EFFECTIVE LAGRANGIAN FOR A LIGHT (COMPOSITE) HIGGS

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partly based on work in progress with M. Ghezzi, C. Grojean, M. Muehlleitner

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) $SU(2)_L \times U(1)_Y$ 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: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$

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

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I will follow the parametrization and the analysis of:

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POWER COUNTING:

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

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

$$\Delta\mathcal{L} = \Delta\mathcal{L}_B + \Delta\mathcal{L}_F$$

$$\begin{aligned}\Delta\mathcal{L}_B =\ & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\big(H^\dagger H\big)\,\partial_\mu\big(H^\dagger H\big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\,\big(H^\dagger H\big)^3 \\
& + \frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c. \\
& + \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW} g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma {g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,\end{aligned}$$

$$\Delta\mathcal{L} = \Delta\mathcal{L}_B + \Delta\mathcal{L}_F$$

the request of
custodial invariance
forbids this operator

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$$+ \frac{i\bar{c}_W g}{2m_W^2}\Big(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\Big)\,(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2}\Big(H^\dagger \overleftrightarrow{D^\mu} H\Big)\,(\partial^\nu B_{\mu\nu})$$

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probe Higgs strong coupling g_*

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probe mass scale Λ
'Form factors'

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- Absence of FCNC from tree-level exchange of the Higgs requires flavor alignment

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NDA estimate:

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_f \sim O\left(\frac{v^2}{f^2}\right), \qquad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right)$$

$$\bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\Delta\mathcal{L} = \Delta\mathcal{L}_B + \Delta\mathcal{L}_F$$

$$\begin{aligned}\Delta\mathcal{L}_F = &\frac{\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\ &+ \frac{\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\ &+ \frac{\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c. \\ &+ \frac{\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) \\ &+ \frac{\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\end{aligned}$$

- To generate these operator New Physics must couple directly to SM fermions

NDA estimate: $\bar{c}_{Hq}, \bar{c}'_{Hq}, \bar{c}_{Hu}, \bar{c}_{Hd}, \bar{c}_{Hud}, \bar{c}_{HL}, \bar{c}'_{HL}, \bar{c}_{Hl} \sim O\left(\frac{\lambda^2}{g_*^2}\frac{v^2}{f^2}\right)$

Probes of Higgs strong interaction

$$\frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$$

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

$$\frac{\bar{c}_6\lambda_4}{v^2}\left(H^\dagger H\right)^3$$

Parametrize corrections to tree-level Higgs couplings:

$$\frac{\Delta c}{c_{SM}} \sim \frac{v^2}{f^2} \equiv \xi$$

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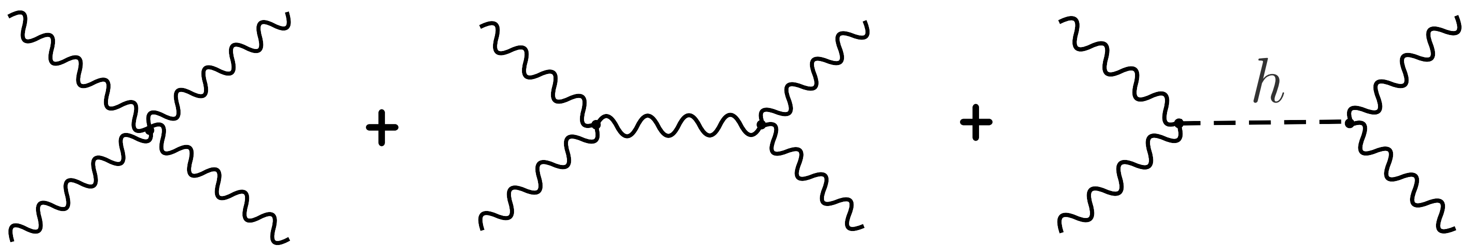
In the unitary gauge:

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \dots$$
$$-\left(m_W^2\,W_\mu W^\mu + \frac{1}{2}m_Z^2\,Z_\mu Z^\mu\right)\left(1 + 2c_V\,\frac{h}{v} + \dots\right) - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \dots\right)$$

$$c_V = 1 - \frac{\bar{c}_H}{2} \qquad c_\psi = 1 - \left(\frac{\bar{c}_H}{2} + \bar{c}_\psi\right) \qquad d_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

For any value $c_V, c_\psi \neq 1$ the theory becomes strongly interacting at high energies

Ex:



$$= \left(1 - c_V^2\right) \frac{s+t}{v^2} + \ldots$$

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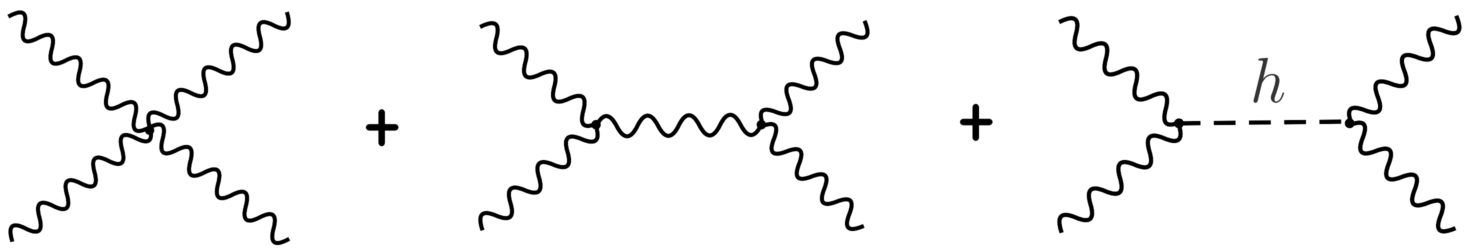

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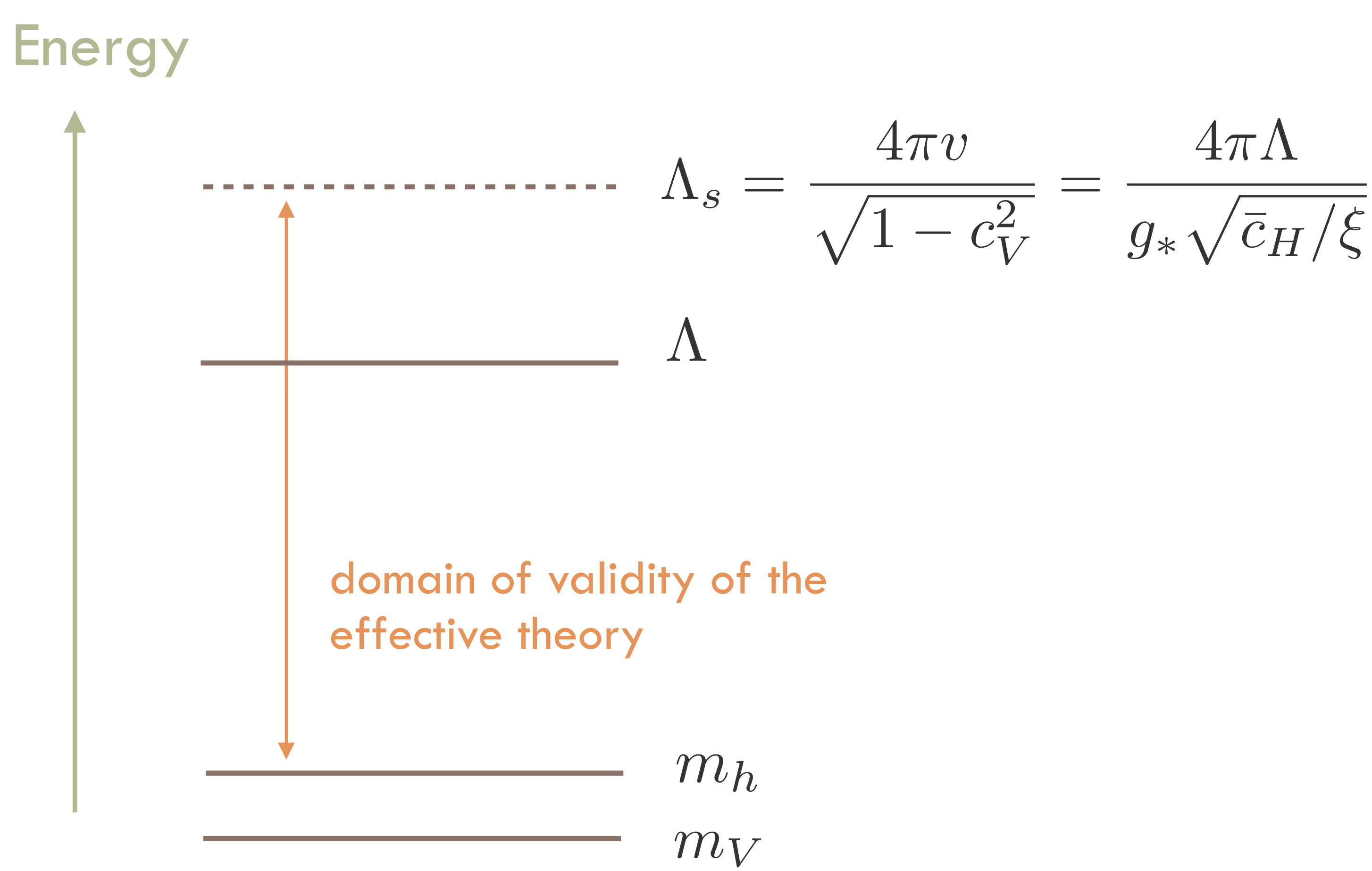

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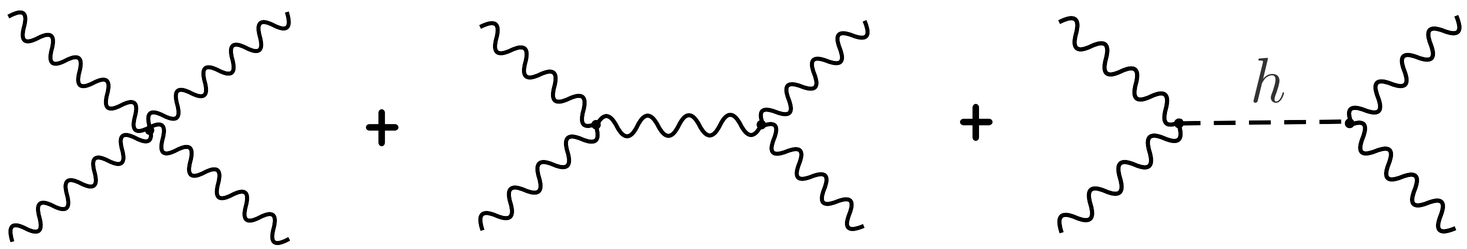

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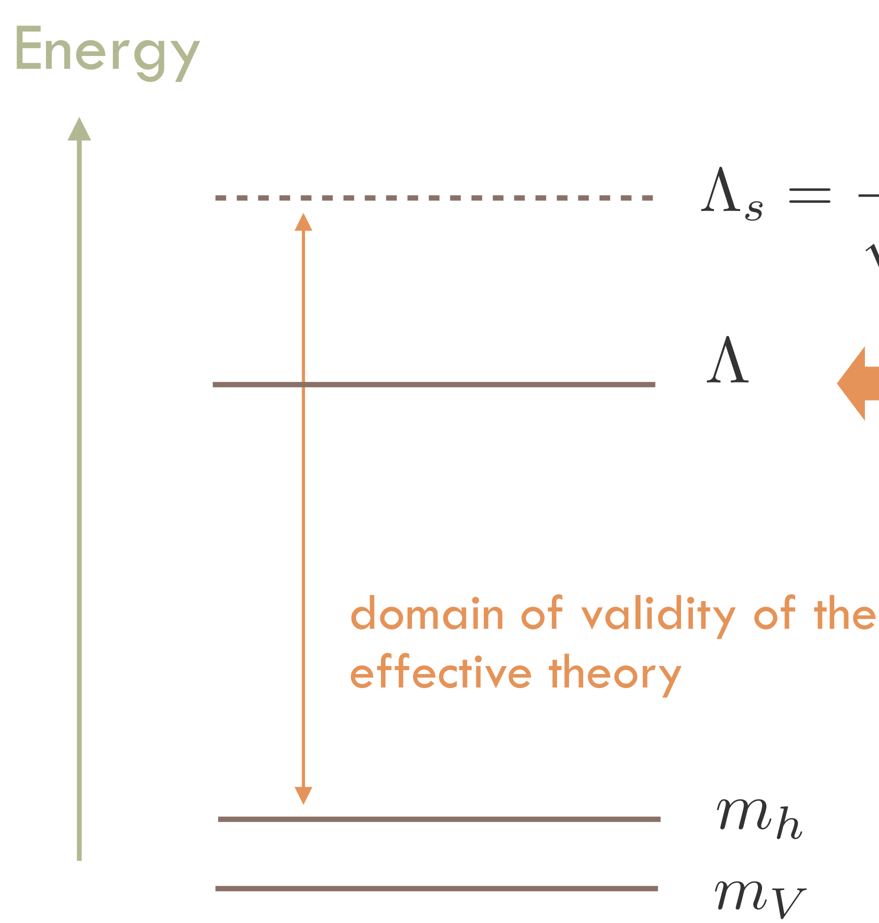
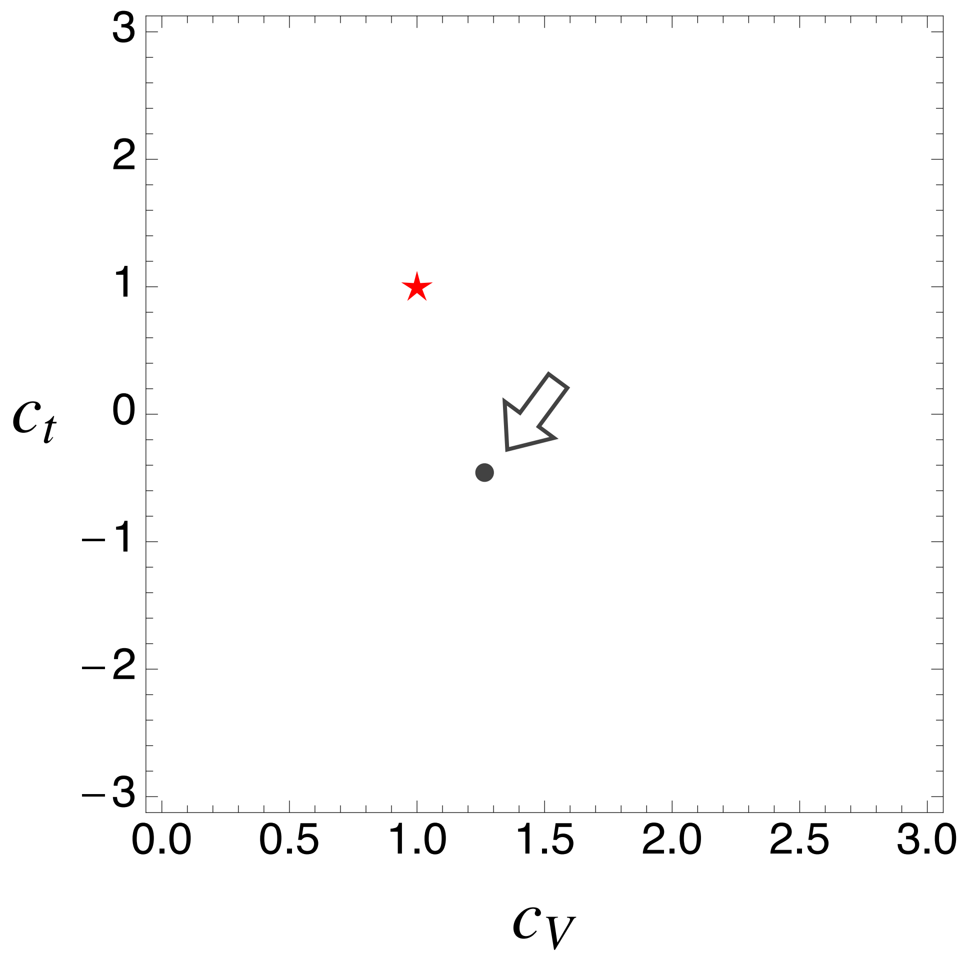


$$\Lambda_s = \frac{4\pi v}{\sqrt{1-c_V^2}} = \frac{4\pi\Lambda}{g_*\sqrt{\bar{c}_H/\xi}}$$

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

Ex: suppose LHC measures $(c_V, c_u) \neq (1,1)$



$$\Lambda_V = \frac{4\pi v}{\sqrt{|1-c_V^2|}}$$

(scale of strong $WW \to WW$)

$$\Lambda_t = \frac{16\pi^2 v^2}{m_t} \frac{1}{|1-c_V c_u|}$$

(scale of strong $WW \to t\bar{t}$)

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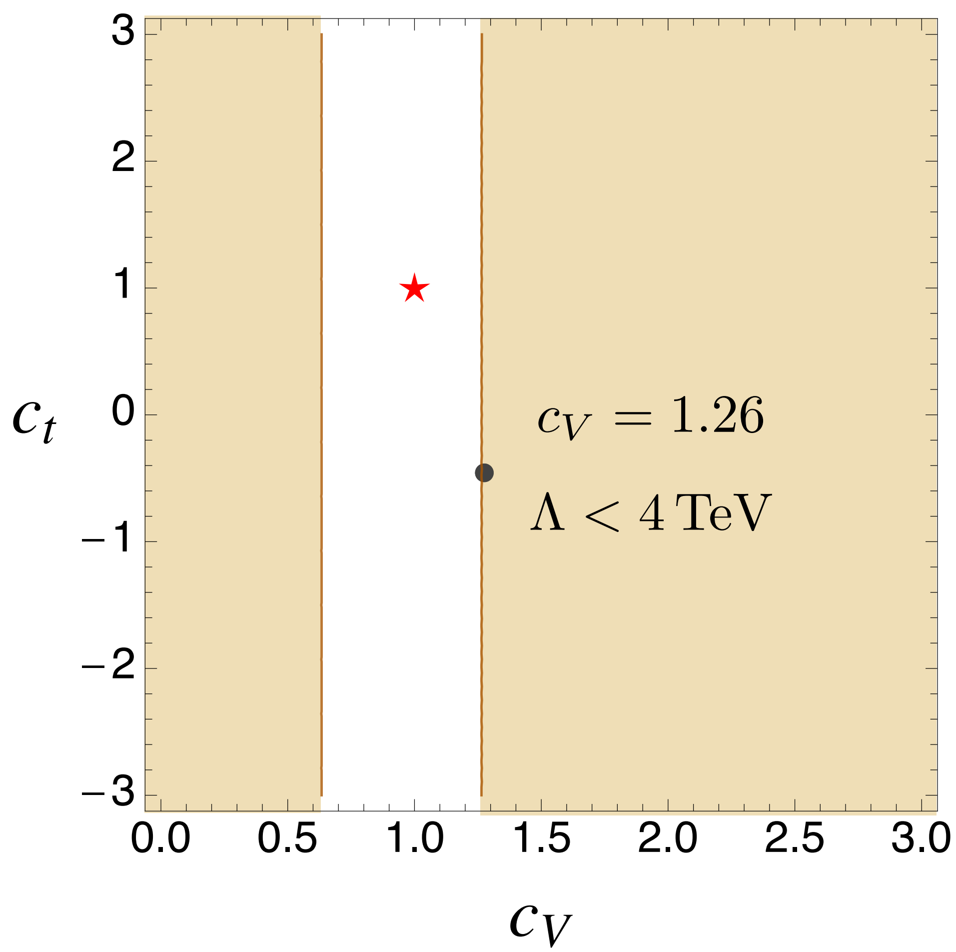

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coupling c_V quite sensitive to strong scale

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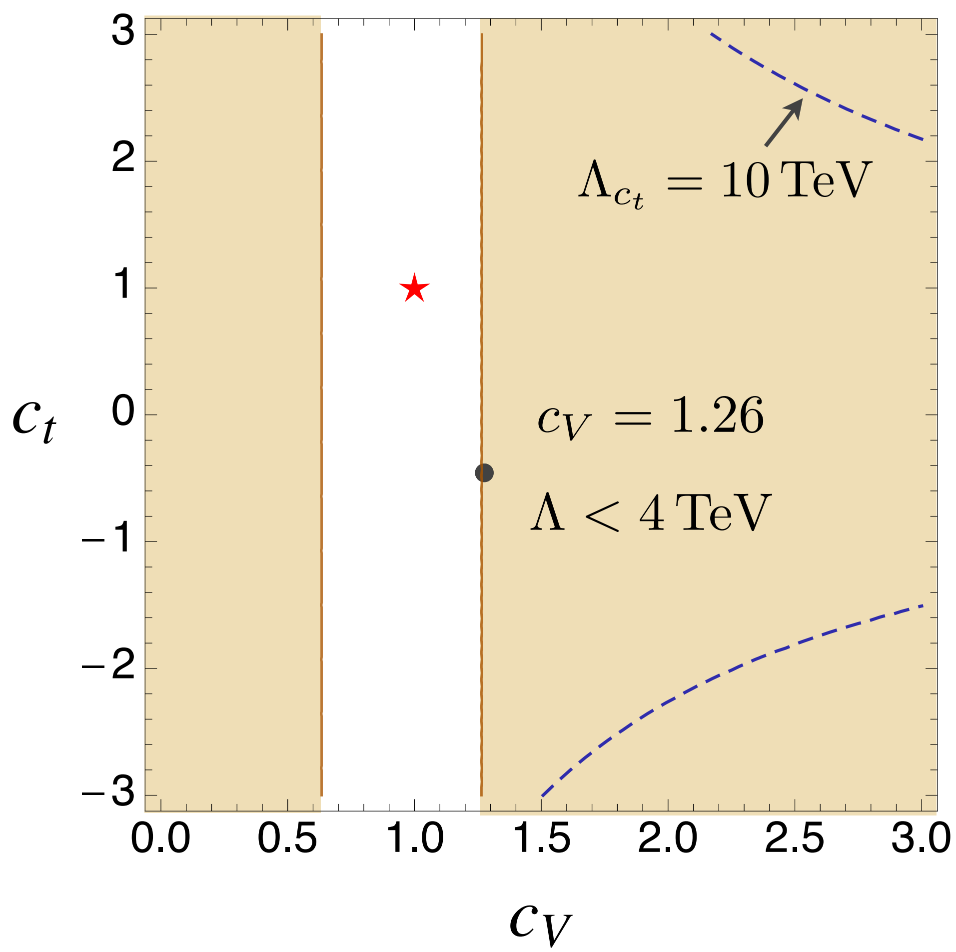

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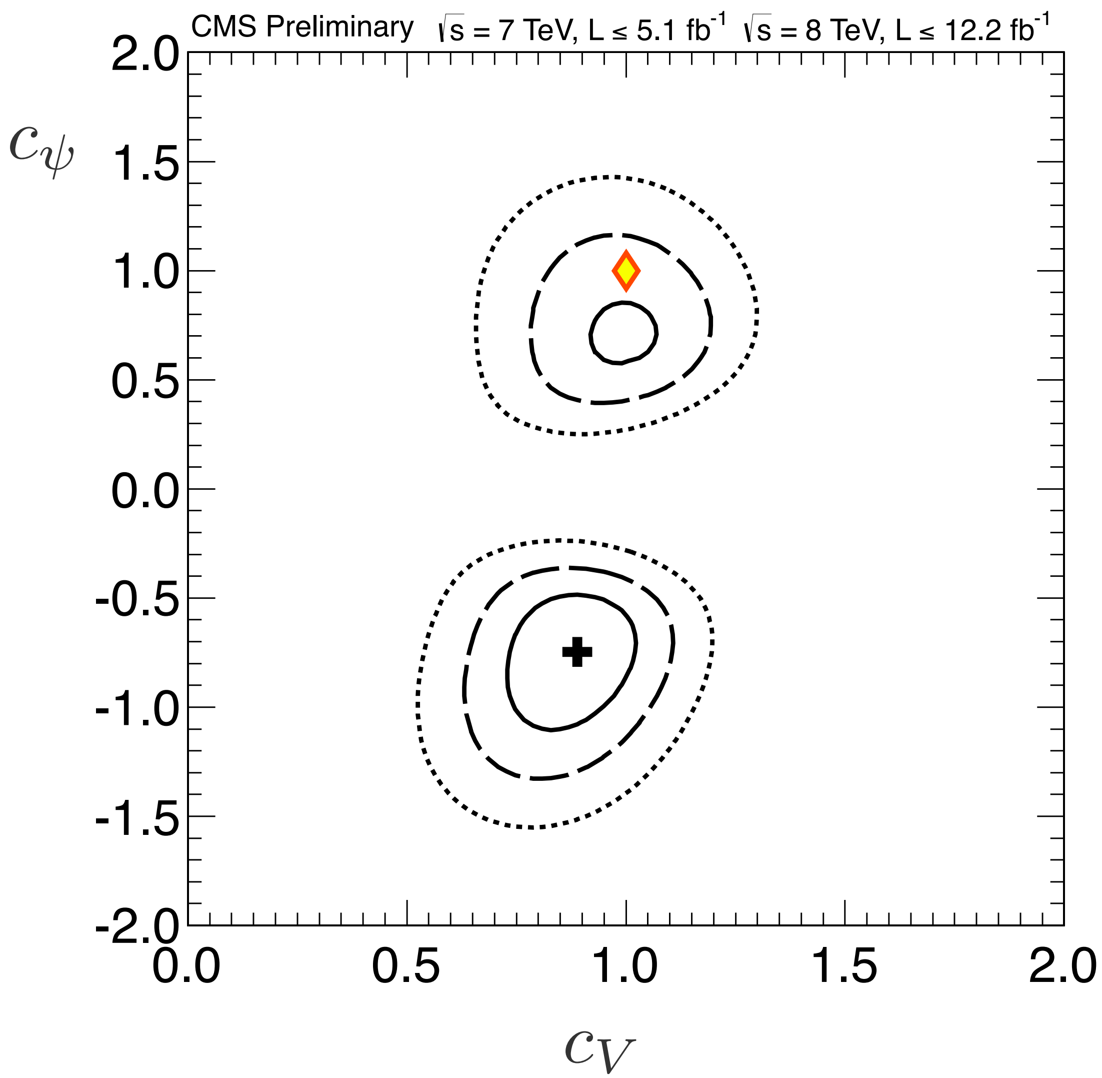
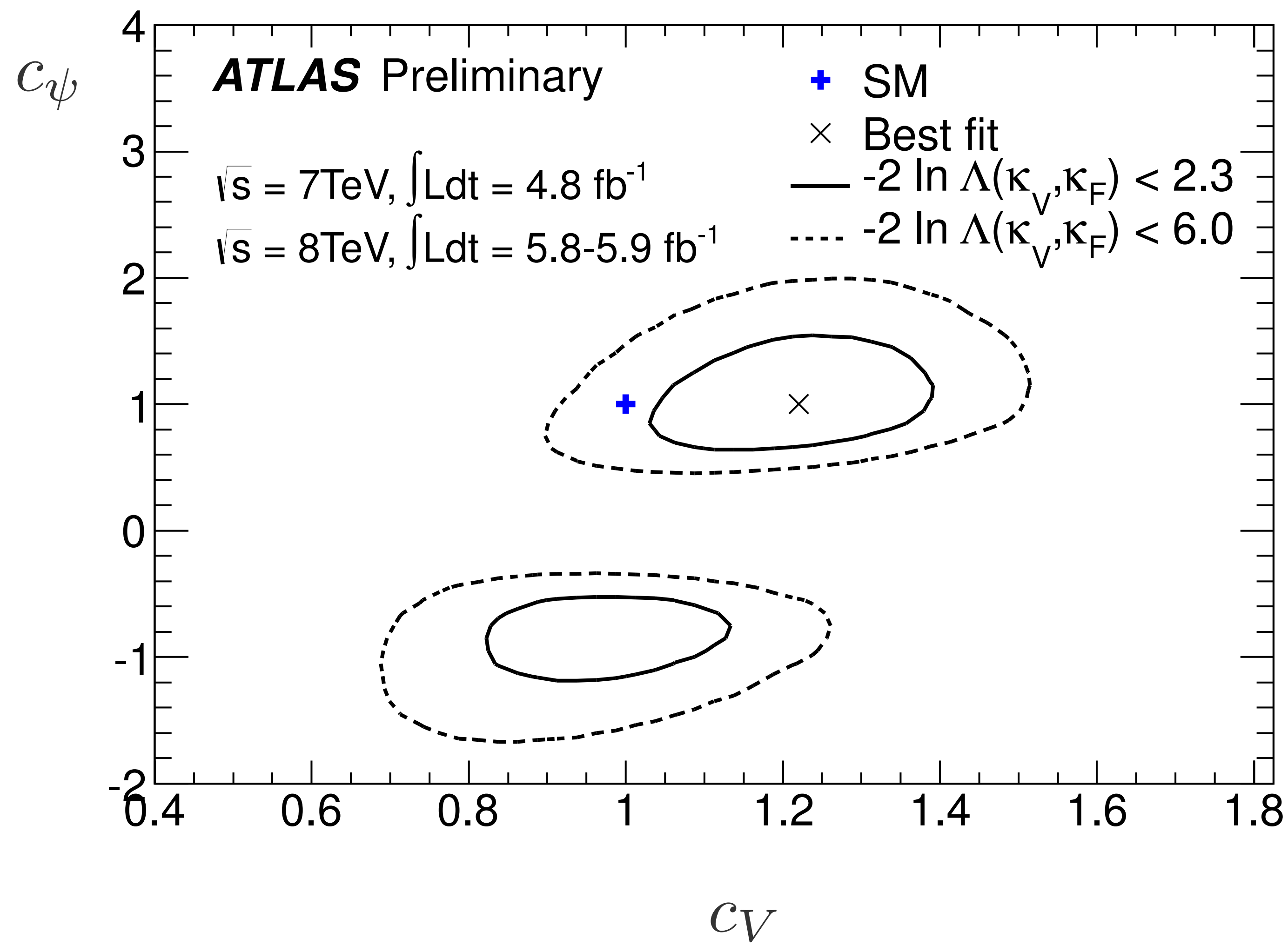
coupling c_V quite sensitive to strong scale

coupling c_t much less sensitive to strong scale

CMS

ATLAS





prefers $c_\psi < 1, c_V \simeq 1$

deeper minimum at $c_\psi < 0$

prefers $c_V > 1, c \simeq 1$

$$\frac{\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right) (D^\nu W_{\mu\nu})^a$$

$$\frac{\bar{c}_B g'}{2m_W^2} \left(H^\dagger i \overleftrightarrow{D}^\mu H\right) (\partial^\nu B_{\mu\nu})$$

$\Rightarrow$

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

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

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

one linear combination fixed due to (accidental) custodial invariance

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subleading correction to tree-level couplings $$\Delta c_{W^\pm, Z} \sim \left(\frac{m_W^2}{\Lambda^2}\right)$$

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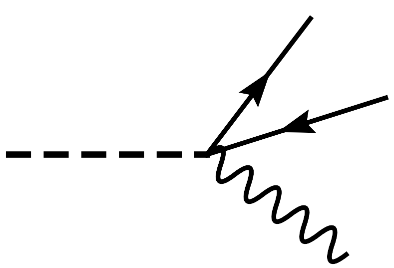
contact correction to three-body decays



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

inclusive WW,ZZ rates

$$\frac{\bar{c}_W g}{2m_W^2}\left(H^\dagger\sigma^a i\overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^a$$

$$\frac{\bar{c}_B g'}{2m_W^2}\left(H^\dagger i\overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

$\Rightarrow$

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

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

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

one linear combination fixed due to (accidental) custodial invariance

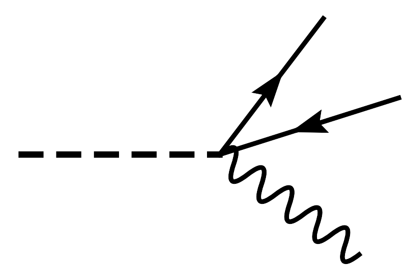
Use equations of motions: $D_\mu V_{\mu\nu} V_\nu h = (m_V^2 V_\nu + \bar{\psi}\gamma_\nu\psi) V_\nu h$

subleading correction to tree-level couplings

$$\Delta c_{W^\pm,Z} \sim \left(\frac{m_W^2}{\Lambda^2}\right)$$

'Form factor' effects

contact correction to three-body decays



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➡

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Use equations of motions: $D_\mu V_{\mu\nu} V_\nu h = (m_V^2 V_\nu + \bar{\psi}\gamma_\nu \psi) V_\nu h$

⇨ LEP already puts strong bounds on these operators $\hat{S} = (\bar{c}_W + \bar{c}_B) \lesssim 10^{-3}$

correction to WW, ZZ decay rates too small

$$\frac{\Gamma(h \to W^{(*)} W^*)}{\Gamma(h \to W^{(*)} W^*)_{SM}} \simeq 1 - 2\,\bar{c}_W$$

$$\frac{\Gamma(h \to Z^{(*)} Z^*)}{\Gamma(h \to Z^{(*)} Z^*)_{SM}} \simeq 1 - 1.8\,\bar{c}_W - 0.6\,\bar{c}_B$$

$$\frac{\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^a$$

$$\frac{\bar{c}_B g'}{2m_W^2}\left(H^\dagger i \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

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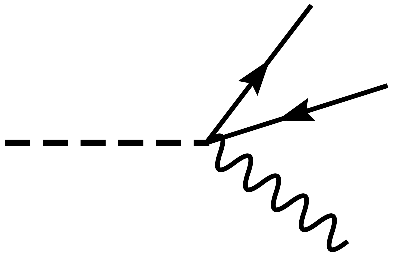
one linear combination fixed due to (accidental) custodial invariance

Use equations of motions: $D_\mu V_{\mu\nu} V_\nu h = (m_V^2 V_\nu + \bar{\psi}\gamma_\nu \psi) V_\nu h$

possible strategy: new contribution is local, cut on $q^2 = m(ll)^2$



$$\frac{d\Gamma}{dq^2} \Big/ \left(\frac{d\Gamma}{dq^2}\right)_{SM} \approx 1 + \bar{c}_{W,B}\left(\frac{q^2}{m_h^2}\right) \lesssim 1 + \bar{c}_{W,B}\,\frac{16\pi^2}{g^2}$$

$$\frac{i\,\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^a (D^\mu H)\,W^a_{\mu\nu}$$

$$\frac{i\,\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger\,(D^\mu H)\,B_{\mu\nu}$$

$$\frac{\bar{c}_\gamma\,g'^2}{m_W^2}\;B_{\mu\nu}B^{\mu\nu}\,H^\dagger H$$

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

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one linear combination starts at dim=8

$$\frac{\bar{c}_g\,g_S^2}{m_W^2}\;G_{\mu\nu}G^{\mu\nu}\,H^\dagger H$$

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

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

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

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

$$\bar{c}_i \sim O\left(\frac{m_W^2}{\Lambda^2}\right) \times \frac{g_*^2}{16\pi^2} \;\sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

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

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

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]

$$\frac{i\,\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

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Corrections to *h→WW, ZZ* rates:

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

too small

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Corrections to *h*→*WW*, *ZZ* rates:

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

too small

Corrections to *h*→*WW*, *ZZ* differential distributions and *h*→γ*Z* rate:

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

test Higgs strong interactions

$$\frac{i\,\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^a (D^\mu H)\,W^a_{\mu\nu}$$

$$\frac{i\,\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger\,(D^\mu H)\,B_{\mu\nu}$$

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

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

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In principle *h*→γγ, *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'

$$\bar{c}_i \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)\times\frac{\lambda^2}{g_*^2}$$

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

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

Fermionic operators

$$\frac{\bar{c}_i}{v^2}\left(\bar{\psi}\gamma^\mu\psi\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \quad \Rightarrow \quad \left(\bar{\psi}\gamma^\mu\psi\right)\left(V_\mu + hV_\mu + \dots\right)$$

In principle they probe the strength of the Higgs coupling to SM fermions:

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

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

In practice fermion compositeness is already strongly constrained:

EWPT at Z pole

$$\bar{c}_{HL} < 1.0\times 10^{-3}, \quad \bar{c}'_{HL} < 1.0\times 10^{-3}, \quad \bar{c}_{Hl} < 1.0\times 10^{-3},$$

$$\bar{c}_{Hq} < 2.0\times 10^{-3}, \quad \bar{c}'_{Hq} < 2.0\times 10^{-3}, \quad \bar{c}_{Hu} < 0.01, \quad \bar{c}_{Hd} < 0.03$$

$$\bar{c}_{Hq_3} < 2.0\times 10^{-3}, \quad \bar{c}'_{Hq_3} < 2.0\times 10^{-3}, \quad \bar{c}_{Hb} < 0.1$$

$b \to s\gamma$

$$-0.4\times 10^{-3} < \bar{c}_{Htb} < 1.3\times 10^{-3}$$

Effective Lagrangian in the unitary basis

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \ldots$$

$$- \left(m_W^2\, W_\mu W^\mu + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\right)\left(1 + 2c_V\,\frac{h}{v} + \ldots\right) - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \ldots\right)$$

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

$$+\ \frac{\alpha_s}{8\pi}\,c_{gg}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v} + c_W\left(W^-_\nu D_\mu W^{+\,\mu\nu} + h.c.\right)\frac{h}{v} + c_Z\,Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v}$$

$$+\ \left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v} + \ldots$$

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$$+ \left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v} + \dots$$

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

  Each term can be dressed up with Nambu-Goldstone bosons and made manifestly $SU(2)_L xU(1)_Y$ 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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$$+ \frac{\alpha_s}{8\pi}\,c_{gg}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v} + c_W\,(W^-_\nu D_\mu W^{+\,\mu\nu} + h.c.)\,\frac{h}{v} + c_Z\,Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v}$$

$$+ \left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v} + \dots$$

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

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

ex: $c_V = 1 + \dfrac{\bar c_H}{2}$

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

Effective Lagrangian in the unitary basis

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$$+ \left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v} + \dots$$

- 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

Nambu-Goldstone boson composite Higgs

Suppose the strong dynamics has a global invariance $SO(5) \rightarrow SO(4)$

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

- four NG bosons form an $SU(2)_L$ doublet H(x): the Higgs

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

- four NG bosons form an $SU(2)_L$ doublet H(x): the Higgs

Invariance under the Goldstone symmetry implies:

- resummation of powers of H/f (Higgs non-linearities), while still assuming expansion in ∂/Λ

- some operators forbidden if SO(5) unbroken

$$H(x) \to \Sigma(x) = e^{i\pi(x)/f}\Sigma_0$$

$$\Sigma_0 = (0,0,0,0,1)$$

$$(D^\mu H)^\dagger (D^\mu H)\,,\ \left[\partial_\mu (H^\dagger H)\right]^2 \to (D_\mu \Sigma)^2$$

$$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \to \left(\Sigma^\dagger \sigma^i \overleftrightarrow{D^\mu} \Sigma\right)(D^\nu W_{\mu\nu})^i$$

$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \to (D^\mu \Sigma)^\dagger \sigma^i (D^\nu \Sigma) W^i_{\mu\nu}$$

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→ $\bar{c}_H$ fixed by choice of coset (ex: SO(5)/SO(4))

$$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \to \left(\Sigma^\dagger \sigma^i \overleftrightarrow{D^\mu} \Sigma\right)(D^\nu W_{\mu\nu})^i$$

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$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \rightarrow (D^\mu \Sigma)^\dagger \sigma^i (D^\nu \Sigma) W^i_{\mu\nu}$$

Operators that require explicit breaking of SO(5):

$$y_\psi\, \bar{\psi}_L H \psi_R \left(1 + \frac{\bar{c}_\psi}{v^2}\, H^\dagger H\right) \rightarrow \bar{\psi}_L \lambda_L \Sigma \Sigma^\dagger \lambda_R \psi$$

$$G^a_{\mu\nu} G^{a\mu\nu} H^\dagger H \rightarrow G^a_{\mu\nu} G^{a\mu\nu} \left(\Sigma^\dagger \lambda^\dagger \lambda \Sigma\right)$$

$$H(x) \to \Sigma(x) = e^{i\pi(x)/f}\Sigma_0$$

$$\Sigma_0 = (0,0,0,0,1)$$

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→ $\bar{c}_\psi$ fixed by choice of spurions $\lambda_{L,R}$

$$G^a_{\mu\nu}G^{a\mu\nu}H^\dagger H \to G^a_{\mu\nu}G^{a\mu\nu}\left(\Sigma^\dagger\lambda^\dagger\lambda\Sigma\right)$$

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$$\Sigma_0 = (0,0,0,0,1)$$

$$(D^\mu H)^\dagger (D^\mu H)\,, \ \left[\partial_\mu (H^\dagger H)\right]^2 \to (D_\mu \Sigma)^2$$

→ $\bar{c}_H$ fixed by choice of coset (ex: SO(5)/SO(4))

$$\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \to \left(\Sigma^\dagger \sigma^i \overleftrightarrow{D^\mu} \Sigma\right)(D^\nu W_{\mu\nu})^i$$

$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \to (D^\mu \Sigma)^\dagger \sigma^i (D^\nu \Sigma) W^i_{\mu\nu}$$

Operators that require explicit breaking of SO(5):

$$y_\psi\, \bar{\psi}_L H \psi_R \left(1 + \frac{\bar{c}_\psi}{v^2}\, H^\dagger H\right) \to \bar{\psi}_L \lambda_L \Sigma \Sigma^\dagger \lambda_R \psi$$

→ $\bar{c}_\psi$ fixed by choice of spurions $\lambda_{L,R}$

$$G^a_{\mu\nu} G^{a\mu\nu} H^\dagger H \to G^a_{\mu\nu} G^{a\mu\nu}\left(\Sigma^\dagger \lambda^\dagger \lambda \Sigma\right)$$

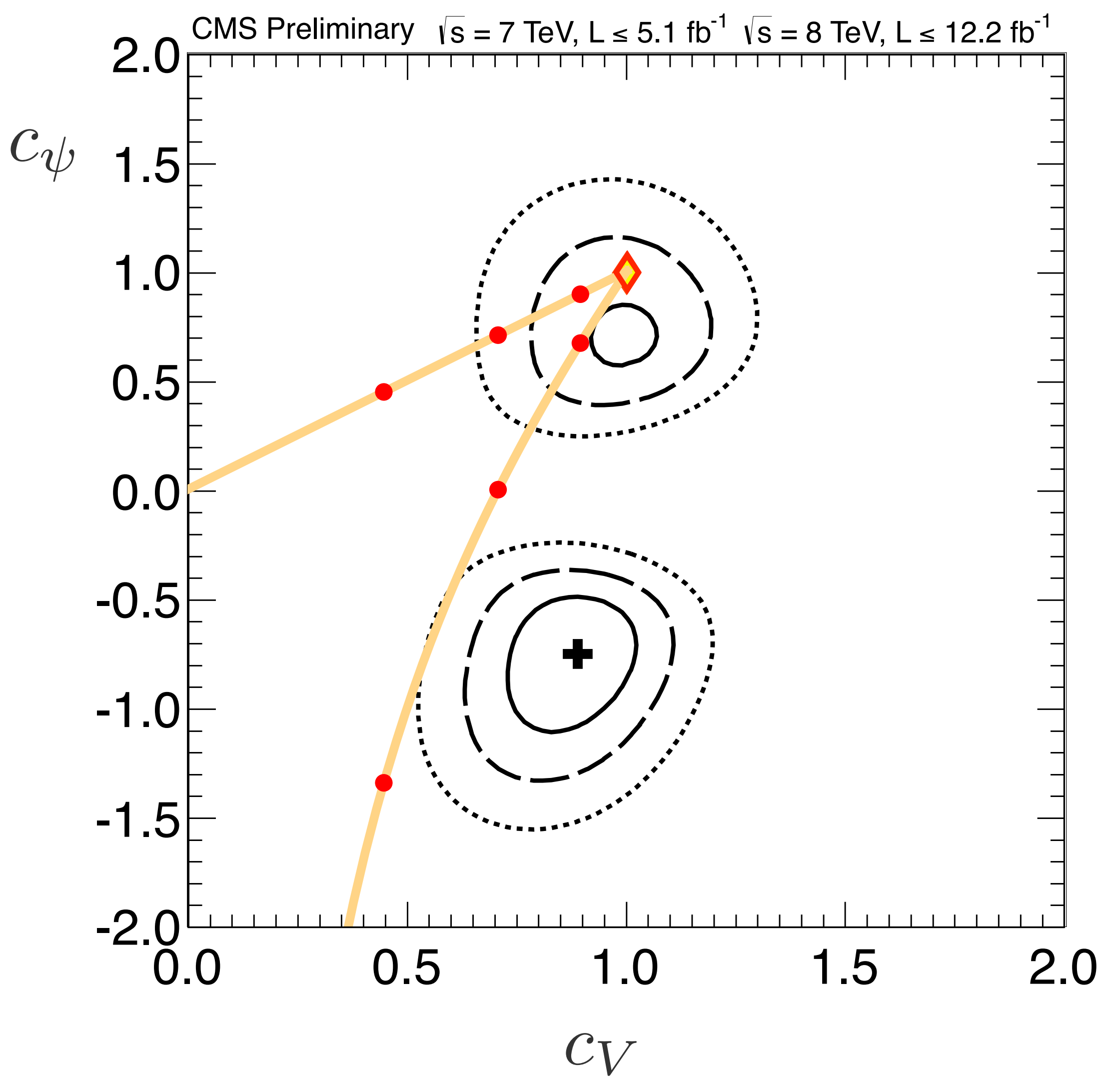
λ^2 suppressed

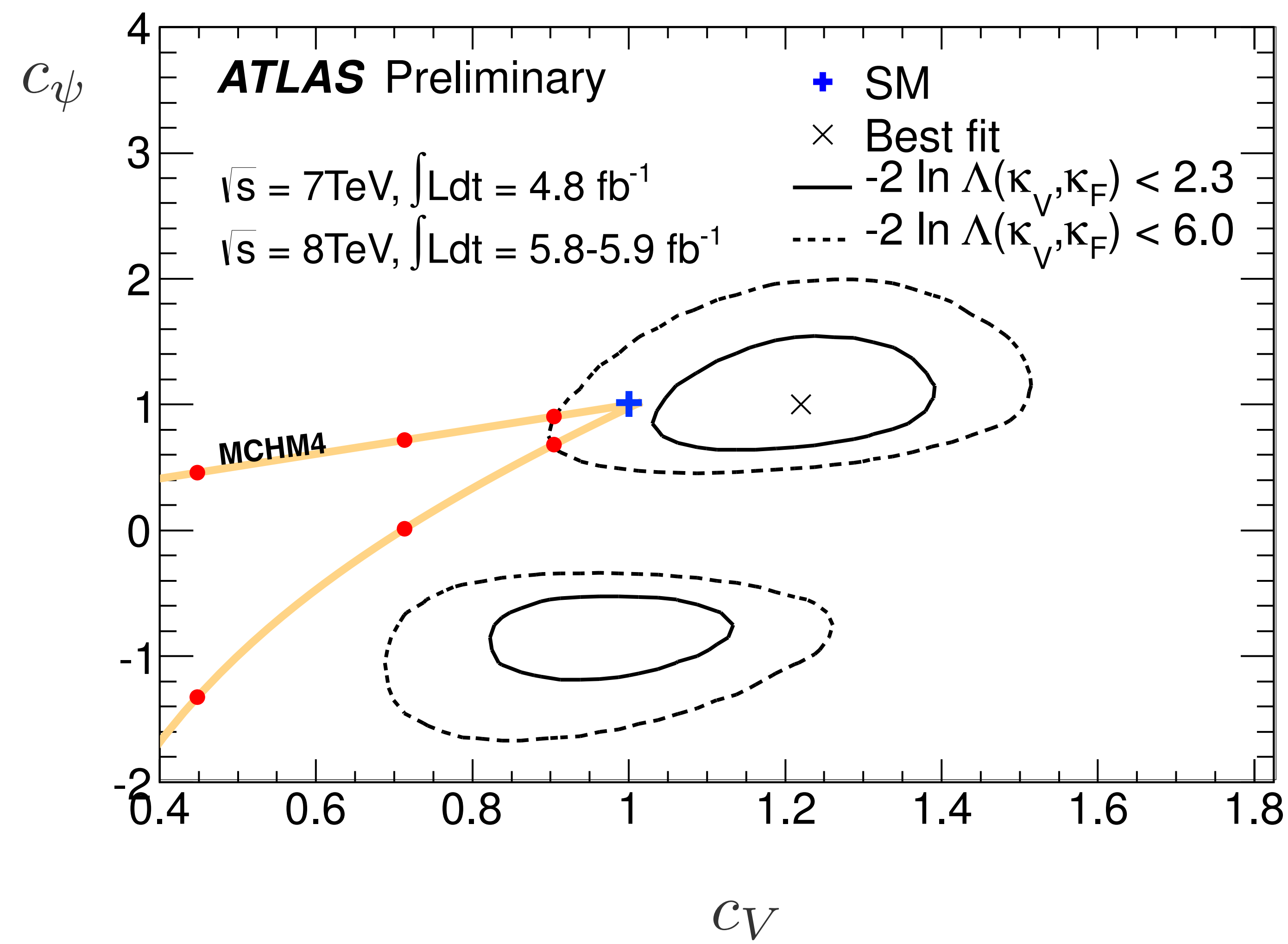
- couplings c_V, c_ψ predicted functions of ξ in a given model

Ex: MCHM5 $c_V = \sqrt{1-\xi}$ $\xi = \frac{v^2}{f^2}$

$$c_\psi = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Red points at $\xi = 0.2,\ 0.5,\ 0.8$





$h \to \gamma\gamma$, $gg \to h$ in composite Higgs models

- Rates modified because of shift in tree-level Higgs couplings

$$A(gg \to h) = A(gg \to h)_{SM} \times c_t(\xi)$$

$$A(h \to \gamma\gamma) = A(h \to \gamma\gamma)^{(t)}_{SM} \times c_t(\xi) + A(h \to \gamma\gamma)^{(W)}_{SM} \times c_V(\xi)$$

- Contribution from heavy states encoded in local operator

$$\frac{\bar{c}_\gamma \, g'^2}{m_W^2} \, B_{\mu\nu} B^{\mu\nu} \, H^\dagger H$$

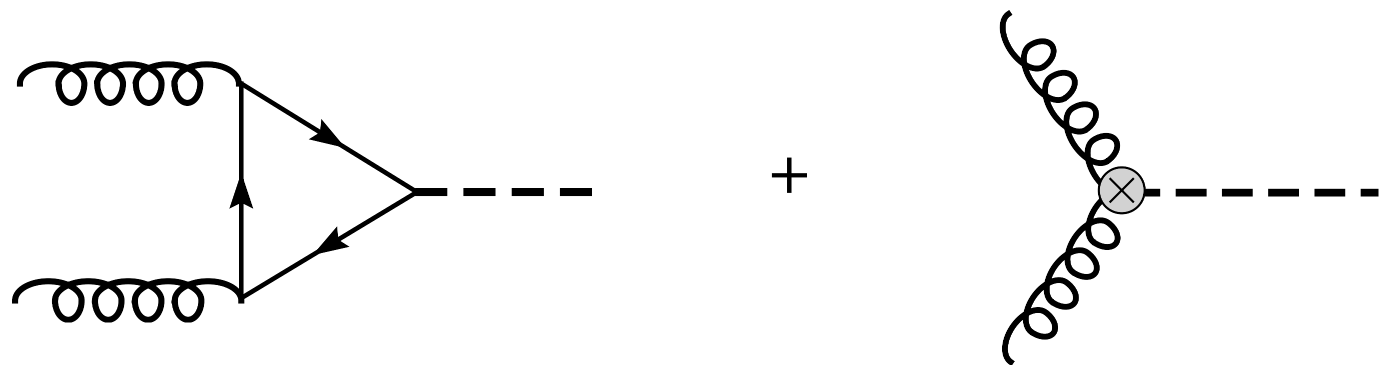
$$\frac{\bar{c}_g \, g_S^2}{m_W^2} \, G_{\mu\nu} G^{\mu\nu} \, H^\dagger H$$

$$\bar{c}_i \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right) \times \frac{\lambda^2}{g_*^2}$$

← suppressed by spurion factor

- A stronger result holds in (minimal) models with partial compositeness:

> The contribution of heavy fermions to the rates
> $\Gamma(gg \to h)\,,\Gamma(h \to \gamma\gamma)$ *vanishes identically*



$$c_t\,\frac{m_h^2}{v}\,\frac{g_s^2}{16\pi^2}\,F\left(\frac{m_h^2}{m_t^2}\right) \qquad\qquad \bar{c}_g\,\frac{m_h^2}{v}\,\frac{g_s^2}{m_W^2}$$

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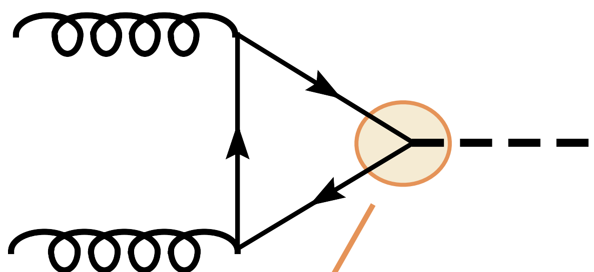

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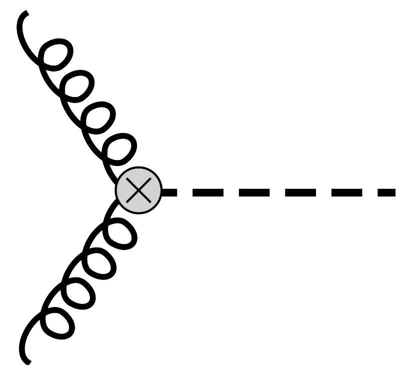

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$$\bar{c}_g \, \frac{m_h^2}{v} \, \frac{g_s^2}{m_W^2}$$

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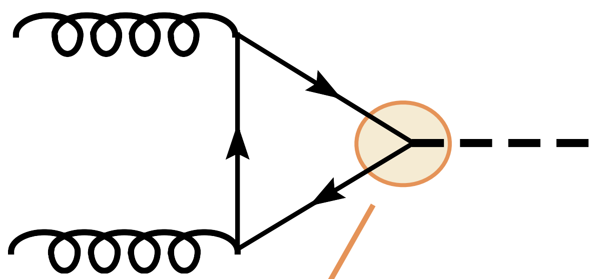

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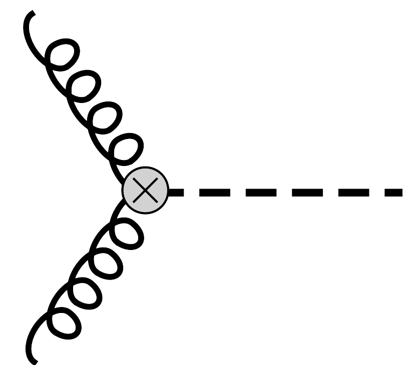

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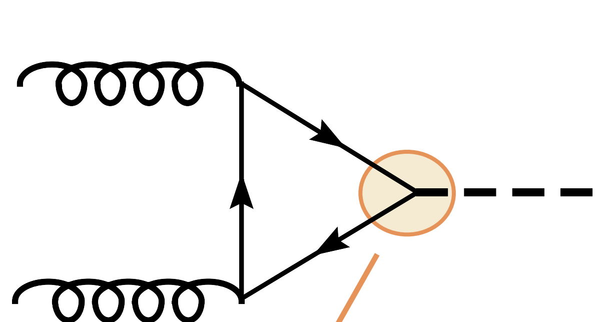

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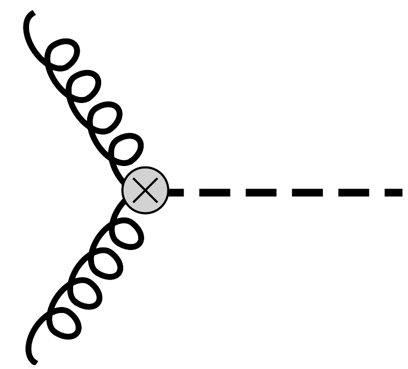

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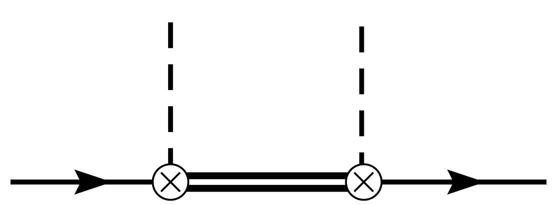

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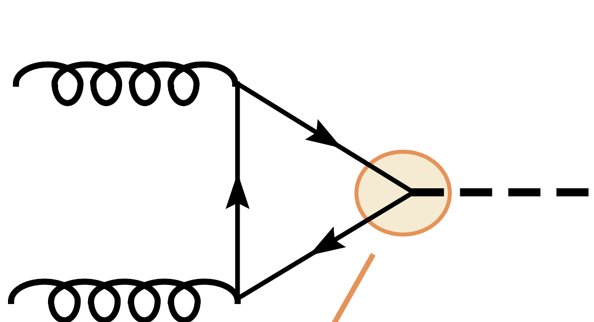

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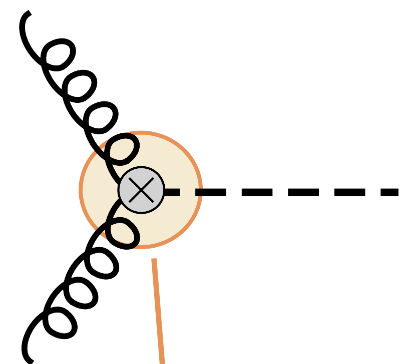

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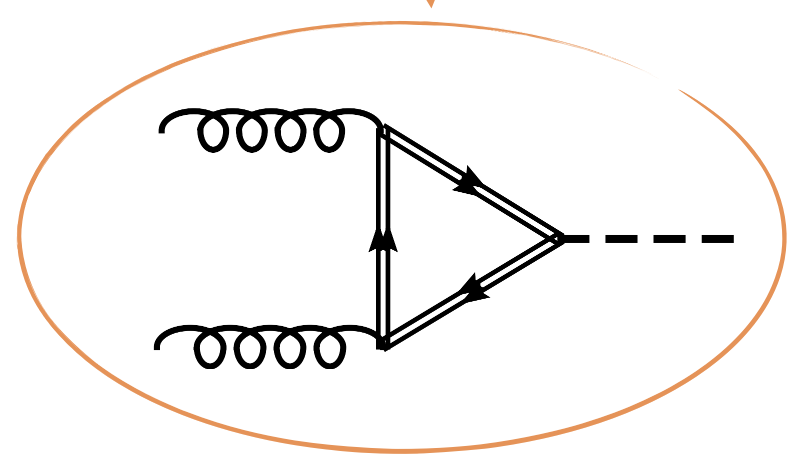

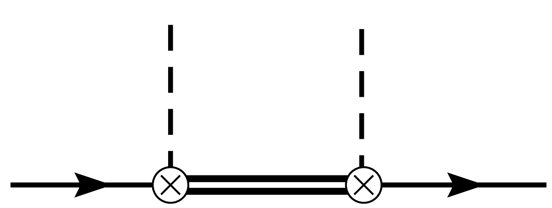

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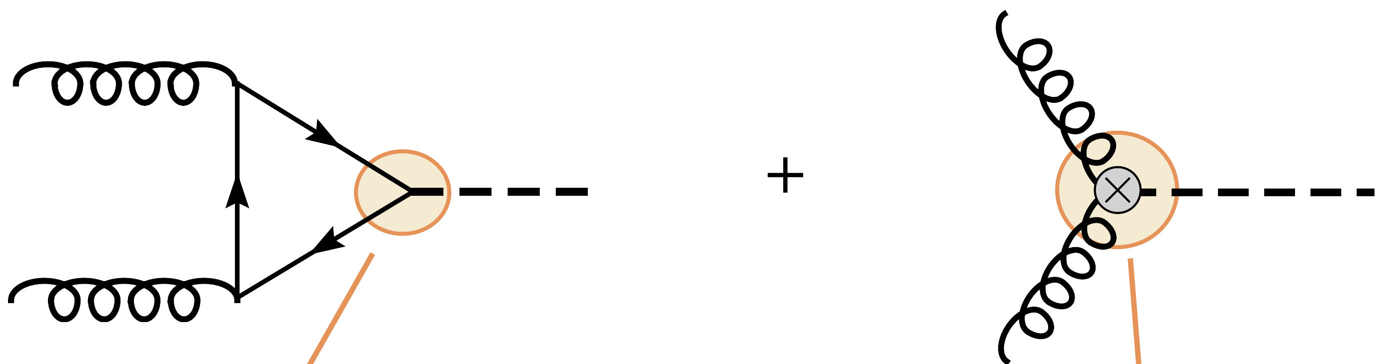

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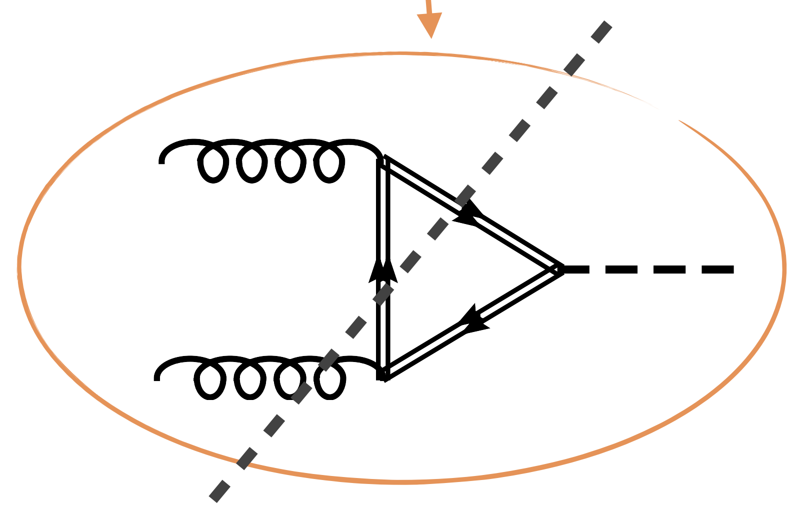

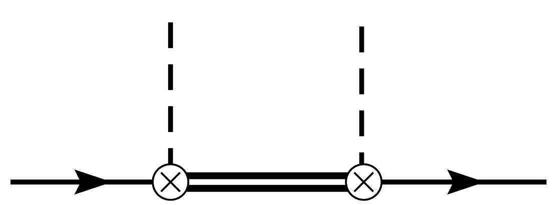

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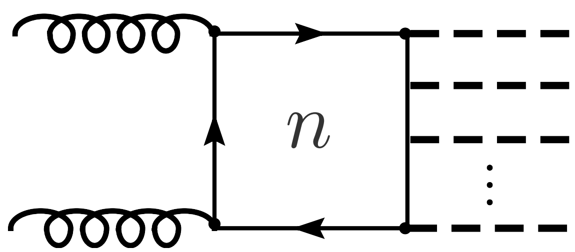
In the limit of soft Higgs emissions

(soft Higgs = vanishing Higgs mass and momentum)

$$\sum_n$$



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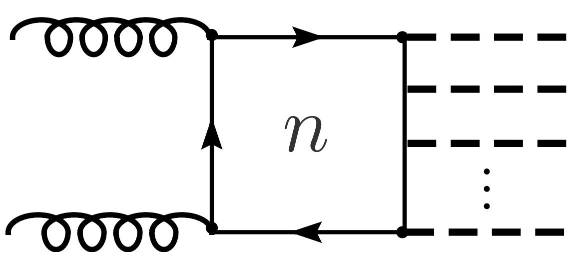

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In minimal composite Higgs models with partial compositeness

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

$$\boxed{A(gg \to h^n) = A(gg \to h^n)_{SM} \times F(\xi)}$$

Falkowski, PRD 77 (2008) 055018
Rattazzi, Vichi, JHEP 1004 (2010) 126
Azatov, Galloway, PRD 85 (2012) 055013

Contribution of heavy fermions cancels out

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- $h \rightarrow \gamma\gamma$ and $gg \rightarrow h$ protected by Goldstone symmetry: contribution from heavy states (ex: top partners) are expected to be very small