30^{+0.15}_{-0.15}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.5	$-0.50^{+0.15}_{-0.10}$	$-0.30^{+0.10}_{-0.10}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$

Extracting $b\,,d_3$ at CLIC with $\sqrt{s}=3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Expected precision on δ_{d_3} with $L = 1\,\mathrm{ab}^{-1}/(a^2 BR(b\bar{b})/BR(b\bar{b})_{SM})^2$

	measured δ_{d_3}				$\bar{\delta}_{d_3}$			
		-0.5	-0.3	-0.1	0	0.1	0.3	0.5
$\bar{\delta}_b$	0	$-0.50^{+0.35}_{-0.25}$	$-0.25^{+0.20}_{-0.50}$	$0.00^{+0.25}_{-0.40}$	$0.05^{+0.30}_{-0.30}$	0.[illegible]$^{+0.25}_{-0.20}$	$0.30^{+0.20}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.01	$-0.45^{+0.35}_{-0.30}$	$-0.20^{+0.30}_{-0.55}$	$-0.05^{+0.30}_{-0.30}$	$0.00^{+0.25}_{-0.25}$	$0.10^{+0.20}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.02	$-0.35^{+0.30}_{-0.35}$	$-0.25^{+0.25}_{-0.60}$	$-0.10^{+0.25}_{-0.30}$	$0.00^{+0.20}_{-0.25}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.03	$-0.40^{+0.30}_{-0.35}$	$-0.25^{+0.20}_{-0.70}$	$-0.10^{+0.20}_{-0.25}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.05	$-0.55^{+0.30}_{-0.40}$	$-0.30^{+0.20}_{-0.30}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.10}_{-0.10}$
	0.1	$-0.50^{+0.15}_{-0.25}$	$-0.30^{+0.15}_{-0.20}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.15}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.3	$-0.50^{+0.15}_{-0.15}$	$-0.30^{+0.15}_{-0.15}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.5	$-0.50^{+0.15}_{-0.10}$	$-0.30^{+0.10}_{-0.10}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$

For injected SM: precision on δ_{d_3} is 30%

Extracting $b\,,d_3$ at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$ through $e^+e^- \to \nu\bar{\nu}\, hh \to \nu\bar{\nu}\, b\bar{b}b\bar{b}$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038

$$\sigma = a^4\,\sigma_{SM}\left(1 + A\,\delta_b + B\,\delta_{d_3} + C\,\delta_b\delta_{d_3} + D\,\delta_b^2 + E\,\delta_{d_3}^2\right)$$

$$\delta_b = 1 - b/a^2$$

$$\delta_{d_3} = 1 - d_3/a$$

Expected precision on δ_{d_3} with $L = 1\,\mathrm{ab}^{-1}/(a^2 BR(b\bar{b})/BR(b\bar{b})_{SM})^2$

	measured δ_{d_3}	$\bar{\delta}_{d_3}$ -0.5	-0.3	-0.1	0	0.1	0.3	0.5
	0	$-0.50^{+0.35}_{-0.25}$	$-0.25^{+0.20}_{-0.50}$	$0.00^{+0.25}_{-0.40}$	$0.05^{+0.30}_{-0.30}$	0.[illegible]0$^{+0.25}_{-0.20}$	$0.30^{+0.20}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.01	$-0.45^{+0.35}_{-0.30}$	$-0.20^{+0.30}_{-0.55}$	$-0.05^{+0.30}_{-0.30}$	$0.00^{+0.25}_{-0.25}$	$0.10^{+0.20}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
$\bar{\delta}_b$	0.02	$-0.35^{+0.30}_{-0.35}$	$-0.25^{+0.25}_{-0.60}$	$-0.10^{+0.25}_{-0.30}$	$0.00^{+0.20}_{-0.25}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.03	$-0.40^{+0.30}_{-0.35}$	$-0.25^{+0.20}_{-0.70}$	$-0.10^{+0.20}_{-0.25}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.20}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.15}_{-0.15}$
	0.05	$-0.55^{+0.30}_{-0.40}$	$-0.30^{+0.20}_{-0.30}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.20}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.15}_{-0.15}$	$0.50^{+0.10}_{-0.10}$
	0.1	$-0.50^{+0.15}_{-0.25}$	$-0.30^{+0.15}_{-0.20}$	$-0.10^{+0.20}_{-0.20}$	$0.00^{+0.15}_{-0.15}$	$0.10^{+0.15}_{-0.15}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.3	$-0.50^{+0.15}_{-0.15}$	$-0.30^{+0.15}_{-0.15}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$
	0.5	$-0.50^{+0.15}_{-0.10}$	$-0.30^{+0.10}_{-0.10}$	$-0.10^{+0.10}_{-0.10}$	$0.00^{+0.10}_{-0.10}$	$0.10^{+0.10}_{-0.10}$	$0.30^{+0.10}_{-0.10}$	$0.50^{+0.10}_{-0.10}$

For injected SM: precision on δ_{d_3} is 30% ⇨ Much stronger sensitivity on b than on d_3

Reach on compositeness scale

	$\xi = (v/f)^2$	$\Lambda = 4\pi f$
LHC 14 TeV $L = 300\,\text{fb}^{-1}$	0.5 (double Higgs [1,2])	4.5 TeV
	0.1 (single Higgs [3,4])	10 TeV
ILC 250 GeV $L = 250\,\text{fb}^{-1}$ + 500 GeV $L = 500\,\text{fb}^{-1}$	0.6-1.2 $\times 10^{-2}$ (single Higgs [5,6])	30-40 TeV
CLIC 3 TeV $L = 1\,\text{ab}^{-1}$	2-5 $\times 10^{-2}$ (double Higgs [7])	15-20 TeV
CLIC 350 GeV $L = 500\,\text{fb}^{-1}$ + 1.4 TeV $L = 1.5\,\text{ab}^{-1}$ + 3.0 TeV $L = 2\,\text{ab}^{-1}$	1.1-2.4 $\times 10^{-3}$ (single Higgs [8])	60-90 TeV

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[7] R. Contino, C. Grojean, D. Pappadopulo, R. Rattazzi and A. Thamm, arXiv:1309.7038 [hep-ph].

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  \- precision: Vhh at 5% ; hhh at 30%

  \- tests of Higgs effective Lagrangian at dim-8 level: PNBG vs SILH

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- Tests of Higgs compositeness (i.e. strong EWSB) can be done by precisely measuring low-energy quantities (e.g. tails of scattering amplitudes)

- From study of $VV \to hh$ at CLIC with $\sqrt{s} = 3\,\mathrm{TeV}$:

  - precision: $VVhh$ at 5% ; hhh at 30%

  - tests of Higgs effective Lagrangian at dim-8 level: PNBG vs SILH

- Take the right approach to look for NP

  Ex: much more information from $VV \to hh$ than just the trilinear coupling

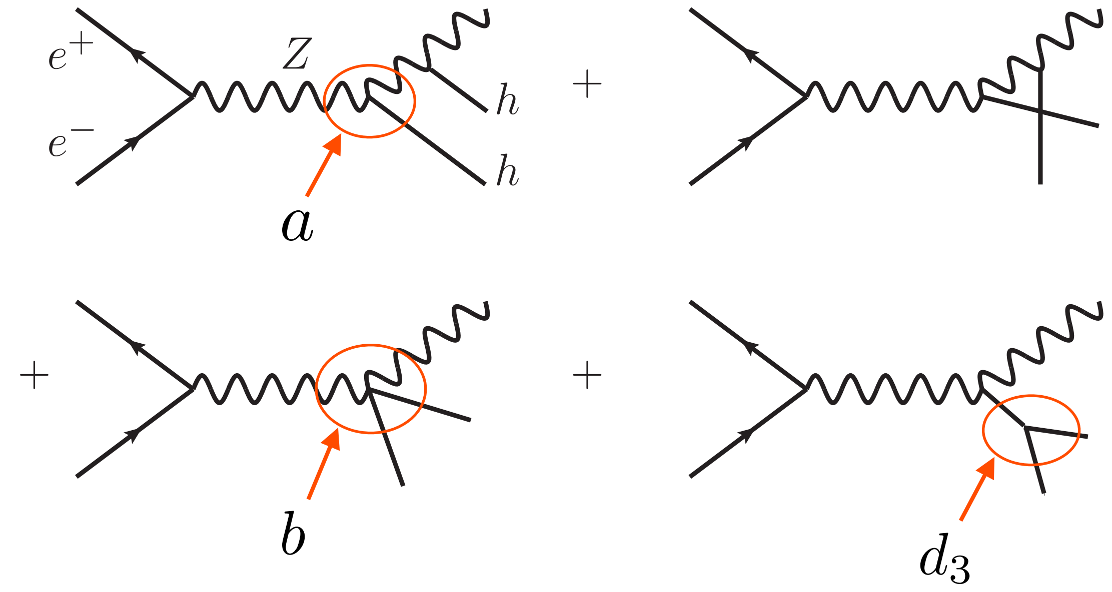
Extra Slides

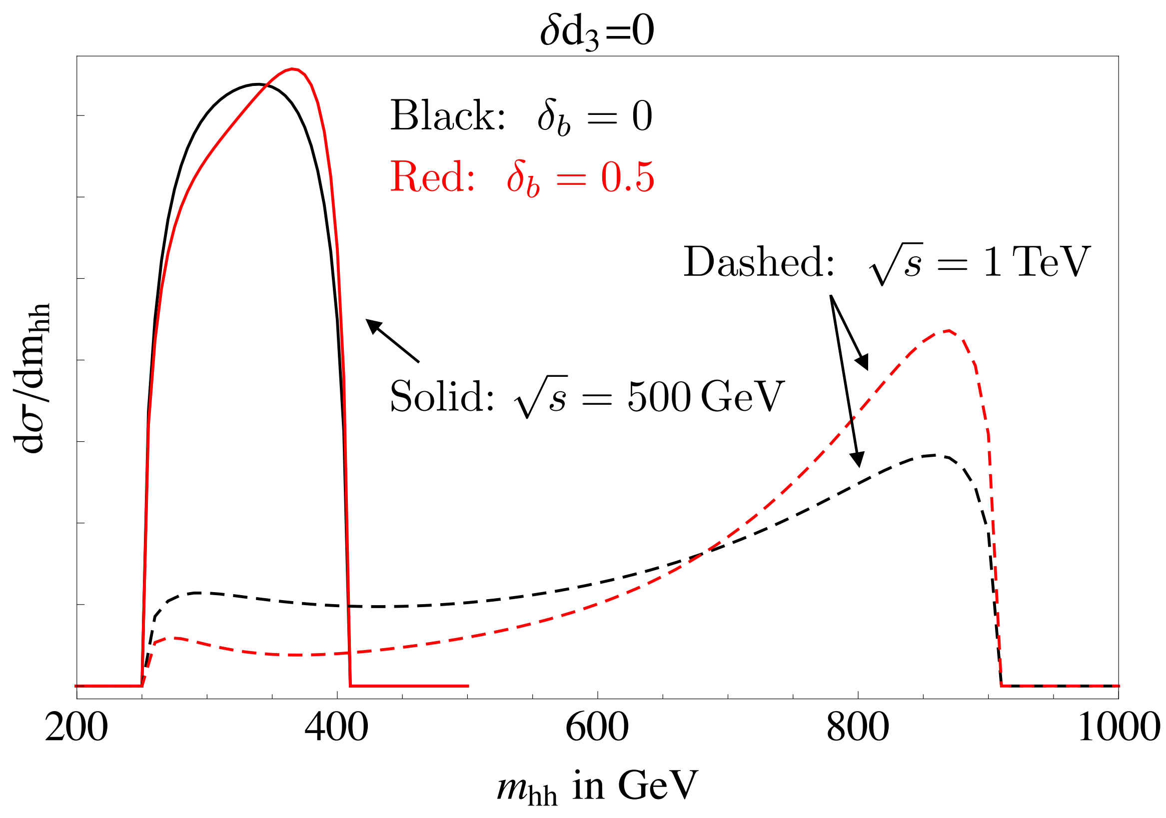
Extracting b, d_3 at the ILC

with $\sqrt{s} = 500\,\mathrm{GeV} - 1\,\mathrm{TeV}$

through double Higgs-strahlung

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038





Extracting b, d_3 at the ILC with $\sqrt{s} = 500\,\text{GeV} - 1\,\text{TeV}$ through double Higgs-strahlung

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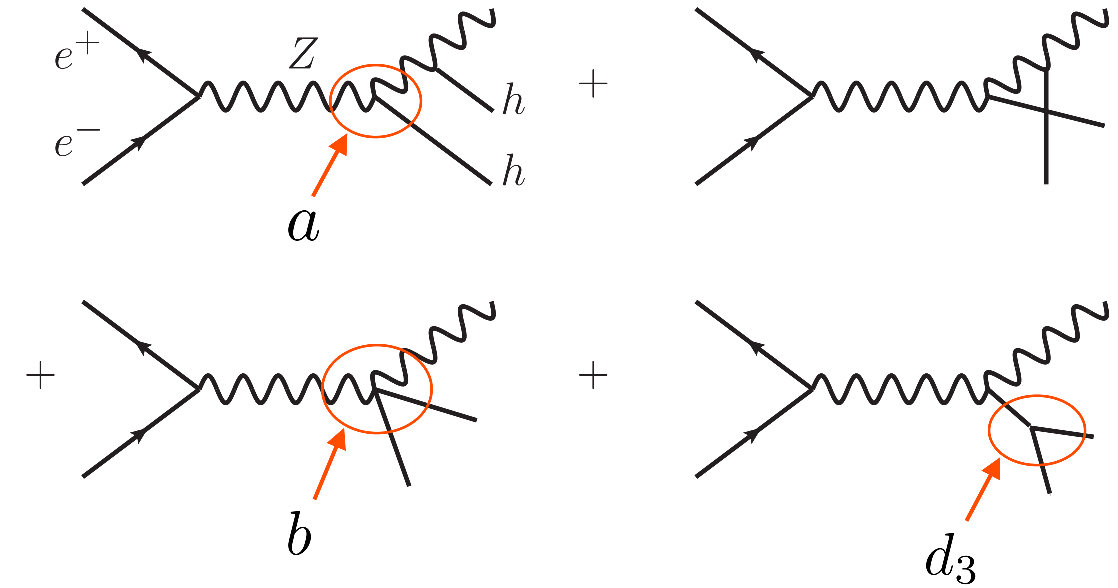

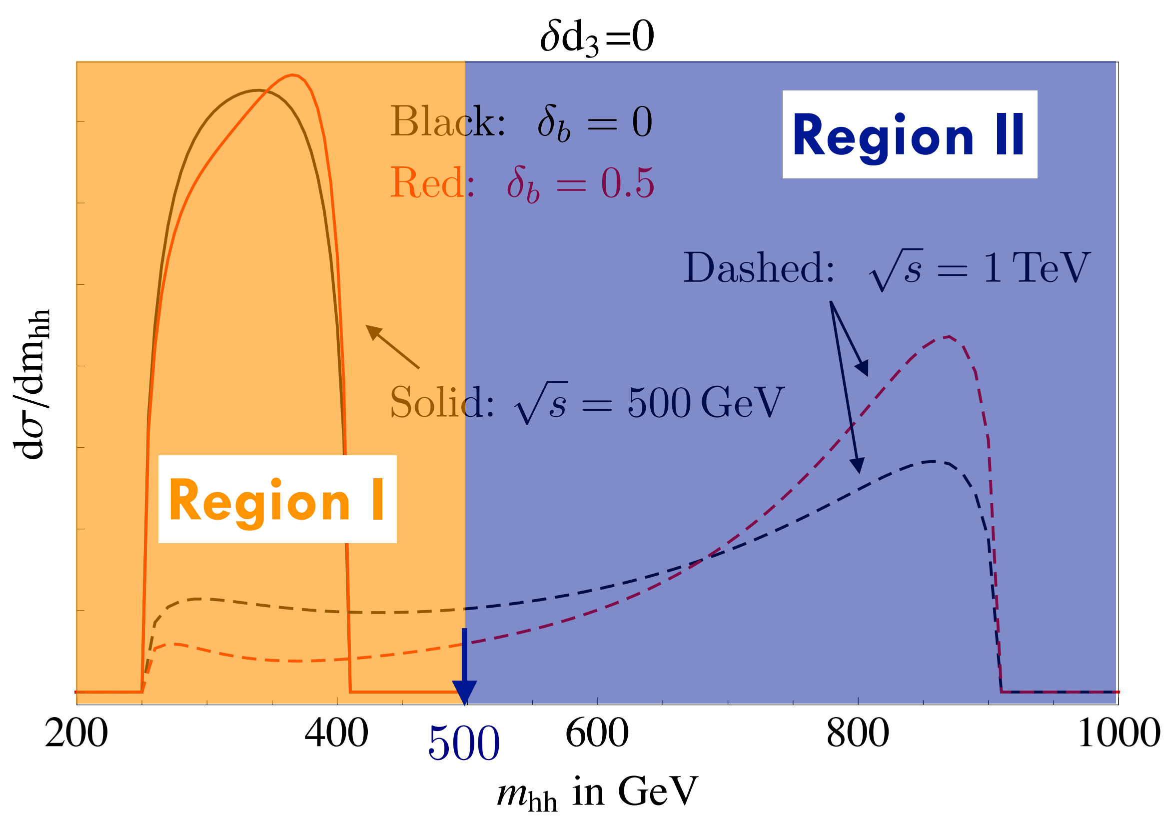

Cut on m_{hh} useful at $\sqrt{s} = 1\,\text{TeV}$

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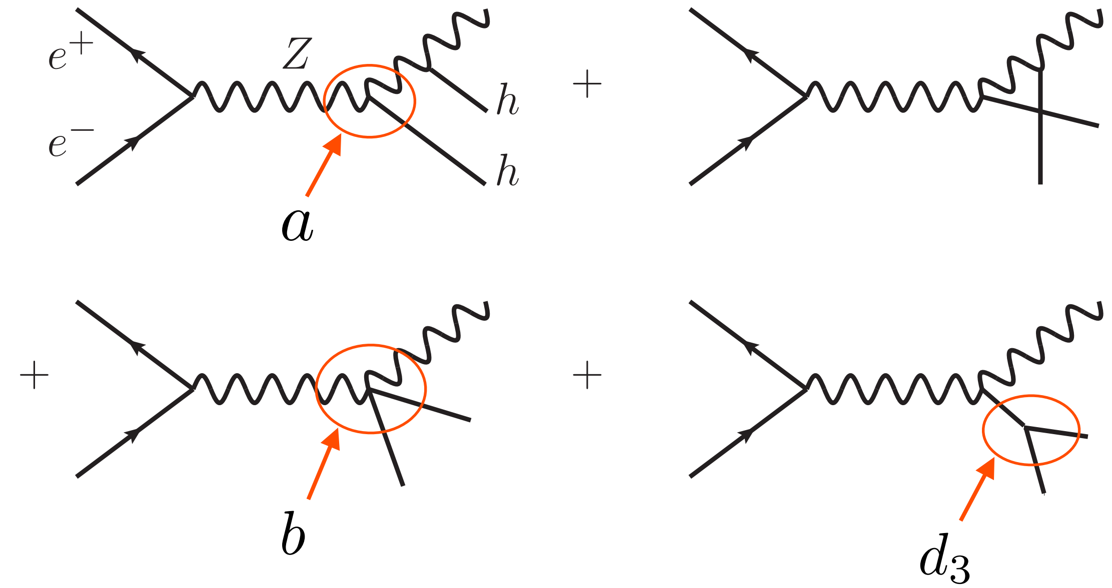

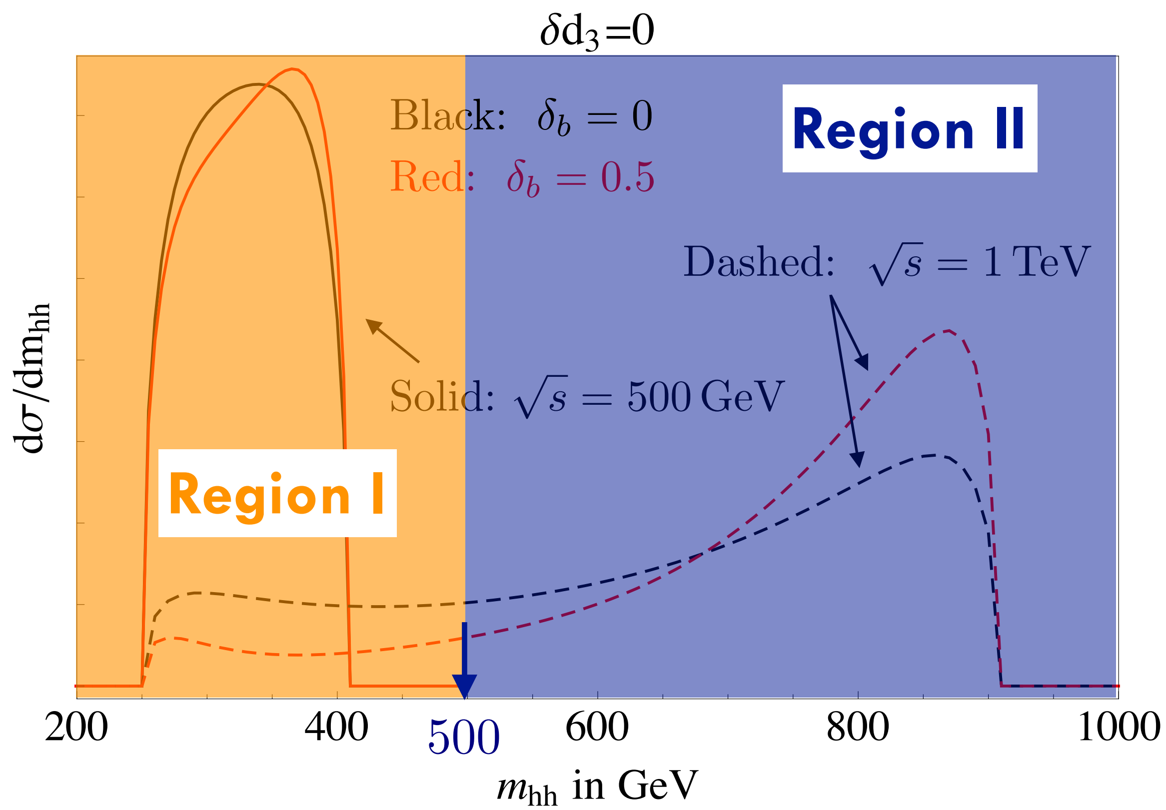

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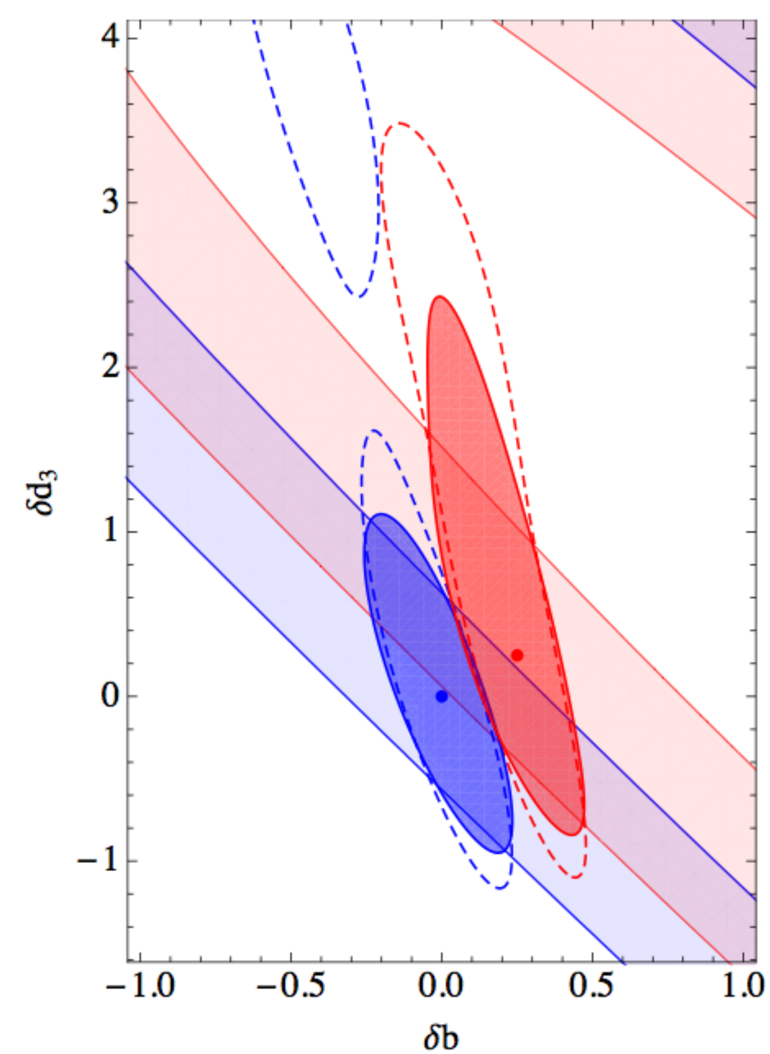
$L = 1\,\mathrm{ab}^{-1}$



$a^2(BR(b\bar{b})/BR(b\bar{b})_{SM}) = 1$

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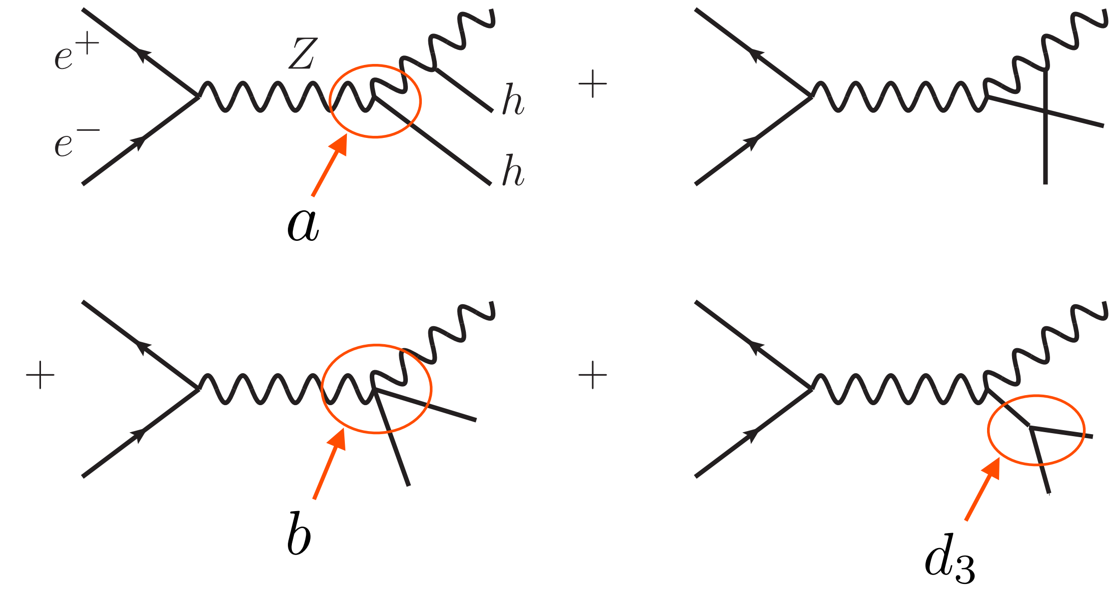

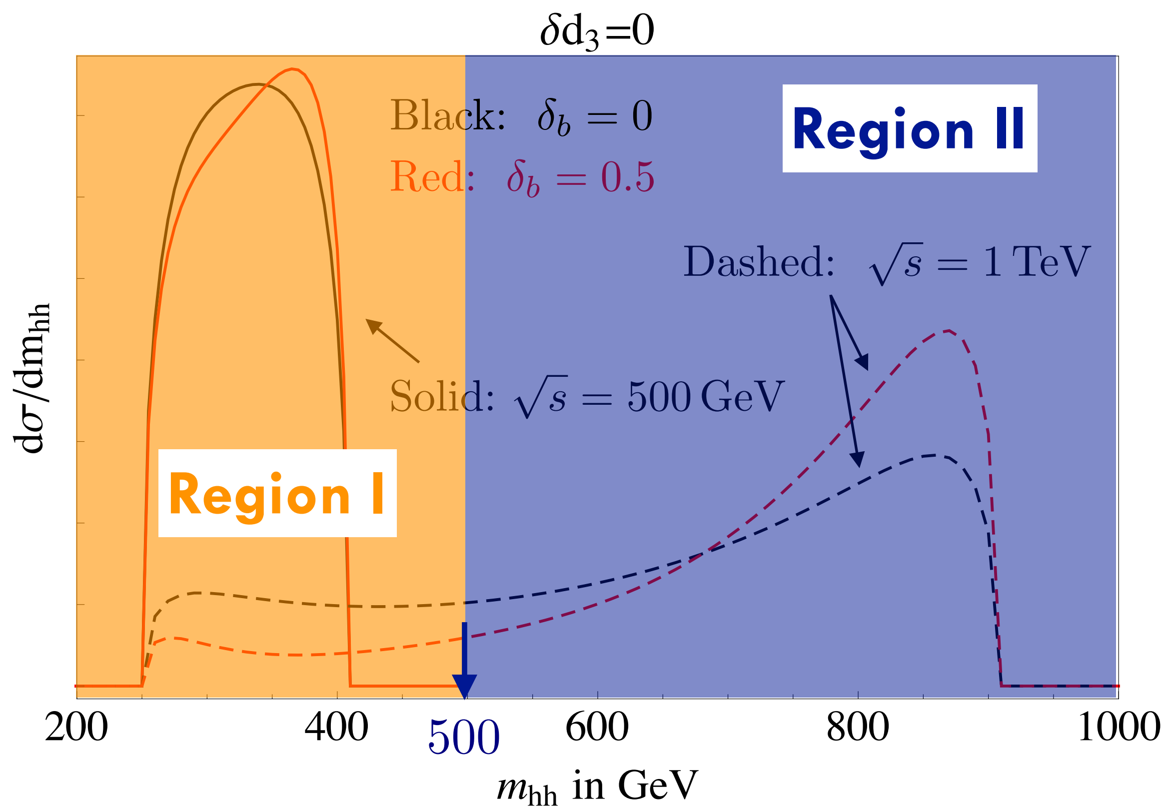

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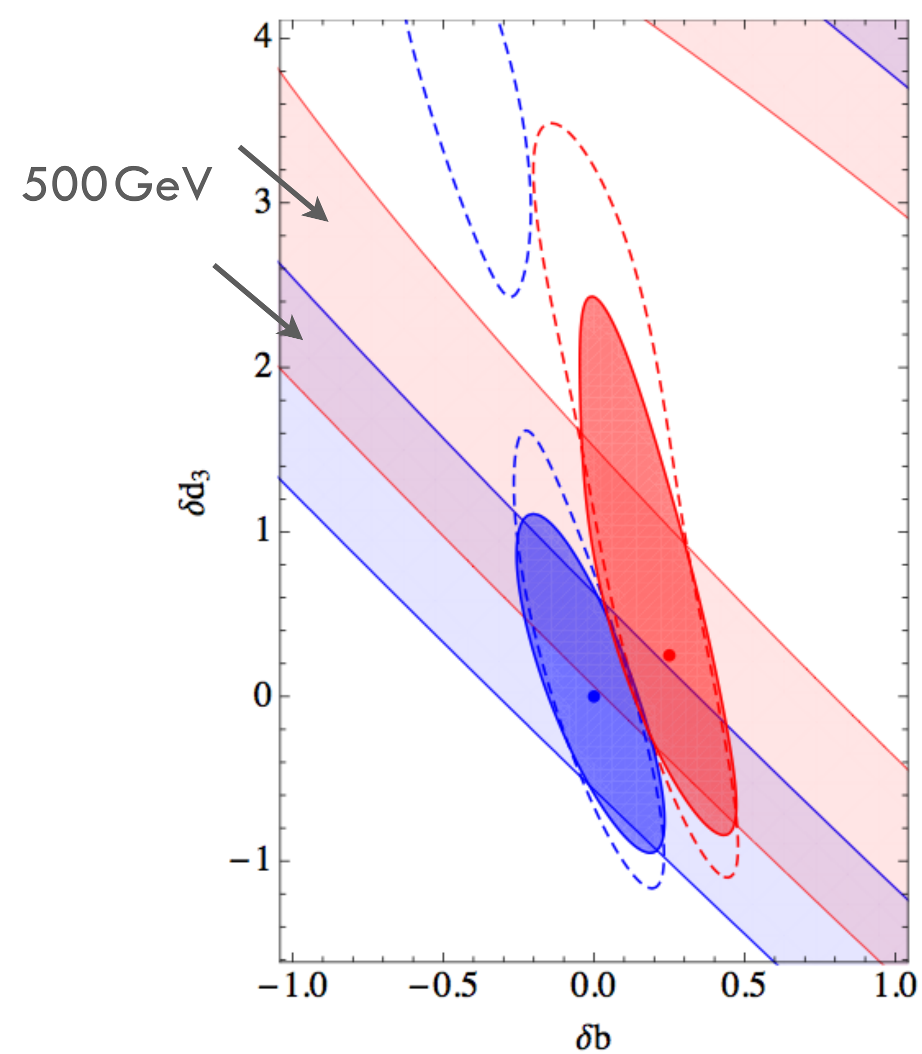

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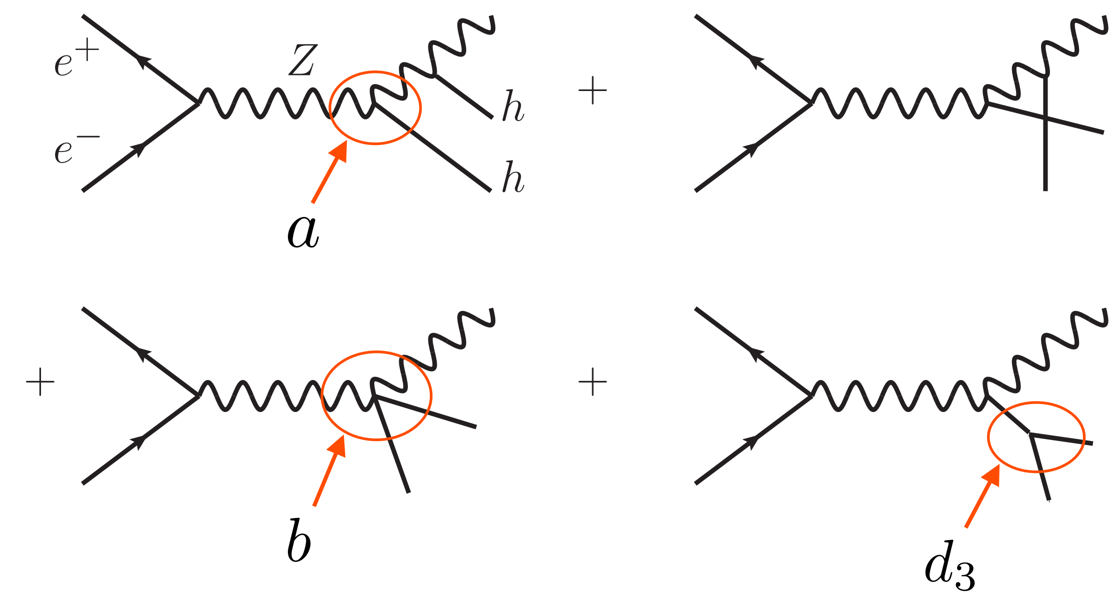

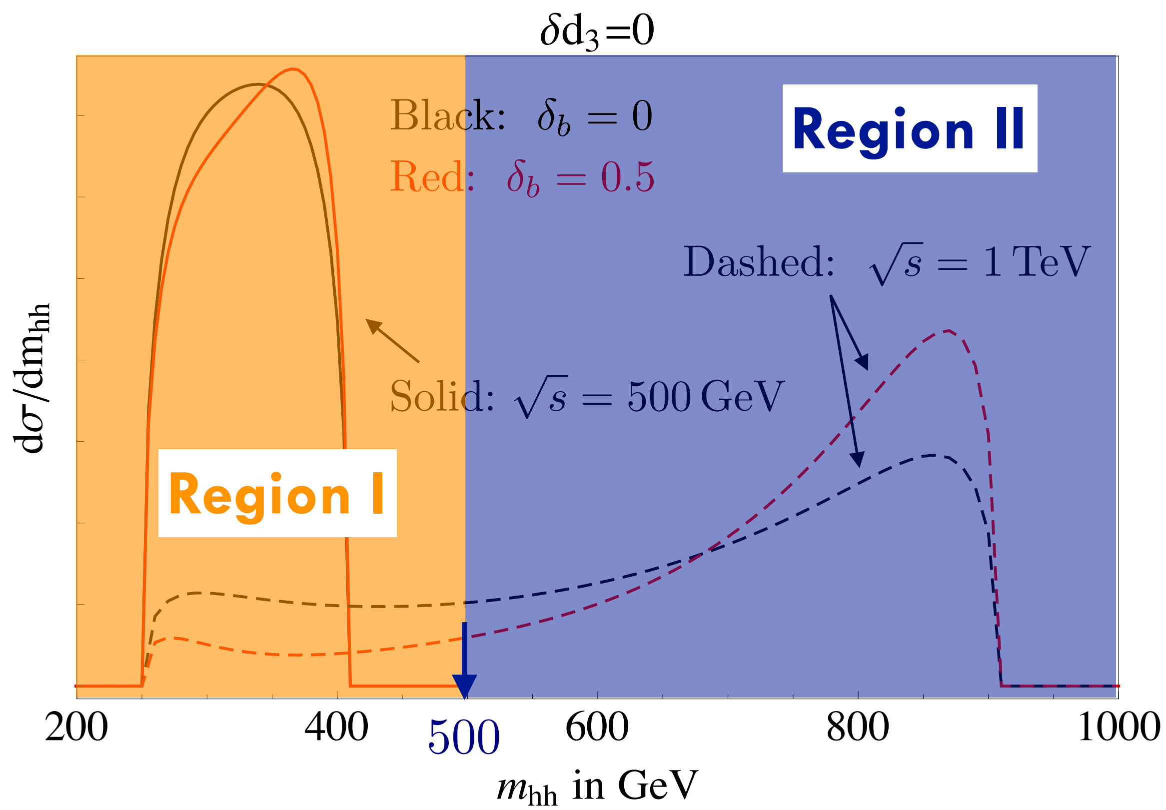

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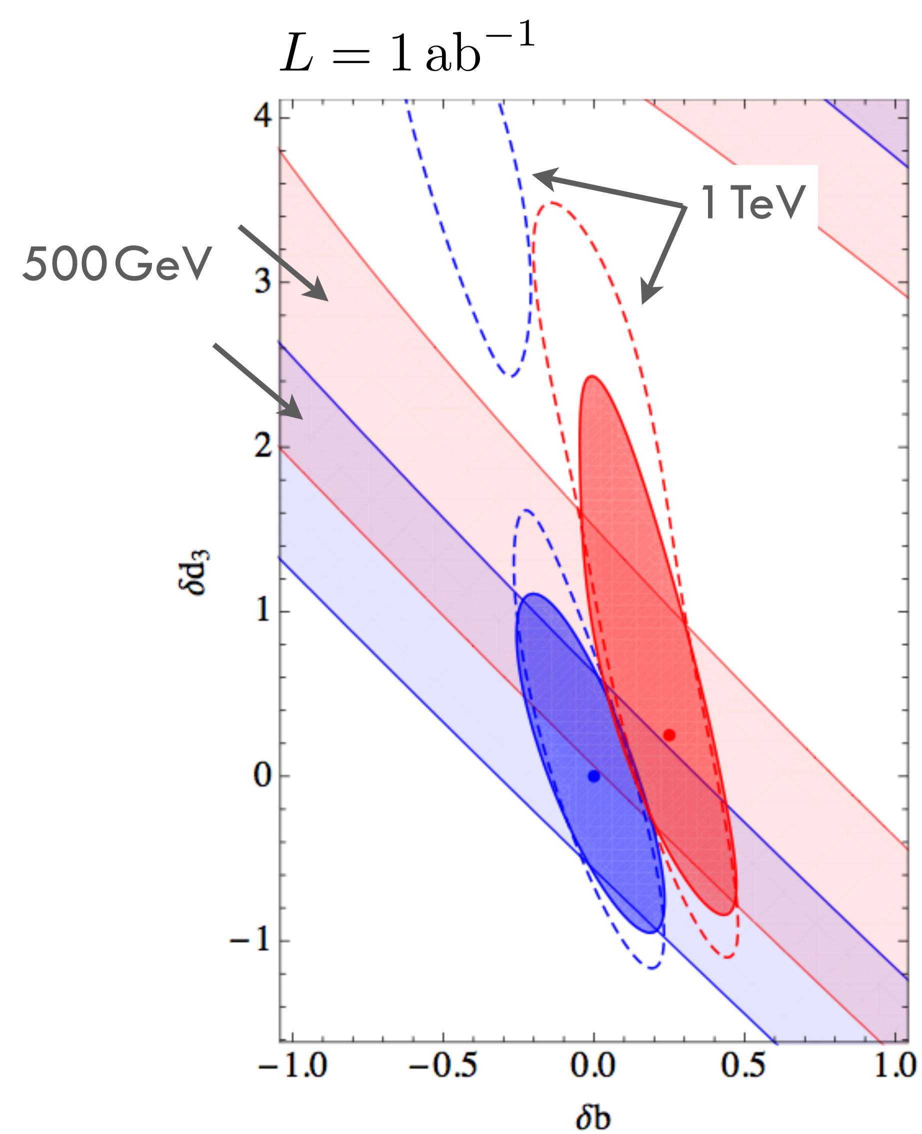

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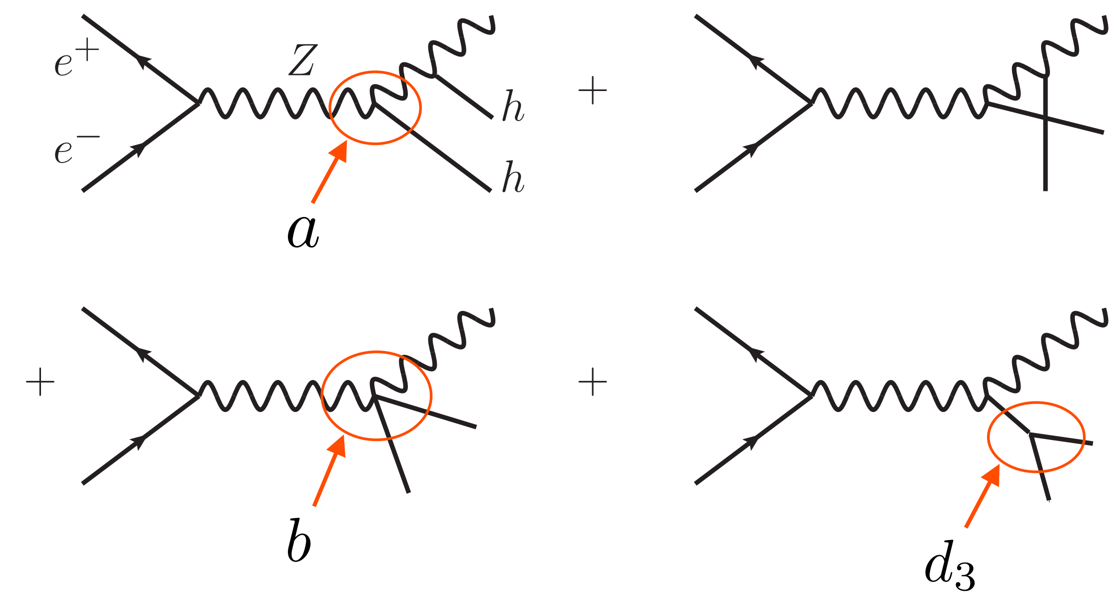

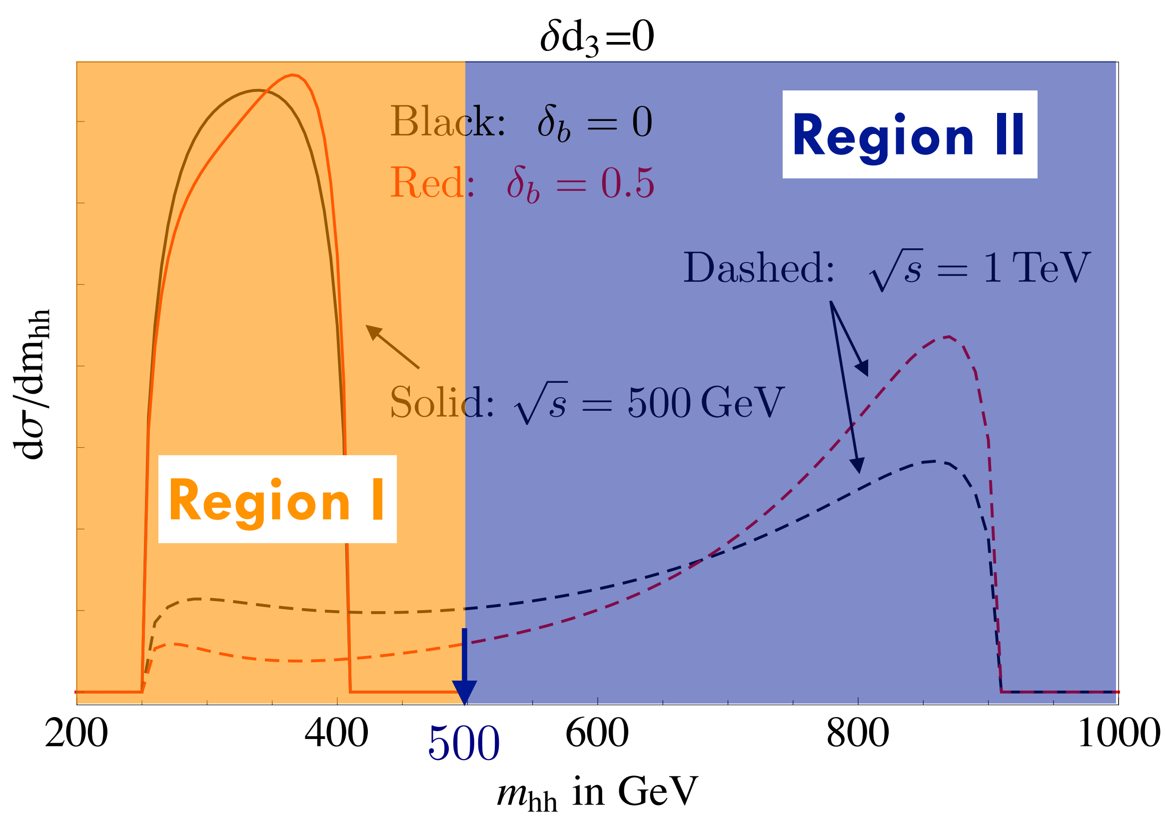

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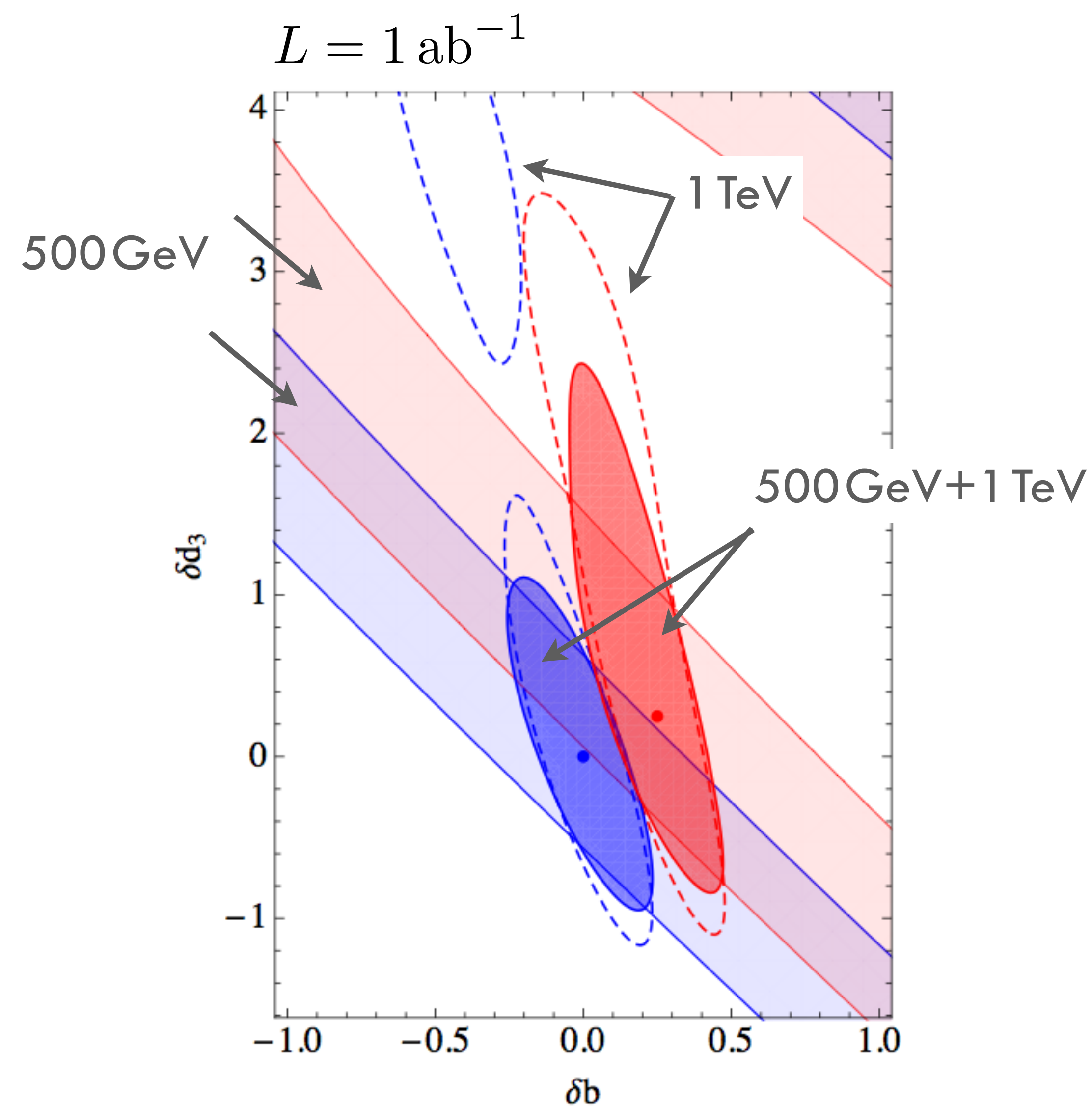

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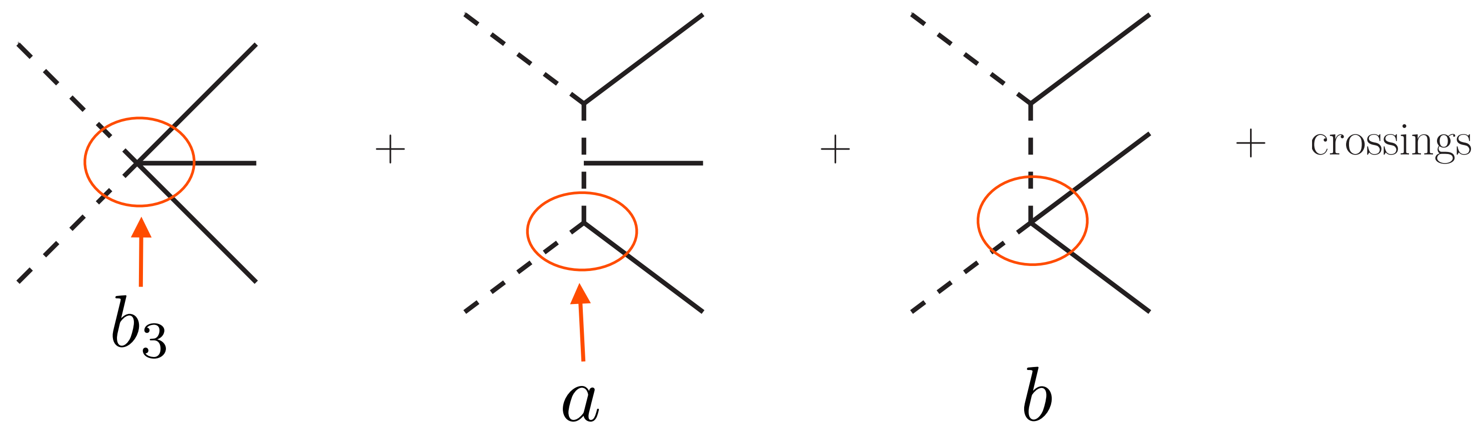
Further test of PNGB vs SILH (more difficult): $WW \to hhh$

RC, Grojean, Pappadopulo, Rattazzi, Thamm arXiv:1309.7038



$$\mathcal{A}(\chi\chi \to hhh) = \frac{i\hat{s}}{v^3}\left(4ab - 4a^3 - 3b_3\right) = 2i\left(c'_H - 2c_H\right)\frac{\hat{s}}{v^3}\left(\frac{v^4}{f^4}\right) + \ldots$$

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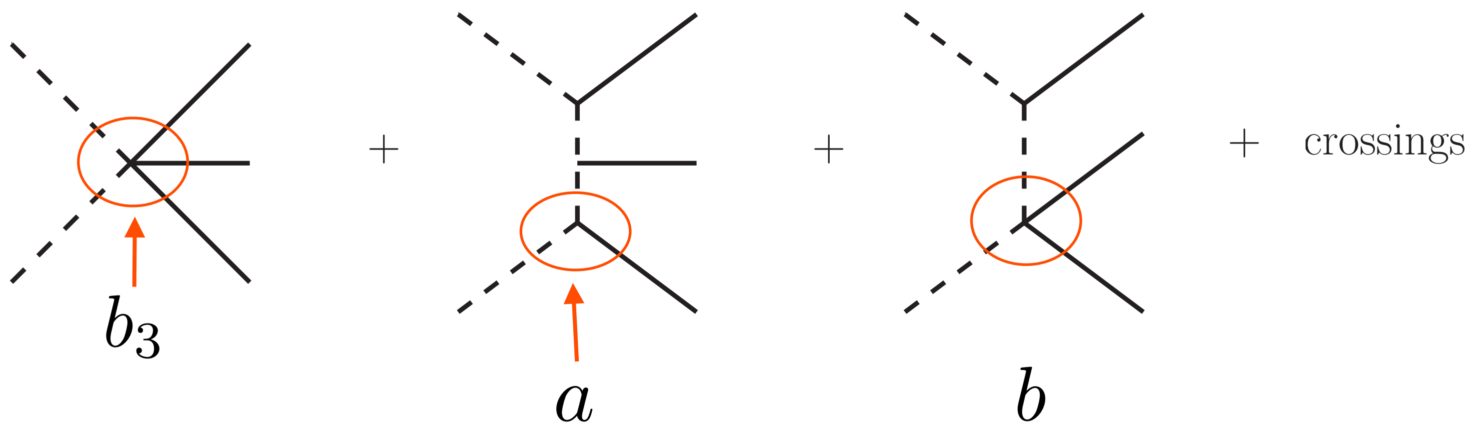

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Test dim-8 operators

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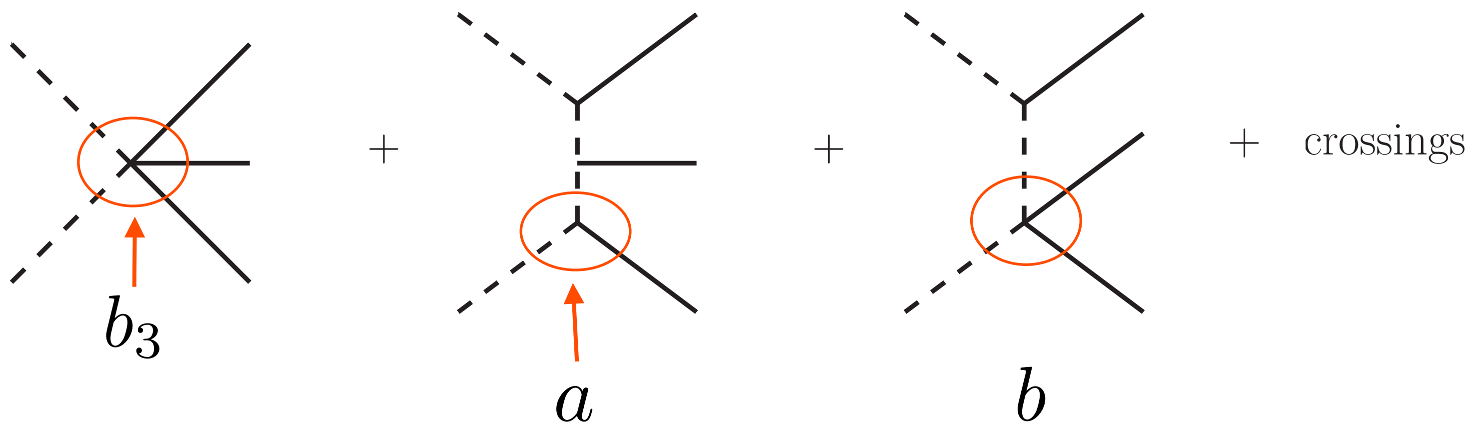

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vanishes for a PNGB (with symmetric coset) due to Z_2 parity $\pi \to -\pi$

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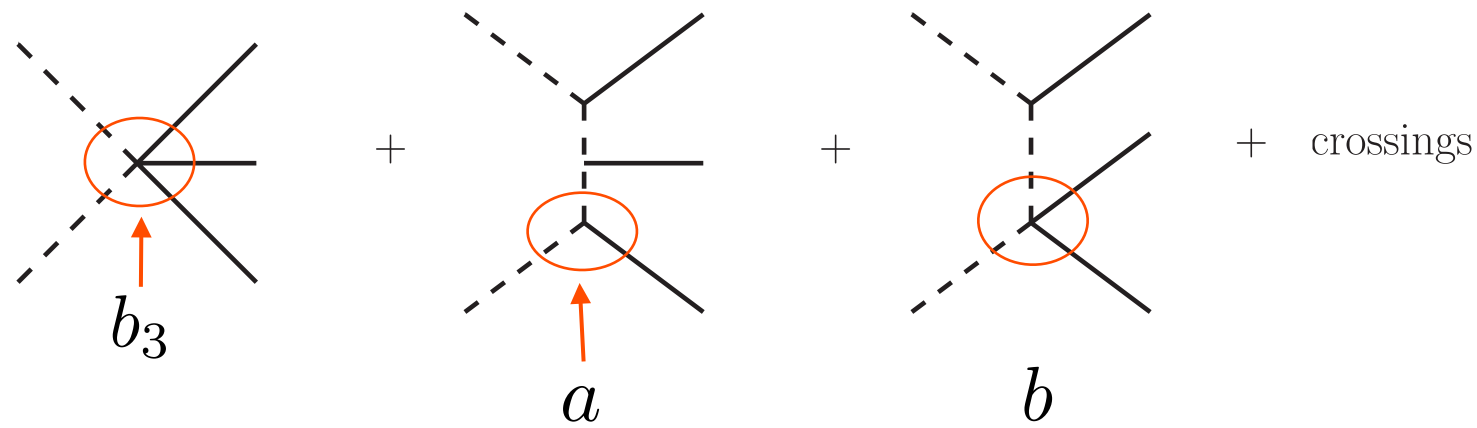

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vanishes for a PNGB (with symmetric coset) due to Z_2 parity $\pi \to -\pi$

σ [ab]	ξ 0	0.05	0.1	0.2	0.3	0.5	0.99
PNGB	0.32	0.46	0.71	1.47	2.41	4.13	0.30
SILH	0.32	0.71	0.87	7.56	42.89	407.9	7808

For $\xi \gtrsim 0.3$ detectable for a SILH (PNGB disproved)