PROBING EWSB AND FUTURE HIGGS PHYSICS

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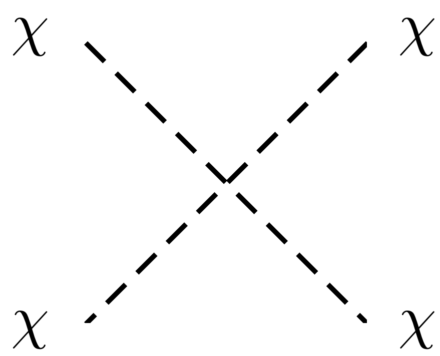
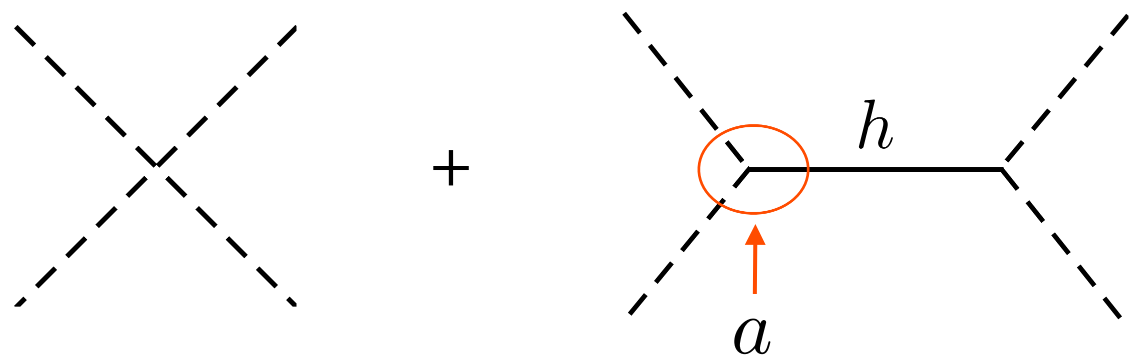
Strong vs Weak EWSB

In the {SM-H}



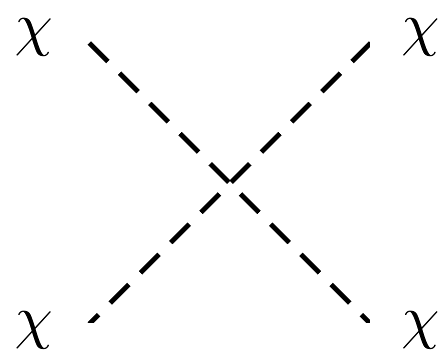
$$A(W_L W_L \to W_L W_L) = A(\chi\chi \to \chi\chi) \sim \frac{E^2}{v^2} \equiv g^2(E)$$

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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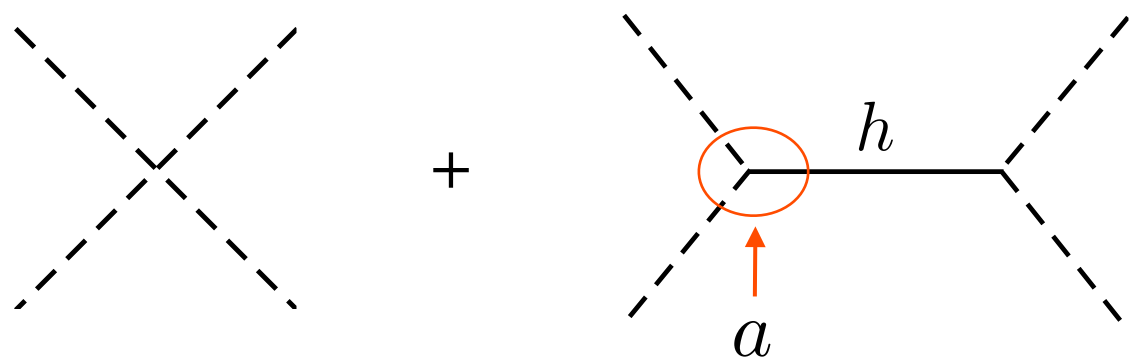
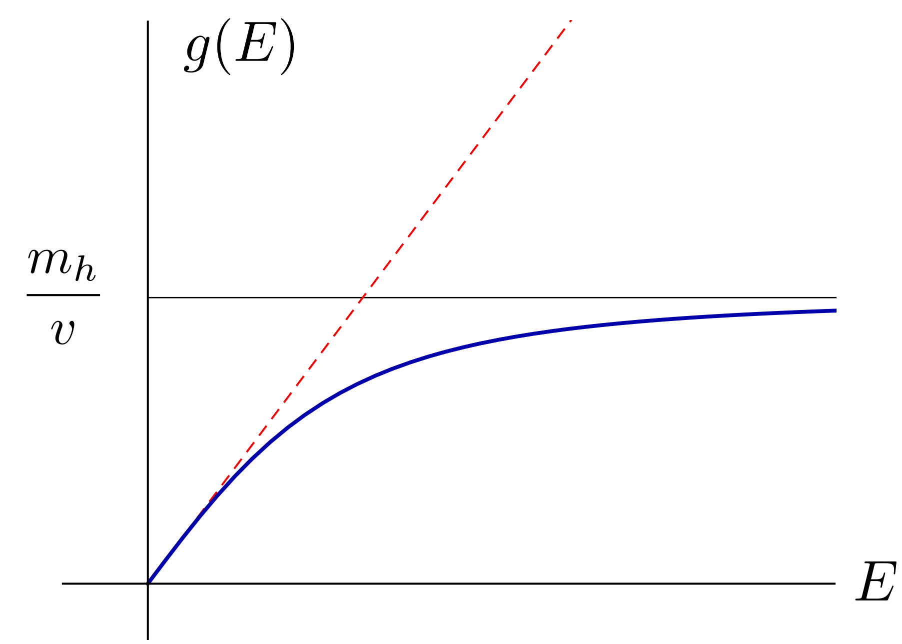


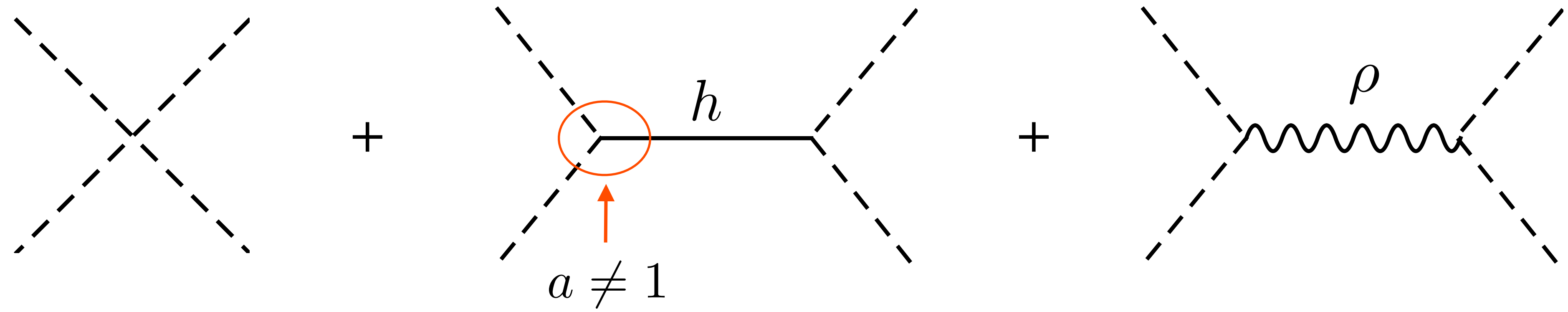
$$A \sim \underbrace{\frac{E^2}{v^2}(1-a^2)}_{=0} - a^2\,\frac{m_h^2}{v^2}\,\frac{s}{s-m_h^2}$$

Elementary Higgs: $a = 1$

weak →

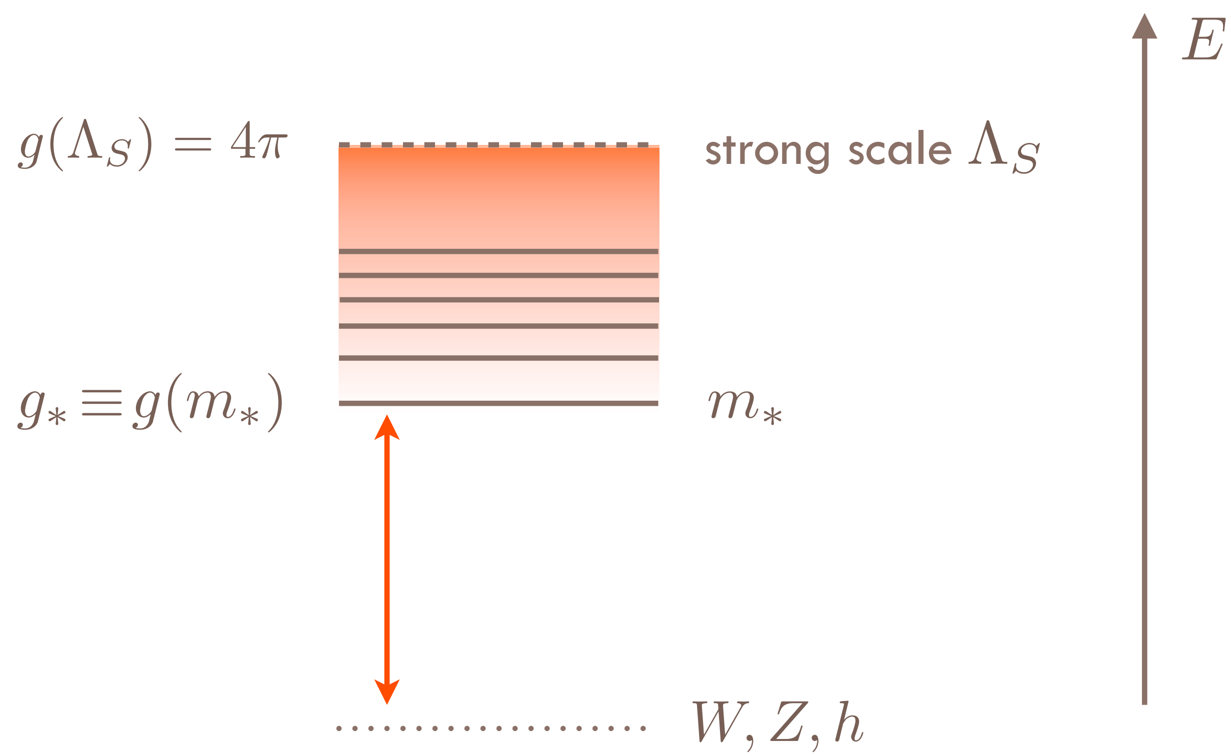


Composite Higgs:



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

Energy cartoon:



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

$\downarrow$

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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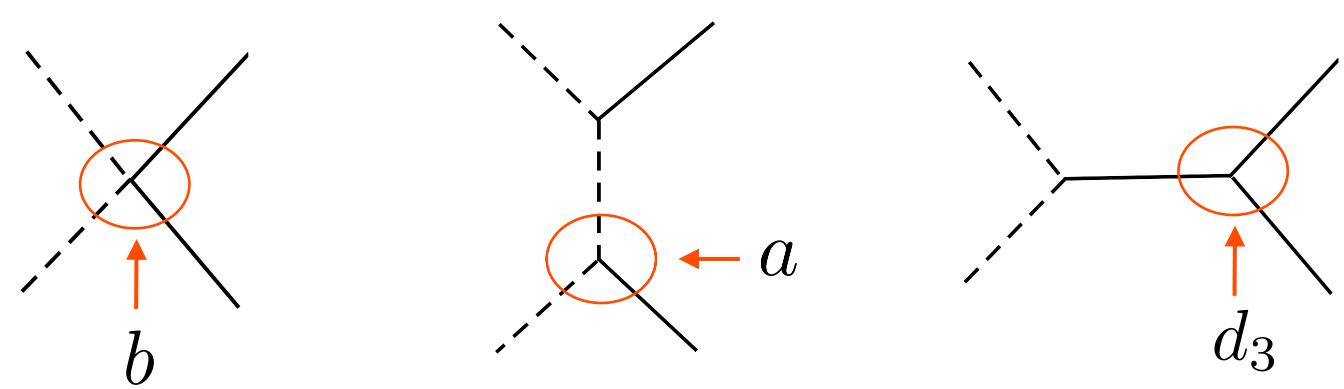
2. Scatterings involving the Higgs also grow with energy

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



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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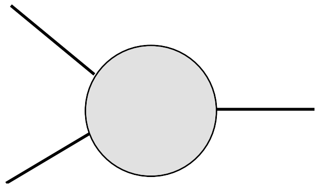
   i) virtual corrections to single-Higgs processes



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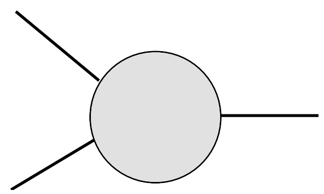
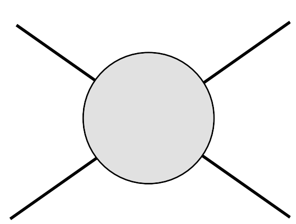
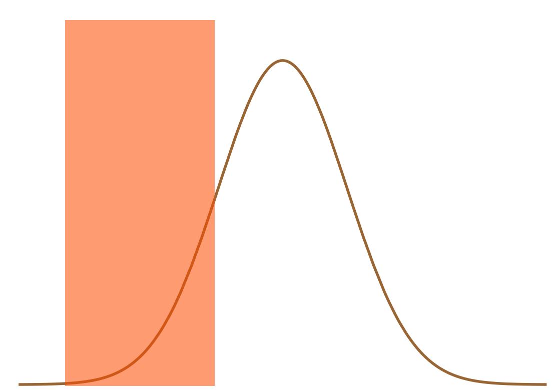


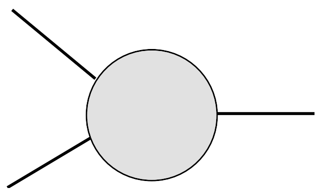
   ii) tails in scattering amplitudes

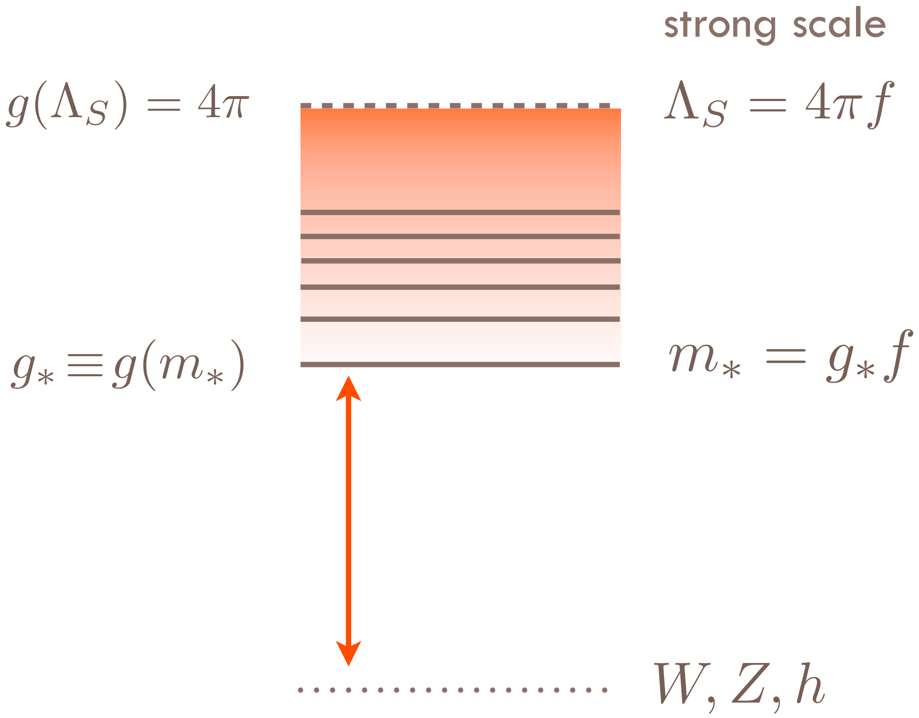




Corrections to Higgs couplings

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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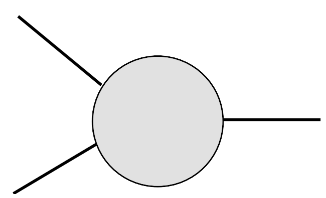

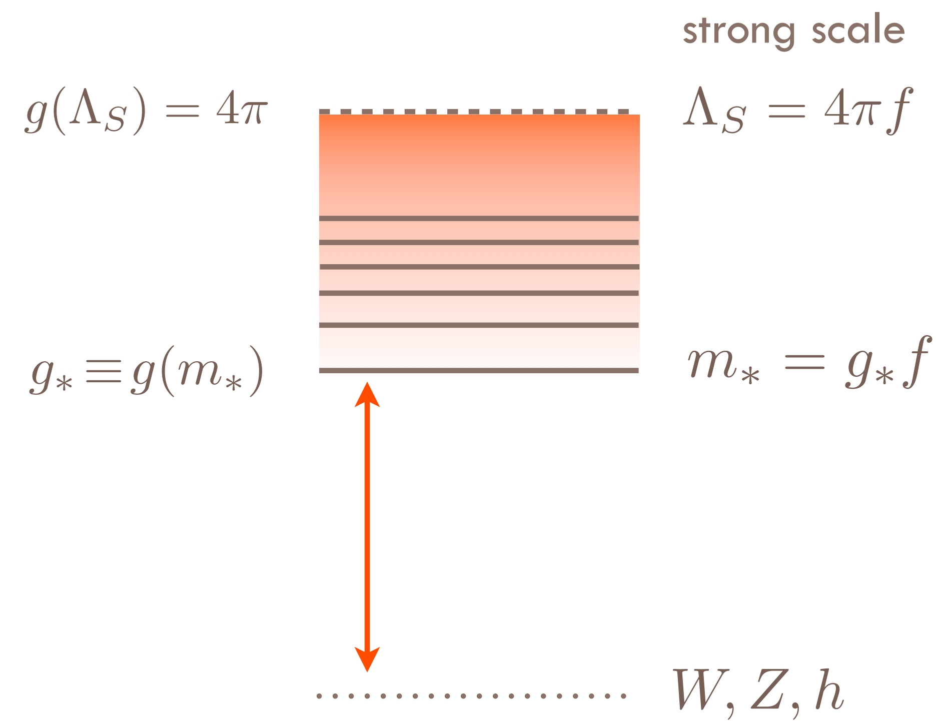

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from NL sigma model

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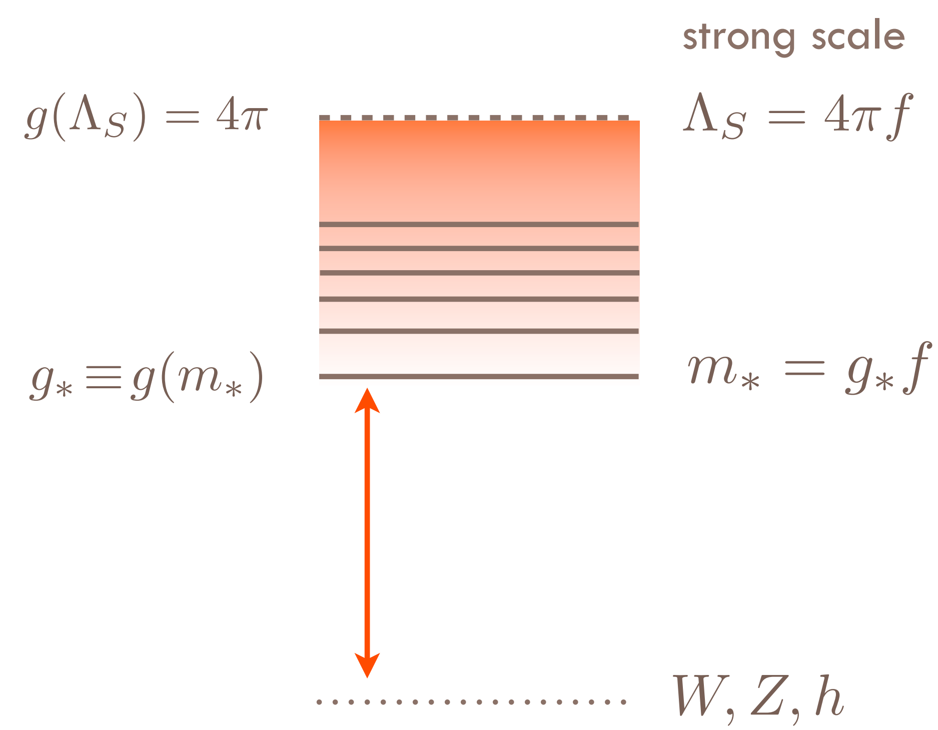

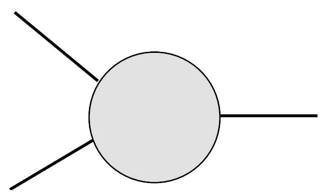

contribution of resonances

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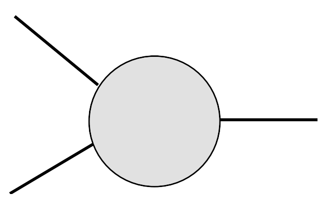

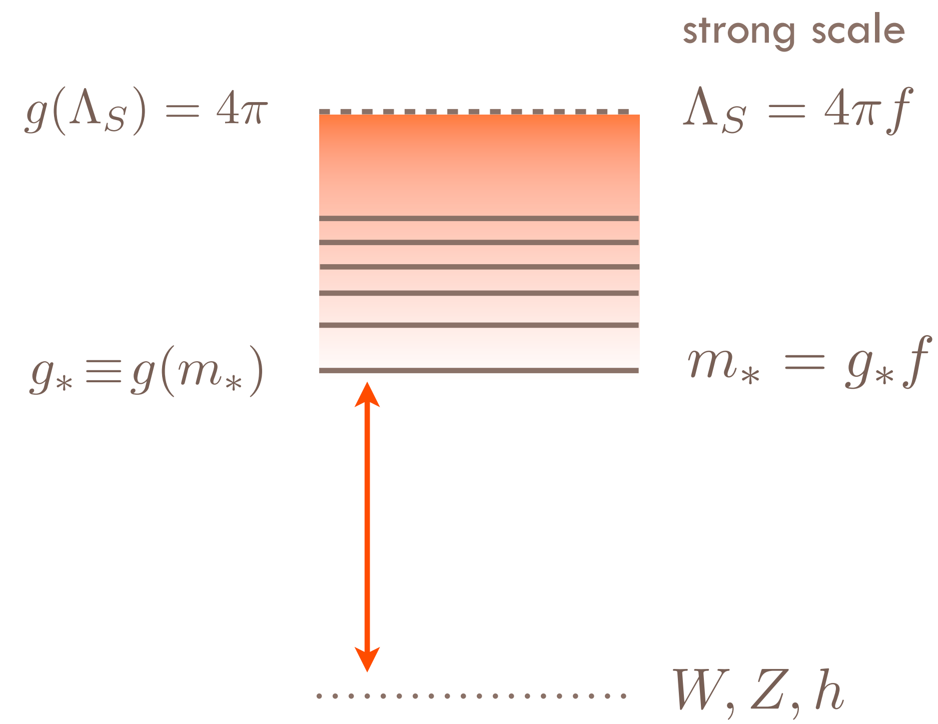

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Suppose we find:

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

$$m_* > M$$

(from direct searches)

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

In practice resonance contribution is further suppressed:

$$\frac{\delta c}{c_{SM}} \sim \frac{v^2}{f^2} + \frac{g_*^2 v^2}{m_*^2} \times \frac{g_{\not{G}}^2}{g_*^2}$$

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$$\left[\partial_\mu (H^\dagger H)\right]^2$$

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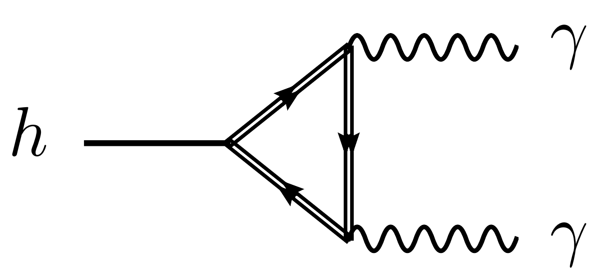
loop-induced h→γγ,gg



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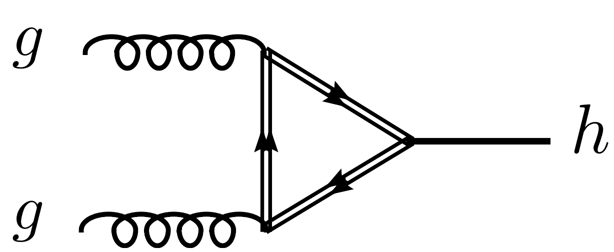

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Effective operators violate
the Higgs shift symmetry:

$$H^i \to H^i + \zeta^i$$

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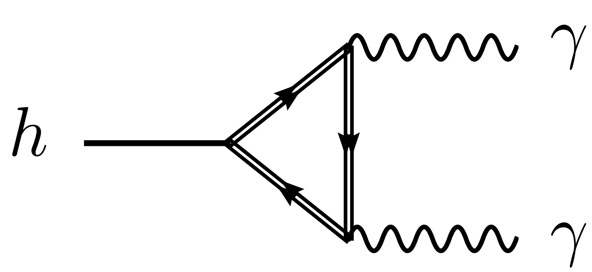

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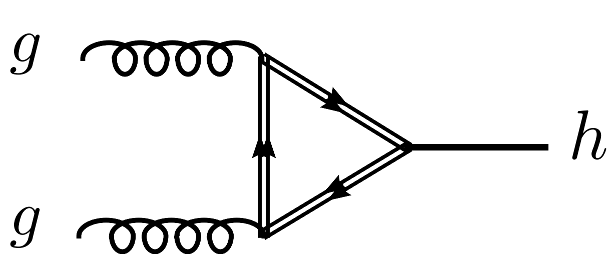

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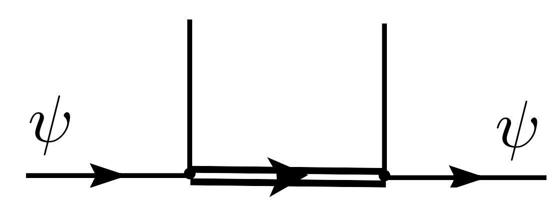
tree-level coupling to fermions



$$\bar{\psi} H \psi \, H^\dagger H$$

resonance corrections arise only from wave-function renormalization in simplest models with partial compositeness

Sum Rule for h→γγ,gg

relies on:

Low Energy Theorem

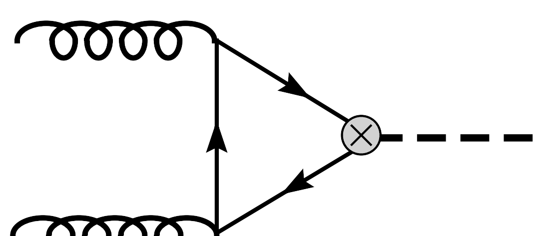
$$A(gg \to h) \propto \frac{\partial}{\partial h} \log \det \left[\mathcal{M}^\dagger(h)\mathcal{M}(h)\right]\Big|_{h=v}$$

Partial compositeness

$$\det \left[\mathcal{M}^\dagger(h)\mathcal{M}(h)\right] \propto \lambda_L(h)\lambda_R(h)$$

$A_{SM} \times c_t$

$\delta A = \frac{g_s^2}{16\pi^2} \times O\left(\frac{\lambda^2 v^2}{m_*^2}\right)$



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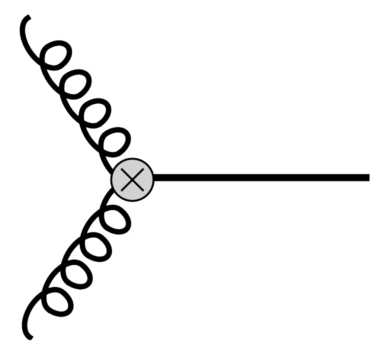

$= \quad A_{SM} \times F(\xi)$

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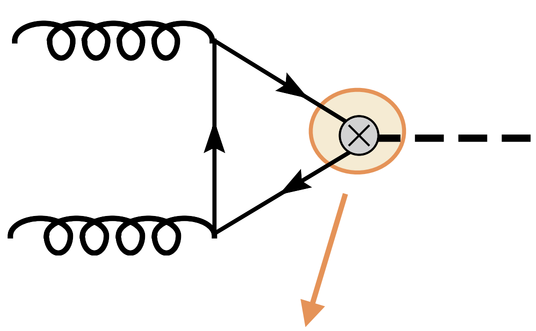

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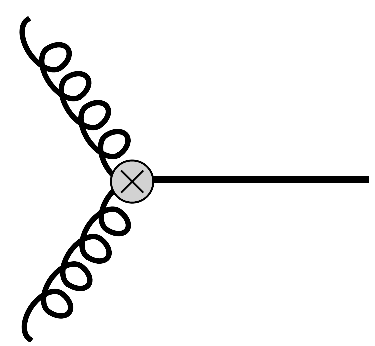


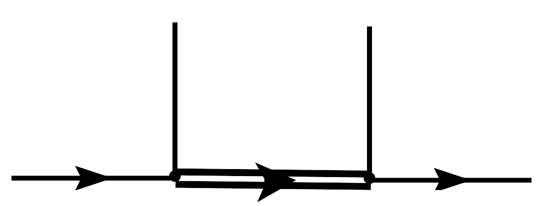
$$= \quad A_{SM} \times F(\xi)$$

$$c_t = F(\xi) + O\left(\frac{\lambda^2 v^2}{M^2}\right)$$

from Higgs nlσm

from correction to wave-functions

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



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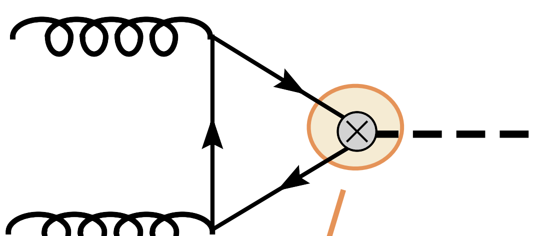

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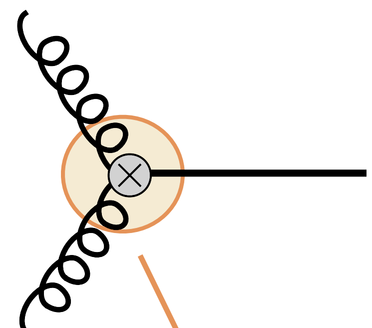

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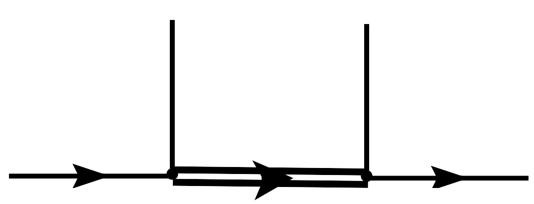
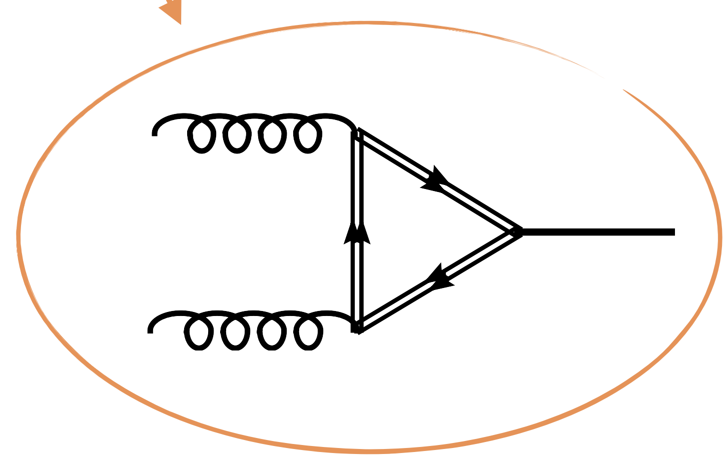




Only exception is: $h \to Z\gamma$

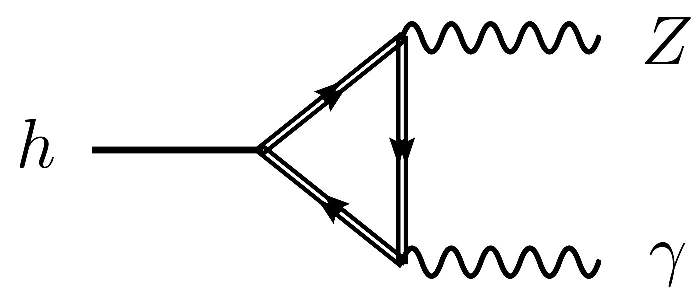
[Azatov, RC , Di Iura, Galloway, work in progress]

$$\frac{\delta c_{Z\gamma}}{c_{Z\gamma}^{SM}} \sim \frac{v^2}{f^2} + \frac{g_*^2 v^2}{m_*^2}$$

Relevant operator is $O_{HW} - O_{HB}$

$$O_{HB} = (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$O_{HW} = (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$



1. Invariant under Higgs shift symmetry
2. Odd under LR exchange

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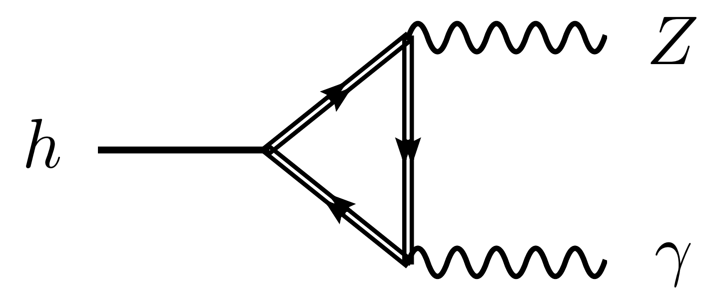

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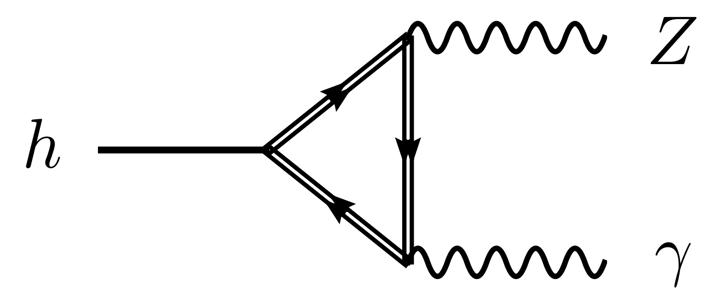

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2. Odd under LR exchange → Strong dynamics MUST break LR

$$A(h \to Z\gamma) = A_{SM} \times F(\xi) + \delta A$$

$$\frac{\delta A}{A_{SM}} \sim N_c N_F \left(\frac{g_*^2 v^2}{m_*^2} \right) \sim N_c N_F \frac{v^2}{f^2} \frac{\Delta m_*^2}{m_*^2}$$

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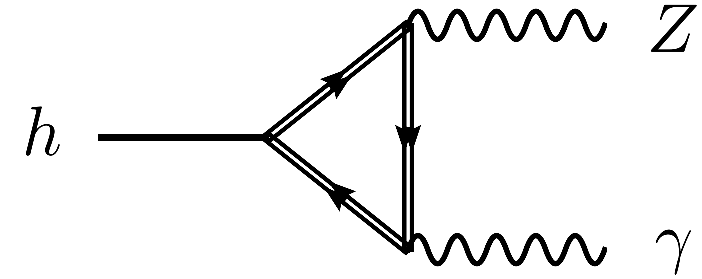

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shift of tree-level Higgs couplings from nlσm $\quad 1 + O\left(\frac{v^2}{f^2}\right)$

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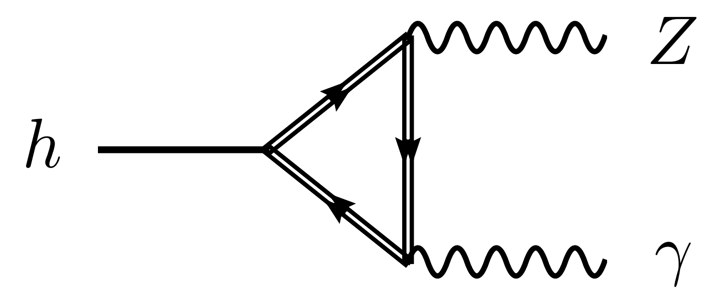
[Azatov, RC , Di Iura, Galloway, work in progress]

$$\frac{\delta c_{Z\gamma}}{c^{SM}_{Z\gamma}} \sim \frac{v^2}{f^2} + \frac{g_*^2 v^2}{m_*^2}$$

Relevant operator is $O_{HW} - O_{HB}$

$$O_{HB} = (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$O_{HW} = (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$



1. Invariant under Higgs shift symmetry
2. Odd under LR exchange → **Strong dynamics MUST break LR**

$$A(h \to Z\gamma) = A_{SM} \times F(\xi) + \delta A$$

$F(\xi)$: shift of tree-level Higgs couplings from nlσm $\quad 1 + O\left(\frac{v^2}{f^2}\right)$

$$\frac{\delta A}{A_{SM}} \sim N_c N_F \left(\frac{g_*^2 v^2}{m_*^2}\right) \sim N_c N_F \, \frac{v^2}{f^2} \, \frac{\Delta m_*^2}{m_*^2}$$

$N_c N_F$: multiplicity of composite states

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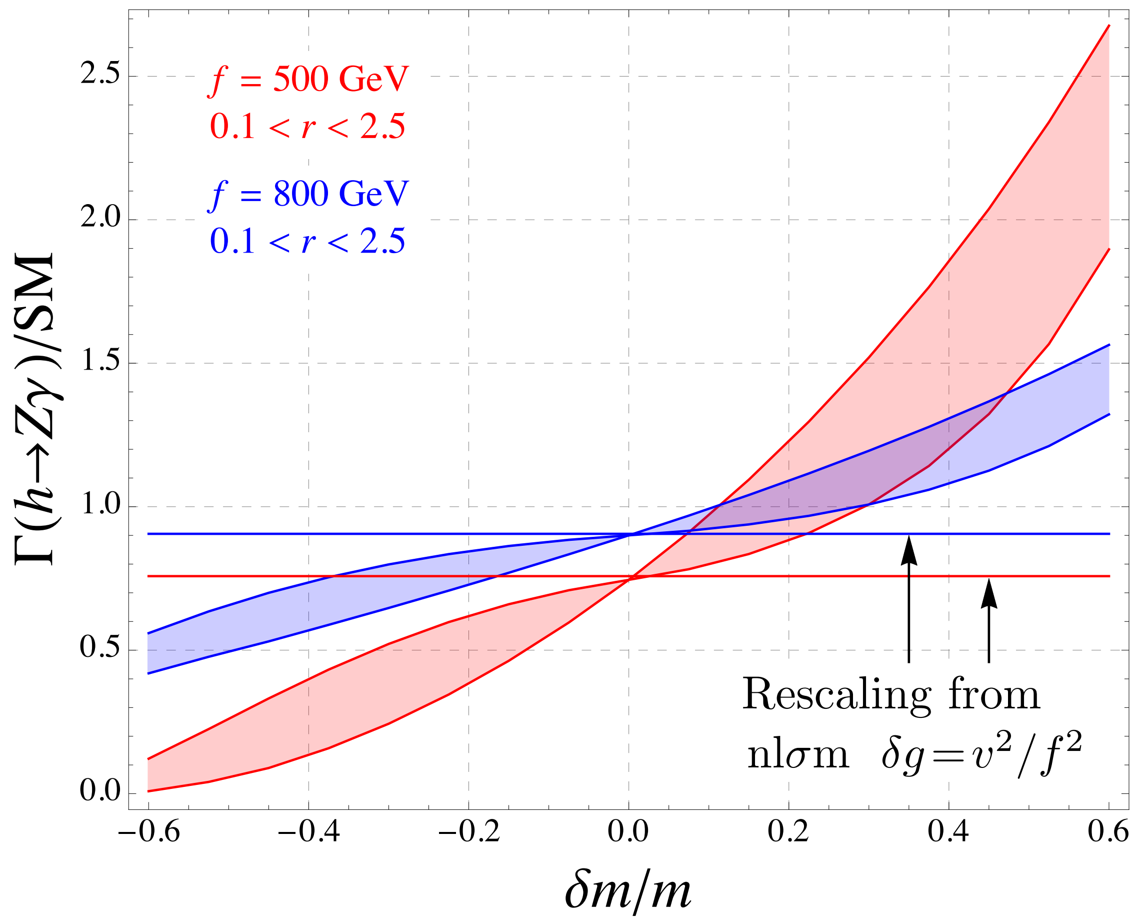

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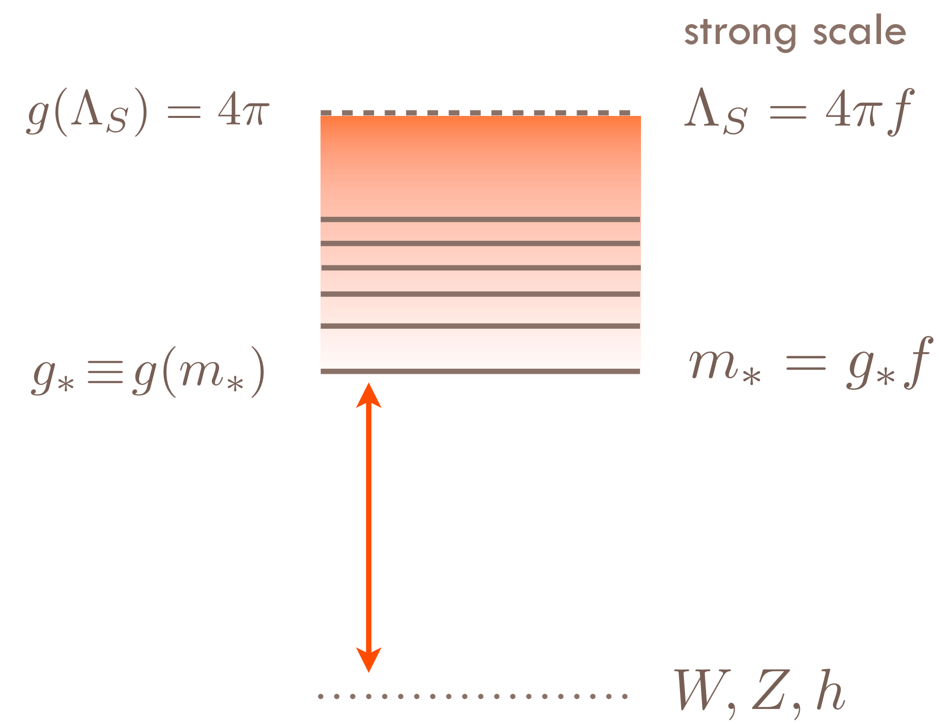
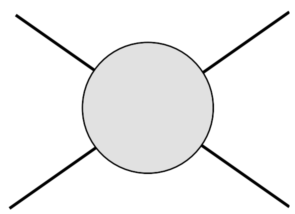
$N_c N_F$ → multiplicity of composite states

Tails in scattering amplitudes

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





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

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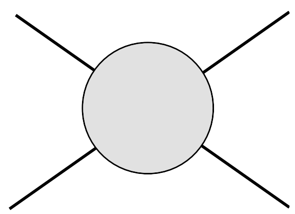

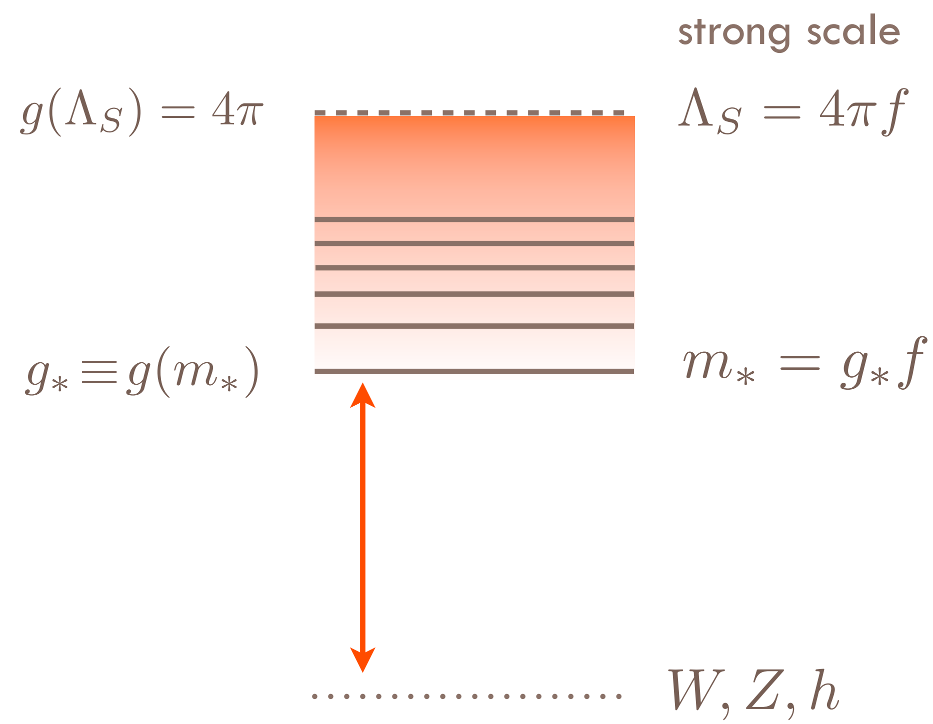

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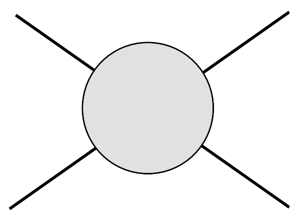

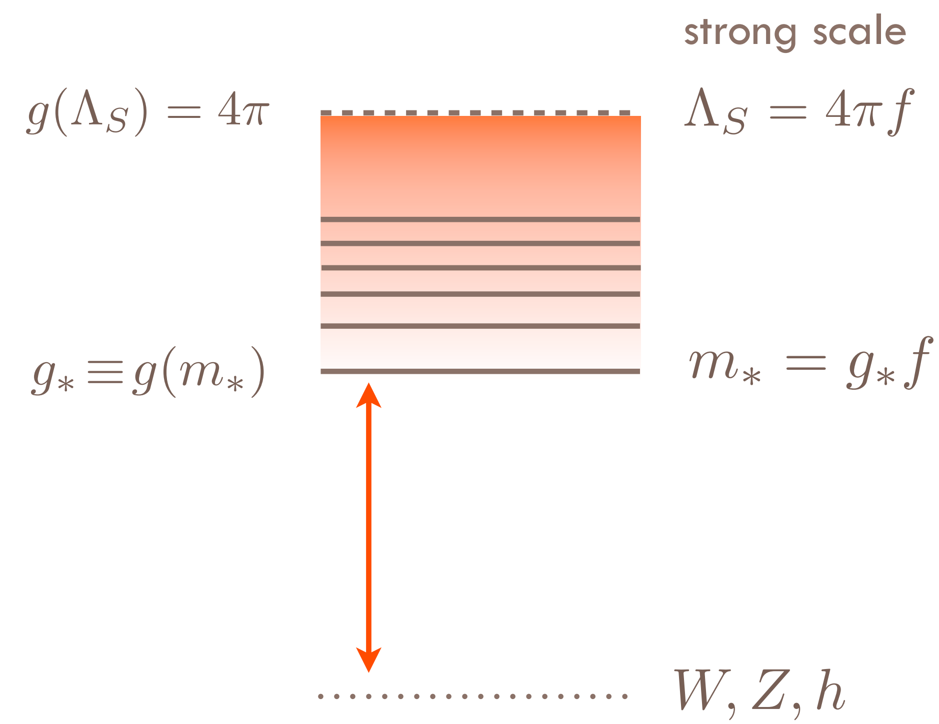

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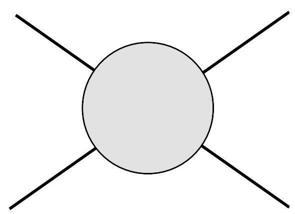
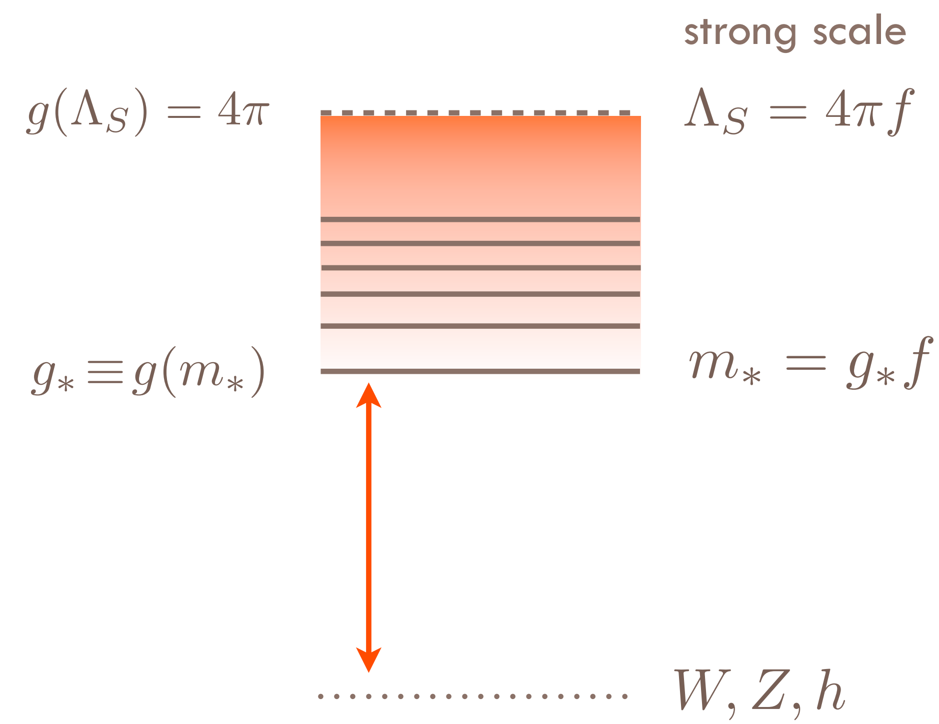
Suppose we find:

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

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

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





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

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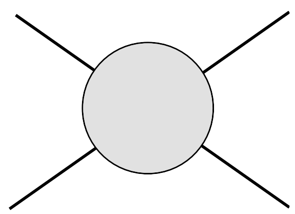

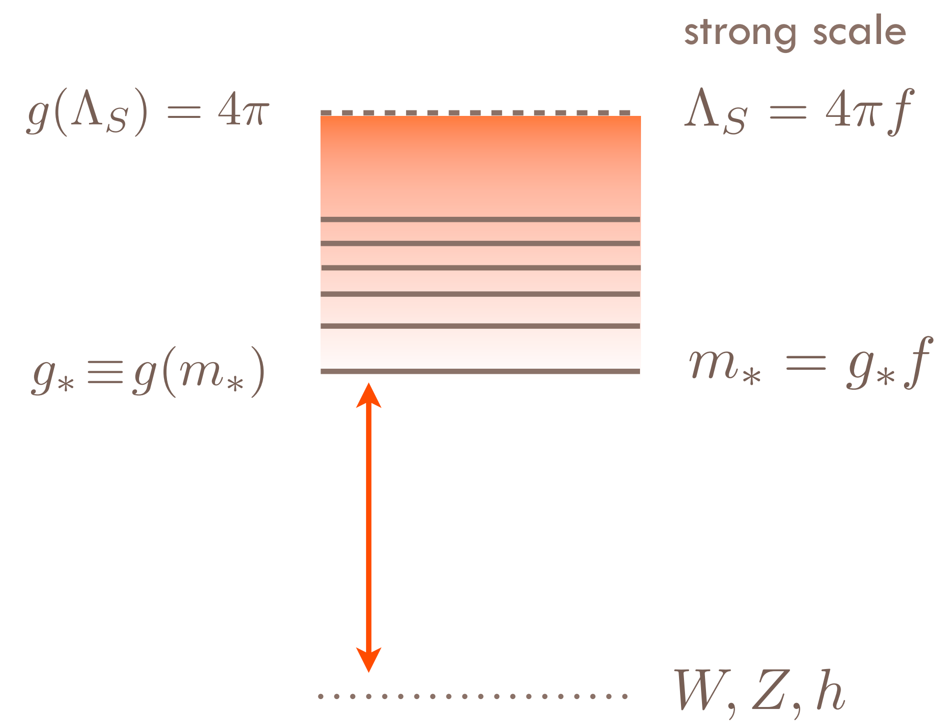

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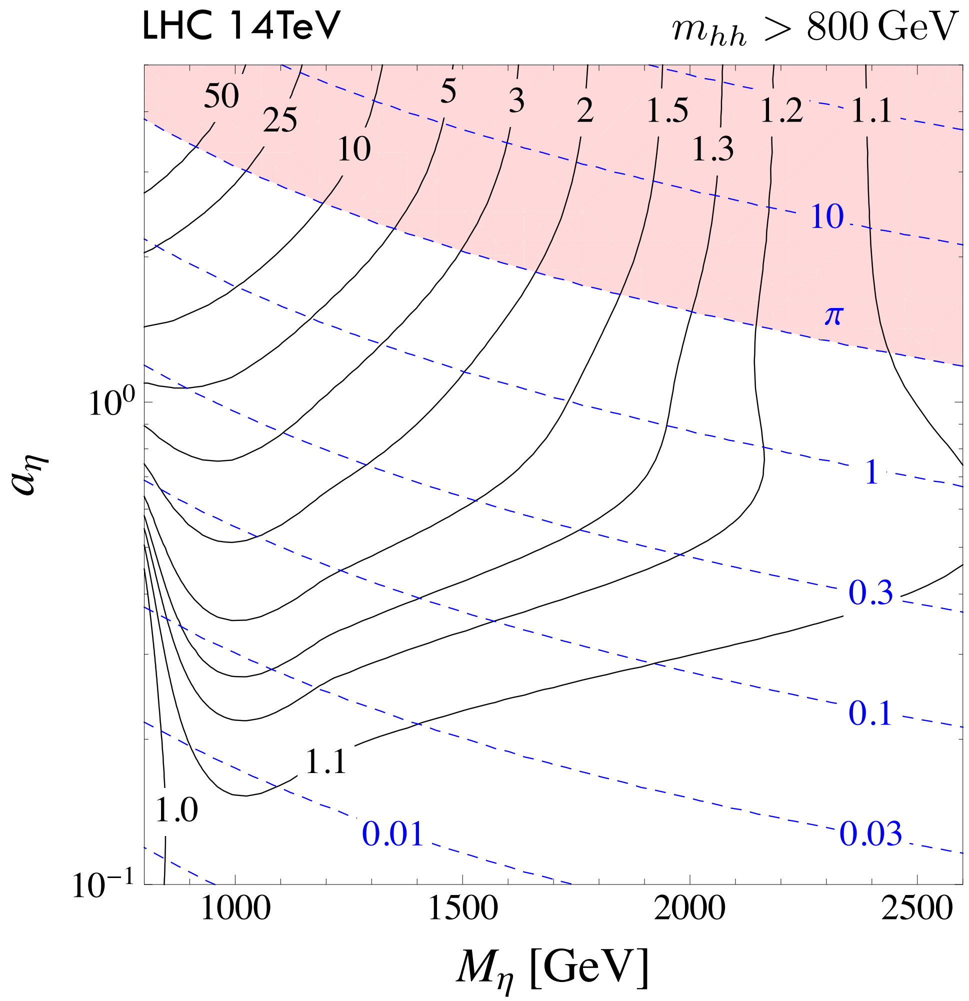
$$g_* > g(E) = \sqrt{\delta_{hh}^{exp}} \frac{E}{v}$$

then we get the stronger limit

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



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

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

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

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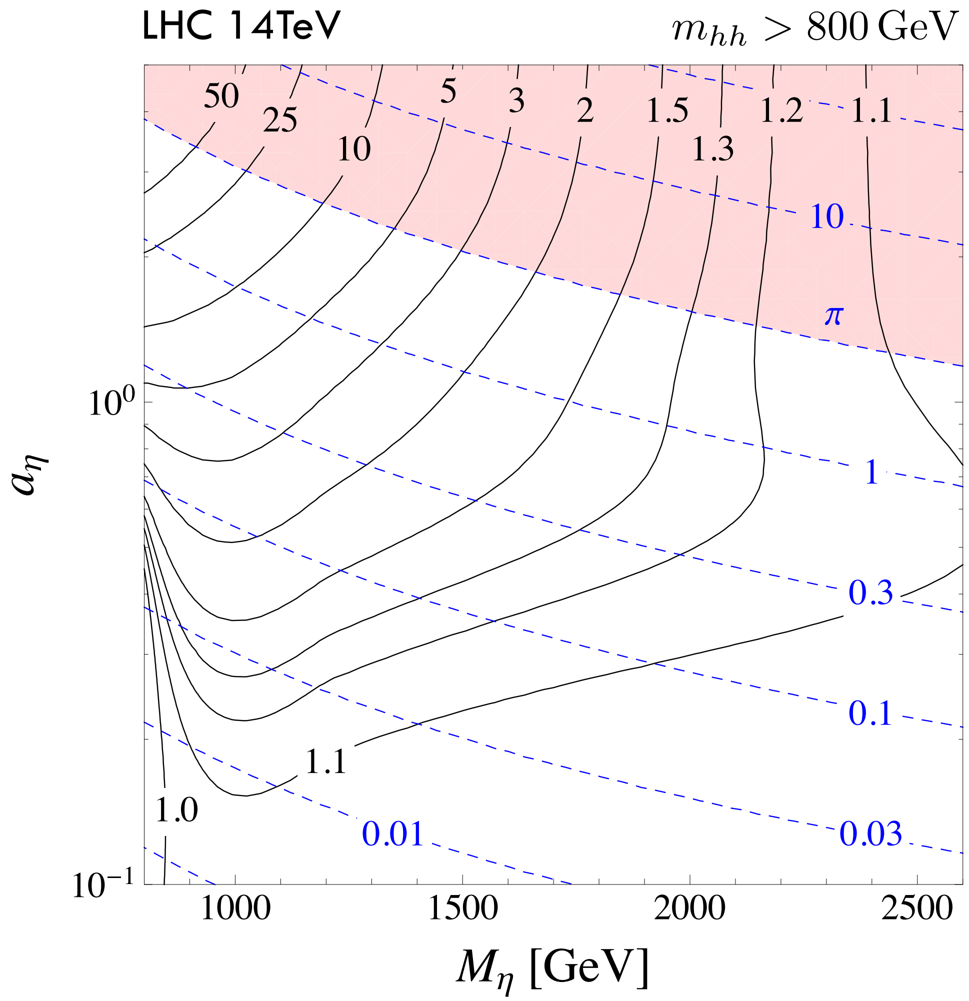
measurement of resonance effects
gives direct access to strong dynamics



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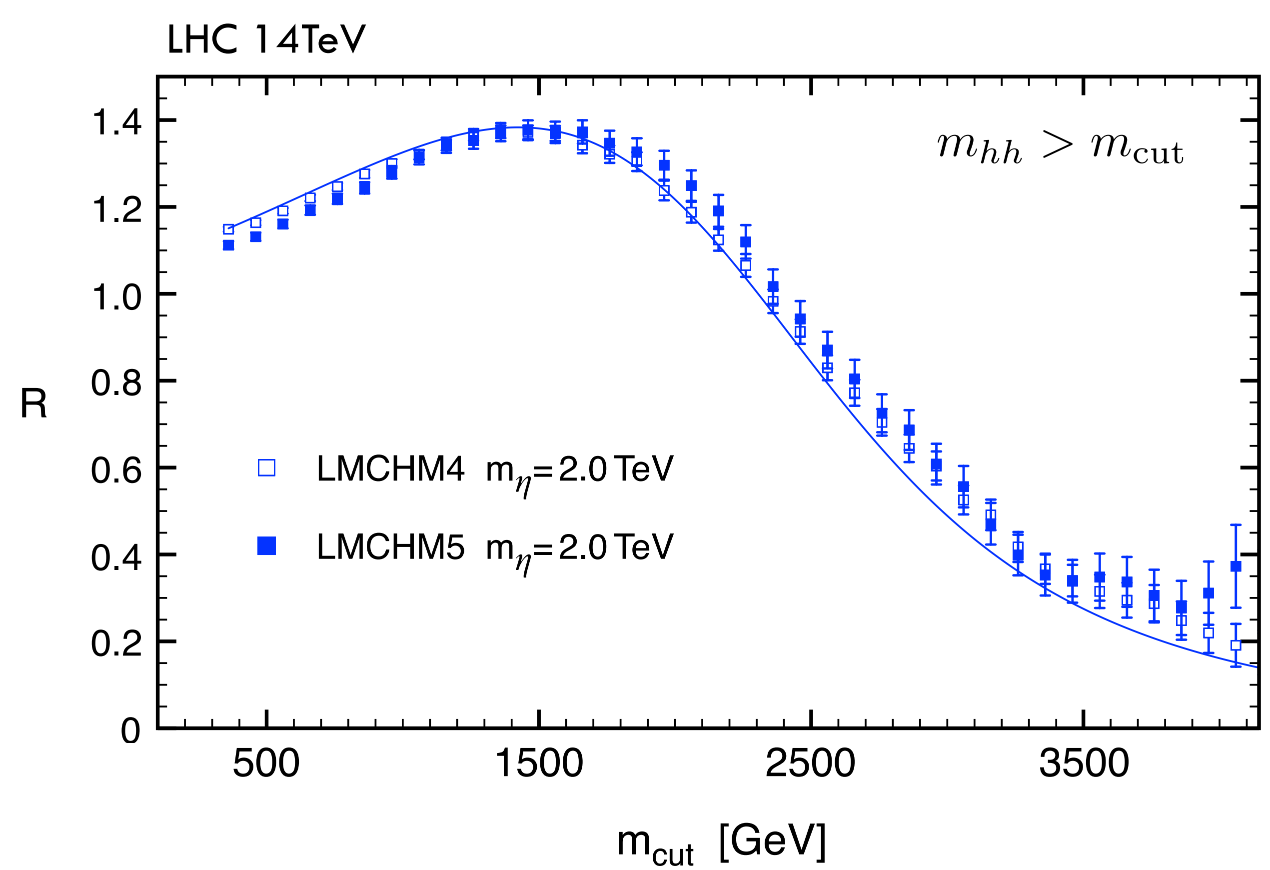
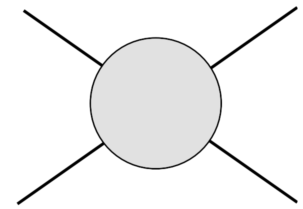
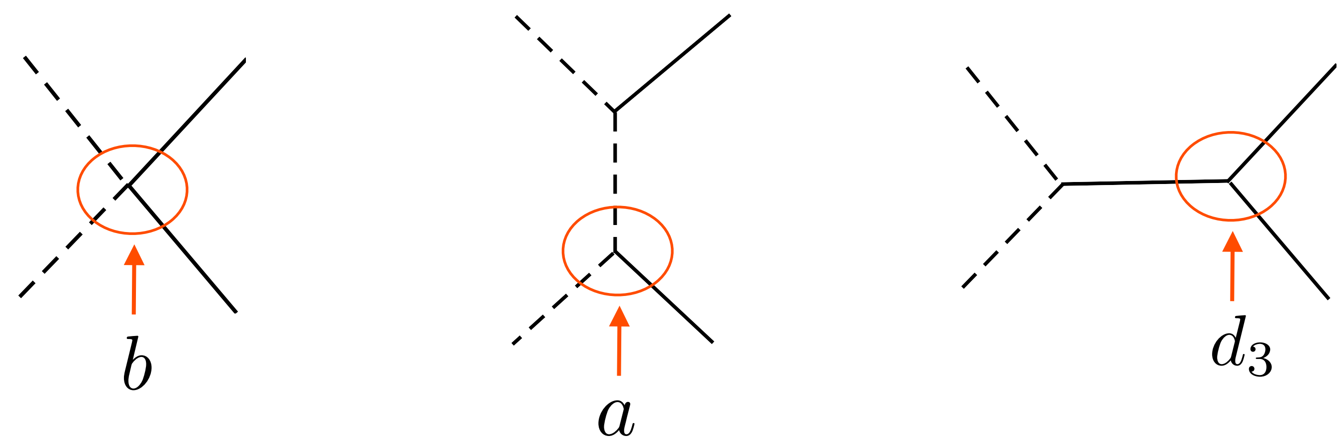


A high-energy e$^+$e$^-$ collider (such as CLIC 3TeV) can provide a clean environment to make precision studies of scattering amplitudes



[RC , Grojean, Pappadopulo, Rattazzi, Thamm, to appear]

Example: $WW \to hh$



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

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

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

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

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

Ex: SO(5)/SO(4)

In PNGB Higgs theories the whole series in H/f can be resummed:

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

$$b = 1 - 2\xi$$

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

At dimension-6 level:

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

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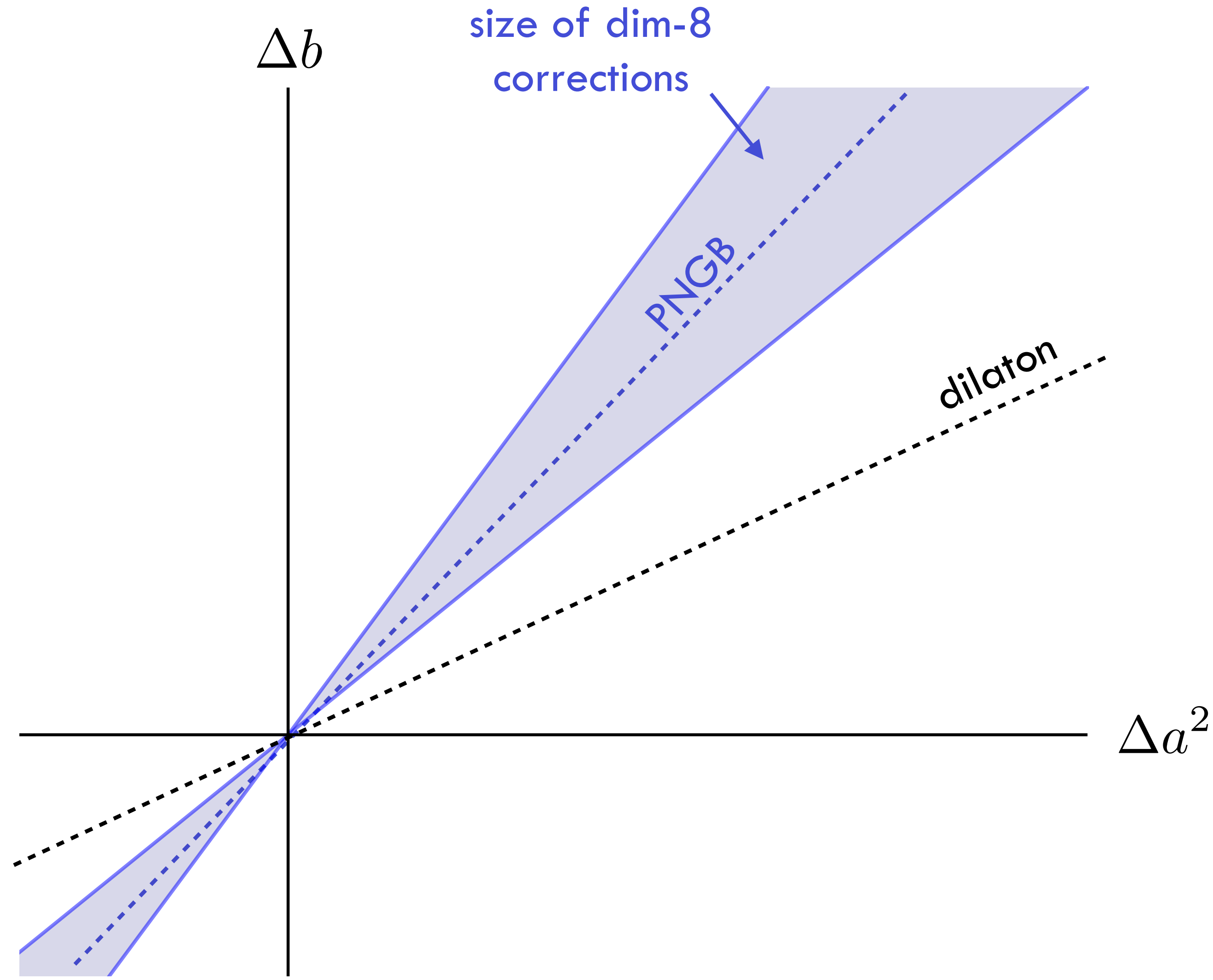
Scenario 1:

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

$\text{Exp. precision} \sim 1\%$ → Test dim-8 operators



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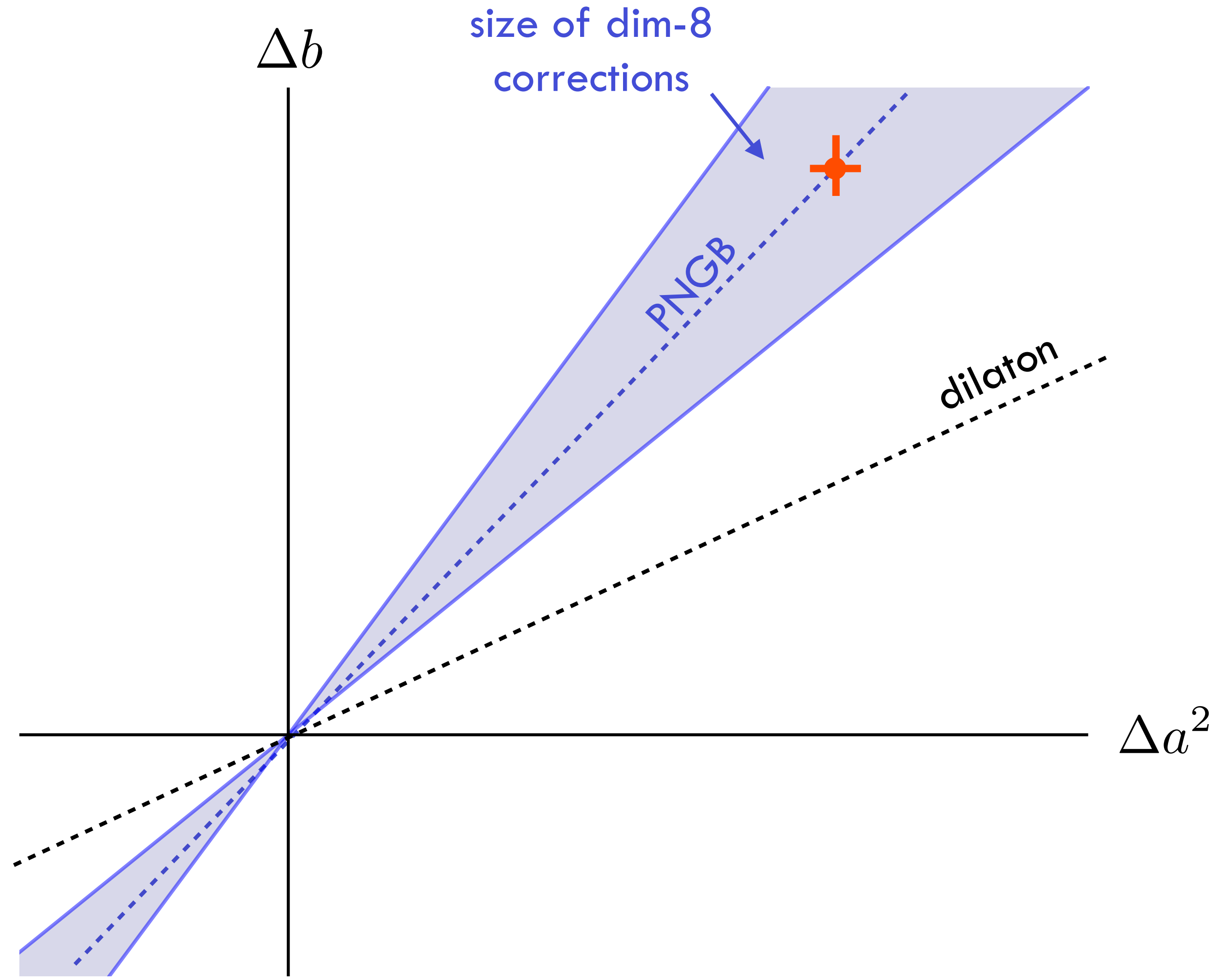

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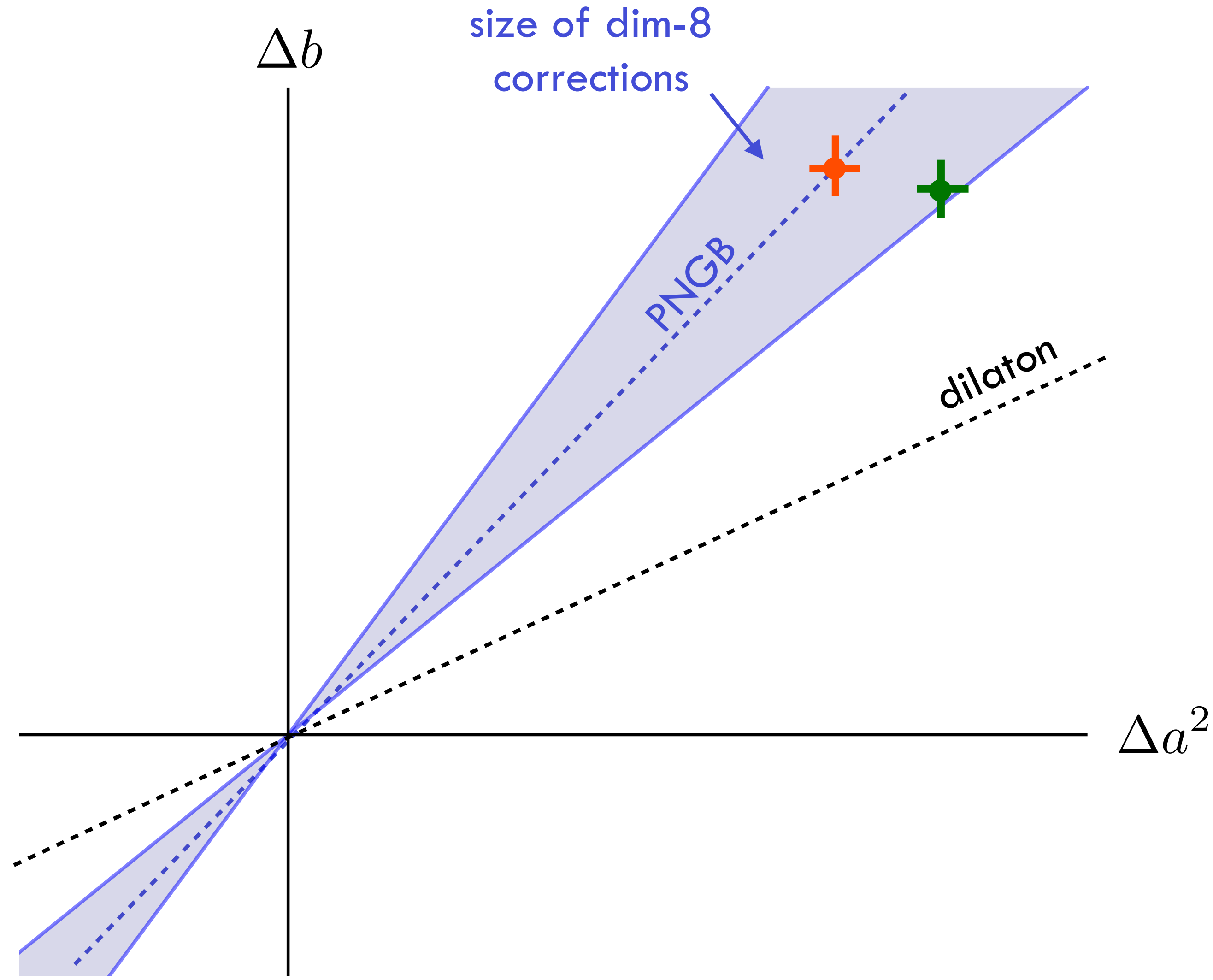

1. PNGB (and specific coset) proved
2. SILH proved, PNGB disproved

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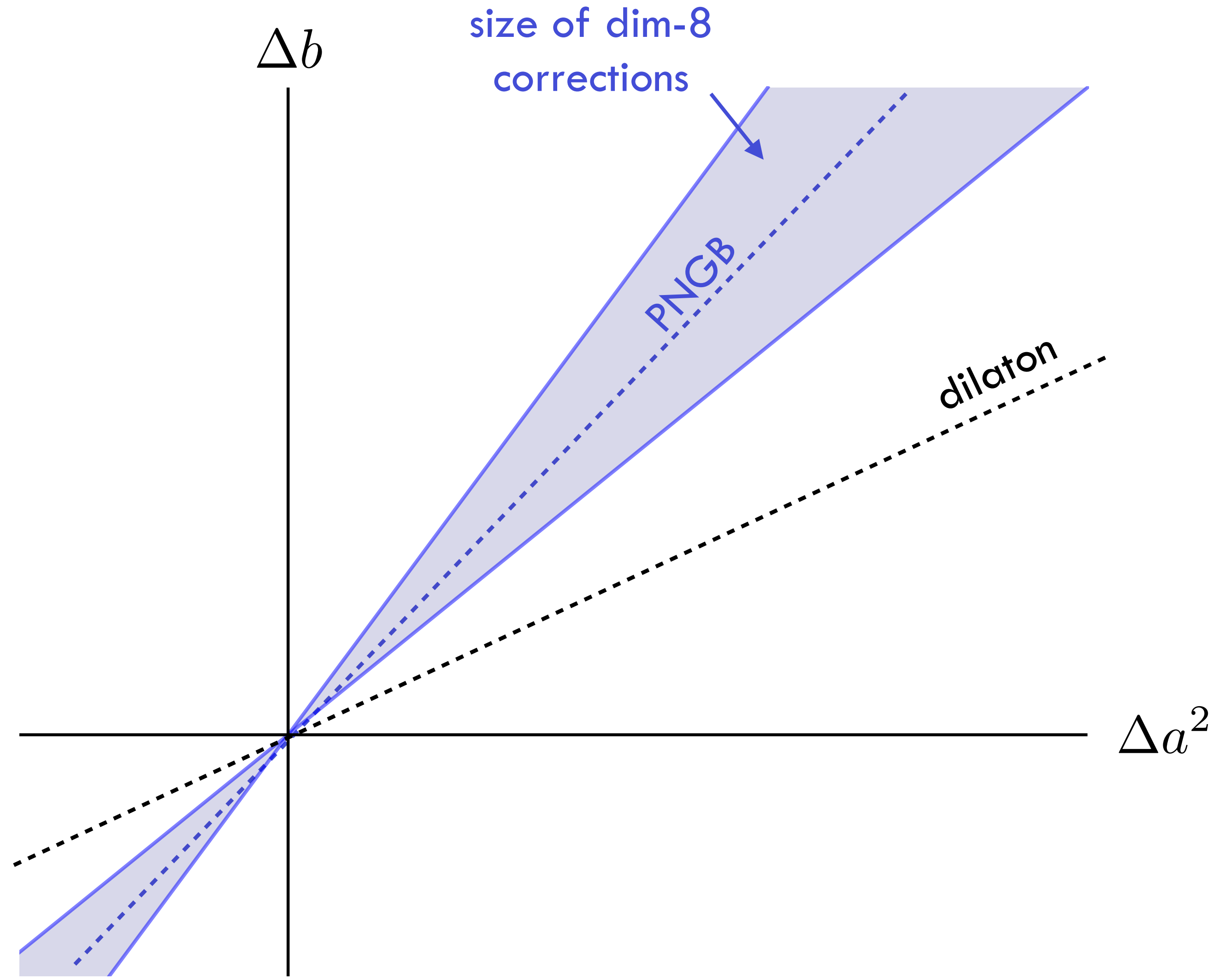
Scenario 2:

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

Exp. precision $\sim 1\%$



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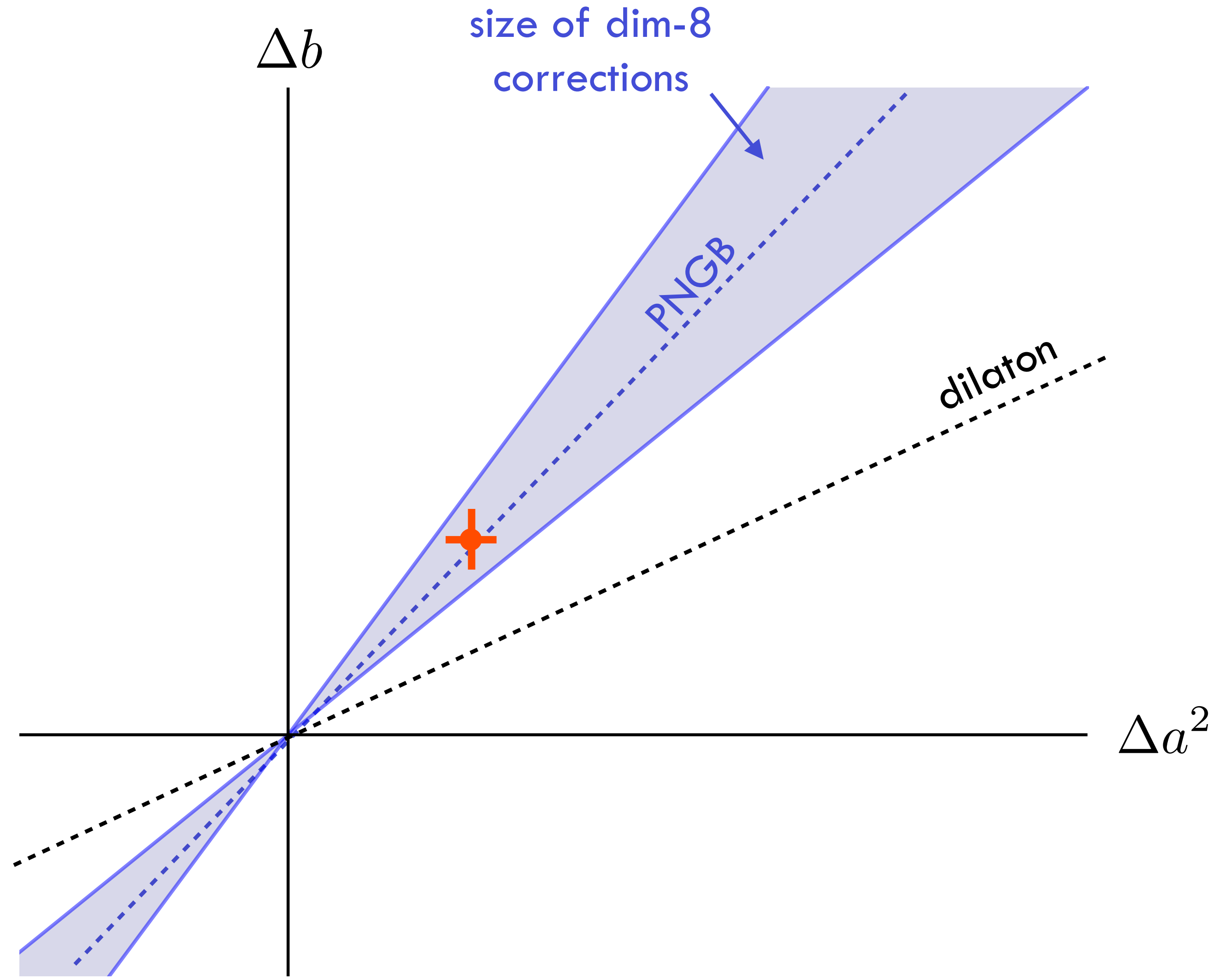

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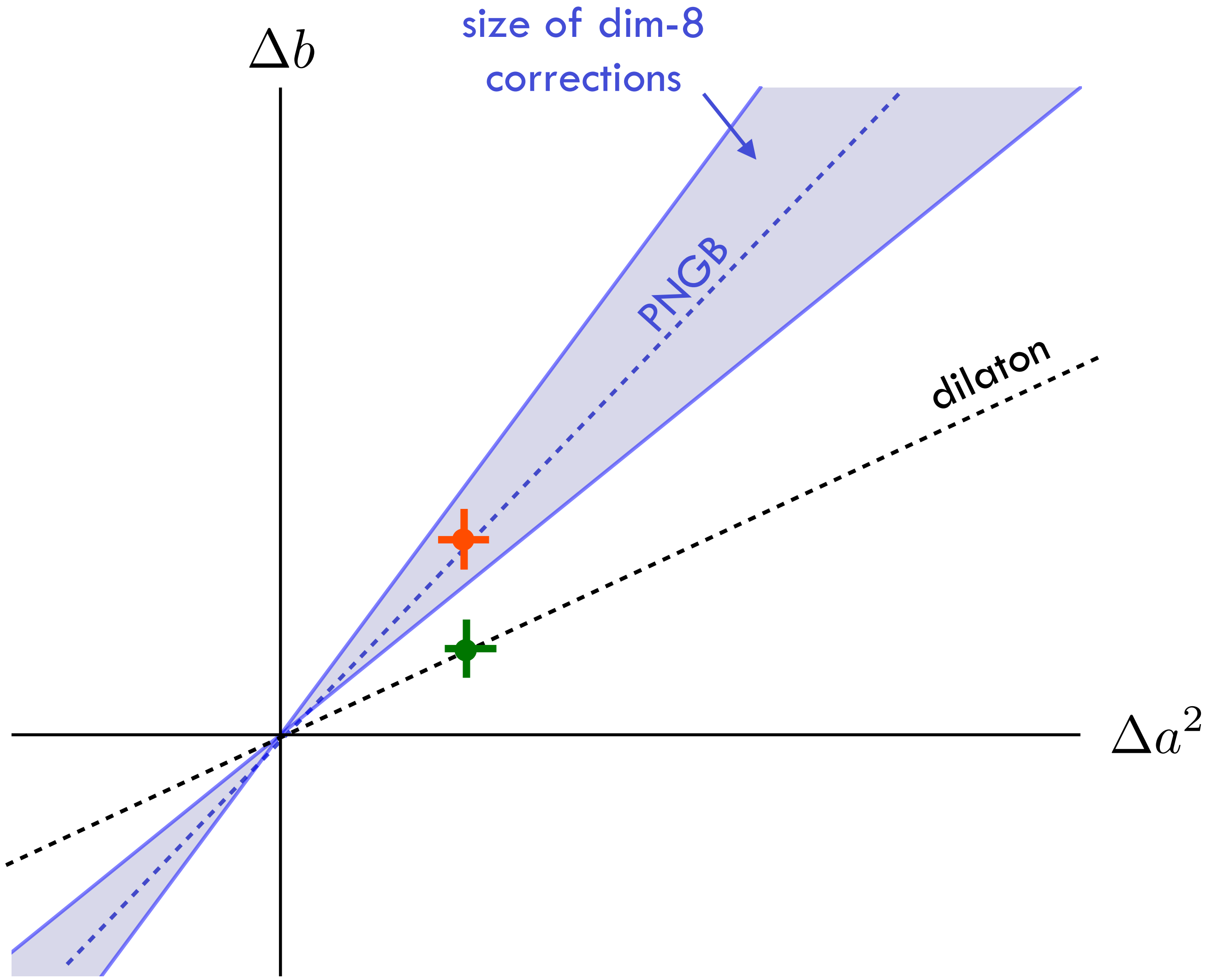
1. SILH proved

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



An e^+e^- collider with $\sqrt{s} = 3\,\mathrm{TeV}$ can reach a precision of a few % on the coupling b through the process $e^+e^- \to \nu\bar{\nu}\,hh \to \nu\bar{\nu}\,b\bar{b}b\bar{b}$

Barger et al. PRD 67 (2003) 115001

RC , Grojean, Pappadopulo, Rattazzi, Thamm, to appear

Expected precision on δ_b with $L = 1\,\mathrm{ab}^{-1}/a^4$

measured δ_b	$\bar{\delta}_{d_3}$ -0.5	-0.3	-0.1	0	0.1	0.3	0.5
$\bar{\delta}_b$ 0	$-0.01^{+0.03}_{-0.09}$	$0.01^{+0.03}_{-0.10}$	$0.01^{+0.03}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.0^{+0.03}_{-0.03}$	$0.0^{+0.02}_{-0.03}$
0.01	$0.01^{+0.03}_{-0.10}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.03}$	$0.01^{+0.03}_{-0.03}$	$0.01^{+0.02}_{-0.03}$
0.02	$0.02^{+0.03}_{-0.04}$	$0.03^{+0.03}_{-0.04}$	$0.03^{+0.04}_{-0.04}$	$0.03^{+0.05}_{-0.03}$	$0.02^{+0.05}_{-0.03}$	$0.02^{+0.02}_{-0.03}$	$0.02^{+0.02}_{-0.03}$
0.03	$0.03^{+0.02}_{-0.04}$	$0.04^{+0.03}_{-0.03}$	$0.04^{+0.04}_{-0.03}$	$0.04^{+0.05}_{-0.03}$	$0.03^{+0.06}_{-0.03}$	$0.03^{+0.08}_{-0.03}$	$0.03^{+0.02}_{-0.03}$
0.05	$0.05^{+0.02}_{-0.03}$	$0.06^{+0.03}_{-0.03}$	$0.07^{+0.05}_{-0.03}$	$0.06^{+0.06}_{-0.03}$	$0.05^{+0.03}_{-0.03}$	$0.05^{+0.09}_{-0.02}$	$0.05^{+0.10}_{-0.02}$
0.1	$0.11^{+0.02}_{-0.03}$	$0.13^{+0.03}_{-0.04}$	$0.11^{+0.07}_{-0.02}$	$0.1^{+0.03}_{-0.02}$	$0.1^{+0.06}_{-0.02}$	$0.1^{+0.02}_{-0.02}$	$0.1^{+0.02}_{-0.02}$
0.3	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$
0.5	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$

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

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0.01	$0.01^{+0.03}_{-0.10}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.03}$	$0.01^{+0.03}_{-0.03}$	$0.01^{+0.02}_{-0.03}$
0.02	$0.02^{+0.03}_{-0.04}$	$0.03^{+0.03}_{-0.04}$	$0.03^{+0.04}_{-0.04}$	$0.03^{+0.05}_{-0.03}$	$0.02^{+0.05}_{-0.03}$	$0.02^{+0.02}_{-0.03}$	$0.02^{+0.02}_{-0.03}$
0.03	$0.03^{+0.02}_{-0.04}$	$0.04^{+0.03}_{-0.03}$	$0.04^{+0.04}_{-0.03}$	$0.04^{+0.05}_{-0.03}$	$0.03^{+0.06}_{-0.03}$	$0.03^{+0.08}_{-0.03}$	$0.03^{+0.02}_{-0.03}$
0.05	$0.05^{+0.02}_{-0.03}$	$0.06^{+0.03}_{-0.03}$	$0.07^{+0.05}_{-0.03}$	$0.06^{+0.06}_{-0.03}$	$0.05^{+0.03}_{-0.03}$	$0.05^{+0.09}_{-0.02}$	$0.05^{+0.10}_{-0.02}$
0.1	$0.11^{+0.02}_{-0.03}$	$0.13^{+0.03}_{-0.04}$	$0.11^{+0.07}_{-0.02}$	$0.1^{+0.03}_{-0.02}$	$0.1^{+0.06}_{-0.02}$	$0.1^{+0.02}_{-0.02}$	$0.1^{+0.02}_{-0.02}$
0.3	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$	$0.3^{+0.02}_{-0.02}$
0.5	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$

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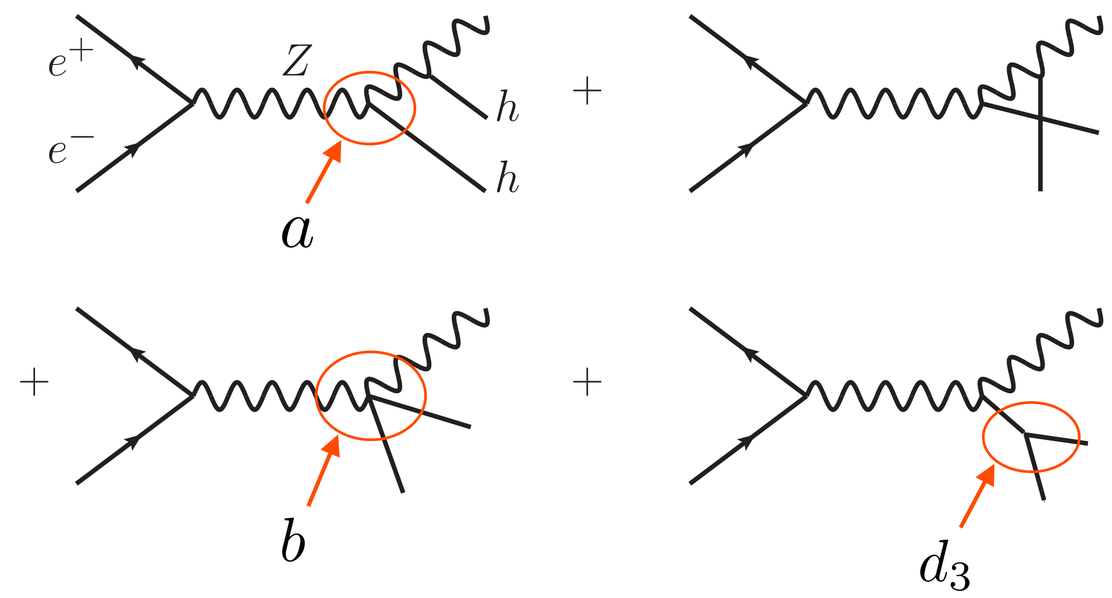
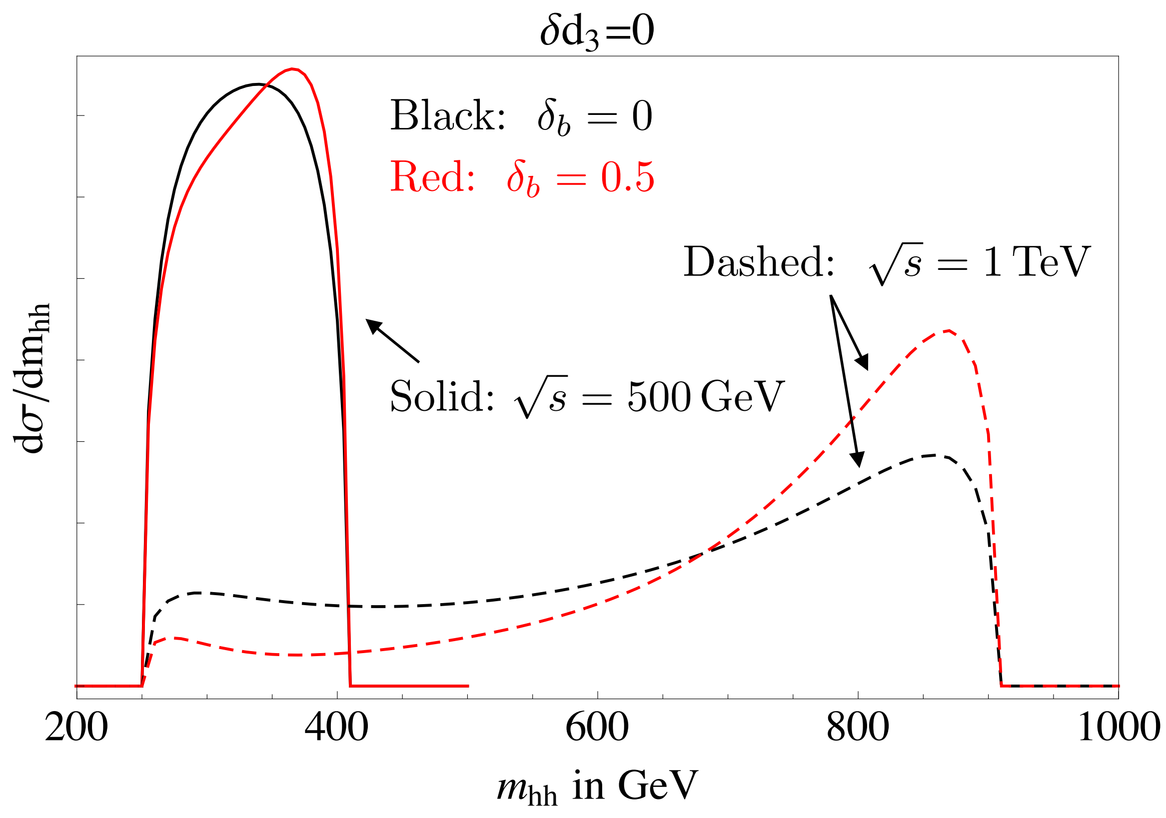
An e^+e^- collider with $\sqrt{s} = 500\,\mathrm{GeV} - 1\,\mathrm{TeV}$ can reach a precision of ~20% on b through the double Higgsstrahlung process

RC , Grojean, Pappadopulo, Rattazzi, Thamm, to appear





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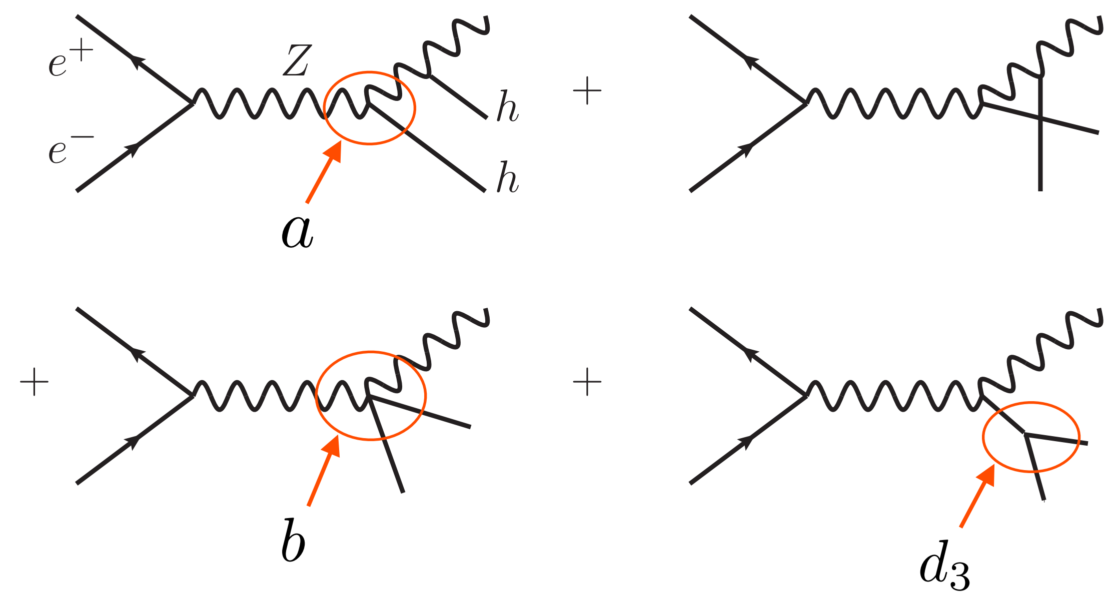
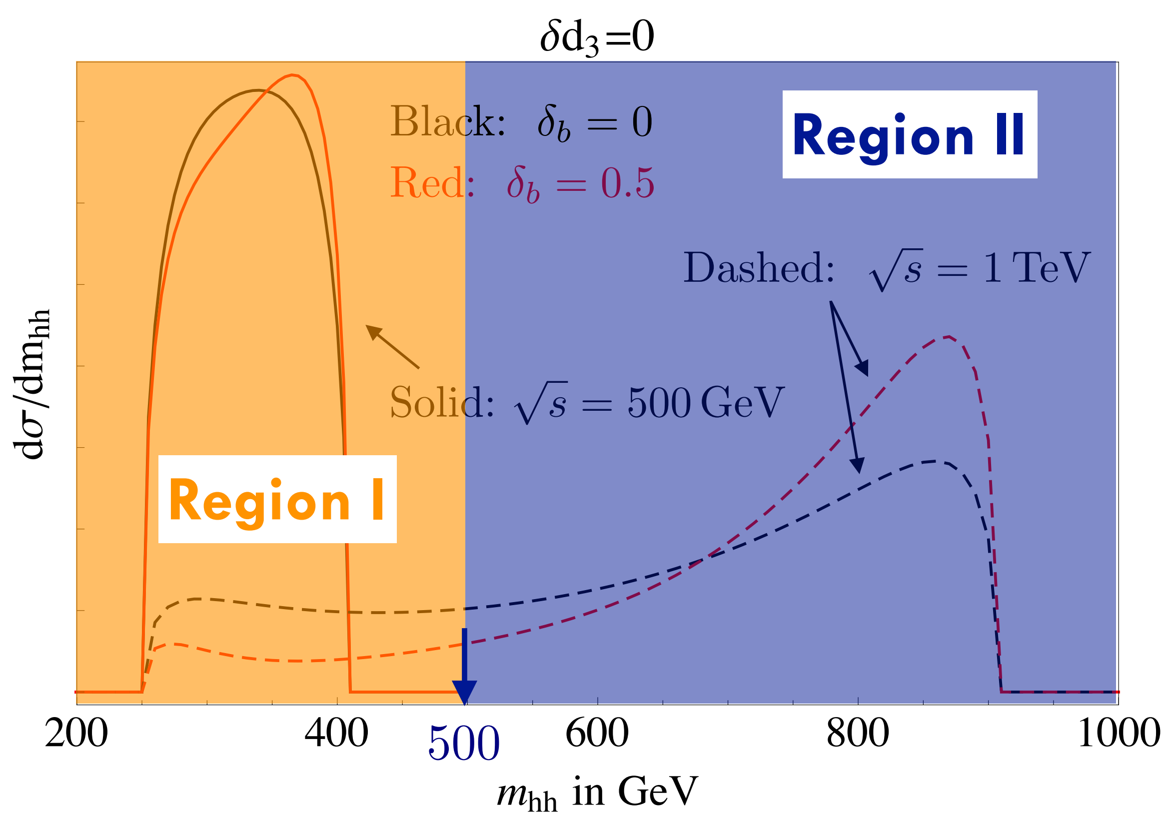
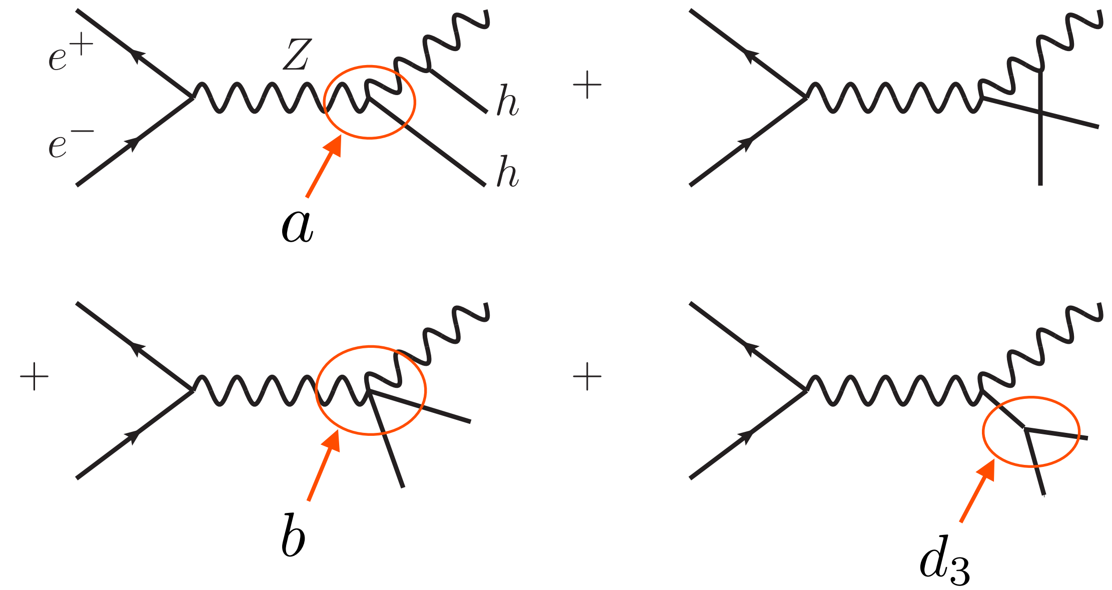


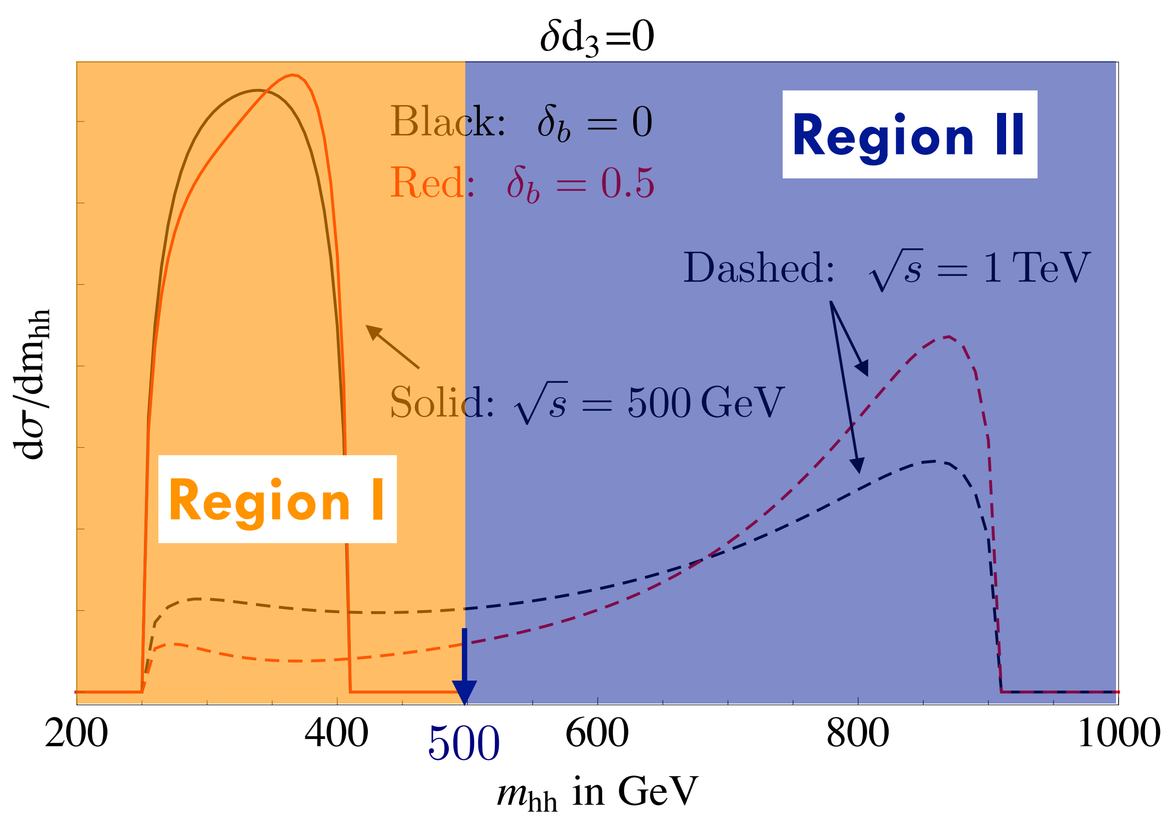


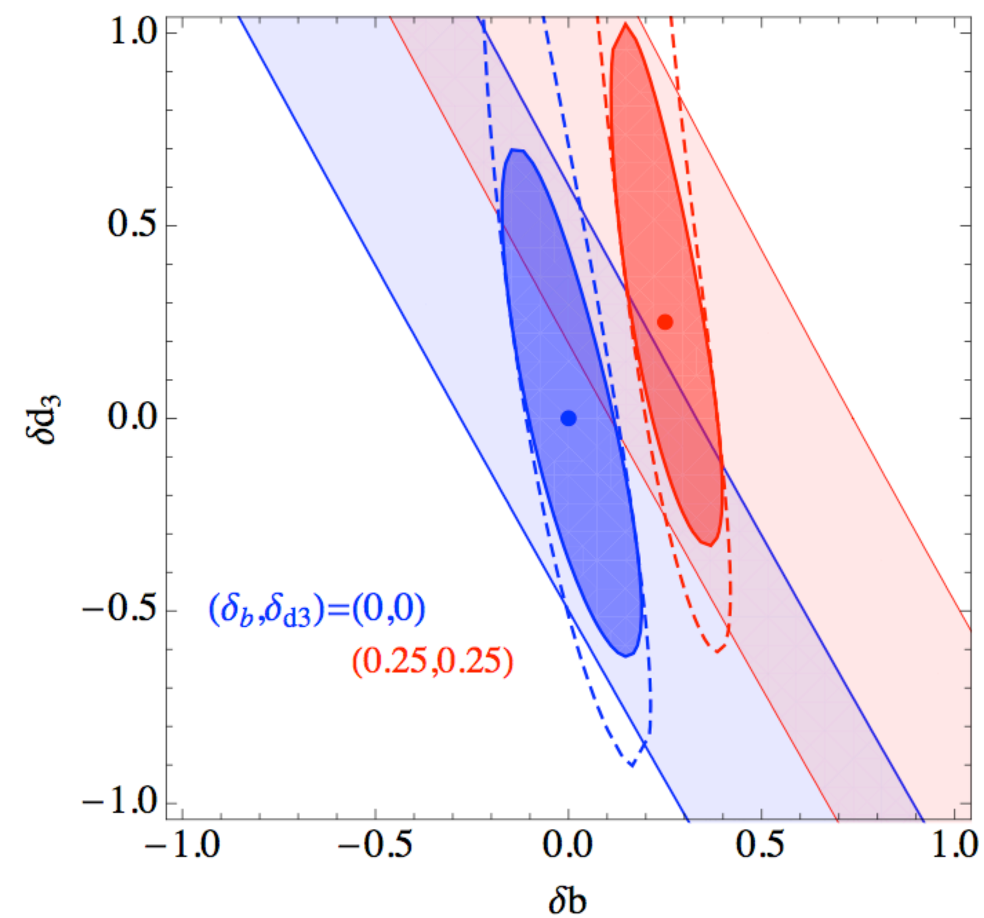
Cut on m_{hh} useful at $\sqrt{s} = 1\,\mathrm{TeV}$

An e⁺e⁻ collider with $\sqrt{s} = 500\,\mathrm{GeV} - 1\,\mathrm{TeV}$ can reach a precision of ~20% on b through the double Higgsstrahlung process

RC , Grojean, Pappadopulo, Rattazzi, Thamm, to appear







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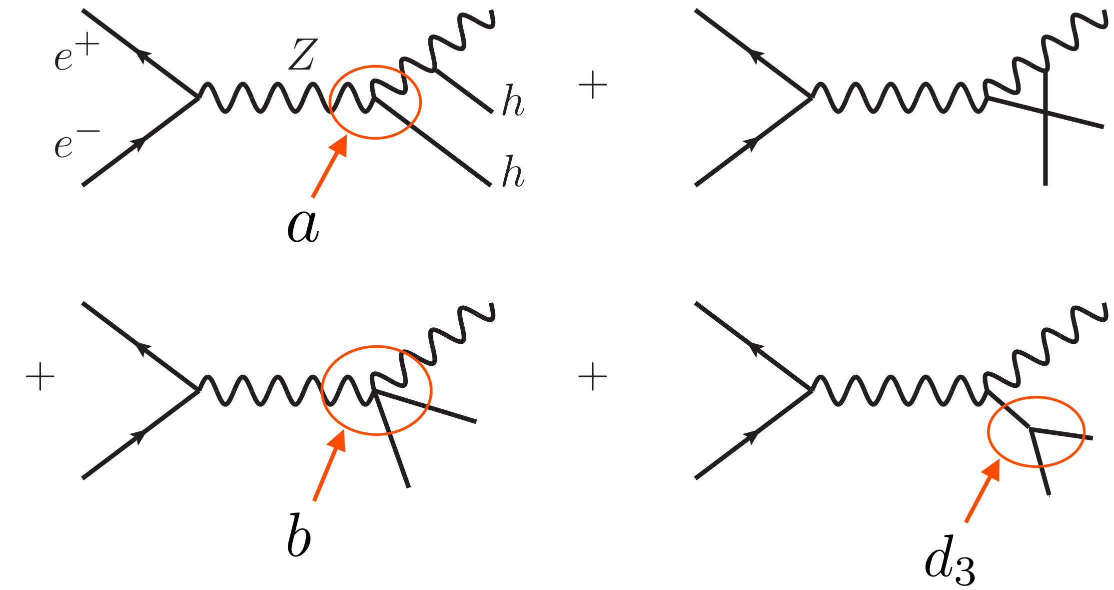

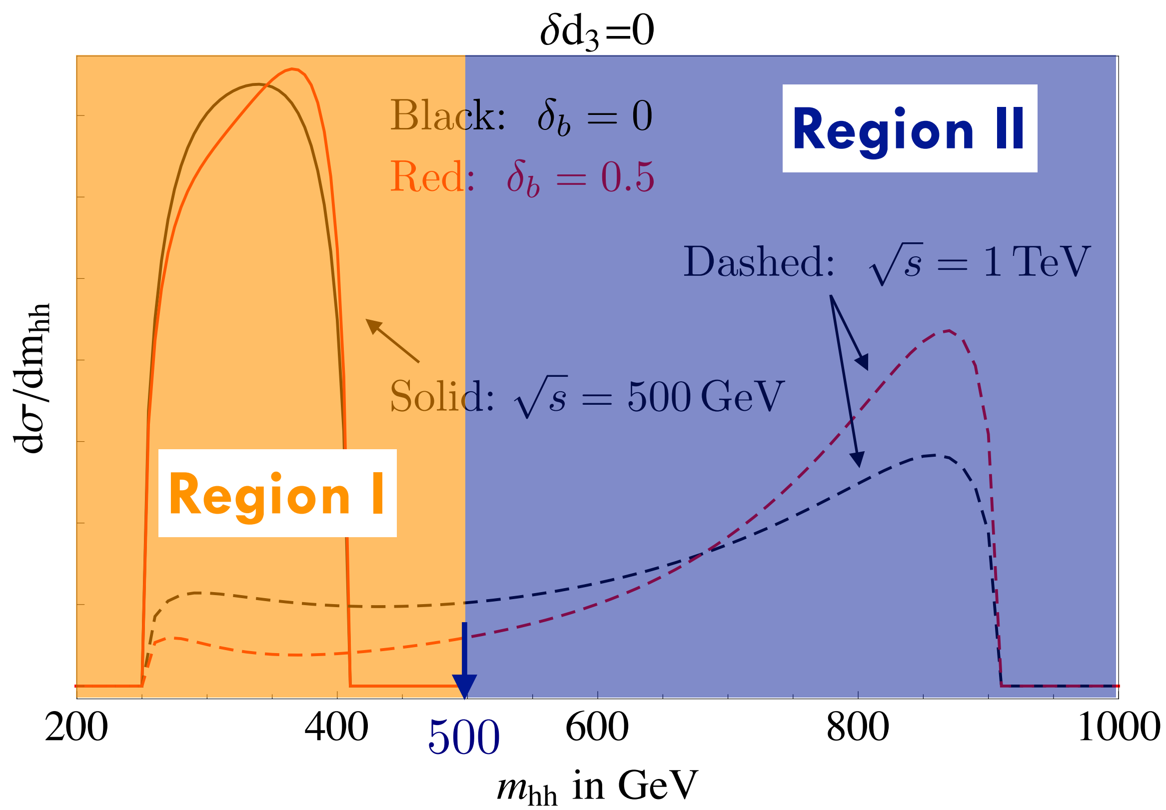

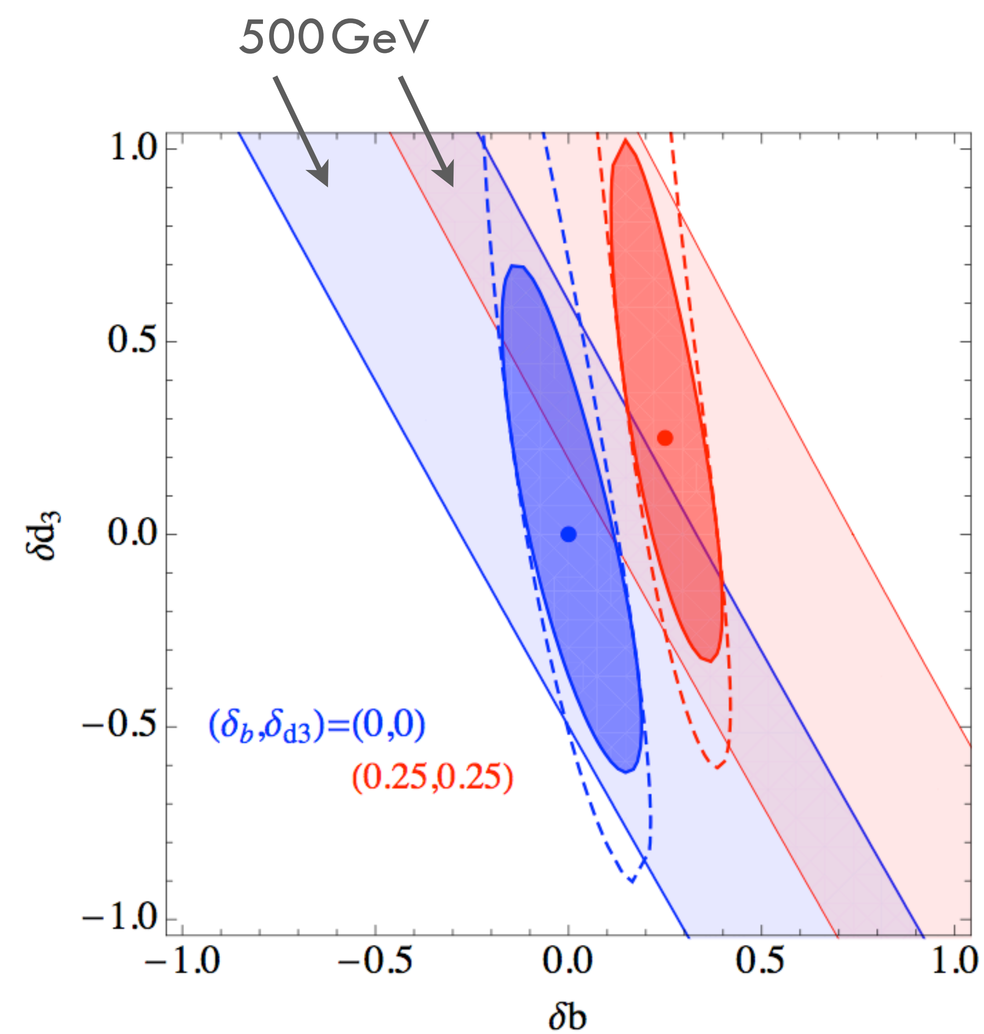

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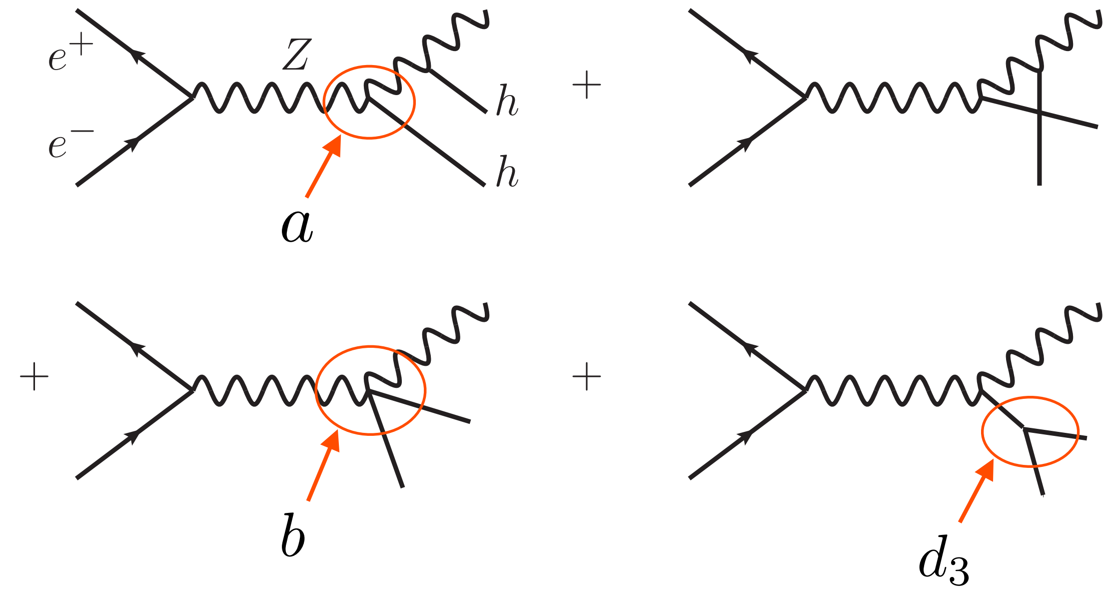

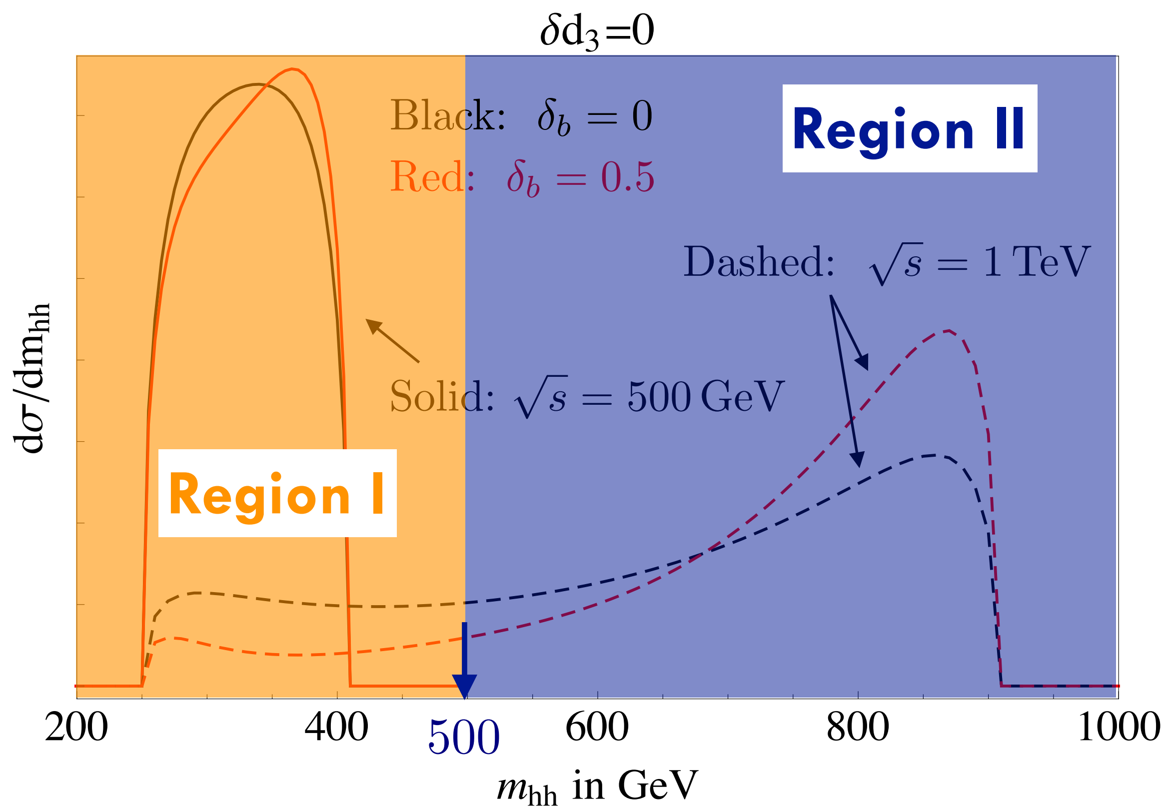

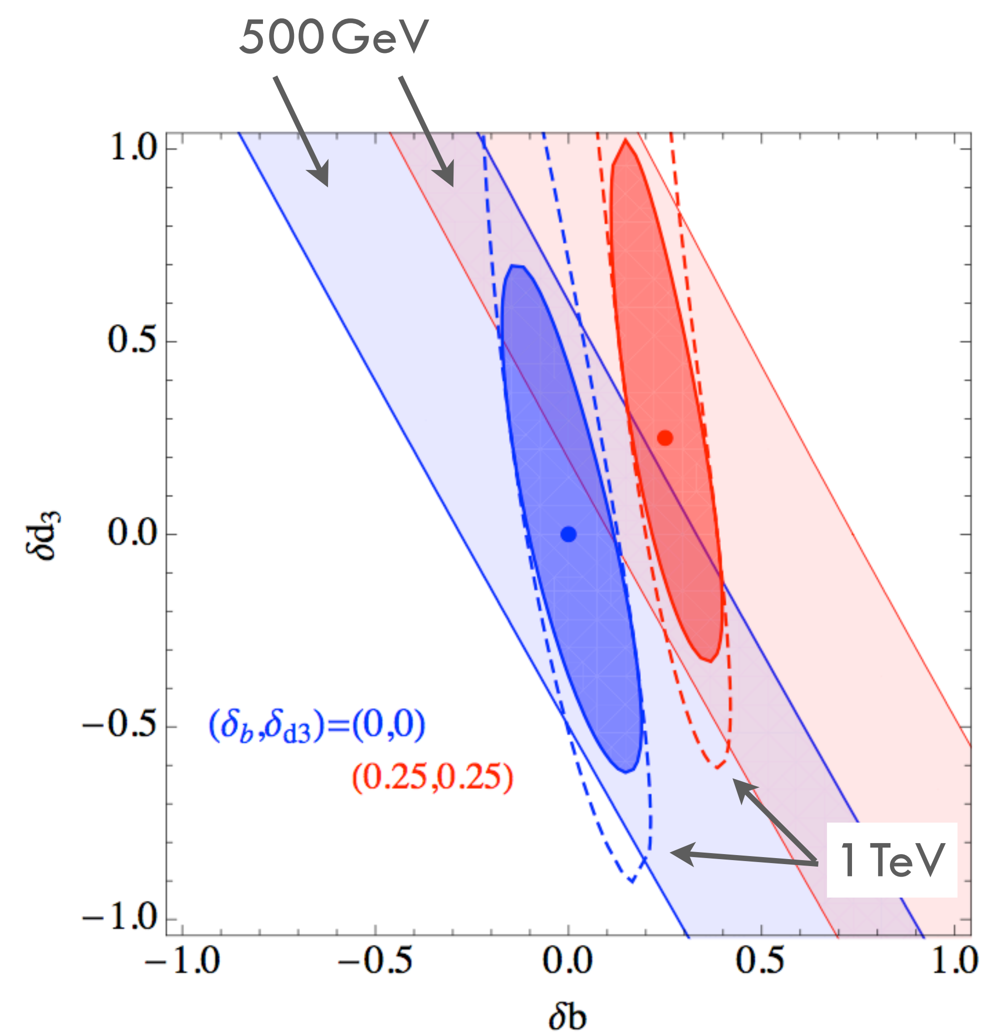

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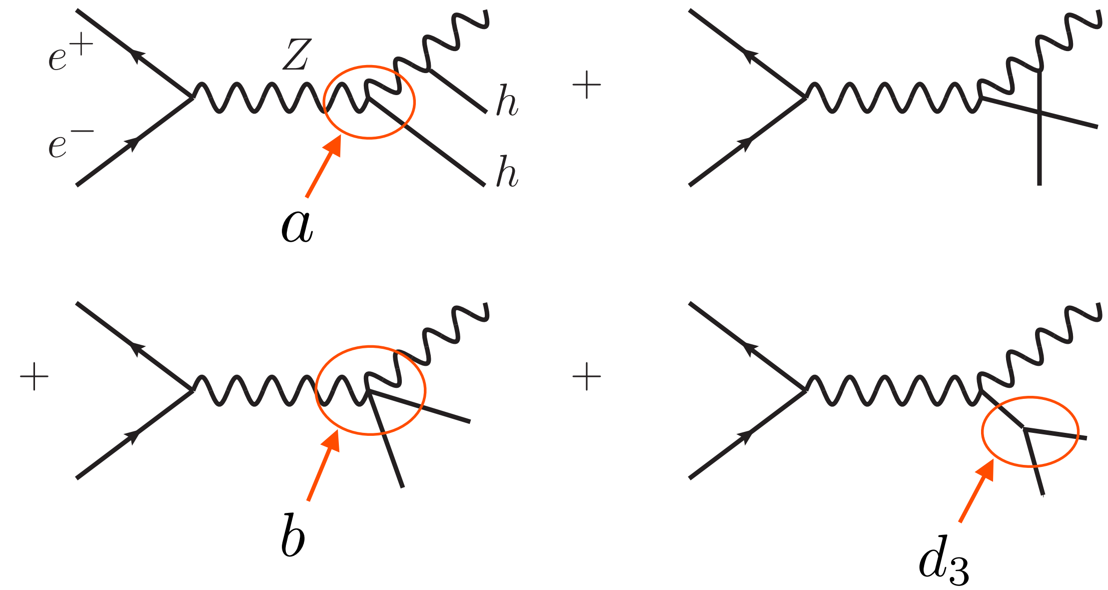

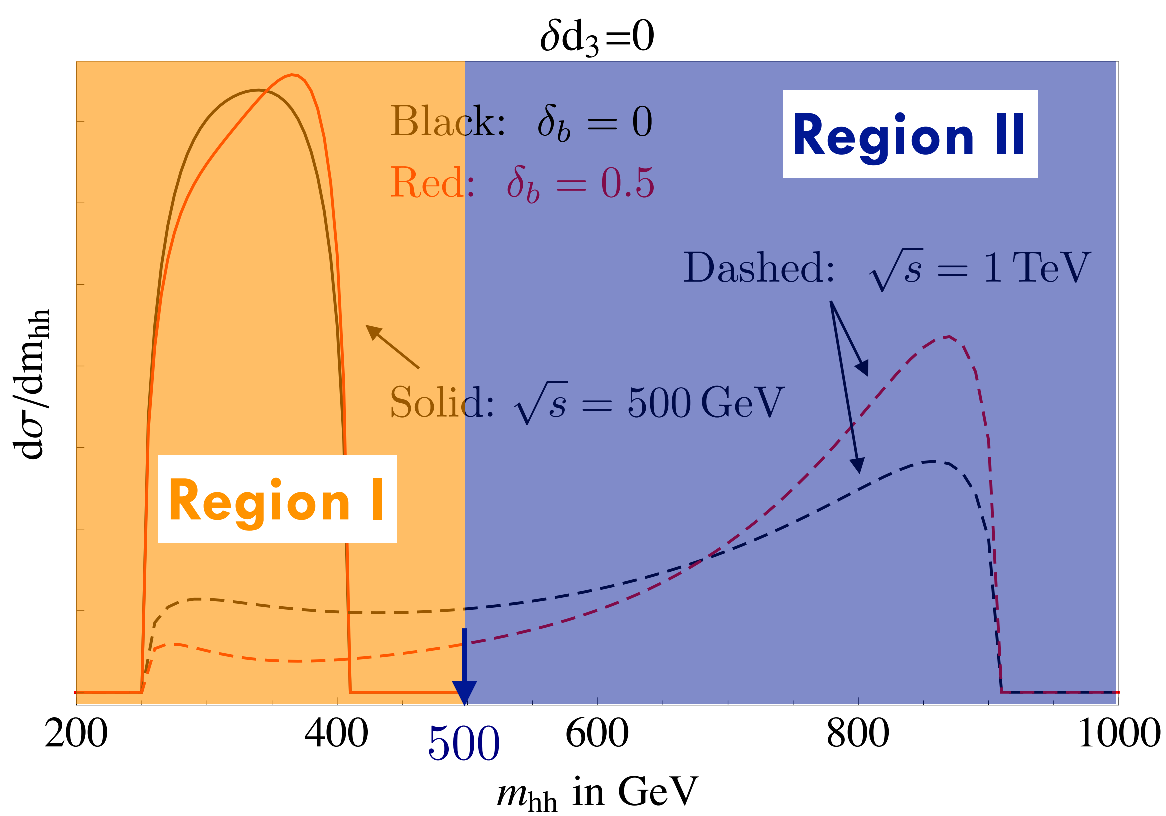

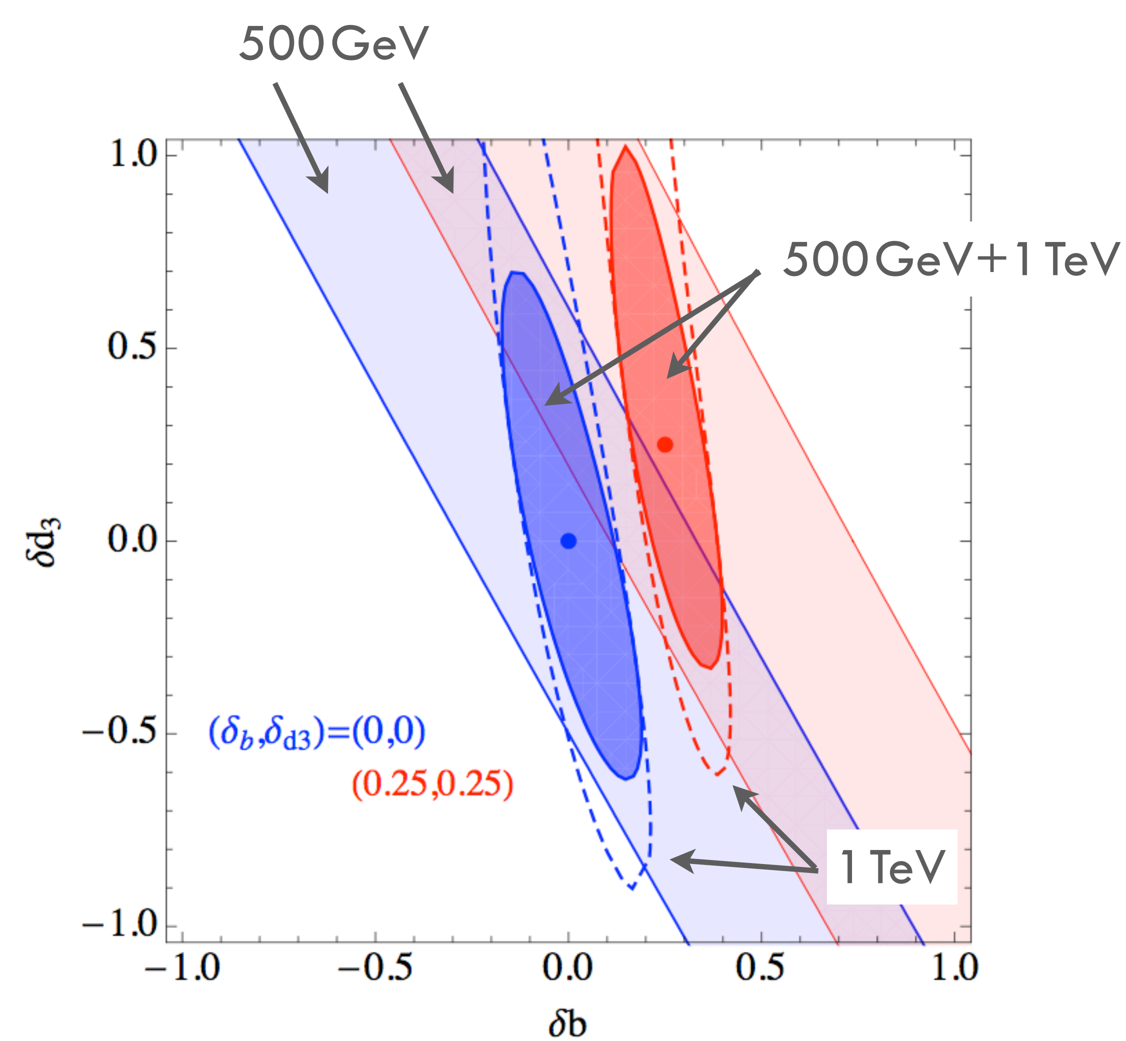

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- From double Higgsstrahlung:

  - coupling hhVV at ~20% (e^+e^- with $\sqrt{s} = 500\,\mathrm{GeV} + 1\,\mathrm{TeV}$)