MODIFIED COUPLINGS FOR A LIGHT COMPOSITE HIGGS

Roberto Contino

Università di Roma La Sapienza

Part 1

Effective Lagrangians for a light Higgs

In absence of a direct observation of new particles, our ignorance of the EWSB sector can be parametrized in terms of an effective Lagrangian

- The explicit form of the Lagrangian depends on the assumptions one makes
- If new particles are discovered they can be included in the Lagrangian in a bottom-up approach

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I WILL ASSUME:

1) $SU(2)_L x U(1)_Y$ is linearly realized at high energies

2) h(x) is a scalar (CP even) and is part of an $SU(2)_L$ doublet H(x)

3) The EWSB dynamics has an (approximate) custodial symmetry

   global symmetry includes: $SU(2)_L x SU(2)_R \rightarrow SU(2)_V$

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Power Counting:

- each extra derivative costs a factor $1/\Lambda$
- each extra power of H(x) costs a factor $g_*/\Lambda \equiv 1/f$

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For a strongly-interacting Higgs: $$\frac{1}{f} \gg \frac{1}{\Lambda}$$

Giudice, Grojean, Pomarol, Rattazzi,
JHEP 0706 (2007) 045

The list of dim=6 operators of the effective Lagrangian has been known in the literature since long time

Buchmuller and Wyler, NPB 268 (1986) 621

In the following I will follow the SILH parametrization proposed in:

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$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\
& + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW} g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
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probe mass scale Λ
'Form factors'

$$+ \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

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Probes of Higgs strong interaction

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

$$\frac{c_y y_\psi}{f^2}\;H^\dagger H\,\bar{\psi}_L H\psi_R + h.c.$$

$$\frac{c_6\lambda_4}{f^2}\,(H^\dagger H)^3$$

Parametrize corrections to tree-level Higgs couplings:

$$\frac{\Delta c}{c_{SM}} \sim \frac{v^2}{f^2} = \left(\frac{g_* v}{\Lambda}\right)^2$$

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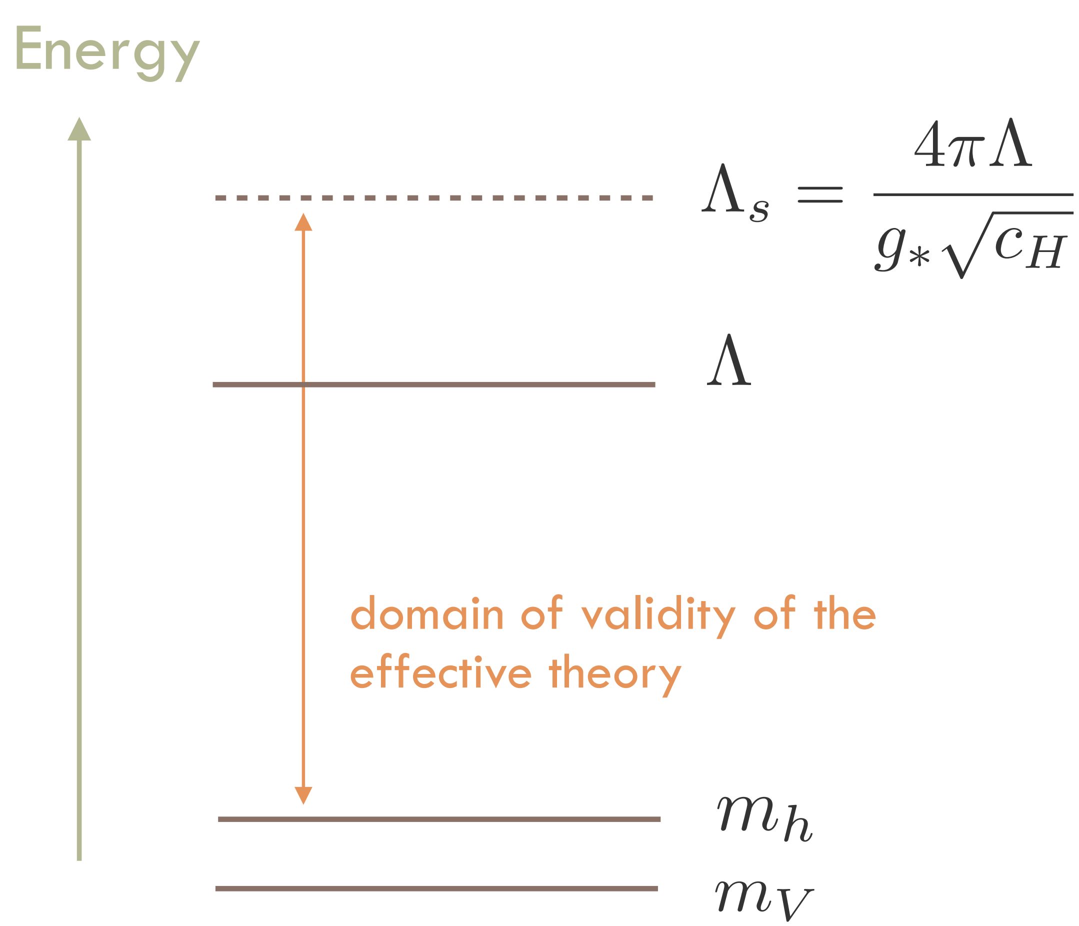

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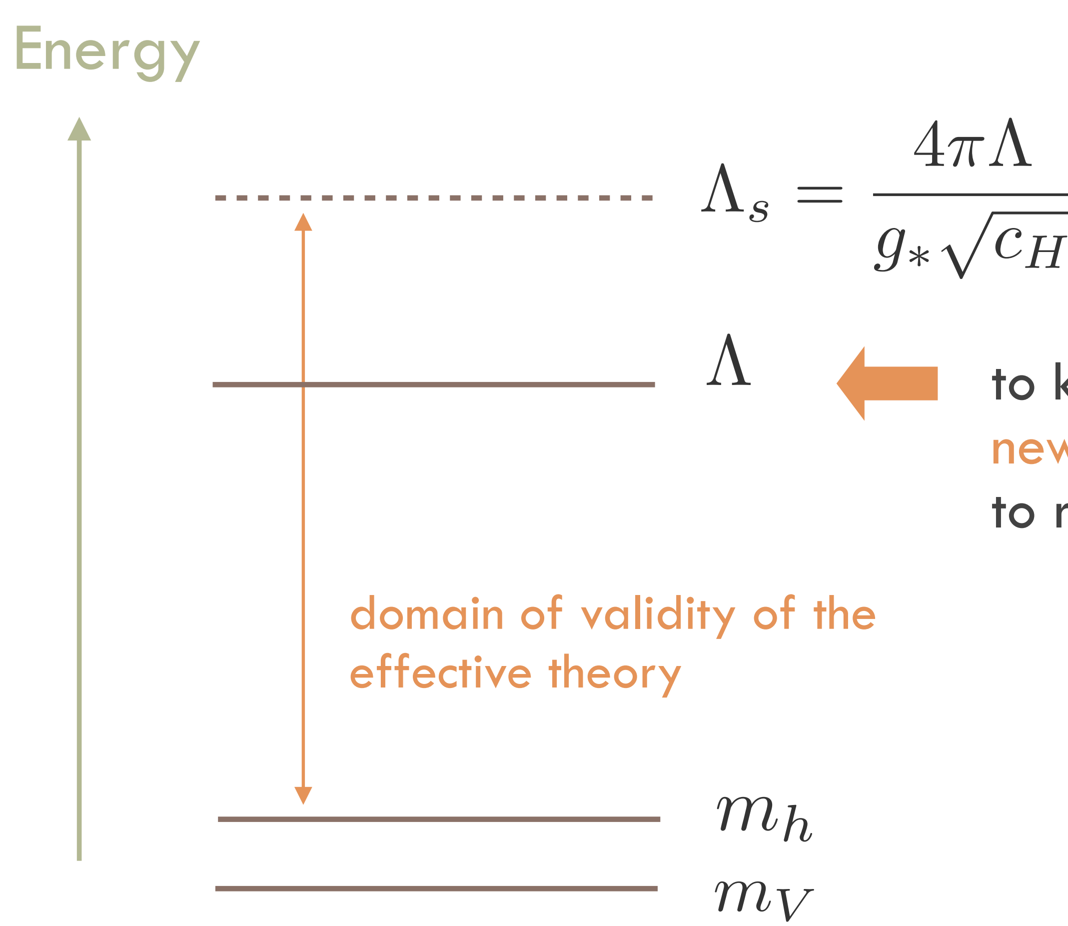

to keep the theory perturbative
new physics must come in before Λ_s
to regulate the scattering amplitudes

$$\frac{c_W g}{2\Lambda^2} \left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right) (D^\nu W_{\mu\nu})^a$$

$$\frac{c_B g'}{2\Lambda^2} \left(H^\dagger i \overleftrightarrow{D}^\mu H\right) (\partial^\nu B_{\mu\nu})$$

➡

$$D_\mu W^+_{\mu\nu} W^-_\nu h$$

$$\partial_\mu Z_{\mu\nu} Z_\nu h$$

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one linear combination fixed due to (accidental) custodial invariance

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

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subleading correction to tree-level couplings

$$\Delta c_V \sim \left(\frac{m_W^2}{\Lambda^2}\right)\left(\frac{v}{f}\right)^2$$

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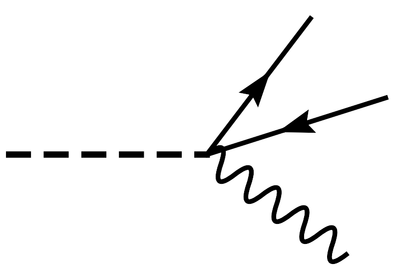
contact correction to three-body decays



$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{\Lambda^2}\right)$$

inclusive WW,ZZ observables

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

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subleading correction to tree-level couplings

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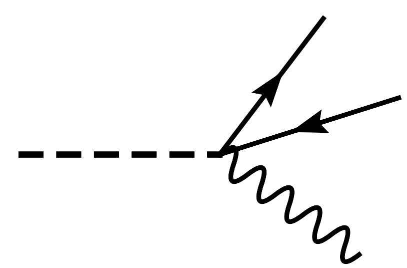
'Form factor' effects

contact correction to three-body decays



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subleading correction to tree-level couplings

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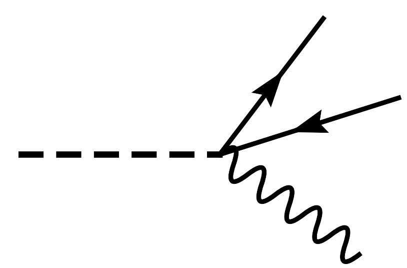

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{\Lambda^2}\right) \times \frac{16\pi^2}{g^2}$$

exclusive WW,ZZ observables and Zγ

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

$$\frac{c_W g}{2\Lambda^2}\left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^a$$

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$$\Delta c_V \sim \left(\frac{m_W^2}{\Lambda^2}\right)\left(\frac{v}{f}\right)^2$$

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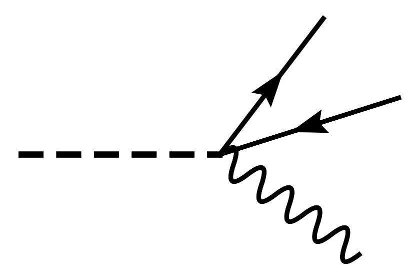

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Notice: LEP already puts strong bounds on these operators

$$\hat{S} = (c_W + c_B)\,\frac{m_W^2}{\Lambda^2} \lesssim 10^{-3}$$

effects expected to be small

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

$$\frac{i\, c_{HW}\, g}{\Lambda^2}\, (D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

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one linear combination starts at dim=8

$$\frac{c_g\, g_S^2}{\Lambda^2}\, G_{\mu\nu} G^{\mu\nu}\, H^\dagger H$$

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$$G_{\mu\nu} G_{\mu\nu} h$$

These operators imply couplings of photon and gluons to neutral particles and give corrections to the gyromagnetic ratios

$$c_{\gamma Z h} \propto (c_{HW} - c_{HB})$$

$$(g-2)_W \propto (c_{HW} + c_{HB})$$

$$\frac{g_*^2}{16\pi^2} \times \frac{i\, c_{HW}\, g}{\Lambda^2}\, (D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

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They cannot be generated by integrating out heavy states at tree-level in a minimally coupled gauge theory

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

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Corrections to *h*→*WW*, *ZZ* rates:

$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{\Lambda^2}\right) \frac{g_*^2}{16\pi^2}$$

'Form factor'

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

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$$\frac{g_*^2}{16\pi^2} \times \frac{c_\gamma\, g'^2}{\Lambda^2}\, B_{\mu\nu} B^{\mu\nu}\, H^\dagger H$$

→

$$W^+_{\mu\nu} W^-_{\mu\nu} h, \quad Z_{\mu\nu} Z_{\mu\nu} h,$$

$$\gamma_{\mu\nu}\gamma_{\mu\nu} h, \quad Z_{\mu\nu}\gamma_{\mu\nu} h$$

one linear combination starts at dim=8

$$\frac{g_*^2}{16\pi^2} \times \frac{c_g\, g_S^2}{\Lambda^2}\, G_{\mu\nu} G^{\mu\nu}\, H^\dagger H$$

$$G_{\mu\nu} G_{\mu\nu} h$$

Corrections to $h \to WW$, ZZ rates:

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{\Lambda^2}\right) \frac{g_*^2}{16\pi^2}$$

'Form factor'

Corrections to $h \to WW$, ZZ angular distributions and $h \to \gamma Z$ rate:

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right)$$

test Higgs strong interactions

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

$$\frac{g_*^2}{16\pi^2} \times \frac{i\,c_{HW}\,g}{\Lambda^2}\,(D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

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➡

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$$G_{\mu\nu}G_{\mu\nu}h$$

In principle *h*→γγ, *gg* rates also probe strong dynamics ...

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$$\frac{\lambda^2}{g_*^2} \times \frac{g_*^2}{16\pi^2} \times \frac{c_\gamma\, g'^2}{\Lambda^2}\; B_{\mu\nu} B^{\mu\nu}\, H^\dagger H$$

→

$$W^+_{\mu\nu} W^-_{\mu\nu} h, \quad Z_{\mu\nu} Z_{\mu\nu} h,$$

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In principle $h \to \gamma\gamma$, gg rates also probe strong dynamics …

$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right) \times \frac{\lambda^2}{g_*^2}$$

‘Form factor’

For a pNG boson Higgs additional suppression follows from breaking the shift symmetry

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

Effective Lagrangian in the unitary basis

$$
\begin{aligned}
\mathcal{L} = &\frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \ldots \\
&- \left(m_W^2\,W_\mu W^\mu + \frac{1}{2}m_Z^2\,Z_\mu Z^\mu\right)\left(1 + 2c_V\,\frac{h}{v} + \ldots\right) - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \ldots\right) \\
&+ \frac{\alpha_{em}}{8\pi}\left(2\,c_{WW}\,W^+_{\mu\nu}W^{-\,\mu\nu} + c_{ZZ}\,Z_{\mu\nu}Z^{\mu\nu} + 2\,c_{Z\gamma}\,Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\,\gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v} \\
&+ \frac{\alpha_s}{8\pi}\,c_{gg}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v} + c_W\left(W^-_\nu D_\mu W^{+\,\mu\nu} + h.c.\right)\frac{h}{v} + c_Z\,Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v} \\
&+ \left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v} + \ldots
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& - \left(m_W^2\, W_\mu W^\mu + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \right) \left(1 + 2 c_V\, \frac{h}{v} + \dots \right) - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)} \psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \dots \right) \\
& + \frac{\alpha_{em}}{8\pi} \left(2\, c_{WW}\, W^+_{\mu\nu} W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu} \gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu} \gamma^{\mu\nu} \right) \frac{h}{v} \\
& + \frac{\alpha_s}{8\pi}\, c_{gg}\, G^a_{\mu\nu} G^{a\,\mu\nu}\, \frac{h}{v} + c_W \left(W^-_\nu D_\mu W^{+\,\mu\nu} + h.c. \right) \frac{h}{v} + c_Z\, Z_\nu \partial_\mu Z^{\mu\nu}\, \frac{h}{v} \\
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\end{aligned}
$$

- The same effective Lagrangian describes a generic scalar h (custodial singlet) with $SU(2)_L x U(1)_Y$ non-linearly realized

  Each term can be dressed up with Nambu-Goldstone bosons and made manifestly $SU(2)_L x U(1)_Y$ invariant

RC, Grojean, Moretti, Piccinini, Rattazzi JHEP 1005 (2010) 089
Azatov, RC, Galloway JHEP 04 (2012) 127

Effective Lagrangian in the unitary basis

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& + \frac{\alpha_{em}}{8\pi} \left(2\, c_{WW}\, W^+_{\mu\nu} W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu}\gamma^{\mu\nu} \right) \frac{h}{v} \\
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\end{aligned}
$$

- The only predictions of SILH (for single Higgs processes) are:

(1) The deviation of each coupling from its SM value must be small

ex: $c_V = 1 + \frac{c_H}{2}\frac{v^2}{f^2}$

(2) The following relation holds: $c_{Z\gamma} = \frac{c_{WW}}{\sin(2\theta_W)} - \frac{c_{ZZ}}{2}\cot(\theta_W) - \frac{c_{\gamma\gamma}}{2}\tan(\theta_W)$

Effective Lagrangian in the unitary basis

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$$+ \frac{\alpha_s}{8\pi}c_{gg}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v} + c_W\,(W^-_\nu D_\mu W^{+\,\mu\nu} + h.c.)\,\frac{h}{v} + c_Z\,Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v}$$
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- Large deviations from SM couplings do not necessarily disprove a Higgs doublet (e.g. non-linearities can be large)

In that case a test of doublet/pNGB Higgs can come from double (and triple) Higgs processes

RC, Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089

RC, Grojean, Pappadopulo, Rattazzi, Thamm, work in progress

SO(5)/SO(4) non-linear sigma-model

Enlarge SO(4)/SO(3) to SO(5)/SO(4):

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

- four NG bosons form an $SU(2)_L$ doublet H(x): the Higgs is the fourth NG boson
- resums powers of H/f (Higgs non-linearities), while still assuming expansion in ∂/Λ

Validity: $E \ll \Lambda \leq 4\pi f$

SO(5)/SO(4) non-linear sigma-model

RULES:

- Dress up all operators with NG bosons and build the most general Lagrangian invariant under *local* SO(4) transformations

Building blocks: CCWZ variables

$$U(\pi) = e^{i\pi(x)/f}$$

$$-i\,U(\pi)^\dagger D_\mu U(\pi) \equiv d_\mu^{\hat{a}}\,T^{\hat{a}} + E_\mu^a\,T^a$$

$$d_\mu \sim \frac{D_\mu \pi}{f} + \dots \qquad E_\mu \sim A_\mu + \frac{1}{f^2}\,\pi \overleftrightarrow{D}_\mu \pi + \dots$$

$$d_\mu \to h(\pi,g)\,d_\mu\,h^{-1}(\pi,g)$$

$$E_\mu \to h(\pi,g)\,E_\mu\,h^{-1}(\pi,g) + i\,[\partial_\mu h(\pi,g)]h^{-1}(\pi,g)$$

$$h \in SO(4)$$

SO(5)/SO(4) non-linear sigma-model

O(p⁴) Lagrangian	SILH Lagrangian
$f^2\,\mathrm{Tr}(d_\mu d^\mu)$	O_H
$O_1^+ = [\mathrm{Tr}(d_\mu d^\mu)]^2$ $O_2^+ = [\mathrm{Tr}(d_\mu d_\nu)]^2$	dim=8
$O_3^\pm = \mathrm{Tr}\big[(E^L_{\mu\nu})^2 \pm (E^R_{\mu\nu})^2\big]$	$O_W\,,O_B$
$O_4^\pm = \mathrm{Tr}\big[(E^L_{\mu\nu} \pm E^R_{\mu\nu})\,i[d^\mu,d^\nu]\big]$	$O_{HW}\,,O_{HB}$
$O_5^- = [\mathrm{Tr}(T^{a_L}[d_\mu,d_\nu])]^2 - [\mathrm{Tr}(T^{a_R}[d_\mu,d_\nu])]^2$	dim=8

[RC, Marzocca, Pappadopulo, Rattazzi JHEP 1110 (2011) 081; Azatov, RC, Di Iura, Galloway, work in progress]

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Not included [require SO(5) breaking]: $B_{\mu\nu}B^{\mu\nu}H^\dagger H$ $\quad G^a_{\mu\nu}G^{a\,\mu\nu}H^\dagger H$ $\quad (H^\dagger H)^3$

[RC, Marzocca, Pappadopulo, Rattazzi JHEP 1110 (2011) 081; Azatov, RC, Di Iura, Galloway, work in progress]

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← Operators with +(−) superscript are even (odd) under a LR parity

P_{LR}:

$$\pi^{\hat{i}} \longrightarrow -\pi^{\hat{i}}$$
$$\pi^{\hat{4}} \longrightarrow +\pi^{\hat{4}}$$
$$\hat{i} = 1, 2, 3$$

$$d_\mu \longrightarrow P_{RL}\, d_\mu\, P_{LR}$$
$$E^L_\mu \leftrightarrow P_{RL}\, E^R_\mu\, P_{RL}$$

$$P_{LR} = \begin{pmatrix} -1 & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & +1 & \\ & & & & +1 \end{pmatrix}$$

$$O_1^+ = [\mathrm{Tr}(d_\mu d^\mu)]^2$$

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Notice: P_{LR}: is an <u>accidental</u> invariance at O(p²)

$$\mathcal{L}^{(2)} = \frac{f^2}{4}\,\mathrm{Tr}(d_\mu d^\mu)$$

Part 2

The decay $h \to Z\gamma$ in composite Higgs models

[Based on: Azatov, RC, Di Iura, Galloway, work in progress]

Why looking at h→Zγ

Mediated by two operators of the SILH Lagrangian:

$$O_{HW} = \frac{i\, c_{HW}\, g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

$$O_{HB} = \frac{i\, c_{HB}\, g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\mu H)\, B_{\mu\nu}$$

$$O_{BB} = \frac{c_{BB}\, g'^2}{16\pi^2 f^2}\, B_{\mu\nu} B^{\mu\nu}\, H^\dagger H$$

→

$$c_{Z\gamma} \left(\frac{\alpha_{em}}{2\pi}\right) \gamma_{\mu\nu} Z^{\mu\nu} \frac{h}{v}$$

$$c_{Z\gamma} = \frac{c_{HB} - c_{HW}}{4\sin(2\theta_W)} - 2\tan\theta_W\, c_{BB}$$

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only one breaks the Higgs shift symmetry

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$$c_{Z\gamma} = \frac{c_{HB} - c_{HW}}{4 \sin(2\theta_W)} - 2 \tan\theta_W\, c_{BB}$$

Unlike $h\to\gamma\gamma$, gg, the rate $h\to\gamma Z$ does not carry the extra spurion suppression:

$$\frac{\Gamma(h \to Z\gamma)}{\Gamma(h \to Z\gamma)_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right)$$

tests Higgs strong interactions

Why looking at h→Zγ

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$$O_{HW} = \frac{i\, c_{HW}\, g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

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$$c_{Z\gamma} = \frac{c_{HB} - c_{HW}}{4\sin(2\theta_W)} - 2\tan\theta_W\, c_{BB}$$

In the SO(5)/SO(4) Lagrangian there is one operator at O(p^4):

$$O_{HW} - O_{HB} \quad \longrightarrow \quad O_4^- = \mathrm{Tr}\big[(E^L_{\mu\nu} - E^R_{\mu\nu})\, i[d^\mu, d^\nu]\big]$$

$$c_{Z\gamma} = g^2 c_4^- \left(\frac{v}{f}\right)^2$$

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$$c_{Z\gamma} = g^2 c_4^- \left(\frac{v}{f}\right)^2$$

By integrating out heavy modes with mass M one expects:

$$c_4^-(m_h) = c_4^-(M) + \frac{b}{16\pi^2} \log \frac{M}{m_h}$$

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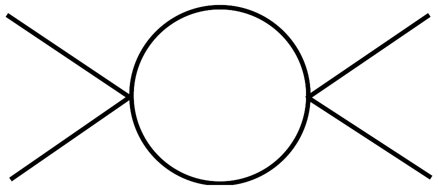
IR running due to light modes



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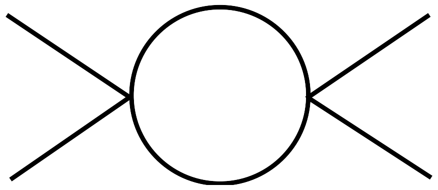

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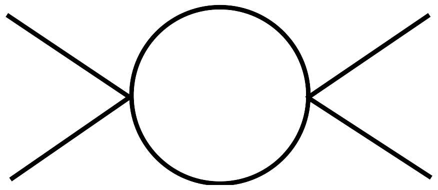

Naively the IR contribution would dominate over the UV one

<u>However</u>: $O_4^- = \mathrm{Tr}\big[(E^L_{\mu\nu} - E^R_{\mu\nu})\, i[d^\mu, d^\nu]\big]$ is *odd* under P_{LR}

Accidental P_{LR} invariance of the $O(p^2)$ Lagrangian forbids any running due NG bosons

By integrating out heavy modes with mass M one expects:

$$c_4^-(m_h) = c_4^-(M) + \frac{b}{16\pi^2}\log\frac{M}{m_h}$$

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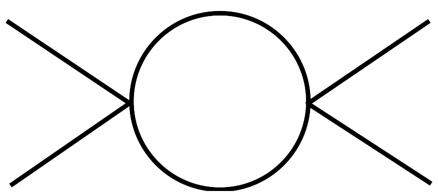
IR running due to light modes



Naively the IR contribution would dominate over the UV one

<u>However</u>: $O_4^- = \mathrm{Tr}\big[(E^L_{\mu\nu} - E^R_{\mu\nu})\, i[d^\mu, d^\nu]\big]$ is *odd* under P_{LR}

Accidental P_{LR} invariance of the $O(p^2)$ Lagrangian forbids any running due NG bosons

c_4^- entirely comes from UV threshold contributions

By integrating out heavy modes with mass M one expects:

$$c_4^-(m_h) = c_4^-(M) + \frac{b}{16\pi^2}\log\frac{M}{m_h}$$

at 1-loop: $\sim \dfrac{1}{16\pi^2}$

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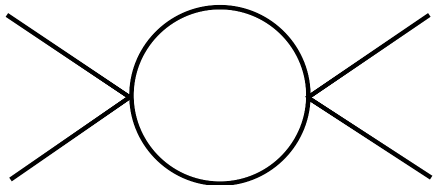

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If P_{LR} is an *exact* invariance of the strong dynamics, generating O_4^- costs an additional *weak* spurion factor:

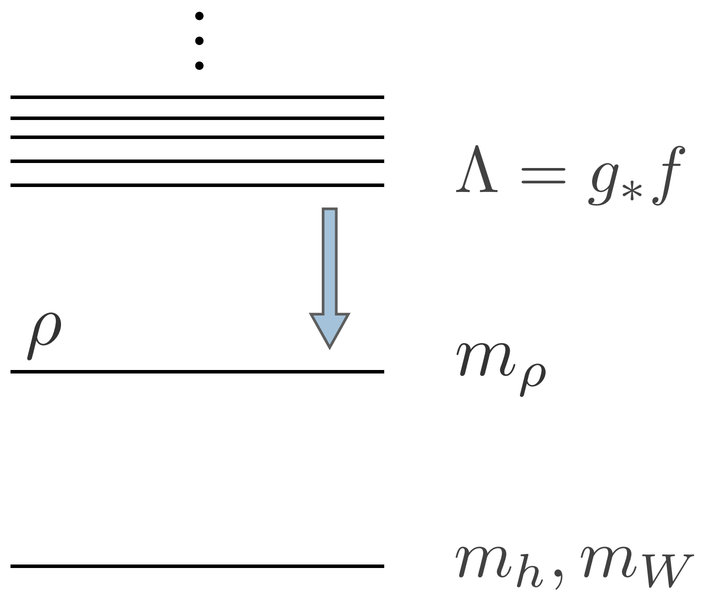
$$c_4^- \sim \frac{1}{16\pi^2} \times \frac{\lambda^2}{g_*^2}$$

← back to the estimate of $\gamma\gamma$, gg

Example #1: tree-level exchange of a heavy spin1

Consider the case of one spin-1 (3,1) of $SU(2)_L x SU(2)_R$ lighter than the other resonances

$$\rho_\mu \to h(\pi, g)\rho_\mu h^{-1}(\pi, g) + [\partial_\mu h(\pi, g)]\, h^{-1}(\pi, g)$$



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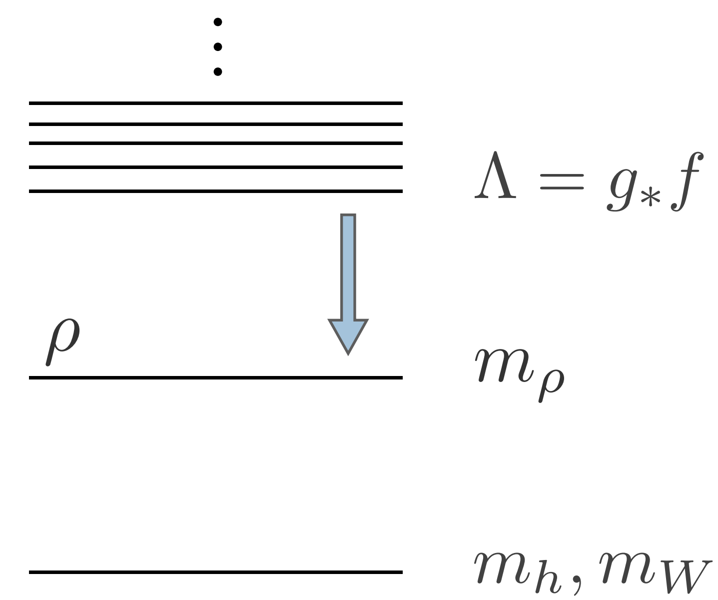

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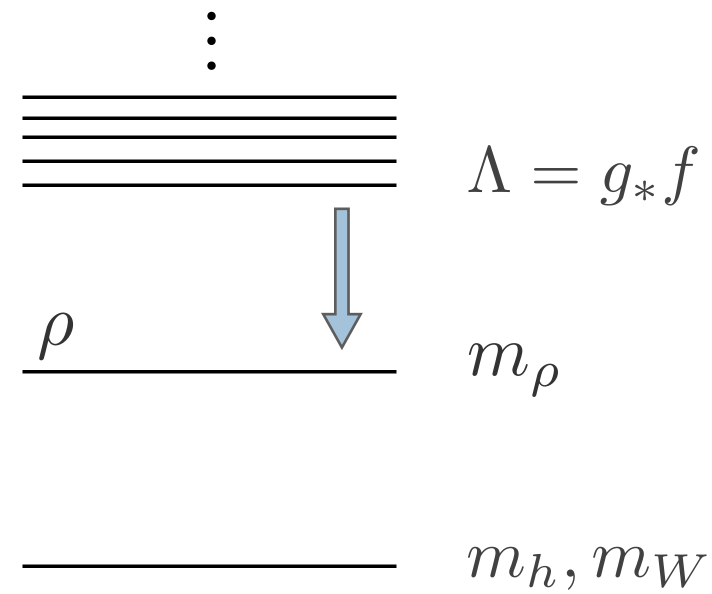

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Assumption: the derivative expansion of the Lagrangian is controlled by (∂/Λ):

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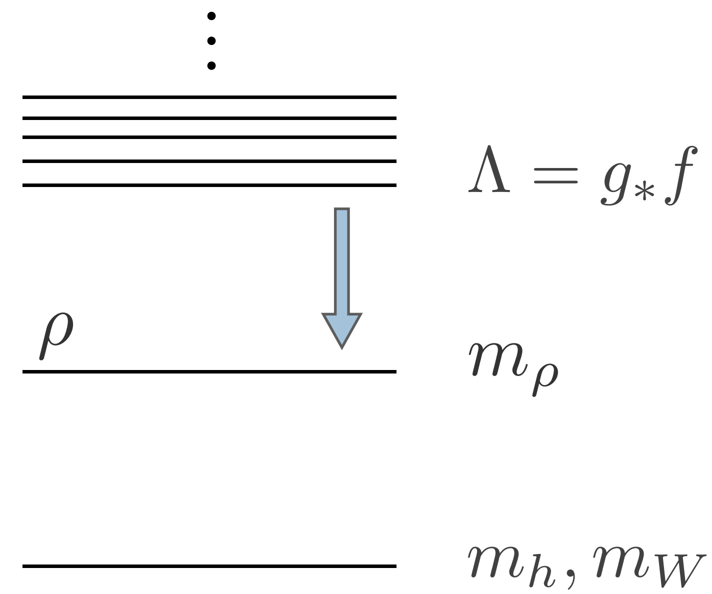

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$$Q_1 = \mathrm{Tr}\left(\rho^{\mu\nu}\, i[d_\mu, d_\nu]\right)$$

$$Q_2 = \mathrm{Tr}\left(\rho^{\mu\nu} f_{\mu\nu}^{+}\right)$$

leading operators in (∂/Λ)

Ex: $\alpha_1' (\nabla^\mu \bar{\rho}_\mu)^2$ has $\alpha_1' \lesssim \dfrac{m_\rho^2}{g_\rho^2 \Lambda^2} \sim \dfrac{1}{g_*^2}$

ρ can be integrated out by solving the e.o.m at lowest order

$$\rho_\mu = E_\mu + O(\partial^2/m_\rho^2)$$

$$\mathcal{L}_{eff} = \left(-\frac{1}{g_\rho^2} + \alpha_2\right) \mathrm{Tr}\Big[\big(E^L_{\mu\nu}\big)^2\Big] + (\alpha_1 - \alpha_2)\,\mathrm{Tr}\big[E^L_{\mu\nu}\, i[d_\mu, d_\nu]\big]$$

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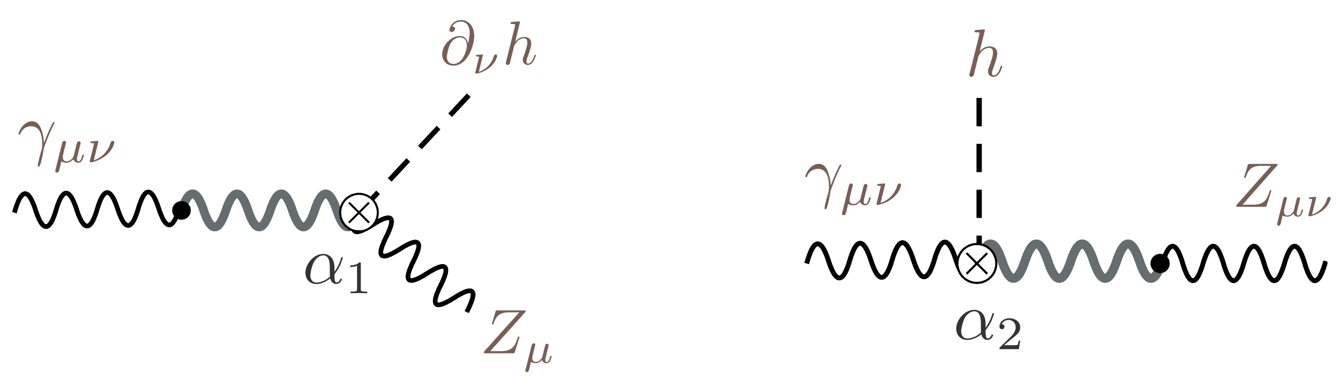
O_4^- generated if α_i are non-vanishing



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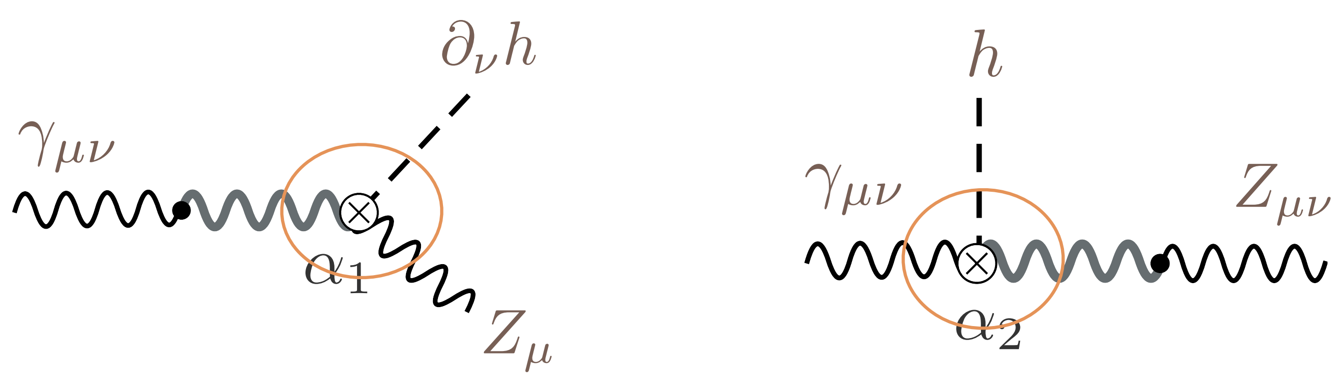

non-minimal couplings
(arise at loop level)

The coefficients α_i can be estimated by assuming the following criterion:

the strength of any interactions of the resonance does not exceed g_* up to the cutoff scale

[Partial UV completion]

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

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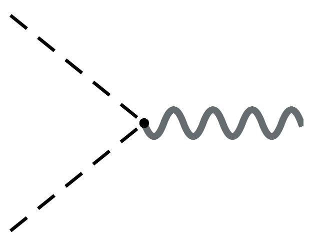

$$\mathcal{A}(\pi\pi\rho^{(T)}) \sim g_\rho \left[a_\rho^2 + \alpha_1 \frac{E^2}{f^2} \right]$$

$$\mathcal{A} \leq g_* \quad \text{for} \quad E \leq \Lambda \quad \longrightarrow \quad \alpha_1 \lesssim \frac{1}{g_* g_\rho} < \frac{1}{g_\rho^2}$$

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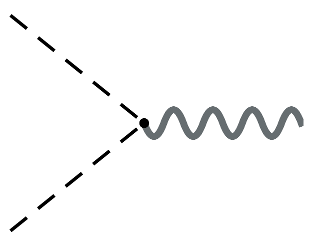

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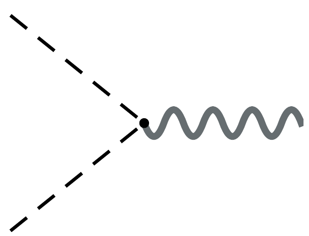

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In general: $$c_4^- = (\alpha_1^L - \alpha_1^R) - (\alpha_2^L - \alpha_2^R) \sim \frac{1}{16\pi^2}$$

Example #2: one loop of heavy fermions

Let us neglect the mixings with elementary fields and work in the CCWZ basis:

$$\mathcal{L} = \bar{\chi}\,(\gamma^\mu\, i\nabla_\mu - m)\,\chi + \zeta\;\bar{\chi}\,\gamma^\mu i d_\mu\,\chi$$

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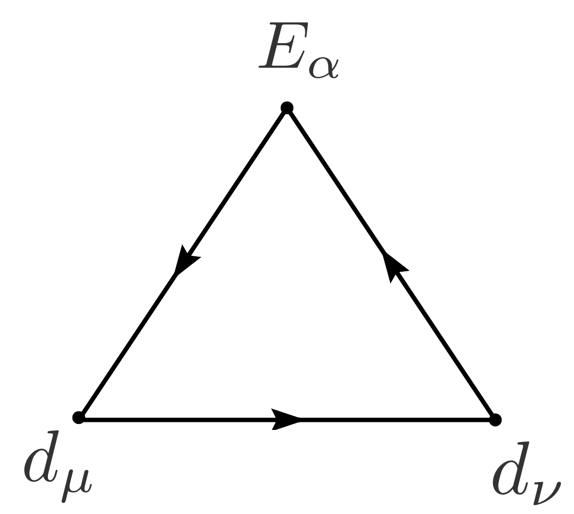
$$O_4^- = \mathrm{Tr}\big[(E^L_{\mu\nu} - E^R_{\mu\nu})\, i[d^\mu, d^\nu]\big]$$



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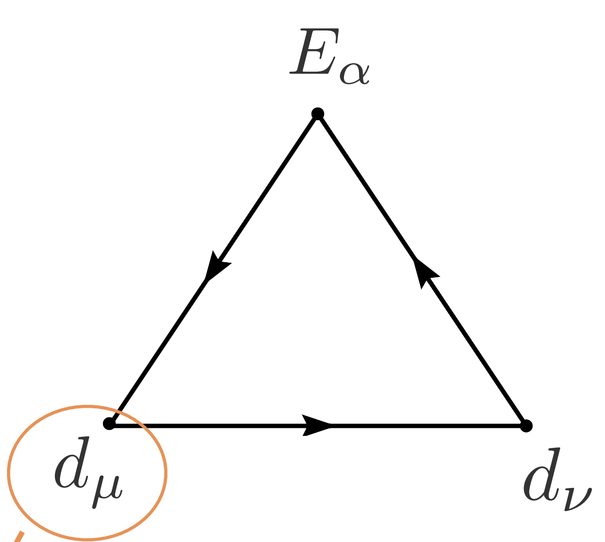

SO(5) explicit breaking from gauging entirely subsumed into the external legs

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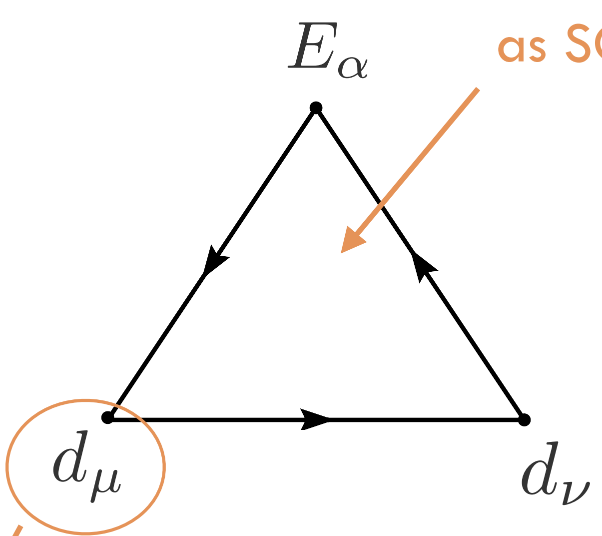
no SO(5) explicit breaking into the loop: fermions can be taken as SO(4) eigenstates



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$$\chi = (2,2) \oplus (1,1) = \{\chi_4, \chi_1\}$$

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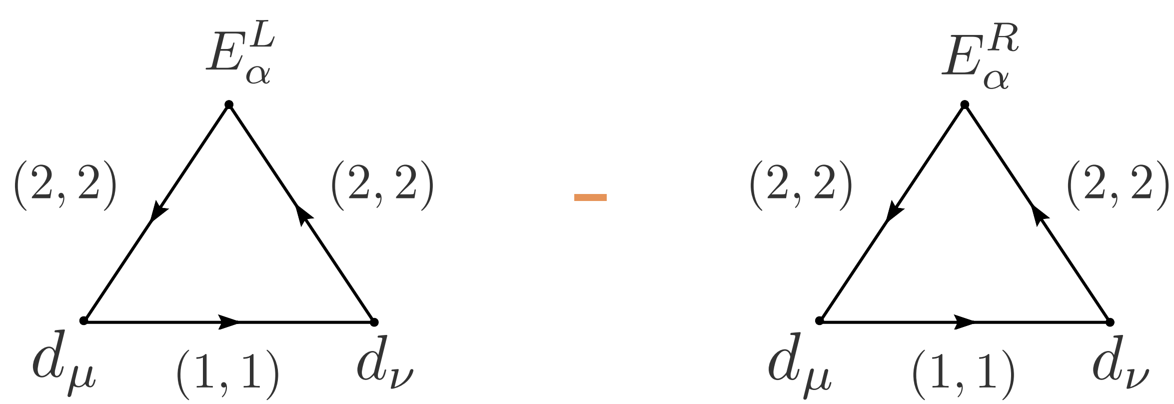

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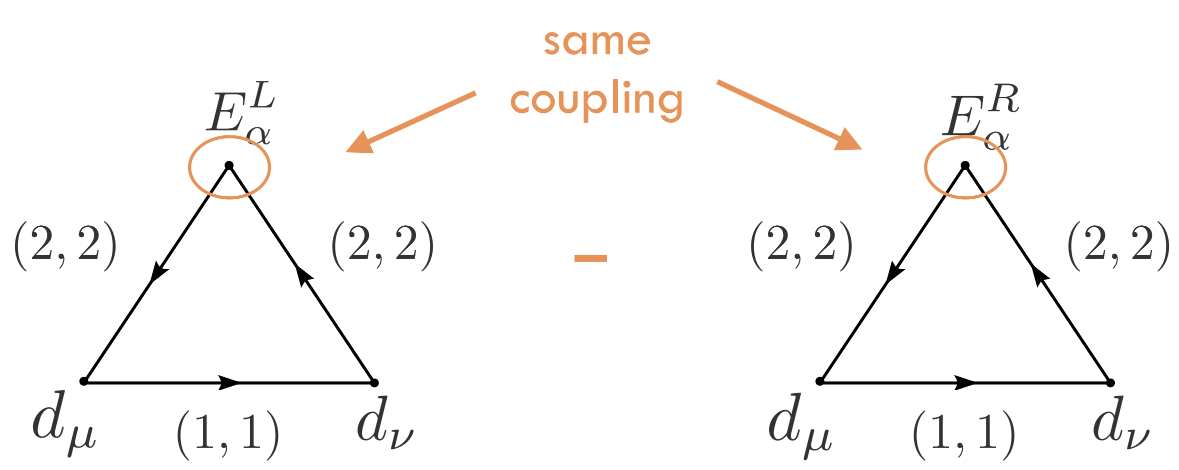

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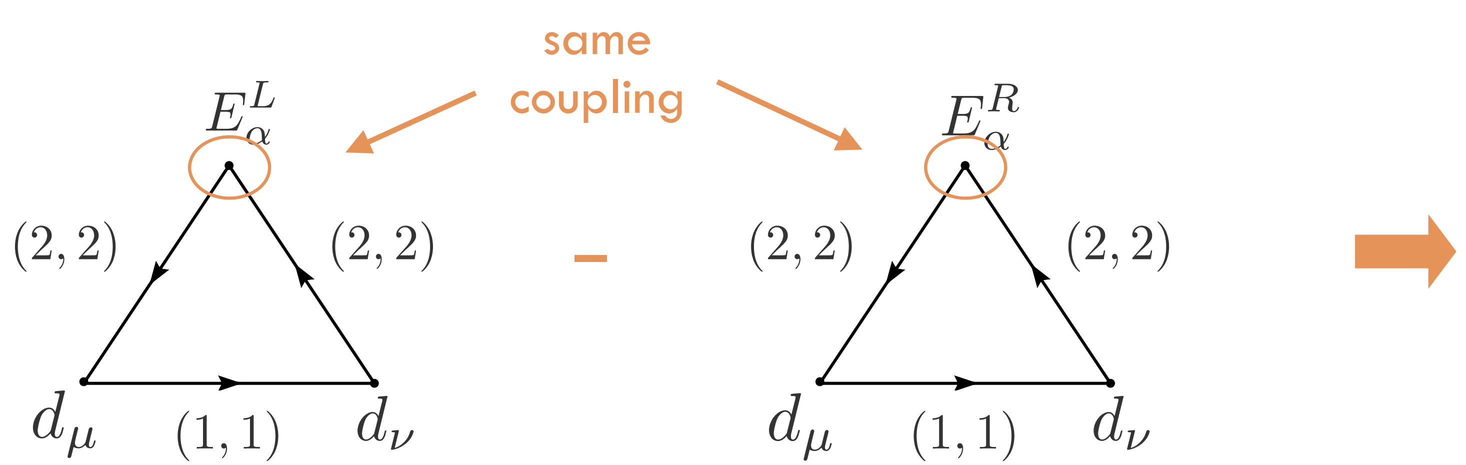

$$c_4^- = 0$$

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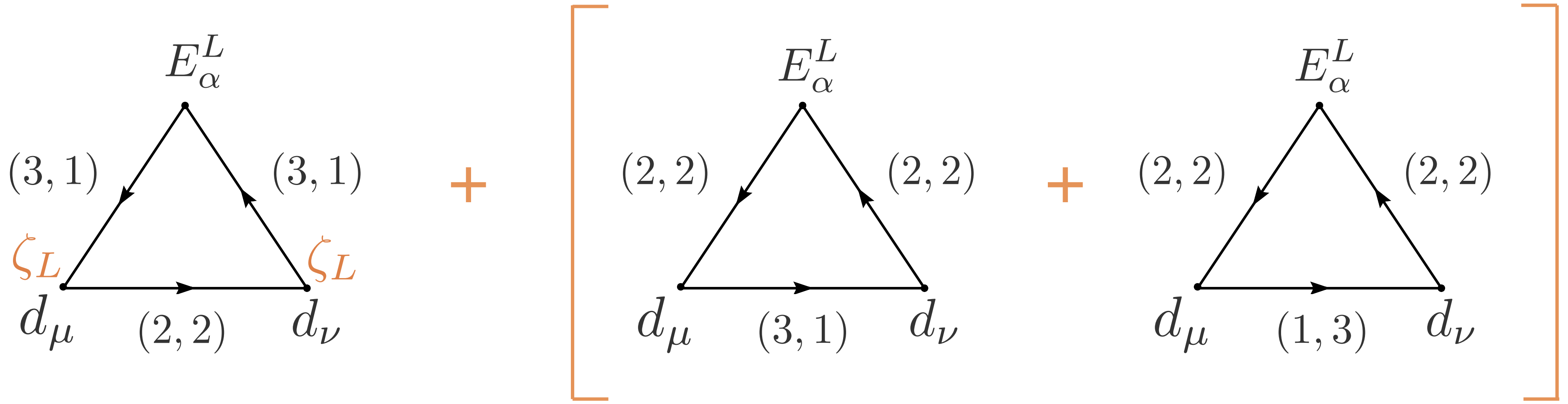

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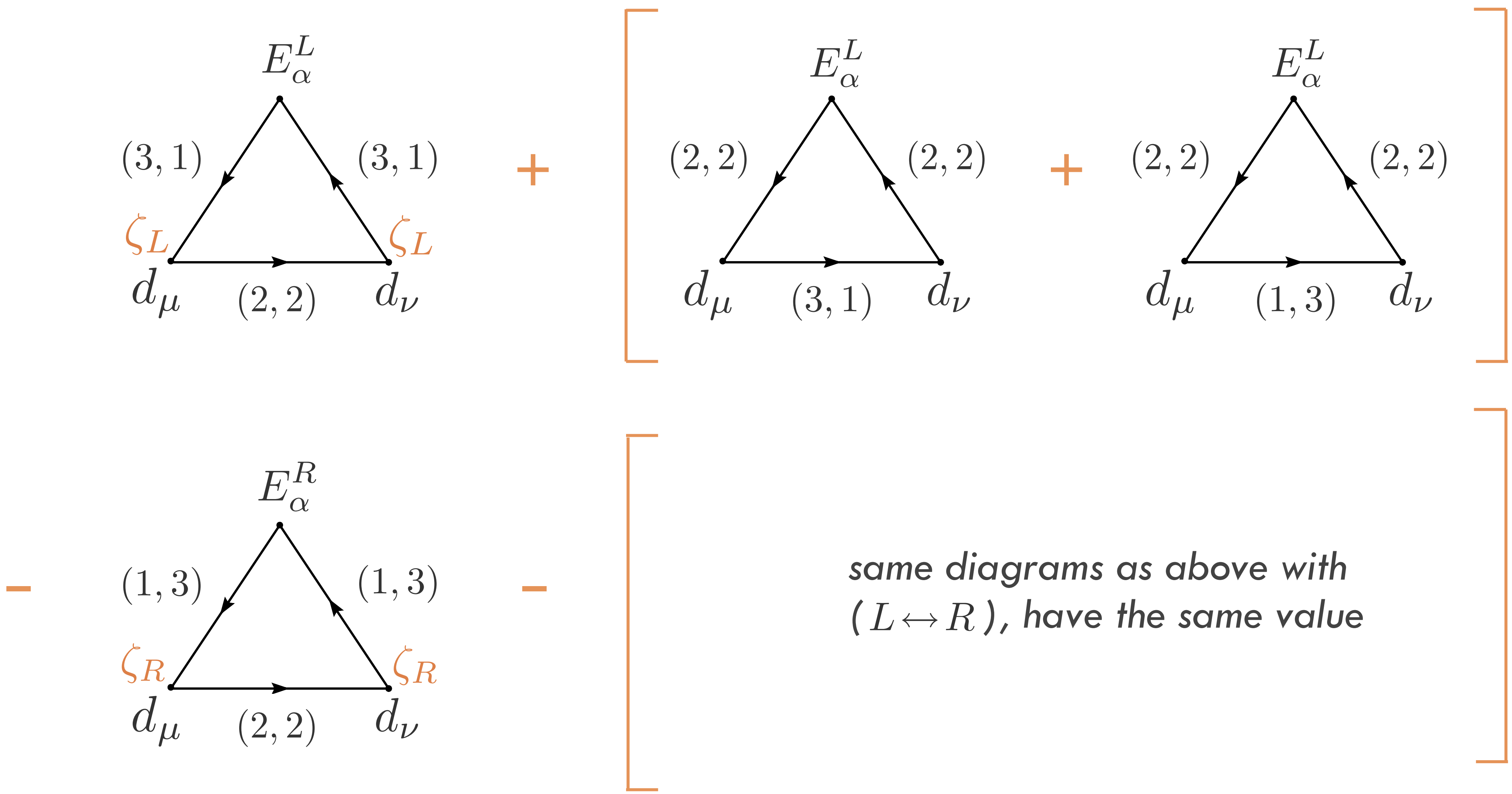

In general:

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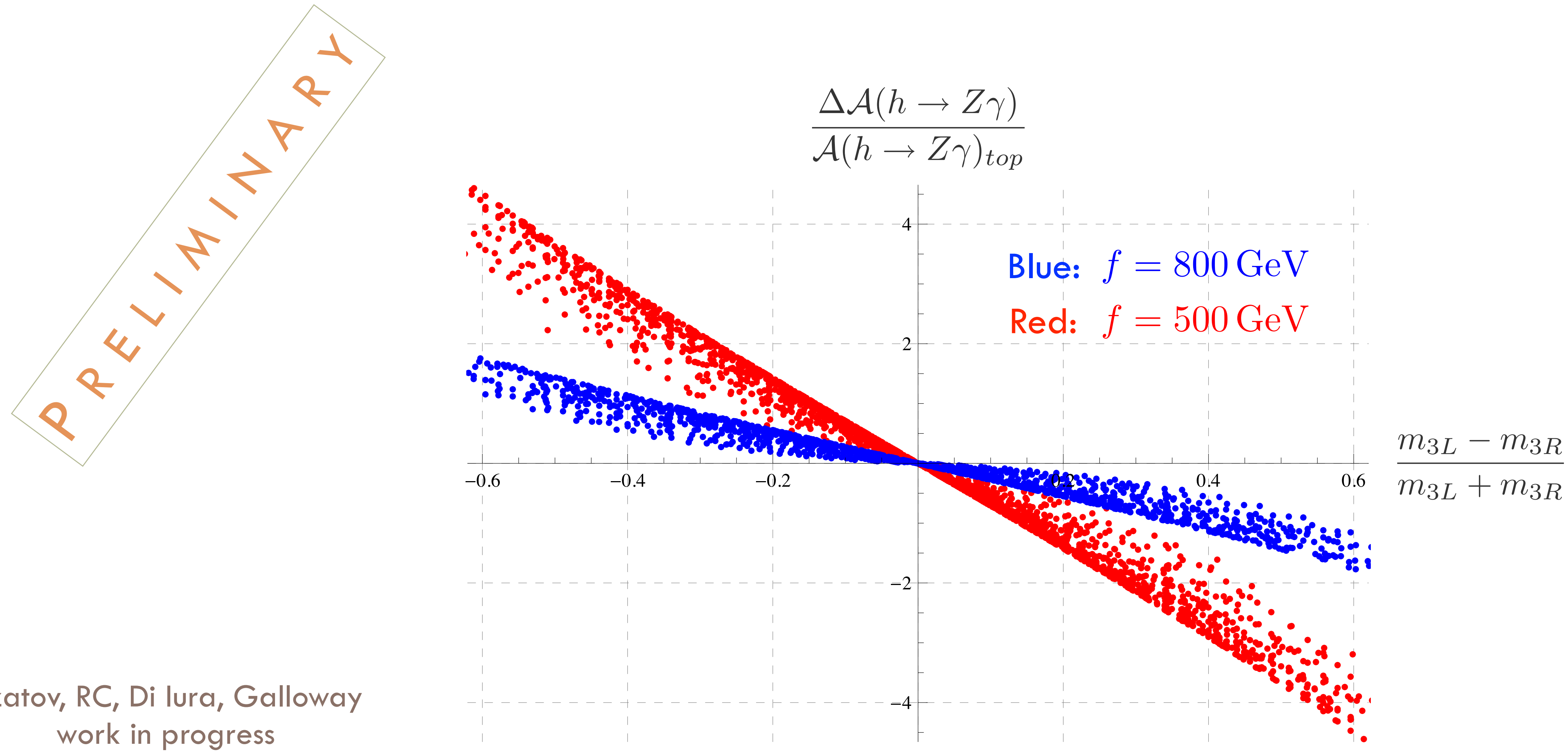

Azatov, RC, Di Iura, Galloway
work in progress

for $\zeta_L = \zeta_R = 1$ varying m_4, m_{3L}, m_{3R} between $[2f, 10f]$

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- Yet scenarios with O(1) enhancements in $h \to Z\gamma$ exist, and an experimental measurement would be important