# Implications of Higgs Searches and Discovery

Michele Papucci
LBNL

SLAC Summer Institute 2012 Aug 1st, 2012

# Implications of ~~Higgs~~ a new particle? Searches and Discovery

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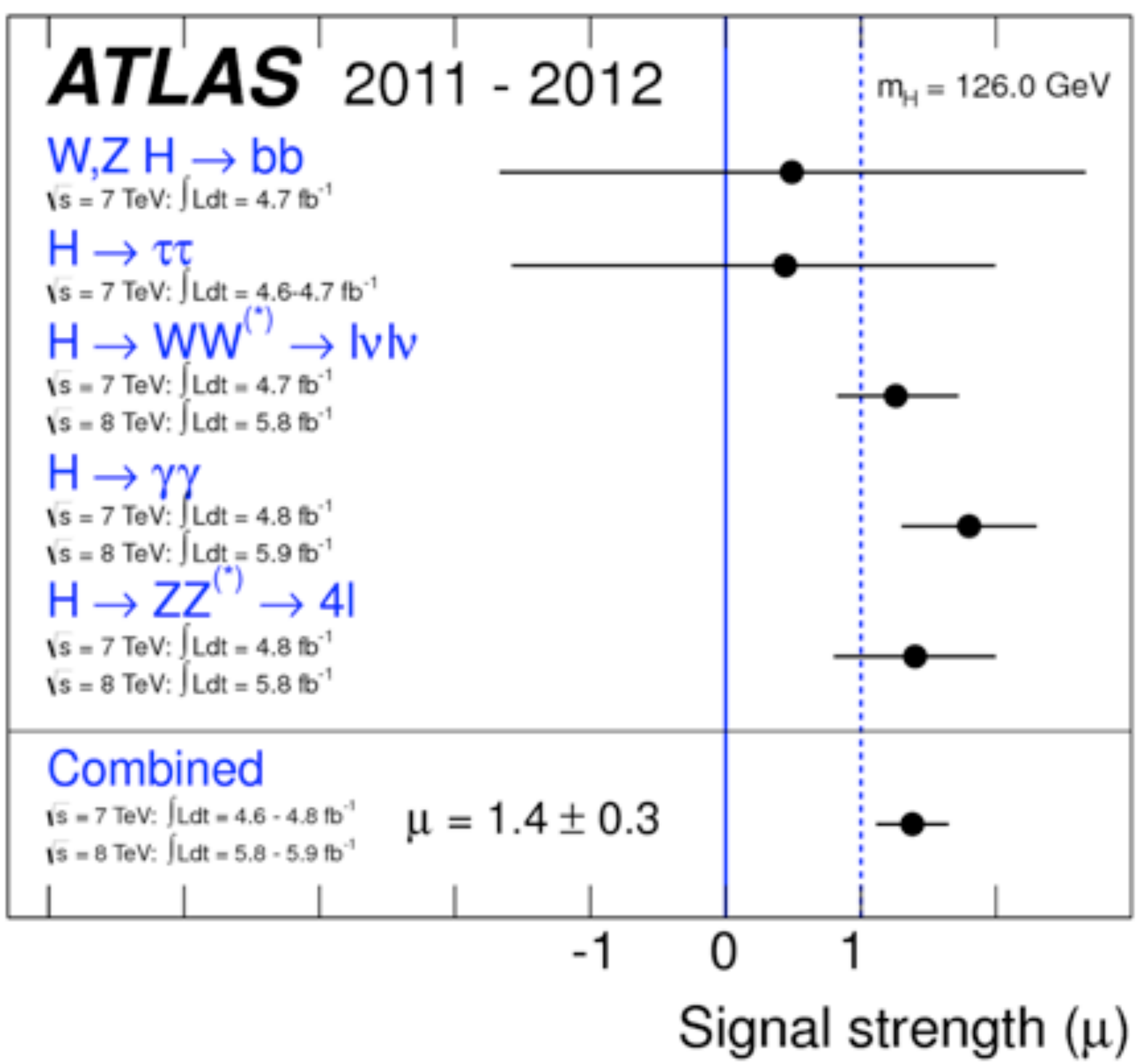
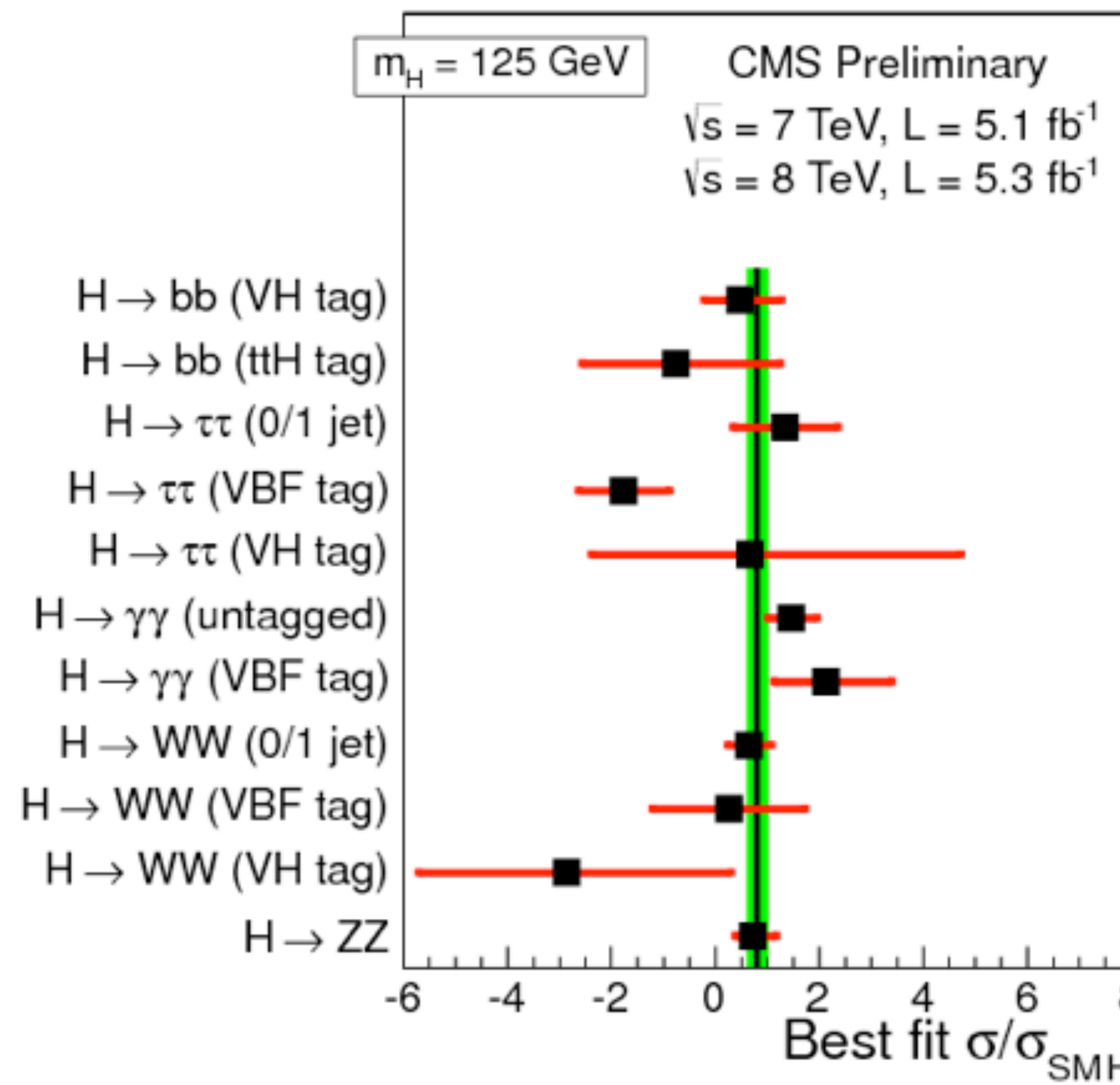
- On July 4th, a new particle has been discovered by ATLAS and CMS around 125-126GeV
- It's a boson, and can decay to $\gamma\gamma$, $ZZ^*$, $WW^*$
- Couplings to fermions ($bb$, $\tau\tau$) are still not very constrained



# Outline

- Is it a Higgs or an impostor? Does it participate in EWSB?
- If it is an Higgs, is it fundamental or composite?
- Implications for specific models?
- ...

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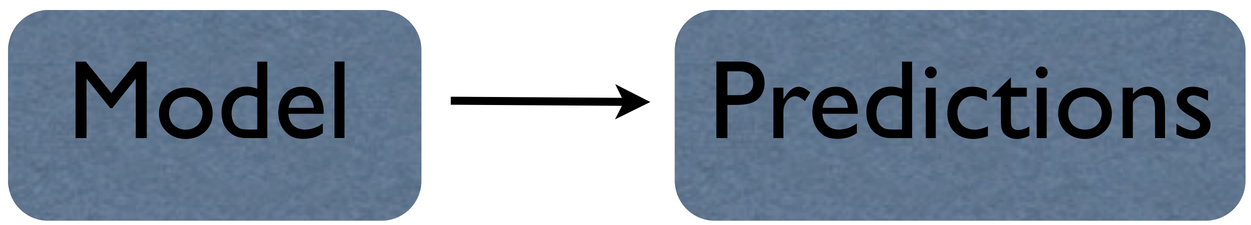

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Model $\longrightarrow$ Predictions $\longleftrightarrow$ Data

ex: SUSY (MSSM in particular) → M. Carena's lecture
(+ other examples tomorrow)

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- Bottom - up: start from effective Lagrangian for EWSB (see H. Haber's lecture)

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Look at what data says about the 125GeV particle being an impostor or being composite, or ...

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Look at what data says about the 125GeV particle being an impostor or being composite, or ...

maybe too early to play these games, but we've bee waiting for so long...

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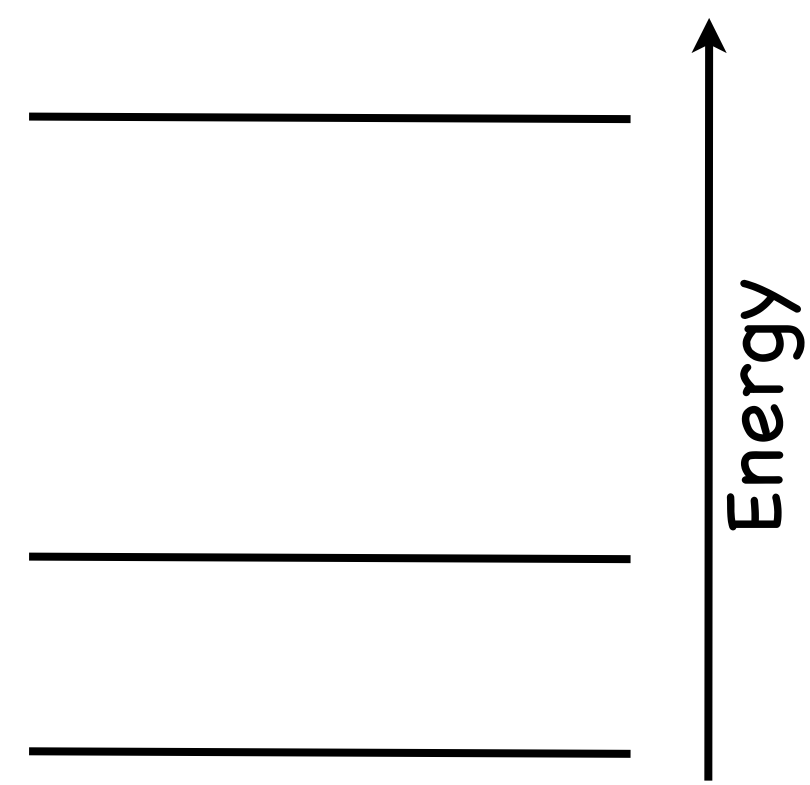
Non-linear realization of $SU(2)_L xU(1)_Y$ (describes Goldstone bosons $G^a$, breaks down around 1TeV)

+ what??



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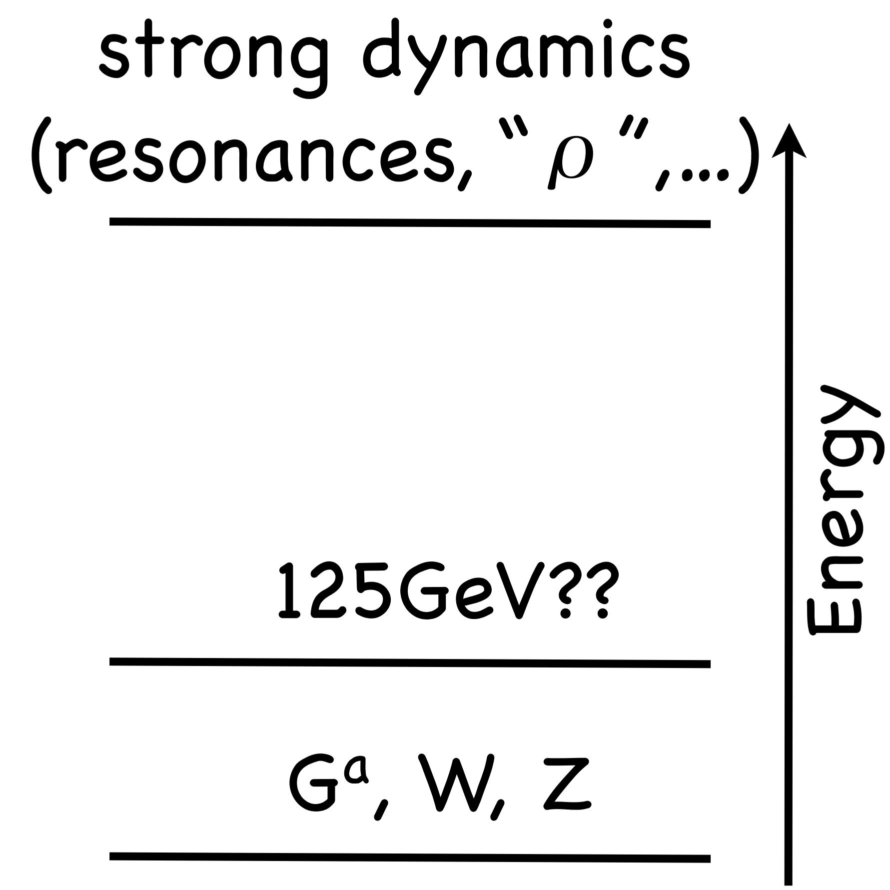

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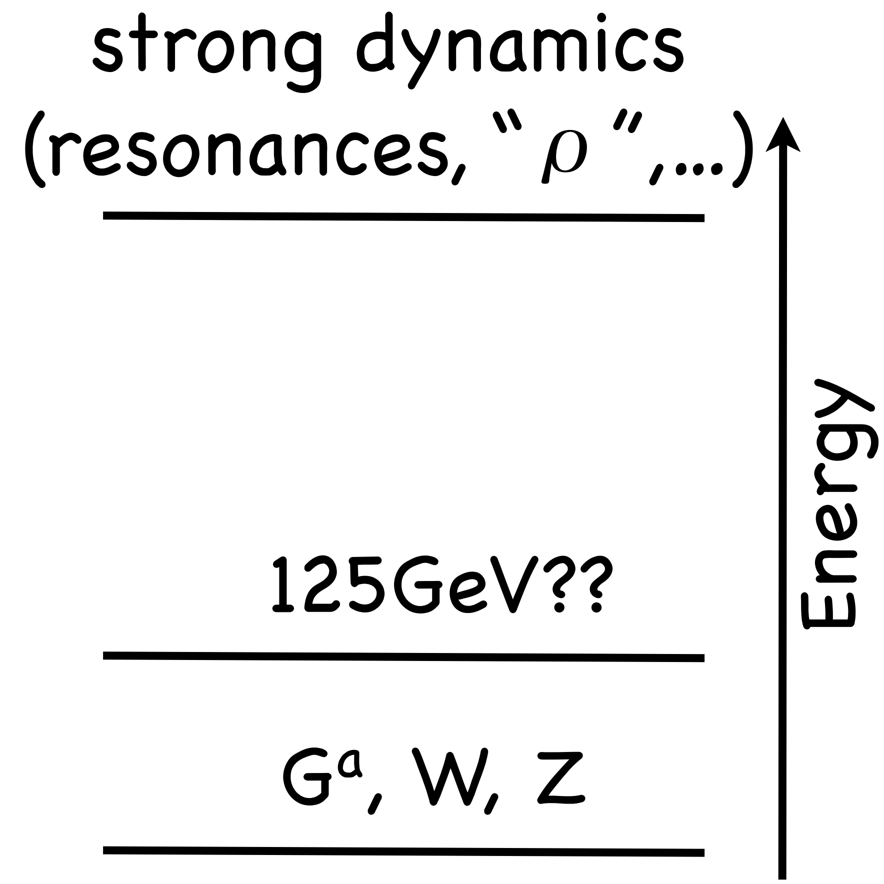


125 GeV scalar is an "impostor"
(more on it later)

Strong dynamics takes care of UV problems of the Goldstone scattering amplitudes

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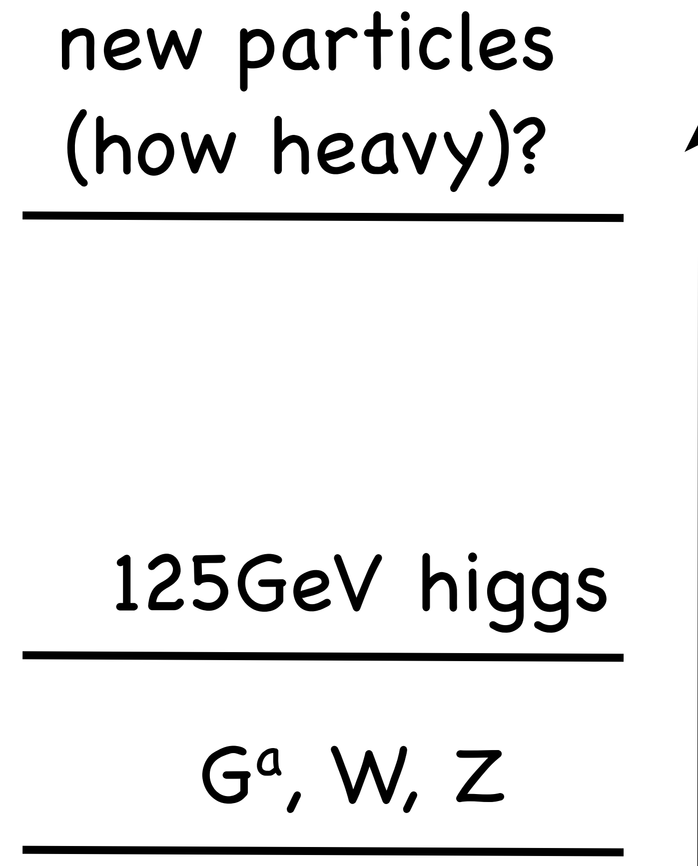

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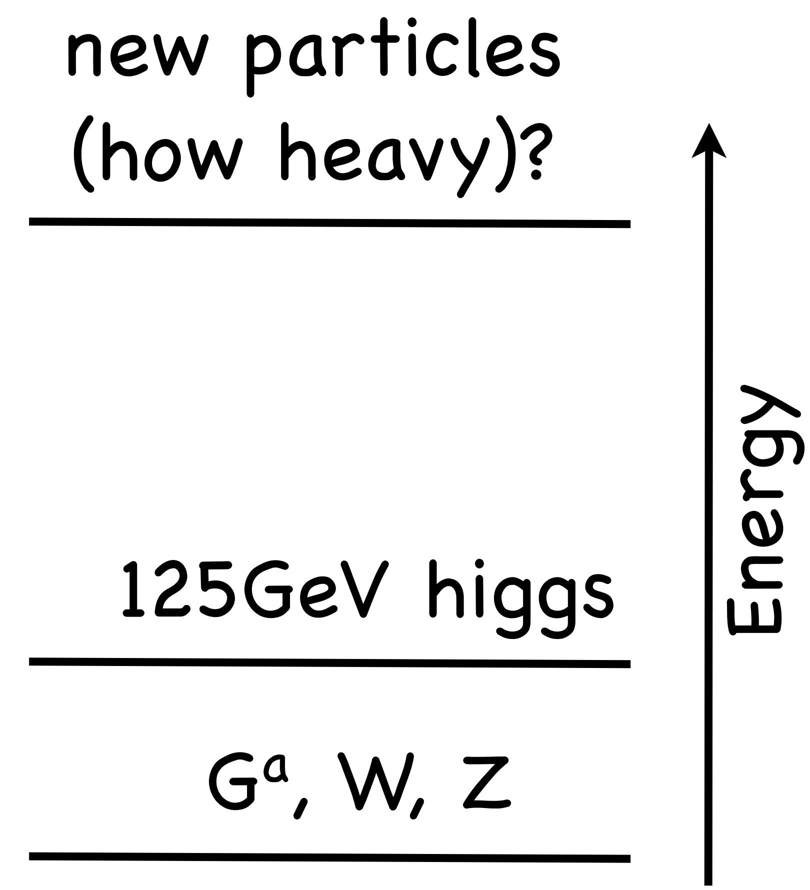


Higgs takes care of UV problems of the Goldstone scattering amplitudes
New particles may be present to fix the hierarchy problem (naturalness)

# Choices for EWSB

Non-linear realization of $SU(2)_L \times U(1)_Y$ (describes Goldstone bosons $G^a$, breaks down around 1TeV)

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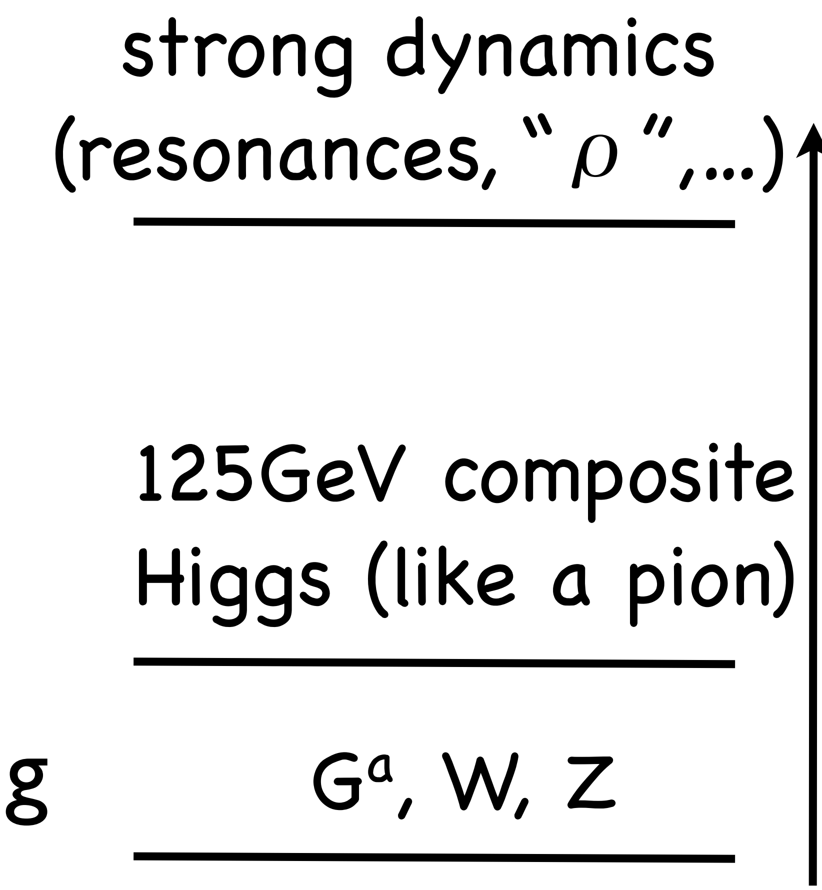
2. $SU(2)_L \times U(1)_Y$ linearly realized and weakly coupled: (a bunch of) fundamental Higgs(es)
3. $SU(2)_L \times U(1)_Y$ linearly realized + strong dynamics ("composite Higgs", etc...)



# Choices for EWSB

Non-linear realization of $SU(2)_L \mathrm{x} U(1)_Y$ (describes Goldstone bosons $G^a$, breaks down around 1TeV)

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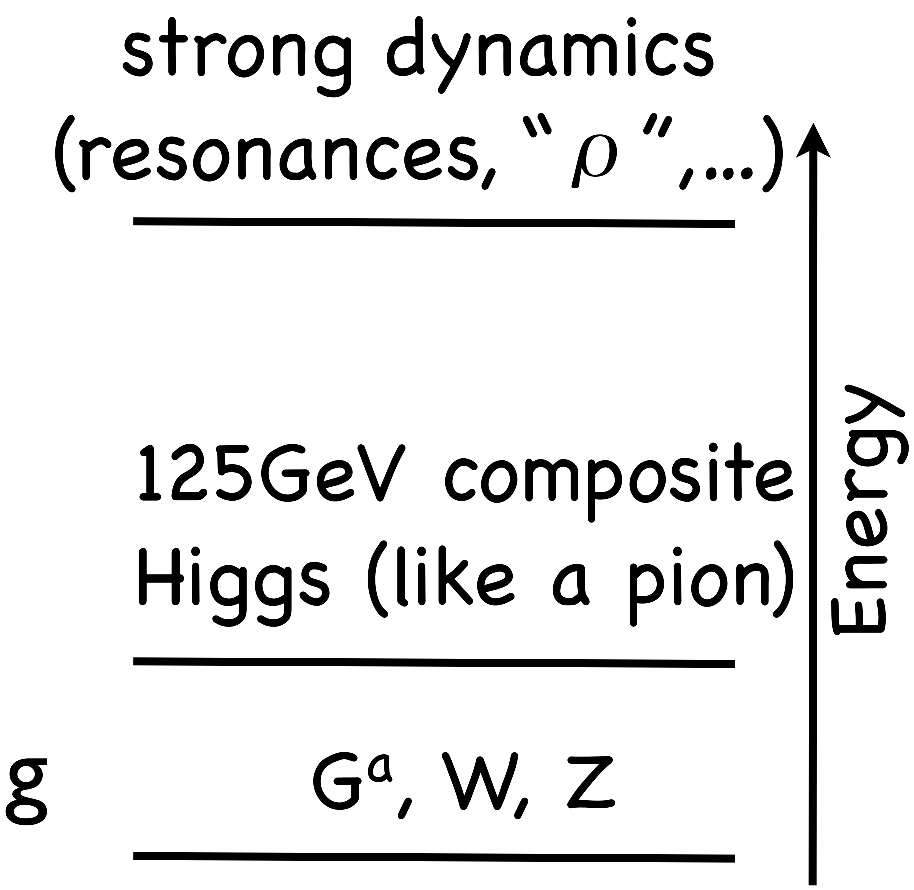


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Higgs only partially takes care of UV problems of the Goldstone scattering amplitudes, rest is done by strong dynamics

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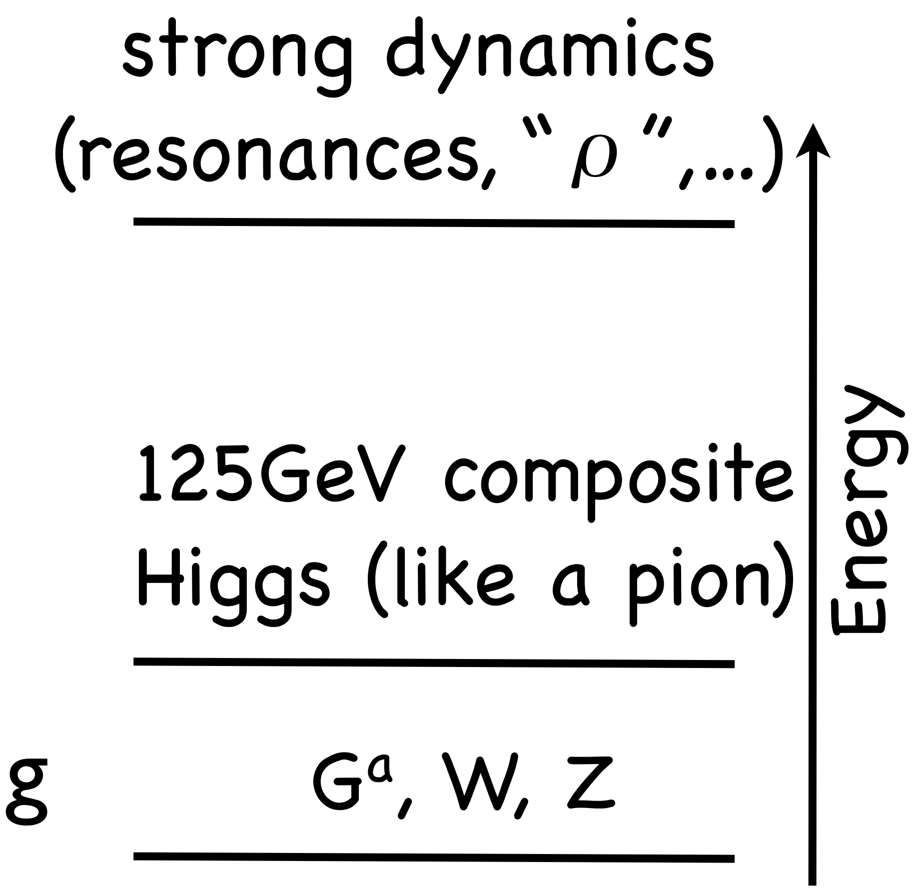


Implication of current data on 1 vs. 2 vs. 3?

# Bottom-up approach

Let's count parameters to fit to Higgs data...

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Motivated by experimental results

(spin-2 unlikely) (story can be adapted to multiple higgses if necessary)

# Effective (chiral) lagrangian for the Higgs

Coleman, Wess, Zumino PRD 117 (1969) 2239
Callan, Coleman, Wess, Zumino PRD 117 (1969) 2247

see H.Haber lecture

Take the $U(1)_{e.m.} \times SU(3)_C$ lagrangian with massive W, Z and restore $SU(2)_L \times U(1)_Y$ invariance by using:

$$\Sigma(x) = e^{i\,T^a G^a(x)/v}$$

example:

$$\begin{aligned} W^a_\mu W^{\mu a} &\to \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] \\ &= (W^a_\mu - \partial_\mu G^a)(W^{a\mu} - \partial^\mu G^a) \end{aligned}$$

+ add the most generic function for the "radial" mode (the Higgs boson)

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e.g. Contino, Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089

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O(p$^2$)

O(p$^4$)

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O(p²)

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**+ O(p⁶) + ...**

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O($p^2$)

$$-\left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}\left(\bar{u}_L^i \bar{d}_L^i\right) \left[1 + c\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right] \begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + \text{h.c.}$$

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**+ O($p^6$) + ...**

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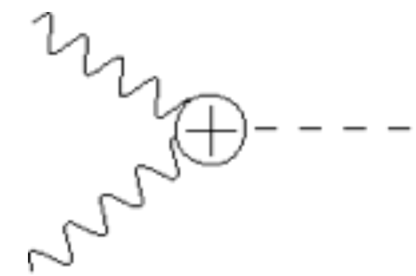

WWh, ZZh

$$- \left( m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right)\left( 1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots \right)$$

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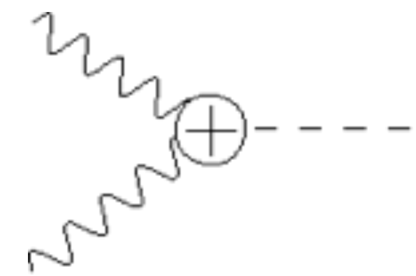
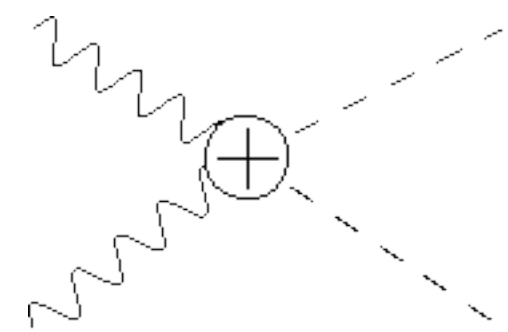


WWh, ZZh



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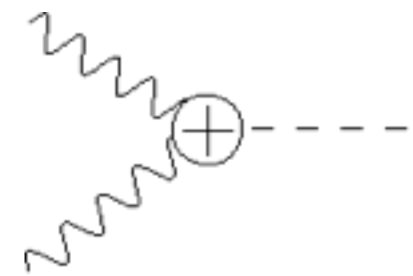

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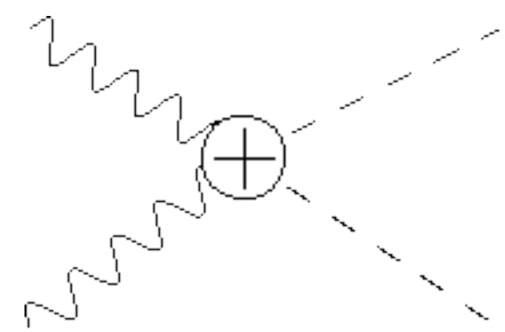
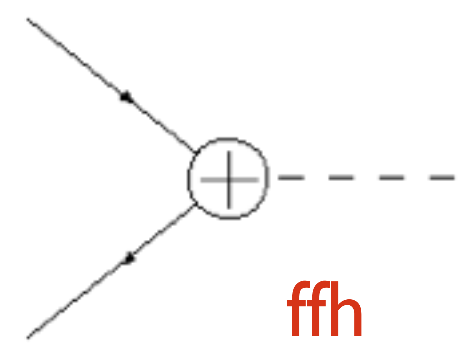


WWhh, ZZhh



ffh

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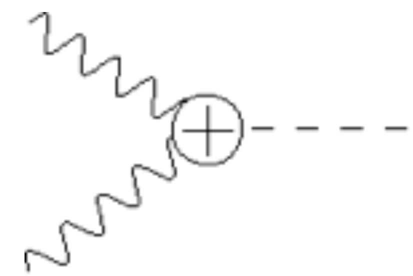

WWh, ZZh

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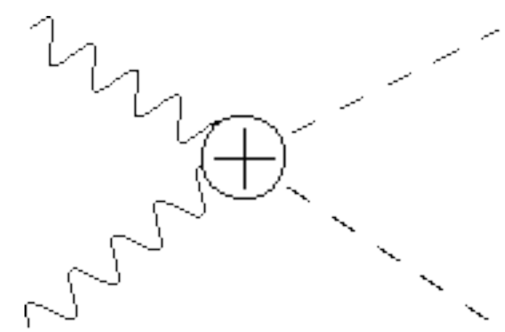

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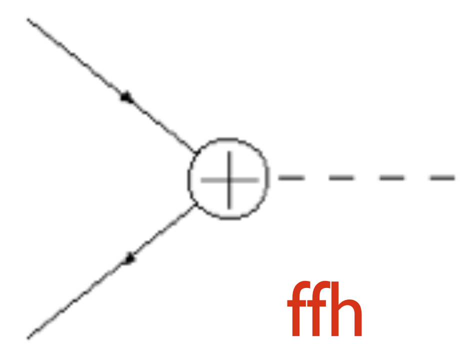

ffh

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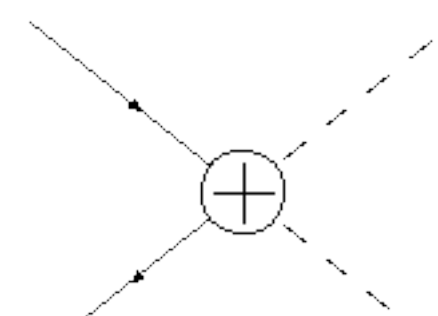

ffhh

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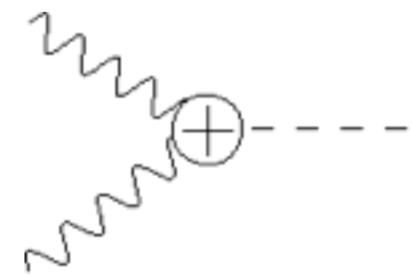

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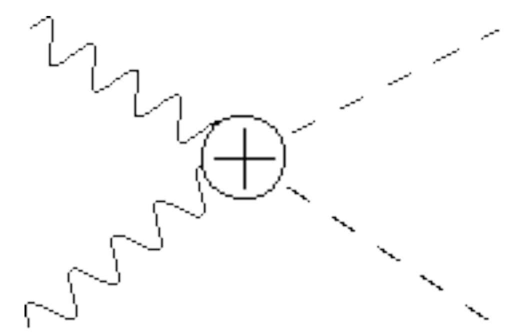

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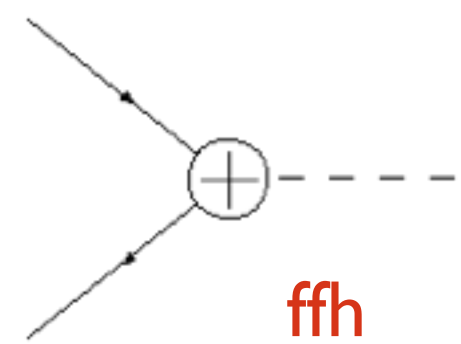

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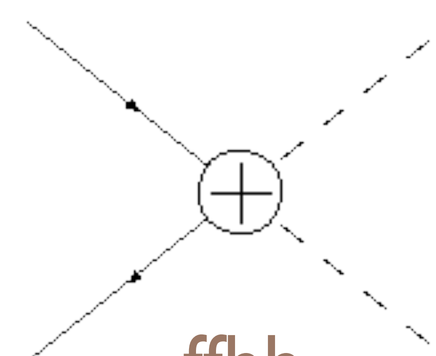

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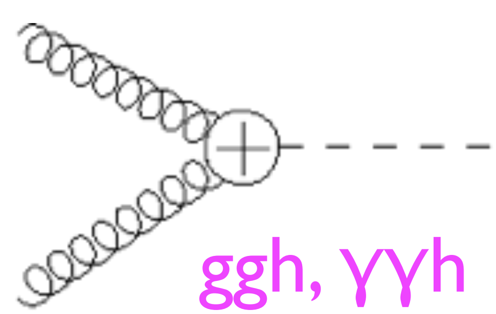

ggh, γγh

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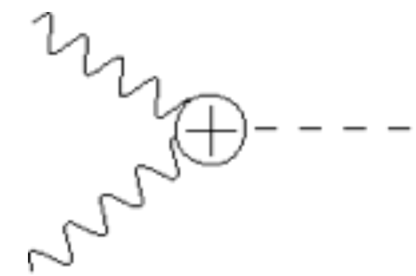
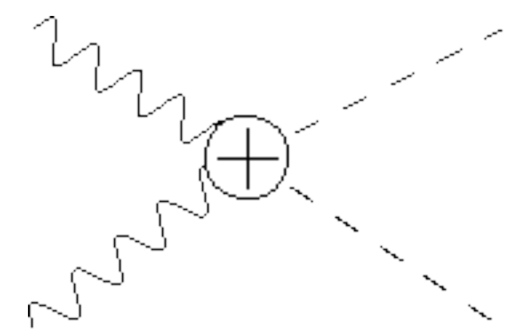
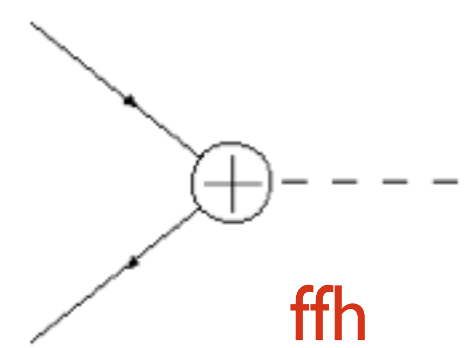

WWh, ZZh


WWhh, ZZhh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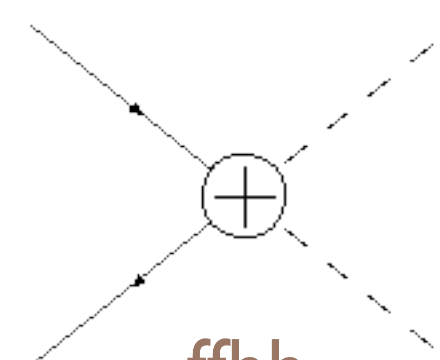
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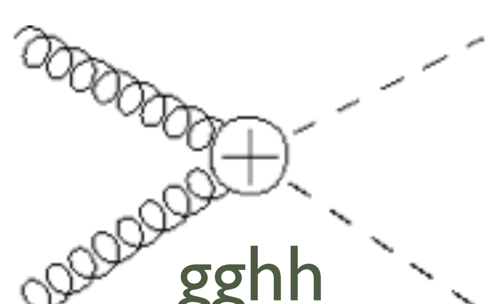
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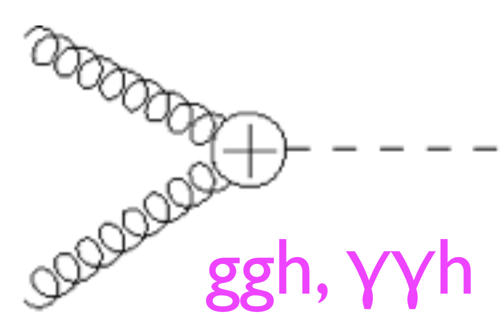
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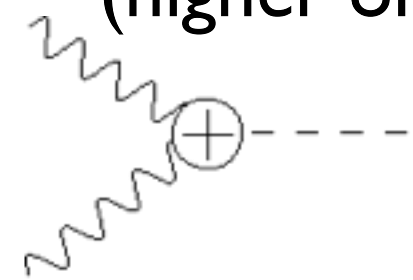
(higher order)



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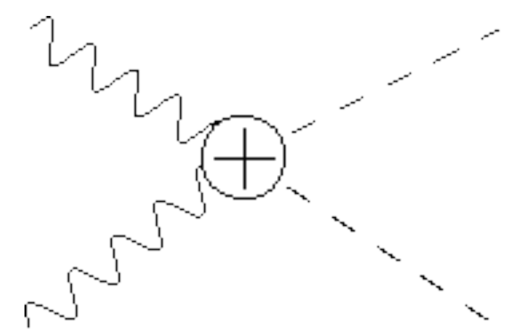

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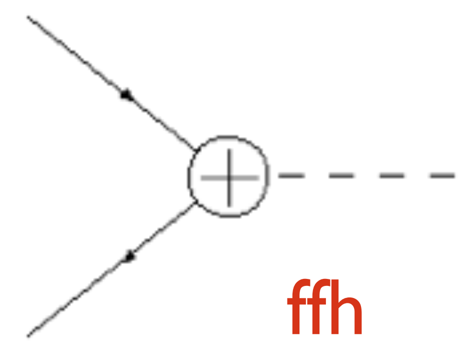

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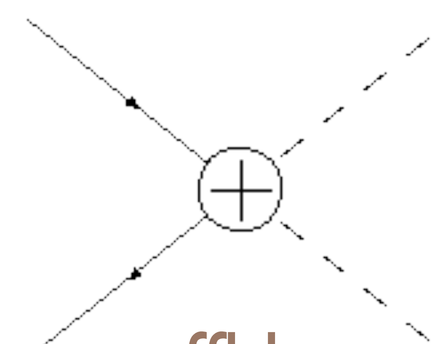

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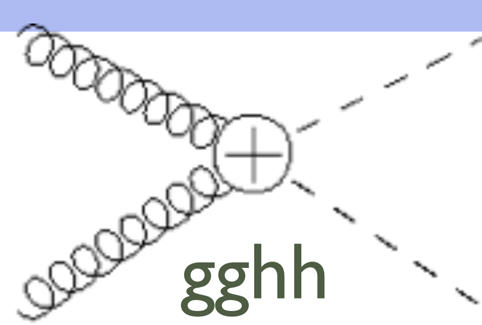

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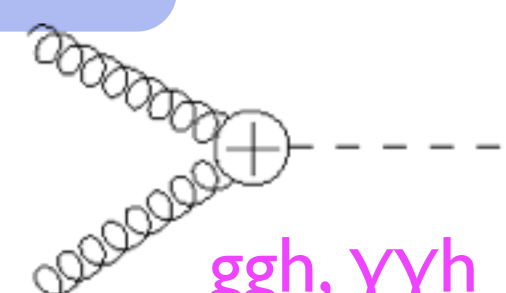

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but too many parameters!!

for early data need more constraints

→ need to add more assumptions

# Composite Higgs

Recall:

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$G^a$ "eaten" by W, Z, h massive with $m_h \sim O(v)$

($\Lambda_c > \Lambda$ b/c h partially unitarize $G^a G^a$ scattering)

# Composite Higgs

To reduce params → have the Higgs boson as another "pion" of some strongly coupled theory

howto: just enlarge the symmetry group to have more Goldstone bosons (and symmetry breaking at above the EW scale)

ex: SO(5) → SO(4) broken at scale f (>v):

4 massless d.o.f.: $G^a$ + h

$$\Lambda_c=4\pi f \;>\; \Lambda=4\pi v$$

$$m\rho \sim \Lambda_c$$

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Improvement of $O(\xi = v^2/f^2)$

# Composite Higgs

"Strongly Interacting Light Higgs" (SILH)

Giudice, Grojean, Pomarol, Rattazzi arXiv:hep-ph/0703164

most general lagrangian for Higgs boson as a pGB, expanded at $O(\xi)$

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| $c$ | $1-(c_H/2 + c_y)\,\xi$ |
| $c_2$ | $-(c_H + 3c_y + c_r/4)\,\xi/2$ |
| $d_3$ | $1+(c_6 - c_r/4 - 3c_H/2)\,\xi$ |
| $d_4$ | $1+(6c_6 - 25c_H/3 - 11c_r/6)\,\xi$ |
| $k_g = k_{2g}$ | $3c_g(y_t^2/g_\rho^2)\xi$ |
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Gillioz, Grober, Grojean, Muhlleitner, Salvioni arXiv:1206.7120

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SILH: for Higgs decays still 4 free parameters: ggh, γγh, VVh, ffh

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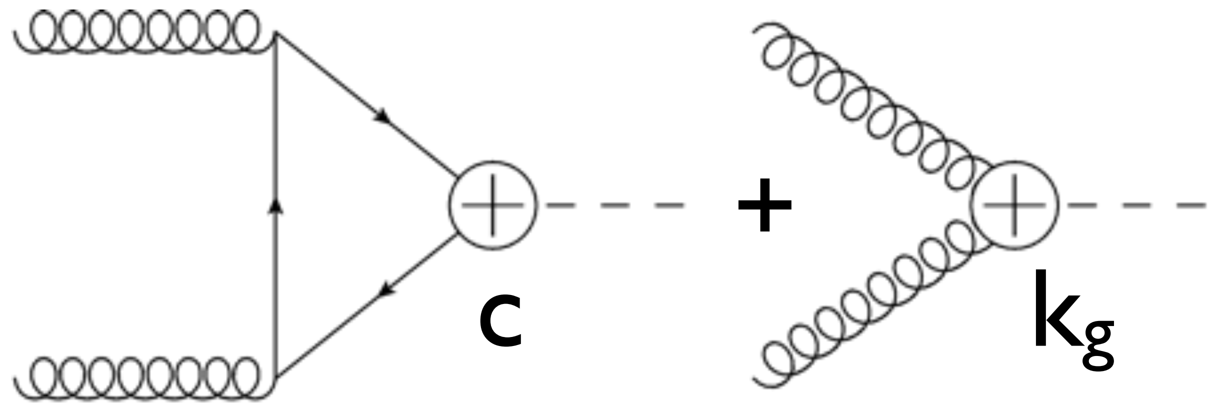

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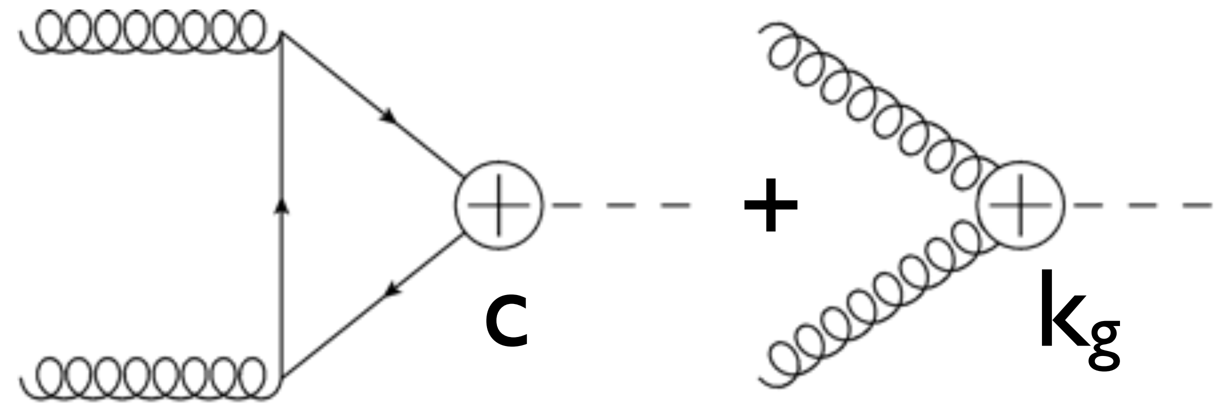


Falkowski, PRD 77 (2008) 055018
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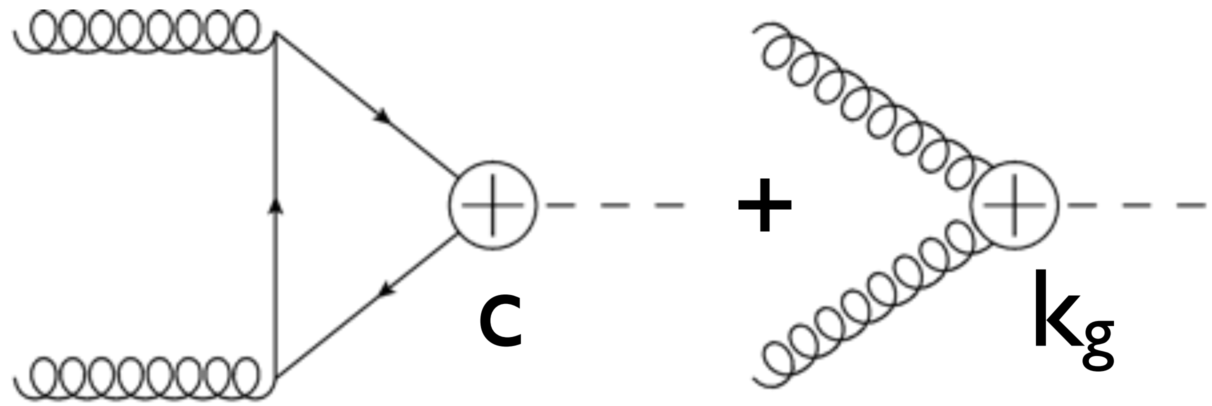


Minimal Composite Higgs Models:
2-paramters Higgs pheno: a & c

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"MCHM4": $a = \sqrt{1-\xi}, \qquad c = \sqrt{1-\xi}$ (also simplest little Higgs with $(SU(3)/SU(2))^2$)

MCHM = Minimal Composite Higgs Model (w/ SO(5)/SO(4))

# Looking at the data

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- In the following I will use fits to Higgs parameters done by theorists, to illustrate the main points

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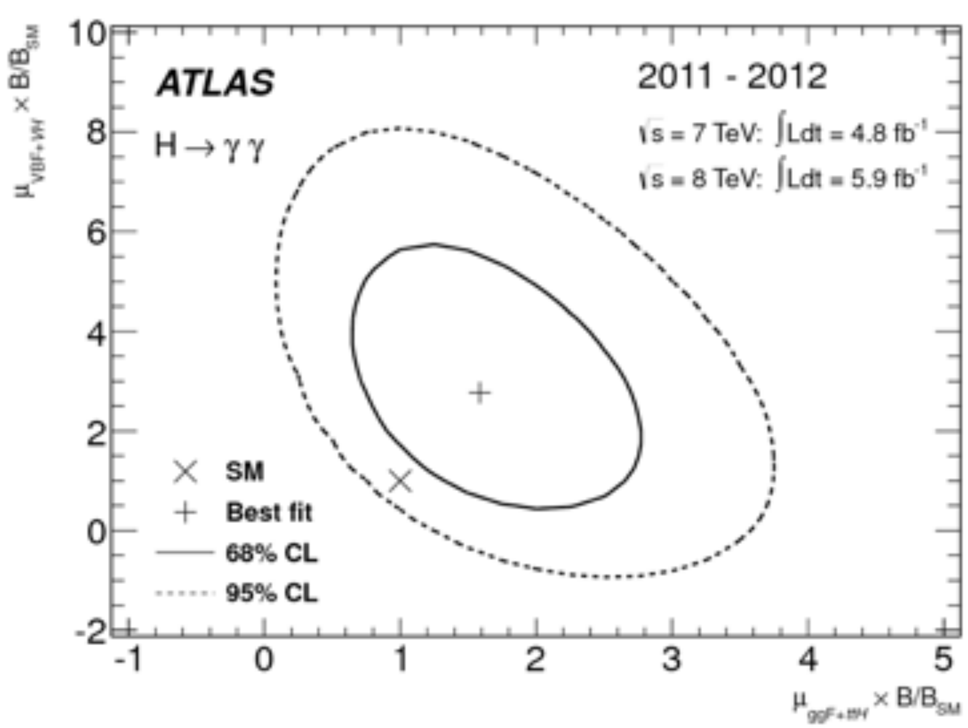


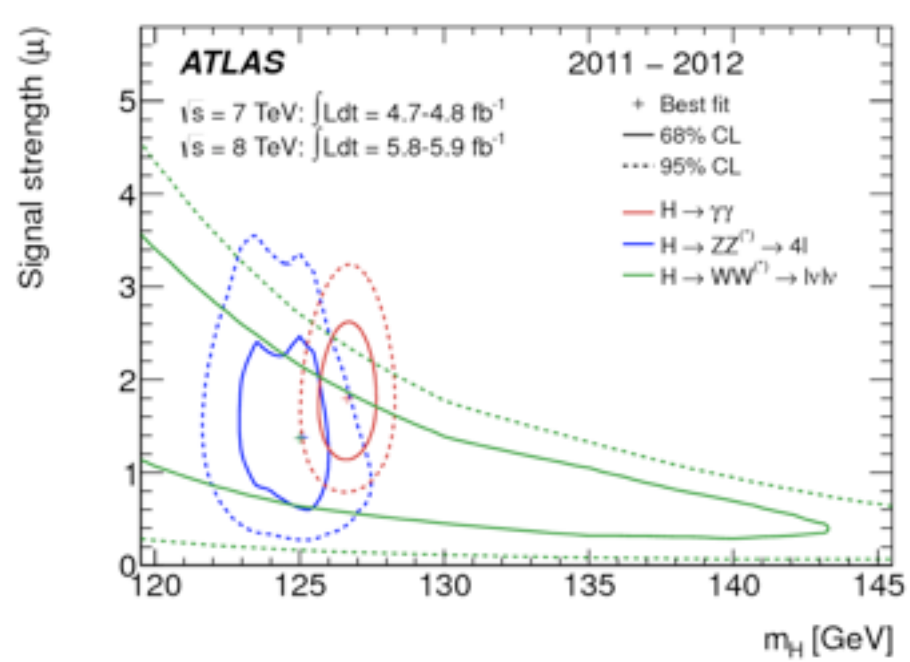


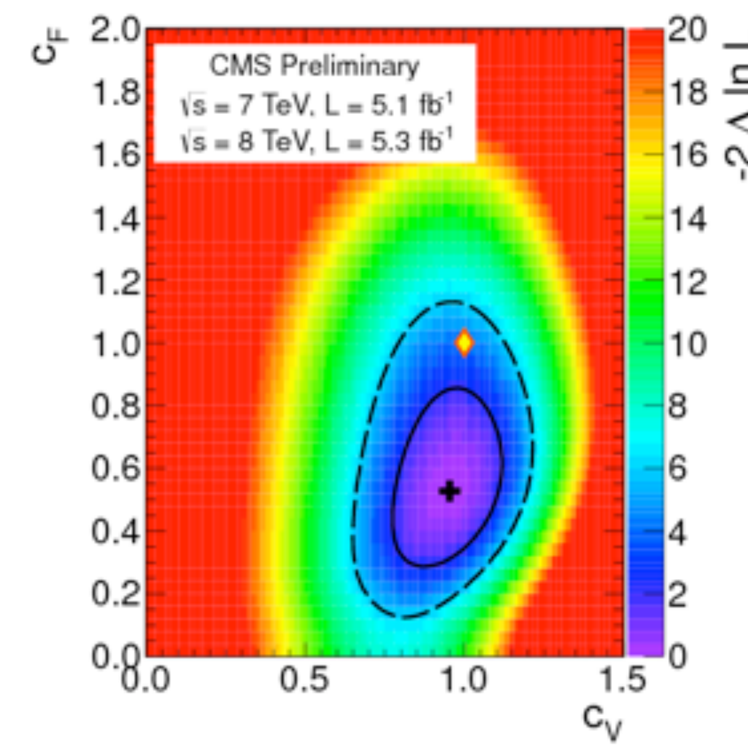

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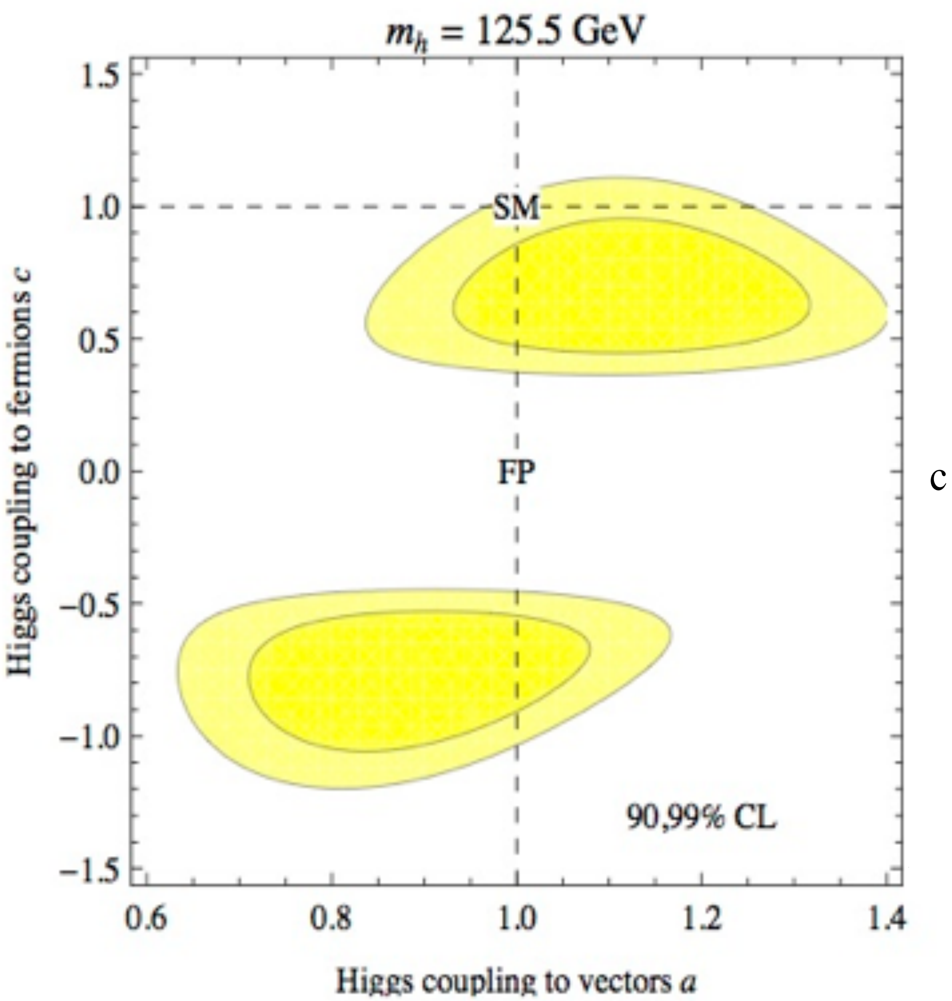
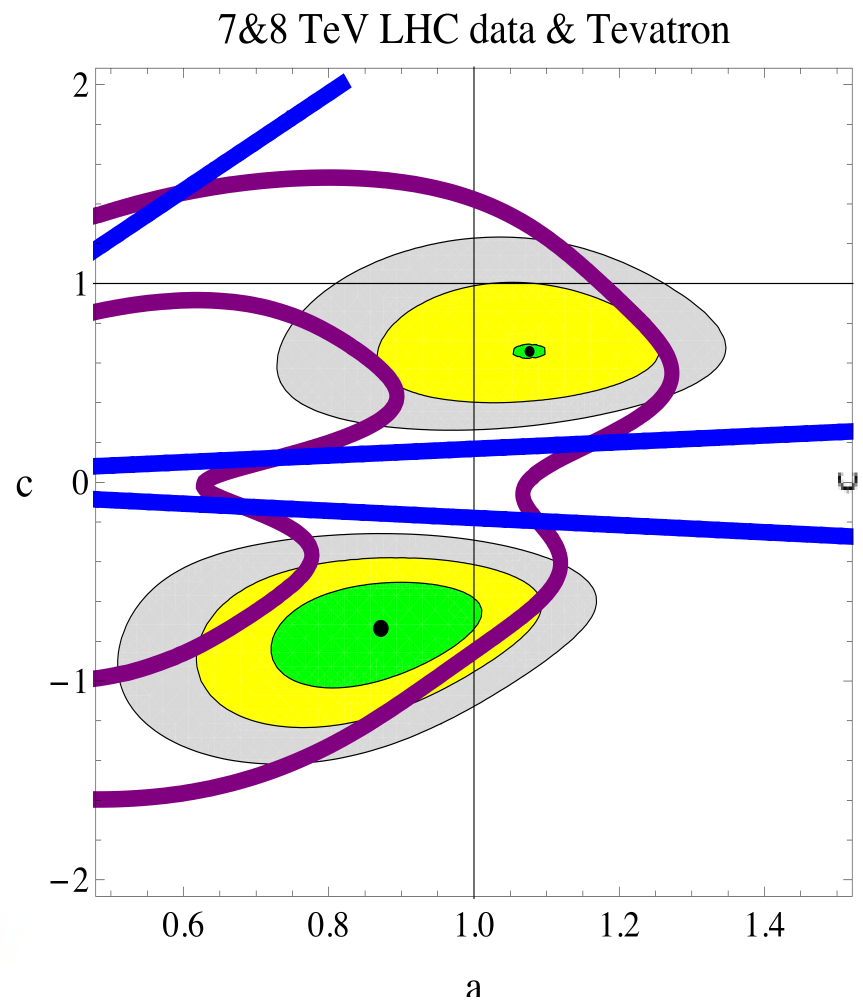
- Caveat: “sigmas” are “theorist sigmas”, but qualitative conclusions should hold

# Looking at the data

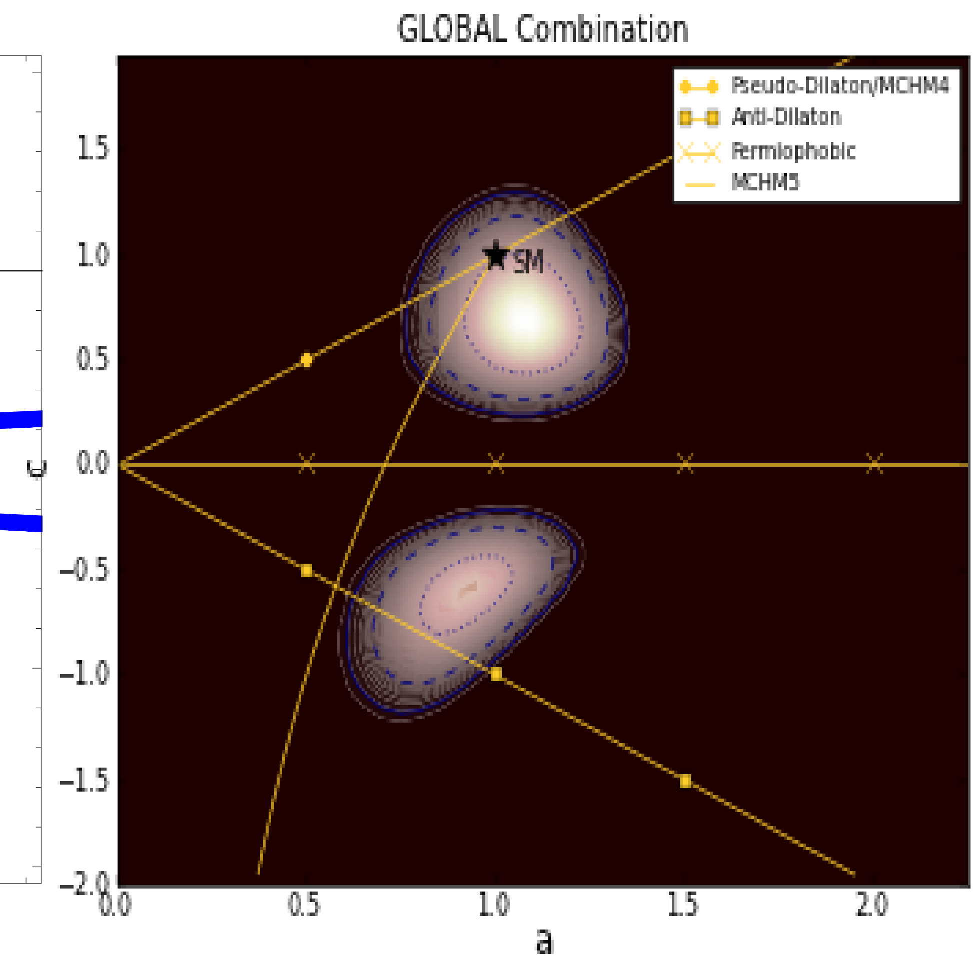
- Theorists views at the (a,c) plane after July 4th (ATLAS+CMS+TeVatron)




Giardino, Kannike, Raidal, Strumia arXiv:1207.1347




Espinosa, Grojean, Muhlleitner, Trott arXiv:1207.1717

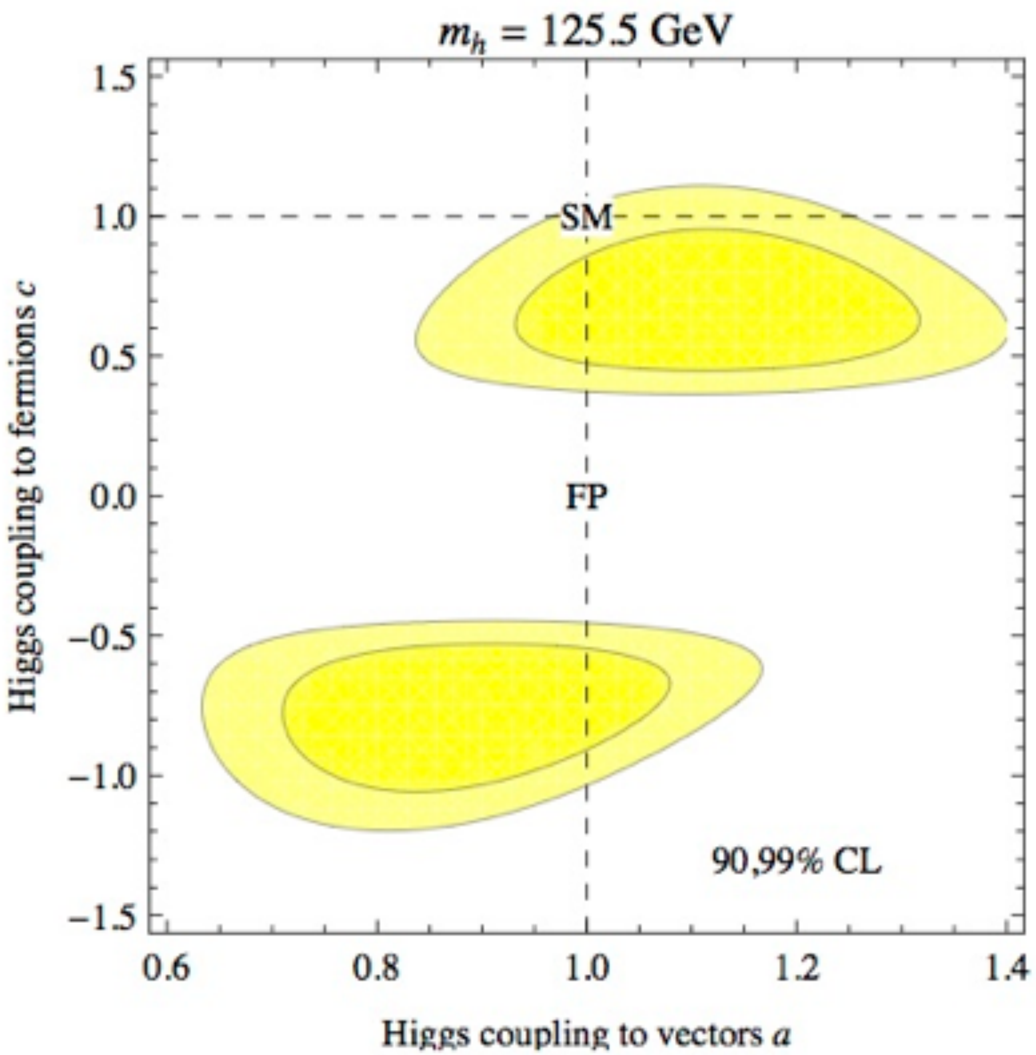



Ellis, You arXiv:1207.1693

The second solution is allowed by a degeneracy in $h\to\gamma\gamma$: $\sim |8.3a-1.8c|^2$

# Looking at the data

- Sanity check with experimental fit (CMS):

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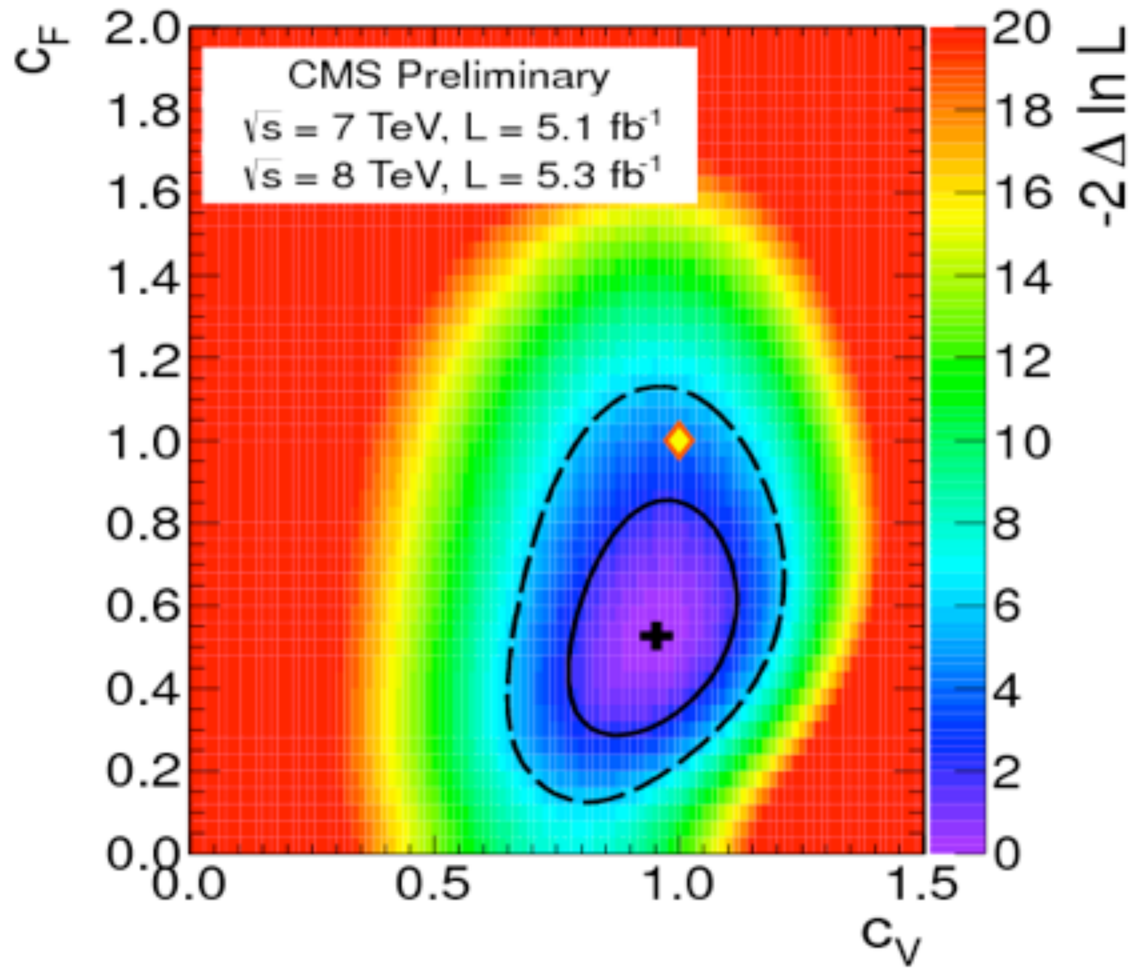
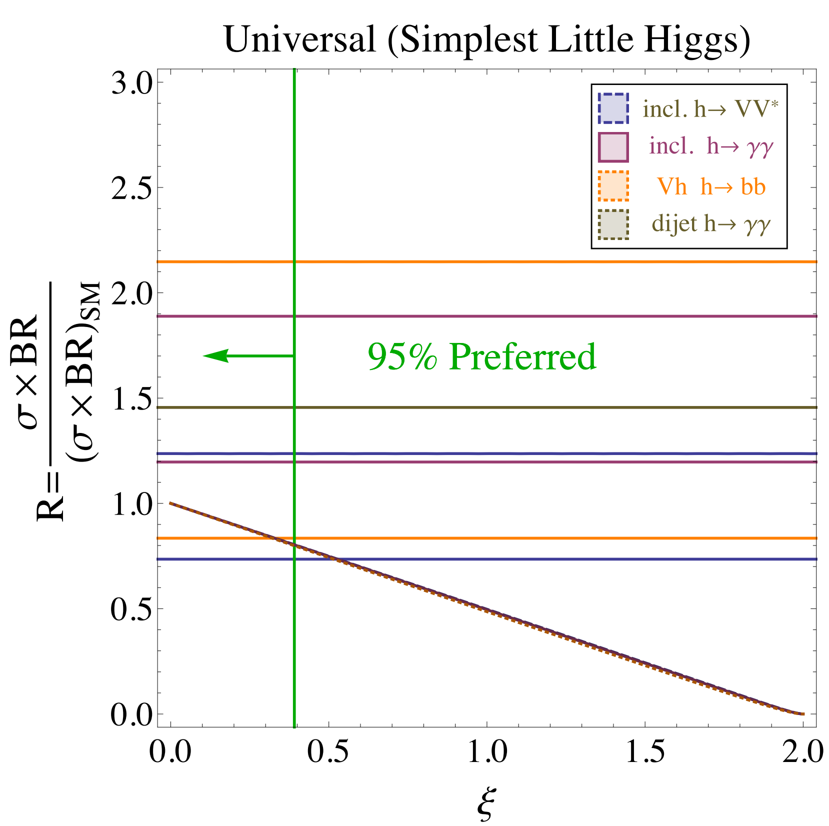
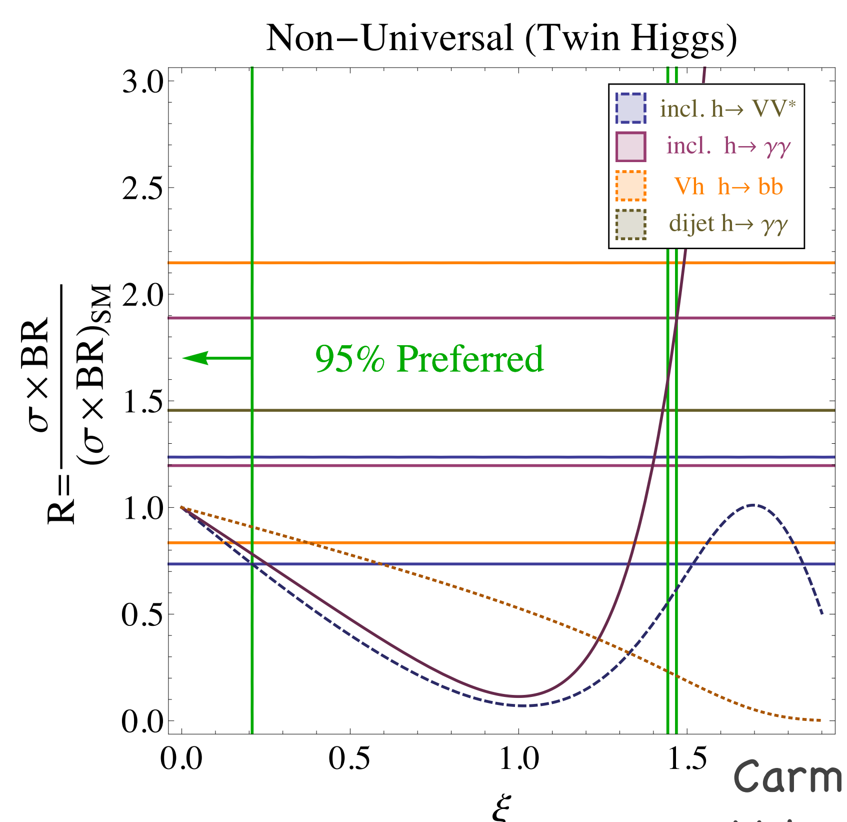


# Looking at the data

- The fact that the new particle walks and talks as the SM Higgs boson constrains the amount of compositeness of the Higgs boson
- ξ<0.3-0.4 is still allowed (and already expected by EW precision data) → f > 1.6-1.8 v




Carmi, Falkowski, Kuflik, Volansky, Zupan arXiv:1207.1718

wait a sec...

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- need to look (at least) at higgs pair production or WW scattering (and s dependence of xsec)...

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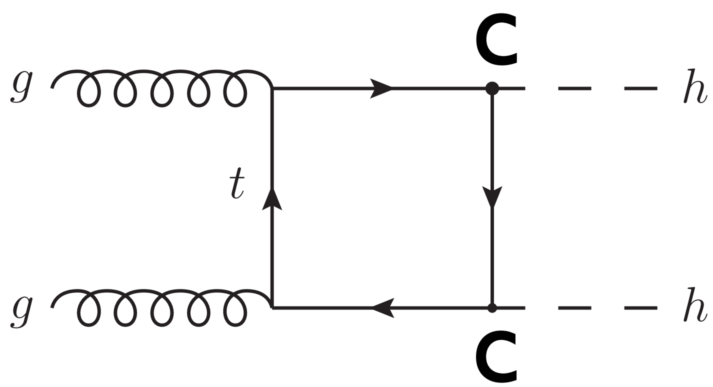


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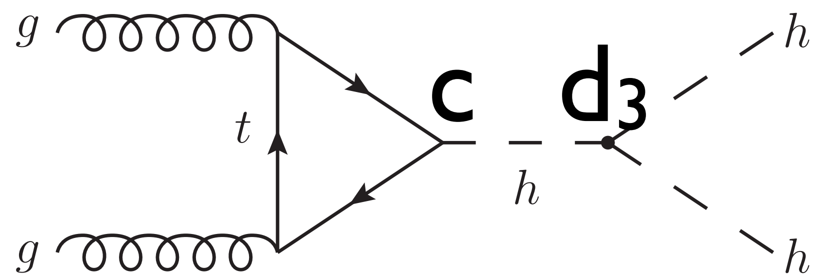


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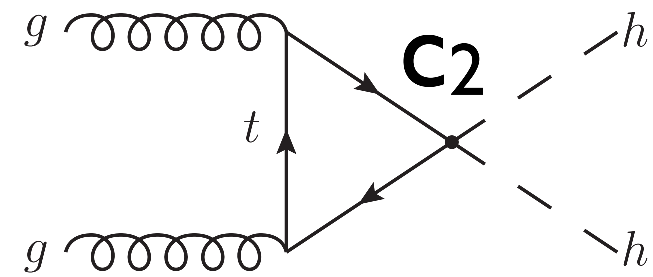


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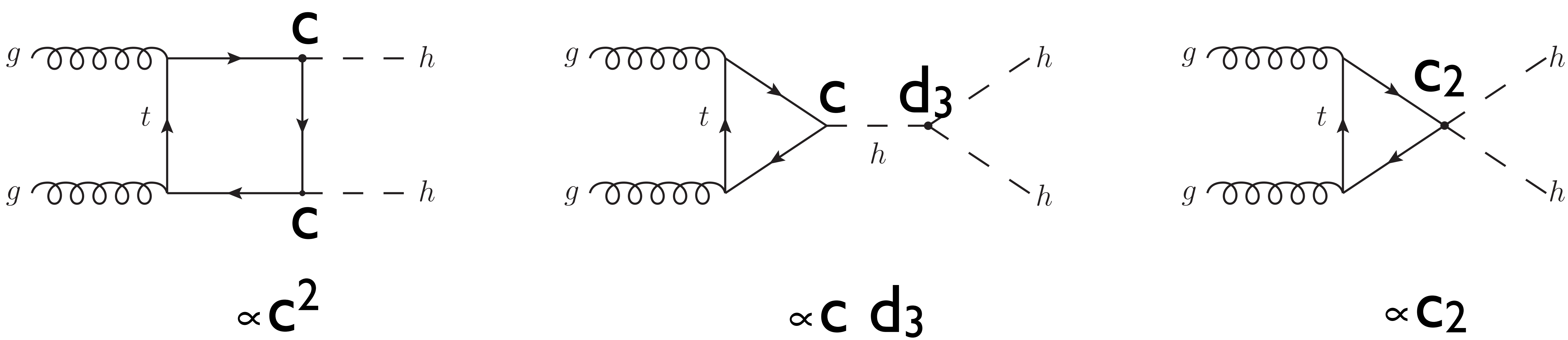


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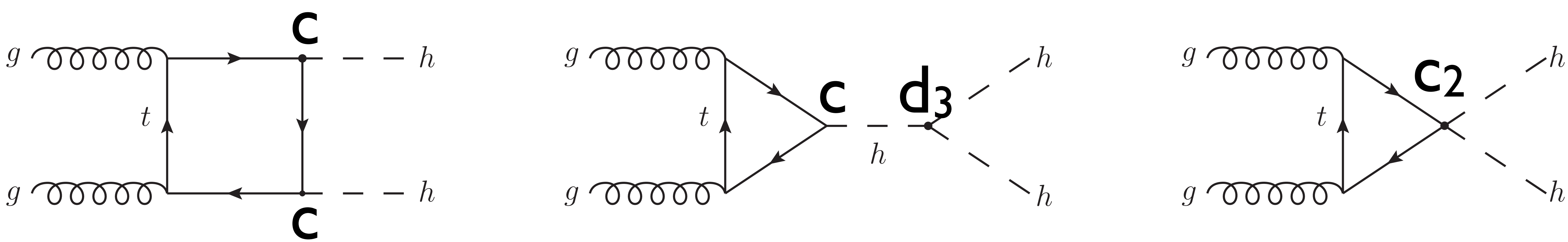


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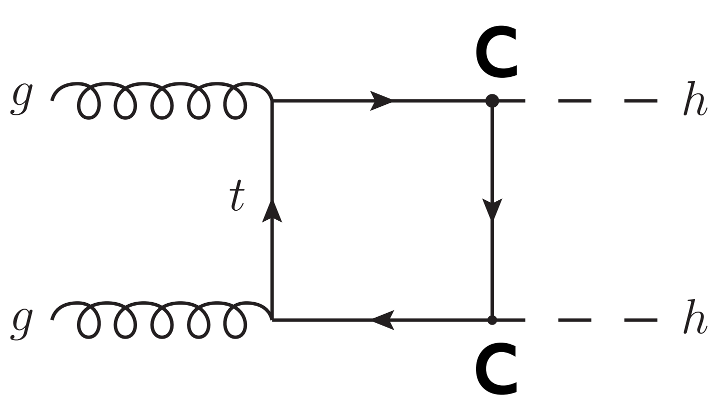


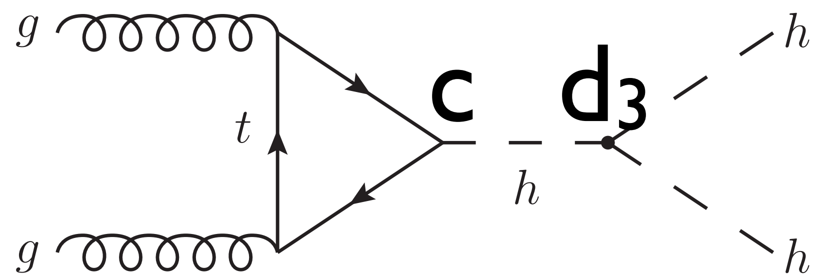


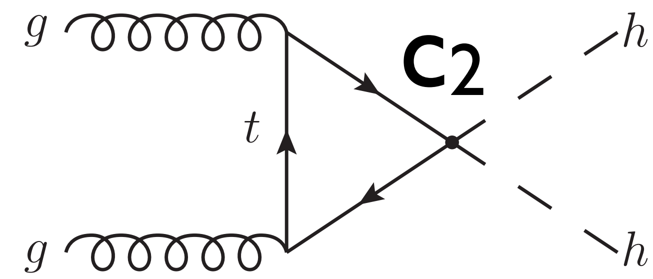


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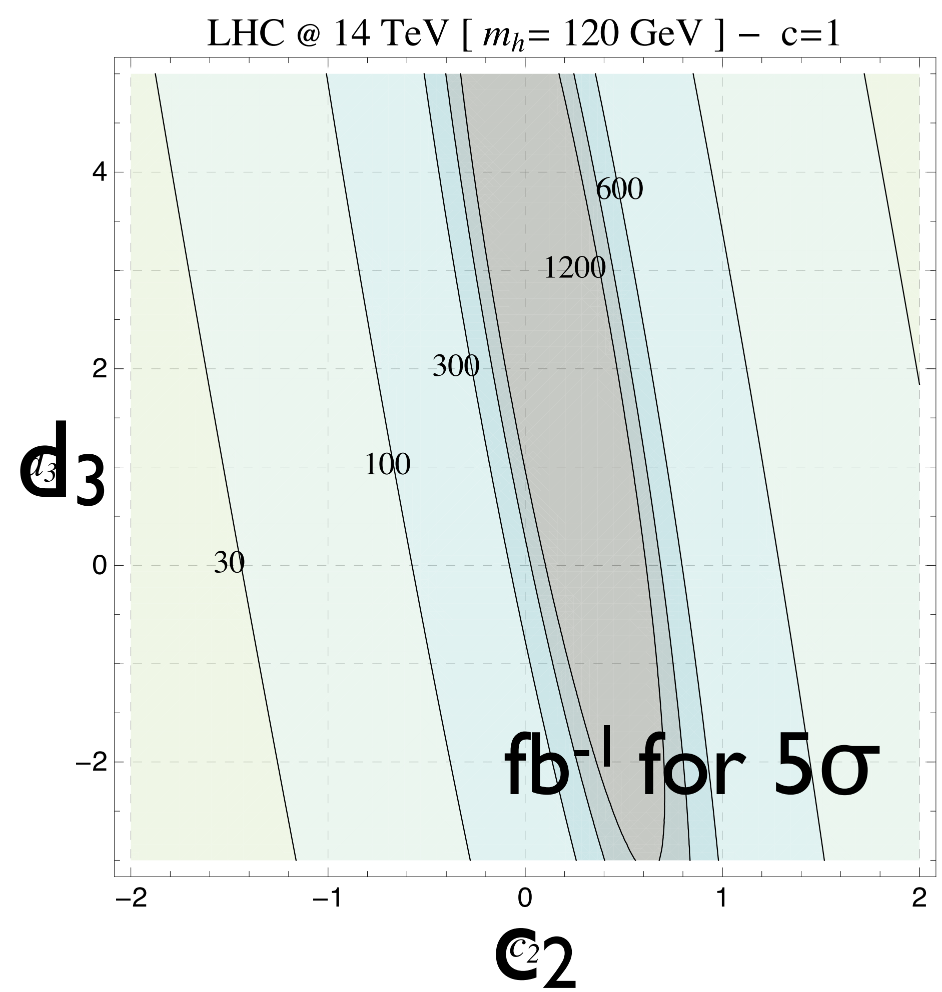
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, arXiv:1205.5444



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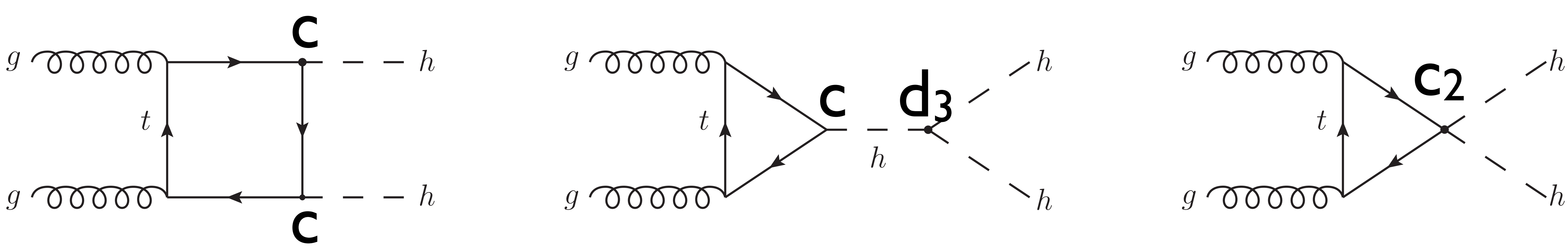


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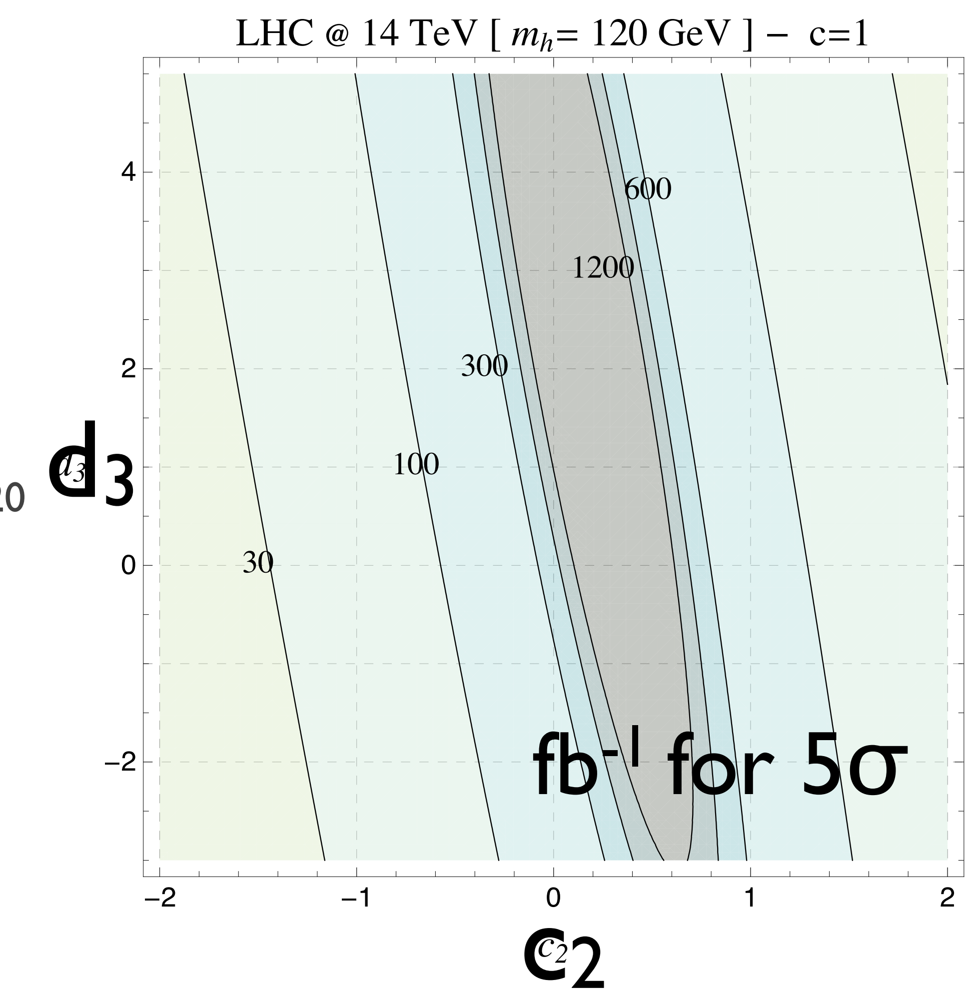


Hard to test compositeness
for a long time...

# What about “impostors”?

here just meant to be a scalar particle that couple to WW, ZZ ($\gamma\gamma$,gg) but has nothing to do with EWSB

if it is an impostor, the Higgs is somewhere else or it is an Higgsless scenario

# How to couple a scalar to VV (not Higgs)

Low, Lykken, Shaughnessy, arXiv:1207.1093

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  - dim-5 couplings? (i.e. "$\Phi W_{\mu\nu} W^{\mu\nu}$") → generic singlet scalar

$$
\begin{aligned}
\mathcal{L}_{sV_1V_2} \;=\; & \kappa_W \frac{\alpha}{8\pi m_s s_w^2}\, s\, W^+_{\mu\nu} W^{-\,\mu\nu} + \left(\kappa_W \frac{c_w^2}{s_w^2} + \kappa_B \frac{s_w^2}{c_w^2}\right) \frac{\alpha}{16\pi m_s}\, s\, Z_{\mu\nu} Z^{\mu\nu} \\
& + \kappa_g \frac{\alpha_s}{16\pi m_s} s\, G^a_{\mu\nu} G^{a\,\mu\nu} + (\kappa_W + \kappa_B) \frac{\alpha}{16\pi m_s} s\, F_{\mu\nu} F^{\mu\nu} \\
& + \left(\kappa_W \frac{c_w}{s_w} - \kappa_B \frac{s_w}{c_w}\right) \frac{\alpha}{8\pi m_s} s\, F_{\mu\nu} Z^{\mu\nu} \,,
\end{aligned}
$$

# How to couple a scalar to VV (not Higgs)

Low, Lykken, Shaughnessy, arXiv:1207.1093

- Look at $SU(2)_L \times U(1)_Y$ singlets (need to get couplings to both WW and ZZ)

  - dim-5 couplings? (i.e. "$\Phi W_{\mu\nu}W^{\mu\nu}$") → generic singlet scalar

$$
\begin{aligned}
\mathcal{L}_{sV_1V_2} \; = \; & \kappa_W \frac{\alpha}{8\pi m_s s_w^2} \, s\, W^+_{\mu\nu} W^{-\,\mu\nu} + \left( \kappa_W \frac{c_w^2}{s_w^2} + \kappa_B \frac{s_w^2}{c_w^2} \right) \frac{\alpha}{16\pi m_s} \, s\, Z_{\mu\nu} Z^{\mu\nu} \\
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\end{aligned}
$$

  - dim-4 couplings? (i.e. "$\Phi\, m_W W_\mu W^\mu$") → "dilaton" or "radion"

$$
\mathcal{L} = c_\phi \frac{\phi}{v} \left( 2 m_W^2 W^+_\mu W^-_\mu + m_Z^2 Z_\mu Z_\mu - \sum_{f \in SM} m_f \bar{f} f \right) \sim \phi T^\mu_\mu
$$

$$
c_g \frac{\alpha_s}{12\pi} \frac{\phi}{v} G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma \frac{\alpha}{\pi} \frac{\phi}{v} F_{\mu\nu} F^{\mu\nu}
$$

$c_g, c_\gamma$ different from SM due to conformal properties of UV

# How to couple a scalar to VV (not Higgs)

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- Dilaton: simplifying assumption: UV is conformal invariant and SM is part of the CFT: $\beta_{UV}+\beta_{IR(SM)}=0$ → additional contribution proportional to $-\beta_{SM}$

$$\delta c_g = \frac{21}{2} c_\phi + (c_\phi - 1)\, A_f(\tau_t)\,, \qquad \delta c_\gamma = -\frac{11}{24} c_\phi + (c_\phi - 1)\, A_f(\tau_t)\,.$$

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- Radion: mode associated to the stabilization of the 5dim bulk size (distance between the two branes). In Randall Sundrum models the bulk is supposed to be dual to a conformal field theory in 4D, with the IR providing a dynamical breaking of conformal invariance: radion is the "dilaton" of the CFT

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- Both dilaton and radion couplings depend on anomalous dimensions of fields above the weak scale (for radion bulk masses and profiles) → some model dependence

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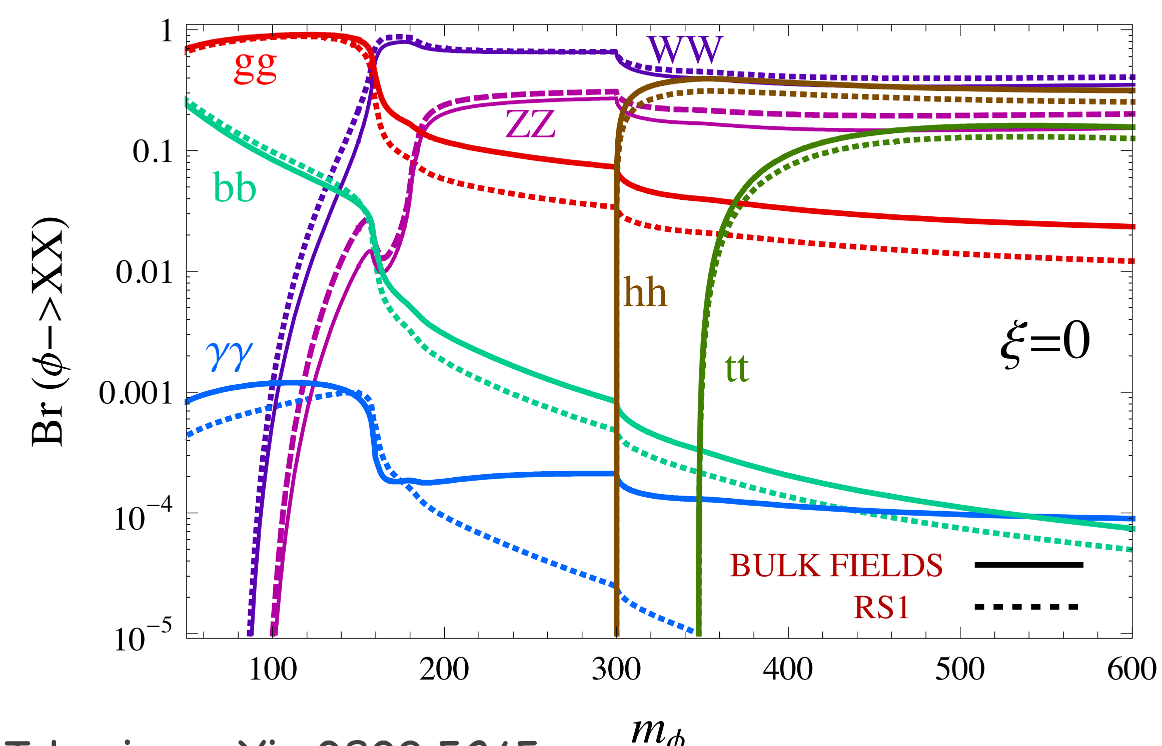


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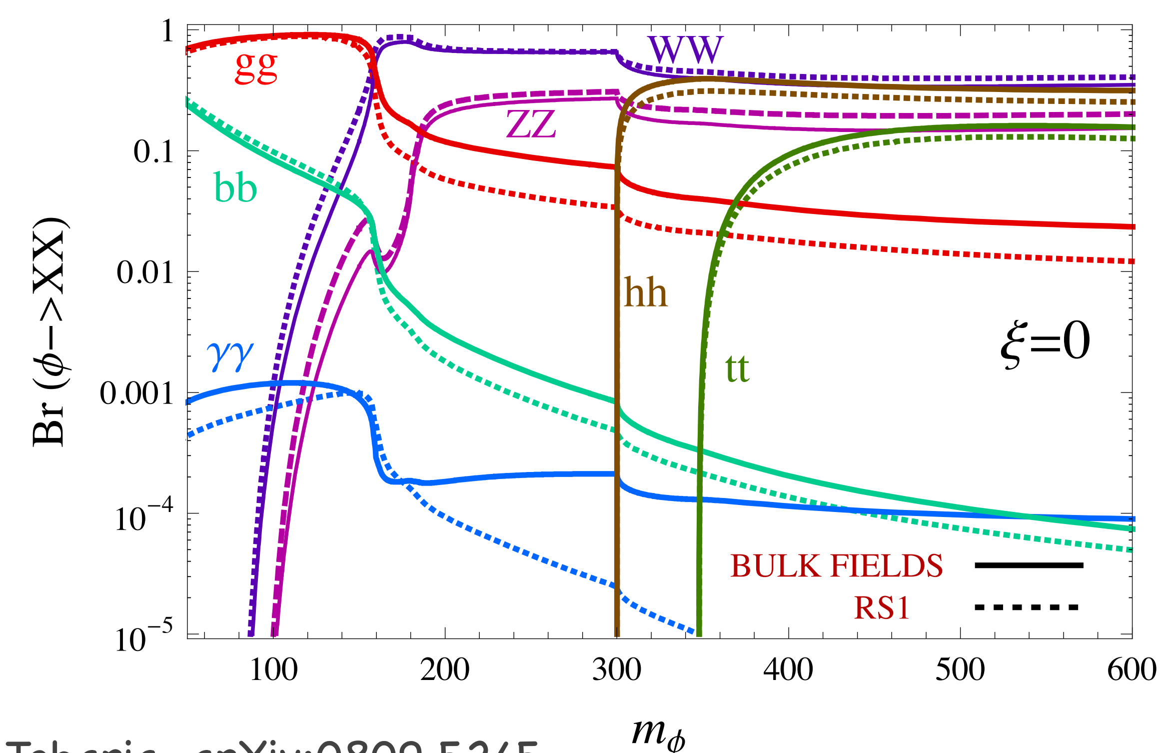


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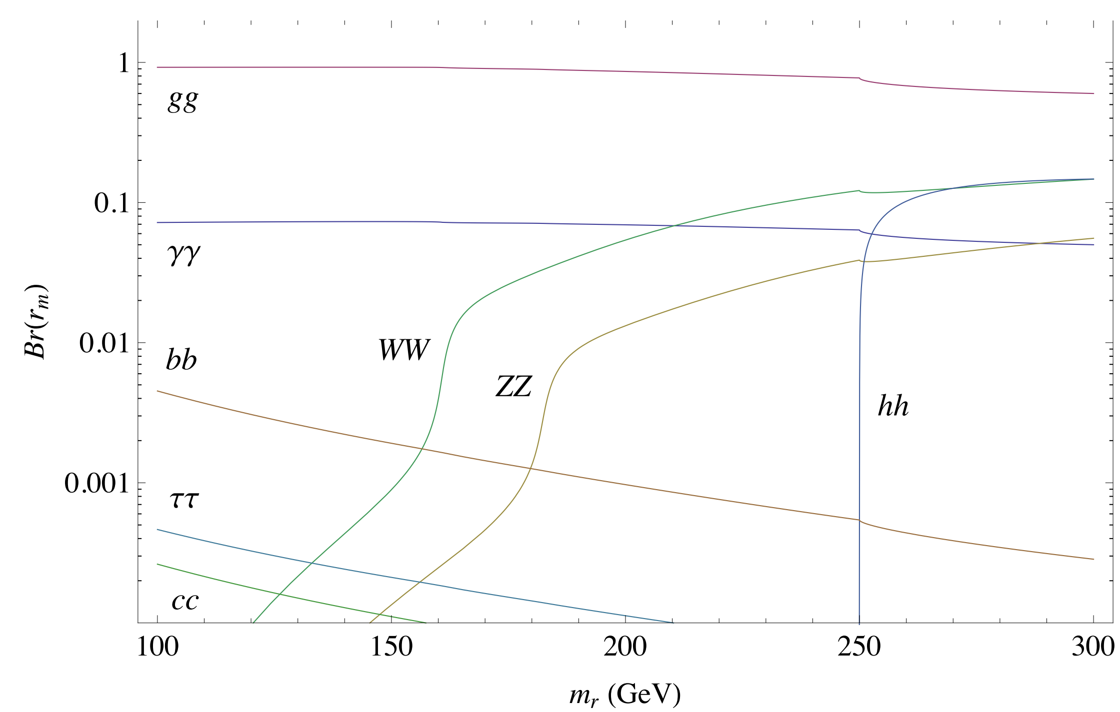


Cox, Gherghetta, arXiv:1203.5870

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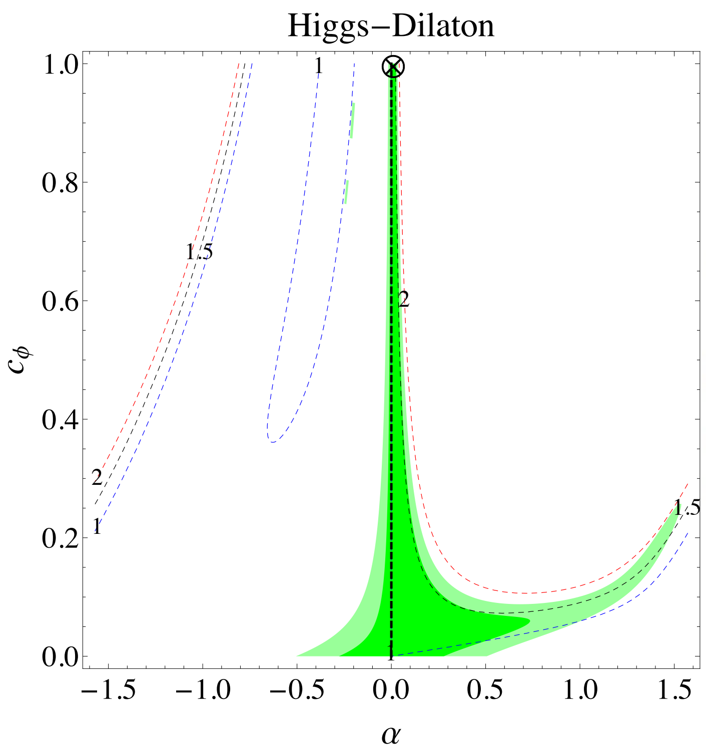
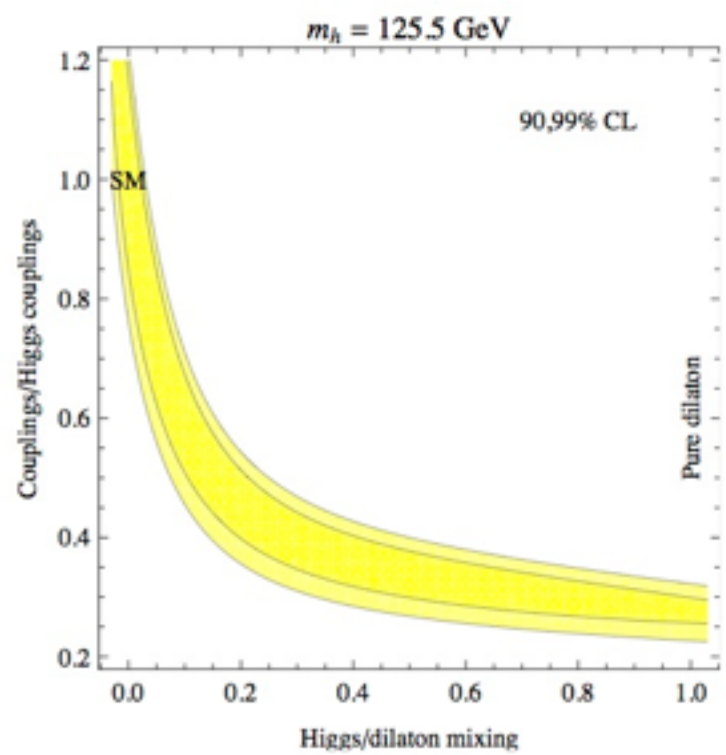



Carmi, Falkowski, Kuflik, Volansky, Zupan arXiv:1207.1718




Giardino, Kannike, Raidal, Strumia arXiv:1207.1347

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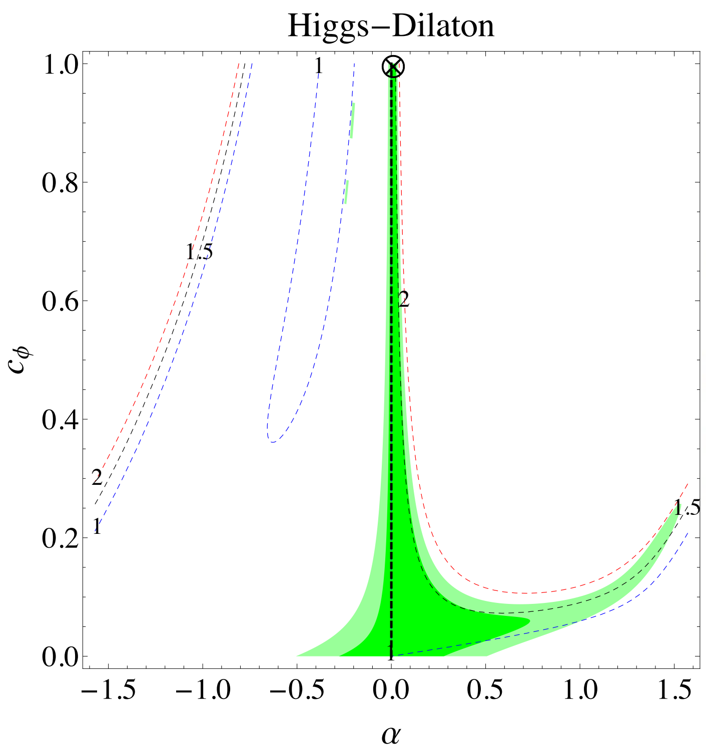


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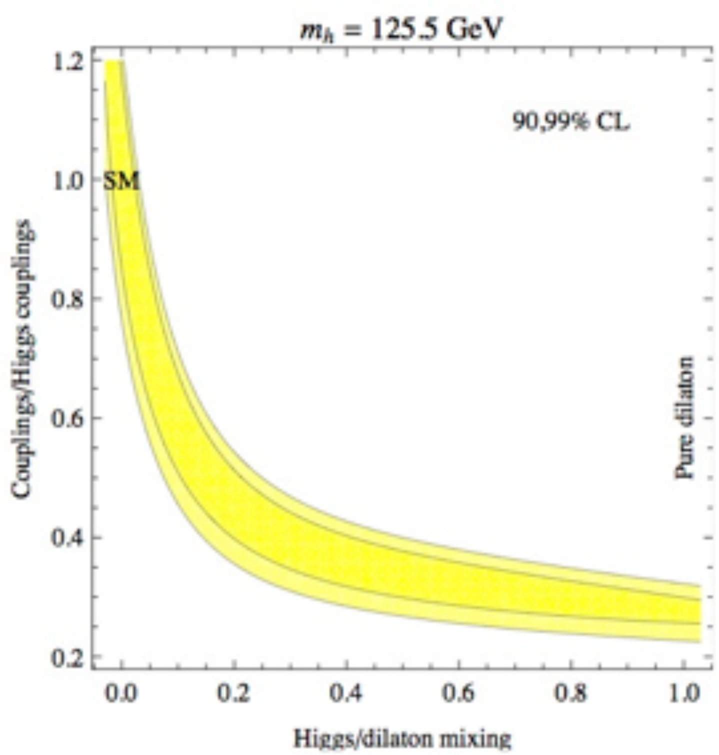


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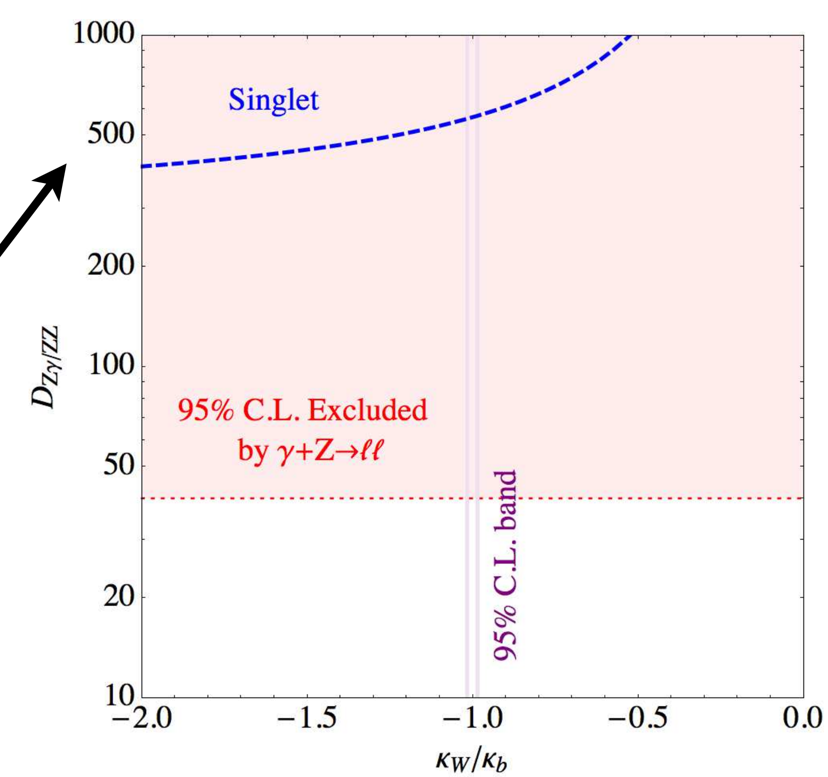


non-dilaton singlet "impostor" is excluded by γZ/ZZ