TESTING HIGGS COMPOSITENESS WITH HIGH LUMINOSITY AND PRECISION

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Based on work in progress with:

1. Azatov, Di Iura, Galloway

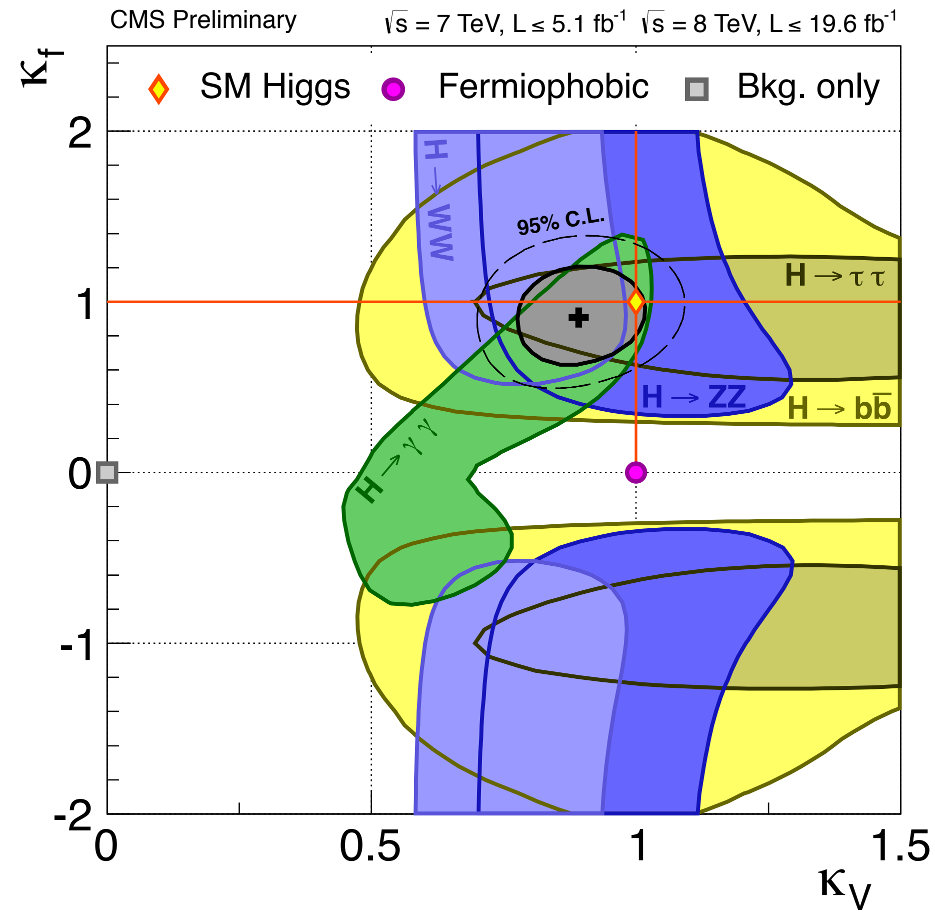
2. Grojean, Pappadopulo, Rattazzi, Thamm

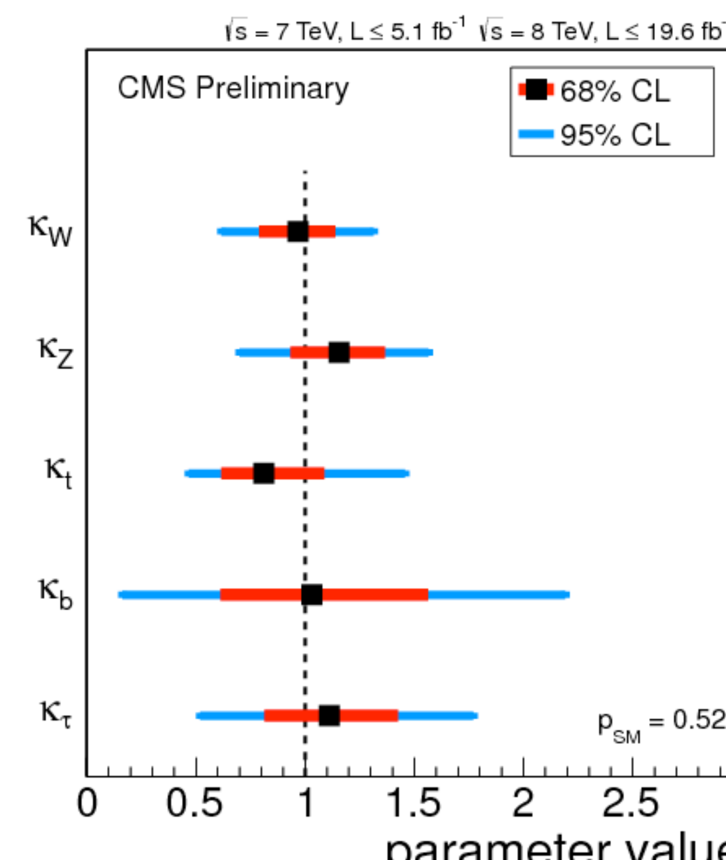
OVERTURE

The first message from the LHC and latest news from EWPTs

The message from the LHC

- Higgs couplings agree with SM prediction within ~20-30%





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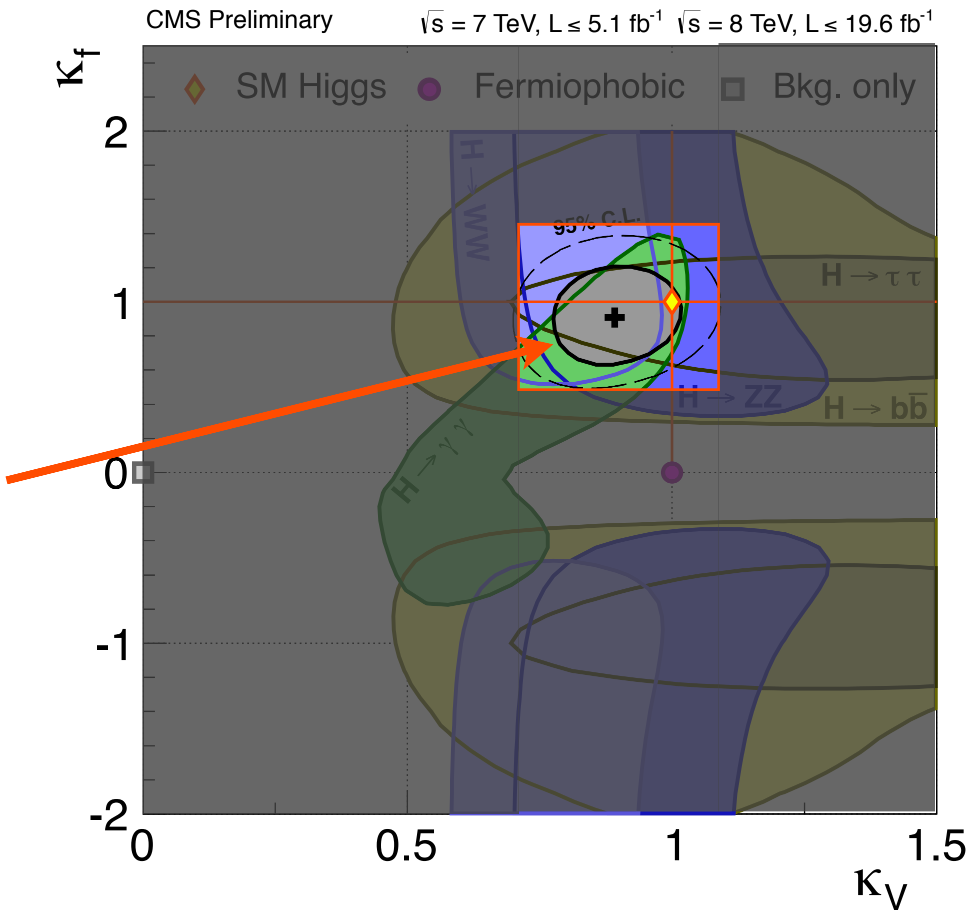

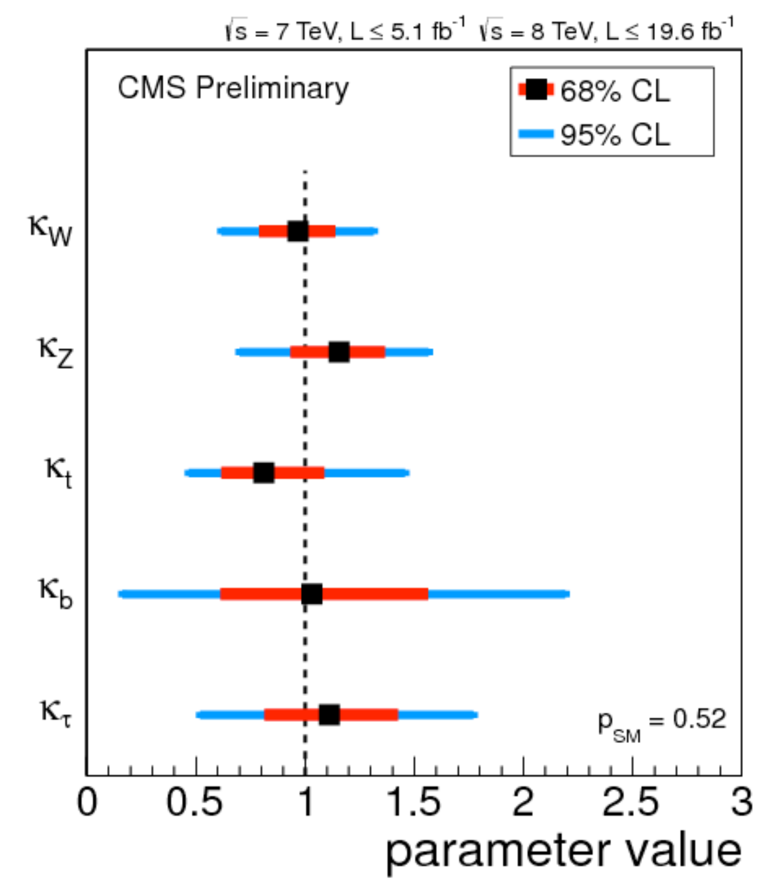

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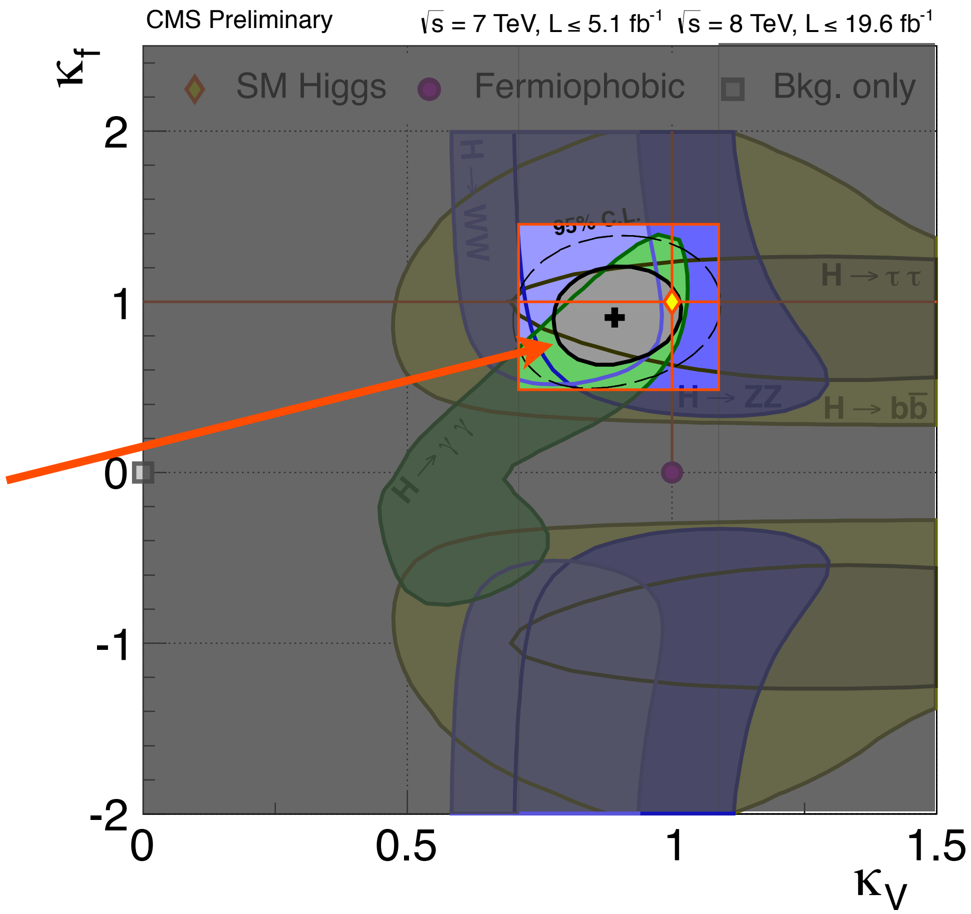


- Higgs couplings agree with SM prediction within ~20-30%

  The focus now is on a region of the parameter space around the SM point

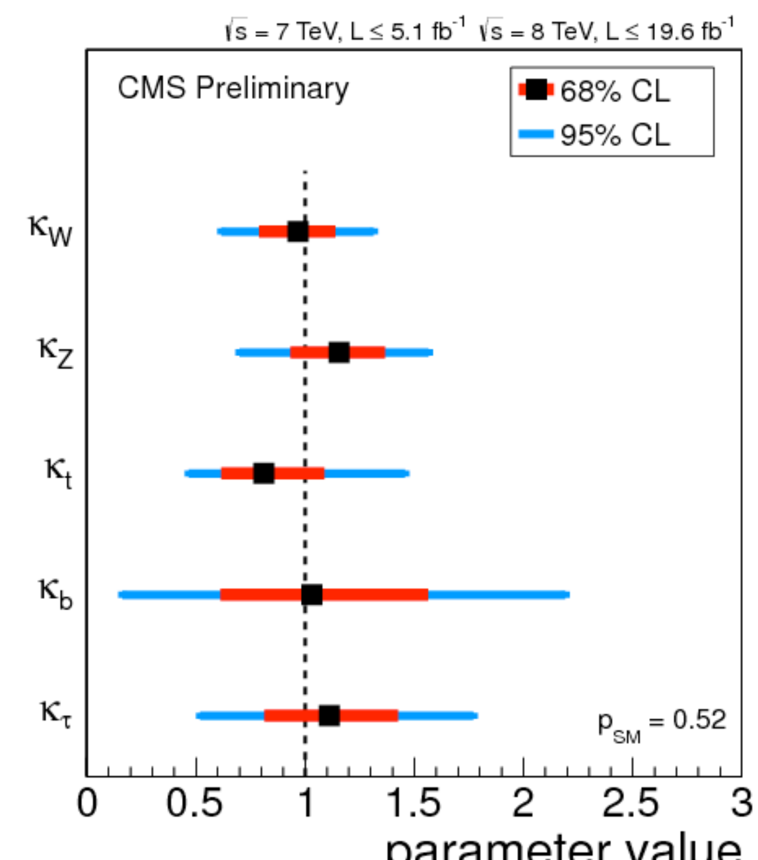
- This is a natural region to live in if:

  1. The new boson is part of an $SU(2)_L$ doublet

  2. There is a gap between the NP scale and m_H

$$\frac{\delta c}{c_{SM}} \sim \frac{g_H^2 v^2}{M^2}$$

g_H = Higgs coupling strength



> Theories w/o a Higgs boson or with strong dynamics at low scale are now excluded
>
> Ex: TC and CH with $M \approx g_H v \approx 4\pi v$

Latest News from EWPTs (LEP+Tevatron)

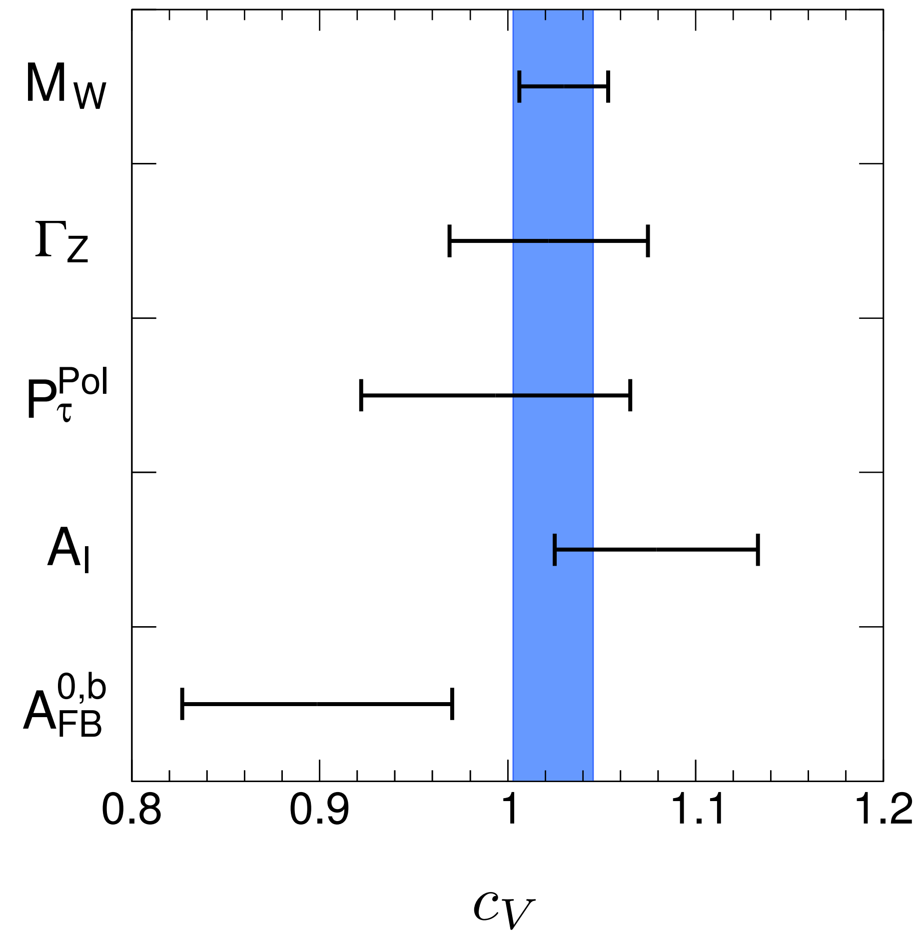
Most recent EW fit much more stringent than before due to:

– mH now precisely known from the LHC

– new m_W from Tevatron

Precision on c_V at the level of ~5% !

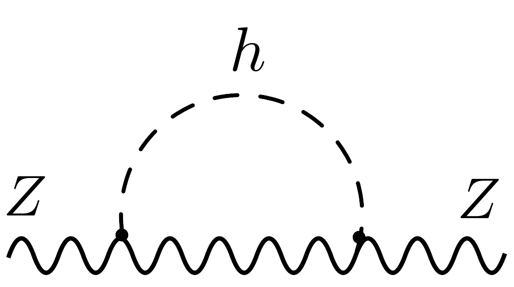
[Assuming no extra contribution to EWPO from new particles]



M. Ciuchini, E. Franco, L. Silvestrini, S. Mishima, arXiv:1306.4644

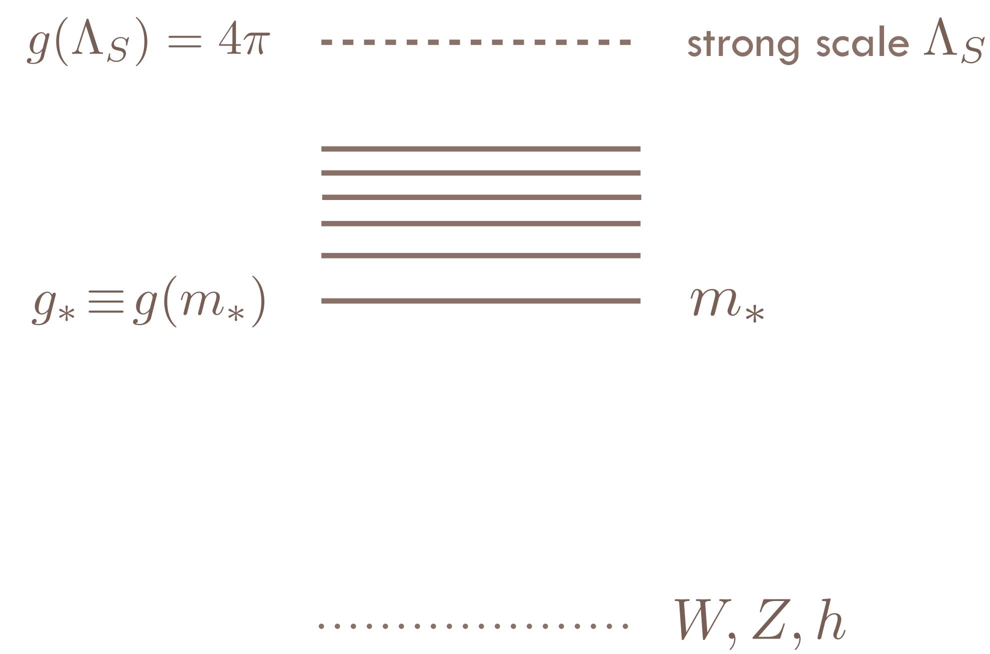
Limitation: 1. evidence is indirect (through loops)

2. only hVV coupling constrained



- New states are probably heavier than what naturalness would suggest

- At the end of its programme the LHC might have only partial access to the spectrum of new particles



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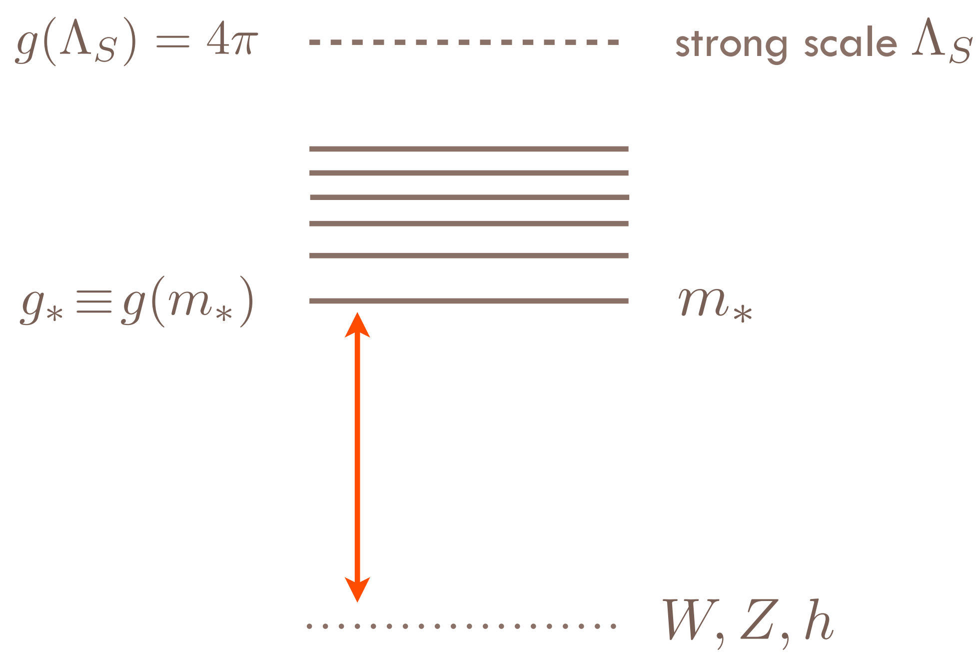

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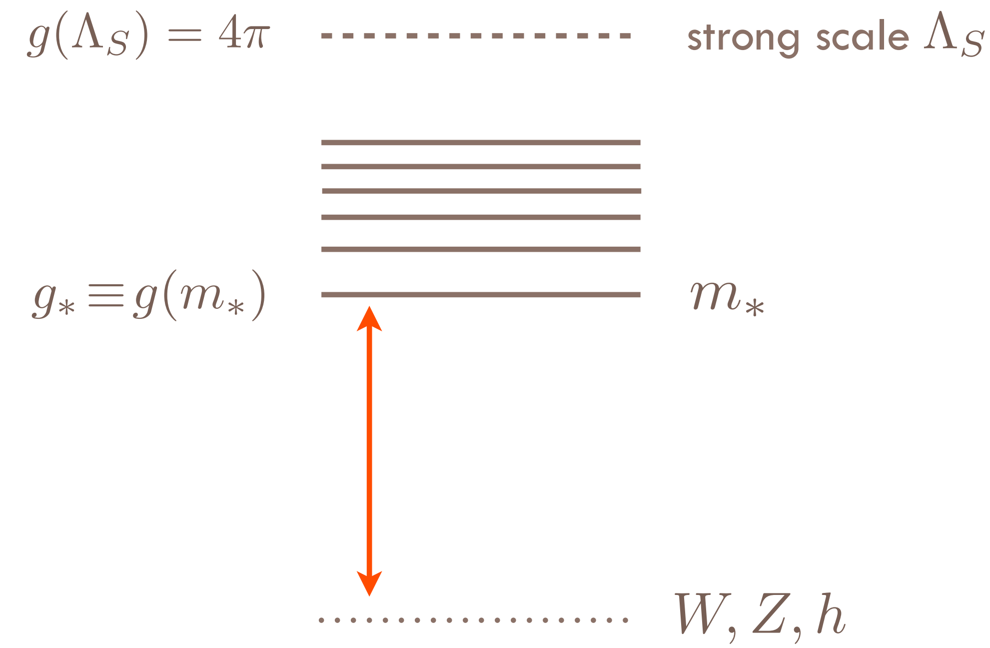
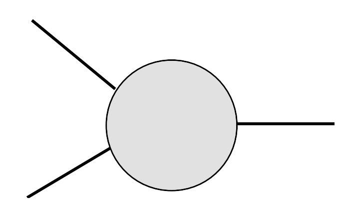
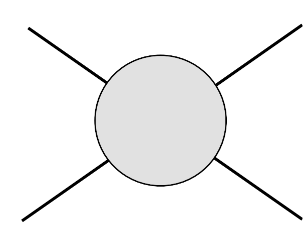


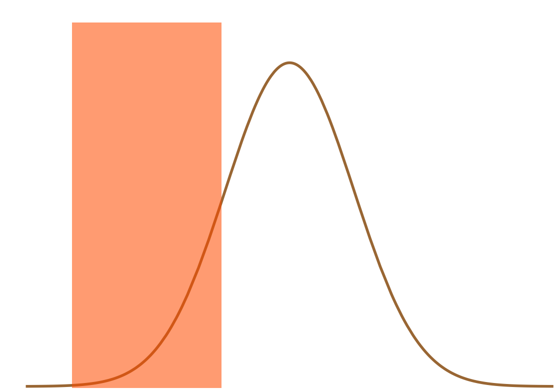
Precision measurement of *low-energy* quantities can give an appraisal of the strength of the underlying interactions



loop effects



tails in scattering



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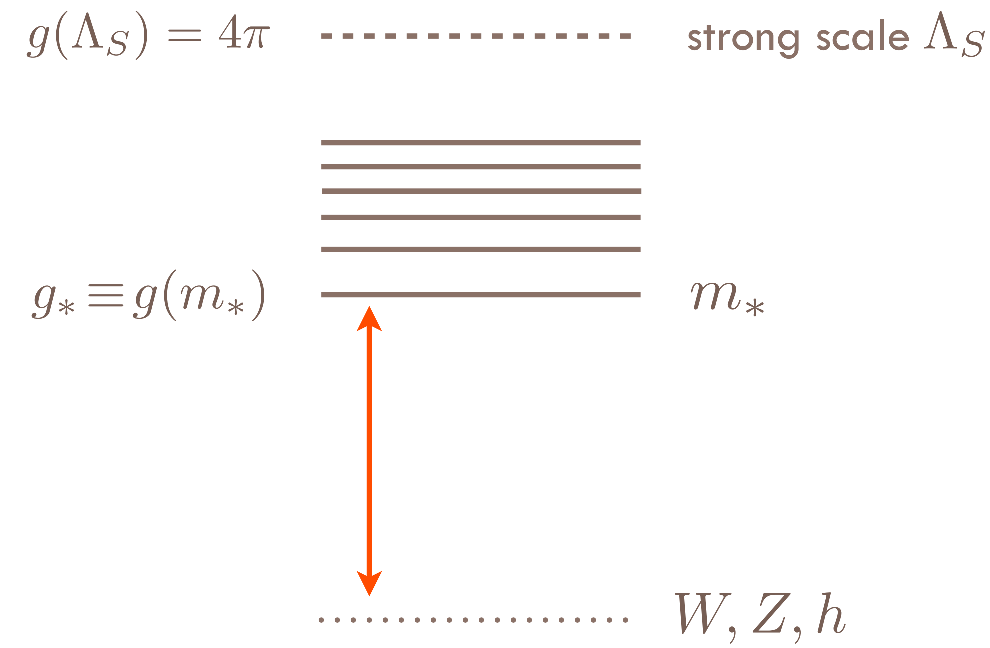

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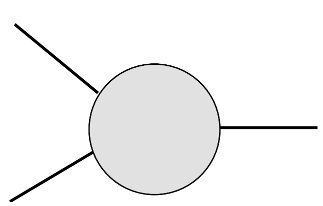

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$$\frac{\delta \mathcal{O}}{\mathcal{O}} \sim \frac{g_*^2 v^2}{m_*^2}$$

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

$$m_* > M$$

(from direct searches)

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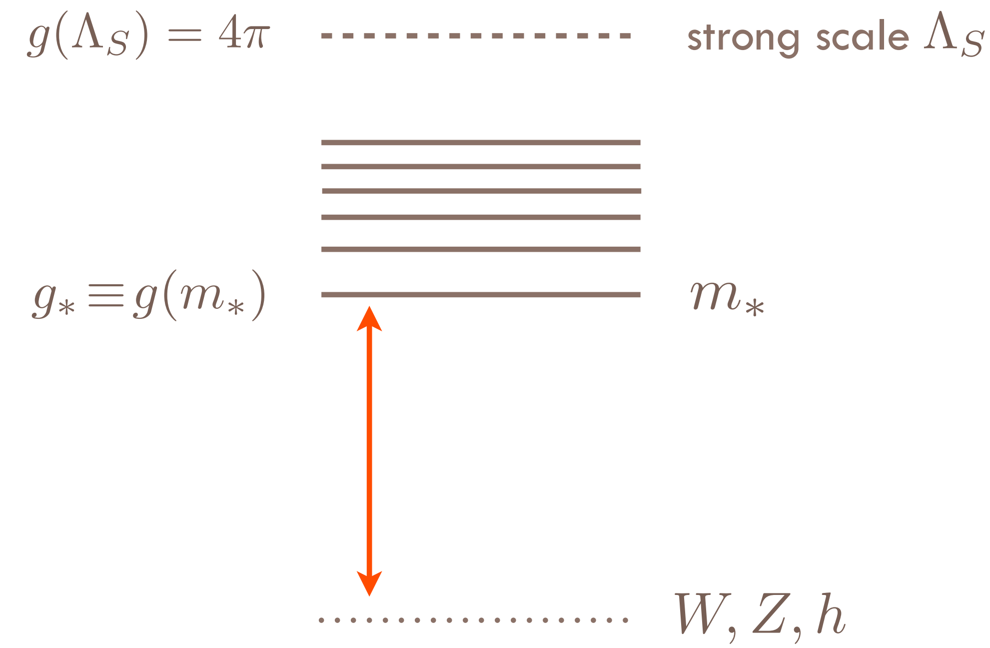

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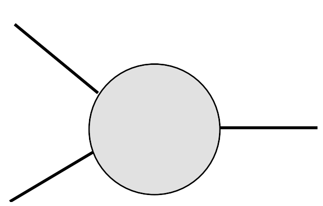

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$$\boxed{g_* > \sqrt{\delta_{\mathcal{O}}^{exp}}\,\frac{M}{v}}$$

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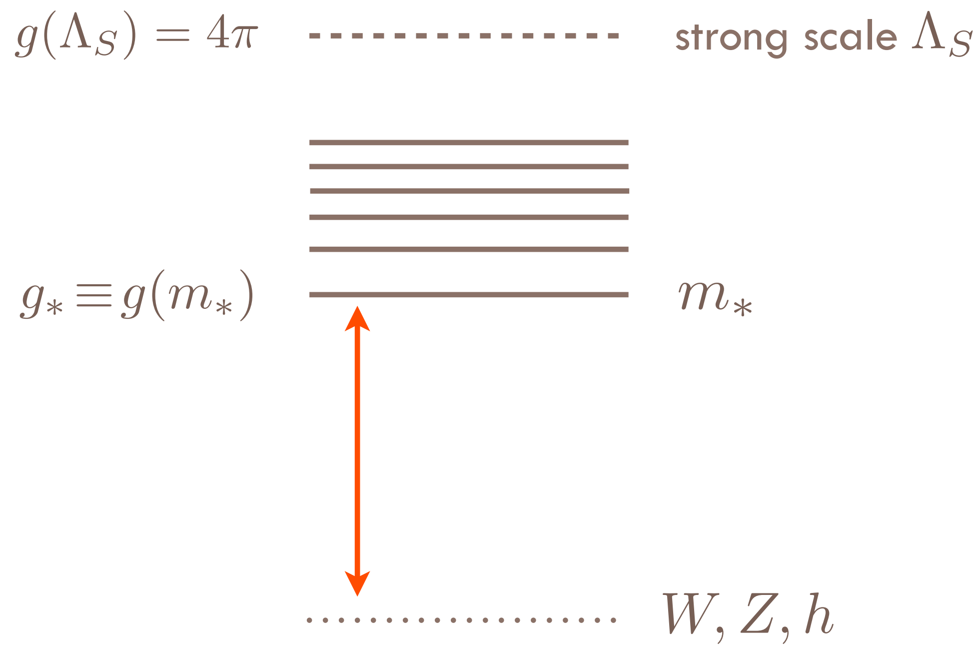

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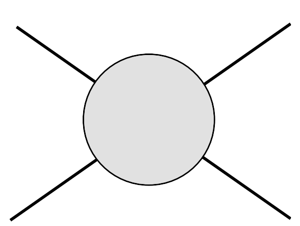

$$\mathcal{A}(2 \to 2) = \delta_{hh} \frac{s}{v^2} \left(1 + O\left(\frac{s}{m_*^2}\right)\right)$$

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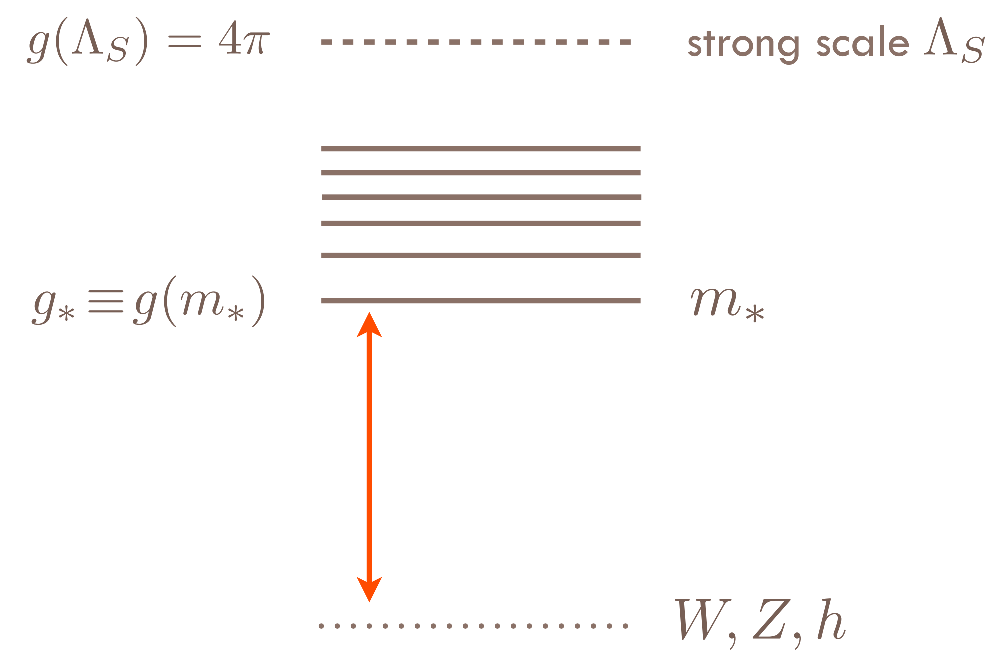

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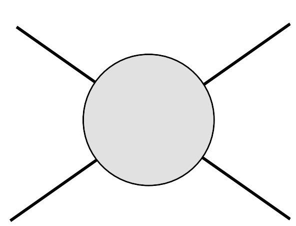

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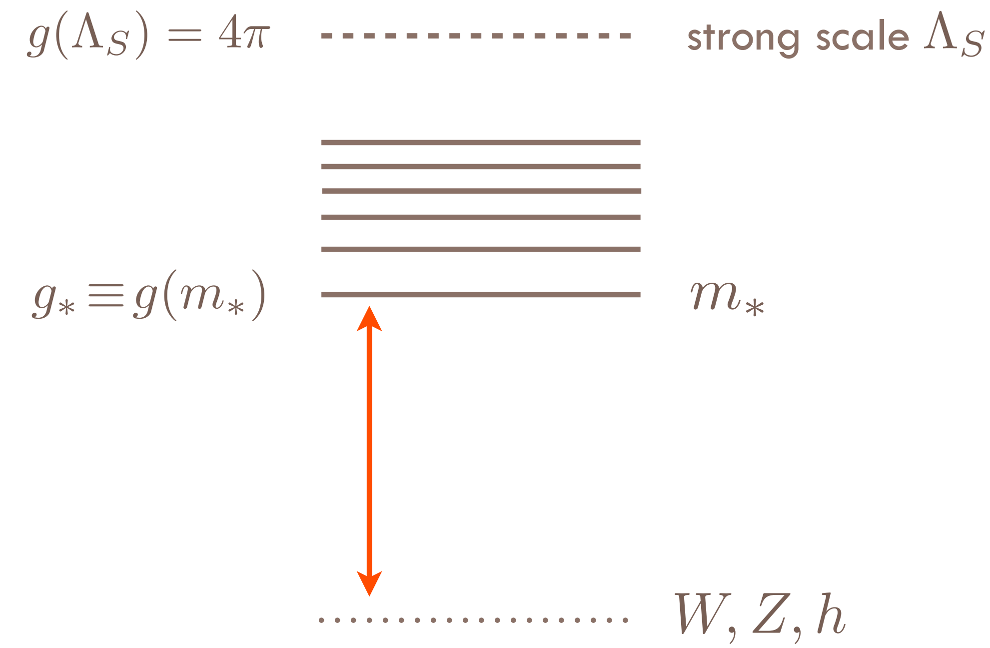

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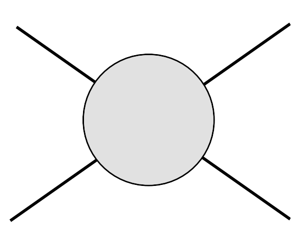

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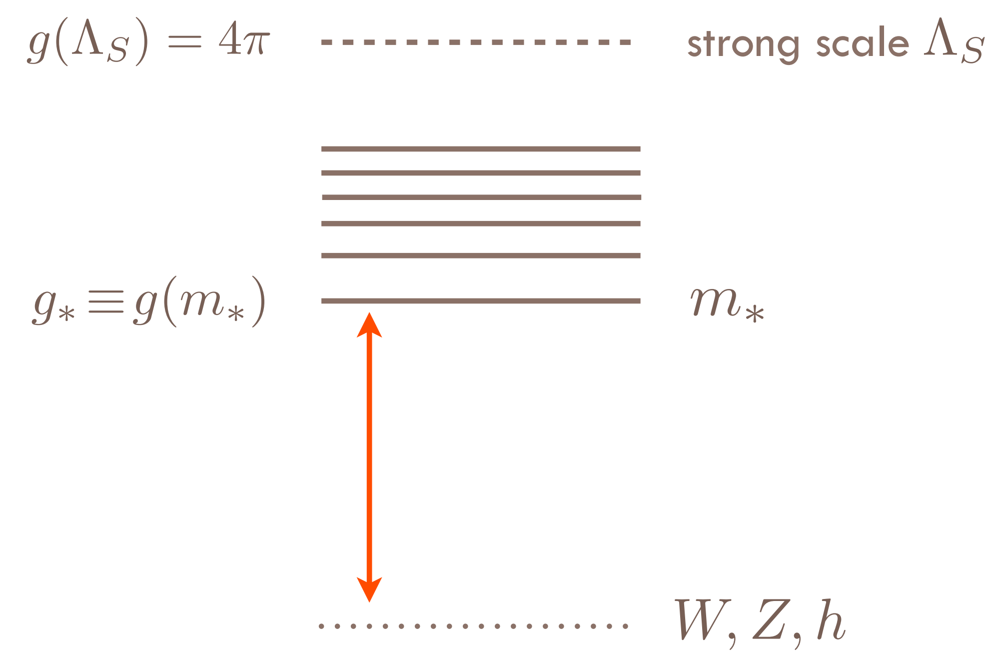

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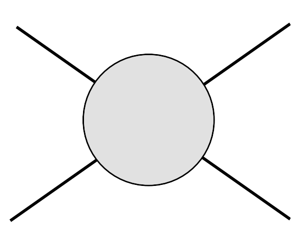

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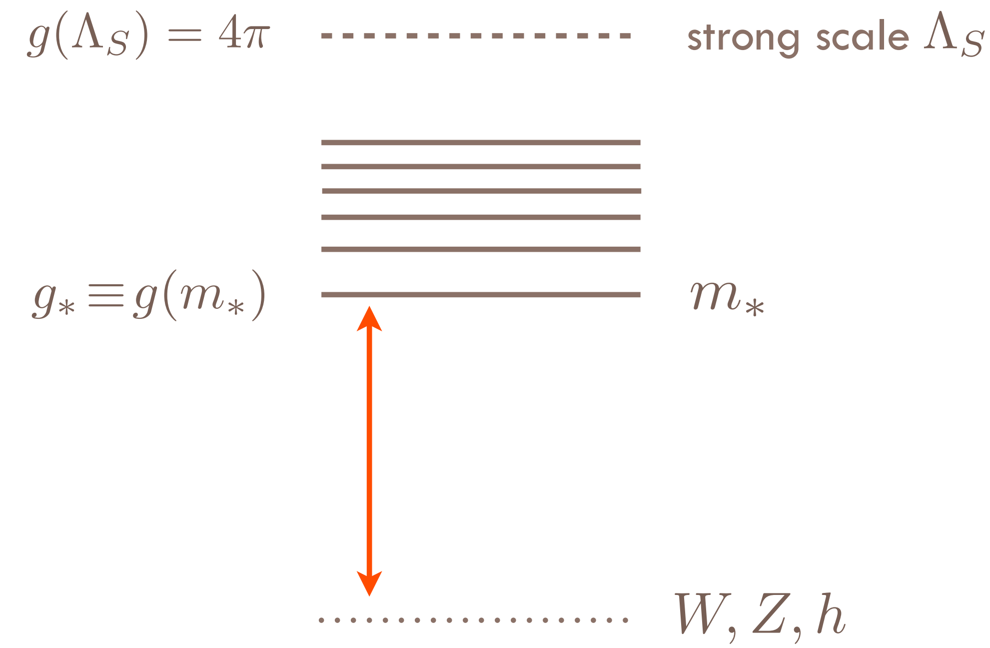

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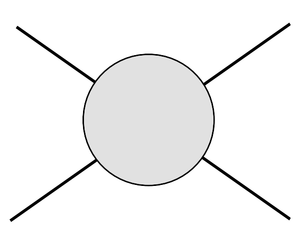

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then we get the stronger limit

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

PART 1

Testing Higgs compositeness with high luminosity at the LHC

Framework: composite NG boson Higgs + partial compositeness

Strategy: Focus on loop effects of pure composites

- no suppression from breaking of Goldstone symmetry
- enhanced by multiplicity of states in the strong sector

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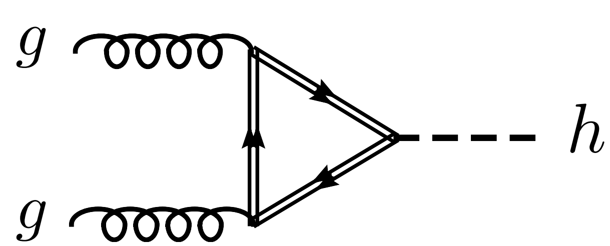
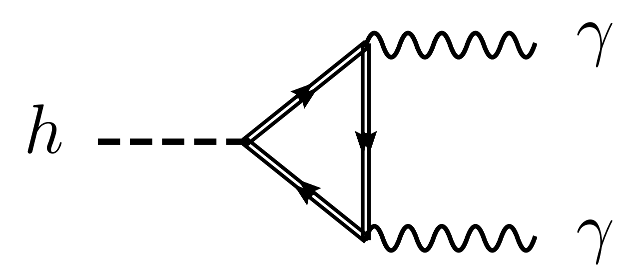
Ex:





$G^2_{\mu\nu} H^\dagger H$ $B^2_{\mu\nu} H^\dagger H$

Amplitudes vanish for pure composite loops by Goldstone invariance

$$A \sim A_{SM} \times O\left(\frac{\lambda^2 v^2}{m_*^2}\right) \qquad \lambda < g_*$$

Effective operators violate the Higgs shift symmetry:

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

Sum Rule:

relies on:

Low Energy Theorem

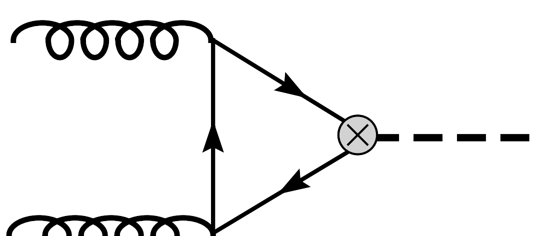
$$A(gg \to h) \propto \frac{\partial}{\partial h} \log \det \left[\mathcal{M}^\dagger(h)\mathcal{M}(h)\right]\Big|_{h=v}$$

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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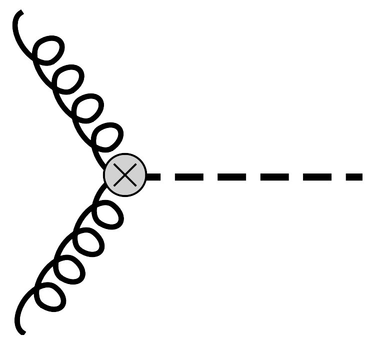

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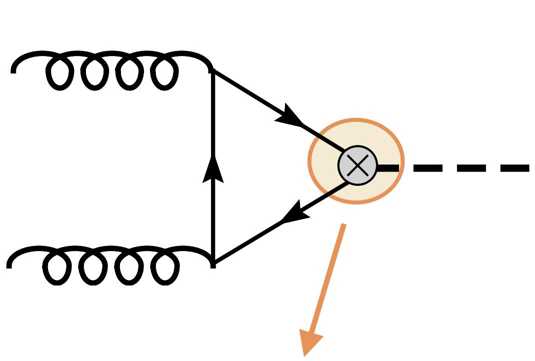

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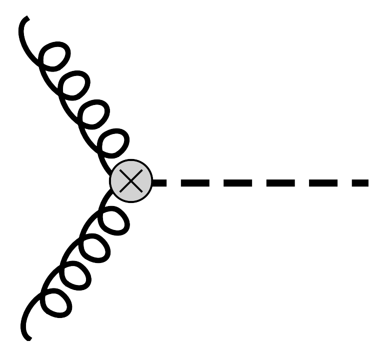

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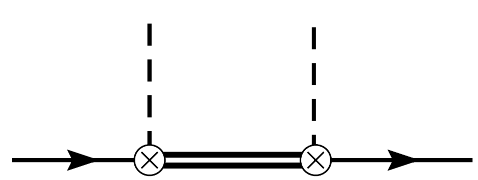

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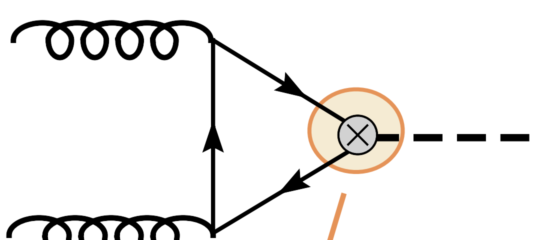

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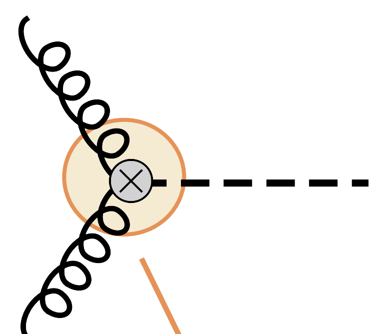

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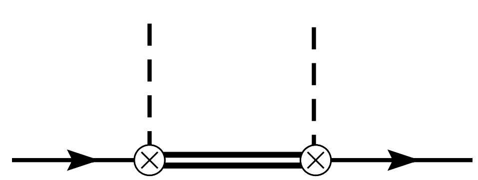
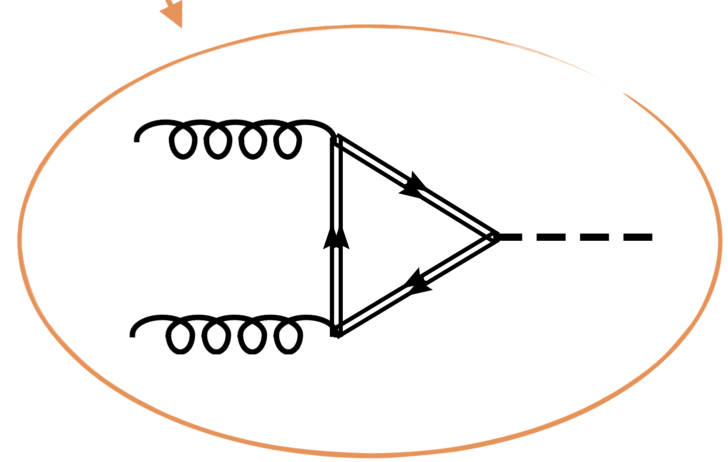
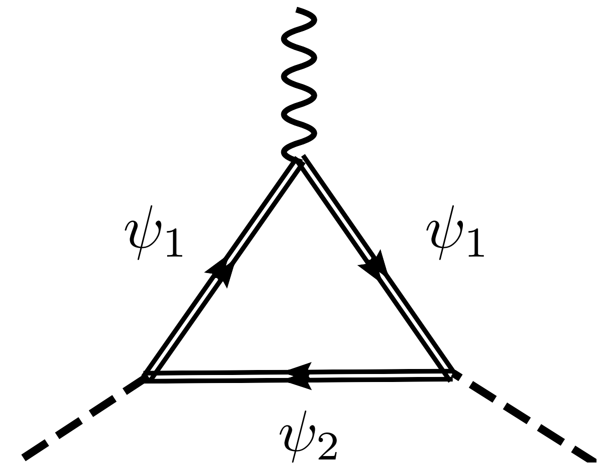




Example: $h \to Z\gamma$

[Azatov, R.C. , Di Iura, Galloway, to appear]



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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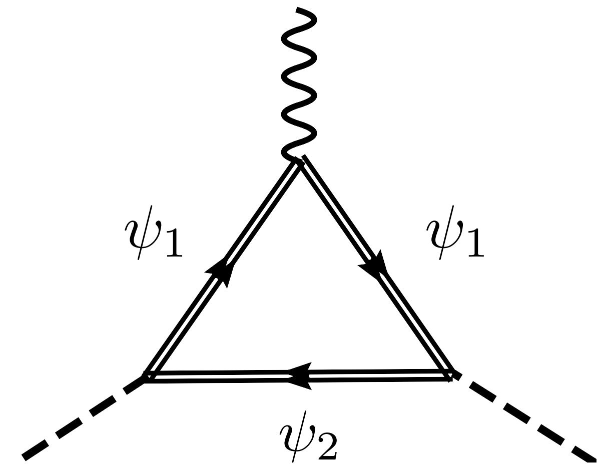

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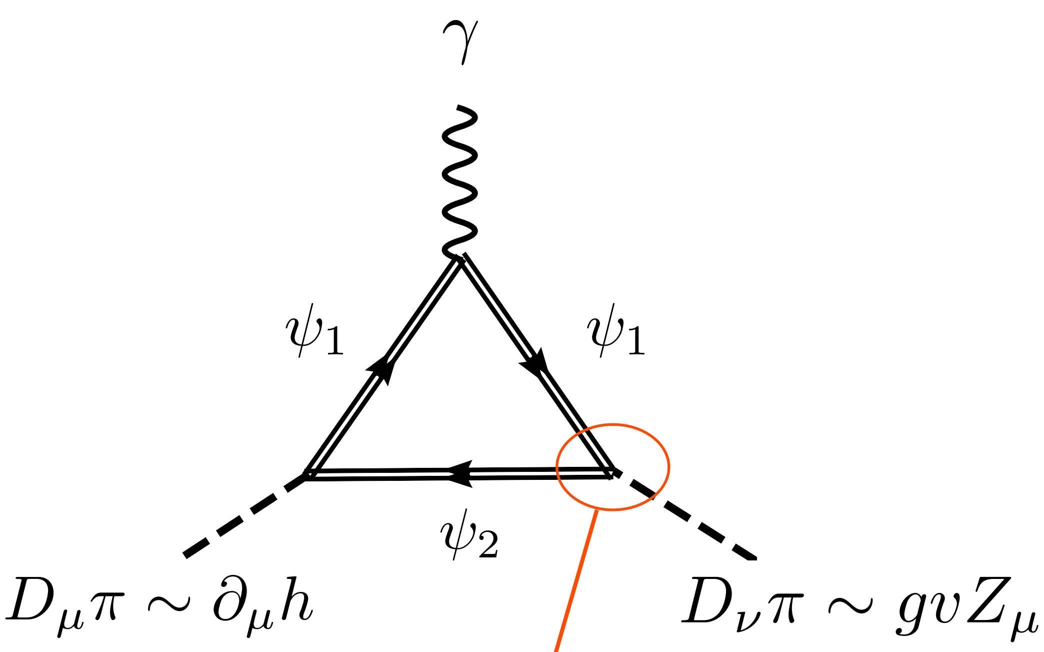

$$\zeta\, \bar\psi_1 \gamma^\mu \frac{\partial_\mu \pi}{f} \psi_2 + h.c.$$

$$\boxed{g_* = g(m_*) = \frac{\Delta m_*}{f}\,\zeta}$$

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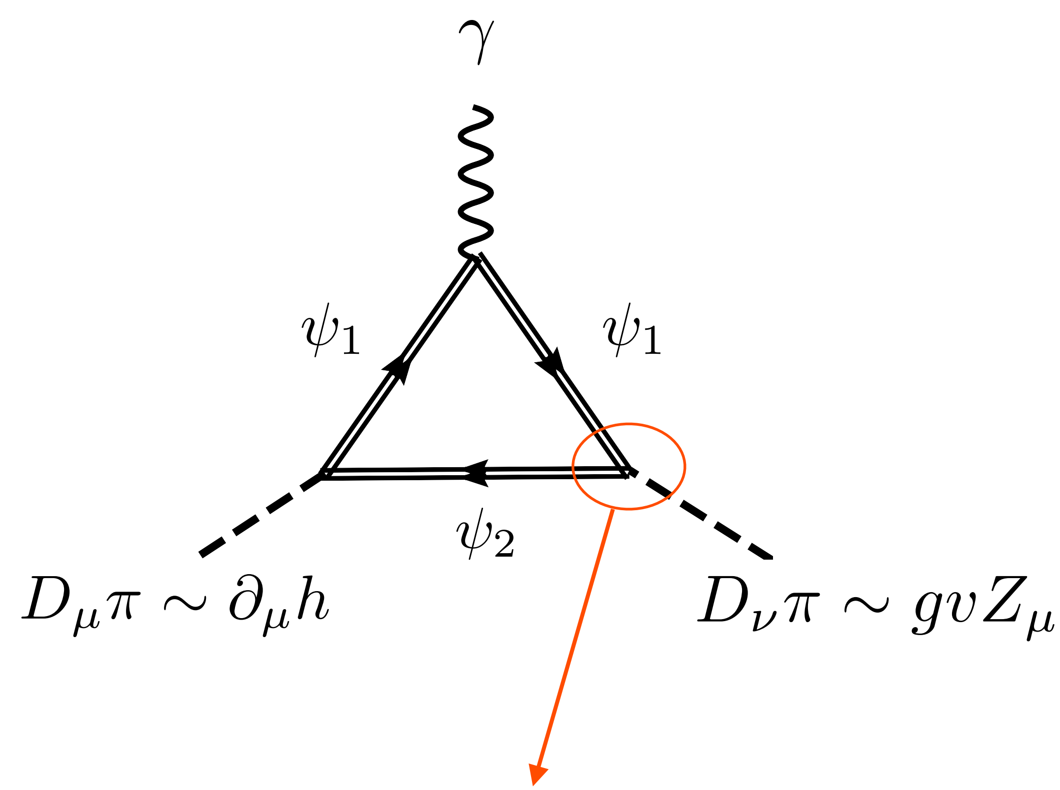

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➡ Strong dynamics MUST break LR

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

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

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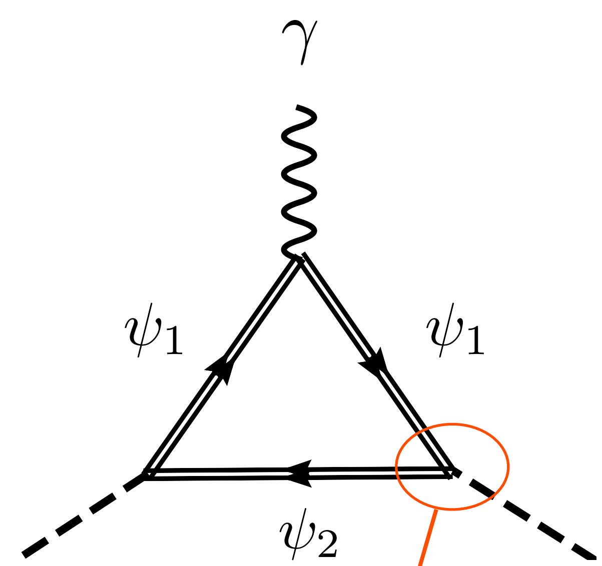

$D_\mu \pi \sim \partial_\mu h$ $\quad$ $D_\nu \pi \sim g v Z_\mu$

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

$$\zeta\, \bar{\psi}_1 \gamma^\mu \frac{\partial_\mu \pi}{f} \psi_2 + h.c.$$

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

$$\boxed{g_* = g(m_*) = \frac{\Delta m_*}{f}\, \zeta} \qquad \zeta \sim O(1)$$

➡ Strong dynamics MUST break LR

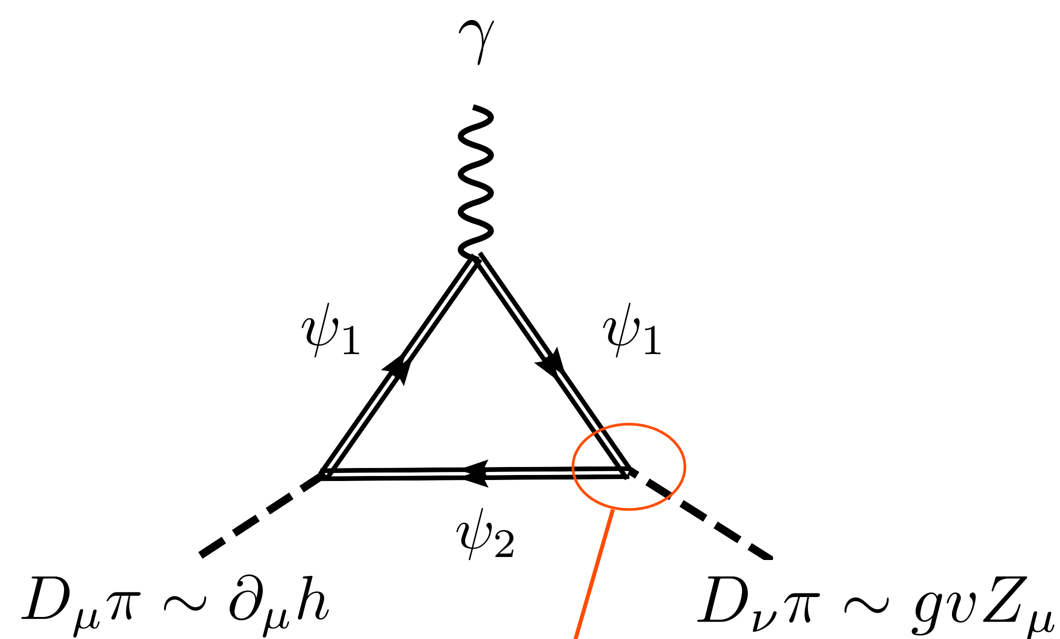
$$A(h \to Z\gamma) = A_{SM} \times F(\xi) + \delta A$$

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

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

Example: $h \to Z\gamma$

[Azatov, R.C. , Di Iura, Galloway, to appear]



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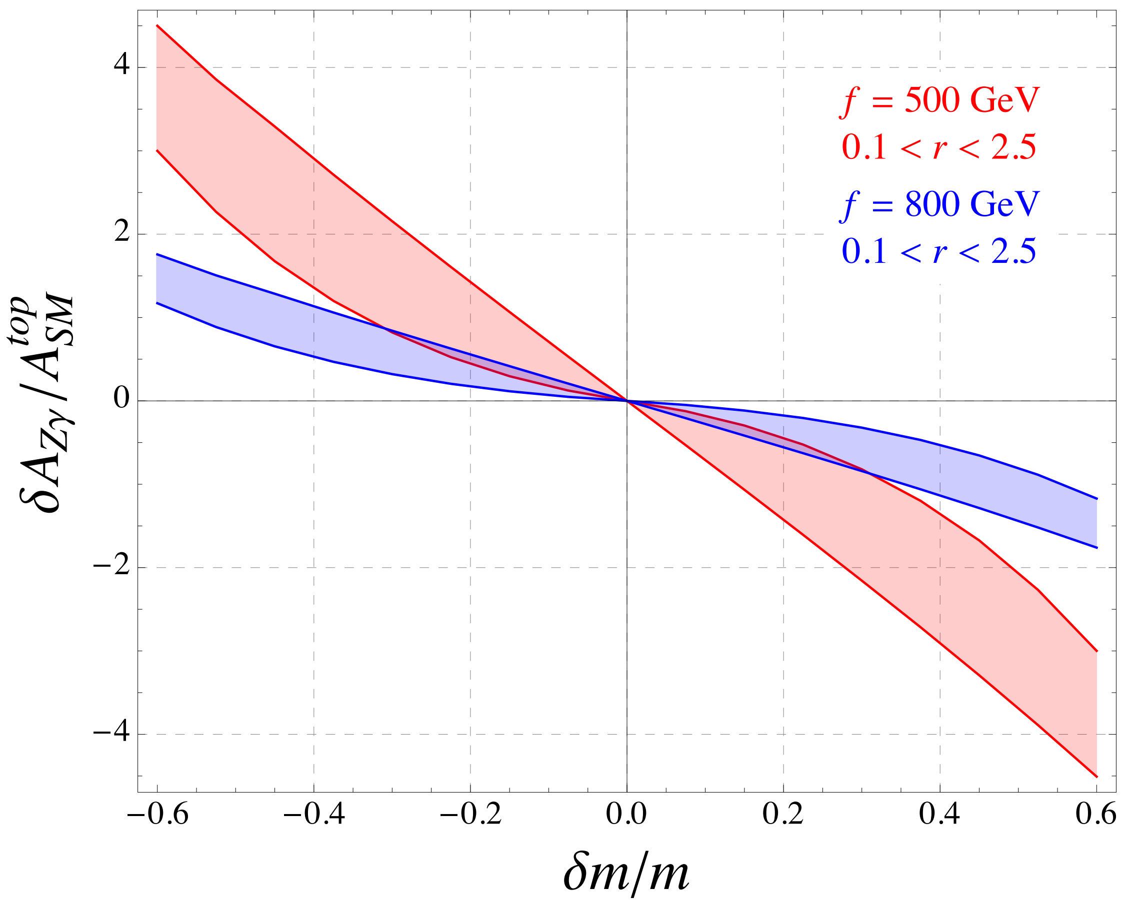
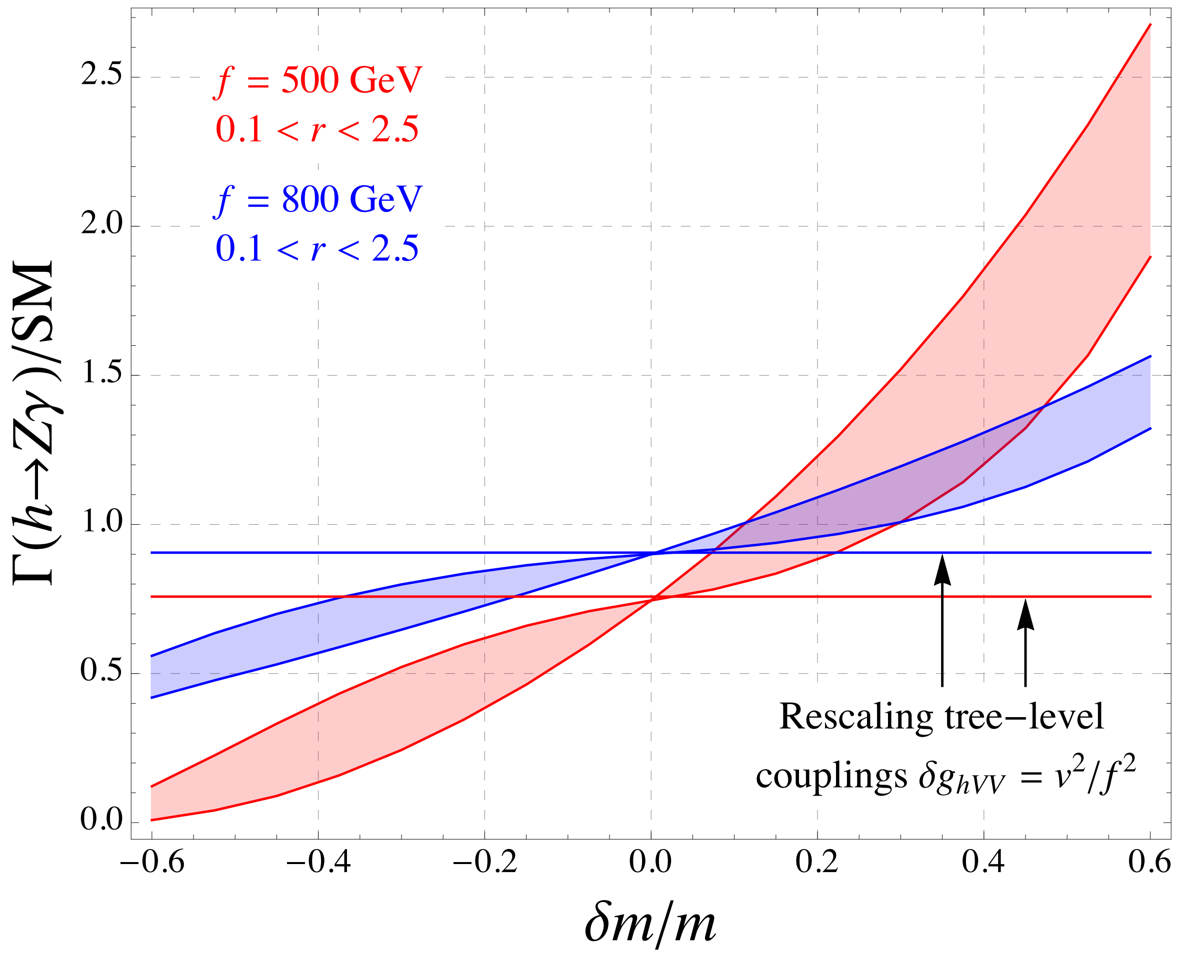
multiplicity of composite states

SO(5)/SO(4) model: $\psi_5 = (1,1)_{2/3} + (2,2)_{2/3}$

$$\psi_{10} = (2,2)_{-1/3} + (1,3)_{-1/3} + (3,1)_{-1/3}$$



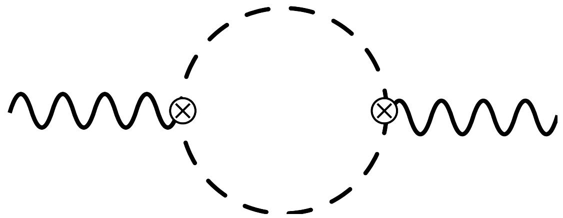


$$\frac{\delta m}{m} \equiv \frac{m_{(3,1)} - m_{(1,3)}}{m_{(3,1)} + m_{(1,3)}} \qquad \zeta_{13} = 1 = \zeta_{31}$$

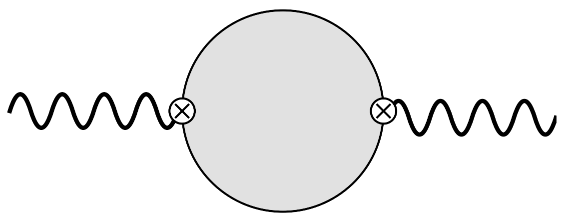
Example: S parameter

$$\hat{S} = \hat{S}_{IR} + \hat{S}_{UV}$$

[Azatov, R.C. , Di Iura, Galloway, to appear]



$$\hat{S}_{IR} \sim \frac{v^2}{f^2}\,\frac{g^2}{16\pi^2}\log\left(\frac{\Lambda}{m_Z}\right)$$



$$\hat{S}_{UV} \sim g^2\frac{v^2}{f^2}\left[\frac{1}{g_*^2} + N_c N_F \frac{1}{16\pi^2}\log\left(\frac{\Lambda}{m_*}\right) + \dots\right]$$

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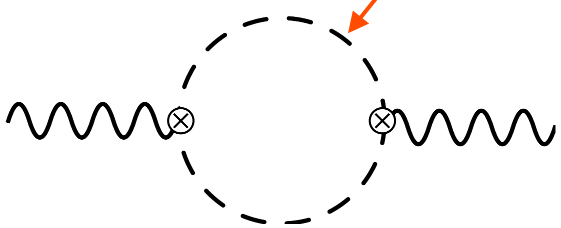
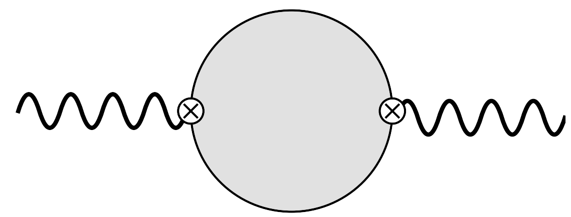
IR contribution from NG bosons





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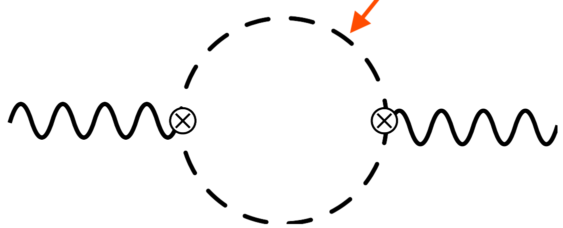

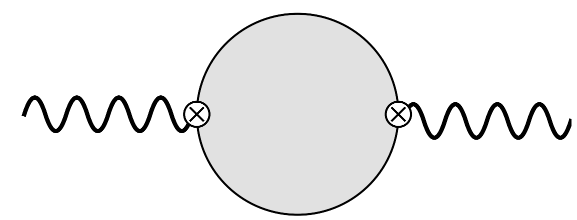

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tree-level (rho)

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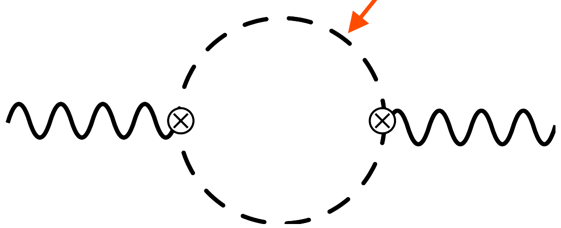

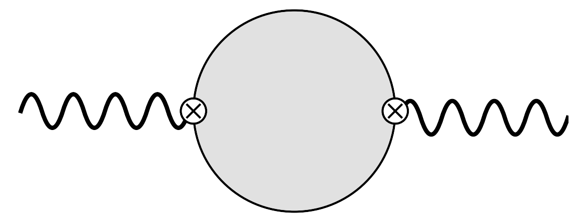

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1-loop (fermions)

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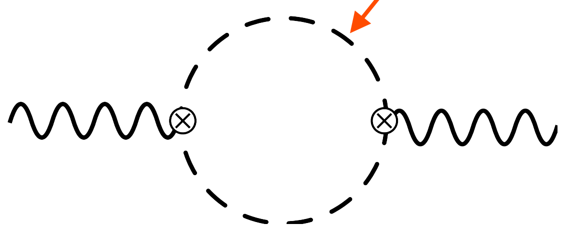

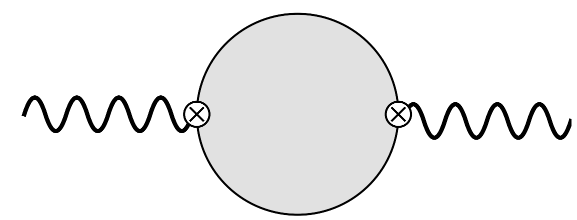

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tree-level (rho) 1-loop (fermions)

➡ 1-loop contribution from fermions can be large (!)

First discussed by: Barbieri, Isidori, Pappadopulo arXiv:0811.2888

Recently reconsidered by: Grojean, Matsedonskyi, Panico arXiv:1306.4655

fermion contribution can be *negative*

Best seen using a dispertion relation:

[Orgogozo and Rychkov, JHEP 1306 (2013) 014]

$$\boxed{\hat{S}_{UV} = \frac{g^2}{4}\sin^2\theta \int \frac{ds}{s}\left[\rho_{LL}(s) + \rho_{RR}(s) - 2\rho_{BB}(s)\right]}$$

$$i\int d^4x\, e^{iq\cdot(x-y)}\langle 0|T(J_\mu(x)J_\nu(y))|0\rangle = (q^2\eta_{\mu\nu} - q_\mu q_\nu)\Pi(q^2)$$

$$\rho(s) = \frac{1}{\pi}\mathrm{Im}(\Pi(s))$$

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negative contribution from spectral function of broken SO(5)/SO(4) currents

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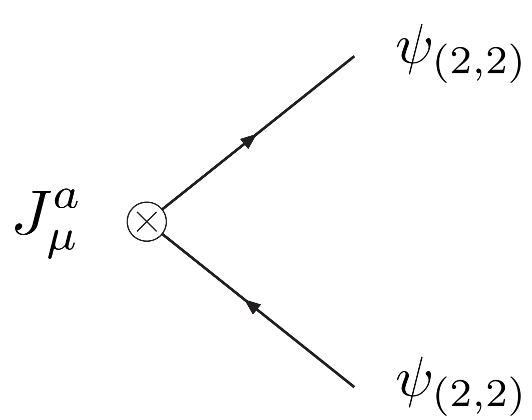
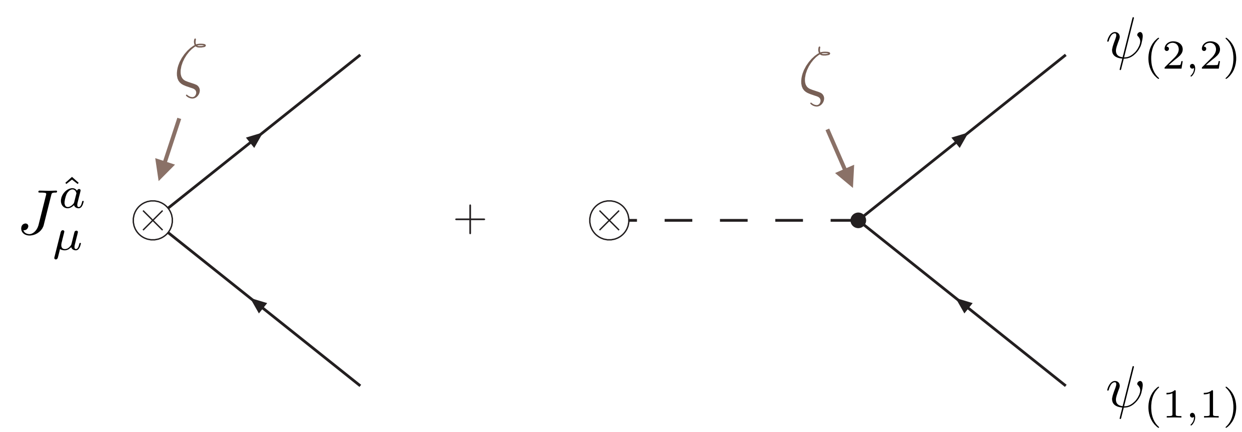


$\rho_{LL,RR}$



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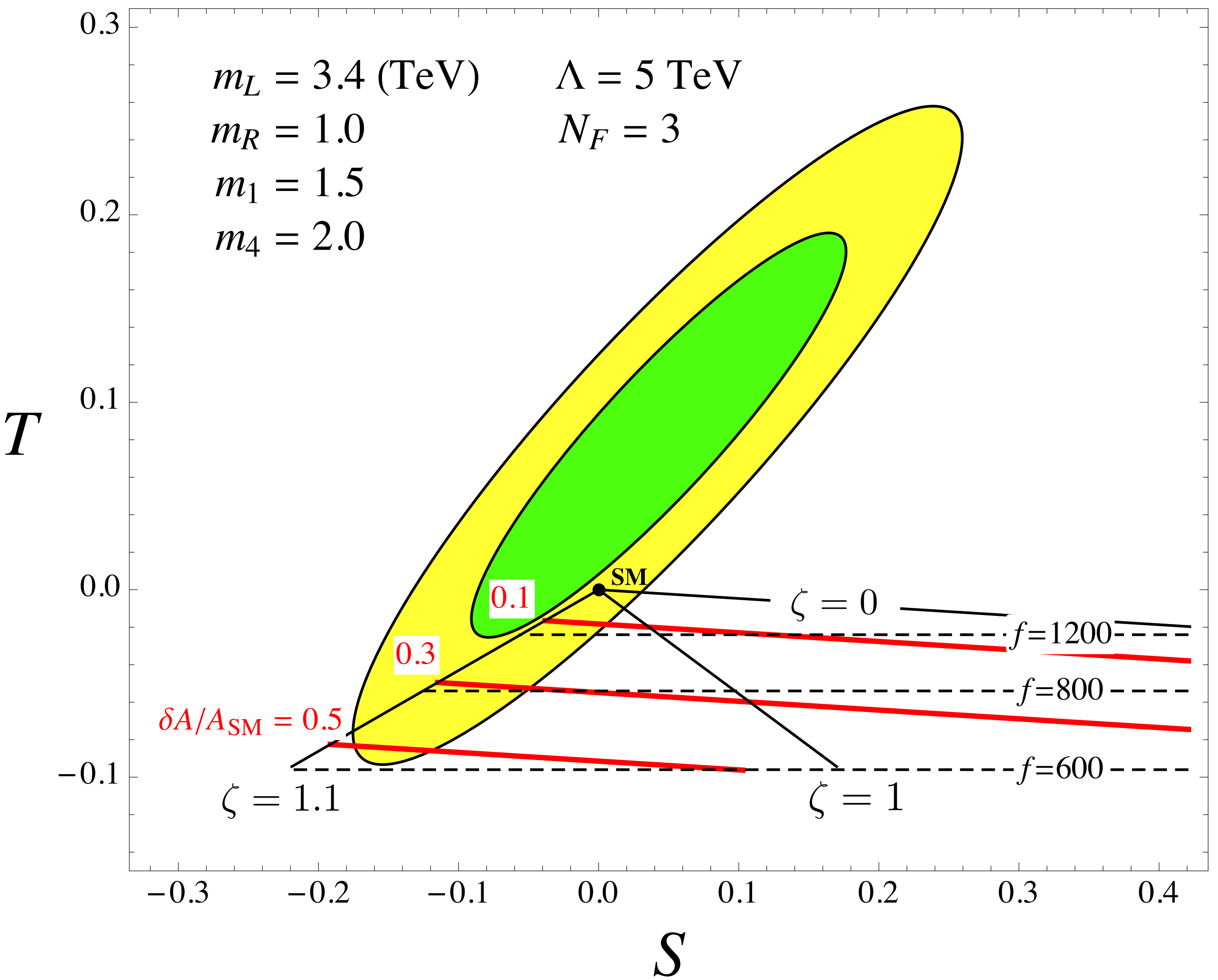
Example: for a $\psi_5 = (1,1) + (2,2)$ of SO(4)

$$S_{UV} = \frac{8}{3}\frac{m_W^2}{16\pi^2 f^2}N_c N_F\left(1 - |\zeta|^2\right)\log\left(\frac{\Lambda^2}{m^2_{(2,2)}}\right) + \text{finite terms}$$

SO(5)/SO(4) model:

$$\psi_5 = (1,1)_{2/3} + (2,2)_{2/3}$$

$$\psi_{10} = (2,2)_{-1/3} + (1,3)_{-1/3} + (3,1)_{-1/3}$$



Some tuning needed to go back into the ellipse

S_{UV} from fermions *can* lead to such tuning (even w/o T)

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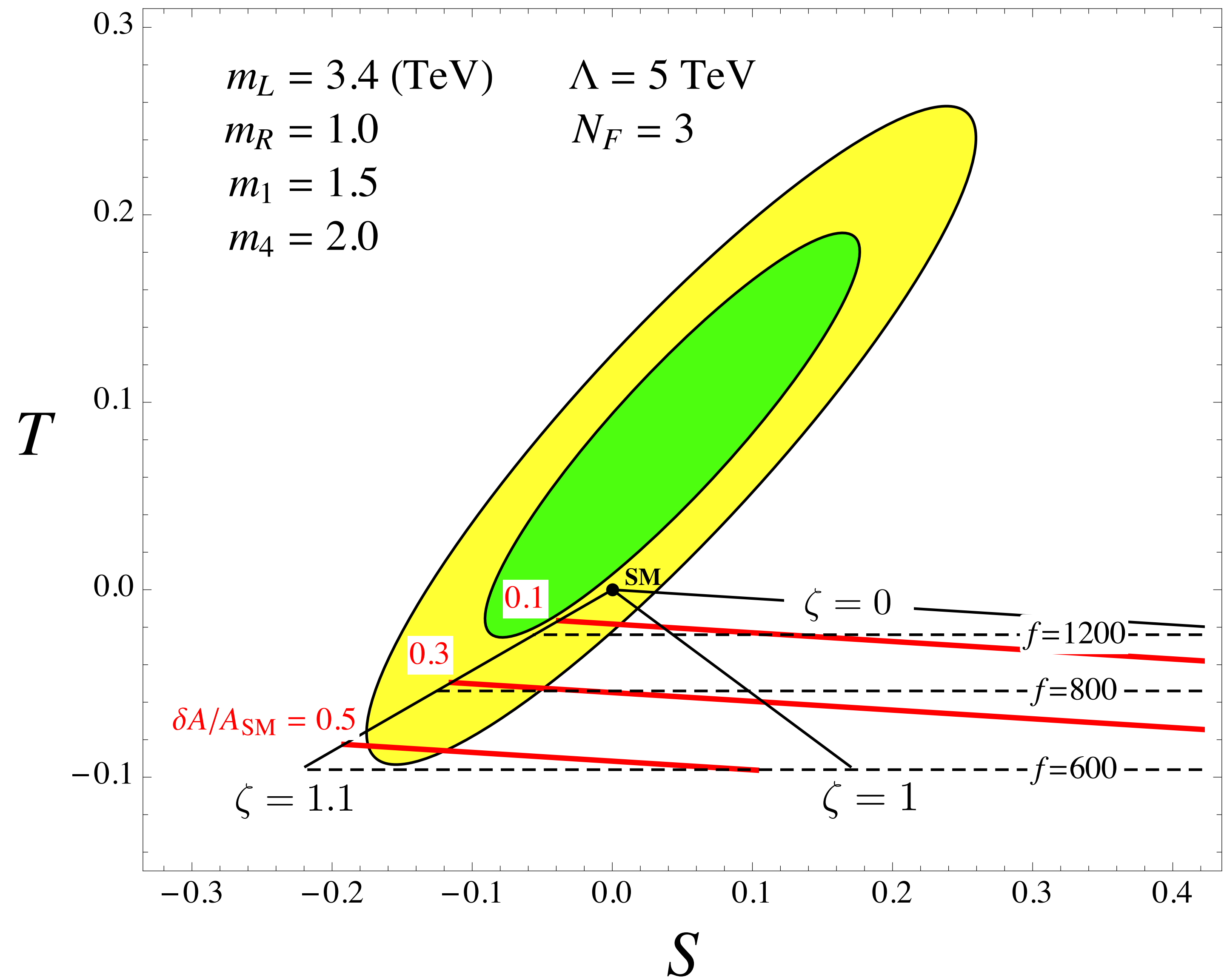


Some tuning needed to go back into the ellipse

S_{UV} from fermions *can* lead to such tuning (even w/o T)

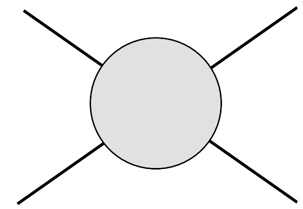
Ex: for $f = 800\,\text{GeV}$ $\quad g_\rho = 3$

$\Delta S_\rho \simeq 0.13$ $\qquad \Delta S_\psi \simeq 0.8 \times (1 - |\zeta|^2)$ → tuning ~ 10%

PART 2

Testing Higgs compositeness with high precision at an e^+e^- (linear) collider

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

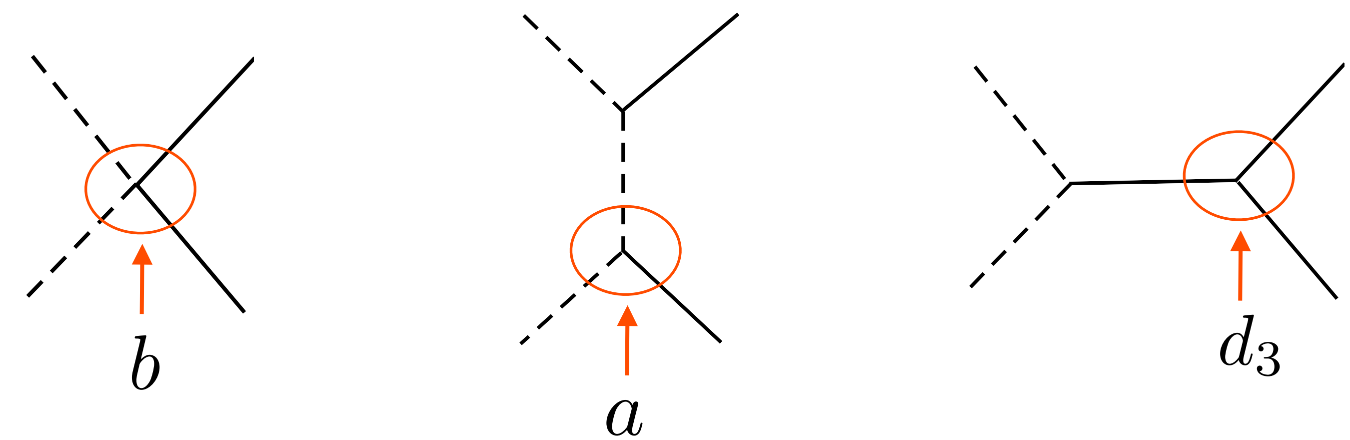


$$\mathcal{A}(2 \to 2) = \delta_{hh} \frac{s}{v^2}\left(1 + O\left(\frac{s}{m_*^2}\right)\right)$$

[R.C. , Grojean, Pappadopulo, Rattazzi, Thamm, to appear]

Example: $WW \to hh$

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



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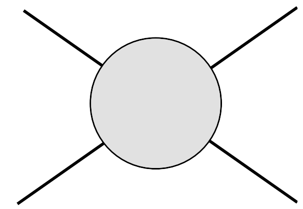

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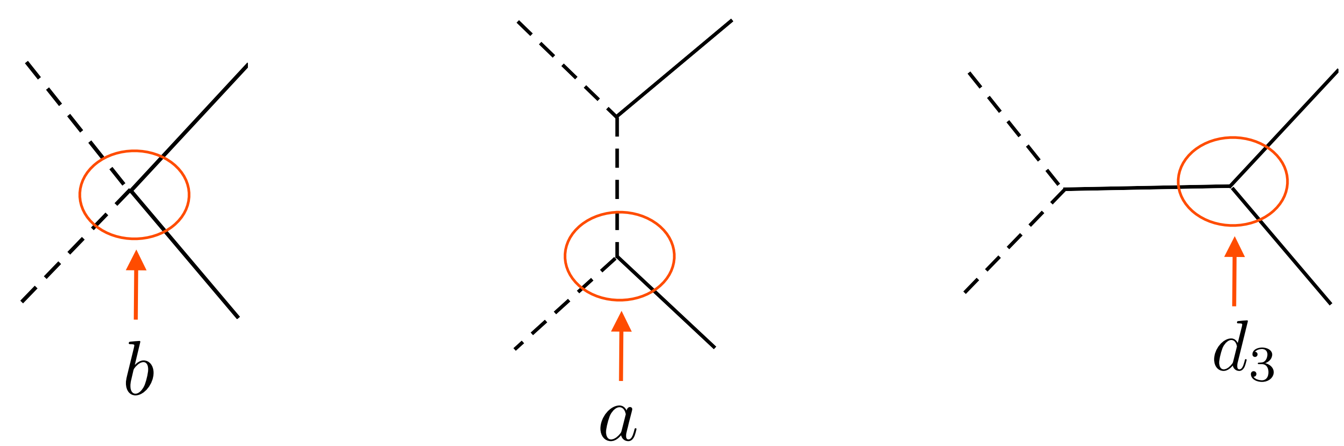

dim 6: $$O_H = \frac{c_H}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

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

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:

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

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

$$b = 1 - 2\xi$$

At dimension-6 level:

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

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

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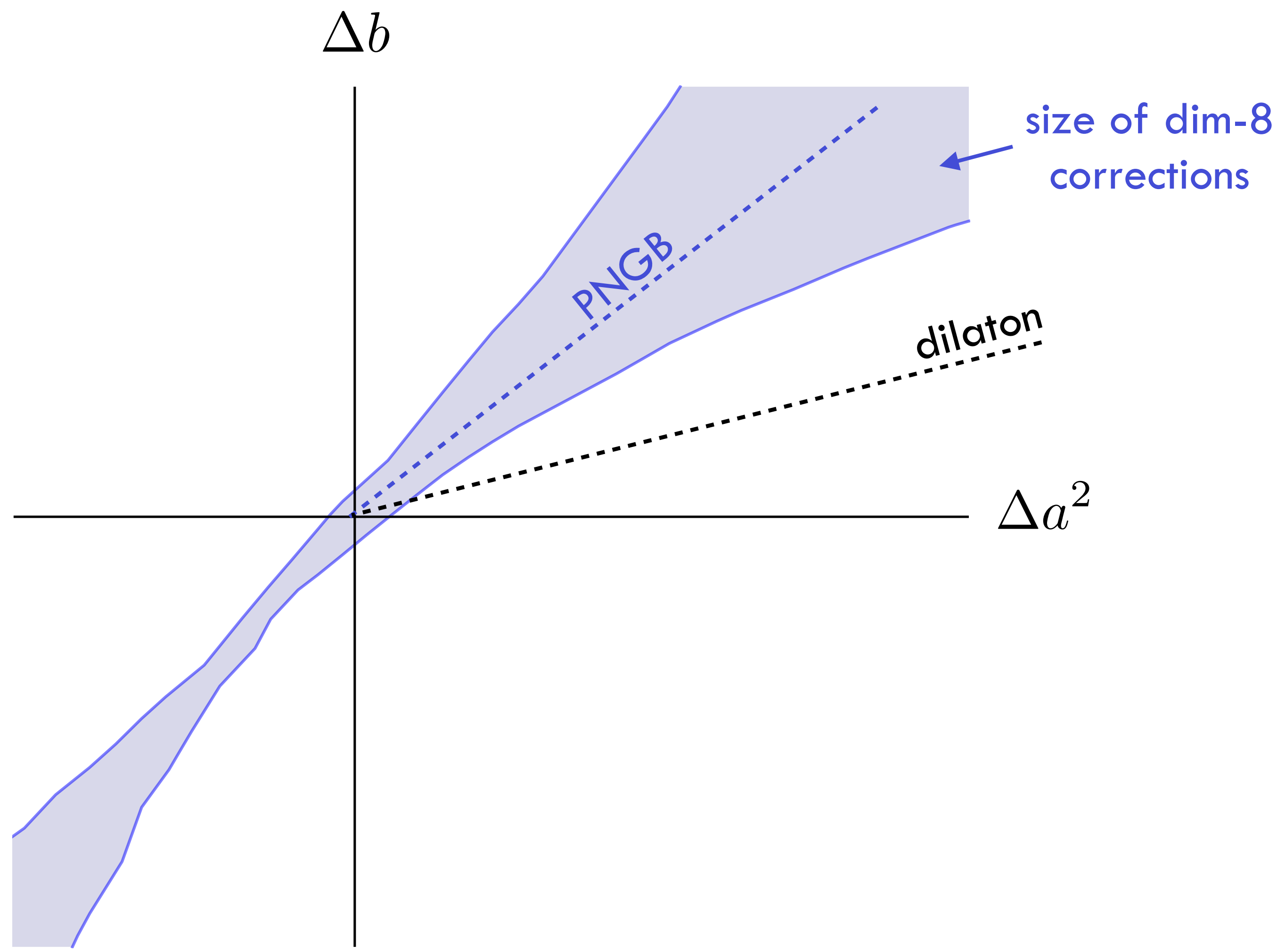
Scenario 1:

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

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

Test dim-8 corrections



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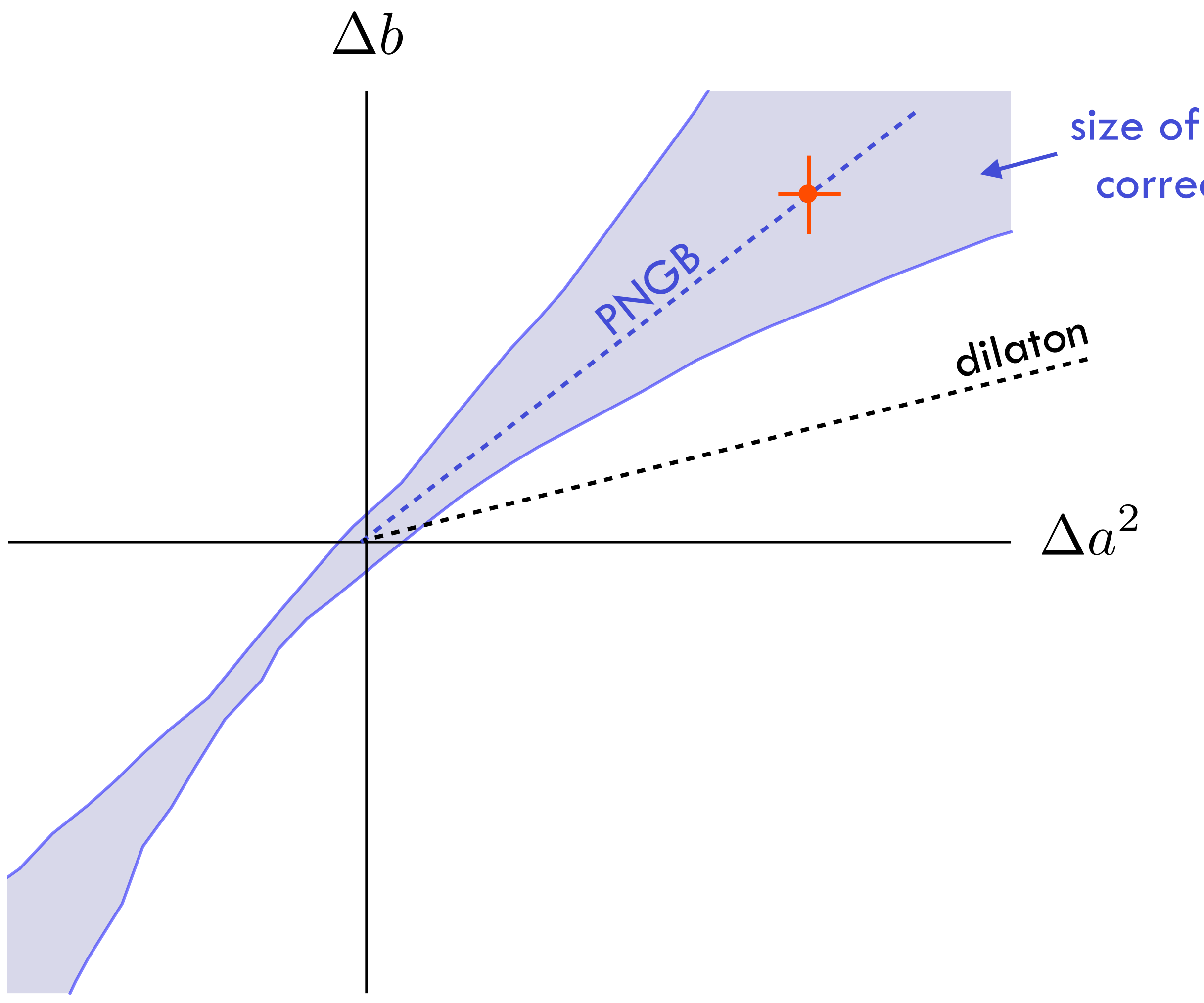

1. PNGB (and specific coset) proved

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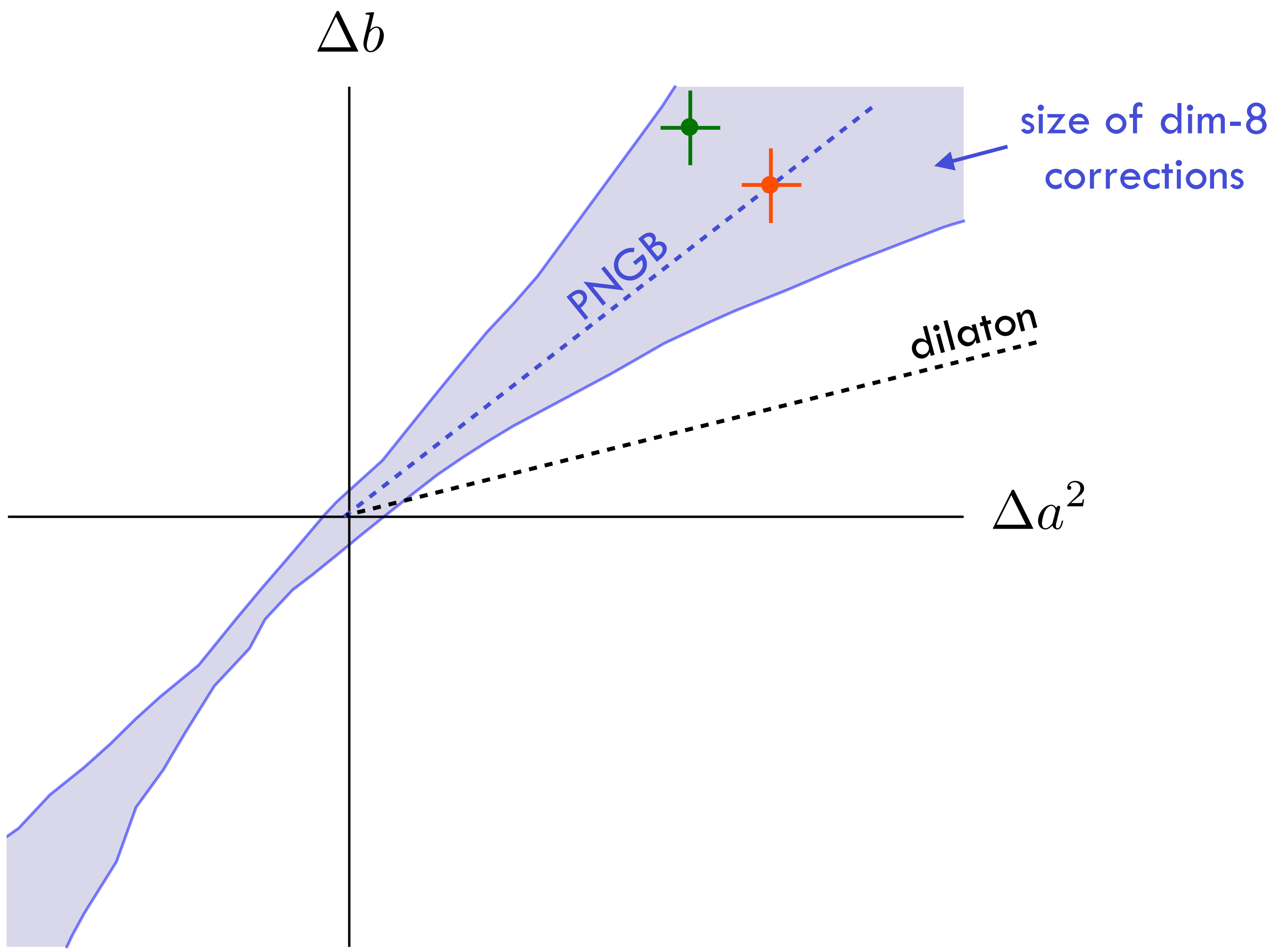

1. PNGB (and specific coset) proved

2. SILH proved, PNGB disproved

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

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Scenario 2:

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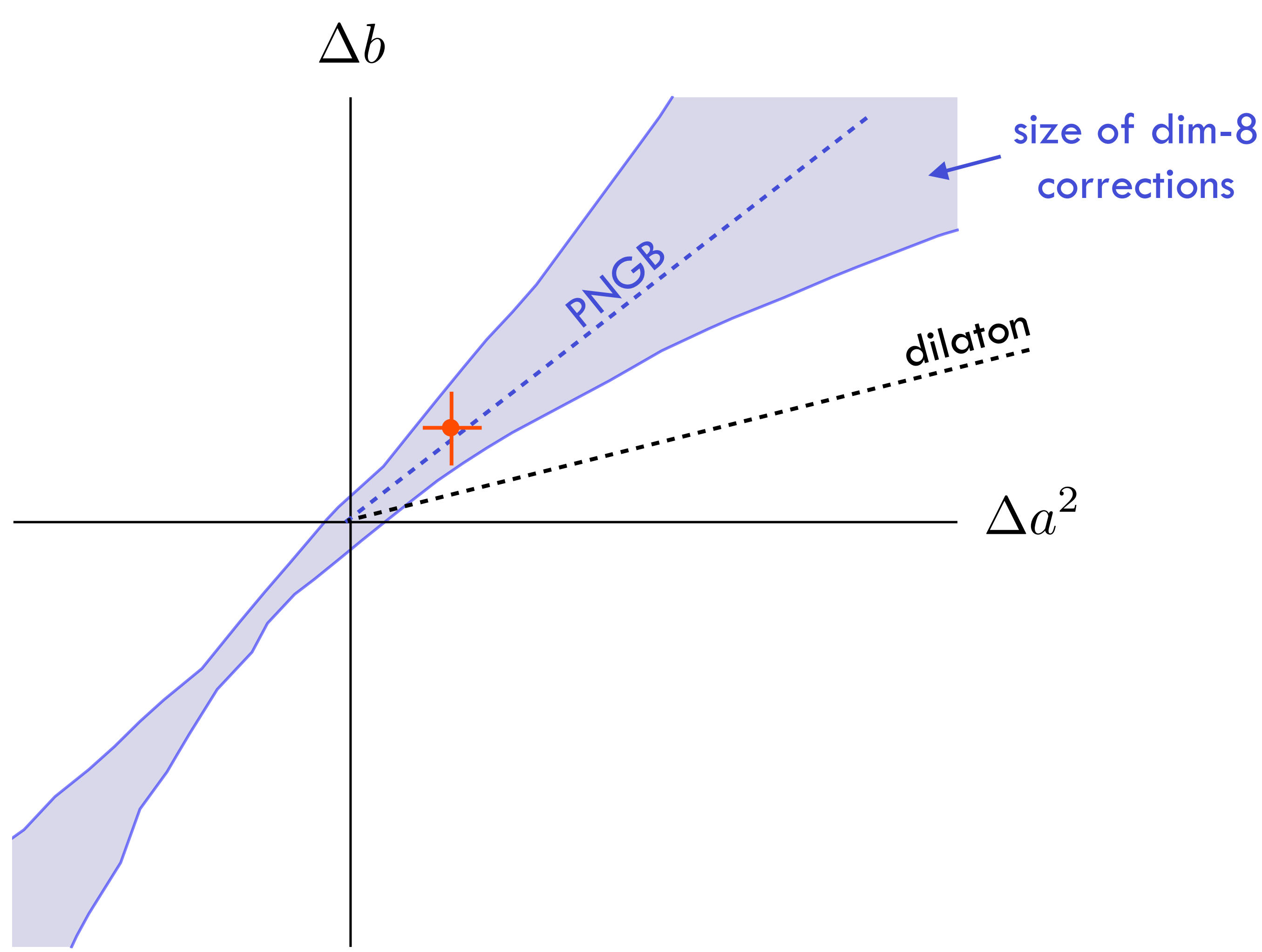
$$\text{Exp. precision} \sim 1\%$$

1. SILH proved



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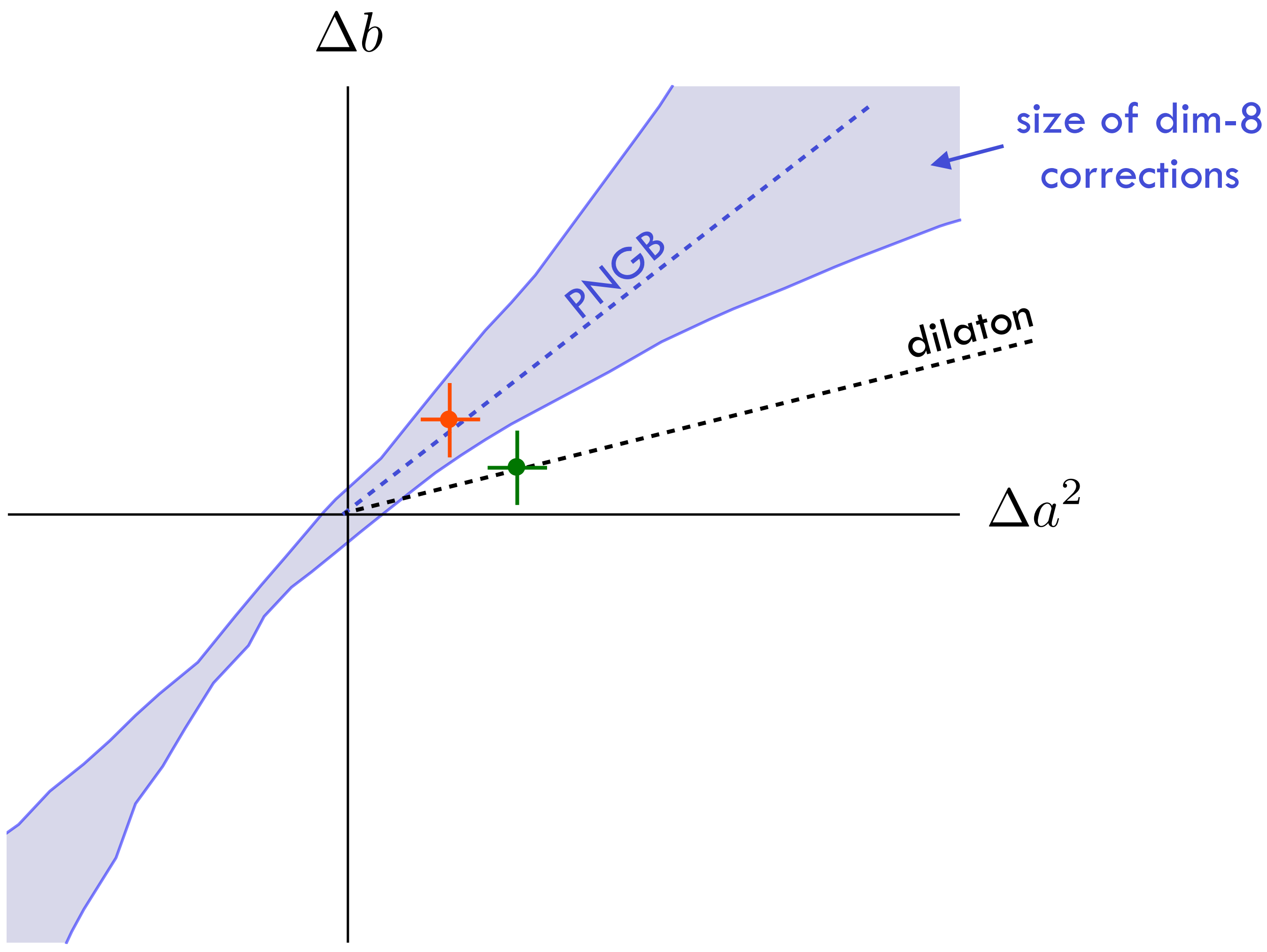
Exp. precision $\sim 1\%$

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



An e^+e^- collider with sqrt[s]=3TeV can reach a precision of a few% on the coupling b

$$e^+e^- \to \nu\bar{\nu}\, hh \to \nu\bar{\nu}\, b\bar{b}b\bar{b}$$

R.C. , Grojean, Pappadopulo, Rattazzi, Thamm, to appear

see also: Barger et al. PRD 67 (2003) 115001

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

δ_b	δ_{d_3} = -0.5	-0.3	-0.1	0	0.1	0.3	0.5
0	$-0.01^{+0.03}_{-0.09}$	$0.01^{+0.03}_{-0.1}$	$0.01^{+0.03}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.^{+0.03}_{-0.03}$	$0.^{+0.02}_{-0.03}$
0.01	$0.01^{+0.03}_{-0.1}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.03}$	$0.01^{+0.03}_{-0.03}$	$0.01^{+0.02}_{-0.03}$
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	$0.05^{+0.02}_{-0.03}$	$0.06^{+0.03}_{-0.03}$	$0.07^{+0.05}_{-0.03}$	$0.06^{+0.06}_{-0.03}$	$0.05^{+0.03}_{-0.03}$	$0.05^{+0.09}_{-0.02}$	$0.05^{+0.1}_{-0.02}$
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	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$	$0.5^{+0.02}_{-0.02}$

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

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

An e^+e^- collider with sqrt[s]=3TeV can reach a precision of a few% on the coupling b

$$e^+e^- \to \nu\bar{\nu}\, hh \to \nu\bar{\nu}\, b\bar{b}b\bar{b}$$

R.C. , Grojean, Pappadopulo, Rattazzi, Thamm, to appear

see also: Barger et al. PRD 67 (2003) 115001

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

δ_b	δ_{d_3} = -0.5	-0.3	-0.1	0	0.1	0.3	0.5
0	$-0.01^{+0.03}_{-0.09}$	$0.01^{+0.03}_{-0.1}$	$0.01^{+0.03}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.01^{+0.04}_{-0.04}$	$0.^{+0.03}_{-0.03}$	$0.^{+0.02}_{-0.03}$
0.01	$0.01^{+0.03}_{-0.1}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.03}_{-0.04}$	$0.02^{+0.04}_{-0.04}$	$0.02^{+0.04}_{-0.03}$	$0.01^{+0.03}_{-0.03}$	$0.01^{+0.02}_{-0.03}$
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	$0.05^{+0.02}_{-0.03}$	$0.06^{+0.03}_{-0.03}$	$0.07^{+0.05}_{-0.03}$	$0.06^{+0.06}_{-0.03}$	$0.05^{+0.03}_{-0.03}$	$0.05^{+0.09}_{-0.02}$	$0.05^{+0.1}_{-0.02}$
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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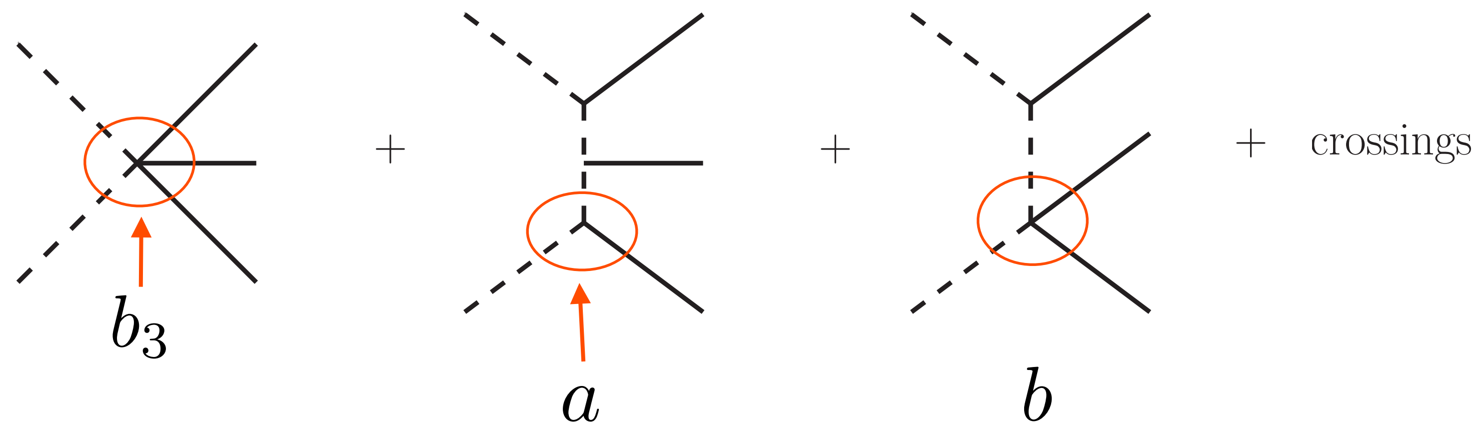
Further test of PNGB vs SILH   (more difficult): $WW \to hhh$



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

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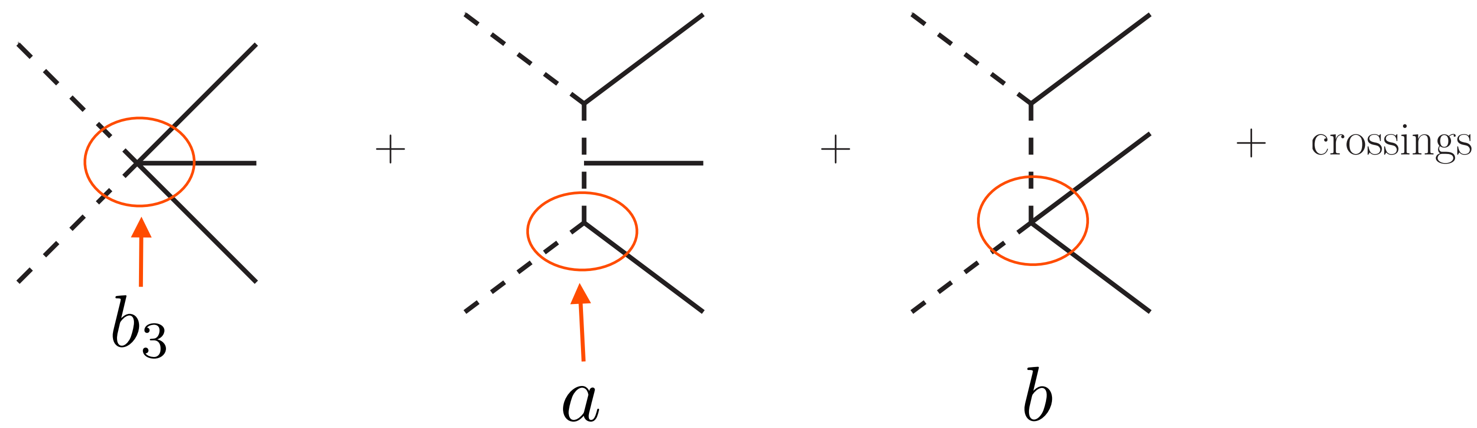

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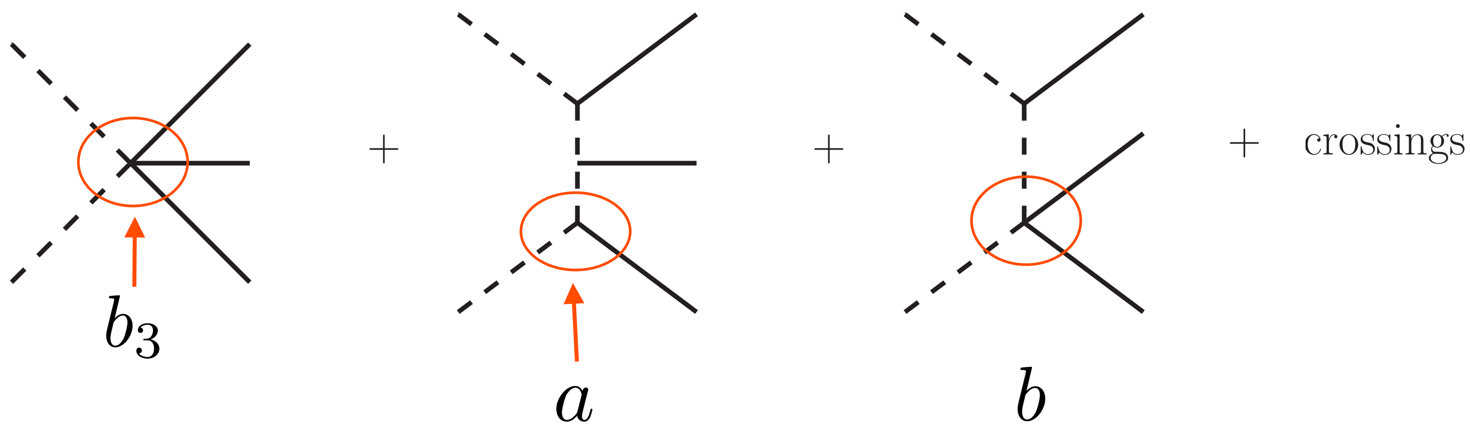

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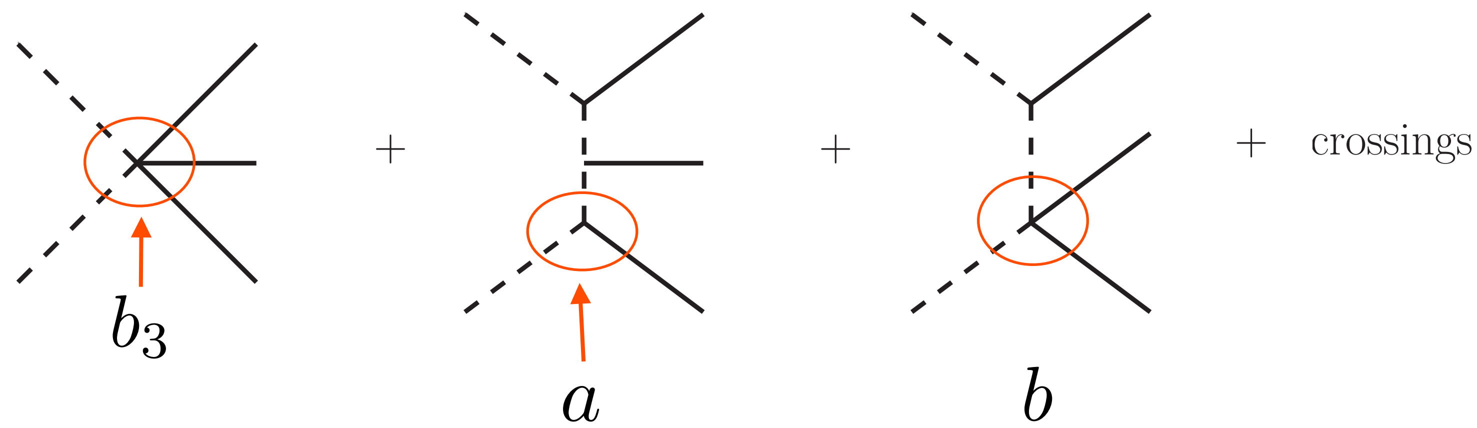

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Test dim-8 corrections

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 $\xi \gtrsim 0.2$ detectable for a SILH (PNGB disproved)

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- With high precision (ex: e^+e^- linear collider at 3TeV)

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