Resonances and unitarity in composite Higgs models

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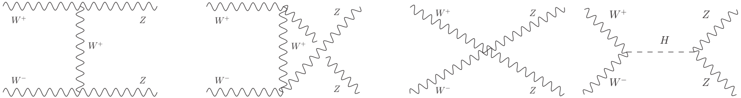
References

D.E. and B. Yencho, PRD 87, 055017 (2013) [1212.4158]
D.E., F. Mescia and B. Yencho, PRD 88, 055002 (2013) [1307.2400]
D.E. and F. Mescia, PRD 90, 015035 (2014) [1403.7386]

Closely related work:
R. Delgado, A. Dobado and F. Llanes, JHEP 1402 (2014) 121 [1311.5993] & arXiv:1502.0484
R. Delgado, A. Dobado, M.J. Hererro and J.J, Sanz-Cillero, JHEP 1407 (2014) 149 [1404.2866]

Motivation

We know that in the SM the Higgs boson unitarizes $W_L W_L$ scattering. Consider e.g. $W_L^+ W_L^- \to Z_L Z_L$



If any of these couplings are different from SM values, the careful balance necessary for perturbative unitarity is lost.

The first 3 diagrams are fixed by gauge invariance, but we can contemplate other Higgs-gauge boson couplings in the last one. For $s >> M_W^2$ the amplitude in the SM goes as

$$\frac{s}{v^2}\frac{M_H^2}{s-M_H^2} \sim \frac{M_H^2}{v^2}$$

Motivation

... but on dimensional grounds it *should* go as (cf. pion physics)

$$\frac{s}{v^2}\frac{s}{s-M_H^2} \sim \frac{s}{v^2}$$

This is what happens after *any modification* of the Higgs couplings and produces *non-unitary* amplitudes.

Adding *new effective operators* typically spoils unitarity too.

$$\mathcal{L}_{SM} \to \mathcal{L}_{SM} + \sum_i a_i \mathcal{O}_i \qquad \mathcal{O}_i \sim s^2$$

New physics may produce either type of modifications

What can the unitarity of longitudinal WW scattering tell us about anomalous couplings in EW sector?

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Parametrizing composite Higgs physics

A light "Higgs boson" with mass $M_H \sim 125$ GeV is coupled to the EW bosons according to (non-linear realization)

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{2}{\rm Tr}\, W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}{\rm Tr}\, B_{\mu\nu}B^{\mu\nu} + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP} + \sum_i \mathcal{L}_{\rm i}$$
$$+ \left[1 + 2a\left(\frac{h}{v}\right) + b\left(\frac{h}{v}\right)^2\right] \frac{v^2}{4}{\rm Tr}\, D_\mu U^\dagger D^\mu U - V(h)$$

$$U = \exp(i\,\omega\cdot\tau/v)$$
$$D_\mu U = \partial_\mu U + \frac{1}{2} i g W^i_\mu \tau^i U - \frac{1}{2} i g' B^i_\mu U \tau^3$$

and additional gauge-invariant operators are encoded in $\mathcal{L}_{\rm i}$.
Setting $a = b = 1$ (and $\mathcal{L}_{\rm i}$=0) reproduces the SM interactions

$\mathcal{O}(p^4)$ operators

The $\mathcal{L}_i$ are a full set of C, P, and $SU(2)_L \times U(1)_Y$ gauge invariant, $d = 4$ operators that parameterize the *low-energy effects* of the *model-dependent high-energy EWSB sector* along with *a,b*.
The two relevant *custodial-symmetry preserving* operators are

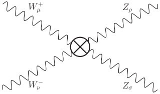
$$\mathcal{L}_4 = a_4 \left(\mathrm{Tr}\left[V_\mu V_\nu\right]\right)^2 \qquad \mathcal{L}_5 = a_5 \left(\mathrm{Tr}\left[V_\mu V^\mu\right]\right)^2 \qquad V_\mu = \left(D_\mu U\right) U^\dagger$$

The a_i could be *functions of* $\frac{h}{v}$

- For example:

		Heavy Higgs	*QCD-like technicolor*
a_4	$=$	0	$-2a_5$
a_5	$=$	$\frac{v^2}{8M_H^2}$	$\frac{N_{TC}}{96\pi^2}$

(up to logarithmic corrections)



$$ig^4\left[a_4\left(g^{\mu\sigma}g^{\nu\rho} + g^{\mu\rho}g^{\nu\sigma}\right) + 2a_5 g^{\mu\nu}g^{\rho\sigma}\right]$$

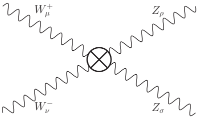
After the Higgs discovery

There are solid indications that the "Higgs" couples to the W, Z *very similarly to the SM rules*

$$\mathcal{L}_{\rm eff} \simeq \mathcal{L}_{\rm SM} + a_4 \left(\mathrm{Tr}\left[V_\mu V_\nu\right]\right)^2 + a_5 \left(\mathrm{Tr}\left[V_\mu V^\mu\right]\right)^2$$

Then a_4 and a_5 represent anomalous 4-point couplings of the W bosons due to an extended EWSBS that however does not manifest with $O(p^2)$ couplings *noticeably different to the ones in the SM*. **Assume now that** $a = b = 1$ **exactly.**

These operators will lead to violations of perturbative unitarity at loop level ($\sim g^4$)



$$\sim \left(\frac{s}{v^2}\right)^2$$

Violations of unitarity are cured by the appearance of new particles or resonances

We can now use well-understood unitarization techniques to constrain these resonances and the effective couplings $\{a_i\}$

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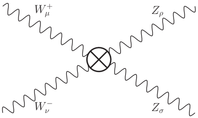

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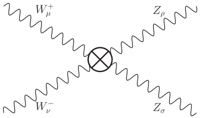

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To take home

- The Higgs unitarizes these amplitudes in SM (where $a = b = 1, \quad \{a_i\} = 0$)
- The theory is renormalizable *without* the $\{a_i\}$ if $a = b = 1$
- The $\{a_i\}$ will then be finite non-running parameters.

We would like to

- Determine how much room is left for the a_i
- Find possible additional resonances imposed by unitarity
- Should we have already seen any?
- To what extent an extended EWSBS is excluded?

Yes, there are new resonances with relatively light masses
No, we should not have seen them yet. Their signal is too weak
Looking for the resonances is an efficient (albeit indirect) way of setting constrains on aTGC and aQGC $\Leftarrow \{a_i\}$

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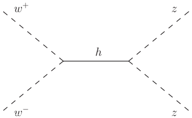
Equivalence Theorem

Most studies concerning unitarity at high energies are (understandbly) carried out using the ET

$$A(W_L^+ W_L^- \to Z_L Z_L) \to A(\omega^+\omega^- \to \omega^0\omega^0) + O(M_W/\sqrt{s})$$

For a light Higgs the region one needs to include tree-level Higgs exchange as well



Then one could make use of the well known chiral lagrangian techniques to derive the amplitudes and compare with experiment, including the Higss as an explicit resonance.

However for s not too large (which obviously is now an interesting region) the ET may be too crude an approximation.
We shall use as much as possible exact amplitudes.

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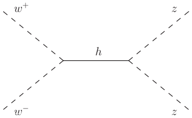

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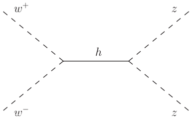

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Partial wave unitarity **requires**

$$\mathrm{Im}\ t_{I\,J}(s) \;=\; \underset{\substack{\text{Elastic} \\ WW \to WW}}{\sigma(s)|t_{I\,J}(s)|^2} \;+\; \underset{\substack{\text{Inelastic} \\ WW \to hh}}{\sigma_H(s)|t_{H,I\,J}(s)|^2}$$

where σ and σ_H are phase space factors.

Given a perturbative expansion

$$t_{I\,J} \;\approx\; \underset{\text{tree}}{t^{(2)}_{I\,J}} \;+\; \underset{\substack{\text{one-loop} \\ +\, a_i \text{ terms}}}{t^{(4)}_{I\,J}} \;+\; \cdots$$

we can require unitarity to hold *exactly* by defining *(Note: non-coupled channels)*

$$t_{I\,J} \approx \frac{t^{(2)}_{I\,J}}{1 - t^{(4)}_{I\,J}/t^{(2)}_{I\,J}}$$

Several mild analyticity assumptions are implied.

New resonances

The unitarization of the amplitudes may result in the appearance of *new heavy resonances* associated with the high-energy theory

$$\begin{aligned} t_{00} &\rightarrow \text{Scalar isoscalar} \\ t_{11} &\rightarrow \text{Vector isovector} \\ t_{20} &\rightarrow \text{Scalar isotensor} \end{aligned}$$

Will search for poles in $t_{IJ}(s)$ up to $(4\pi v) \sim 3$ TeV (domain of applicability)

True resonances will have the phase shift pass through $+\pi/2$

$$\delta_{IJ} = \tan^{-1}\left(\frac{\text{Im } t_{IJ}}{\text{Re } t_{IJ}}\right)$$

This method is known to work remarkably well in strong interactions: $\pi\pi$ scattering $\Rightarrow$ σ and ρ meson masses and widths

Criticisms

Is this unitarization method unique?

No, it is not. Many methods exist: IAM, K-matrix approach, N/D expansions, Roy equations,...

While the quantitative results differ slightly, the gross picture does not change

For a very detailed discussion of different methods see 1502.0484 (Delgado et al.)

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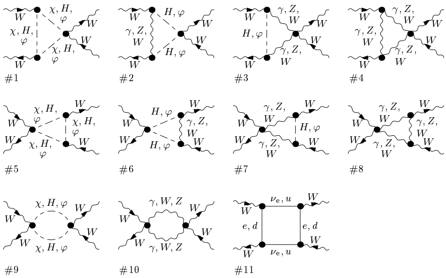
Real problem: one-loop calculation *extremely difficult*



+ *more than 1000 other diagrams!*

Denner & Hahn (1998) [hep-ph/9711302]

Shortcut

We can take a shortcut:

$$t_{IJ}^{(4)} = \mathrm{Re}\, t_{IJ}^{(4)} + i\mathrm{Im}\, t_{IJ}^{(4)}$$

The **Optical Theorem** implies the *perturbative* relation

$$\underbrace{\mathrm{Im}\; t_{I\,J}^{(4)}(s)}_{\text{one-loop}} = \underbrace{\sigma(s)|t_{I\,J}^{(2)}(s)|^2 + \sigma_H(s)|t_{H,I\,J}^{(2)}(s)|^2}_{\text{tree}}$$

For *real part*, note that

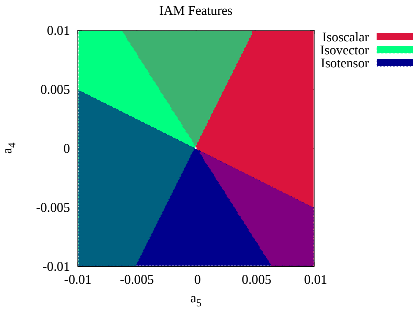
$$\begin{aligned} \mathrm{Re}\, t_{IJ}^{(4)} &= a_i\text{-dependent terms} \quad + \quad \text{real part of loop calculation} \\ &\approx a_i\text{-dependent terms} \\ &\quad (\text{for large } s,\ a_i) \end{aligned}$$

We approximate *real part of loop contribution* with one-loop Goldstone boson amplitudes using the Equivalence Theorem

Are there resonances?

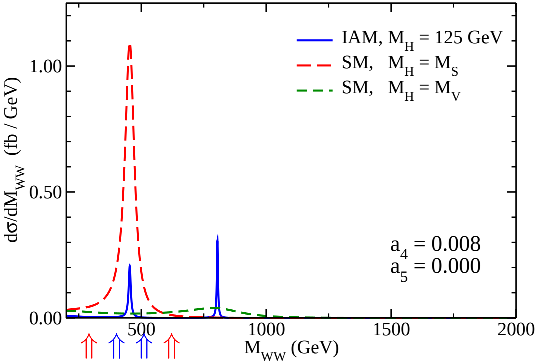
Must search for poles in the second Riemann sheet — the phase shift must go through $+\pi/2$ at the resonance.

Are there any *physically acceptable* resonances?



The blue-shaded area leads to *acausal resonances*. These values for a_4 and a_5 are *unphysical* — they cannot be realized in any effective theory with a meaningful UV completion.

Are these resonances detectable?

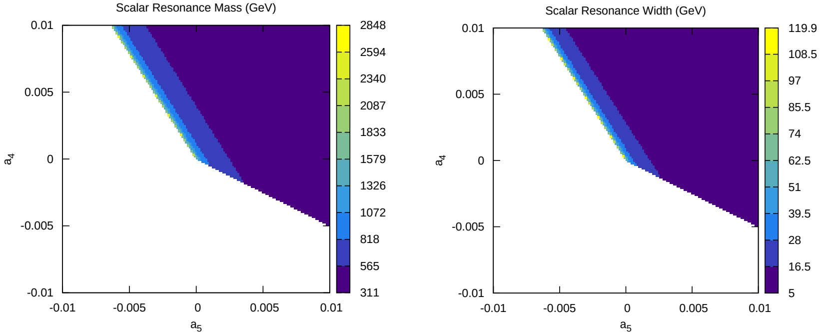


Signal of IAM scalar/vector vs. SM Higgs of *same mass*

The large contribution that the SM Higgs represents leaves little room for additional resonances. They *could still be there*, but would give a small signal.

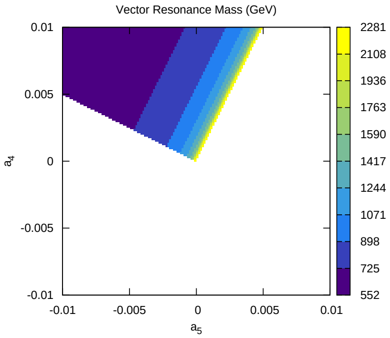
Note: only in $WW \to WW$ or $WW \to ZZ$ channels!

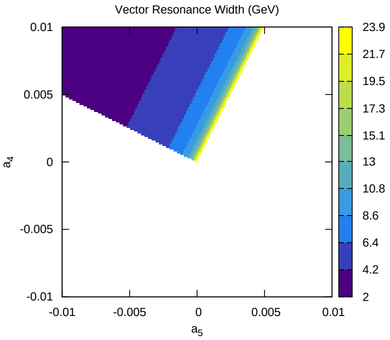
Scalar properties



- $M_S \sim 300 - 3000$ GeV
- $\Gamma_S \sim 5 - 120$ GeV

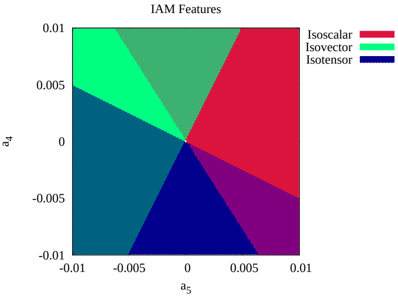
Vector properties



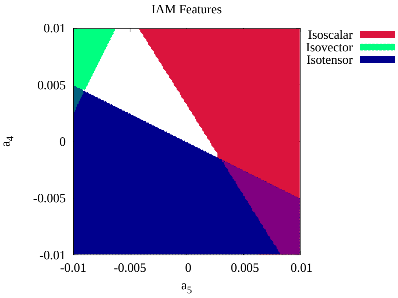


- $M_V \sim 550 - 2300$ GeV
- $\Gamma_V \sim 2 - 24$ GeV

Allowed regions for the anomalous couplings a_i (in white) if no resonance is found below ...



< 3 TeV



< 600 GeV

What if the hWW couplings are not exactly the SM ones?

Nothing prevents us from carrying out the same programme

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}{\rm Tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}{\rm Tr}B_{\mu\nu}B^{\mu\nu} + \sum_i \mathcal{L}_{\rm i} + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$

$$+ \left[1 + 2a\left(\frac{h}{v}\right) + b(\frac{h}{v})^2\right]\frac{v^2}{4}{\rm Tr}D_\mu U^\dagger D^\mu U + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}M_H^2 h^2$$

$$-d_3(\lambda v)h^3 - d_4\frac{1}{4}h^4$$

This *effective theory* is *non-renormalizable* and the a_i will be required to absorb the divergences

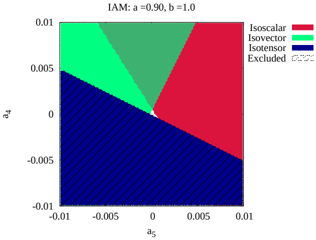
$$\delta a_4 = \Delta_\epsilon \frac{1}{(4\pi)^2}\frac{-1}{12}(1-a^2)^2$$

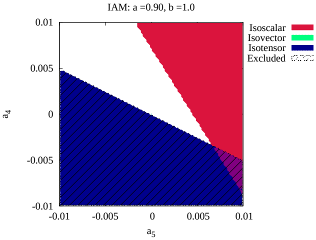
$$\delta a_5 = \Delta_\epsilon \frac{1}{(4\pi)^2}\frac{-1}{24}\left[(1-a^2)^2 + \frac{3}{2}((1-a^2)-(1-b))^2\right]$$

We have set $d_3 = d_4 = 1$ for simplicity.

Looking for resonances when $a \neq 1$

Exclusion zones and bounds on a_i for $a = 0.9$ ($b = a^2$)





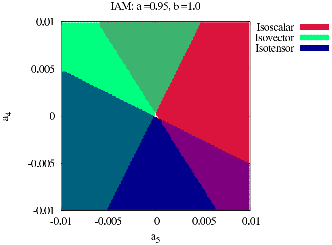
No resonances < 3 TeV

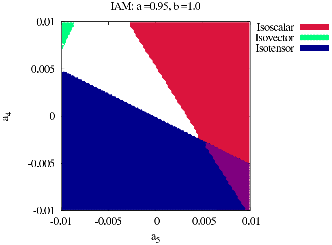
$M_R > 600$ GeV

The allowed regions for the anomalous couplings are slightly larger.

Looking for resonances when $a \neq 1$

Bounds on a_i for $a = 0.95$ $(b = a^2)$

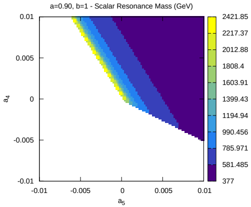


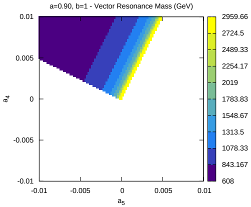


No resonances $\quad\quad$ $M_R < 600$ GeV

The characteristics of the resonances tend smoothly to the $a = 1$ case (hWW coupling as in the SM).

Masses of scalar and vector resonances for $a = 0.9$





Resonances tend to be slightly heavier and broader than for $a = 1$

The parameter b is only marginally visible in the widths.

There are constraints on vector masses from S, T, U parameter constraints in some models. *e.g. Pich, Rosell, Sanz-Cillero, 2013*.

Visibility of resonances for $a < 1$

Like for $a = 1$ the signal is always much lower than the one for a Higgs of the same mass.

For $a = 1$ typically $\sigma_{\text{resonance}}/\sigma_{\text{Higgs}} < 0.1$,
now $\sigma_{\text{resonance}}/\sigma_{\text{Higgs}} \simeq 0.2$.

The situation for $a < 1$ is not radically different from $a = 1$

Resonances (particularly in the vector channel) are slightly more difficult to appear

They tend to be slightly heavier and broader

They give a slightly larger experimental signal

This situation changes drastically for $a > 1$

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The situation for $a < 1$ is not radically different from $a = 1$

Resonances (particularly in the vector channel) are slightly more difficult to appear

They tend to be slightly heavier and broader

They give a slightly larger experimental signal

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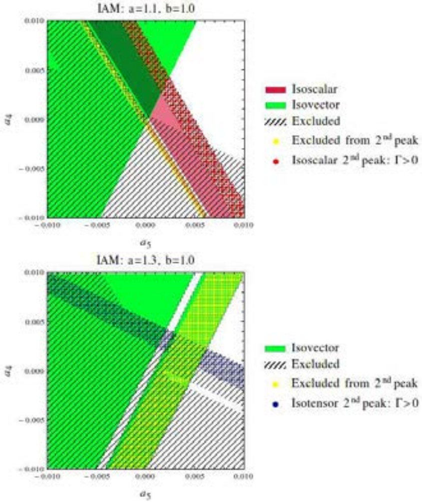
Spectrum of resonances for $a > 1$



'Something' happens when $a > 1$... *(Falkowski, Rychkov, Urbano [2012]; Espriu, Mescia [2014]; Bellazzini, Martucci, Torre [2014])*

Conclusions I

- Unitarity is a powerful constraint on scattering amplitudes. Its validity is well tested.
- Even in the presence of a light Higgs, it can help constrain anomalous couplings by helping predict heavier resonances.
- An extended EWSBS would typically have such resonances even in the presence of a light 'Higgs'
- However their properties are radically different from the 'standard lore'
- Current LHC Higgs search results do not yet probe the IAM resonances: at least 10$\times$ statistics is required
- . . . .

Using form factors (in preparation)

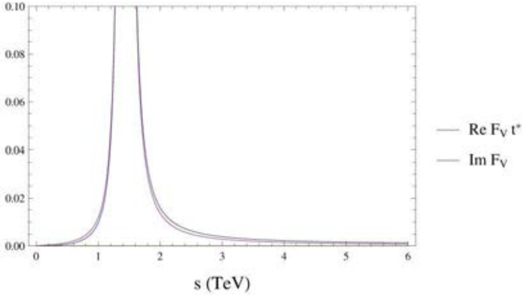
$$\langle 0|V_\mu|\omega(q)\omega(q')\rangle = iF_V^+(q+q')_\mu + iF_V^-(q-q')_\mu$$

Unitarity implies

$$\mathrm{Im}F_V = F_V t^* \quad t = A(\omega\omega \to \omega\omega) \quad K_V \equiv (s-M_V)^2 F_V$$

Then

$$t = iK_V \frac{1}{s-M_V^2} iK_V = \frac{t^{(2)}}{1-t^{(4)}/t^{(2)}}$$



Conclusions II

- Unitarity is a powerful constraint on scattering amplitudes. Its validity is well tested.
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- Current LHC Higgs search results do not yet probe the IAM resonances: at least $10\times$ statistics is required
- Resonances can be included in MC generators using unitarized form factors: stay tuned!

THANK YOU!

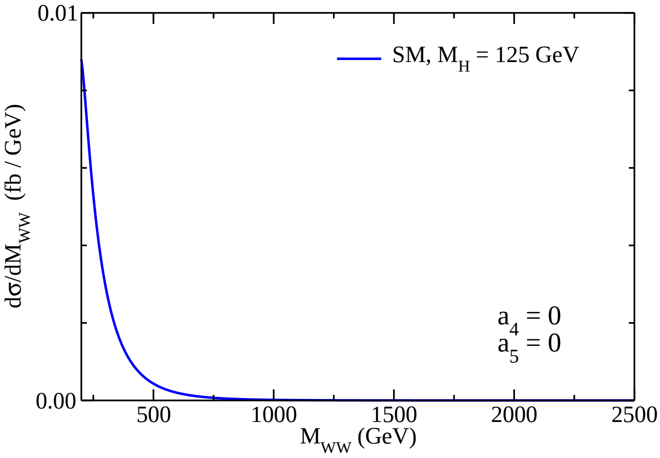
Back-up slides

$$\mathcal{L}_{QGC} = e^2 \left[g_1^{\gamma\gamma} A^\mu A^\nu W_\mu^- W_\nu^+ - g_2^{\gamma\gamma} A^\mu A_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ e^2 \frac{c_w}{s_w} \left[g_1^{\gamma Z} A^\mu Z^\nu \left(W_\mu^- W_\nu^+ + W_\mu^+ W_\nu^- \right) - 2 g_2^{\gamma Z} A^\mu Z_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ e^2 \frac{c_w^2}{s_w^2} \left[g_1^{ZZ} Z^\mu Z^\nu W_\mu^- W_\nu^+ - g_2^{ZZ} Z^\mu Z_\mu W^{-\nu} W_\nu^+ \right]$$
$$+ \frac{e^2}{2 s_w^2} \left[g_1^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - g_2^{WW} \left(W^{-\mu} W_\mu^+ \right)^2 \right] + \frac{e^2}{4 s_w^2 c_w^4} h^{ZZ} (Z^\mu Z_\mu)^2$$

SM values: $g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1$, $\lambda^{\gamma,Z} = 0$ and $\delta_Z = \frac{\beta_1 + g'^2 \alpha_1}{c_w^2 - s_w^2}$ $\quad g_{1/2}^{VV'} = 1$, $h^{ZZ} = 0$

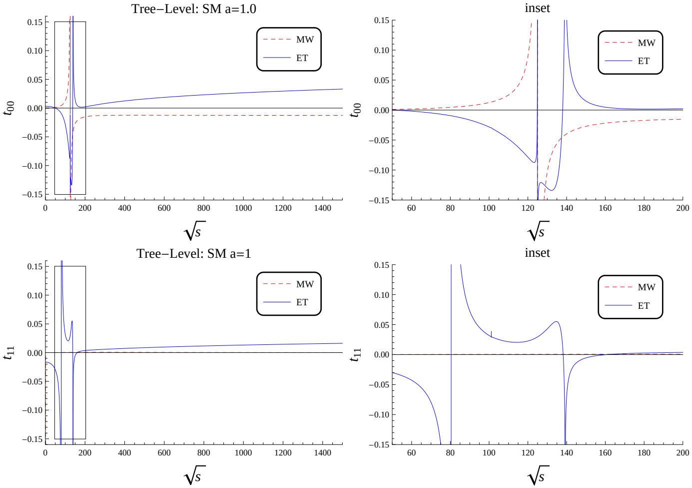
$$\Delta g_1^\gamma = 0 \qquad \Delta \kappa^\gamma = g^2(\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2(\alpha_9 - \alpha_8)$$
$$\Delta g_1^Z = \delta_Z + \frac{g^2}{c_w^2} \alpha_3 \qquad \Delta \kappa^Z = \delta_Z - g'^2(\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2(\alpha_9 - \alpha_8)$$

$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_2^{ZZ} = 2 \Delta g_1^{\gamma Z} - \frac{g^2}{c_w^4} (\alpha_5 + \alpha_7)$$
$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_w^2} \alpha_3 \qquad \Delta g_1^{WW} = 2 c_w^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) + g^2 \alpha_4$$
$$\Delta g_1^{ZZ} = 2 \Delta g_1^{\gamma Z} + \frac{g^2}{c_w^4} (\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2 c_w^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) - g^2 (\alpha_4 + 2\alpha_5)$$
$$h^{ZZ} = g^2 \left[\alpha_4 + \alpha_5 + 2 (\alpha_6 + \alpha_7 + \alpha_{10}) \right]$$



For SM ($a_4 = a_5 = 0$) there are *no additional resonances*.

$a = 1$



Tree-level amplitudes for $a \neq 1$

$a < 1$

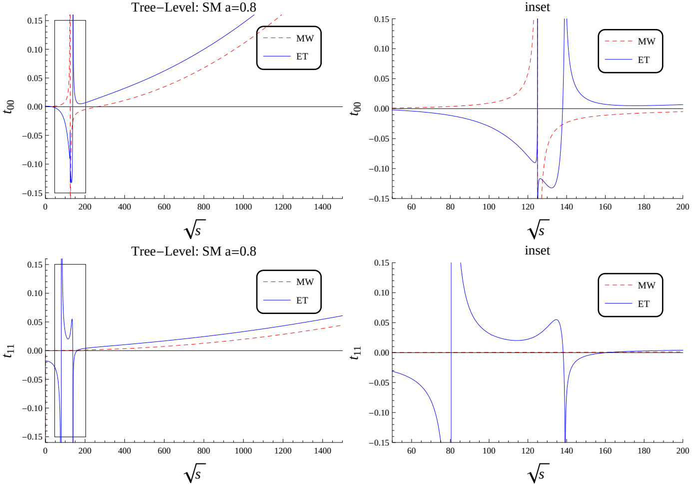


Figure : Tree-level amplitudes for $a = 0.8$

Tree-level amplitudes for $a \neq 1$

$a > 1$

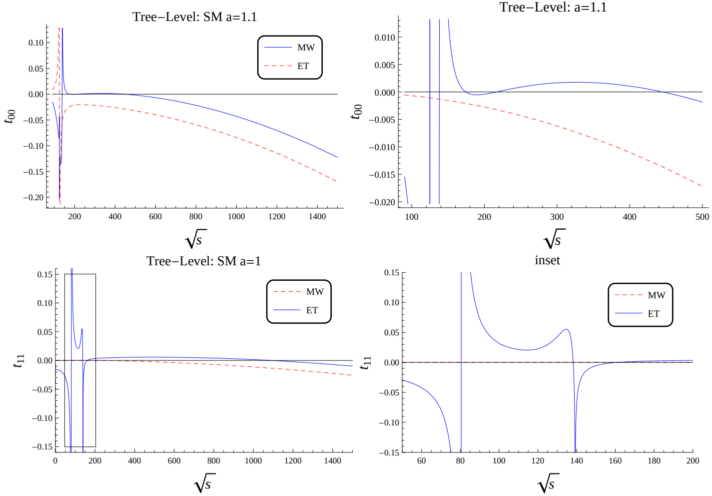
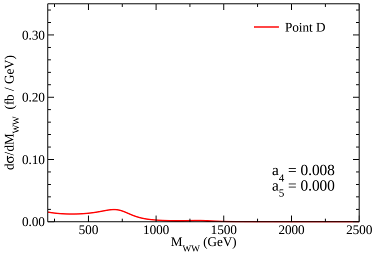


Figure : Tree-level amplitudes for $a = 1.1$

Comparison Higgsless/Higgs with $M_H = 125$ GeV



No light Higgs — With light Higgs

Here $\sqrt{s} = 8$ TeV

Compare before/after for same point (ex: Point D $a_4 = 0.008$, $a_5 = 0.000$)

- Different continuum
- Masses have changed positions
- Widths are *much narrower*

Are these resonances detectable?

We can estimate how observable these signals are by comparing to a heavy SM Higgs of the same mass $\rightarrow$ *look at LHC Higgs search data*

For a resonance of mass M_R and width Γ_R, let

$$\sigma^{peak} \equiv \int_{M_R-2\Gamma_R}^{M_R+2\Gamma_R} \left[dM_{WW} \times \frac{d\sigma}{dM_{WW}} \right]$$

$$\sigma^{peak}_{SM} \equiv \int_{M_H-2\Gamma_H}^{M_H+2\Gamma_H} \left[dM_{WW} \times \frac{d\sigma_{SM}}{dM_{WW}} \right]$$

Then for a heavy Higgs with $M_H \rightarrow M_R$ and $\Gamma_H(M_H \rightarrow M_R)$

$$R \equiv \left(\frac{\sigma^{peak}}{\sigma^{peak}_{SM}} \right)$$

compares the strength of the resonance regions of the same mass.

What if the *hWW* couplings are not exactly the SM ones?

For $a = b = 1$ these results reproduce the SM prediction, i.e. no counterterms (renormalizable theory)

$$\delta a_4 = 0, \qquad \delta a_5 = 0$$

For $a = b = 0$ one gets the 'no Higgs' results (EChL)

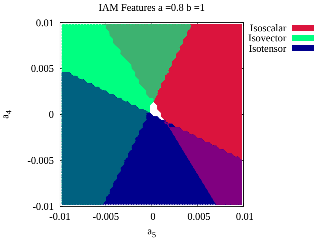
$$\delta a_4 = \Delta_\epsilon \frac{1}{(4\pi)^2} \frac{-1}{12}, \qquad \delta a_5 = \Delta_\epsilon \frac{1}{(4\pi)^2} \frac{-1}{24}$$

They should bring 'natural' finite contributions from NP:

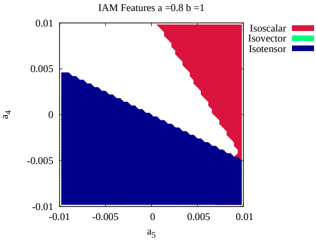
$$a_4|_{\rm finite} \simeq \frac{1}{(4\pi)^2} \frac{-1}{12} (1 - a^2)^2 \log \frac{v^2}{f^2}$$

$$a_5|_{\rm finite} \simeq \frac{1}{(4\pi)^2} \frac{-1}{24} \left[(1 - a^2)^2 + \frac{3}{2} ((1 - a^2) - (1 - b))^2 \right] \log \frac{v^2}{f^2},$$

Bounds on a_i for $a = 0.8$ ($b = a^2$)

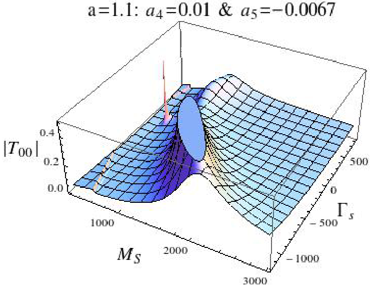


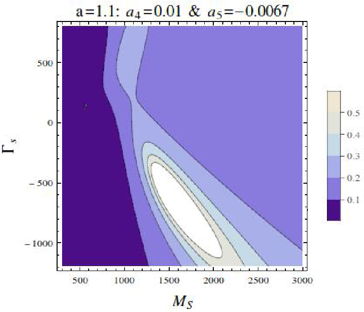
All Resonances

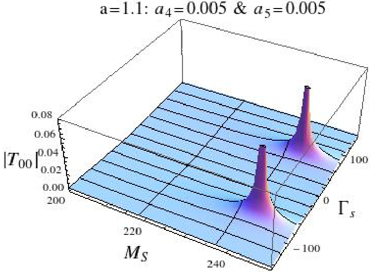


$M_R < 600$ GeV

Some diseases







Sum rule

Why?

Assuming the strict ET for all s and a moderate growth as $|s| \to \infty$

$$1 - a^2 = \frac{v^2}{6\pi} \int_0^\infty \frac{ds}{s} (2\sigma_{I=0}(s)^{tot} + 3\sigma_{I=1}(s)^{tot} - 5\sigma_{I=2}(s)^{tot}),$$

(Falkowski, Rychkov and Urbano, 2012)

However, we the analytic structure of the amplitudes is more complex away from the ET. Then

- LHS is modified to $3 - a^2 + \mathcal{O}(g^2)$
- The integral along the $|s| \to \infty$ does not necessarily vanish. *(Bellazzini, Martucci and Torre, 2014)*
- LHS gets renormalized while RHS does not...

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Forgetting about $O(g^2)$ corrections the proper SR reads:

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The difference between $1 - a^2$ and $3 - a^2$ can be traced back to the inclusion of W exchange in the t-channel.

If the propagationg degrees of freedom remain *unchanged* all the way to $s = \infty$ (big 'if' !) the W t-channel contributes to the exterior circuit and gives $c_\infty = 2$ and restores the $1 - a^2$ on the LHS of the sum rule obtained when W propagation is ignored. *A trivial consequence of Cauchy's theorem*

However, there is no guarantee that the propagating degrees of freedom remain *unchanged*. In fact in strongly interacting theories one might expect $c_\infty = 0$

Yet, as we have seen there is a substantial difference between $a > 1$ and $a < 1$ in the spectrum of dynamical resonances.

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