Unitarity and causality constraints in composite Higgs models

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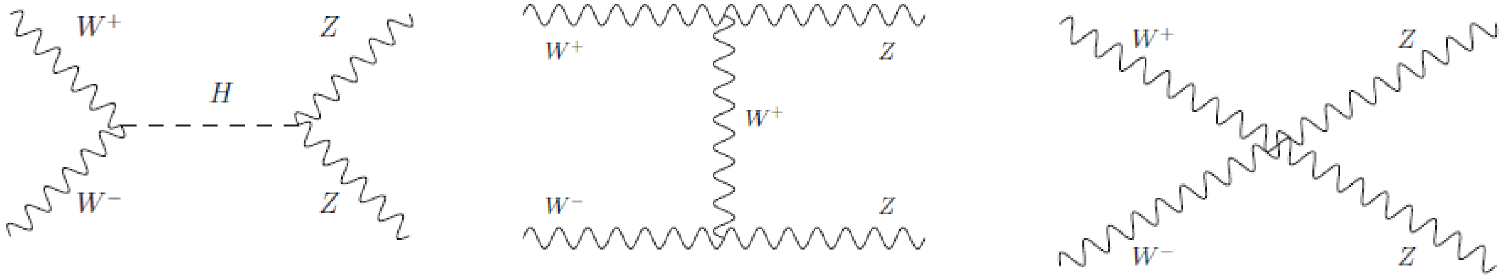
- Outline

- ✓ $W_L W_L$ scattering in extensions of the Standard Model:
  - ➲ *Anomalous couplings ↔ Unitarity Violations*
  - ➲ Unitarization of $W_L W_L$ scattering: *Inverse Amplitude Method (IAM)*
- ✓ What can the unitarized *WW* scattering tell us about H/W anomalous couplings?
  - ➲ *Dynamical Resonances and indirect constraint of anomalous couplings*

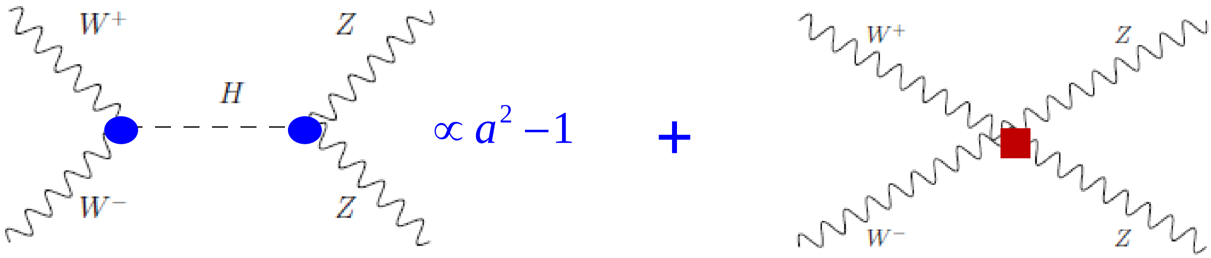
ICHEP'14, July 4th, Valencia

Introduction: $W_L^+W_L^- \to ZZ$ *in extended EW sector*

SM



BSM



$\propto a^2 - 1$ **+**

$\propto a_4, a_5$

O(p^4) operators

From current LHC bounds, still room for anomalous Higgs/*W* couplings *and/or* corrections to W/Z self couplings.

$$a = [0.67, 1.33]$$

$$a_4 = [-0.09, 0.10], a_5 = [-0.23, 0.26]$$

SM $a = \mathrm{b} = 1$

$a_4 = a_5 = 0$

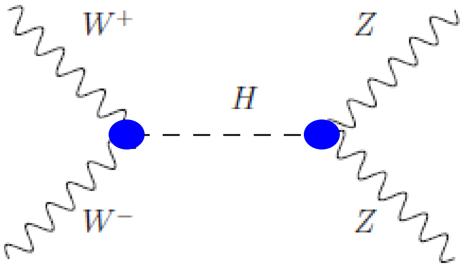
$$\mathcal{L}_{eff} = -\frac{1}{2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}\mathrm{Tr}B_{\mu\nu}B^{\mu\nu} + a_4\left(g^2\mathrm{Tr}W_\mu W_\nu\right)^2 + a_5\left(g^2\mathrm{Tr}W_\mu W^\nu\right)^2 + \ldots$$

$$+\frac{v^2g^2}{4}\left(1+2a\left(\frac{h}{v}\right)+b\left(\frac{h}{v}\right)^2\right)\mathrm{Tr}W_\mu W^\mu - V(h)$$

Unitary Gauge
Custodial Sym.

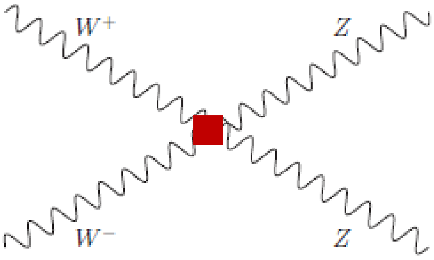
Introduction: $W_L^+W_L^- \to ZZ$ *& anomalous couplings*

SM +



$\propto (a^2-1)s$

+



$\propto a_4 s^2, a_5 s^2$

+ loops at $O(p^4)$

Anomalous Couplings	**LHC bounds**	$a=[0.67,1.33]$ $a_4=[-0.09,0.10], a_5=[-0.23,0.26]$	**Falkowski et '13** **Brivio et '13** **+ many others**

☹ **BUT just small deviations of these couplings from SM values imply a big problem**: <u>$W_L W_L$ scattering breaks unitarity</u>

⟹ ☹ Unitarity violation ↔ possible resonances ☺

Then, unitarization techniques to $W_L W_L$ scattering *useful to diagnose possible resonances and to probe them at LHC ⟶ indirect constraint of anomalous couplings!*

Unitarization: Inverse Amplitude Method (IAM)

- IAM approximately **resum** amplitudes to require unitarity
  - ✓ First, we project on defined *Isospin* and spin amplitudes

$$t_{IJ}(s)=\frac{1}{64\pi}\int_{-1}^{1} d\cos\theta\, P_J(\cos\theta)\, A_I(W_L W_L\to ZZ)$$

  - ✓ We study amplitudes up to loop order $O(p^4)$

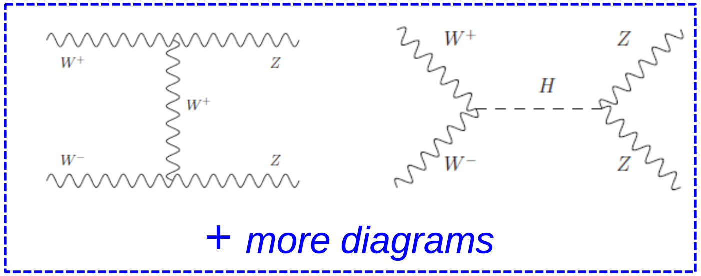
$$t_{IJ}(s)\approx t_{IJ}^{(2)}(s) + t_{IJ}^{(4)}(s)$$

tree

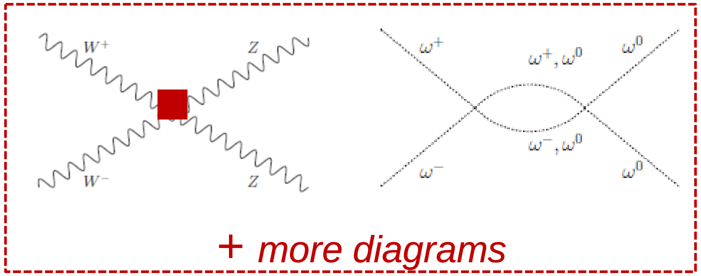
+ *a* terms

one loop

+ $a_{4,5}$ terms



+ *more diagrams*



+ *more diagrams*

Unitarization: Inverse Amplitude Method (IAM)

- IAM approximately **resum** amplitudes to require unitarity

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$$t_{IJ}(s) = \frac{1}{64\pi}\int_{-1}^{1} d\cos\theta P_J(\cos\theta) A_I(W_L W_L \to ZZ)$$

  - ✓ We study amplitudes up to loop order, $O(p^4)$

$$t_{IJ}(s) \approx \underbrace{t_{IJ}^{(2)}(s)}_{\propto s} + \underbrace{t_{IJ}^{(4)}(s)}_{\propto s^2 \log s}$$

unitarity violation

  - ✓ We resum $t_{IJ}(s)$ to define a unitary amplitude

$$t_{IJ}(s) \approx \frac{t_{IJ}^{(2)}}{1 - t_{IJ}^{(4)} / t_{IJ}^{(2)}} \qquad |t_{IJ}(s)| < 1$$

Unitarization: Inverse Amplitude Method (IAM)

- ❖ IAM approximately **resum** amplitudes to require unitarity

  - ✓ First, we project on defined *Isospin* and spin amplitudes

$$t_{IJ}(s) = \frac{1}{64\pi} \int_{-1}^{1} d\cos\theta P_J(\cos\theta) A_I(W_L W_L \to ZZ)$$

  - ✓ We resum t_{IJ}(s) to define a unitary amplitude

IAM method

$$t_{IJ}(s) \approx \frac{t_{IJ}^{(2)}}{1 - t_{IJ}^{(4)} / t_{IJ}^{(2)}} \qquad |t_{IJ}(s)| < 1$$

  - ✓ *Criticism*: Many unitarization methods exist: IAM, K-matrix approach, N/D expansion, Roy equations
  - ✓ *While results can slightly differ, the overall picture is consistent among methods*
  - ✓ *Successful applications in pion and nuclear physics.*

Unitarization: *Looking for dynamical resonances*

Unitarity IAM amplitude

$$t_{IJ}(s) \approx \frac{t_{IJ}^{(2)}}{1 - t_{IJ}^{(4)} / t_{IJ}^{(2)}}$$

function of anomalous couplings

⇨ Now, we look for poles in $t_{IJ}(s)$ in the second Riemann sheet,

$$1/t_{IJ}(s_R)=0 \quad \text{at } \sqrt{s_R} = M - i\,\Gamma/2 \text{ and } \Gamma>0$$

⇨ We study the following three channels

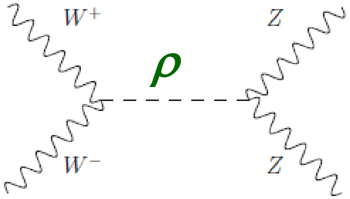
$t_{00} \rightarrow$ Scalar isoscalar

$t_{11} \rightarrow$ Vector isovector

$t_{20} \rightarrow$ Scalar isotensor

MIND: Resonances only those poles with Γ>0.

Mind: resonances coupled to *W* and *Z*!!



Results

Appearance of resonances for *a*, *b* and $a_{4,5}$ free

Our initial setup:

Singlet + Triplet of $SU(2)_V$

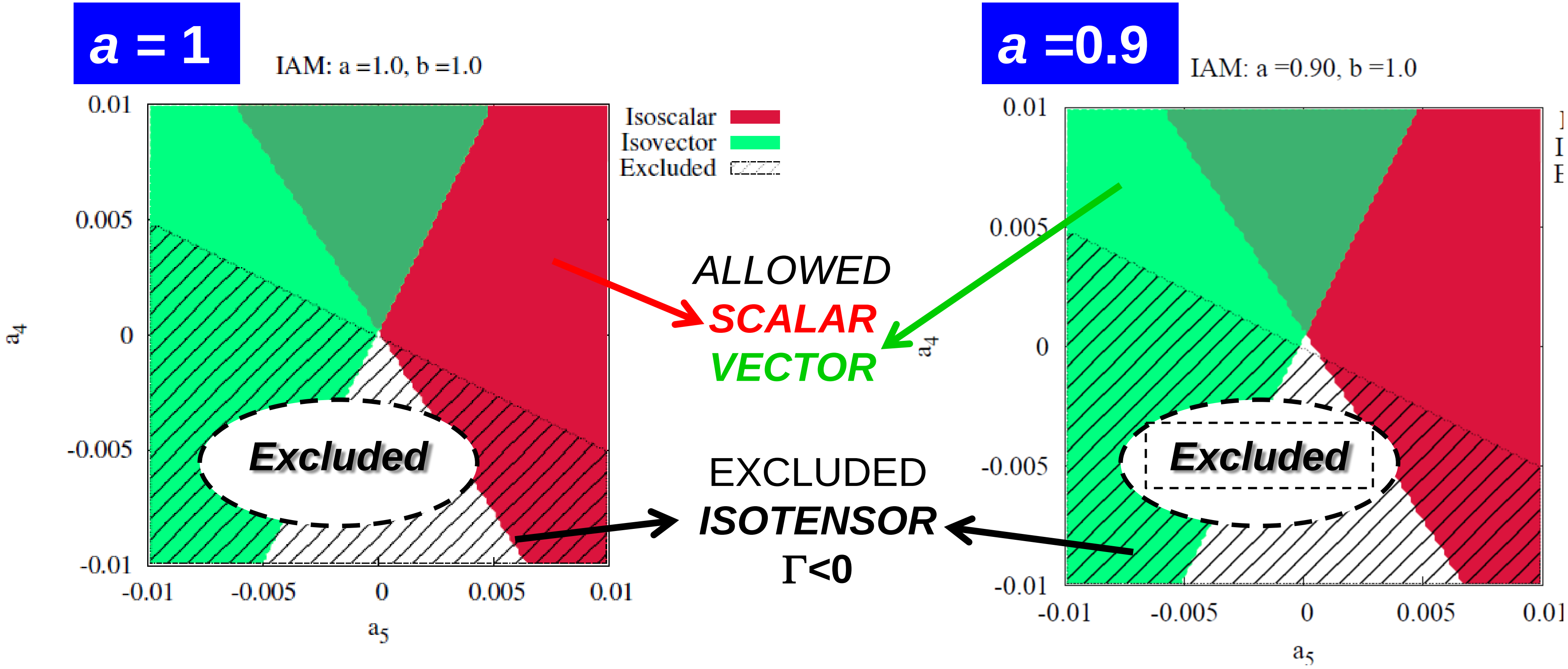
H *W*

- ☐ Unitarization → **Dynamical resonances by H/W self interactions?**

Resonances: case a ≤1

- Resonance appearance crucially depends on the anomalous couplings ***a*** ***-> 2 cases*** *a* ≤1 *and a*>1.

- *a*=1 *or a*<1 common features!



a = 1

a =0.9

ALLOWED

SCALAR

VECTOR

EXCLUDED

ISOTENSOR

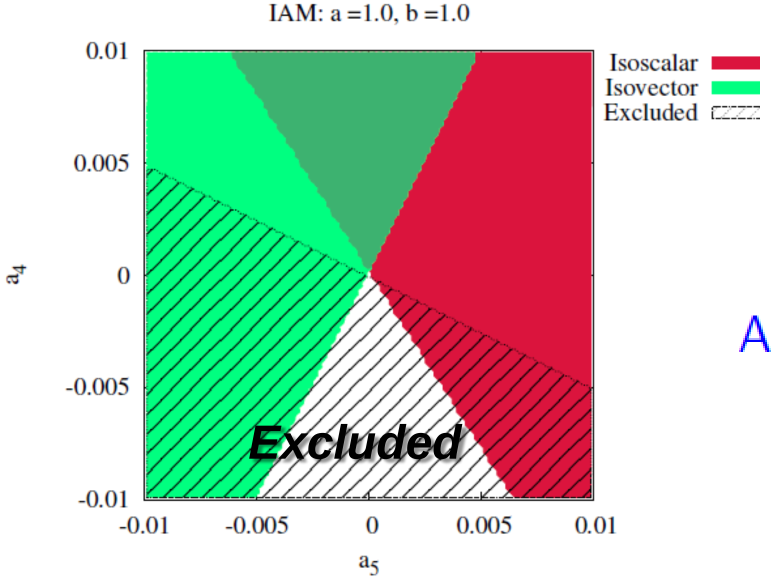
Γ<0

- Forbidden region has isotensor "resonances" in which phase δ_{20} goes through $-\pi/2$ (*violates causality*)

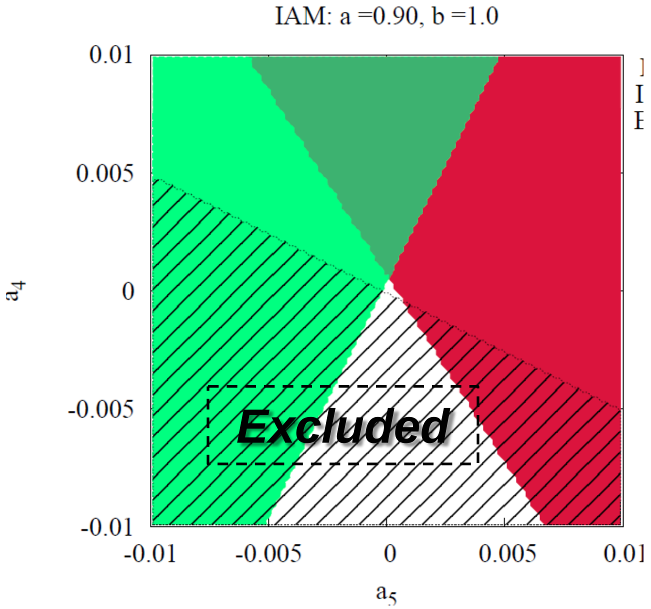
Resonances: case a ≤1

a = 1

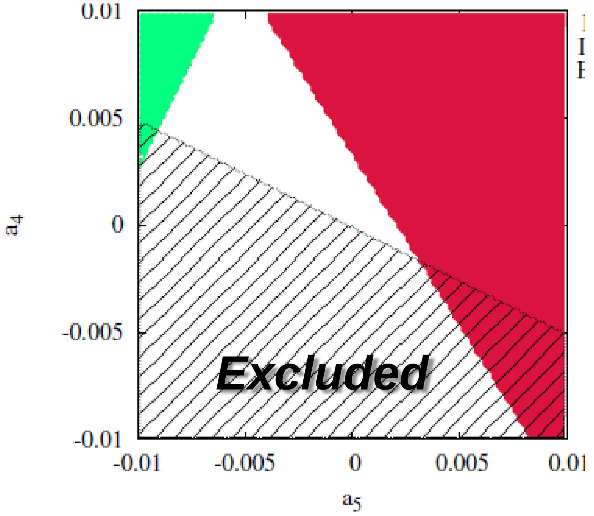
a = 0.9



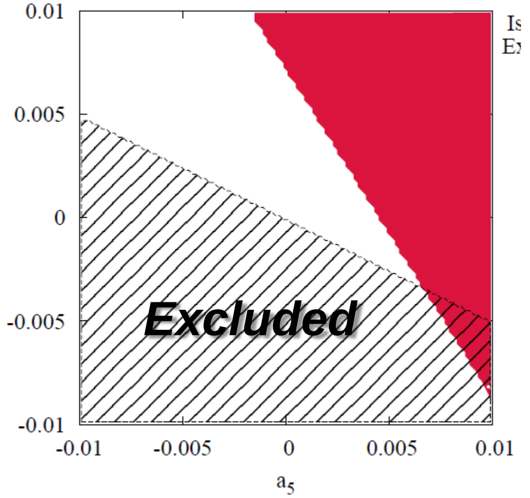
All Resonances



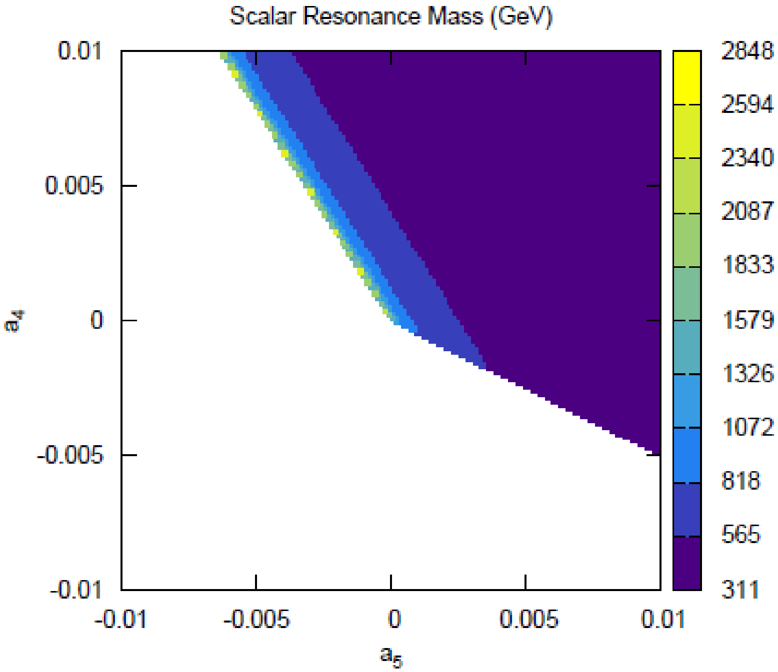
If excluding



$M_R < 600\ \text{GeV}$



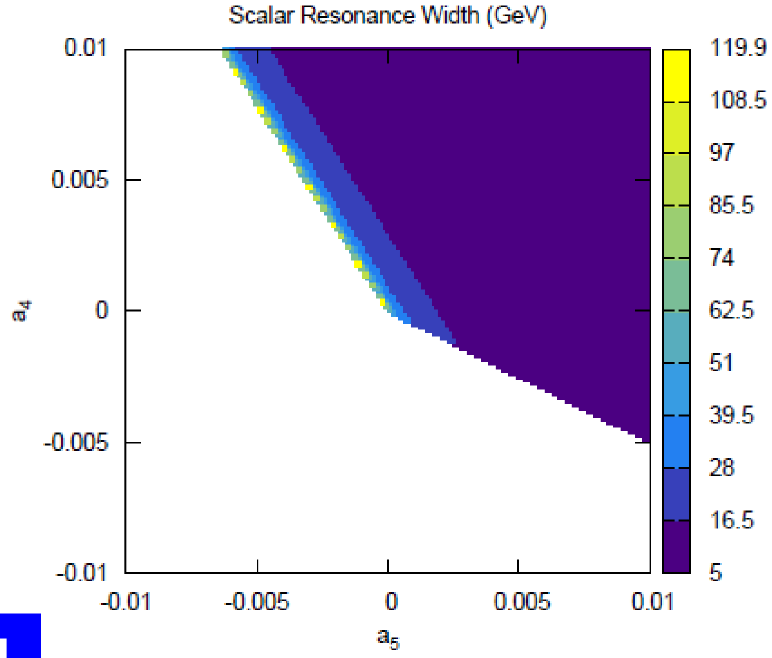
Resonances: Masses and Widths for *a* ≤1



Mass

- $M_S \sim 300 - 3000$ GeV
- $M_V \sim 550 - 2300$ GeV

***a* = 1**
***b* = 1**



Width

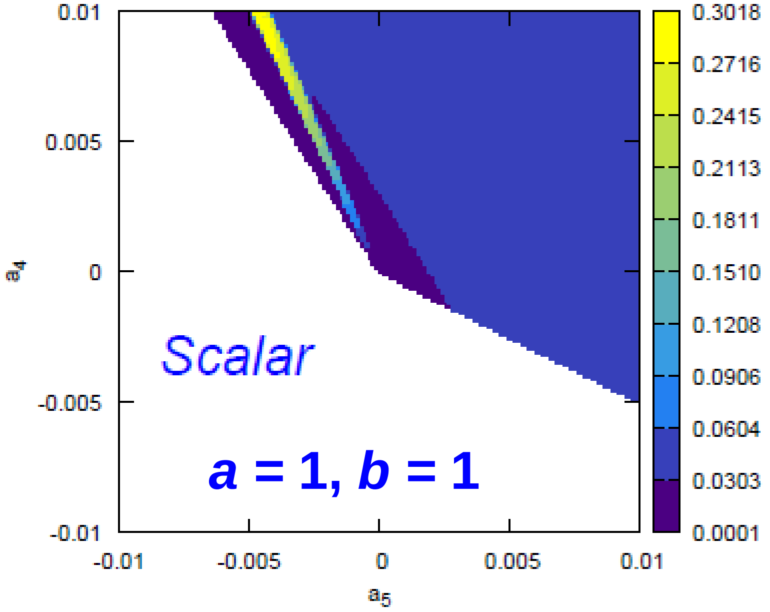
- $\Gamma_S \sim 5 - 120$ GeV
- $\Gamma_V \sim 2 - 24$ GeV

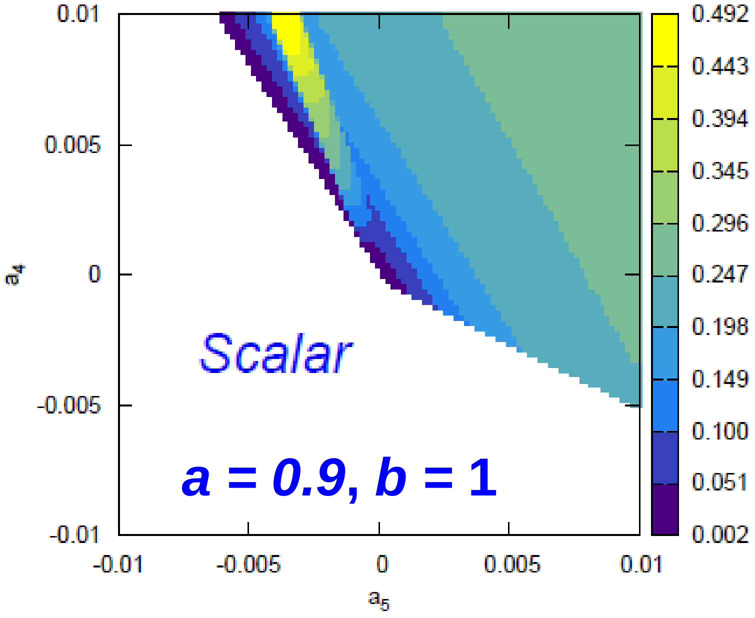
- For *a*<1, resonances tend to be slightly heavier and broader than for a=1
- The coupling b ≠ 1 is only marginally visible in the widths (loops)

Resonances : Signal strengths for $a \leq 1$

$$R = \frac{\sigma_R(pp \to VV \to R \to VV)}{\sigma^{SM}(pp \to VV \to H \to VV)}$$

σ^{SM}
for $M_H = M_R$





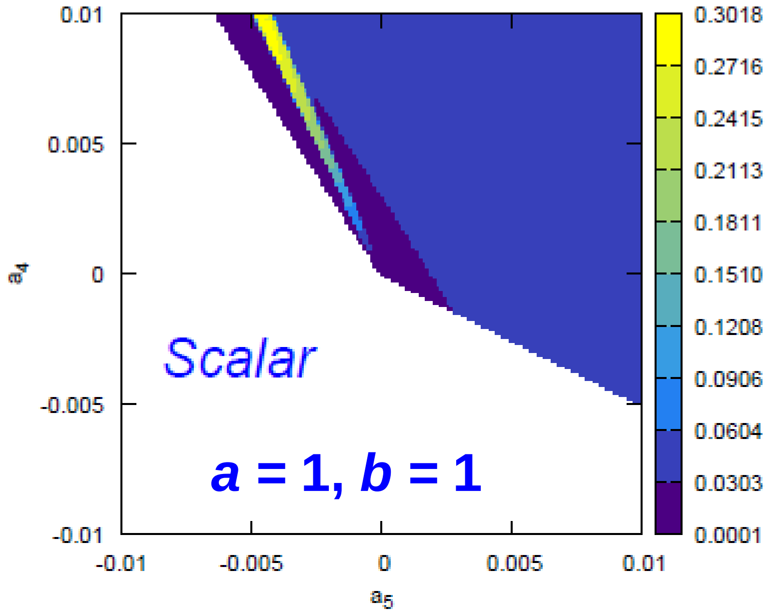
- $\sigma_R/\sigma^{SM} < 0.5$: ***The signal is always much lower than the one for a Higgs of the same mass***
- For a<1, the signal σ_R/σ^{SM} is slightly larger than the one for a=1.

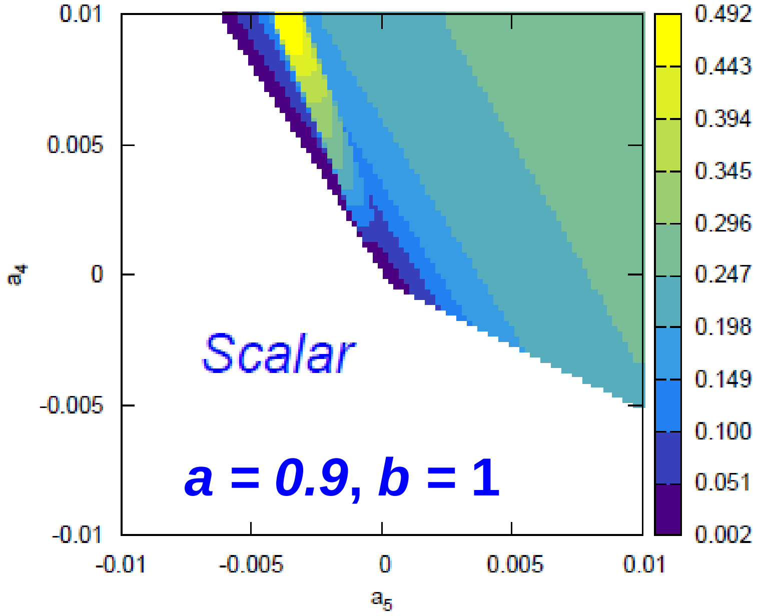
Typically, $\sigma_R/\sigma^{SM} \sim 0.01\text{-}0.1$

Resonances : Signal strengths for *a* ≤1

$$R = \frac{\sigma_R(pp \rightarrow VV \rightarrow R \rightarrow VV)}{\sigma^{SM}(pp \rightarrow VV \rightarrow H \rightarrow VV)}$$

σ^{SM}
for $M_H = M_R$





- Typically, σ_R/σ^{SM}~0.01- 0.1 (σ^{SM} only from VBF Higgs production)
- Currently at LHC probing, at best *R* ~ 0.1 -1 including gluon *H* production

Resonances : case *a* >1

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

Resonances (particularly in the vector channel) are slightly more difficult to appear per $a<1$

They tend to be slightly heavier and broader

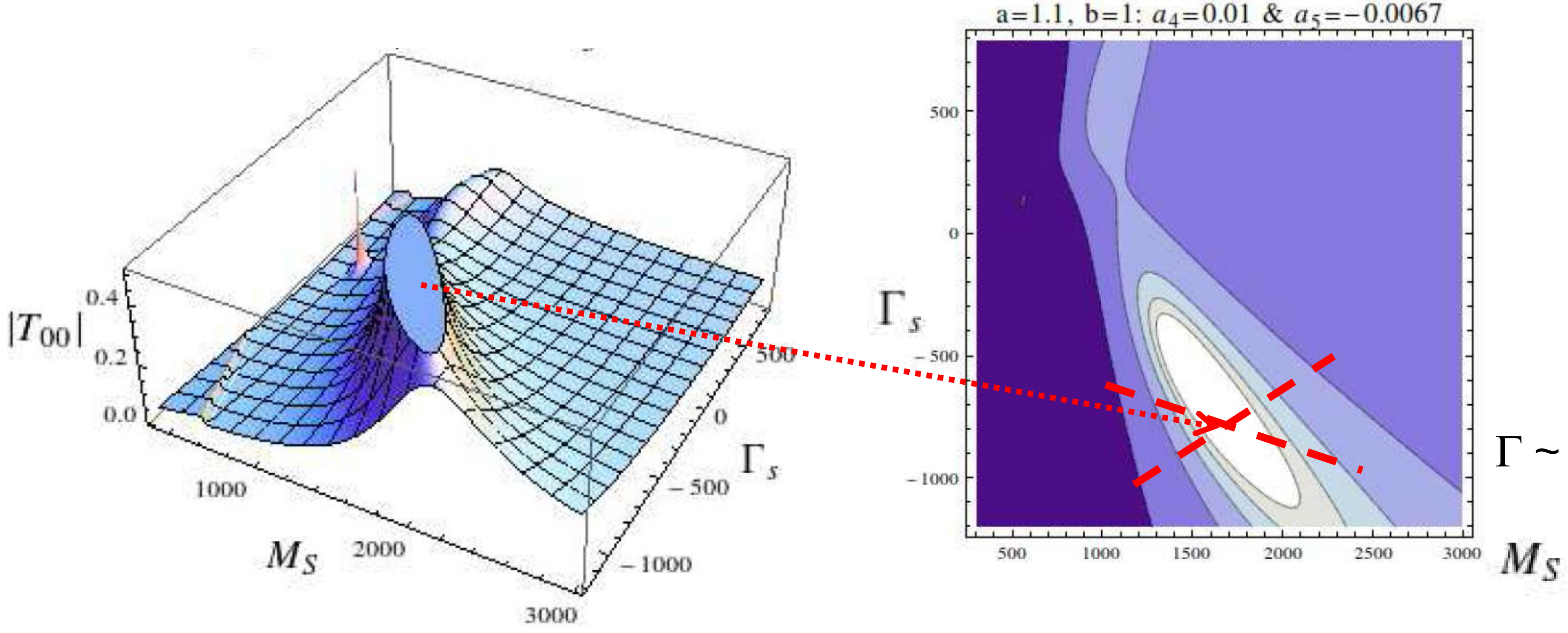
They give a larger experimental signal (at least in the EWA)

This situation is quite different for $a > 1$

Resonances : case *a* >1

new features for a>1:

1) For a given a_4-a_5 values, often 2 poles → one with $\Gamma<0$ ***(causality violation)***



Γ ~ -500 GeV

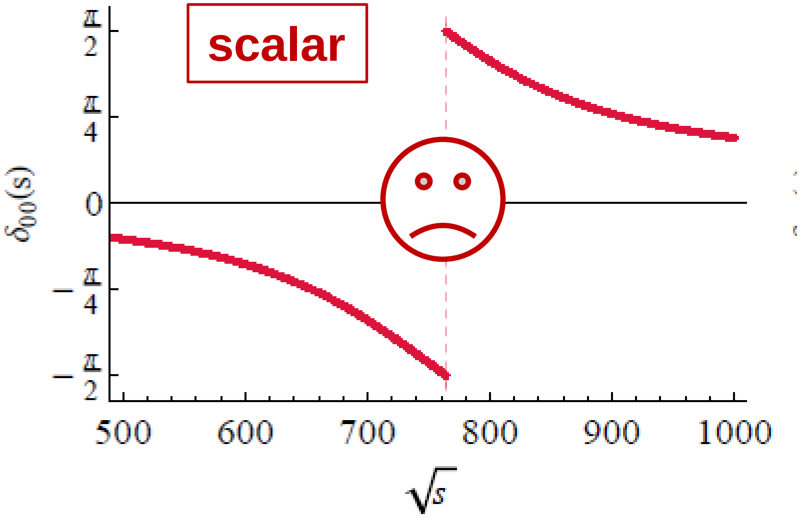
a=1.1, b=1: $a_4=0.01$ & $a_5=-0.0067$

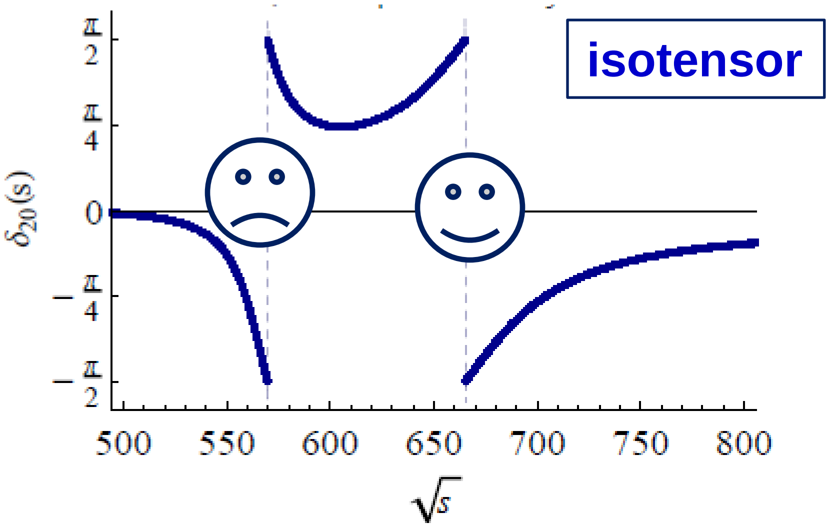
We exclude those values of a_4 & a_5 where causality is violated

Resonances : case *a* >1

some new features:

2) NOW, causality Violations shows up on all isospin amplitudes, t_{00}, t_{10}, t_{20}



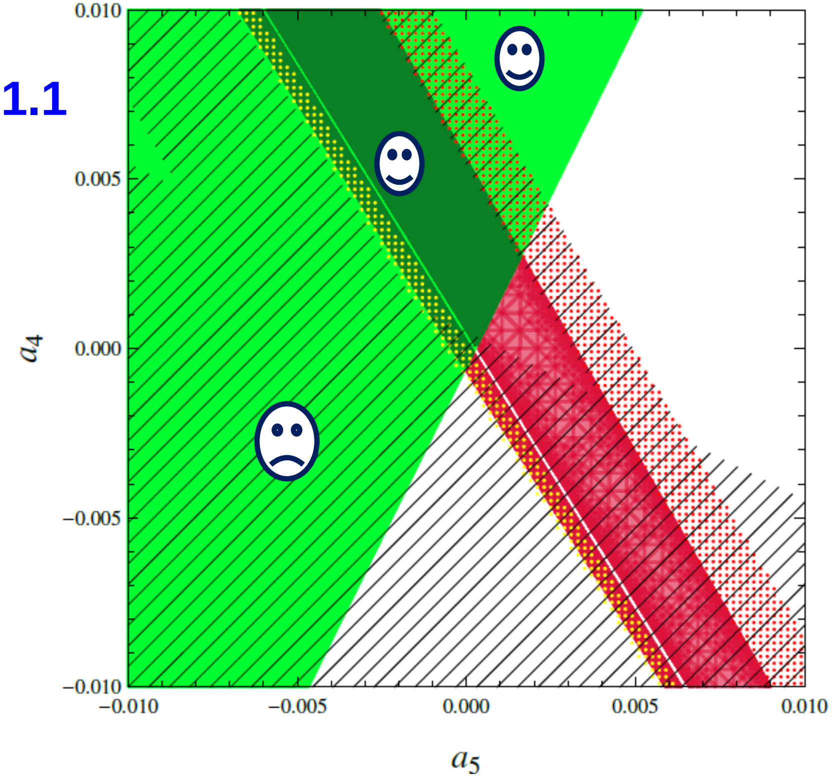


True resonances if the phase shift goes through $+\pi/2$

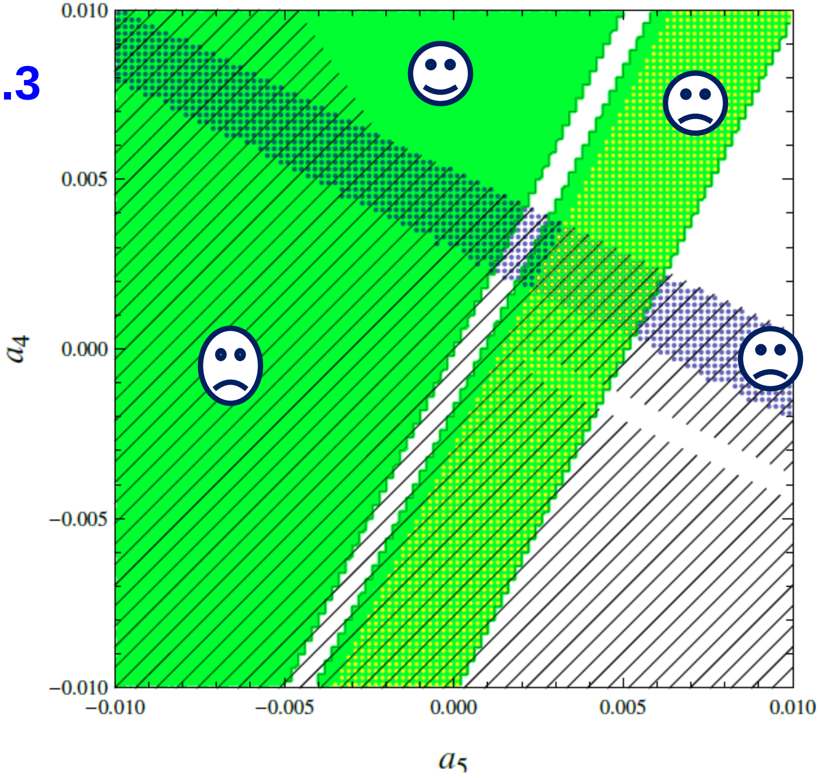
We exclude those values of a_4 & a_5 where causality is violated

Resonance: a_4-a_5 appearance plot for a>1

a=1.1



a=1.3



🟥 Isoscalar

🟩 Isovector

▨ Excluded

● Excluded from 2ndpeak

● Isoscalar 2ndpeak: Γ>0

● Isotensor 2ndpeak: Γ>0

Our initial setup:

Singlet + Triplet of $SU(2)_V$

H *W*

No large room for dynamical resonances by H/W self interactions

Conclusions

❖ Unitarity is a powerful tool to study *WW* scattering amplitudes.

❖ It can help constrain anomalous couplings by helping to predict heavier resonances (>300 GeV) whose absence exclude regions of the a_4-a_5 parameter space

❖ Current LHC Higgs search results likely do not yet probe these IAM resonances, but may be possible in near future.

Conclusions

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- It can help constrain anomalous couplings by helping to predict heavier resonances (>300 GeV) whose absence exclude regions of the a_4-a_5 parameter space

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THANK YOU!

Introduction: $W_L^+W_L^- \longrightarrow ZZ$ *& anomalous coupling constraints*

$$\mathcal{L}_{eff} = -\frac{1}{2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}\mathrm{Tr}B_{\mu\nu}B^{\mu\nu} + a_4\left(\mathrm{Tr}V_\mu V_\nu\right)^2 + a_5\left(\mathrm{Tr}V_\mu V^\nu\right)^2 + \ldots$$
$$+\frac{v^2}{4}\left(1 + 2a\left(\frac{h}{v}\right) + b\left(\frac{h}{v}\right)^2\right)\mathrm{Tr}D_\mu U^\dagger D^\mu U - V(h)$$

SM $a = \mathrm{b} = 1$
$a_4 = a_5 = 0$

LHC bounds

$a = [0.67, 1.33]$

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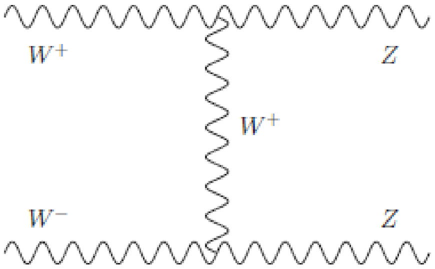
Falkowski et '13
Brivio et '13

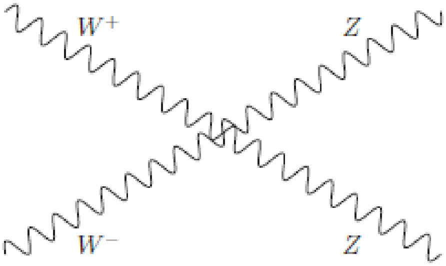
☹ BUT just small deviations of these couplings from SM values imply a big problem: <u>*unitarity violation of the* $W_L W_L$ scattering</u>

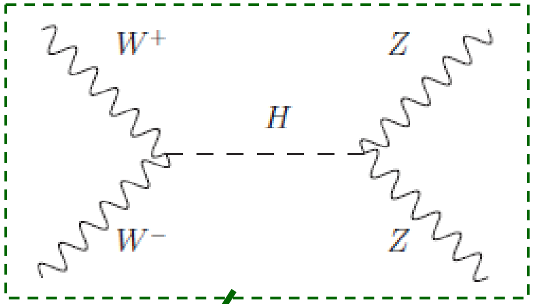
➡ ☹ Unitarity violation ↔ possible resonances ☺

Then, unitarization techniques to $W_L W_L$ scattering *useful to diagnose possible resonances, match to LHC → constraint indirectly the anomalous couplings!*

$W_L^+ W_L^- \to ZZ$







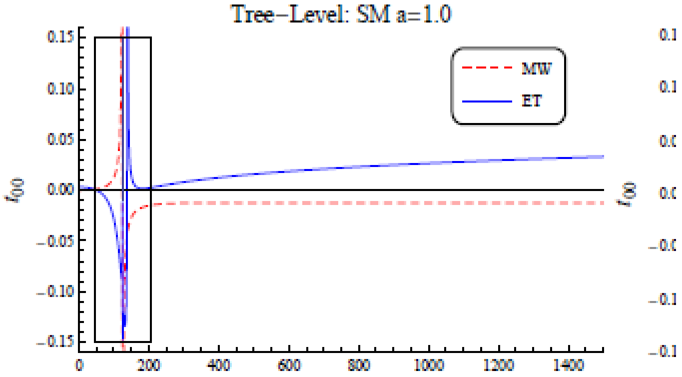
In the SM, the Higgs boson unitarizes $W_L W_L$ scattering

$$\mathcal{L}_{SM} = -\frac{1}{2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}\mathrm{Tr}B_{\mu\nu}B^{\mu\nu}$$

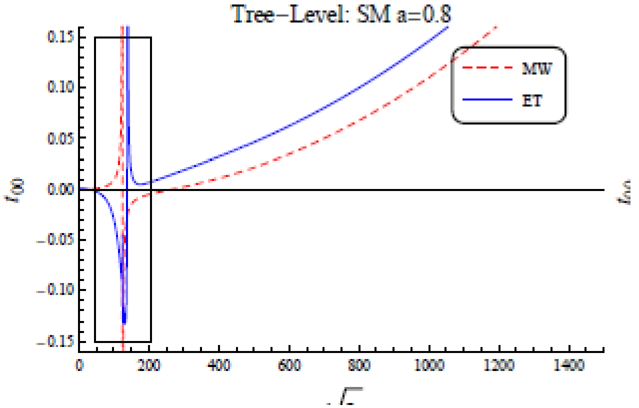
$$+\frac{v^2}{4}\left(1+2\left(\frac{h}{v}\right)+\left(\frac{h}{v}\right)^2\right)\mathrm{Tr}D_\mu U^\dagger D^\mu U - V(h)$$

$$D_\mu U = \partial_\mu U + \frac{i}{2} g \tau^i W_\mu^i U - \frac{i}{2} g' B_\mu U \tau^3$$

$a = 1$



$a < 1$



$a > 1$

Figure paper