Interpreting a possible 2 TeV resonance in WW scattering

Domènec Espriu

Institut de Ciències del Cosmos (ICCUB),
Universitat de Barcelona

HEP16, Valparaiso, January 2016

UNIVERSITAT DE BARCELONA

ICCUB Institut de Ciències del Cosmos

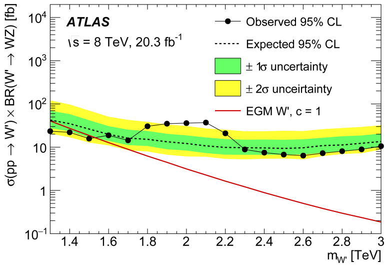
EXCELENCIA MARÍA DE MAEZTU

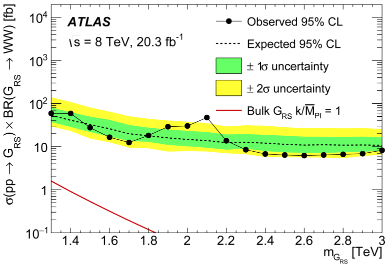
References

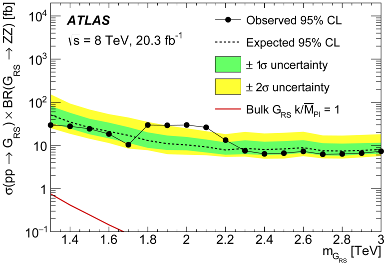
D.E. and B. Yencho, PRD 87, 055017 (2013) [1212.4158]
D.E., F. Mescia and B. Yencho, PRD 88, 055002 (2013) [1307.2400]
D.E. and F. Mescia, PRD 90, 015035 (2014) [1403.7386]
P. Arnan, D.E. and F. Mescia, 1508.00174
R. Delgado, A. Dobado, D.E., F. Llanes, 1510.03761

Closely related work:
R. Delgado, A. Dobado and F. Llanes, JHEP 1402 (2014) 121 [1311.5993] & 1502.04841, 1509.04725
R. Delgado, A. Dobado, M.J. Hererro and J.J, Sanz-Cillero, JHEP 1407 (2014) 149 [1404.2866]
A. Dobado, F-K. Guo, F. Llanes, 1508.03544

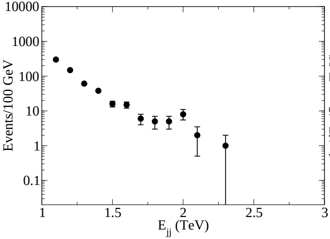
A resonance at 2 TeV?

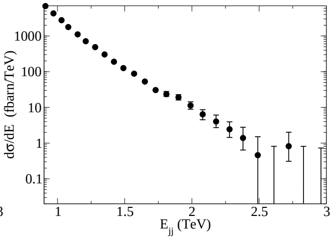






Excess events at 2 TeV

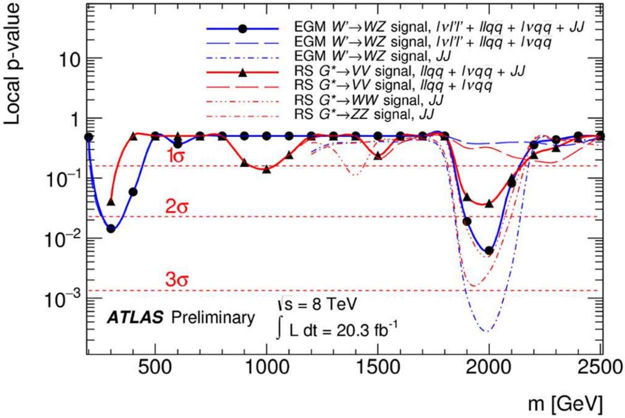




ATLAS WZ events

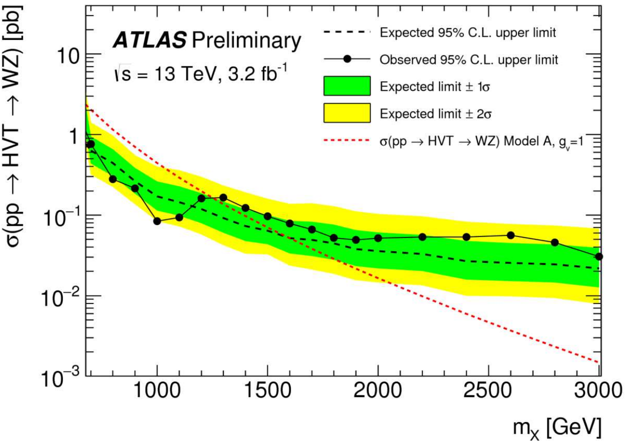
CMS WW events

Excess events at 2 TeV



p-values for ATLAS WZ events

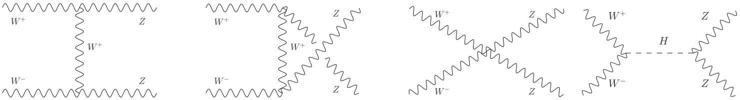
Excess events at 2 TeV



However...no significant signal in early 13 TeV results

$W_L W_L$ resonances?

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. For $s >> M_W^2$ the amplitude in the SM goes for $s \to \infty$ as

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

... 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?

$W_L W_L$ resonances?

... 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?

$W_L W_L$ resonances?

... 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?

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)

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

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

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 $\mathcal{L}_{\rm i}$ 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

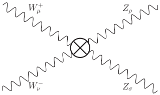
$$\mathcal{L}_4 = a_4 \left(\mathrm{Tr}\left[V_\mu V_\nu\right]\right)^2 \qquad \mathcal{L}_5 = a_5 \left(\mathrm{Tr}\left[V_\mu V^\mu\right]\right)^2 \qquad V_\mu = \left(D_\mu U\right) U^\dagger$$

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

- For example: *Heavy Higgs* *QCD-like technicolor*

		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)



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

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

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}{\rm Tr} W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}{\rm Tr} B_{\mu\nu}B^{\mu\nu} + \sum_i \mathcal{L}_{\rm i} + \mathcal{L}_{\rm GF} + \mathcal{L}_{\rm FP}$$
$$+ \left[1 + 2a\left(\frac{h}{v}\right) + b\left(\frac{h}{v}\right)^2\right] \frac{v^2}{4}{\rm Tr} D_\mu U^\dagger D^\mu U + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}M_H^2 h^2$$
$$- d_3(\lambda v)h^3 - d_4\frac{1}{4}h^4$$

This *effective theory* is *non-renormalizable* and the a_i will be required to absorb the divergences. They will be running parameters (unlike for $a = b = 1$)

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

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

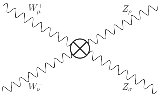
We have set $d_3 = d_4 = 1$ for simplicity.

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

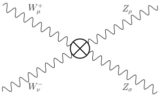
We can now use well-understood unitarization techniques to constrain these resonances and the effective couplings $\{a_i\}$

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 $\{a_i\}$

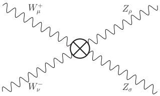
Early Higgs measurements

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

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

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 $\{a_i\}$

Our plan

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?
- What about this putative 2 TeV resonance?

Yes, there are new resonances even with relatively light masses Their signal is very weak. Can a 2 TeV EWSBS resonance be visible?

Searching for resonances is an efficient (albeit indirect) way of setting constrains on aTGC and aQGC $\Leftarrow \{a_i\}$

IMPORTANT: even very small values of a_4 and a_5 can lead to resonances. Their effect is more important than having $a \neq 1$ (within reason).

Our plan

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?
- What about this putative 2 TeV resonance?

Yes, there are new resonances even with relatively light masses
Their signal is very weak. Can a 2 TeV EWSBS resonance be visible?
Searching for resonances is an efficient (albeit indirect) way of setting constrains on aTGC and aQGC $\Leftarrow \{a_i\}$

IMPORTANT: even very small values of a_4 and a_5 can lead to resonances. Their effect is more important than having $a \neq 1$ (within reason).

Our plan

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?
- What about this putative 2 TeV resonance?

Yes, there are new resonances even with relatively light masses Their signal is very weak. Can a 2 TeV EWSBS resonance be visible?

Searching for resonances is an efficient (albeit indirect) way of setting constrains on aTGC and aQGC $\Leftarrow \{a_i\}$

IMPORTANT: even very small values of a_4 and a_5 can lead to resonances. Their effect is more important than having $a \neq 1$ (within reason).

Our plan

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?
- What about this putative 2 TeV resonance?

Yes, there are new resonances even with relatively light masses Their signal is very weak. Can a 2 TeV EWSBS resonance be visible?
Searching for resonances is an efficient (albeit indirect) way of setting constrains on aTGC and aQGC $\Leftarrow \{a_i\}$

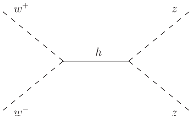
IMPORTANT: even very small values of a_4 and a_5 can lead to resonances. Their effect is more important than having $a \neq 1$ (within reason).

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.

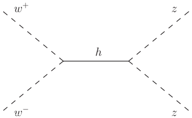
We shall use as much as possible exact amplitudes

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.

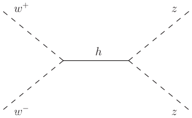
We shall use as much as possible exact amplitudes

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.

Partial wave amplitudes

We will assume $e = 0$ *(no e.m.)* i.e. the custodial limit $c_w = 1$.
The *WW* scattering amplitudes can then be deconstructed into amplitudes of *fixed isospin* T_I

$$\begin{aligned} T_0 &= 3A^{+-00} + A^{++++} \\ T_1 &= 2A^{+-+-} - 2A^{+-00} - A^{++++} \\ T_2 &= A^{++++} \end{aligned}$$

where $A^{+-00} = A(W_L^+ W_L^- \to Z_L Z_L)$ and all others may be expressed in terms of this amplitude through isospin and crossing symmetries

These can then be written in terms of *partial waves*

$$t_{I\,J}(s) = \frac{1}{64\pi} \int_{-1}^{1} d(\cos\theta) P_J(\cos\theta) T_I$$

which are constrained by unitarity at high energies to be $|t_{I\,J}| < 1$.
Most discussions based on unitarity are based on this simple constraint (*tree-level unitarity*)

Inverse Amplitude method

Partial wave unitarity **requires**

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

where σ and σ_H are phase space factors.

Given a perturbative expansion

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

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

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

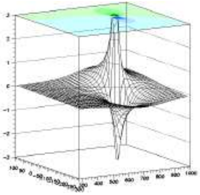
Will search for poles in $t_{I\,J}(s)$ up to $(4\pi v) \sim 3$ TeV (domain of applicability)

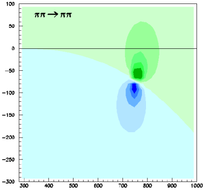
True resonances will have the phase shift pass through $+\pi/2$

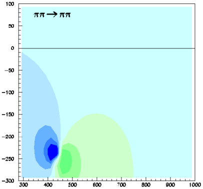
$$\delta_{IJ} = \tan^{-1}\left(\frac{\mathrm{Im}\; t_{IJ}}{\mathrm{Re}\; t_{IJ}}\right)$$

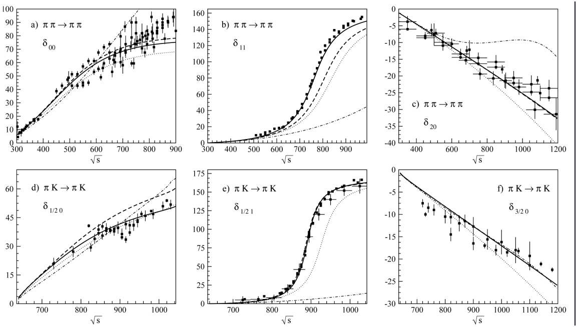
This method is known to work remarkably well in strong interactions: $\pi\pi$ scattering $\Rightarrow$ σ and ρ meson masses and widths

In hadronic physics









Truong '89, Truong,Dobado,Herrero, '90, Dobado, Pelaez,'93,'96

In the heavy Higgs limit

Integrating out a heavy higgs and recovering the resonance:

	Tree level		1-loop ($\mu = M_W$)		1-loop ($\mu = M_H$)	
MH	Mass	Width	Mass	Width	Mass	Width
500	446	28	442	27	455	30
600	521	46	511	43	538	50
700	599	70	580	63	627	81
800	680	105	647	90	726	133
900	767	157	712	121	840	201
1000	862	226	776	164	980	351
1100	968	344	838	210	1166	617
1200	1091	485	899	260	1460	1868

$$a_4 = \frac{-1}{16\pi^2}\frac{1}{12}\left(\Delta_\epsilon - \log\left(\frac{M_H^2}{\mu^2}\right) + \frac{17}{6}\right)$$

$$a_5 = \frac{M_W^2}{2g^2 M_H^2} - \frac{1}{16\pi^2}\frac{1}{24}\left(\Delta_\epsilon - \log\left(\frac{M_H^2}{\mu^2}\right) + \frac{79}{3} - \frac{27\pi}{2\sqrt{3}}\right)$$

(On-shell scheme)

See also recent work by Corbett, Eboli, Gonzalez-Garcia

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.)

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.)

Criticisms

Is this unitarization method unique?

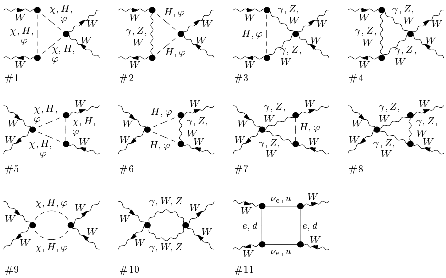
No, it is not. Many methods exist: IAM, K-matrix approach, N/D expansions, Roy equations,...

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.)

The calculation

Real problem: one-loop calculation *extremely difficult*



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

+

more than 1000 other diagrams!

Shortcut

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

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

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

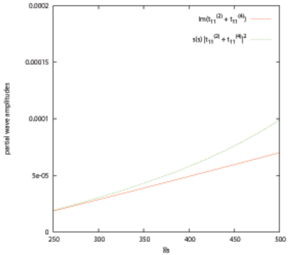
For *real part*, note that

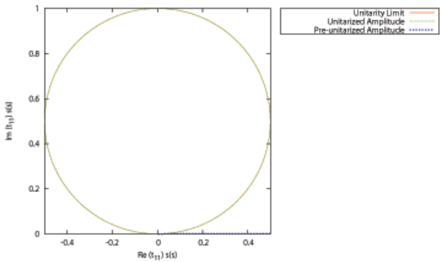
$$\begin{aligned} \mathrm{Re}\, t_{IJ}^{(4)} &= a_i\text{-dependent terms} \quad + \quad \text{real part of loop calculation} \\ &\approx a_i\text{-dependent terms} \\ &\quad (\text{for large } s,\ a_i) \end{aligned}$$

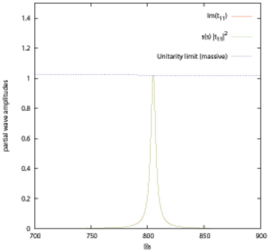
We approximate *real part of loop contribution* with one-loop Goldstone boson amplitudes using the Equivalence Theorem In

addition, we neglect coupled channels (justified in as much as $a^2 - b$ is zero or very small in all cases).
(Results from the Madrid group further justify this assumption)

Unitarity checks





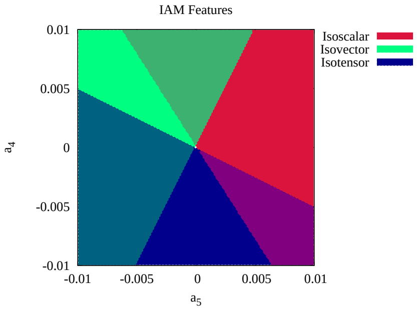


Vector channel ($a_4 = 0.008, \quad a_5 = 0$)

Are there genuine EWSBS 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?

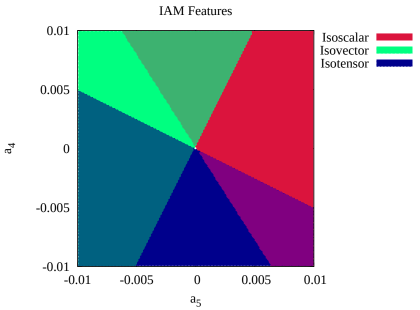


The blue-shaded area leads to *acausal resonances*. These values for a_4 and a_5 are *unphysical* — they cannot be realized in any effective theory with a meaningful UV completion.

Are there genuine EWSBS resonances?

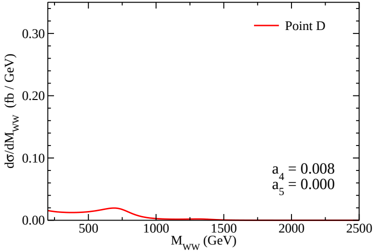
Must search for poles in the second Riemann sheet — the phase shift must go through $+\pi/2$ at the resonance.

Are there any *physically acceptable* resonances?

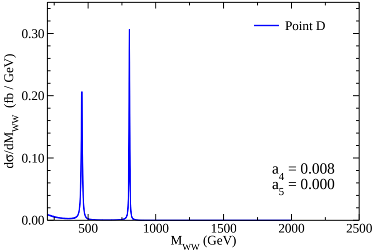


The blue-shaded area leads to *acausal resonances*. These values for a_4 and a_5 are *unphysical* — they cannot be realized in any effective theory with a meaningful UV completion.

Comparison Higgsless/Higgs with $M_H = 125$ GeV



No light Higgs

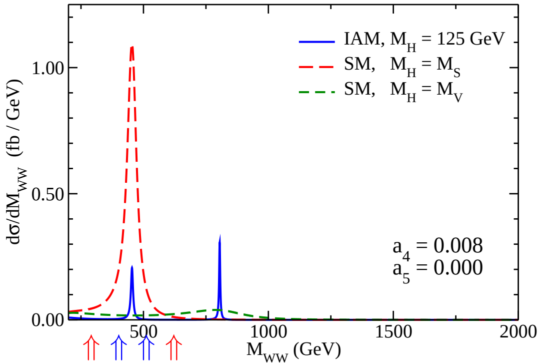


With light Higgs

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*

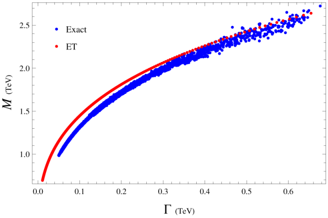


Signal of IAM scalar/vector vs. SM Higgs of *same mass*

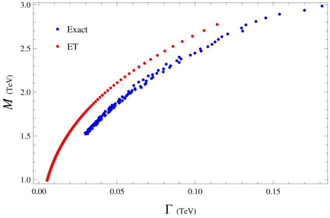
The large contribution that the SM Higgs represents leaves little room for additional resonances.

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

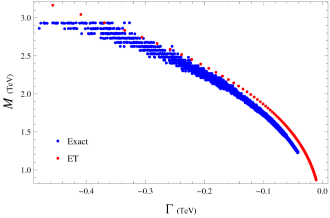
Aside: comparing ET and 'exact' calculations



(a) Scalar

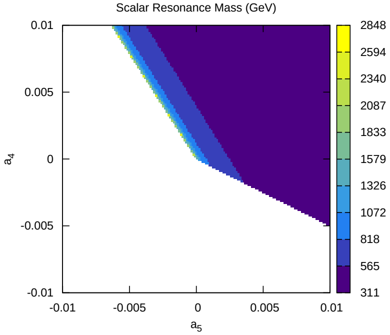


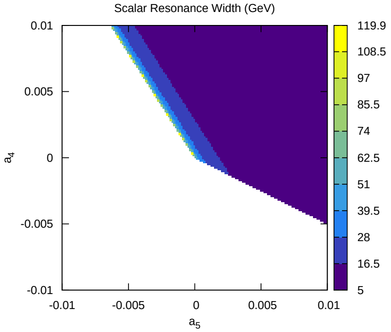
(b) Vector



(c) Tensor

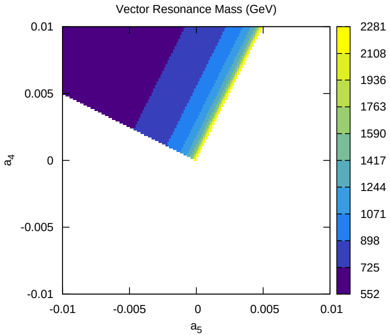
Scalar properties

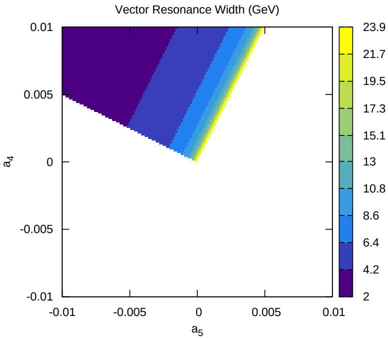




- $M_S \sim 300 - 3000$ GeV
- $\Gamma_S \sim 5 - 120$ GeV

Vector properties



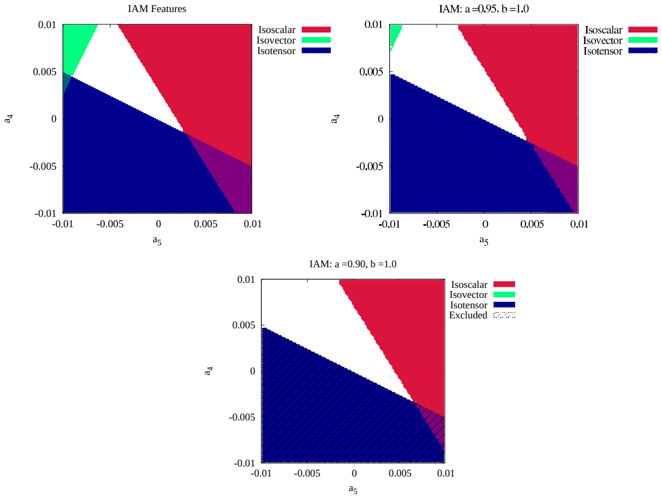


- $M_V \sim 550 - 2300$ GeV
- $\Gamma_V \sim 2 - 24$ GeV

There are constraints on vector masses from S, T, U parameter constraints in some models. Typically $M_V > 1.5$ TeV. *e.g. Pich, Rosell, Sanz-Cillero, 2013*.

Resonances and bounds on the anomalous QGC a_4 and a_5

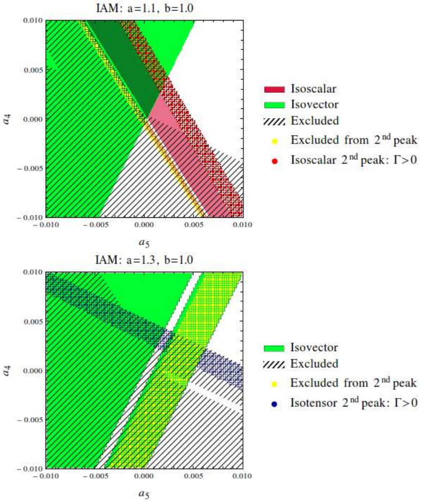
Allowed regions for a_i (in white) if no resonance below 600 GeV



$$a = 1/0.95/0.9 \text{ with } a^2 = b$$

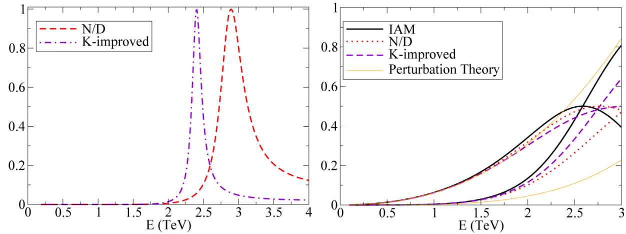
Current direct limits: $a_4 \in [-0.094, 0.10]$; $a_5 \in [-0.23, 0.26]$

Spectrum of resonances for $a > 1$



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

Exotic resonances



Left: Generating an $IJ = 02$ resonance in the electroweak sector is possible with adequate values of a_4, a_5.
Right: positive values of $a^2 - 1$ generate an isotensor $I = 2$ resonance in the ET approximation (but not when the 'exact' amplitudes are used).
In hadron physics the isotensor wave is repulsive, and thus, not resonant.

Sum rule

Assuming the strict ET for all s

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

(Falkowski, Rychkov and Urbano, 2012)

However, we have seen that the analytic structure of the real amplitudes is more complex. 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...

Sum rule

Assuming the strict ET for all s

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

(Falkowski, Rychkov and Urbano, 2012)

However, we have seen that the analytic structure of the real amplitudes is more complex. 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...

Sum rule

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

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

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 propagating 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 $c_\infty = 0$

Sum rule

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

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

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 $c_\infty = 0$

Sum rule

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

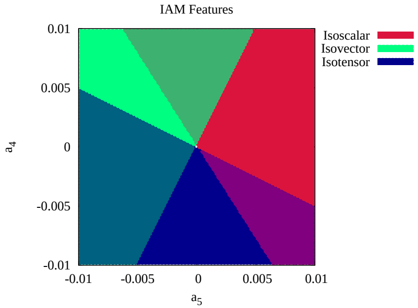
$$3 - a^2 = \frac{v^2}{6\pi} \int_0^\infty \frac{ds}{s} (2\sigma_{I=0}(s)^{tot} + 3\sigma_{I=1}(s)^{tot} - 5\sigma_{I=2}(s)^{tot}) + c_\infty$$

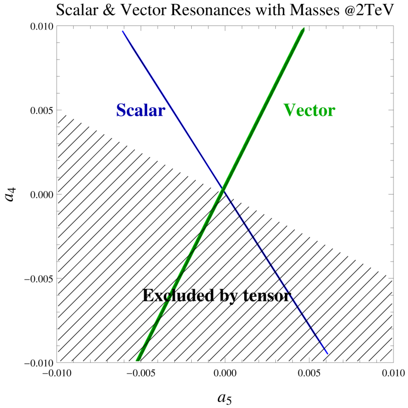
The difference between $1 - a^2$ and $3 - a^2$ can be traced back to the inclusion of W exchange in the t-channel.

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

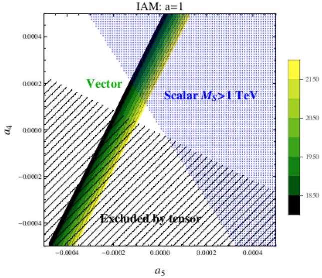
However, there is no guarantee that the propagating degrees of freedom remain *unchanged*. In fact in strongly interacting theories one might expect $c_\infty = 0$

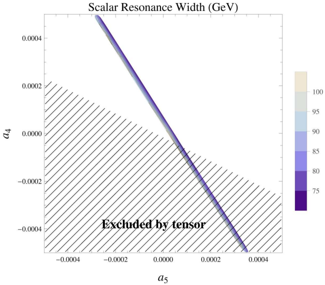
Reduction of parameter space if 1800 GeV $\leq M_R \leq$ 2200 GeV

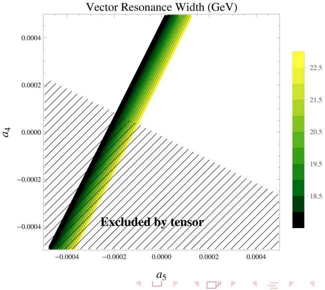




Blow-up and widths







Resonance signal

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

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

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

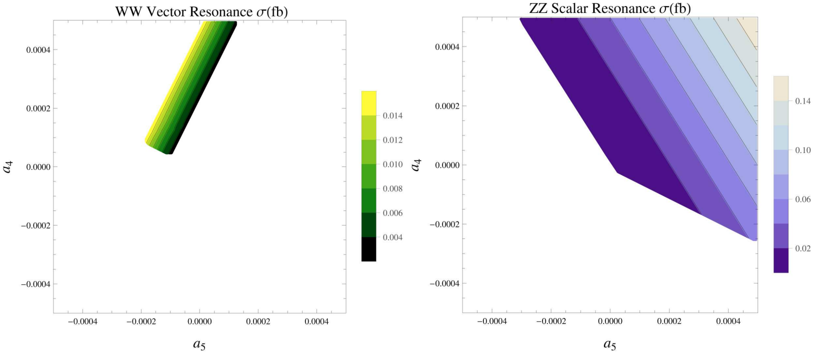
Then for a heavy Higgs with $M_H \rightarrow M_R$ and $\Gamma_H(M_H \rightarrow M_R)$

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

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

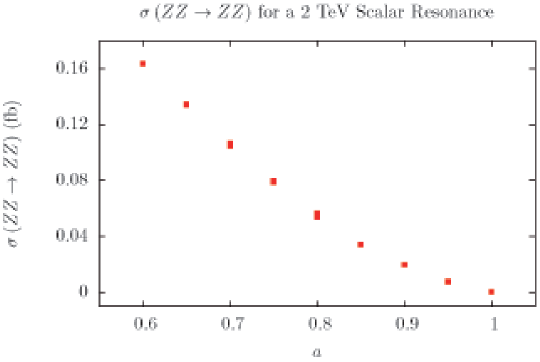
Cross-sections

ATLAS results suggest cross-sections around *10 fb*.
Channel identification is dubious.



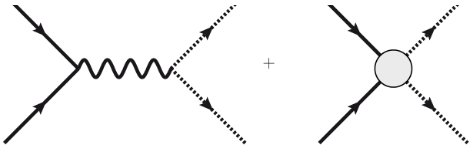
WW channel can be mediated by *I=1,2*. ZZ channel can be mediated by *I=0,2*. (But $I = 2$ .....)
Only resonant contributions to the cross-section is shown.

Dependence of ZZ cross-section on a



Changes in a are insufficient to increase substantially the cross-section

DY: anomalous $\bar{q}_L q_L$ coupling

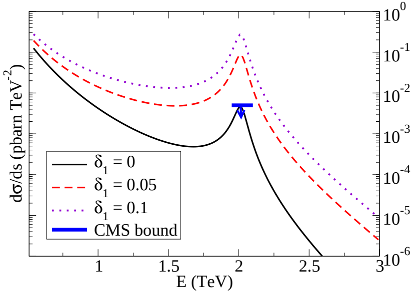


Production of a pair of Goldstone bosons by $\bar{q}q'$ annihilation through a W-meson and anomalous BSM vertex enhancing it

Gauge invariant operator: $\delta_1 \bar{\psi}_L U \not{D} U^\dagger \psi_L$
(one of several $D = 4$ Longhitano's operators)

Changes the relation between G_F and the TGB vertex

Effect of an anomalous $\bar{q}_L q_L$ coupling



$$\left[\frac{d\hat{\sigma}}{d\Omega}\right]_{\rm cm} = \frac{1}{64\pi^2 s}\frac{g^4}{32}\sin^2\theta\left(1+\frac{\delta_1 s}{v^2}\right)^2 |F_V(s)|^2 \,,$$

F_V : Form factor (Watson's theorem)

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 'naive expectations'
- Current LHC Higgs search results do not yet probe the IAM resonances: at least $10\times$ statistics is required

Comments and conclusions II

Cross sections are at least one order order of magnitude too small to explain the ‘resonance’

However:

- Near-degeneracy of scalar and vector gives also enhancement (also helps to explain the signal in *all* 3 channels
- Departures from $a = 1$ enhances the scalar signal.
  - Ex: going from $a = 1$ to $a = 0.95$ doubles the cross-section
  - Current experimental limit (90 % CL): $a \in [0.67, 1.33]$
  - In some models $a < 1$ implies breaking of custodial symmetry $\Rightarrow$ scalar isotriplets can exist, coupling proportionally to the custodial breaking parameter.
- Direct coupling of the resonances to quarks? (Drell-Yan)

All this is under current investigation!

THANK YOU!

Back-up slides

General hWW couplings

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)

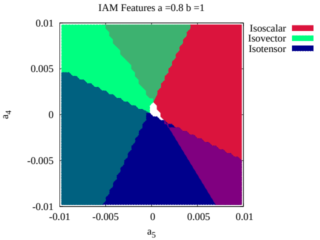
$$\delta a_4 = \Delta_\epsilon \frac{1}{(4\pi)^2} \frac{-1}{12}, \qquad \delta a_5 = \Delta_\epsilon \frac{1}{(4\pi)^2} \frac{-1}{24}$$

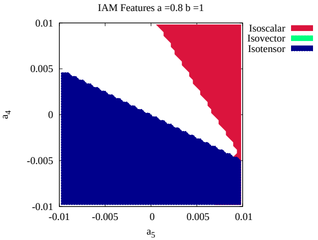
They should bring 'natural' finite contributions from NP:

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

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

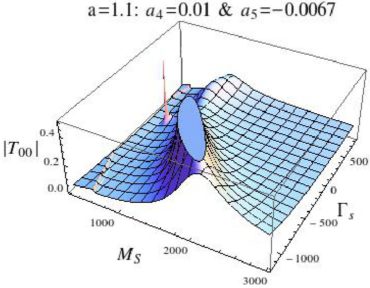
Bounds on a_i for $a = 0.8$ ($b = a^2$)

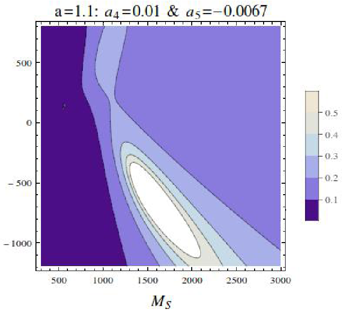


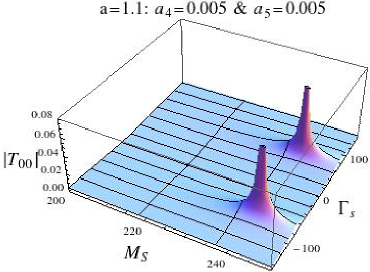


All Resonances

$M_R < 600$ GeV


a=1.1: a_4=0.01 & a_5=−0.0067
$|T_{00}|$
0.4
0.2
0.0
1000
2000
3000
M_S
500
0
−500
−1000
Γ_s


a=1.1: a_4=0.01 & a_5=−0.0067
500
0
−500
−1000
Γ_s
500
1000
1500
2000
2500
3000
M_S
0.5
0.4
0.3
0.2
0.1


a=1.1: a_4=0.005 & a_5=0.005
$|T_{00}|$
0.08
0.06
0.04
0.02
0.00
200
220
240
M_S
100
0
−100
Γ_s

Anomalous TGC and QGC

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

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

$$\Delta g_1^\gamma = 0 \qquad \Delta\kappa^\gamma = g^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$

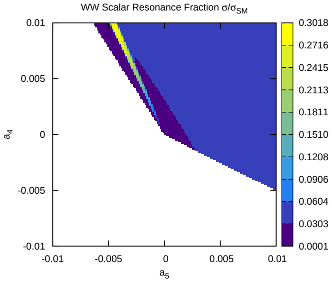
$$\Delta g_1^Z = \delta_Z + \frac{g^2}{c_{\rm w}^2}\alpha_3 \qquad \Delta\kappa^Z = \delta_Z - g'^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$

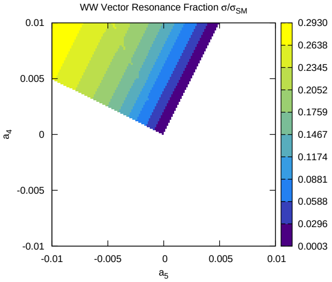
$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_2^{ZZ} = 2\Delta g_1^{\gamma Z} - \frac{g^2}{c_{\rm w}^4}(\alpha_5 + \alpha_7)$$

$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_{\rm w}^2}\alpha_3 \qquad \Delta g_1^{WW} = 2c_{\rm w}^2\Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) + g^2\alpha_4$$

$$\Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_{\rm w}^4}(\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2c_{\rm w}^2\Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) - g^2(\alpha_4 + 2\alpha_5)$$

$$h^{ZZ} = g^2\left[\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})\right]$$





Scalar

$R \sim 0.0001 - 0.30$

$Typically < 0.1$

Vector

$R \sim 0.0003 - 0.3$

$Typically \sim 0.2$

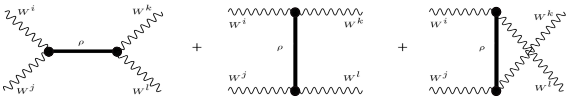
They *could still be there*, but would give a small signal.

Introducing form factors

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

CVC $\Rightarrow$ $F_V^+ = 0$. Unitarity implies

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

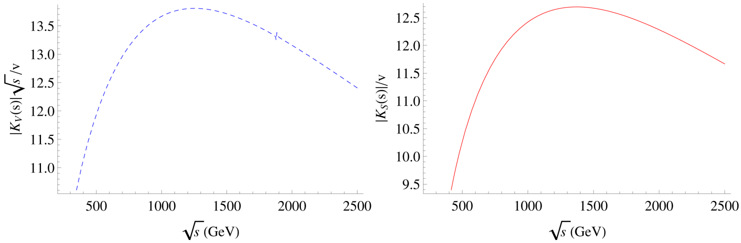


Then (symbolically)

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

(Note: for I=1 u and t channels cancel each other)

Form factors



Assuming $g_V V^i_\mu \partial^\mu w^j w^k \epsilon_{ijk} \Rightarrow g_V(\sqrt{s} = 2\,TeV) \simeq 1.6$