A light Higgs in a strongly interacting electroweak symmetry breaking sector

Rafael L. Delgado, Antonio Dobado, M.J. Herrero,
Felipe J. Llanes-Estrada and J.J. Sanz-Cillero

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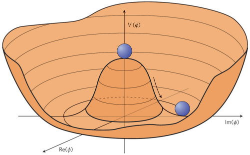
arXiv:1408.1193 [hep-ph], JHEP **1407** (2014) 149, JHEP **1402** (2014) 121
and J. Phys. G: Nucl. Part. Phys. **41** 025002 (2014)

Empirical situation



doi:10.1038/nphys1874

- Electroweak symmetry breaking: $SU(2)_L \times SU(2)_R \to SU(2)_C$
- Three would-be Goldstone bosons ω.
- Equivalence theorem: for $s \gg 100\,\mathrm{GeV}$, Identify them with the longitudinal components of W and Z.
- Recent claim of a 125-126 GeV scalar "Higgs" resonance φ.

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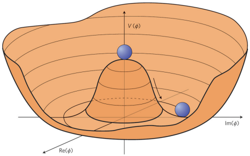

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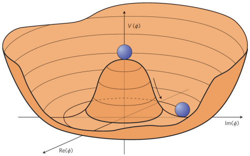

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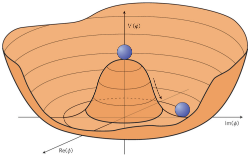

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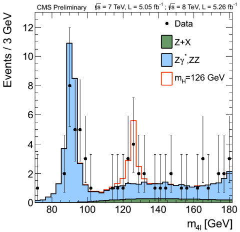

arXiv:1207.7235 [hep-ex]

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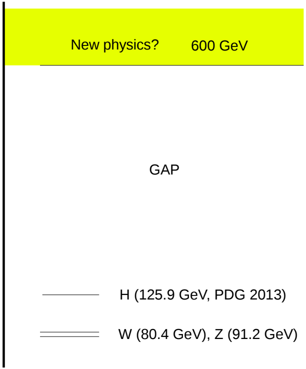

- IMPORTANT: No new physics!! *If there is any...*
- Four scalar light modes, a strong gap.
- Natural: further spontaneous symmetry breaking at $f > v = 246\,\mathrm{GeV}$?

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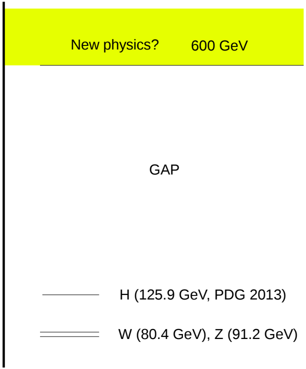

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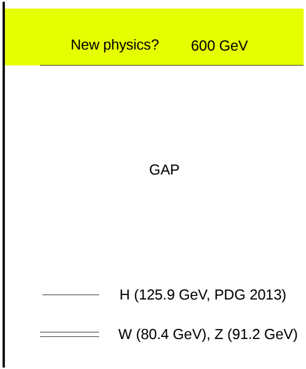

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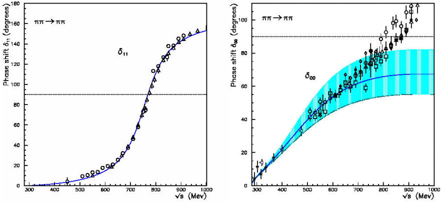
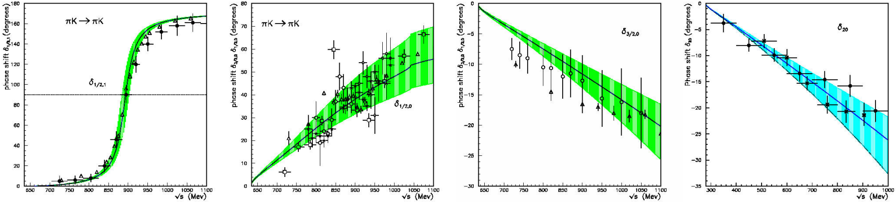
Chiral Perturbation Theory plus Dispersion Relations.

Simultaneous description of $\pi\pi \to \pi\pi$ and $\pi K \pi K \to \pi K \pi K$ up to 800-1000 MeV including resonances.

Lowest order ChPT (WeinbergTheorems) and even one-loop computations are only valid at very low energies.





A. Dobado, J.R. Peláez

An example of Unitarization Method: K matrix

$$\tilde{T} = T(1 - J(s)T)^{-1}, \quad , J(s) = -\frac{1}{\pi} \log\left[\frac{-s}{\Lambda^2}\right],$$

so that, for $\tilde{t}_\omega$ (partial waves, an spherical harmonics expansion),

$$\tilde{t}_\omega = \frac{t_\omega - J(t_\omega t_\varphi - t_{\omega\varphi}^2)}{1 - J(t_\omega + t_\varphi) + J^2(t_\omega t_\varphi - t_{\omega\varphi}^2)}$$

For the elastic case (only t_ω),

$$\tilde{t}_\omega = \frac{t_\omega}{1 - J t_\omega}$$

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$W_L \, W_L$ scattering

We have no clue of what, how or if new physics...
Most general NLO Lagrangian for ω, h at low energy

$$
\begin{aligned}
\mathcal{L} \;=\;& \left[1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right] \frac{\partial_\mu \omega^a \partial^\mu \omega^b}{2} \left(\delta^{ab} + \frac{\omega^a \omega^b}{v^2}\right) \\
&+ \frac{4a_4}{v^4} \partial_\mu \omega^a \partial_\nu \omega^a \partial^\mu \omega^b \partial^\nu \omega^b + \frac{4a_5}{v^4} \partial_\mu \omega^a \partial^\mu \omega^a \partial_\nu \omega^b \partial^\nu \omega^b \\
&+ \frac{2d}{v^4} \partial_\mu h \partial^\mu h \partial_\nu \omega^a \partial^\nu \omega^a + \frac{2e}{v^4} \partial_\mu h \partial^\mu \omega^a \partial_\nu h \partial^\nu \omega^a \\
&+ \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{g}{v^4} (\partial_\mu h \partial^\mu h)^2
\end{aligned}
$$

Particular cases of the theory

- $a^2 = b = 1$, SM
- $a^2 = b = 0$, Higgsless ECL[1]
- $a^2 = 1 - \frac{v^2}{f^2}$, $b = 1 - \frac{2v^2}{f^2}$, $SO(5)/SO(4)$ MCHM[2]
- $a^2 = b = \frac{v^2}{\hat{f}^2}$, Dilaton[3]

[1] See J. Gasser and H. Leutwyler, Annal Phys. **158** (1984) 142 Nucl. Phys. B **250** (1985) 465 and 517

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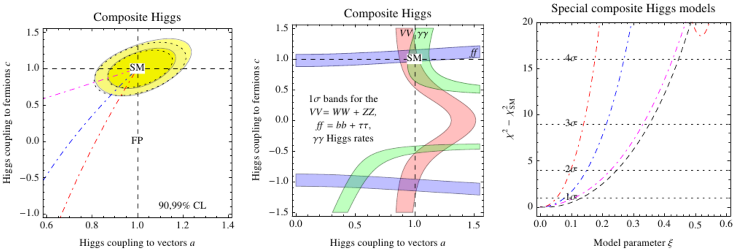
Experimental bounds on low-energy constants

- As it would require measuring the coupling of two Higgses, there is no experimental bound over the value of b parameter. Over a, at a confidence level of 2σ (95%),
  - CMS[4] .... $a \in (0.70, 1.1)$
  - ATLAS[5] .... $a \in (0.87, 1.3)$



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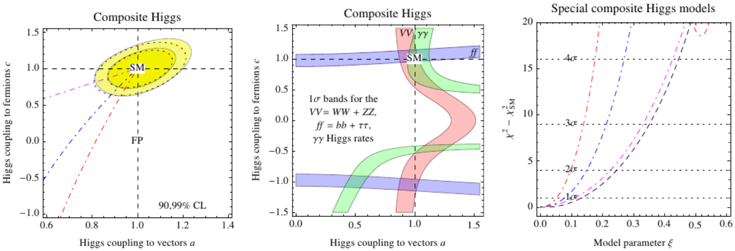

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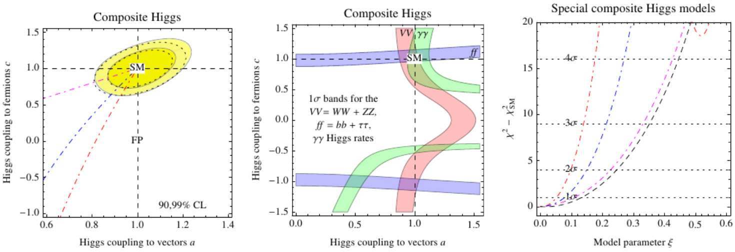

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$\gamma\gamma$ scattering

- We also consider[6] the case of the $\gamma\gamma \to W_L^+ W_L^-$ and $\gamma\gamma \to Z_L Z_L$ scattering.
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- Graphs from CMS, JHEP **07** (2013) 116.
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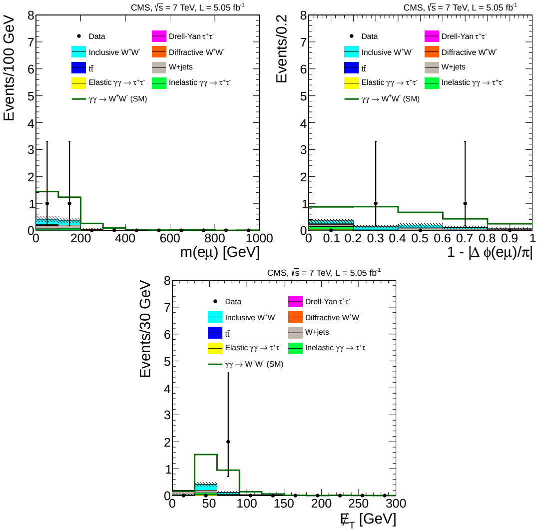

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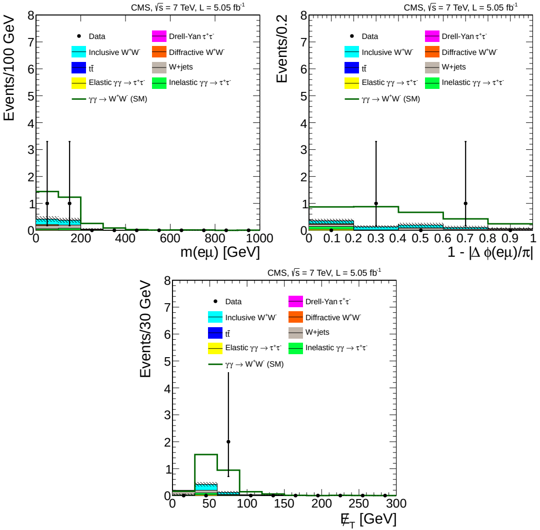

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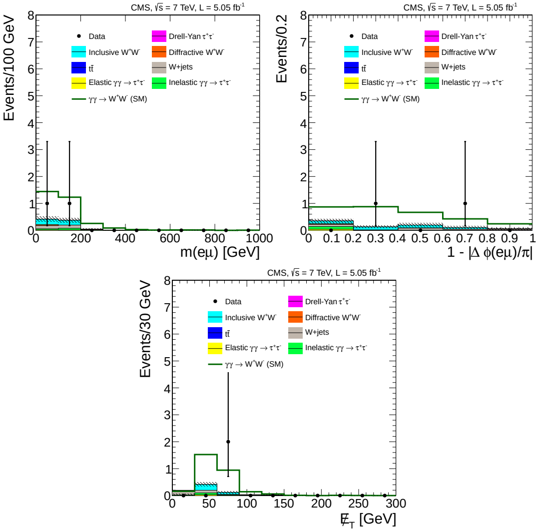

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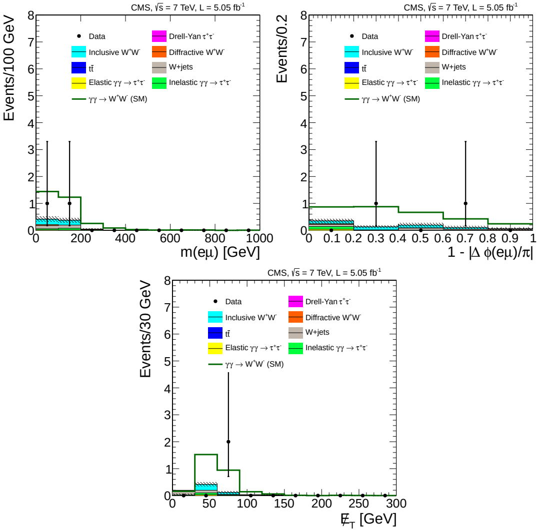

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Resonance from $W_L W_L \to hh$

$a = 1,\ b = 2,$
elastic channel $W_L W_L \to W_L W_L$

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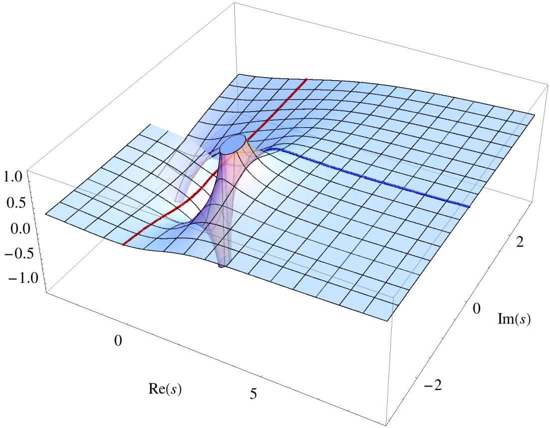

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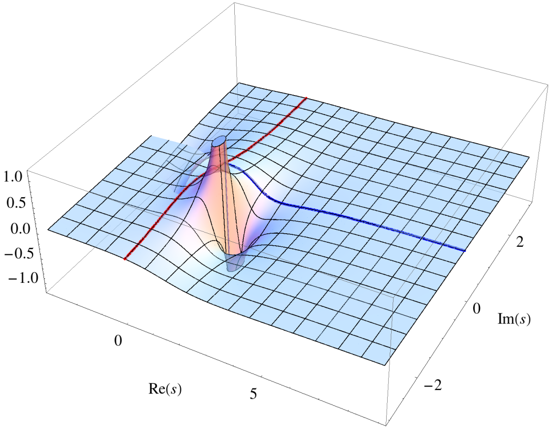
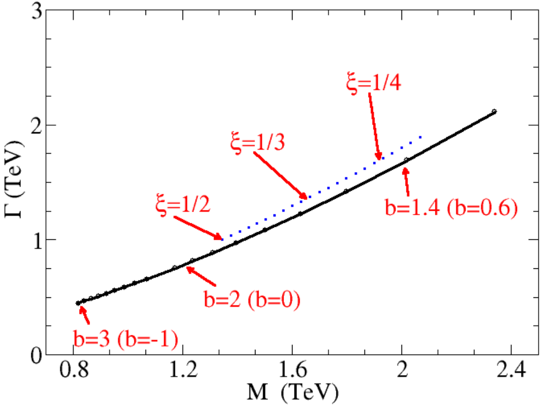
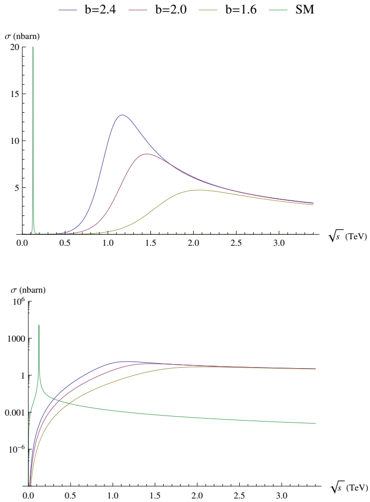


Motion of the resonance mass and width

Dependence on b with $a^2 = 1$ fixed (upper curve) and for $a = 1\xi$ and $b = 12\xi$ with $\xi = v/f$ as in the MCHM (lower blue curve).

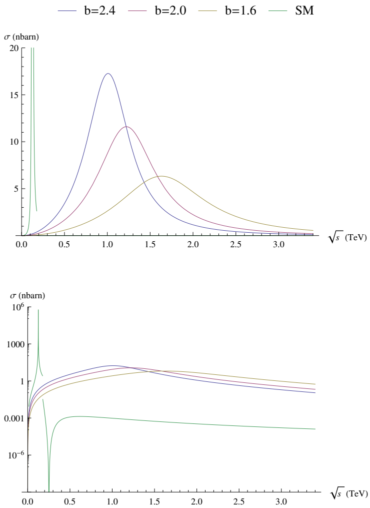


Cross section



$\omega\omega \to \omega\omega$, $a = 1$, $b = 2$, $\mu = 3\,\mathrm{TeV}$,

all others null



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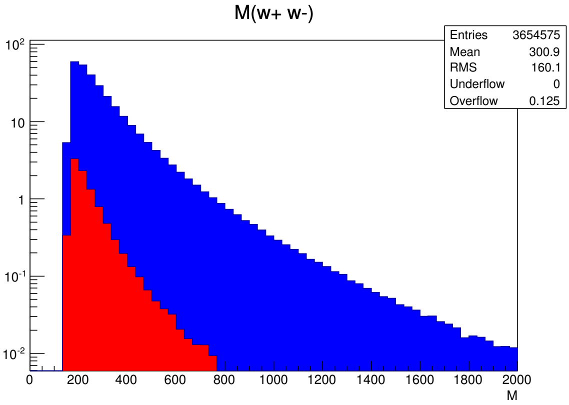
Experimental challenge

$\sqrt{s} = 13\,\mathrm{TeV}$, $L = 10\,\mathrm{fb}^{-1}$
Production of W^+W^- (blue)
vs. $W_L^+W_L^-$ (red)
x–axis in GeV
y–axis in events / $33.3\,\mathrm{GeV}$.

MadGraph5_aMC@NLO used.

We acknowledge the computer resources, technical expertise, and assistance provided by the BCS and the Tirant supercomputer staff at Valencia.



$\gamma\gamma$ scattering

- Two parameterizations have been considered (two effective Lagrangians obtained), giving the same results.
- One loop computation for the process $\gamma\gamma \to \omega_L^a \omega_L^b$.
- Siple result compared with the complexity of the computation.

$$
\begin{aligned}
\mathcal{M} &= ie^2(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(1)})A(s,t,u) + ie^2(\epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}^{(2)})B(s,t,u) \\
T_{\mu\nu}^{(1)} &= \frac{s}{2}(\epsilon_1 \epsilon_2) - (\epsilon_1 k_2)(\epsilon_2 k_1) \\
T_{\mu\nu}^{(2)} &= 2s(\epsilon_1 \Delta)(\epsilon_2 \Delta) - (t-u)^2(\epsilon_1 \epsilon_2) \\
&\quad -2(t-u)[(\epsilon_1 \Delta)(\epsilon_2 k_1) - (\epsilon_1 k_2)(\epsilon_2 \Delta)] \\
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\begin{aligned}
M(\gamma\gamma \to zz)_{\rm LO} &= 0 \\
A(\gamma\gamma \to zz)_{\rm NLO} &= \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{4\pi^2 v^2} \\
B(\gamma\gamma \to zz)_{\rm NLO} &= 0 \\
A(\gamma\gamma \to \omega^+\omega^-)_{\rm LO} &= 2sB(\gamma\gamma \to \omega^+\omega^-)_{\rm LO} = -\frac{1}{t} - \frac{1}{\mu} \\
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$$

Work in progress

- Ref. arXiv:1408.1193 [hep-ph] (unitarized scattering $W_L W_L$ at 1–loop) is soon to be extended. Wait for our long paper in which we analyze the effect of the renormalization parameters d, e and g.
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Conclusions

- New scalar particle + mass gap
- New physics would very likely imply strong interactions, in elastic $W_L W_L$ and inelastic $\to hh$ scattering.
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- For $a^2 = b \neq 1$, strong elastic interactions are expected for $W_L W_L$, and a second, broad scalar analogous to the σ in nuclear physics possibly appears. We identify a pole at 800 GeV or above in the second Riemann sheet very clearly, the question is whether it corresponds to a physical particle since it is so broad.
- Even if $a \simeq 1$, with small λ_i (higher powers of h), but we allow $b > a^2$, one can have strong dynamics resonating between the $W_L W_L$ and hh channels, likewise possibly generating a new scalar pole of the scattering amplitude in the sub-TeV region.
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- SM $\rightarrow$ unitarity.
- Higgsless model (now experimentally excluded) $\rightarrow$ unitarity violation in WW scattering $\rightarrow$ new physics.
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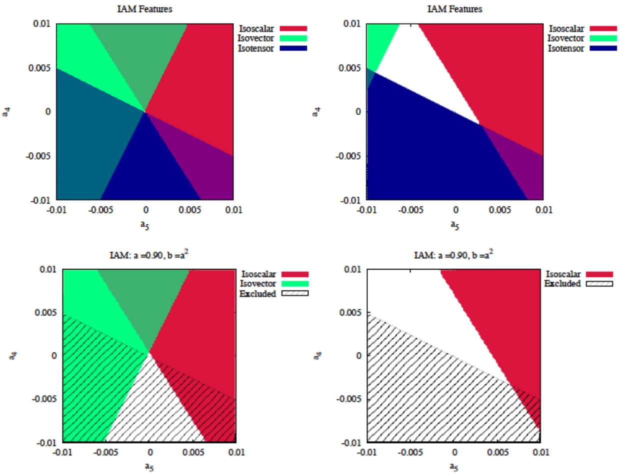
BACKUP SLIDES

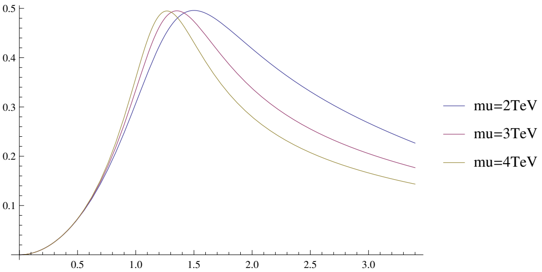
Resonances in $W_L W_L \to W_L W_L$ due to a_4 and a_5 parameters

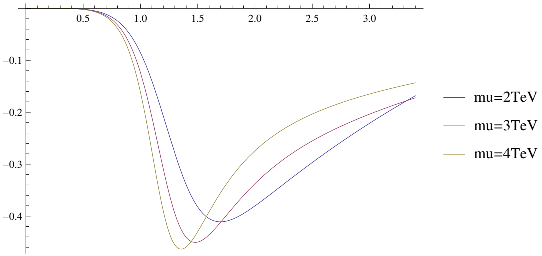


Espriu, Yencho, Mescia
PRD**88**, 055002
PRD**90**, 015035

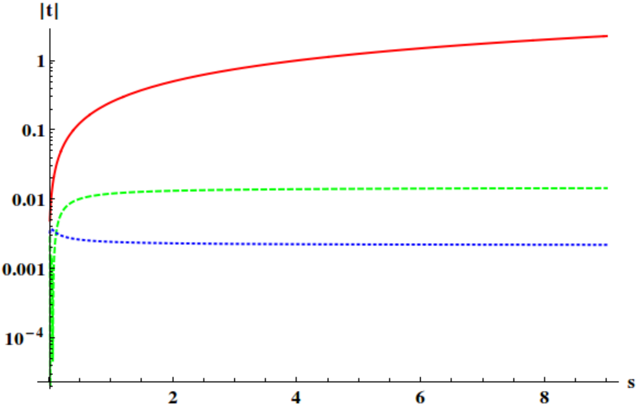
Changing the cutoff μ

From top to bottom, absolut and imaginary value of matrix element A for the $\omega\omega \to hh$ channel. $a = 1$, $b = 2$, all the other parameters null.



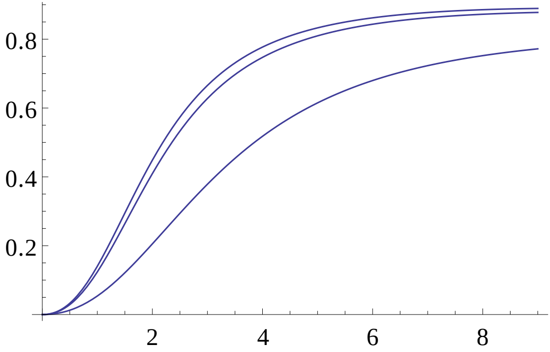


Coupled channels, tree level amplitudes



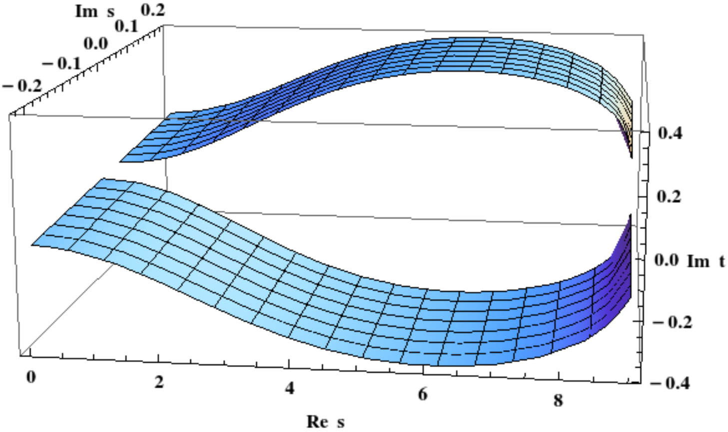
$f = 2v$, $\beta = \alpha^2 = 1$, $\lambda_3 = M_\varphi^2/f$, $\lambda_4 = M_\varphi^2/f^2$. OX axis: s in TeV^2.

Tree level, modulus of $\tilde{t}_\omega$, K matrix

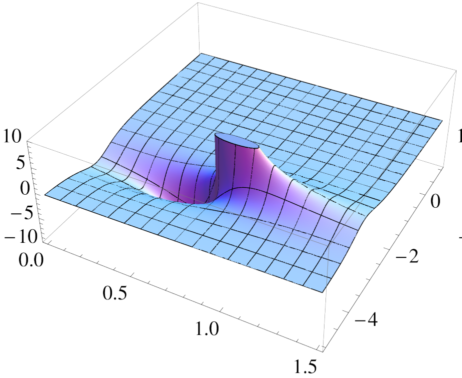


- All units in TeV.
- From top to bottom, $f = 1.2,\ 0.8,\ 0.4\,\mathrm{TeV}$
- $\Lambda = 3\,\mathrm{TeV}$
- $\mu = 100\,\mathrm{GeV}$

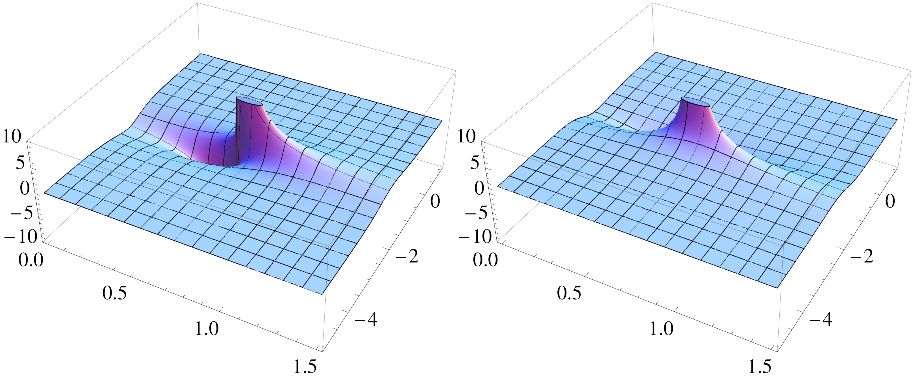
Im t_ω in the N/D method, $f = 1\,\mathrm{TeV}$, $\beta = 1$, $m = 150\,\mathrm{GeV}$



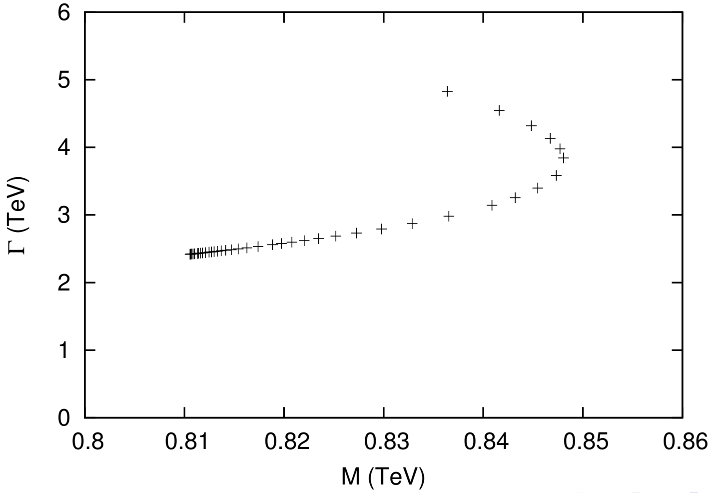
$\mathrm{Re}\, t_\omega$ and $\mathrm{Im}\, t_\omega$, large N, $f = 400\,\mathrm{GeV}$



Re t_ω and Im t_ω, large N, $f = 4\,\mathrm{TeV}$



Tree level, motion of the pole position of t_ω K–matrix, $M_\phi = 125\,\mathrm{GeV}$, $f \in (250\,\mathrm{GeV}, 6\,\mathrm{TeV}))$



I) IAM method

This method needs a NLO computation,

$$\tilde{t}^{\omega} = \frac{t_0^{\omega}}{1 - \frac{t_0^{\omega}}{t_1^{\omega}}},$$

where

$$t_1^{\omega} = s^2 \left(D \log\left[\frac{s}{\mu^2}\right] + E \log\left[\frac{-s}{\mu^2}\right] + (D+E) \log\left[\frac{\mu^2}{\mu_0^2}\right] \right)$$

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Check at tree level

We have checked[7], for the tree level case,

$$\mathcal{L} = \frac{1}{2}g(\varphi/f)\partial_\mu\omega^a\partial^\mu\omega^b\left(\delta_{ab}+\frac{\omega^a\omega^b}{v^2-\omega^2}\right) + \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}M_\varphi^2\varphi^2 - \lambda_3\varphi^3 - \lambda_4\varphi^4 + \ldots$$

$$g(\varphi/f) = 1+\sum_{n=1}^{\infty}g_n\left(\frac{\varphi}{f}\right)^n = 1+2\alpha\frac{\varphi}{f}+\beta\left(\frac{\varphi}{f}\right)^2+..$$

where $a \equiv \alpha v/f$, $b = \beta v^2/f^2$, and so one, the concordance with the methods

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II) K matrix

$$\tilde{T} = T(1 - J(s)T)^{-1}, \quad , J(s) = -\frac{1}{\pi}\log\left[\frac{-s}{\Lambda^2}\right],$$

so that, for $\tilde{t}_\omega$,

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$N \to \infty$, with v^2/N fixed. The amplitude A_N to order $1/N$ is a Lippmann-Schwinger series,

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A_N &= A - A\frac{NI}{2}A + A\frac{NI}{2}A\frac{NI}{2}A - \dots \\
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Note: actually, $N = 3$. For the (iso)scalar partial wave (chiral limit, $I = J = 0$),

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IV) N/D

(elastic scattering at tree level only $\beta = \alpha^2$. See ref. J.Phys. G41 (2014) 025002). Ansatz

$$\tilde{t}^\omega(s) = \frac{N(s)}{D(s)},$$

where $N(s)$ has a left hand cut (and $\mathrm{Im}\, N(s > 0) = 0$)
$D(s)$ has a right hand cut (and $\Im D(s < 0) = 0$);

$$\begin{aligned} D(s) &= 1 - \frac{s}{\pi}\int_0^\infty \frac{ds' N(s')}{s'(s' - s - i\epsilon)} \\ N(s) &= \frac{s}{\pi}\int_{-\infty}^0 \frac{ds' \,\mathrm{Im}\, N(s')}{s'(s' - s - i\epsilon)} \end{aligned}$$