Validity of EFT for VBS

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Theoretical Study of the TeV scale

- From Top to Bottom: construct a full theory (renormalizable and UV complete), and describe the TeV scale in terms of the parameters of the BSM Lagrangian. For instance: MSSM has ~ 100 free parameters.
    - Advantage: a full model. Renormalizability.
    - Problems: no hints about the UV completion chosen by nature.
    - Examples: MSSM (~ 100 free parameters), non-MSSM SUSY, Technicolor, KK,...
- From Bottom to Top: construct an Effective Field Theory (EFT), based on the symmetries and available degrees of freedom at low energy.
    - Advantage: we do not rely on a specific UV completion.
    - Disadvantage: valid only at certain energy scale. Non-renormalizable in the classical QFT sense, but in the ChPT one.
    - The usual EFT approach breaks when the low energy EFT reaches the unitarity bound, becoming non-perturbative.
    - For phenomenology, EFTs with the BSM physics (resonances) as explicit degrees of freedom are used.

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Non-linear Electroweak Chiral Lagrangian

Non-linear EFT[1] for VV scattering at NLO level, minimally coupled to hh,

$$\mathcal{L} = \frac{v^2}{4} g(h/f)\,\mathrm{Tr}[(D_\mu U)^\dagger D^\mu U] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h),$$

where

$$g(h/v) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \ldots$$

$$V(h) = V_0 + \frac{M_h^2}{2}h^2 + \sum_{n=3}^{\infty} \lambda_n h^n$$

$$D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu.$$

M_h and λ_n are subleading in chiral counting.

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We need the parameterization of the $U(\omega^a) \in SU(2)_L \times SU(2)_R / SU(2)_C$ coset. In either case, whatever the non–linear term is,

$$U(x) = \mathbb{1} + i\frac{\tau^a \omega^a(x)}{v} + \mathcal{O}\left(\omega^2\right).$$

Two choices have been used:

Spherical parameterization

$$U(x) = \mathbb{1}\sqrt{1 - \frac{\omega^2(x)}{v^2}} + i\frac{\tau^a \omega^a(x)}{v}$$

Exponential parameterization (here, a cross-check for EWSBS+$\gamma\gamma$)

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EFT for VV scattering, minimally coupled to hh

Since we are considering scattering processes within the EWSBS, the covariant derivate reduces to

$$D_\mu U = \partial_\mu U.$$

Define

$$V_\mu \equiv (D_\mu U)U^\dagger.$$

The next counterterms are needed for the NLO computation of the VV scattering, minimally coupled to hh

$$\begin{aligned}\mathcal{L}_4 = a_4[\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5[\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] \\ + \frac{d}{v^2}(\partial_\mu h \partial^\mu h)\,\mathrm{Tr}[(D_\nu U)^\dagger D^\nu U] + \frac{e}{v^2}(\partial_\mu h \partial^\nu h)\,\mathrm{Tr}[(D^\mu U)^\dagger D_\nu U] \\ + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)(\partial_\nu h \partial^\nu h).\end{aligned}$$

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Validity of EFTs

- We are interested in the collider phenomenology of Vector Bosons Scattering since it is very sensitive to new physics in the EW sector in the LHC.
- The NLO-computed EFT groves with the CM energy like $A \sim s^2$. Hence, it will eventually reach the unitarity bound, becoming non-perturbative. 2 options available:
  - The common one: limit the validity range of the EFT to the perturbative region. I.e., until the unitarity bound is reached (see the talk of Matthias, *Unitarity limits for EFT parameters*). Consider the EFT as a useful parameterization of slight deviations from the SM in the range under the TeV scale.
  - Take advantage of the analytical properties of the S-Matrix (encoded inside dispersion relations and unitarization procedures) to study the non-perturbative region (TeV scale) of the theory. A decomposition in partial waves required. Going back from partial waves to scattering amplitude can be tricky, because of contributions from higher order spherical harmonics.

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Unitarity for partial waves

- Unit. cond. for $S - matrix$: $SS^\dagger = \mathbb{1}$,
- plus analytical properties of matrix elements,
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Unitarity condition for partial waves

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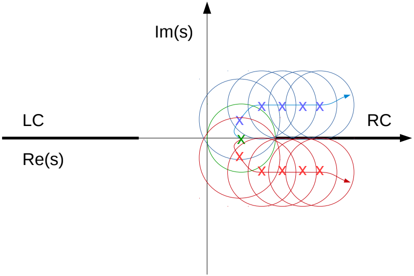

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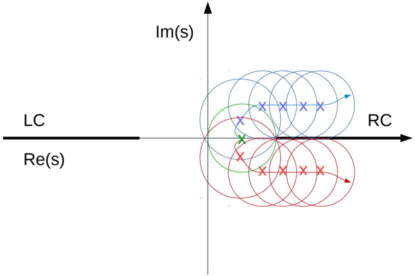

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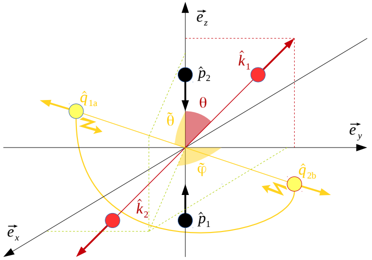

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EWSBS partial waves

The form of the partial wave is

$$A_{IJ}(s) = A_{IJ}^{(0)} + A_{IJ}^{(1)} + \mathcal{O}\left[(s/v^2)^3\right].$$

Which will be decomposed as

$$A_{IJ}^{(0)} = Ks$$

$$A_{IJ}^{(1)} = \left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right)s^2.$$

As $A_{IJ}(s)$ must be scale independent,

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$$\begin{aligned} A_{IJ}^{(0)} &= Ks \\ A_{IJ}^{(1)} &= \left(B(\mu) + D \log \frac{s}{\mu^2} + E \log \frac{-s}{\mu^2} \right) s^2. \end{aligned}$$

As $A_{IJ}(s)$ must be scale independent,

$$\begin{aligned} B(\mu) &= B(\mu_0) + (D+E) \log \frac{\mu^2}{\mu_0^2} \\ &= B_0 + p_4 a_4(\mu) + p_5 a_5(\mu). \end{aligned}$$

Unitarization procedures for elastic processes

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$$g(s) = \frac{1}{\pi}\left(\frac{B(\mu)}{D+E} + \log\frac{-s}{\mu^2}\right)$$

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Usability channel of unitarization procedures

IJ	00	02	11	20	22
Method of choice	Any	N/D IK	IAM	Any	N/D IK

- The IAM method cannot be used when $A^{(0)} = 0$, because it would give a vanishing value.
- The N/D and the IK methods cannot be used if $D + E = 0$, because in this case computing $A_L(s)$ and $A_R(s)$ is not possible.
- The naive K-matrix method,

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

fails because it is not analytical in the first Riemann sheet and, consequently, it is not a proper partial wave compatible with microcausality.

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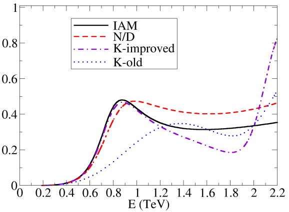
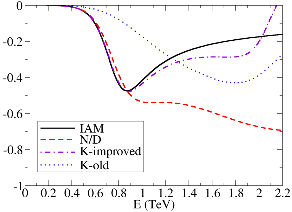
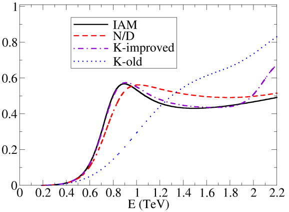
Scalar-isoscalar channels

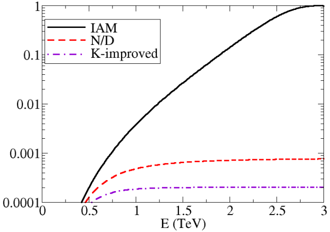


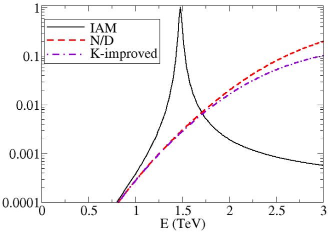




From left to right and top to bottom, elastic $\omega\omega$, elastic hh, and cross channel $\omega\omega \to hh$, for $a = 0.88$, $b = 3$, $\mu = 3\,\mathrm{TeV}$ and all NLO parameters set to 0.
PRL **114** (2015) 221803, PRD **91** (2015) 075017.

Vector-isovector channels

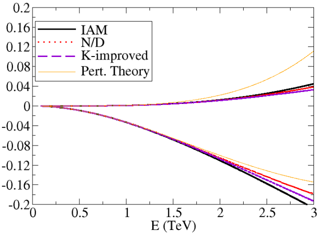


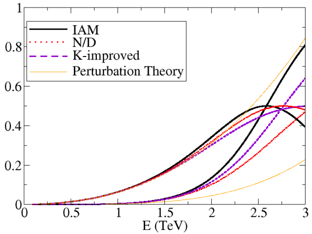


From our ref[2]. We have taken $a = 0.88$ and $b = 1.5$, but while for the left plot all the NLO parameters vanish, for the right plot we have taken $a_4 = 0.003$, known to yield an IAM resonance according to the Barcelona group[3].

[2] PRD **91** (2015) 075017
[3] PRD **90** (2014) 015035

Scalar-isotensor channels ($IJ = 20$)

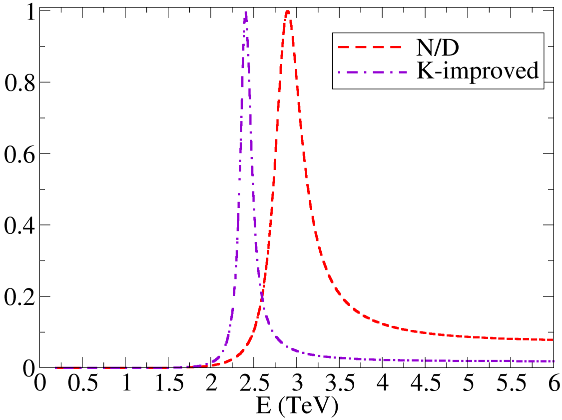




From our ref[4]. From left to right, $a = 0.88$, $a = 1.15$. We have taken $b = a^2$ and the NLO parameters set to zero. Both real and imaginary part shown. Real ones correspond to bottom lines at left and upper at low E at right.

[4] PRD **91** (2015) 075017

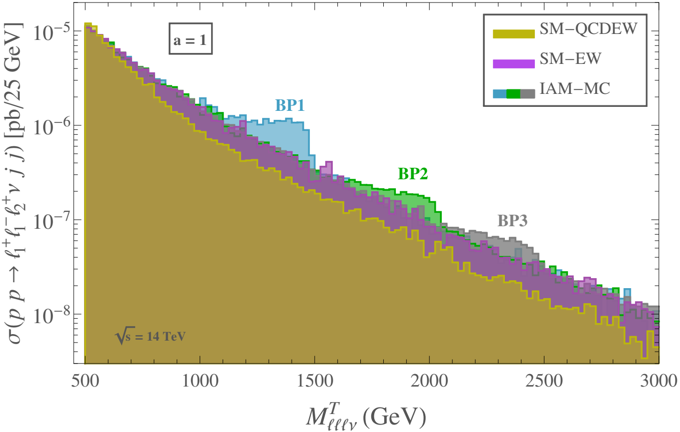
Isotensor-scalar channels ($IJ = 02$)



$a = 0.88$, $b = a^2$, $a_4 = -2a_5 = 3/(192\pi)$, all the other NLO param. set to zero. PRD **91** (2015) 075017.

New MadGraph model, Isovector Resonance: leptonic final state

arXiv:1707.04580 [hep-ph]



$a = 1$; $a_4 \cdot 10^4 = 3.5$ (BP1), 1 (BP2), 0.5 (BP3);

Conclusions

- Studied $2 \to 2$ VBF processes within the EWSBS, including coupled channels (hh).
- An extensive analysis of the validity of unitarization methods.
- We provide a MadGraph v5 model for the unitarized ChPT, without relying on the naive K-matrix.
- Prospects for the Benchmark Points at the LHC (14 TeV, $WZ \to WZ$ process, arXiv:1707.04580 [hep-ph]):

	$\mathcal{L} = 300\,\mathrm{fb}^{-1}$			$\mathcal{L} = 1000\,\mathrm{fb}^{-1}$			$\mathcal{L} = 3000\,\mathrm{fb}^{-1}$		
	N_l^{IAM}	N_l^{SM}	σ_l^{stat}	N_l^{IAM}	N_l^{SM}	σ_l^{stat}	N_l^{IAM}	N_l^{SM}	σ_l^{stat}
BP1	2	1	0.6	6	4	1.1	19	13	1.8
BP2	0.6	0.4	-	1	1	0	4	3	0.1
BP3	0.1	0.1	-	0.4	0.3	-	1	1	0
BP1'	6	2	2.3	19	8	4.2	57	23	7.2
BP2'	2	0.9	1	6	3	1.8	19	9	3.7
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Let's start the discussion!!

Backup Slides

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- With $1000\,\mathrm{fb}^{-1}$, we estimate that these type of resonances could be observed with $\sigma_I^{\rm stat} > 4$ and new hints of the heavier resonances with masses close to $2\,\mathrm{TeV}$ could also appear.
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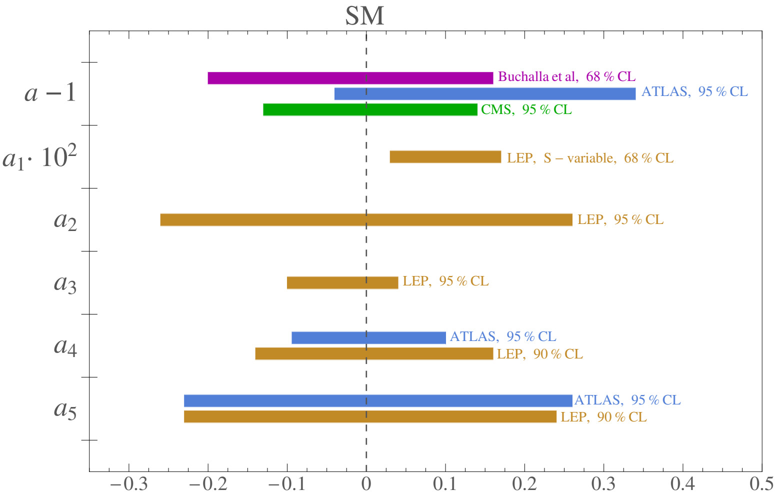
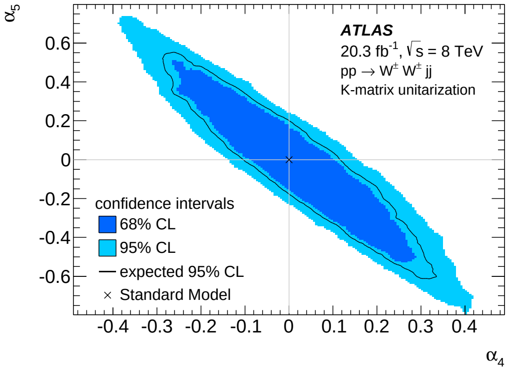
Experimental bounds on low-energy constants



[arXiv:1707.04580 [hep-ph]]

Experimental bounds on low-energy constants, NLO a_4-a_5

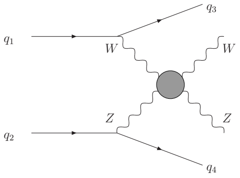


Direct constraint over a_4-a_5 from ATLAS, [PRL**113** (2014) 141803]. Note that the naive K-matrix unitarization procedure from Kilian et al [JHEP 0811, 010] is used here.

A custom model for MadGraph v5

$pp \to WZj_1j_2$

by $WZ \to WZ$ scattering



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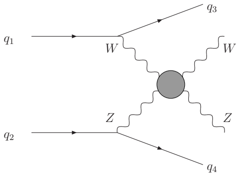

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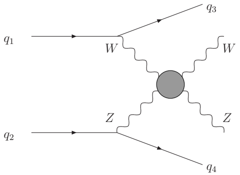

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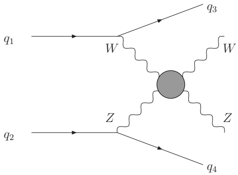

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Isovector Resonance: *WZ* in final state

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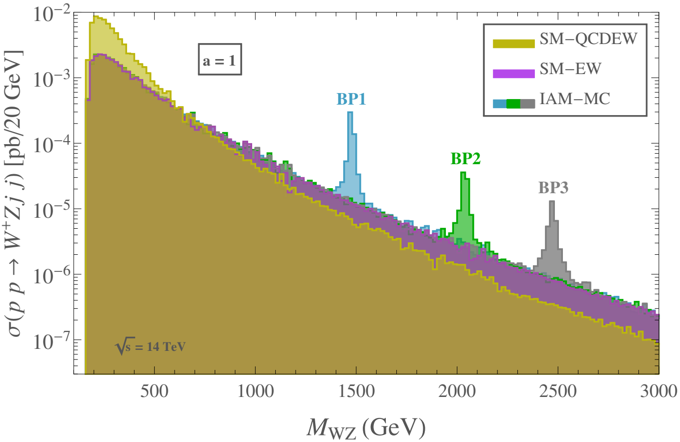

$a = 1$; $a_4 \cdot 10^4 = 3.5$ (BP1), 1 (BP2), 0.5 (BP3);

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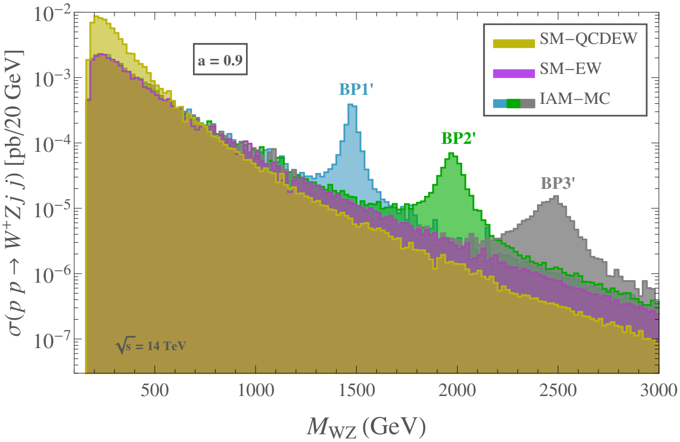

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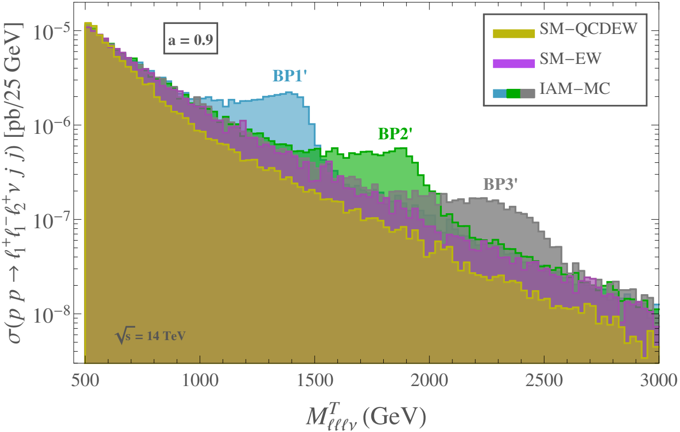

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Isovector Resonance

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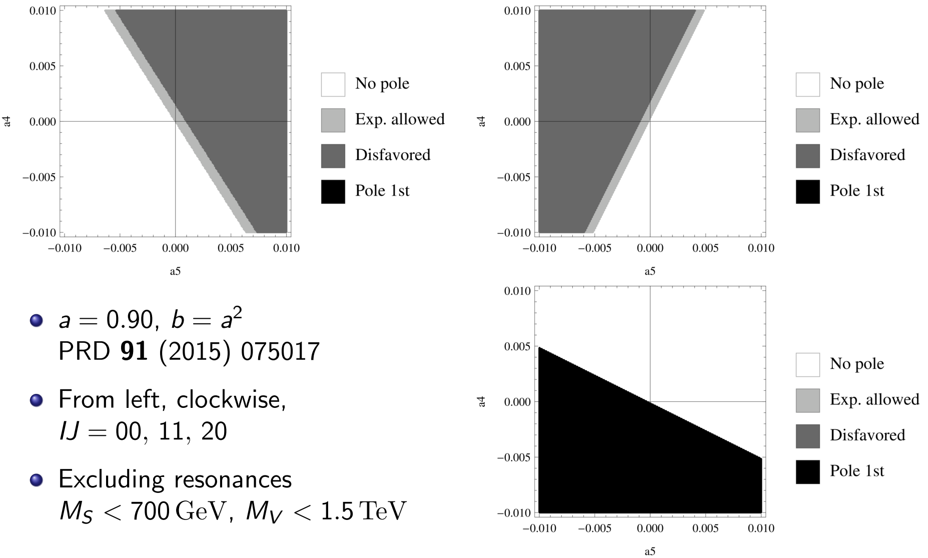
BP	M_V(GeV)	Γ_V(GeV)	$g_V(M_V^2)$	a	$a_4 \cdot 10^4$	$a_5 \cdot 10^4$
BP1	1476	14	0.033	1	3.5	-3
BP2	2039	21	0.018	1	1	-1
BP3	2472	27	0.013	1	0.5	-0.5
BP1'	1479	42	0.058	0.9	9.5	-6.5
BP2'	1980	97	0.042	0.9	5.5	-2.5
BP3'	2480	183	0.033	0.9	4	-1

These BPs have been selected for vector resonances emerging at mass and width values that are of phenomenological interest for the LHC.

Considered backgrounds: The pure SM-EW background, of order $\mathcal{O}(\alpha_{em}^2)$.

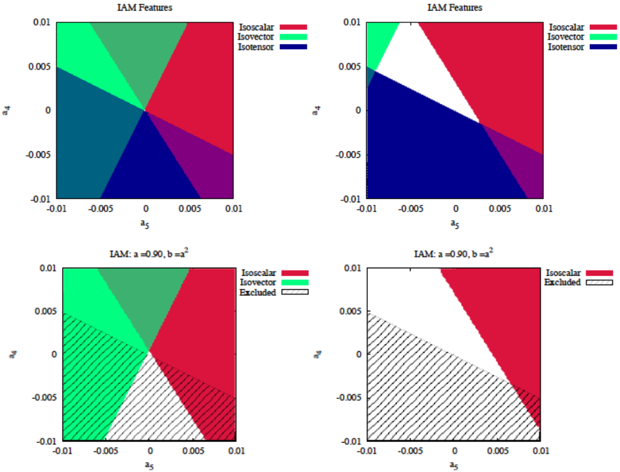
The mixed SM-QCDEW background, of order $\mathcal{O}(\alpha_{em}\alpha_s)$.



- $a = 0.90$, $b = a^2$
  PRD **91** (2015) 075017
- From left, clockwise,
  $IJ = 00, 11, 20$
- Excluding resonances
  $M_S < 700\,\mathrm{GeV}$, $M_V < 1.5\,\mathrm{TeV}$

Reson. in $W_L W_L \to W_L W_L$ due to a_4 and a_5, Barcelona

CROSS-CHECK: Espriu, Yencho, Mescia
PRD**88**, 055002
PRD**90**, 015035
At right, exclusion regions include resonances with $M_{S,V} < 600\,\mathrm{GeV}$.



Standard lore

- The gauge bosons $W^{\pm}$ and Z are massive.
- This is problematic: the massive terms are not gauge invariant. Gauge boson scattering amplitudes diverge with s at LO.
- Standard Model solution: Higgs-mechanism, which predicts the SM Higgs boson. Global symmetry breaking pattern: $SU(2)_L \times SU(2)_R \to SU(2)_C$.
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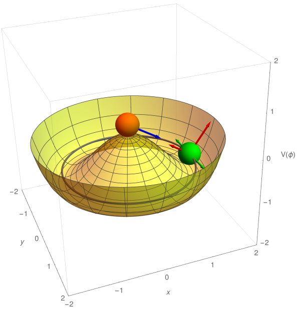

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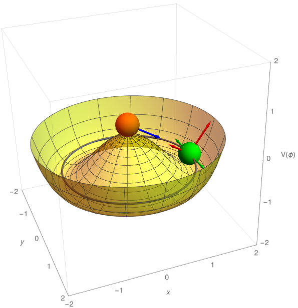

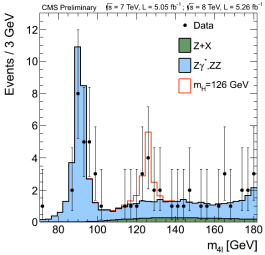

Phys. Lett. **B716**, 30-61.

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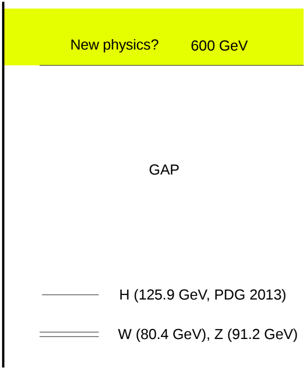
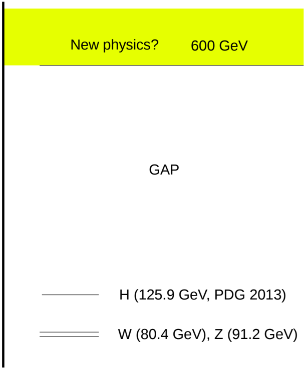


- AND: No new physics!!
  If there is any...
- The SM until the Planck mass?
- Some issues: mass of neutrinos, gravity explanation (*naturalness problem*), astrophysical observation (dark matter, dark energy),...
- Four scalar light modes, a large gap.
- Natural: further spontaneous symmetry breaking at $f > v = 246\,\mathrm{GeV}$?

Empirical situation



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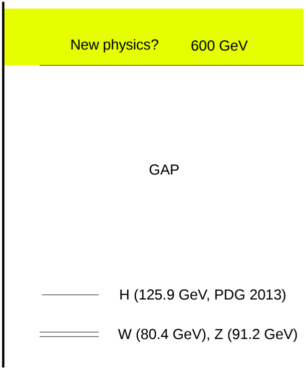

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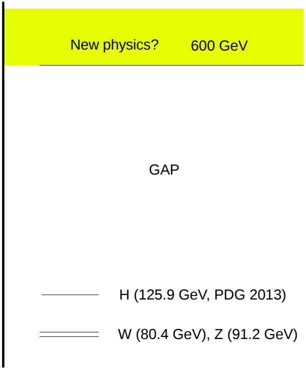

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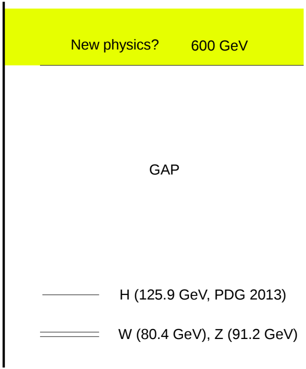

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- Current efforts to measure $\gamma\gamma \to W_L^+ W_L^-$ and $\gamma\gamma \to Z_L Z_L$ channels.
- Only 2 events measured. Graphs from CMS[5].
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[5] JHEP **07** (2013) 116

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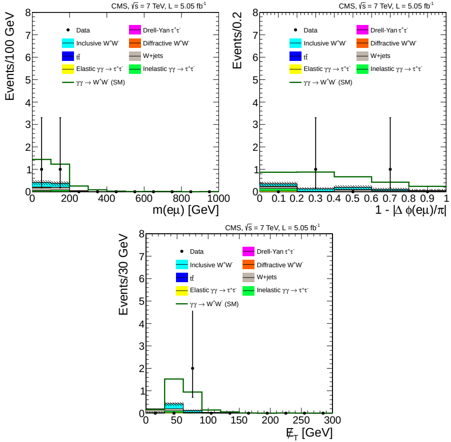

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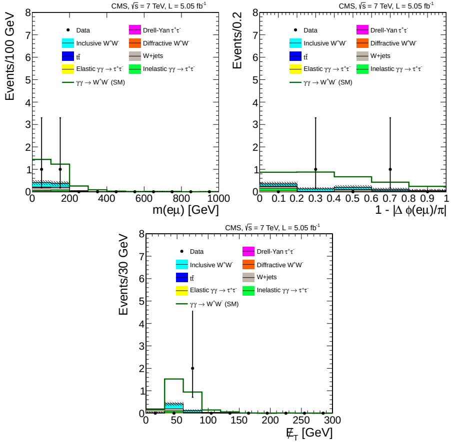

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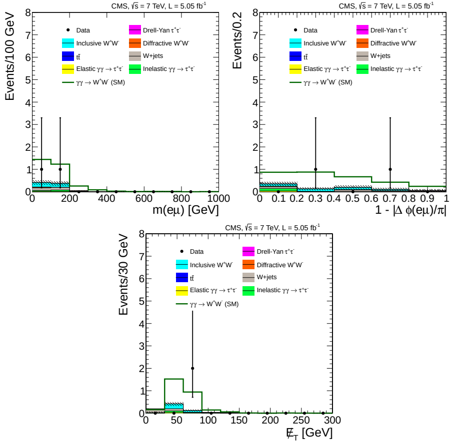

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Empirical situation: $t\bar{t}$ physics

- Initial $t\bar{t}$ states are important because of gluon fusion processes, with a large cross section at the LHC.
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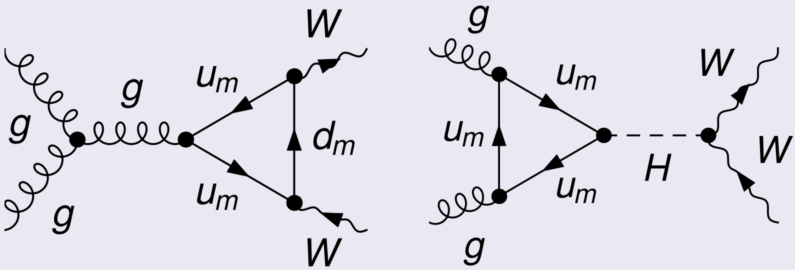
Top quark loop in the SM: VV states from gluon fusion



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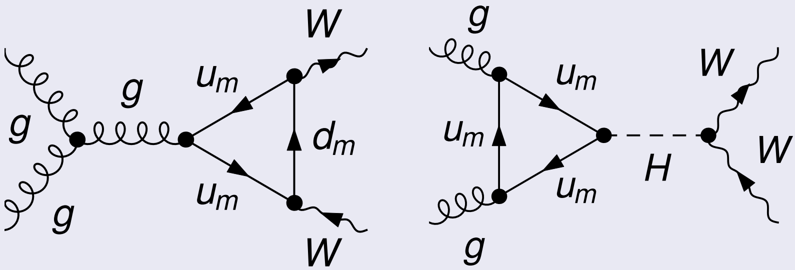

Studied framework

- We consider a strongly interacting EWSBS, in contrast to the weakly interacting one of the SM.
- We study the processes $VV \to VV$, $VV \to hh$ and $hh \to hh$, and extend the result to include $\gamma\gamma$ and $t\bar{t}$ states.
- Our LO scattering amplitudes within the EWSBS diverge, but are controlled by strongly interacting dynamics which respect unitarity. This situation is similar to low-energy QCD (hadron physics).
- In order to minimize our assumptions over the (hypothetical) underlying theory, we will
  - use dispersion relations over a partial wave decomposition (the so-called unitarization procedures);
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Strongly Interacting Effective Field Theory + Unitarity: similarity with hadronic physics

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.

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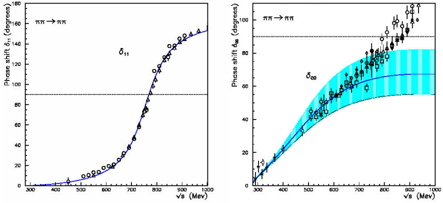

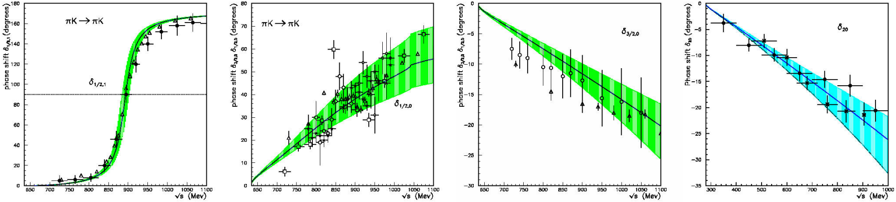

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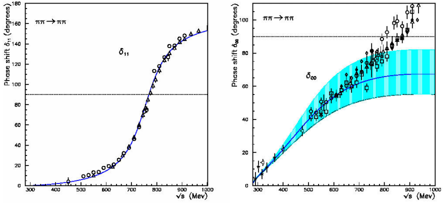

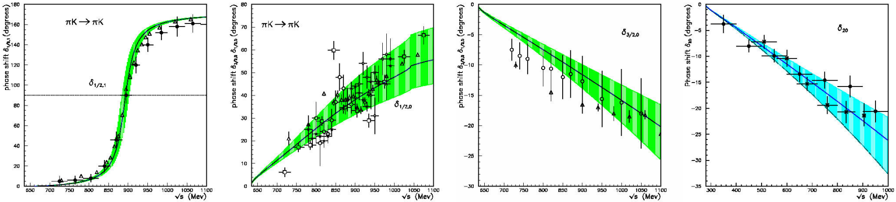

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Equivalence Theorem

- For $s \gg M_h^2, M_W^2, M_Z^2 \approx (100\,\mathrm{GeV})^2$, longitudinal modes of gauge bosons can be identified with the would-be Goldstones. For instance,

$$T(W_L^a W_L^b \to W_L^c W_L^d) = T(\omega^a \omega^b \to \omega^c \omega^d) + \mathcal{O}\left(M_W/\sqrt{s}\right)$$

- The EWSBS behaves as if the would-be Goldstone bosons were physical states. The non-gauged Lagragian can be used directly to compute scattering amplitudes.
- During the 90's, the limits of applicability of this theorem were studied in detail, leading to the conclusion that it is valid for chiral Lagrangians, like those used in this presentation:

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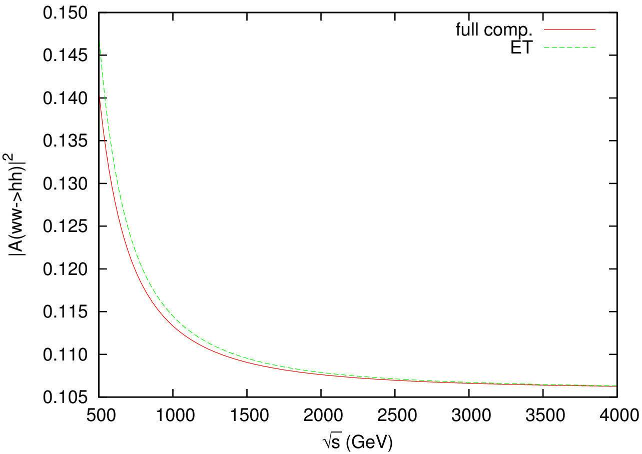

Comparison between the full LO $\omega\omega \to hh$ ($\cos\theta = 3$) and that computed through the ET. The SM is used here. Work in collaboration with S. Moretti, to test a modified version of MadGraph.

Non-linear Electroweak Chiral Lagrangian

We have no clue of what, how or if new physics...
Non-linear EFT[6] for VV scattering at NLO level, minimally coupled to hh,

$$\mathcal{L} = \frac{v^2}{4} g(h/f)\,\mathrm{Tr}[(D_\mu U)^\dagger D^\mu U] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h),$$

where

$$g(h/v) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \dots$$

$$V(h) = V_0 + \frac{M_h^2}{2}h^2 + \sum_{n=3}^{\infty} \lambda_n h^n$$

$$D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu.$$

M_h and λ_n are subleading in chiral counting.

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We need the parameterization of the $U(\omega^a) \in SU(2)_L \times SU(2)_R / SU(2)_C$ coset. In either case, whatever the non–linear term is,

$$U(x) = \mathbb{1} + i\frac{\tau^a \omega^a(x)}{v} + \mathcal{O}\left(\omega^2\right).$$

Two choices have been used:

Spherical parameterization

$$U(x) = \mathbb{1}\sqrt{1 - \frac{\omega^2(x)}{v^2}} + i\frac{\tau^a \omega^a(x)}{v}$$

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EFT for VV scattering, minimally coupled to hh

Since we are considering scattering processes within the EWSBS, the covariant derivate reduces to

$$D_\mu U = \partial_\mu U.$$

Define

$$V_\mu \equiv (D_\mu U)U^\dagger.$$

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$$\begin{aligned}\mathcal{L}_4 = {} & a_4[\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5[\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] \\ & + \frac{d}{v^2}(\partial_\mu h \partial^\mu h)\,\mathrm{Tr}[(D_\nu U)^\dagger D^\nu U] + \frac{e}{v^2}(\partial_\mu h \partial^\nu h)\,\mathrm{Tr}[(D^\mu U)^\dagger D_\nu U] \\ & + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)(\partial_\nu h \partial^\nu h).\end{aligned}$$

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Using the spherical parameterization for the $SU(2)$ coset and neglecting the couplings with photons and quarks, we have the next Lagrangian describing $VV \to VV$, $VV \to hh$ and $hh \to hh$ processes:

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

Extension to $\gamma\gamma$ states

Since coupling with photons are considered[7], the covariant derivative is defined as

$$D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu .$$

The photon field A arises from the couplings with $\hat{W}_{\mu\nu}$ and $\hat{B}_{\mu\nu}$ through a rotation to the physical basis; an anomalous three-particle coupling may appear

$$-c_W \frac{h}{v}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu} - c_B \frac{h}{v}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} = -\frac{c_\gamma}{2}\frac{h}{v}e^2 A_{\mu\nu}A^{\mu\nu}$$

The next additional NLO counterterms are needed,

$$\begin{aligned}\mathcal{L}_{4'} = {} & a_1 \operatorname{Tr}(U\hat{B}_{\mu\nu}U^\dagger \hat{W}^{\mu\nu}) \\ & + ia_2 \operatorname{Tr}(U\hat{B}_{\mu\nu}U^\dagger [V^\mu, V^\nu]) \\ & - ia_3 \operatorname{Tr}(\hat{W}_{\mu\nu}[V^\mu, V^\nu])\end{aligned}$$

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Extension to $t\bar{t}$ states

Lagrangian additions[8]:

$$\mathcal{L}' = i\bar{Q}\partial Q - v\mathcal{G}(h)\left[\bar{Q}'_L U H_Q Q'_R + h.c.\right].$$

This expression, for the heaviest quark generation, expands to[9]

$$\mathcal{L}_Y = -\mathcal{G}(h)\left\{\sqrt{1-\frac{\omega^2}{v^2}}\left(M_t t\bar{t} + M_b\bar{b}b\right) + \frac{i\omega^0}{v}\left(M_t\bar{t}\gamma^5 t - M_b\bar{b}\gamma^5 b\right)\right.$$
$$\left. + \frac{i\sqrt{2}\omega^+}{v}\left(M_b\bar{t}_L b_R - M_t\bar{t}_R b_L\right) + \frac{i\sqrt{2}\omega^-}{v}\left(M_t\bar{b}_L t_R - M_b\bar{b}_R t_L\right)\right\}$$

Two NLO counterterms needed for renormalization,

$$\mathcal{L}_{4''} = g_t\frac{M_t}{v^4}\partial_\mu\omega^a\partial^\mu\omega^b t\bar{t} + g'_t\frac{M_t}{v^4}\partial_\mu h\partial^\mu h t\bar{t}$$

[8] Work in collaboration with A.Castillo, arXiv:1607.01158 [hep-ph], accepted in EPJC.

[9] $\mathcal{G}(h) = 1 + c_1(h/v) + c_2(h/v)^2 + \ldots$, V_{tb} very close to unity

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Two NLO counterterms needed for renormalization,

$$\mathcal{L}_{4''} = g_t \frac{M_t}{v^4}\partial_\mu \omega^a \partial^\mu \omega^b t\bar{t} + g'_t \frac{M_t}{v^4}\partial_\mu h \partial^\mu h t\bar{t}$$

[8] Work in collaboration with A.Castillo, arXiv:1607.01158 [hep-ph], accepted in EPJC.
[9] $\mathcal{G}(h) = 1 + c_1(h/v) + c_2(h/v)^2 + \ldots$, V_{tb} very close to unity

Extension to $t\bar{t}$ states

Lagrangian additions[8]:

$$\mathcal{L}' = i\bar{Q}\partial Q - v\mathcal{G}(h)\left[\bar{Q}'_L U H_Q Q'_R + h.c.\right].$$

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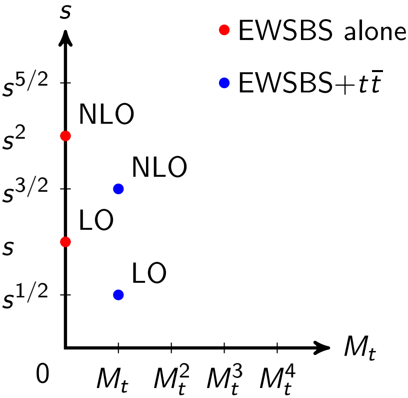

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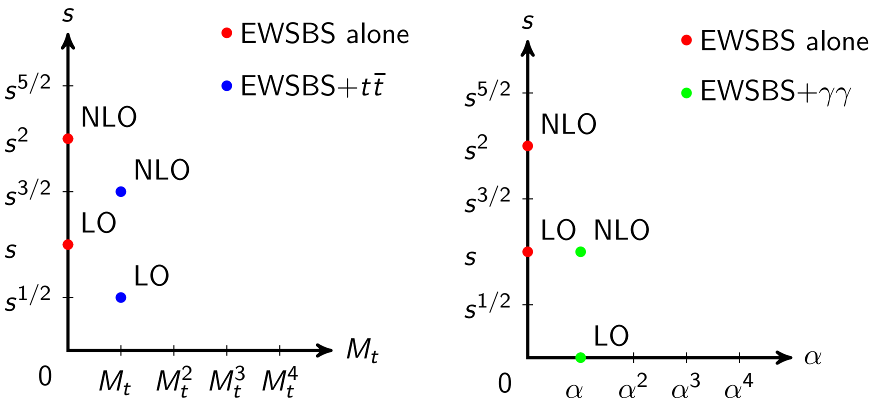
[10] G.Buchalla and O.Catà, JHEP**07** (2012) 101; G.Buchalla, O.Catà and C.Krause, Phys.Lett.**B731** (2014) 80; S.Weinberg, Physica **A96** (1979) 327



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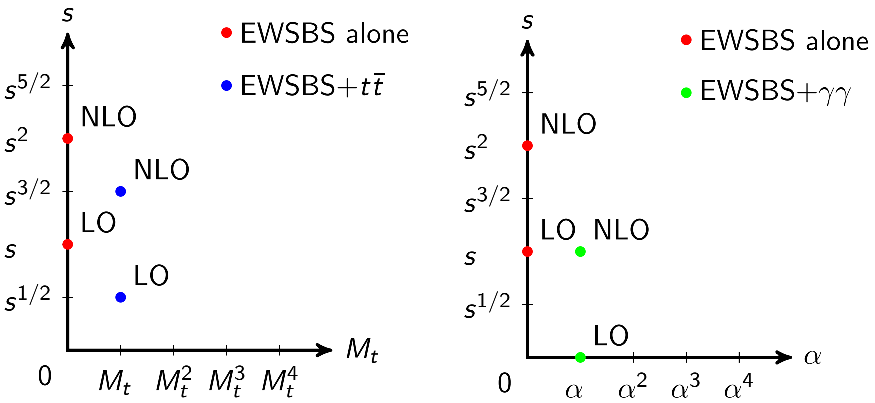

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Higgsless ECL, now experimentally discarded.
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$a^2 = 1 - v^2/f^2$, $b = 1 - 2v^2/f^2$

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K.Agashe, R.Contino and A.Pomarol, Nucl.Phys.B**719**, 165
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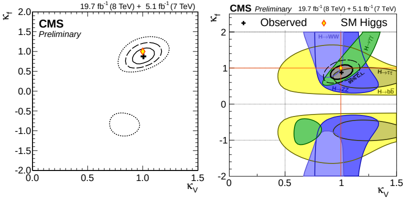

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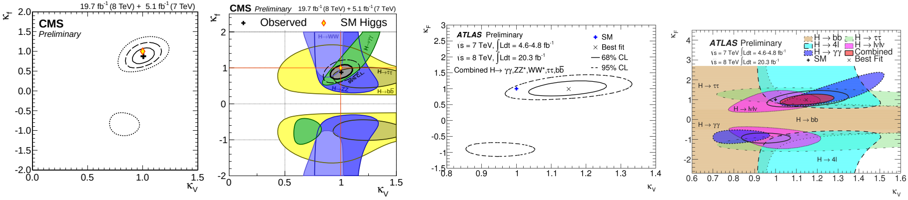

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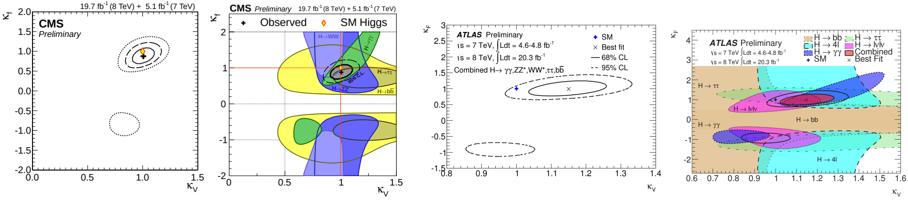

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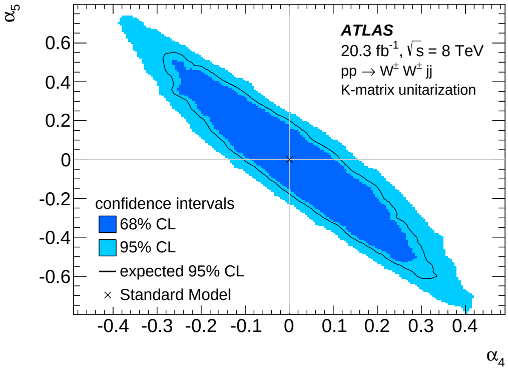
Experimental bounds on low-energy constants, NLO a_4-a_5



Direct constraint over a_4-a_5 from ATLAS Collaboration[15]

[15] Taken from ref. [PRL**113** (2014) 141803]. Note that CMS [PRL**114** (2015) 051801] gives a constraint in terms of F_{S0}/Λ^4 and F_{S1}/Λ^4 parameters, which have no direct translation to the a_4 and a_5 ones [arXiv:1310.6708, [hep-ph]].

Partial wave decomposition

EWSBS alone (+eventually $t\bar{t}$)

$$A_{IJ}(s) = \frac{1}{32\pi K}\int_{-1}^{1} dx\, P_J(x) A_I[s, t(s,x), u(s,x)]$$

Matrix element from partial wave decomposition

$$A_I(s,t,u) = 16\pi K \sum_{J=0}^{\infty} (2J+1) P_J[x(s,t)] A_{IJ}(s)$$

Helicity partial waves for EWSBS+$\gamma\gamma$

$$F_{IJ}^{\lambda_1\lambda_2}(s) = \frac{1}{64\pi^2 K}\sqrt{\frac{4\pi}{2J+1}}\int d\Omega\, A_I^{\lambda_1\lambda_2}(s,\Omega) Y_{J,\lambda_1-\lambda_2}(\Omega)$$

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EWSBS partial waves

The form of the partial wave is

$$A_{IJ}(s) = A_{IJ}^{(0)} + A_{IJ}^{(1)} + \mathcal{O}\left[(s/v^2)^3\right].$$

Which will be decomposed as

$$A_{IJ}^{(0)} = Ks$$

$$A_{IJ}^{(1)} = \left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right)s^2.$$

As $A_{IJ}(s)$ must be scale independent,

$$B(\mu) = B(\mu_0) + (D+E)\log\frac{\mu^2}{\mu_0^2}$$

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Partial wave decomposition: $\gamma\gamma$ states

The form of the partial wave is

$$P_{IJ,\Lambda}(s) = P^{(0)}_{IJ,\Lambda} + \mathcal{O}(\alpha_{\rm em}^2) + \mathcal{O}(\alpha_{\rm em} s^2).$$

Note that $\gamma\gamma$ with $J = 2$, $\Lambda = \pm 2$ also couples with the EWSBS, following

$$P^{(0)}_{I0,0} \propto \alpha s \qquad P^{(0)}_{I2,\pm 2} \propto \alpha$$

- Based on a collaboration with profs. M.J.Herrero and J.J.Sanz-Cillero: JHEP**1407** (2014) 149.
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Unitarity for partial waves

- Unit. cond. for $S - matrix$: $SS^\dagger = \mathbb{1}$,
- plus analytical properties of matrix elements,
- plus time reversal invariance,

Unitarity condition for partial waves

$$\mathrm{Im}\, A_{IJ,p_i\to k_1}(s) = \sum_{\{a,b\}} \sqrt{1-\frac{4m_q^2}{s}}[A_{IJ,p_i\to q_{i,ab}}(s)][A_{IJ,q_{i,ab}\to k_i}(s)]^*$$

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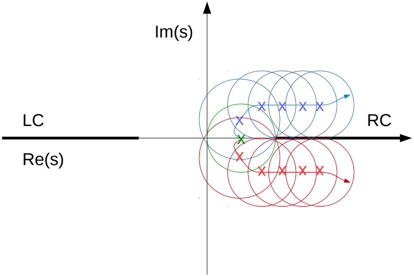

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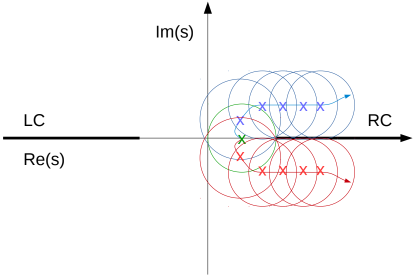

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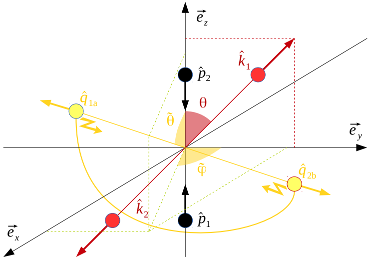

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Unitarization procedures for elastic processes

$$A^{IAM}(s) = \frac{[A^{(0)}(s)]^2}{A^{(0)}(s) - A^{(1)}(s)},$$

$$A^{N/D}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + \frac{1}{2} g(s) A_L(-s)},$$

$$A^{IK}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + g(s) A_L(s)},$$

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

where

$$g(s) = \frac{1}{\pi}\left(\frac{B(\mu)}{D+E} + \log\frac{-s}{\mu^2}\right)$$

$$A_L(s) = \pi g(-s) D s^2$$

$$A_R(s) = \pi g(s) E s^2$$

PRD **91** (2015) 075017

Unitarization procedures for elastic processes

$$A^{IAM}(s) = \frac{[A^{(0)}(s)]^2}{A^{(0)}(s) - A^{(1)}(s)},$$

$$A^{N/D}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + \frac{1}{2}g(s)A_L(-s)},$$

$$A^{IK}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + g(s)A_L(s)},$$

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

where

$$g(s) = \frac{1}{\pi}\left(\frac{B(\mu)}{D+E} + \log\frac{-s}{\mu^2}\right)$$

$$A_L(s) = \pi g(-s) D s^2$$

$$A_R(s) = \pi g(s) E s^2$$

PRD **91** (2015) 075017

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PRD **91** (2015) 075017

Matricial versions of the methods

$$F^{IAM}(s) = \left[F^{(0)}(s)\right]^{-1} \cdot \left[F^{(0)}(s) - F^{(1)}(s)\right] \cdot \left[F^{(0)}(s)\right]^{-1},$$

$$F^{N/D}(s) = \left[1 - F_R(s) \cdot \left(F^{(0)}(s)\right)^{-1} + \frac{1}{2}G(s)F_L(-s)\right]^{-1} \cdot N_0(s),$$

$$F^{IK}(s) = [1 + G(s) \cdot N_0(s)]^{-1} \cdot N_0(s),$$

where $G(s)$, $F_L(s)$, $F_R(s)$ and $N_0(s)$ are defined as

$$G(s) = \frac{1}{\pi}\left(B(\mu)(D+E)^{-1} + \log\frac{-s}{\mu^2}\right)$$

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PRD **91** (2015) 075017

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PRD **91** (2015) 075017

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PRD **91** (2015) 075017

Extension to $\gamma\gamma$ and $t\bar{t}$ scattering

Basic assumption

- EWSBS is strongly interacting. $\gamma\gamma$ and $t\bar{t}$ are perturbative.
- Coupling with photons, controlled by $\alpha = e^2/4\pi \ll s/v^2$.
- Coupling with top quarks, controlled by $M_t\sqrt{s}/v^2 \ll s/v^2$.

Perturbative unitarization: $\omega\omega \to \{\gamma\gamma, t\bar{t}\}$

$$\tilde{P} = \frac{\tilde{A}_{IJ}}{A_{IJ}^{(0)}} P^{(0)}$$

Perturbative unitarization: $\{\omega\omega, hh\} \to \{\gamma\gamma, t\bar{t}\}$

$$\begin{pmatrix} \tilde{P} \\ \tilde{R} \end{pmatrix} = \tilde{F} \left(F^{(0)}\right)^{-1} \begin{pmatrix} P^{(0)} \\ R^{(0)} \end{pmatrix}$$

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Usability channel of unitarization procedures

IJ	00	02	11	20	22
Method of choice	Any	N/D IK	IAM	Any	N/D IK

- The IAM method cannot be used when $A^{(0)} = 0$, because it would give a vanishing value.
- The N/D and the IK methods cannot be used if $D + E = 0$, because in this case computing $A_L(s)$ and $A_R(s)$ is not possible.
- The naive K-matrix method,

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

fails because it is not analytical in the first Riemann sheet and, consequently, it is not a proper partial wave compatible with microcausality.

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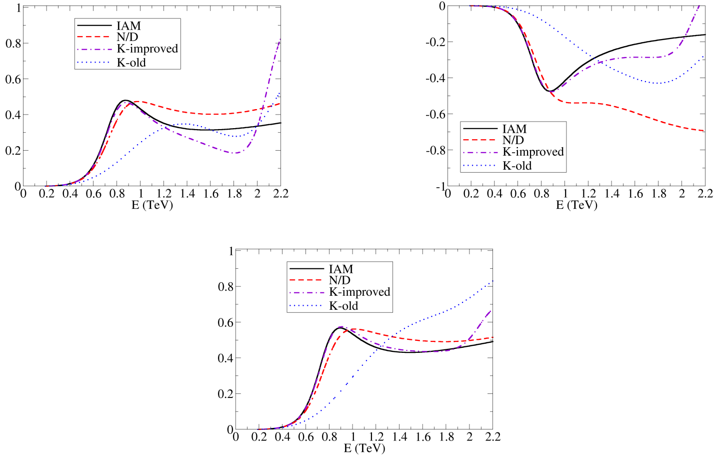
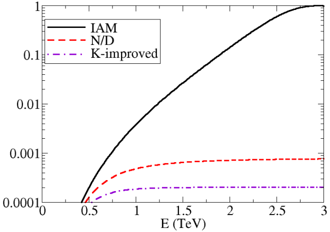
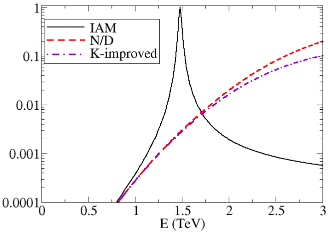
Scalar-isoscalar channels



From left to right and top to bottom, elastic $\omega\omega$, elastic hh, and cross channel $\omega\omega \to hh$, for $a = 0.88$, $b = 3$, $\mu = 3\,\mathrm{TeV}$ and all NLO parameters set to 0. PRL **114** (2015) 221803, PRD **91** (2015) 075017.

Vector-isovector channels

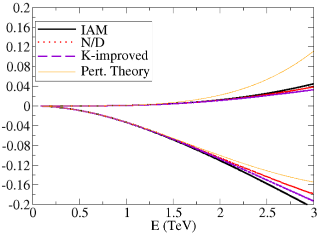


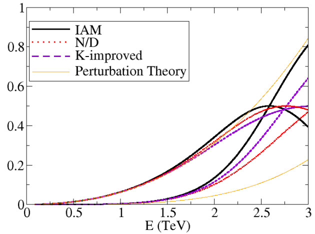


From our ref[16]. We have taken $a = 0.88$ and $b = 1.5$, but while for the left plot all the NLO parameters vanish, for the right plot we have taken $a_4 = 0.003$, known to yield an IAM resonance according to the Barcelona group[17].

[16] PRD **91** (2015) 075017
[17] PRD **90** (2014) 015035

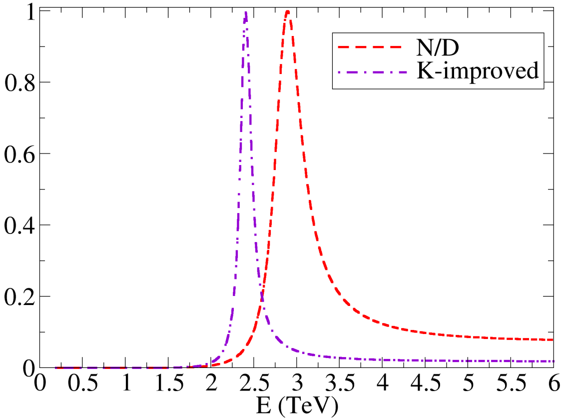
Scalar-isotensor channels ($IJ = 20$)





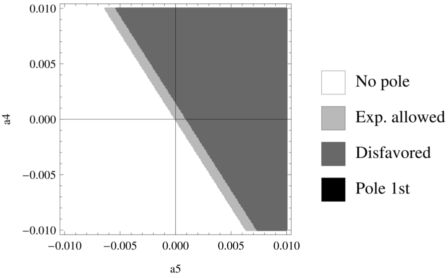
From our ref[18]. From left to right, $a = 0.88$, $a = 1.15$. We have taken $b = a^2$ and the NLO parameters set to zero. Both real and imaginary part shown. Real ones correspond to bottom lines at left and upper at low E at right.

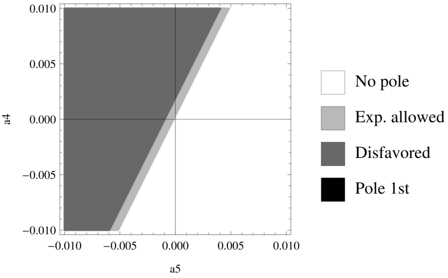
[18] PRD **91** (2015) 075017



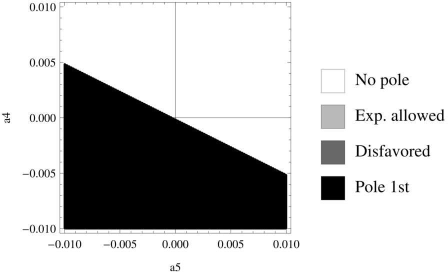
$a = 0.88$, $b = a^2$, $a_4 = -2a_5 = 3/(192\pi)$, all the other NLO param. set to zero.
PRD **91** (2015) 075017.

Reson. in $W_L W_L \to W_L W_L$ due to a_4 and a_5, ours



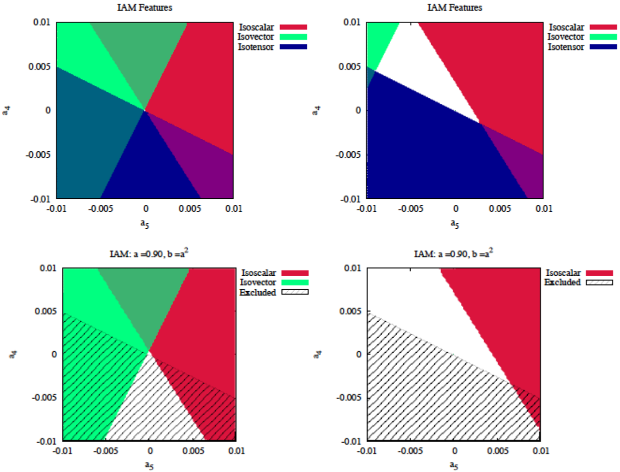


- $a = 0.90$, $b = a^2$
  PRD **91** (2015) 075017
- From left, clockwise,
  $IJ = 00, 11, 20$
- Excluding resonances
  $M_S < 700\,\mathrm{GeV}$, $M_V < 1.5\,\mathrm{TeV}$



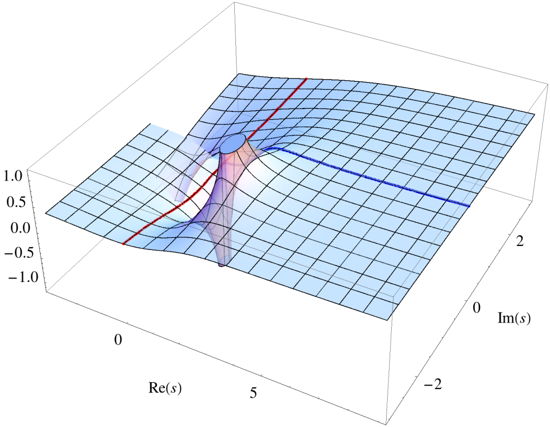
Reson. in $W_L W_L \to W_L W_L$ due to a_4 and a_5, Barcelona

CROSS-CHECK: Espriu, Yencho, Mescia
PRD**88**, 055002
PRD**90**, 015035
At right, exclusion regions include resonances with $M_{S,V} < 600\,\mathrm{GeV}$.



Resonance from $W_L W_L \to hh$

$a = 1$, $b = 2$, IAM,
elastic chann. $W_L W_L \to W_L W_L$,
red figure from 3D-printer



Rafael L. Delgado,
Antonio Dobado,
Felipe J. Llanes-Estrada,
Possible New Resonance from W_L W_L-hh Interchannel Coupling,

PRL **114** (2015) 221803

Resonance from $W_L W_L \to hh$

$a = 1,\ b = 2$, IAM,
inelastic chann. $W_L W_L \to hh$,
yellow figure from 3D-printer

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Antonio Dobado,
Felipe J. Llanes-Estrada,
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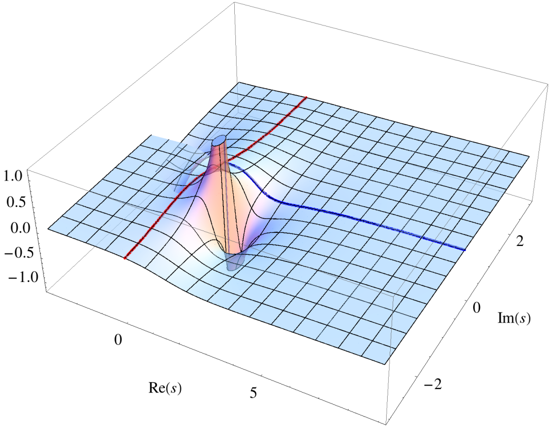
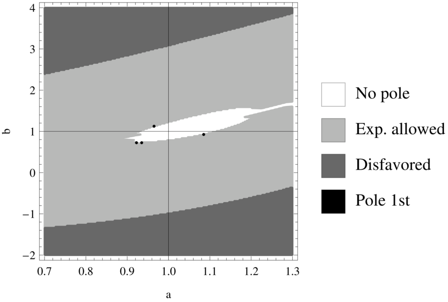
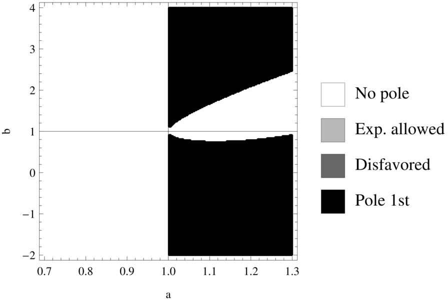
PRL **114** (2015) 221803

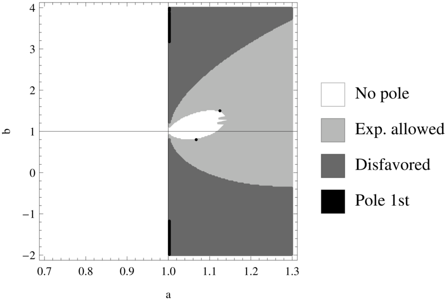


Resonances in $W_L W_L \to W_L W_L$ due to a and b parameters





- PRL & PRD **91** (2015) 075017
- From left, clockwise, $IJ = 00,\ 11,\ 20$
- Excluding resonances $M_S < 700\,\mathrm{GeV}$, $M_V < 1.5\,\mathrm{TeV}$
- Constraint over b even without data about $W_L W_L \to hh$ and $hh \to hh$ scattering processes.

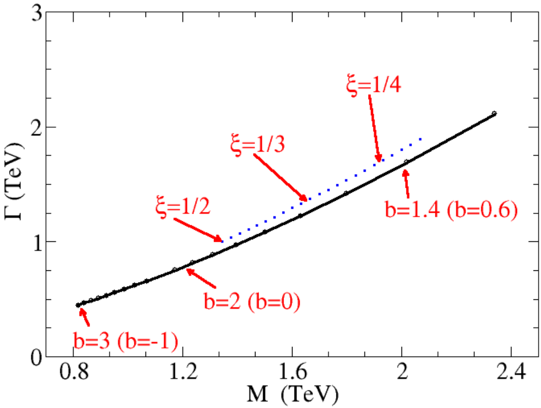


Motion of the resonance mass and width

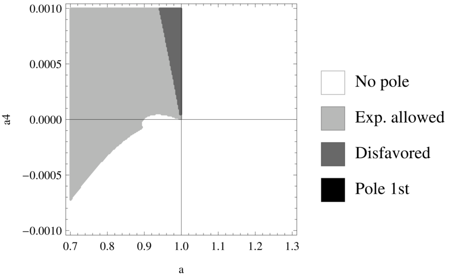
Dependence on b with $a^2 = 1$ fixed (upper curve) and for $a = 1 - \xi$ and $b = 1 - 2\xi$ with $\xi = v/f$ as in the MCHM (lower blue curve).

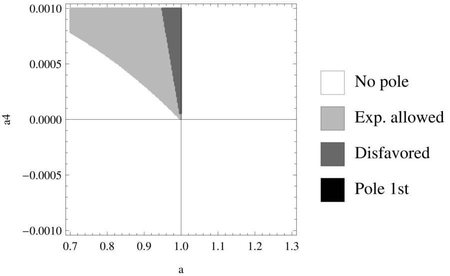
PRL **114** (2015) 221803

Video, (a,b) param. space



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





- $b = a^2$
  PRD **91** (2015) 075017
- From left, clockwise,
  $IJ = 00,\ 11,\ 20$
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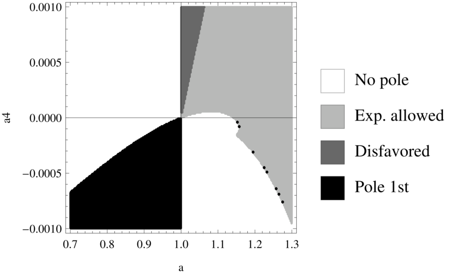
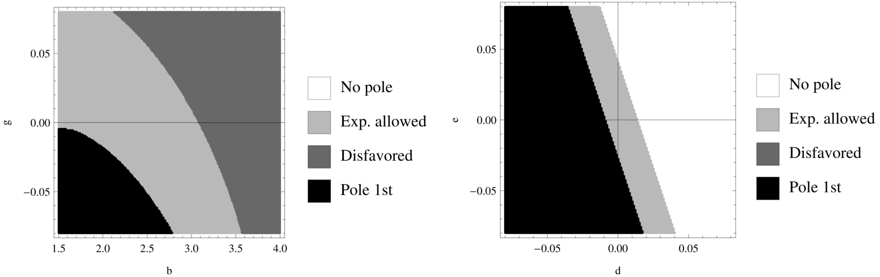
  $M_S < 700\,\mathrm{GeV},\ M_V < 1.5\,\mathrm{TeV}$



Resonances in $W_L W_L \to W_L W_L$ due to b, g, d and e parameters



Effective Theory, PRD **91** (2015) 075017, isoscalar channels ($I = J = 0$).

I) IAM method

This method needs a NLO computation,

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

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

Check at tree level

We have checked[19], 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

[19] See J.Phys. G41 (2014) 025002.

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

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\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) \\
&\quad +\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+..
\end{aligned}
$$

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

[19] See J.Phys. G41 (2014) 025002.

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 $\tilde{t}_\omega$,

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

for $\beta = \alpha^2$ (elastic case),

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III)Large N

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

$$\begin{aligned} A_N &= A - A\frac{NI}{2}A + A\frac{NI}{2}A\frac{NI}{2}A - \dots \\ I(s) &= \int \frac{d^4q}{(2\pi)^4}\frac{i}{q^2(q+p)^2} = \frac{1}{16\pi^2}\log\left[\frac{-s}{\Lambda^2}\right] = -\frac{1}{8\pi}J(s) \end{aligned}$$

Note: actually, $N=3$. For the (iso)scalar partial wave (chiral limit, $I=J=0$),

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IV) N/D

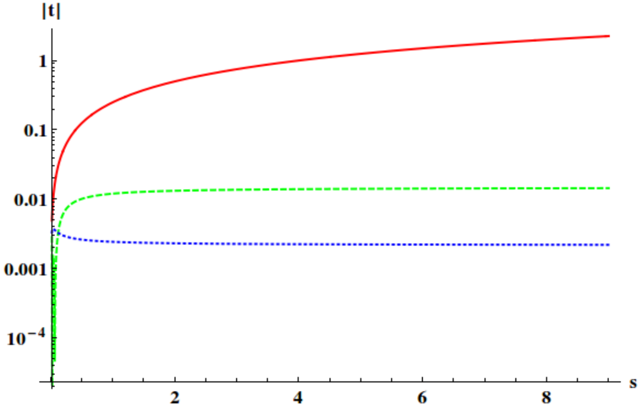
(elastic scattering at tree level only $\beta = \alpha^2$. See ref. J.Phys. G41 (2014) 025002). Ansatz

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

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

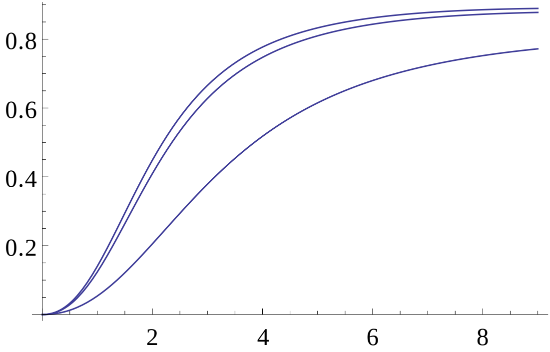
$$\begin{aligned} D(s) &= 1 - \frac{s}{\pi} \int_0^{\infty} \frac{ds' N(s')}{s'(s' - s - i\epsilon)} \\ N(s) &= \frac{s}{\pi} \int_{-\infty}^{0} \frac{ds' \,\mathrm{Im}\, N(s')}{s'(s' - s - i\epsilon)} \end{aligned}$$

Coupled channels, tree level amplitudes



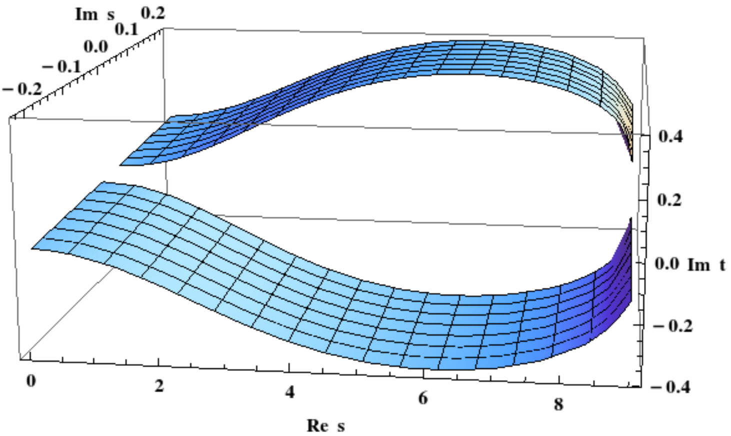
$f = 2v$, $\beta = \alpha^2 = 1$, $\lambda_3 = M_\varphi^2/f$, $\lambda_4 = M_\varphi^2/f^2$. OX axis: s in TeV^2.

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

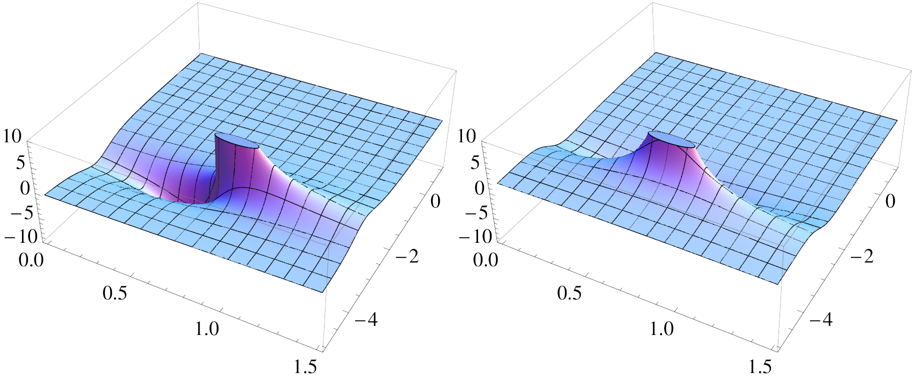


- All units in TeV.
- From top to bottom, $f = 1.2,\ 0.8,\ 0.4\,\mathrm{TeV}$
- $\Lambda = 3\,\mathrm{TeV}$
- $\mu = 100\,\mathrm{GeV}$

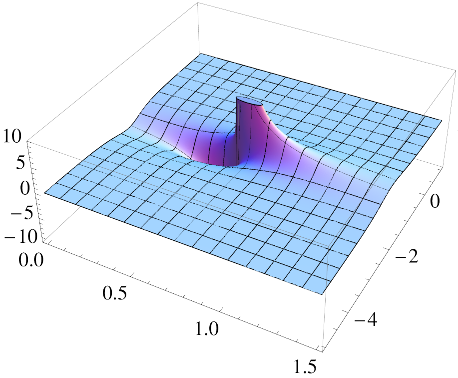
$\mathrm{Im}\, t_\omega$ in the N/D method, $f = 1\,\mathrm{TeV}$, $\beta = 1$, $m = 150\,\mathrm{GeV}$

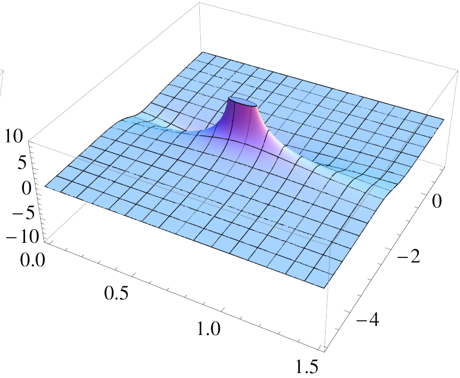


$\mathrm{Re}\, t_\omega$ and $\mathrm{Im}\, t_\omega$, large N, $f = 400\,\mathrm{GeV}$

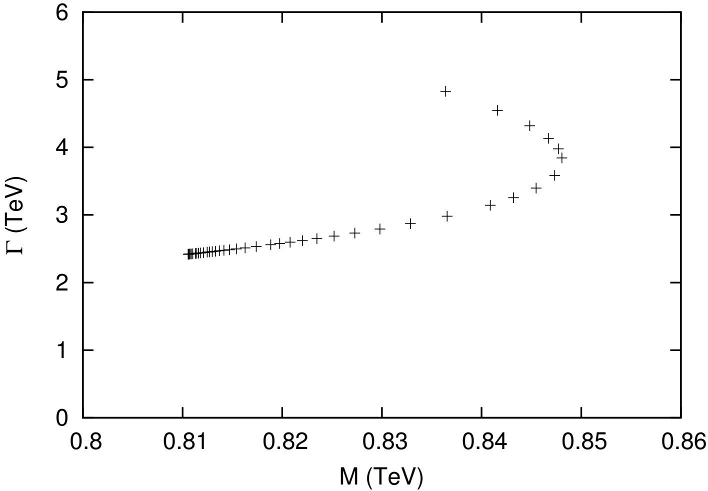


Re t_ω and Im t_ω, large N, $f = 4\,\mathrm{TeV}$

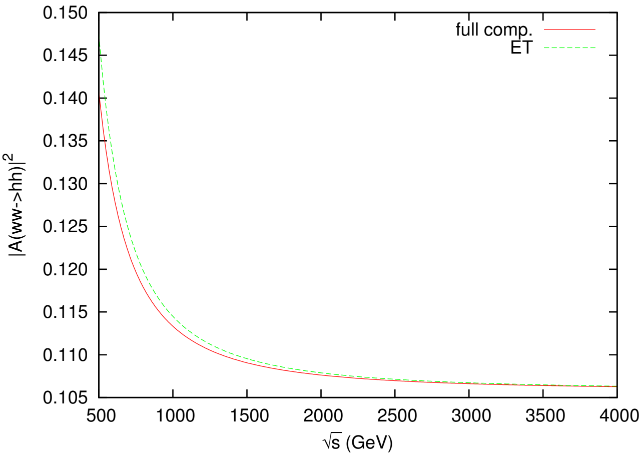




Tree level, motion of the pole position of t_ω K–matrix, $M_\phi = 125\,\mathrm{GeV}$, $f \in (250\,\mathrm{GeV}, 6\,\mathrm{TeV})$)



Equivalence Theorem



Comparison between the full LO $\omega\omega \to hh$ $(\cos\theta = 3)$ and that computed through the ET. The SM is used here. Work in collaboration with S. Moretti, to test a modified version of MadGraph.

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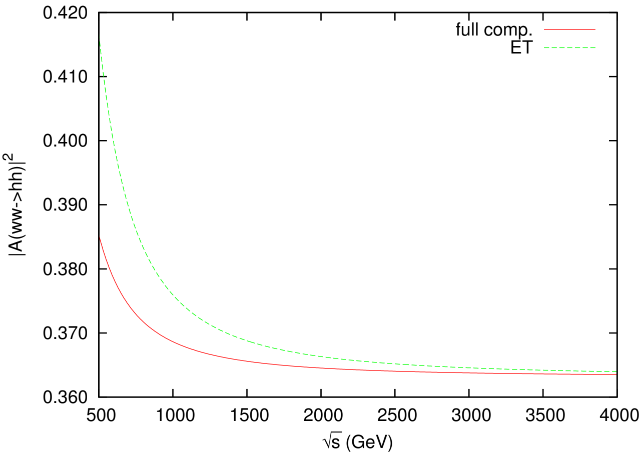

Comparison between the full LO $\omega\omega \to hh$ ($\cos\theta = 6$) and that computed through the ET. The SM is used here. Work in collaboration with S. Moretti, to test a modified version of MadGraph.