# EFFECTIVE THEORIES FOR THE HIGGS: VIRTUES AND LIMITATIONS

Roberto Contino
EPFL & CERN

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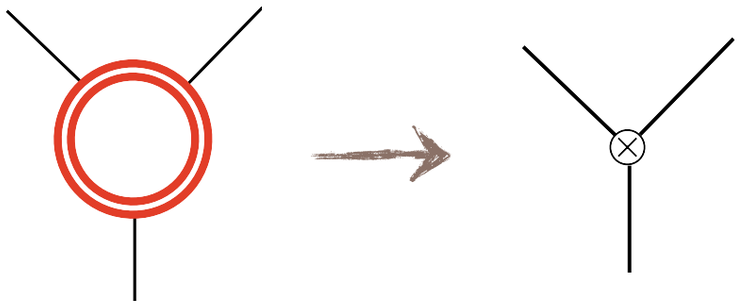
# Effective Lagrangian for the Higgs boson

- At low energies, $E \ll m_*$ , NP effects are well approximated by local operators

$$\mathcal{L} = \sum_i \bar{c}_i \, O_i(x)$$



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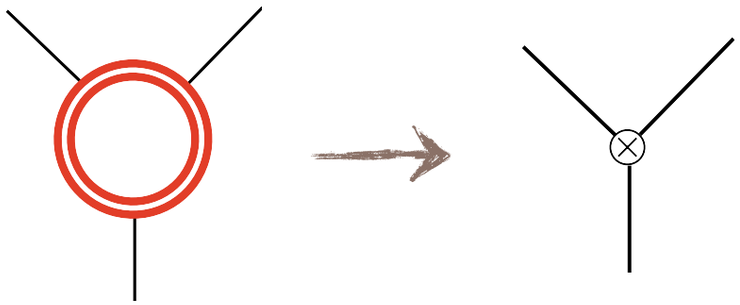

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**Assumptions:**

1. There is a <u>gap</u> between the NP scale $m_*$ and $m_h$

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

$$H = e^{i\pi/v} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

# Effective Lagrangian for the Higgs boson

- Operators can be classified according to their dimension

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Leading effects from dim-6 operators

59 independent operators for 1 SM family

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Grzadkowski et al. JHEP 1010 (2010) 085

For a review see:
RC, Ghezzi, Grojean, Muhlleitner, Spira JHEP 1307 (2013) 035

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Giudice et al. JHEP 0706 (2007) 045

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For a strongly-interacting light Higgs (SILH):

$$g_* \gg 1 \quad \Rightarrow \quad \frac{1}{f} \gg \frac{1}{m_*}$$

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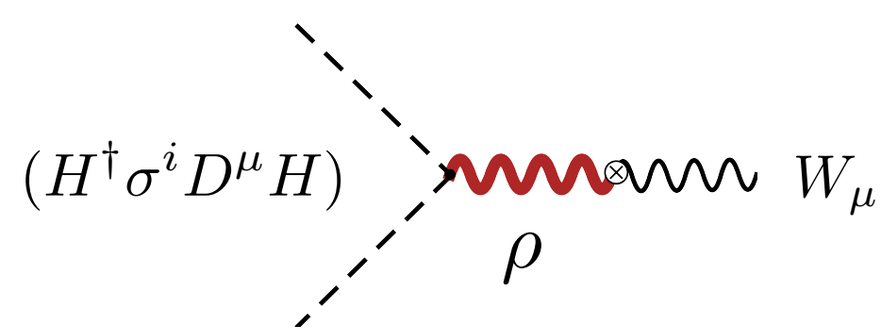
Example: $$O_W = \frac{ig}{2m_W^2}\left(H^\dagger \sigma^i D^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i$$

$$\bar{c}_W \sim \left(\frac{m_W^2}{m_*^2}\right)$$



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Expansion parameters: $\frac{\partial_\mu}{m_*}$ , $\frac{v}{f}$ , $\frac{\alpha_{SM}}{4\pi}$

derivative expansion

expansion in powers of the Higgs field $H/f$

expansion in powers of the SM couplings

## Secondary Assumptions:

1. The UV physics is minimally coupled

True for some of the popular models (e.g. weakly-coupled SUSY, holographic Higgs), but not necessarily so in more general contexts

see for example: Jenkins, Manohar, Trott JHEP 1309 (2013) 063

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2. (light) SM fermions are weakly coupled to the UV dynamics

Equivalent to assuming "universality" of NP effects, easier to comply with LEP

☞ current-current operators subdominant

# Probing the strength of the EWSB dynamics

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- At LHC Run1 Higgs searches have focussed on single-Higgs on-shell production and decay

→ gives information on on-shell couplings at a fixed scale $Q = m_h$

$$\frac{\delta c}{c} \sim O\left(\frac{m_h^2}{m_*^2}\right) \text{ or } O\left(\frac{g_*^2}{g_{SM}^2} \times \frac{m_h^2}{m_*^2} = \frac{v^2}{f^2}\right) < 1$$

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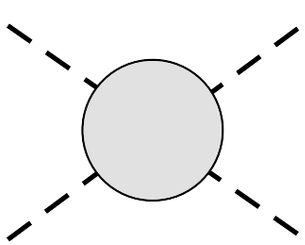
- Next frontier for Run2: probe *directly* the strength of SSB dynamics at energies $E \gg m_h$ through 2→2 scattering processes



$$\sim g(E)^2$$

# Validity of the EFT description

Inspired by:
R. Rattazzi, talk at "BSM physics opportunities at 100TeV", Cern 2014

In general:

$$A = g_{SM}^2 \times \left(1 + O\left(\frac{v^2}{f^2}\right)\right) + O\left(\frac{g_*^2 E^2}{m_*^2}\right) + \dots$$

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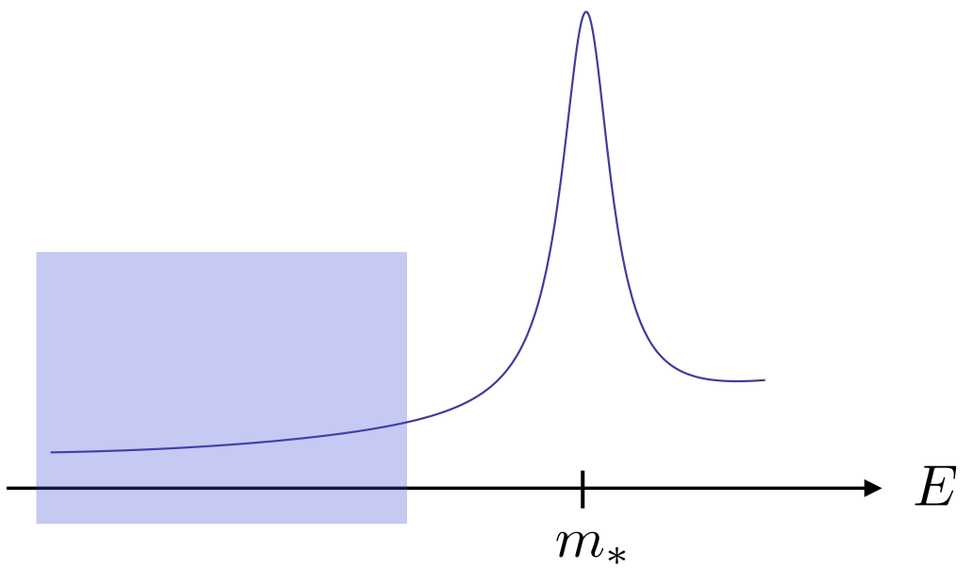
Interesting coupling range: $g_{SM} < g(E) < g_* \lesssim 4\pi$

Interesting energy window: $g_{SM}\, f < E < m_*$



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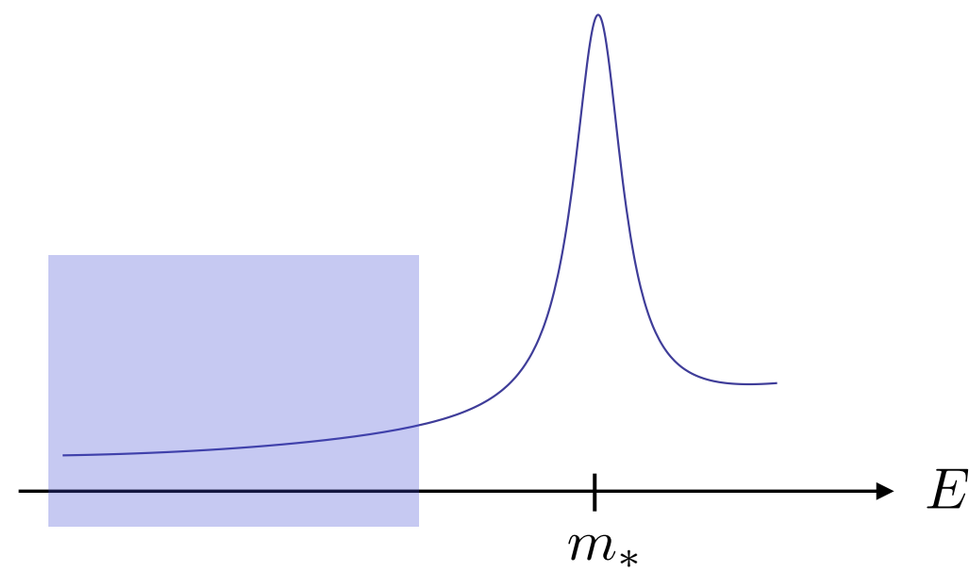


Thus: $\dfrac{\delta A}{A_{SM}} \sim \dfrac{g(E)^2}{g_{SM}^2}$ can be $> 1$ if NP dynamics is *strongly coupled* ($g_* > g_{SM}$)

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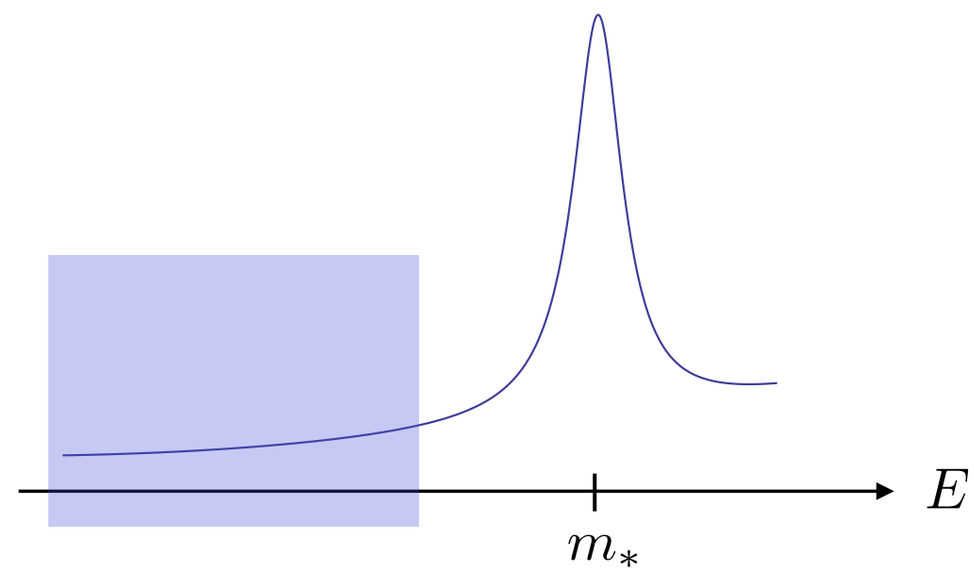



For:

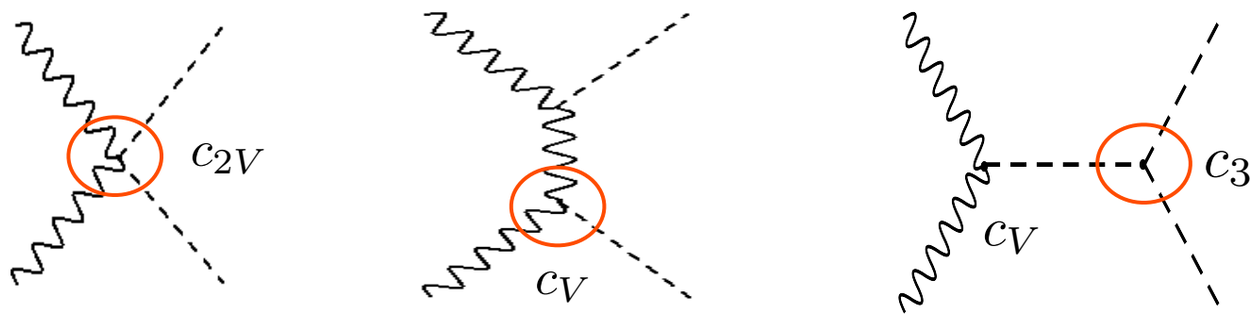
$\bar{f} =$ best sensitivity on $f$

$\bar{E} =$ largest energy probed

$$g_{min} \equiv \frac{\bar{E}}{\bar{f}} < g_* \leq 4\pi$$

Parameter space under scrutiny *within* the validity of EFT

# Example #1: Double Higgs production via VBF ( $V_L V_L \to hh$ )

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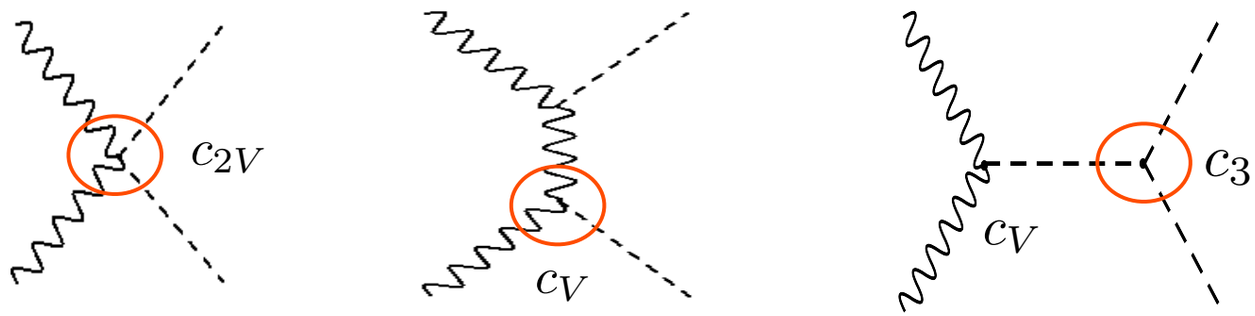


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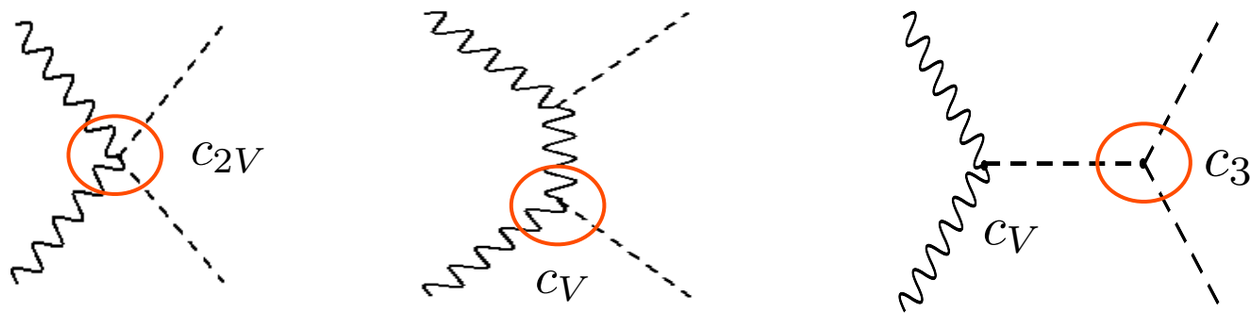


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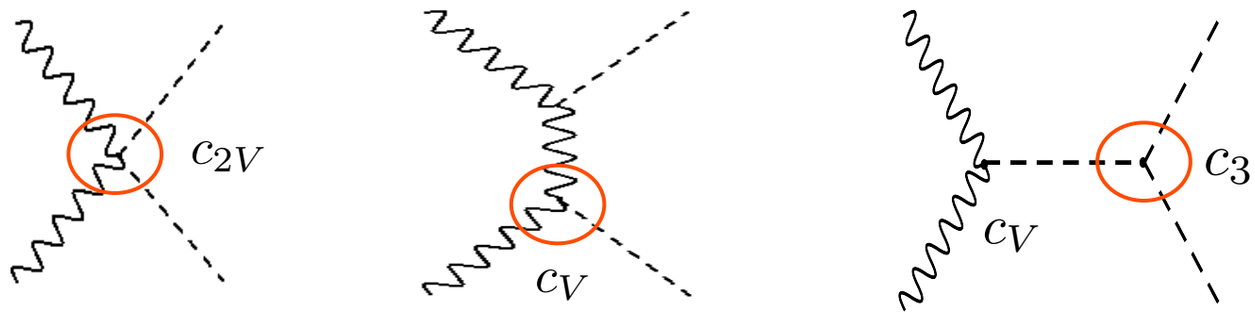


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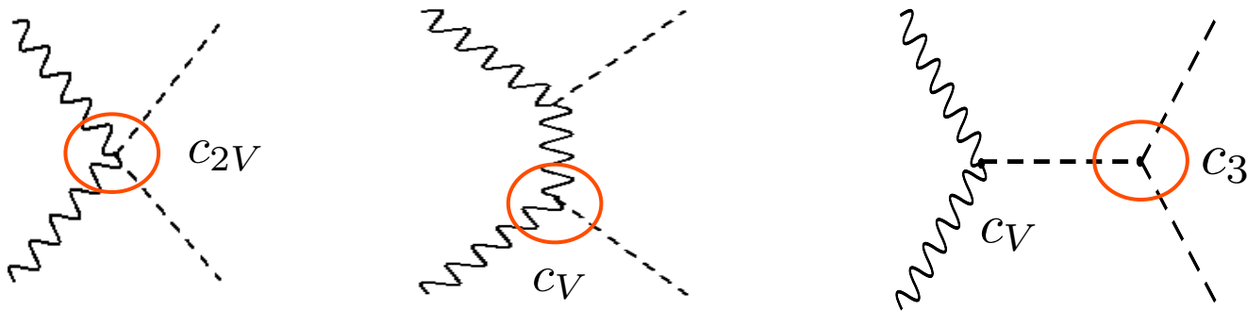


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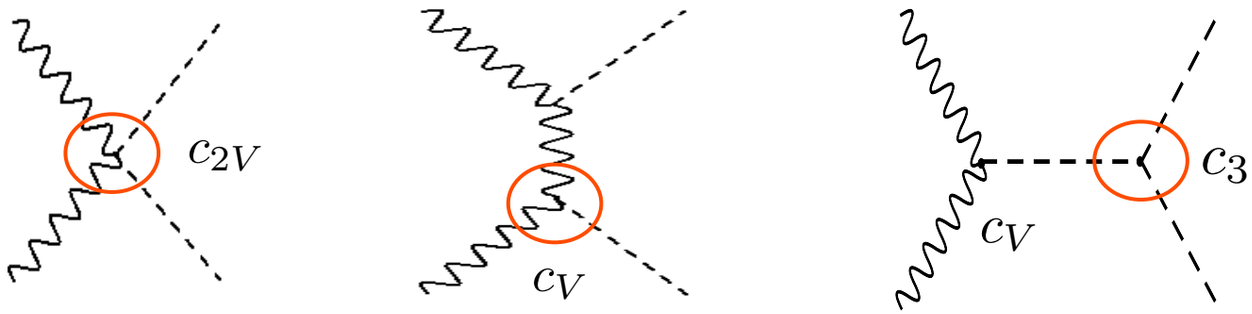


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If best sensitivity $(\delta_2)_{min}$ comes from events with invariant mass $m(hh) \sim \bar{E}$ :

$$\sqrt{(\delta_2)_{min}}\,\frac{\bar{E}}{v} = g_{min} < g_* \lesssim 4\pi$$

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pp colliders $pp \to hh\, jj \to 4b\, jj$

| | $(\delta_3)_{min}$ | $(\delta_2)_{min}$ | $\bar{E}$ | $g_{min}$ |
|---|---|---|---|---|
| $14\,\text{TeV},\quad L = 300\,\text{fb}^{-1}$ | $8-9$ | 0.35 | 1.5 TeV | 3.6 |
| $14\,\text{TeV},\quad L = 3\,\text{ab}^{-1}$ | $5-8$ | 0.2 | 1.5 TeV | 2.7 |
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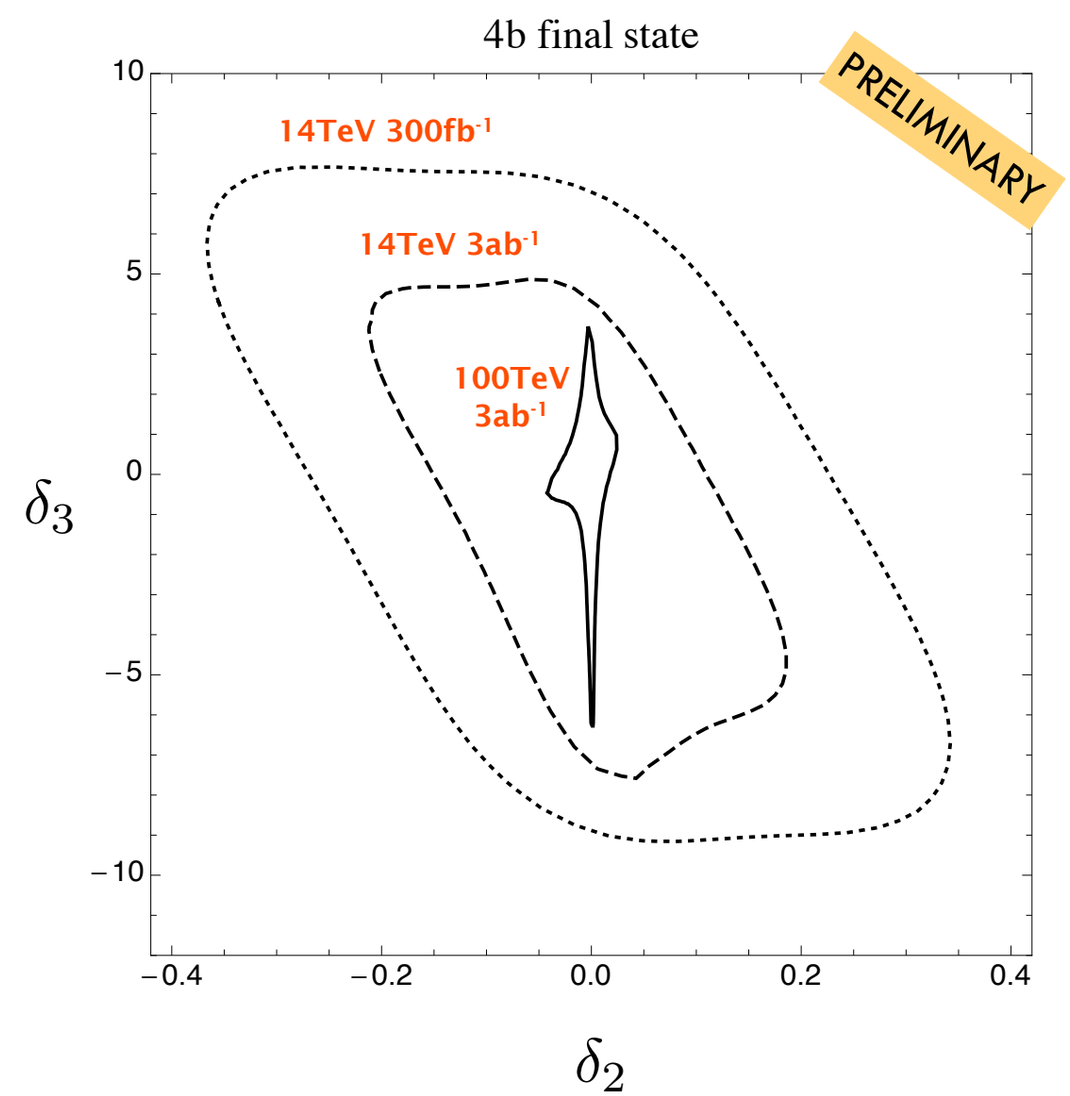
work in progress with J. Rojo

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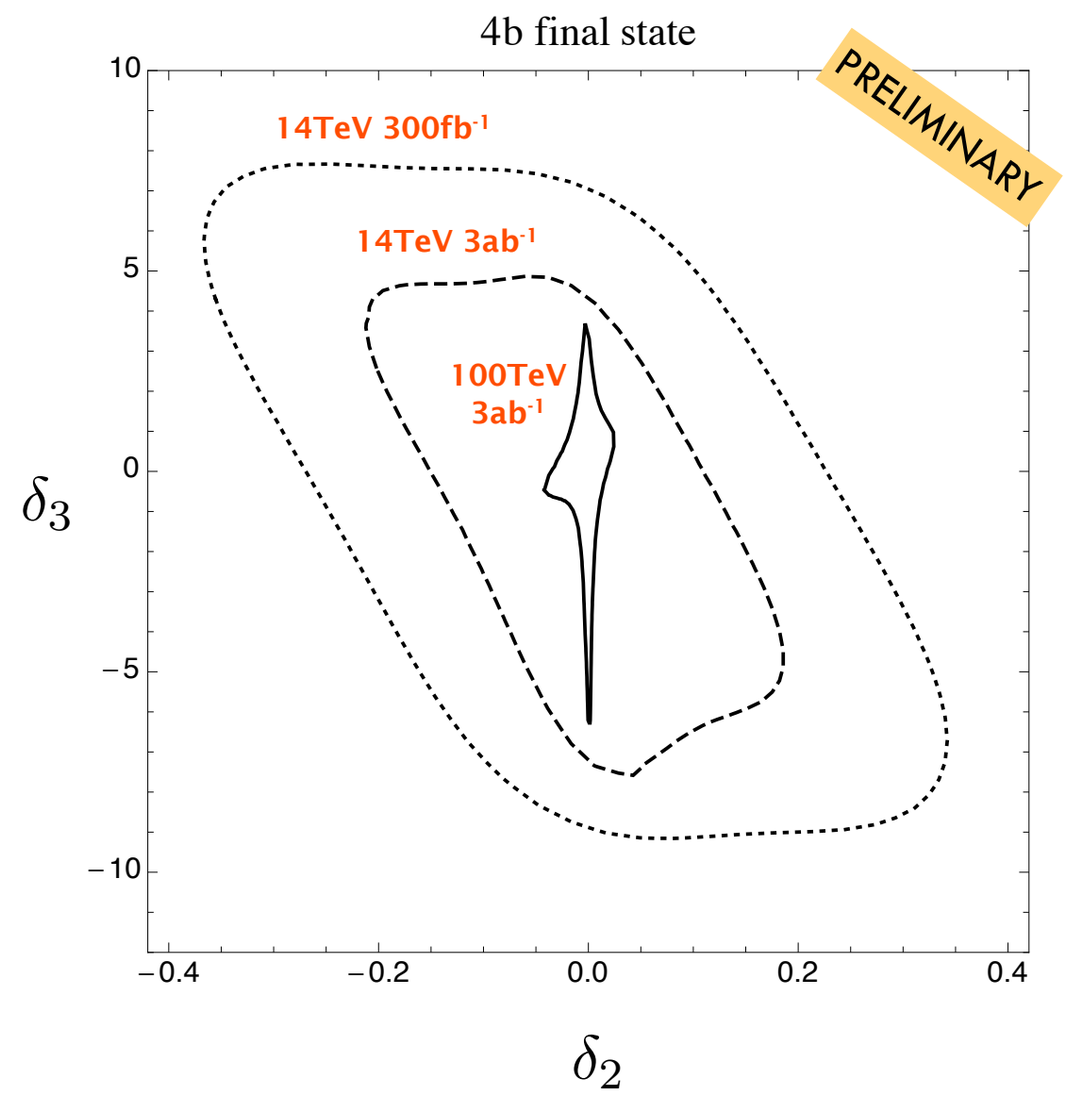


**CLIC** $e^+e^- \to hh\, \nu\bar{\nu} \to 4b\, \nu\bar{\nu}$

| | $(\delta_3)_{min}$ | $(\delta_2)_{min}$ | $\bar{E}$ | $g_{min}$ |
|---|---|---|---|---|
| $3\,\text{TeV},\quad L = 1\,\text{ab}^{-1}$ | 0.3 | 0.05 | 1.8 TeV | 1.6 |

RC, Grojean, Pappadopulo, Rattazzi, Thamm JHEP 1402 (2014) 006

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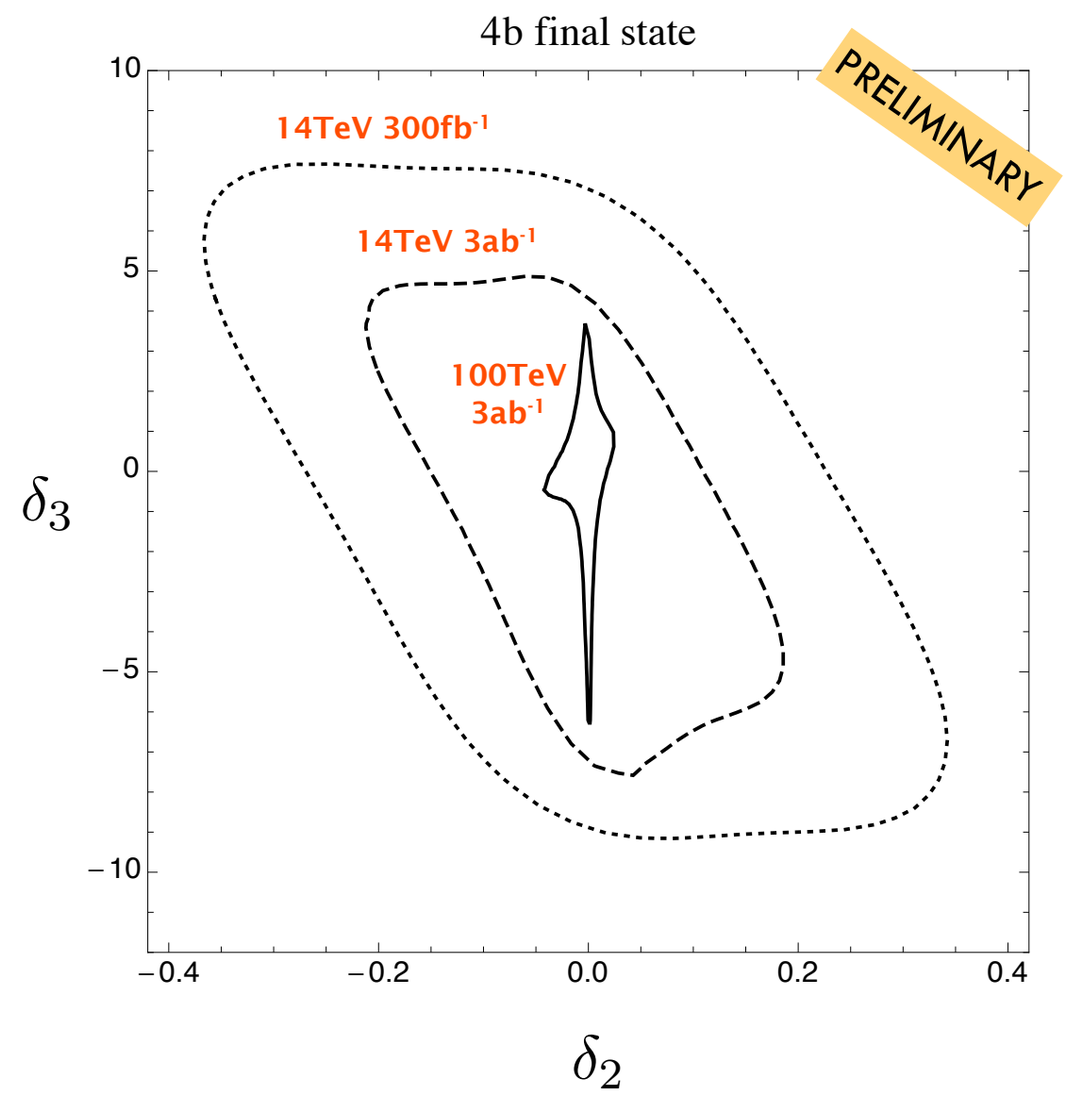


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EFT better justified at high-precision machines (such as $e^+e^-$ colliders)

$$\delta_2 \equiv 1 - c_{2V}/c_V^2$$

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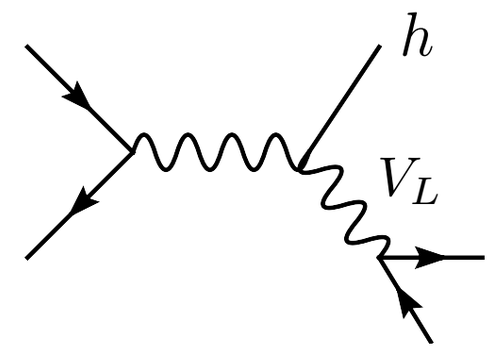
# Example #2: Higgs associated production ( $q\bar{q} \to V_L h$ )

$$A = g^2 + O\left(g^2 \frac{E^2}{m_W^2}\, \bar{c}_{i=HB,(W-B)}\right) + O\left(g^2 \frac{E^2}{m_W^2}\, \bar{c}_{H\psi}\right)$$




$$O_W = \frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$O_B = \frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$$

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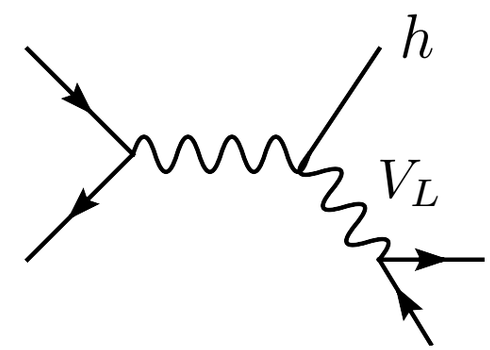


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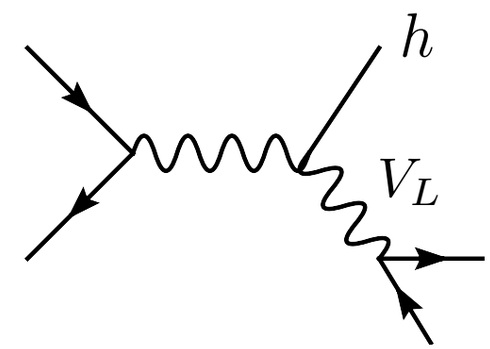


Riva et al.
arXiv:1406.7320

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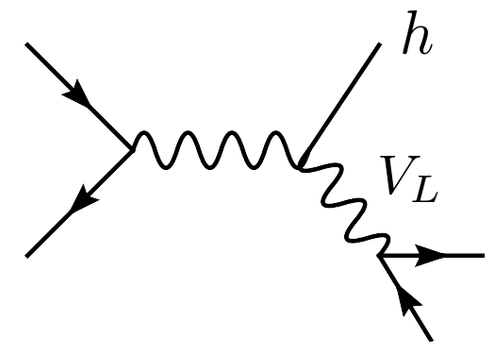


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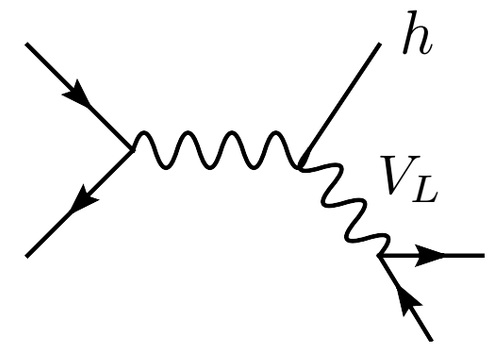


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$\rightarrow$ $O_{HB}, (O_W - O_B)$
constrained by TGC

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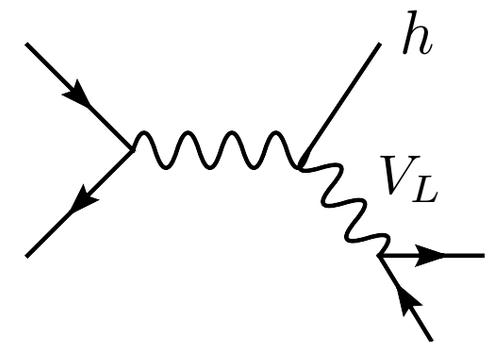


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→ $O_{HB}, (O_W - O_B)$
constrained by TGC

$$O_{H\psi} = \frac{i}{v^2}\left(\bar{\psi}\gamma^\mu \psi\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

→ constrained by Z-pole data at LEP1

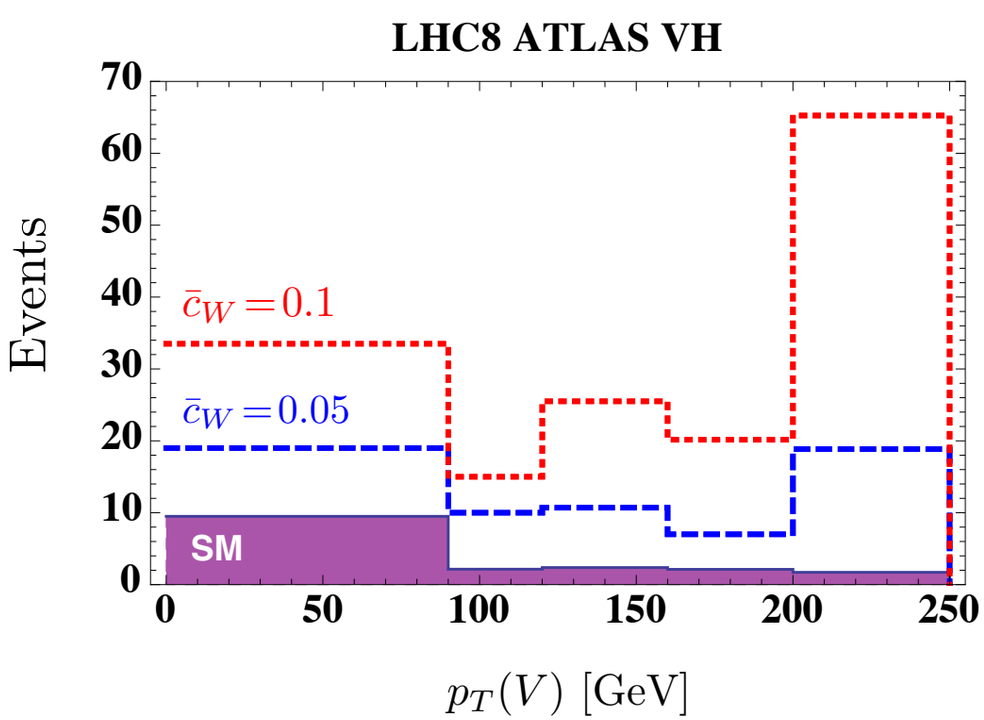
# Example #2: Higgs associated production ( $q\bar{q} \to V_L h$ )

Experimental searches not yet sensitive to SM Higgs signal

ATLAS-CONF-2013-079
CMS PAS-HIG-13-012
D0, PRL 109 (2012) 121802

EFT <u>not</u> valid when setting limits on $\bar{c}_{HB}, (\bar{c}_W - \bar{c}_B)$

Riva et al. arXiv:1406.7320




from: Ellis et al. arXiv:1404.3667

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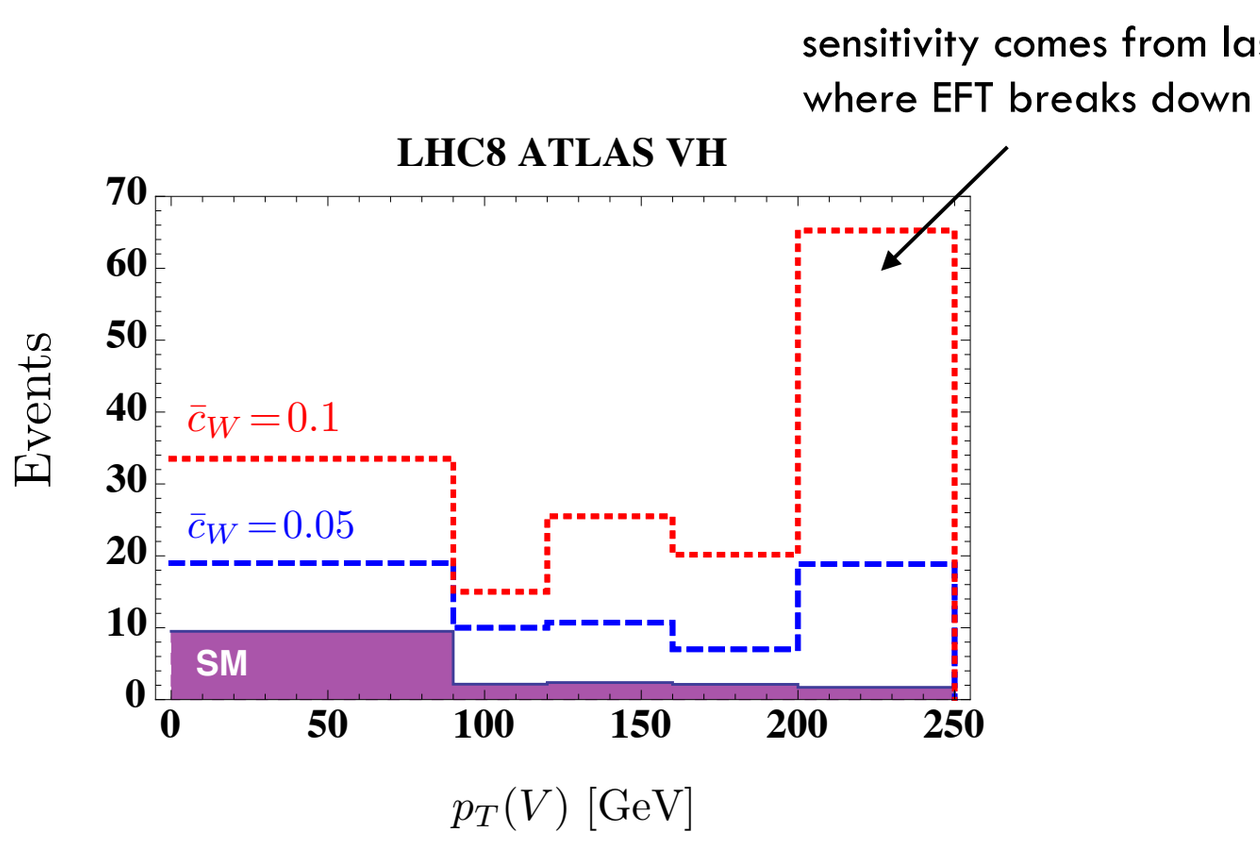


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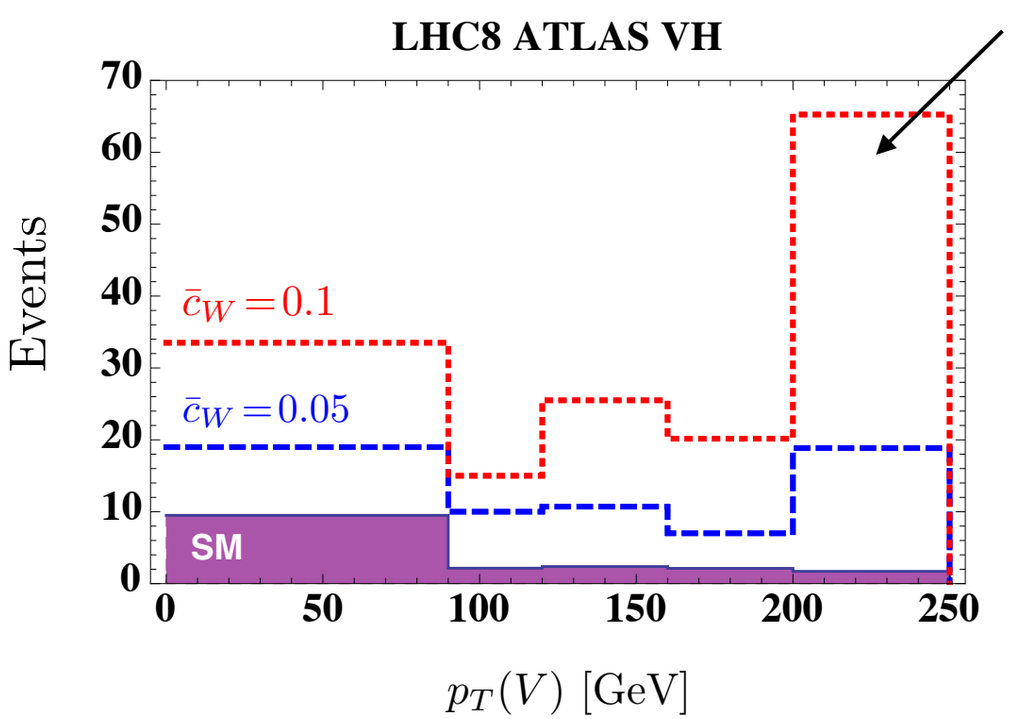
Compare with LEP2 (TGCs):

✓ strongest bounds
✓ EFT valid

sensitivity comes from last bin where EFT breaks down

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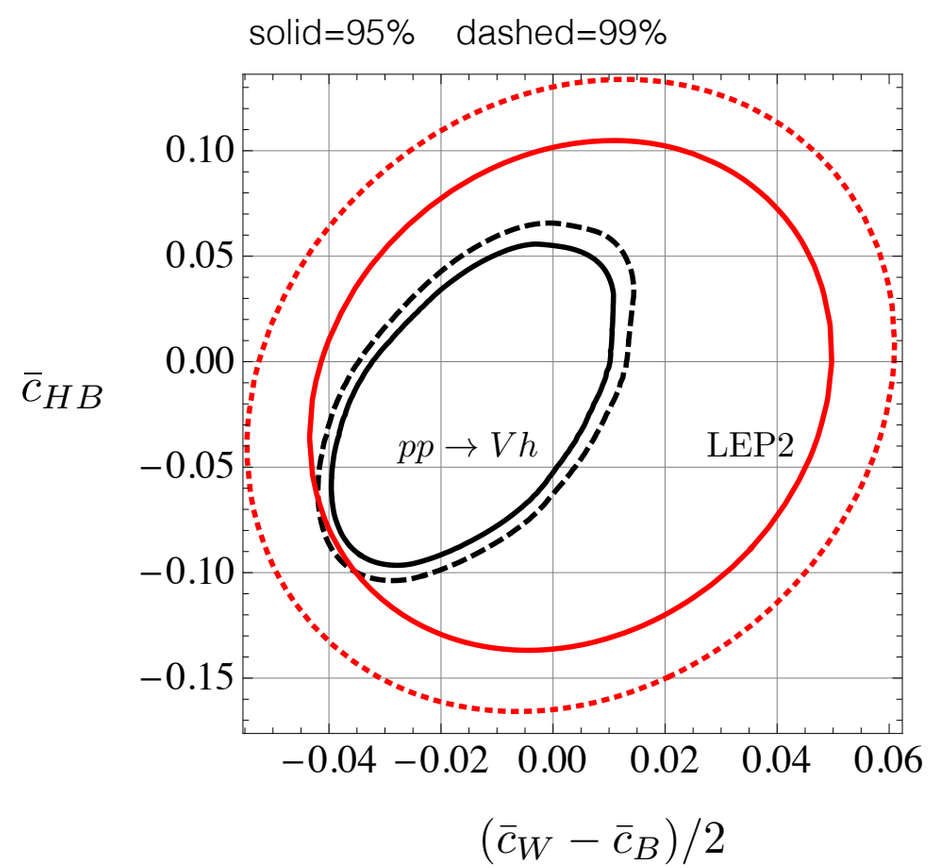


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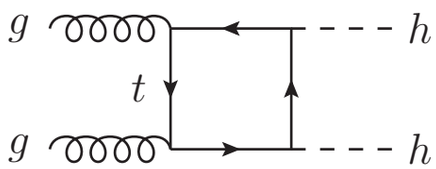
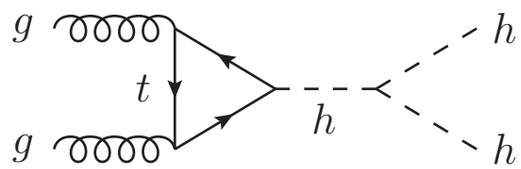
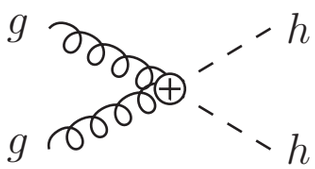
# Example #3: Double Higgs production via GF ( $gg \to hh$ )

work in progress with A. Azatov, G. Panico, M. Son




$$A(gg \to hh) \sim \left(\frac{\alpha_s}{4\pi}\right) \times \left[ y_t^2 \left(1 + O\left(\frac{v^2}{f^2}\right)\right) + g_6^2(E) + g_8^2(E) + \ldots \right]$$

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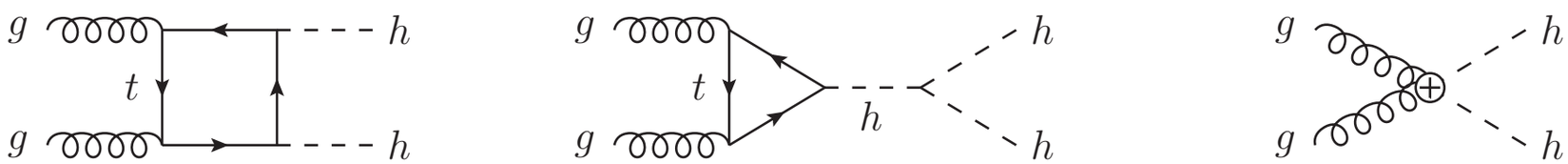


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from modified
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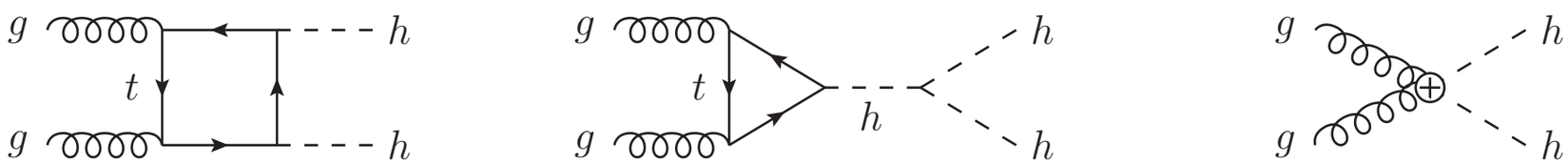


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from dim-6 operator: $O_g = \frac{g_s^2}{m_W^2} H^\dagger H \, G^a_{\mu\nu} G^{a\,\mu\nu}$

$$g_6^2(E) \sim \bar{c}_g \frac{4\pi}{\alpha_2} \frac{E^2}{v^2} \sim \frac{\lambda^2 E^2}{m_*^2}$$

suppressed by weak spurion $\lambda$ for a pNGB Higgs

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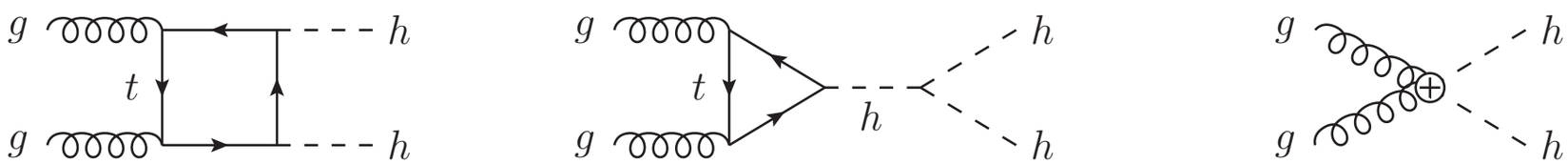


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from dim-8 operators:

$$O_{gD0} = \frac{g_s^2}{m_W^4} \left(D_\rho H^\dagger D^\rho H\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$O_{gD2} = \frac{g_s^2}{m_W^4} \Big[ \eta^{\mu\nu} D_\rho H^\dagger D^\rho H - 4\, D^\mu H^\dagger D^\nu H \Big] G^a_{\mu\alpha} G^{a\,\alpha}_{\nu}$$

$$g_8^2(E) \sim \bar{c}_{gD0,2} \frac{4\pi}{\alpha_2} \frac{E^4}{v^2 m_W^2} \sim \frac{g_*^2 E^4}{m_*^4}$$

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- EFT valid for $E \ll m_*$ :

$$\boxed{g_6(E) < \lambda \lesssim g_*}$$

$$\boxed{g_8(E) < g_*}$$

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- dim-8 operators are more important than dim-6 ones for $m_*(\lambda/g_*) < E < m_*$

Condition for neglecting dim-8 operators:

$$\boxed{g_6(E) < \frac{\lambda^2}{g_*}}$$

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  Condition for neglecting dim-8 operators:

$$\boxed{g_6(E) < \frac{\lambda^2}{g_*}}$$

- Let $\delta$ be the precision obtained on $\bar{c}_g(4\pi/\alpha_2)$ using events with invariant mass $m(hh) \sim \bar{E}$

$$g_6(E)_{min} \equiv g_{min} \sim \sqrt{\delta}\, \frac{\bar{E}}{v} \quad \Rightarrow \quad \boxed{\lambda > g_{min}} \qquad \boxed{\frac{\lambda^2}{g_*} > g_{min}}$$

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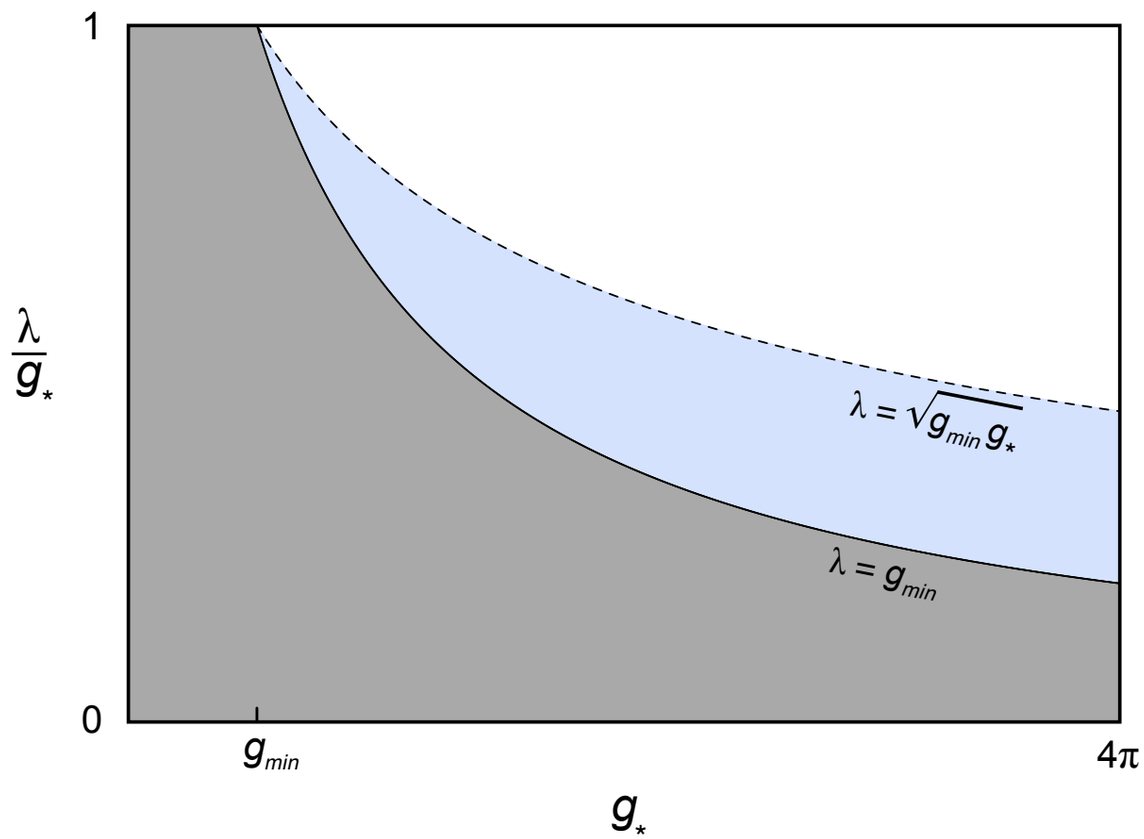


- Let $\delta$ be the precision obtained on $\bar{c}_g(4\pi/\alpha_2)$ using events with invariant mass up to $\bar{E}$

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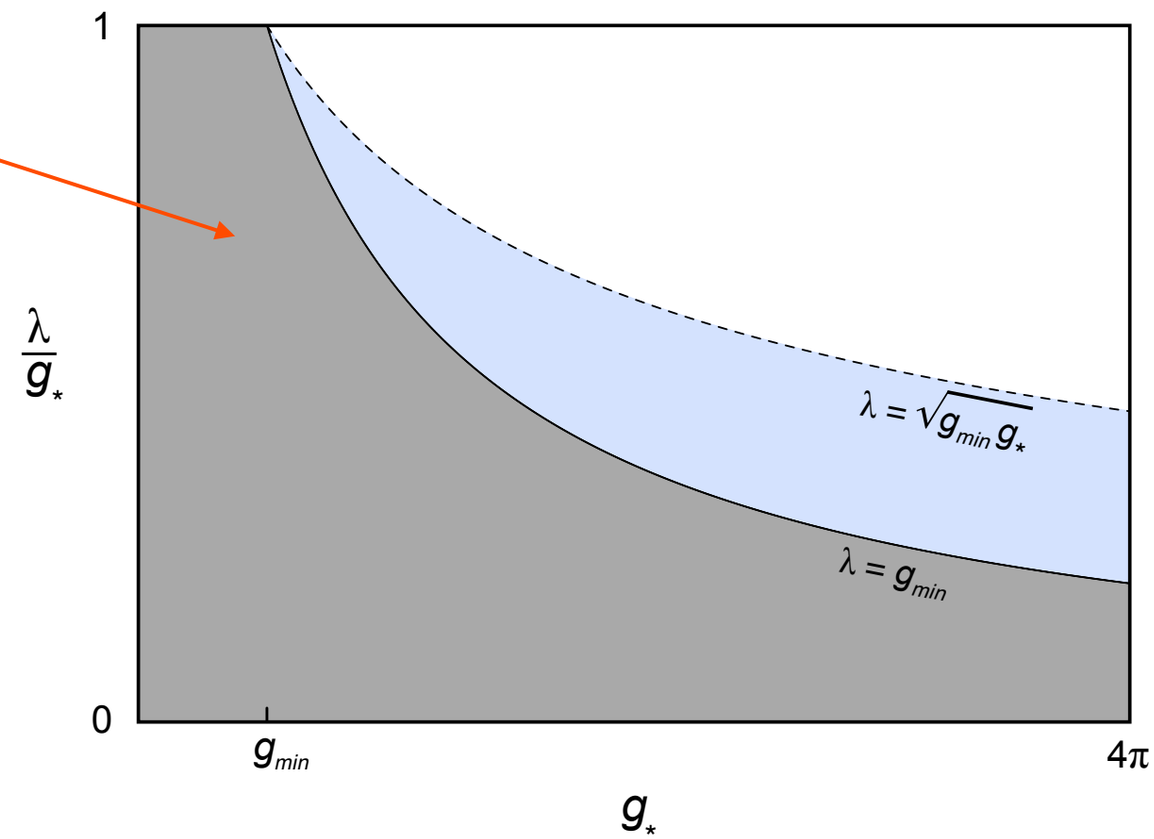
work in progress with A. Azatov, G. Panico, M. Son

EFT not valid in the gray region

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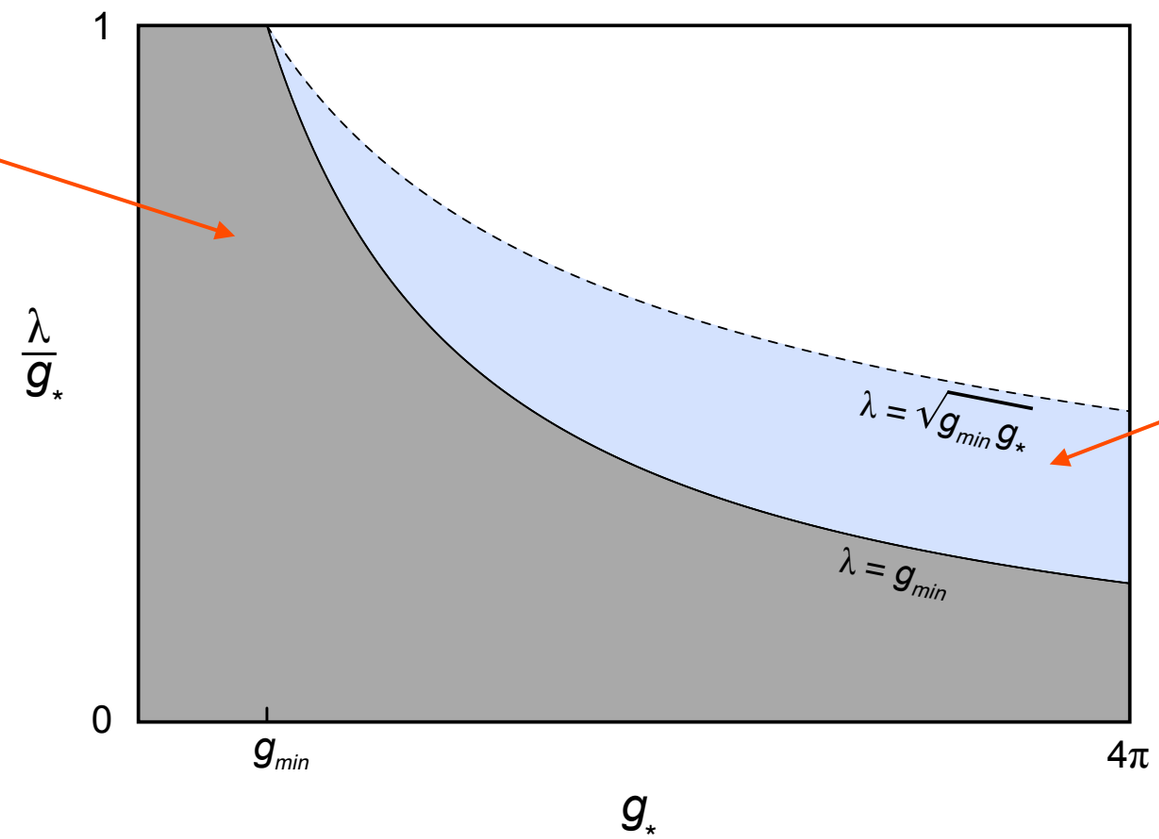


dim-8 operators not negligible in the light blue region

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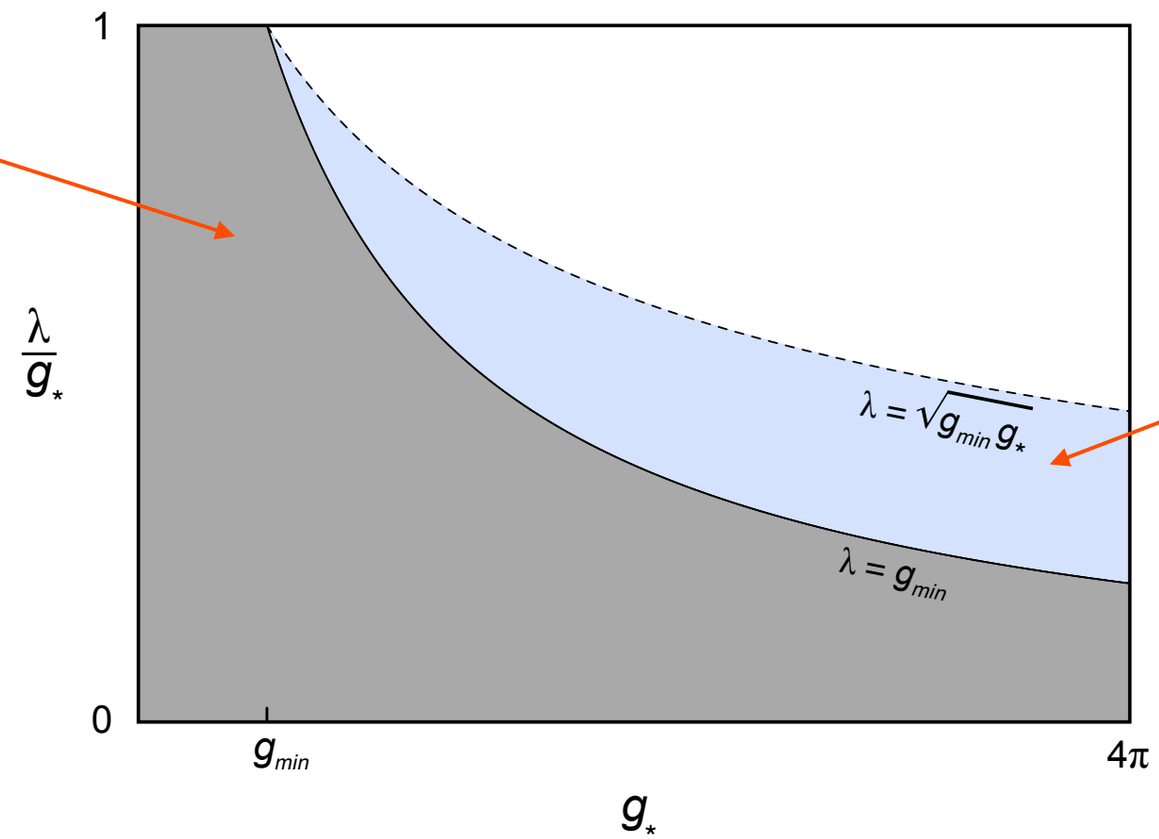


dim-8 operators not negligible in the light blue region

Notice:

Fully composite $t_R$ ( $\lambda = y_t$ ) and partially composite $t_R$ and $t_L$ ( $\lambda = \sqrt{g_* y_t}$ ) can be probed only if $g_{min} < y_t$ (requires sensitivity to the SM cross section)

$$\lambda > g_{min}$$

$$\frac{\lambda^2}{g_*} > g_{min}$$

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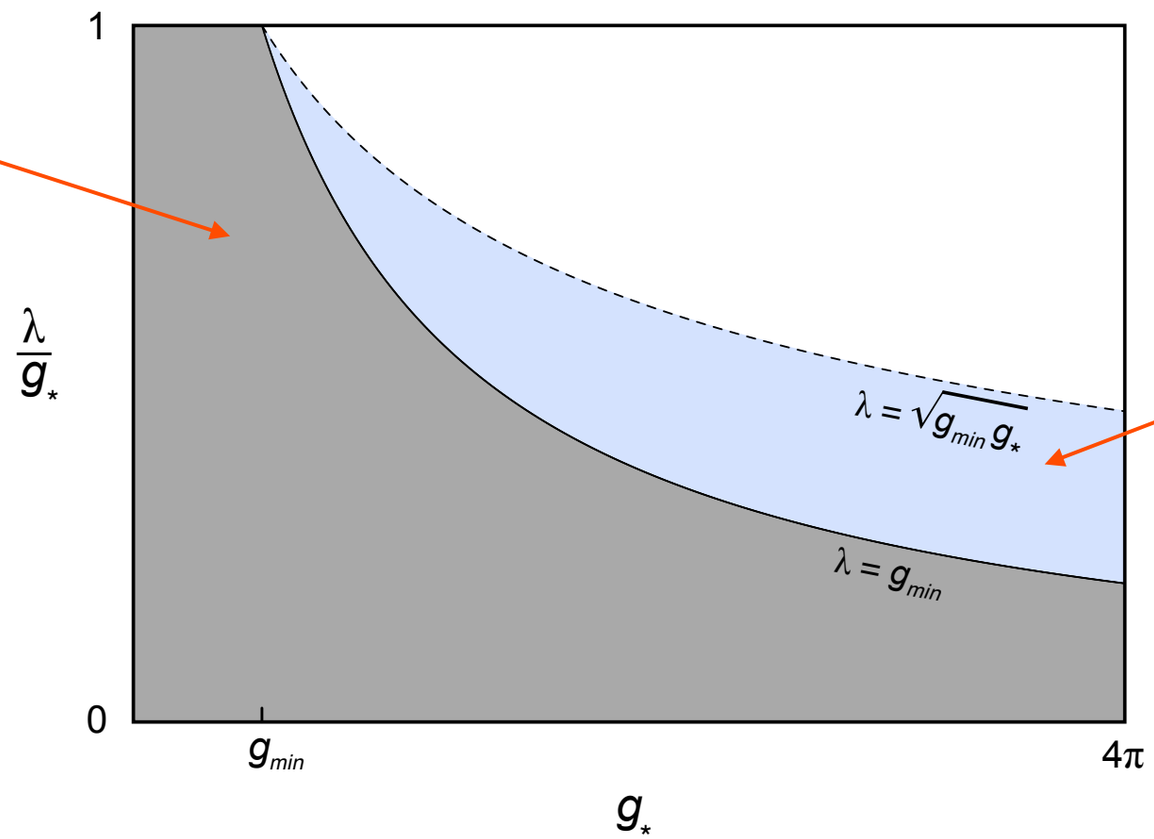
work in progress with A. Azatov, G. Panico, M. Son

EFT not valid in the gray region




dim-8 operators not negligible in the light blue region

Notice:

Fully composite $t_R$ ( $\lambda = y_t$ ) and partially composite $t_R$ and $t_L$ ( $\lambda = \sqrt{g_* y_t}$ ) can be probed only if $g_{min} < y_t$ (requires sensitivity to the SM cross section)

Results for channel $pp \to hh \to b\bar{b}\gamma\gamma$

| 14 TeV, 300 fb$^{-1}$ | 14 TeV, 3 ab$^{-1}$ | 100 TeV, 3 ab$^{-1}$ |
|---|---|---|
| $\delta \simeq 0.15$ | $\delta \simeq 0.1$ | $\delta \simeq 0.05$ |
| $\bar{E} \simeq 1.0$ TeV | $\bar{E} \simeq 1.0$ TeV | $\bar{E} \simeq 1.0$ TeV |
| $g_{min} = 1.6$ | $g_{min} = 1.3$ | $g_{min} = 0.9$ |

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- Next frontier for LHC Run2: $2 \to 2$ scattering processes to probe strength of EWSB dynamics at $E \gg m_h$

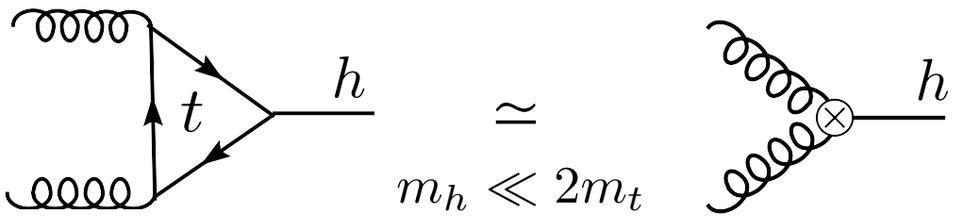
- Assessing the validity of EFT requires power counting.

  Dim-8 operators can be relevant if dim-6 ones are suppressed

# Extra slides

# Example #4: Telling the top loop from a point

On-shell single-Higgs cannot distinguish the top loop from a point-like interaction:




$$A(gg \to h) = A_{SM}\left(1 - \underbrace{\bar{c}_u}_{O(v^2/f^2)} + 12\underbrace{\left(\frac{4\pi}{\alpha_2}\right)\bar{c}_g}_{O\left(\frac{\lambda^2}{y_t^2}\frac{m_t^2}{m_*^2}\right)}\right) + \ldots$$

$$O_u = \frac{y_u}{v^2}\, H^\dagger H\, \bar{q}_L H^c u_R$$

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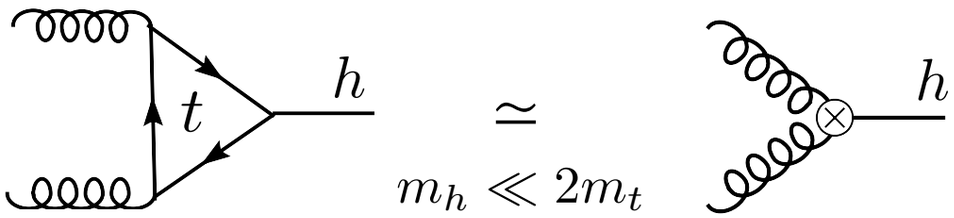


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An extra hard jet can probe the top loop and break the degeneracy:

Banfi et al. arXiv:1308.4771
Azatov, Paul arXiv:1309.5273
Grojean et al. arXiv:1312.3317
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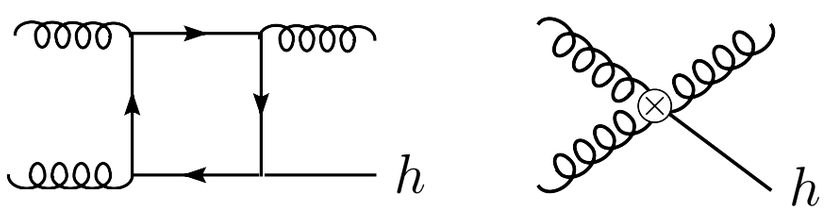


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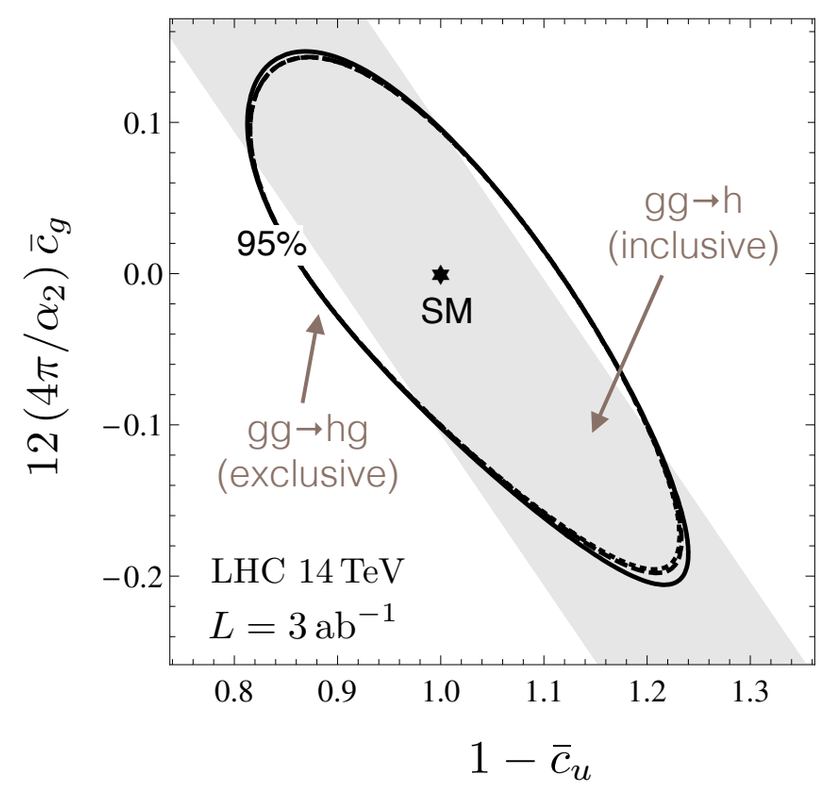

# Example #4: Telling the top loop from a point

For the effective theory to be valid one needs:

$$12\left(\frac{4\pi}{\alpha_2}\right)\bar{c}_g \times \frac{p_T^2}{m_t^2} \approx \frac{\lambda^2}{y_t^2}\frac{E^2}{m_*^2} < \frac{\lambda^2}{y_t^2}$$

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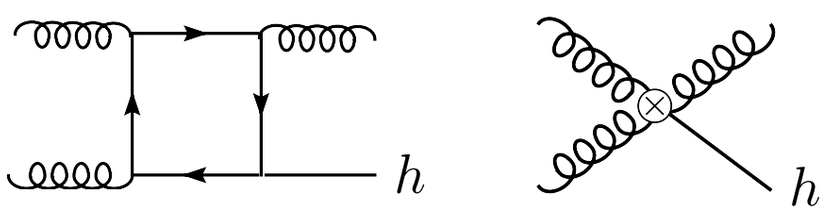


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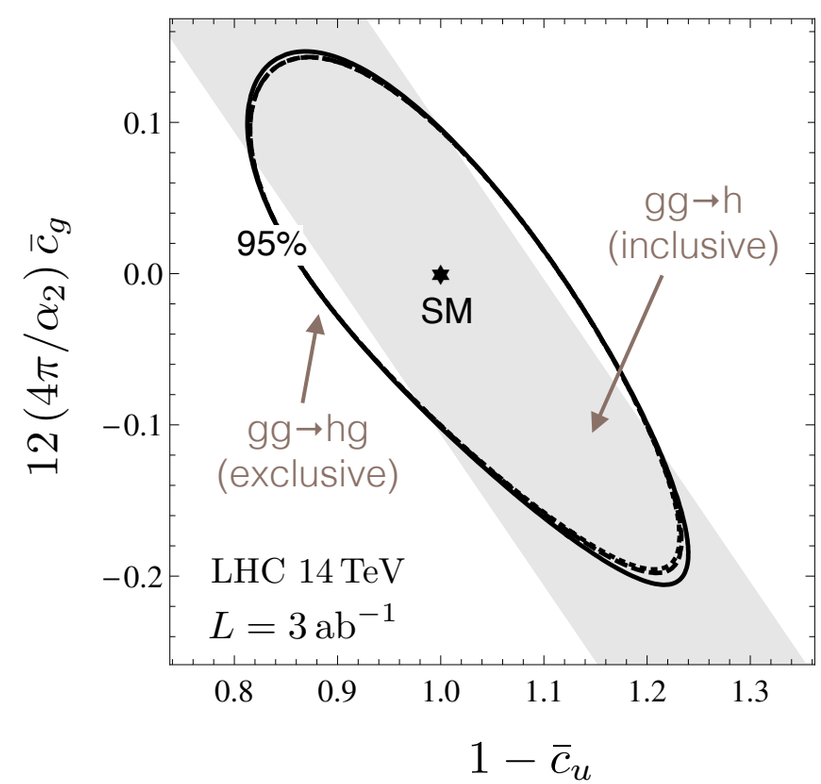

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For a cut $p_T > 650\,\mathrm{GeV}$
(as done in arXiv:1312.3317)

$$3 < \frac{\lambda^2}{y_t^2}$$

$$1.7\, y_t \lesssim \lambda < g_* < 4\pi$$

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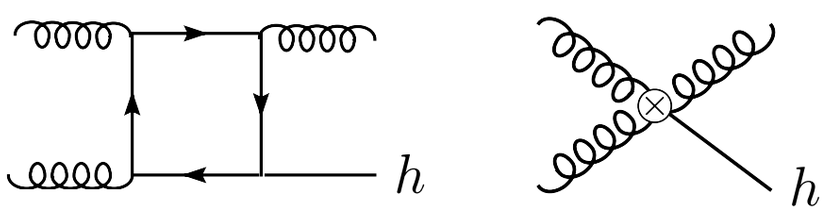


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