Loop effects on Higgs and Vector Boson production in HEFT

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Higgs and Effective Field Theory
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Although the Standard Model (SM) is remarkably sucessful, new physics must be included to explain new phenomena.

Additionally, some couplings of the SM have not been measured with high accuracy. In HEFT language ($a = \kappa_V$ and $b = \kappa_{2V}$):

$$a - hWW, hZZ \text{ coupling}$$
$$a \in [0.9,\ 1.1] \text{ roughly}$$

$$b - hhWW, hhZZ \text{ coupling}$$
$$b \in [-0.1, 2.2] \quad \text{CMS} - hh \to b\bar{b}b\bar{b}$$ [A. Tumasyan et al. (CMS Collaboration),22]
$$b \in [-0.03, 2.11] \quad \text{ATLAS} - hh \to b\bar{b}b\bar{b}$$ [G. Aad et al. (ATLAS Collaboration),22]

2. HEFT and SMEFT

[Brivio,Trott,2017]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \mathcal{L}^{(8)} \ldots,$$

$$\mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4$$

Each term $\mathcal{L}^{(d)}$ is written in the unbroken phase (before EW symmetry breaking) in terms of the complex doublet Φ

[Feruglio,1992]

$$\mathcal{L}_{HEFT} = \mathcal{L}_2 + \mathcal{L}_{(4)} + \mathcal{L}_{(6)} + \ldots, \quad \text{expansion in chiral dimensions}$$

Each term $\mathcal{L}_{(d)}$ of HEFT is written in the broken phase (after EW symmetry breaking) in terms of the Higgs and Goldstone fields

Chiral counting

$$\partial_\mu,\ M_W,\ M_Z,\ M_h \sim \mathcal{O}(p)$$
$$D_\mu U,\ V_\mu,\ g' v \mathcal{T},\ \hat{W}_\mu,\ \hat{B}_\mu \sim \mathcal{O}(p)$$
$$\hat{W}_{\mu\nu},\ \hat{B}_{\mu\nu} \sim \mathcal{O}(p^2)$$

2. HEFT

The lagrangian at lowest order (chiral dimension 2)

Equivalence Theorem

$$\mathscr{L}_2 = \frac{v^2}{4}\mathscr{F}(h)\,\mathrm{Tr}\left[(D_\mu U)^\dagger D^\mu U\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + i\bar{Q}\partial Q - v\mathscr{G}(h)\left[\bar{Q}'_L U H_Q Q'_R + \text{h.c.}\right]$$

ω^a (GB) + h
+ Yukawa sector

[Castillo,Delgado Dobado,Llanes-Estrada,2016]

Spherical parametrization for the GB

$$U = \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\bar{\omega}}{v} \qquad \bar{\omega} = \tau^a \omega^a \qquad Q^{(\prime)} = \begin{pmatrix} \mathscr{U}^{(\prime)} \\ \mathscr{D}^{(\prime)} \end{pmatrix}$$

$$\mathcal{U}' = (u, c, t)' \qquad \mathcal{D}' = (d, s, b)'$$

Quarks

Analytic functions of powers of the Higgs field. Inspired by most of low energy HEFT models.

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots \qquad \mathcal{G}(h) = 1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \ldots$$

$$V(h) = \frac{1}{2}M_h^2 h^2 + d_3\frac{M_h^2}{2v}h^3 + d_4\frac{M_h^2}{8v^2}h^4 + \ldots$$

Modifications on the Higgs SM couplings and beyond

Recover the SM

$a = b = 1$
$d_3 = d_4 = 1$
$c_1 = 1$
rest $\kappa_{HEFT} = 0$

2. HEFT

$$\mathcal{L}_4 = a_4[\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5[\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)^2$$

$$+\frac{d}{v^2}(\partial_\mu h \partial^\mu h)\mathrm{Tr}[(D_\nu U)^\dagger D^\nu U] + \frac{e}{v^2}(\partial_\mu h \partial^\nu h)\mathrm{Tr}[(D^\mu U)^\dagger D_\nu U] +$$

$$a_1 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}) + i a_2 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]) - i a_3 \mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu, V^\nu])$$

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

NLO in HEFT $\subset$ Tree level $\mathcal{O}(p^4)$ + one-loop level formed by $\mathcal{O}(p^2)$ vertices

$$\mathcal{A}(W_L^a W_L^b \to W_L^c W_L^d) = \mathcal{A}(\omega^a \omega^b \to \omega^c \omega^d) + \mathcal{O}(\frac{M_W}{\sqrt{s}})$$

Equivalence Theorem

GB and Higgs production at tree-level in the Equivalence Theorem

$$A(s,t,u) = \frac{1-a^2}{v^2}s \qquad \omega^a\omega^b \to \omega^c\omega^d$$

$$M(s,t,u) = \frac{a^2-b}{v^2}s \qquad \omega^a\omega^b \to hh$$

$$T(s,t,u) = 0 \qquad hh \to hh$$

[Delgado,Dobado,Llanes, 1710.07548]

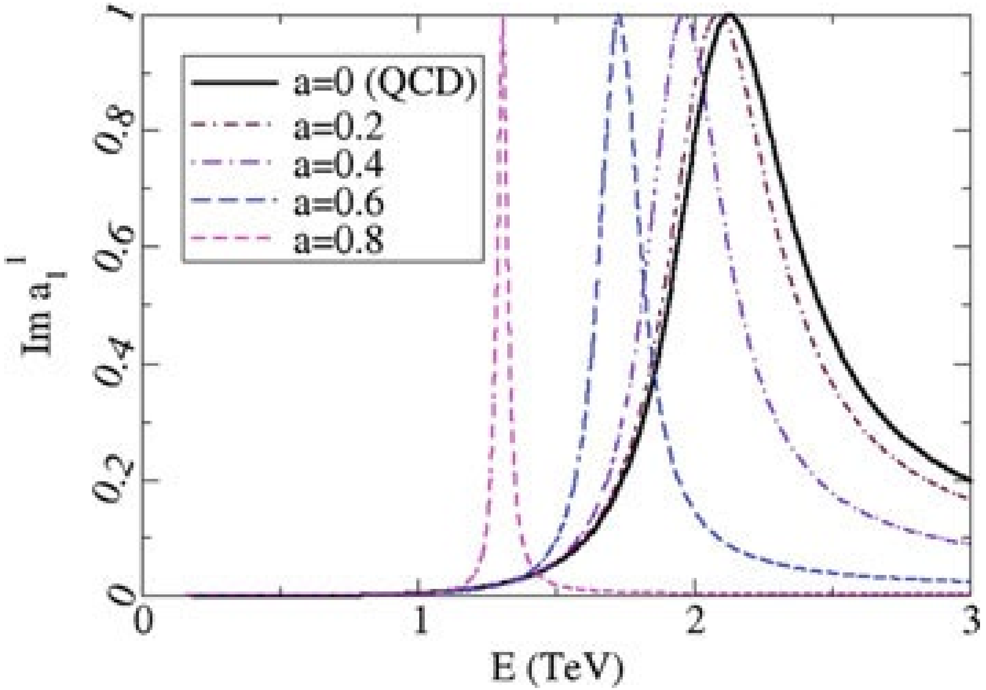
In the SM, $a = b = 1$, these amplitudes are zero but in general they break unitarity.

Amplitudes can be unitarized according to different methods

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

$\omega^a \omega^b \to \omega^a \omega^b$

[Delgado,Dobado,Llanes, 1710.07548]



QCD-like ρ resonance for I=J=1 for $a^2 = b$ and $a_4 = -2a_4/192\pi^2$

3. Loop effects for Vector Boson Scattering

We want to consider all relevant loops for Vector Boson Scattering.

Many studies in HEFT use GB to calculate Vector Boson Scattering at LO and the effect of boson loops at NLO.

[Delgado, Dobado, Herrero, Sanz-Cillero,2014]
[Delgado, Dobado, Llanes-Estrada,2013]
[Castillo, Delgado, Dobado, Llanes-Estrada,2016]
[Espriu, Yencho, 2014]
[Espriu, Mescia,2014]
[García-García, Herrero, Morales,2019]
[Asiáin, Espriu, Mescia,2021]

[Castillo, Delgado, Dobado, Llanes-Estrada,2016]

Some works study processes involving top quarks at LO but not at NLO in HEFT.

$$\mathcal{O}(M_{Fer}^2 s/v^4) \quad vs. \quad \mathcal{O}(s^2/v^4)$$

We have studied the effect of both boson loops and top quark loops for all combinations of $\omega^a\omega^b \to \omega^c\omega^d$ and $\omega^a\omega^b \to hh$

$$\mathcal{A}^{\text{VBS}} = \mathcal{A}_2^{\text{tree}} + \mathcal{A}_4^{\text{boson loops}} + \mathcal{A}_4^{\text{fermion loops}}$$

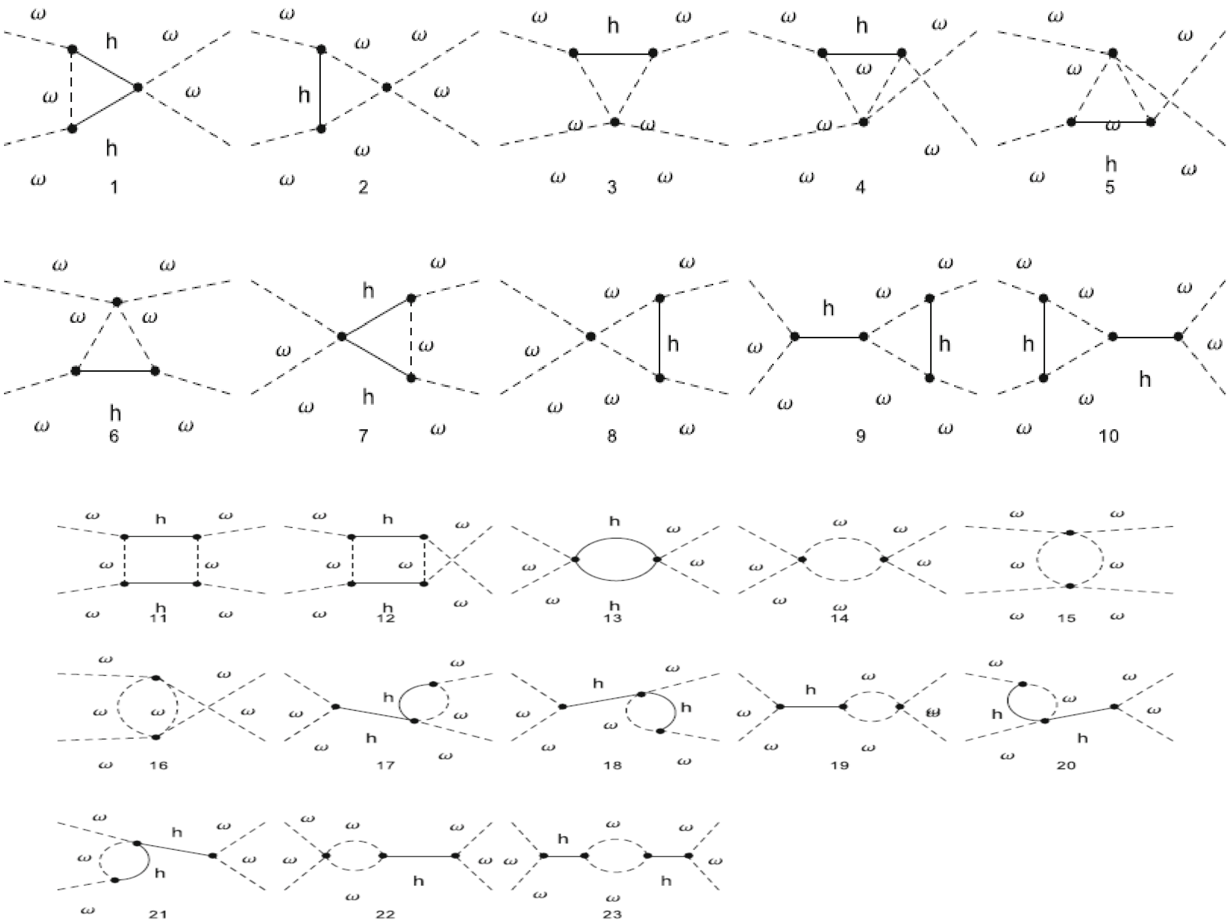
$$A(s,t,u) = \frac{1-a^2}{v^2}s \qquad \omega^a\omega^b \to \omega^c\omega^d$$

$$M(s,t,u) = \frac{a^2-b}{v^2}s \qquad \omega^a\omega^b \to hh$$

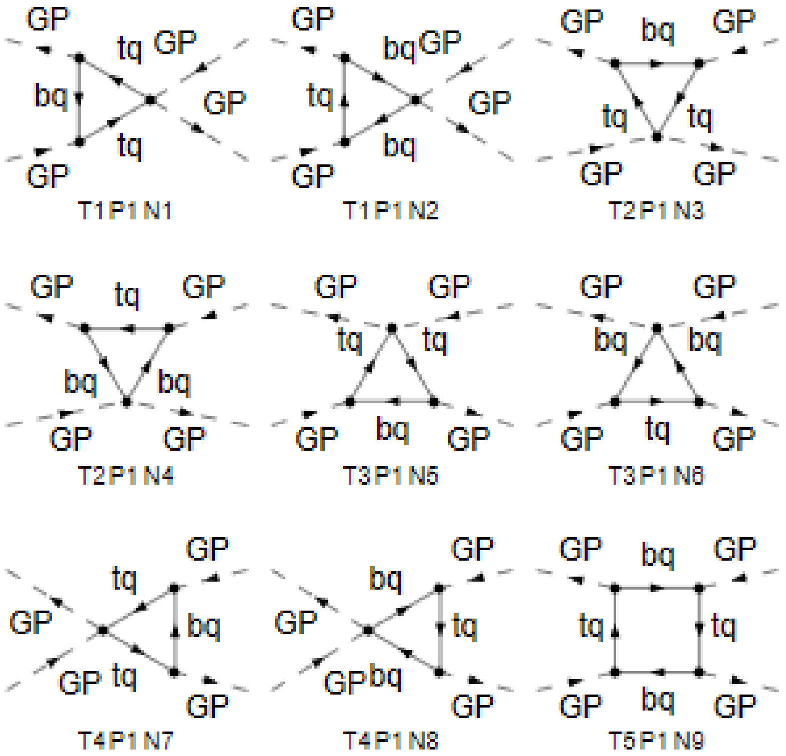
We will focus on the process $\omega^+\omega^- \to \omega^+\omega^-$ (similar results for all combinations of GB and Higgs)

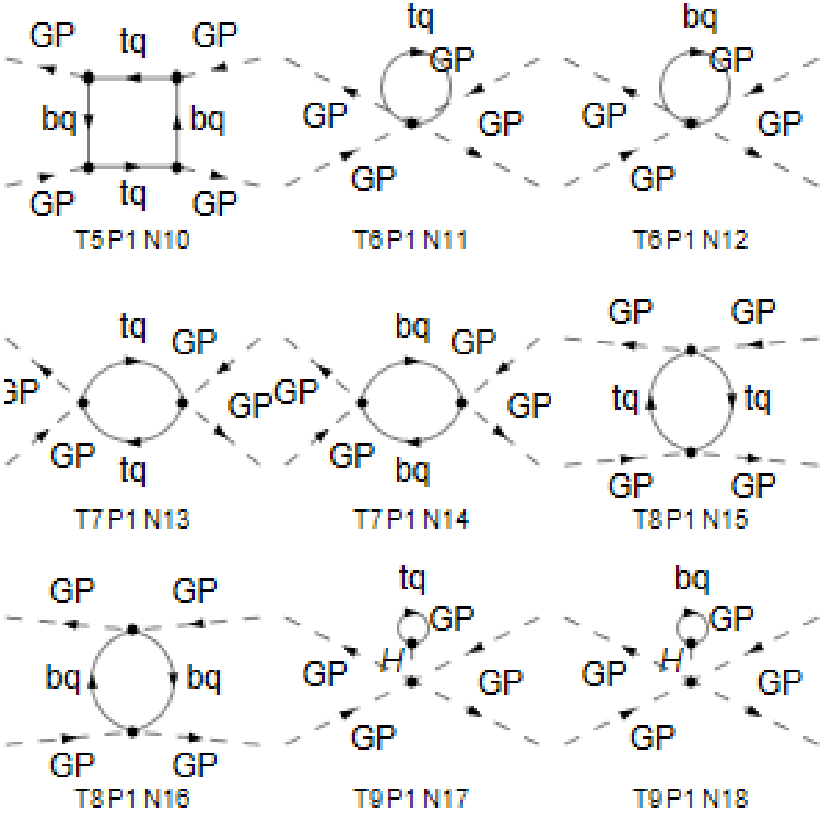
We will allow a ± 0.1 deviation from 1 for the HEFT coefficients

Boson loops



Fermion loops



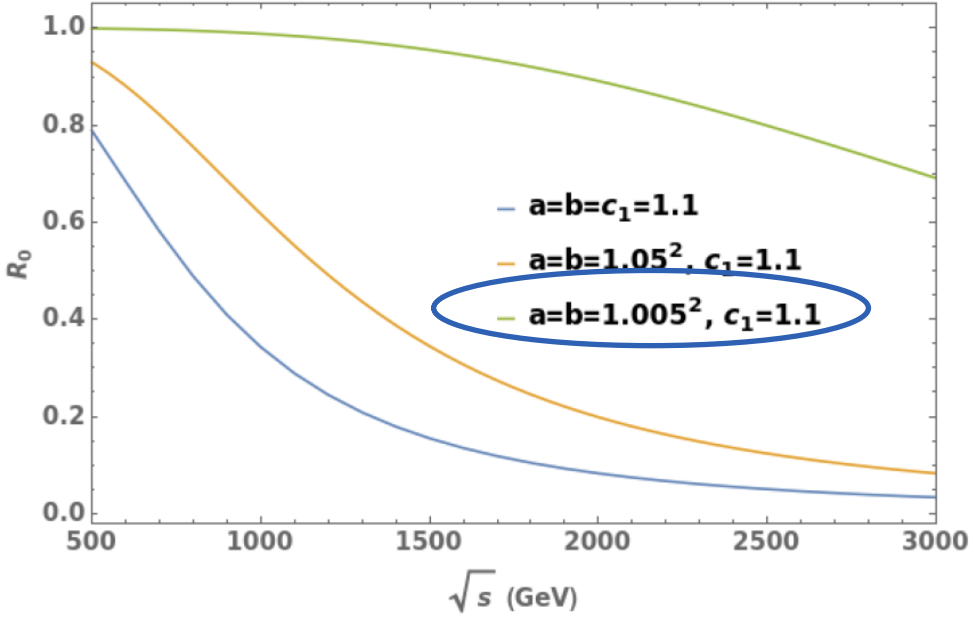


PWA study and ± 0.1 deviation from 1 for the HEFT coefficients

$$R_0 = \frac{|a_0^{\text{fermions}}|}{|a_0^{\text{fermions}}| + |a_0^{\text{bosons}}|}$$

R $\sim$ 0 bosons dominate
R $\sim$ 1 fermions dominate

Fermion corrections are dominant for values close to the SM and relevant for intermediate energies



R_0 ratio for different values of a, b and c_1

In this region of the parameter space the GB approximation breaks down → Necessary to go beyond the Equivalence Theorem

[Quezada-Calonge, Dobado, Sanz-Cillero, 22]

Imaginary part to physical VBS: $W_L^+ W_L^- \to W_L^+ W_L^-$

$$\mathrm{Im}[\mathrm{Bosons}] = \mathrm{Im}[a_J]|_{\gamma\gamma,\gamma Z,\gamma h,W^+W^-,ZZ,Zh,hh}$$
$$\mathrm{Im}[\mathrm{Fermions}] = \mathrm{Im}[a_J]|_{b\bar{b},t\bar{t}}$$

Im[Bosons] depend on a, b and d_3

Im[Fermions] depend on a and c_1

$$R_J = \frac{\mathrm{Im}[a_J^{Fermions}]}{\mathrm{Im}[a_J^{Bosons}] + \mathrm{Im}[a_J^{Fermions}]}$$

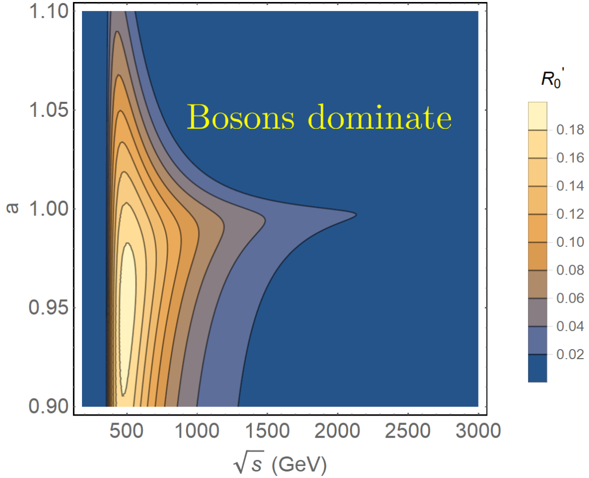
We will allow a ± 0.1 deviation from 1 for the HEFT coefficients

Scenario 1 PWA for $\cos\theta \in [-1, 1]$

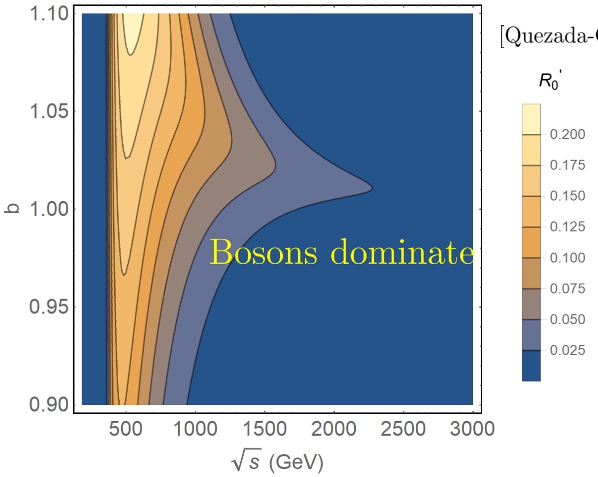
Scenario 2 pseudo-PWA (p-PWA) for $\cos\theta \in [-0.9, 0.9]$

a_0

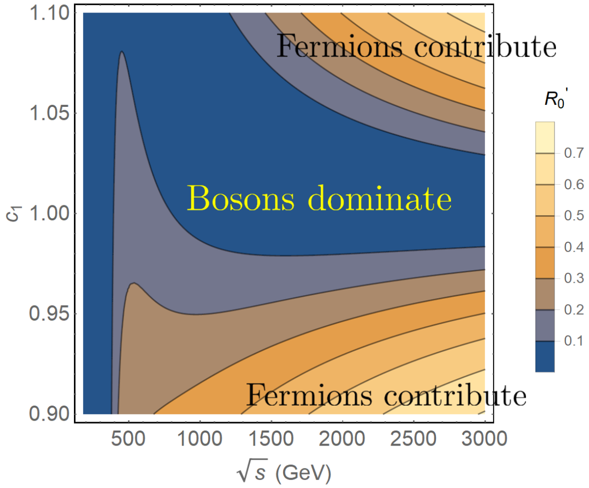
Scan for one parameter rest set to SM

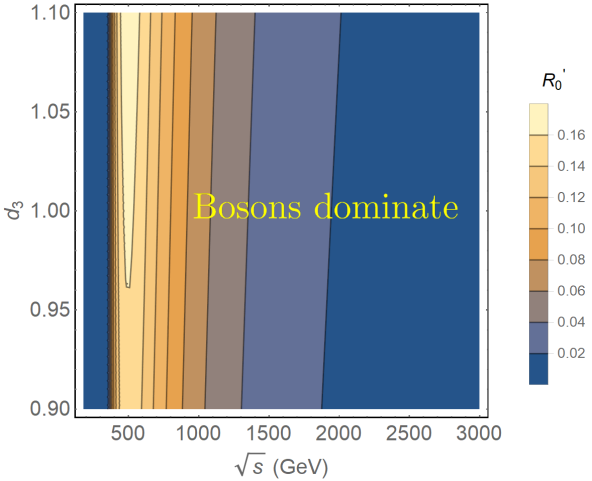


[Quezada-Calonge, Dobado, Sanz-Cillero, 22]



70% at 3 TeV





d_3 not relevant

Parameter scan for a_0

[Quezada-Calonge, Dobado, Sanz-Cillero, 22]

$\sqrt{s}$ (TeV)	$a-1$	$b-1$	c_1-1	d_3-1	$J=0$
1.5 (PWA)	0.023	0.100	-0.100	0.100	R_0=76%
3 (PWA)	0.008	0.035	0.100	-0.100	R_0=94%
1.5 (p-PWA)	0.011	0.045	-0.100	0.094	R'_0=81%
3 (p-PWA)	0.003	0.011	0.100	0.100	R'_0=93%

Parameter scan for a_0

[Quezada-Calonge, Dobado, Sanz-Cillero, 22]

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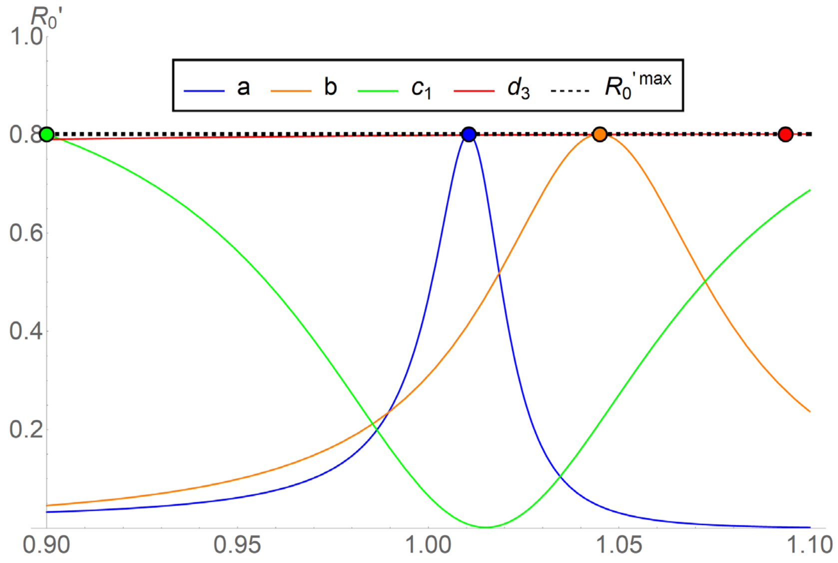
1.5 (p-PWA)	0.011	0.045	-0.100	0.094	R_0'=81%
3 (p-PWA)	0.003	0.011	0.100	0.100	R_0'=93%



Conclusions:

We have studied the effect of loops on VBS and Higgs production in the context of HEFT and the Equivalence Theorem.

We have found that there are regions where only bosons suffice to characterize the loop effects, but also sections of the parameter space where top loops need to be included.

Additionally, we have considered a more realistic case involving physical vector bosons and have found comaparable results.

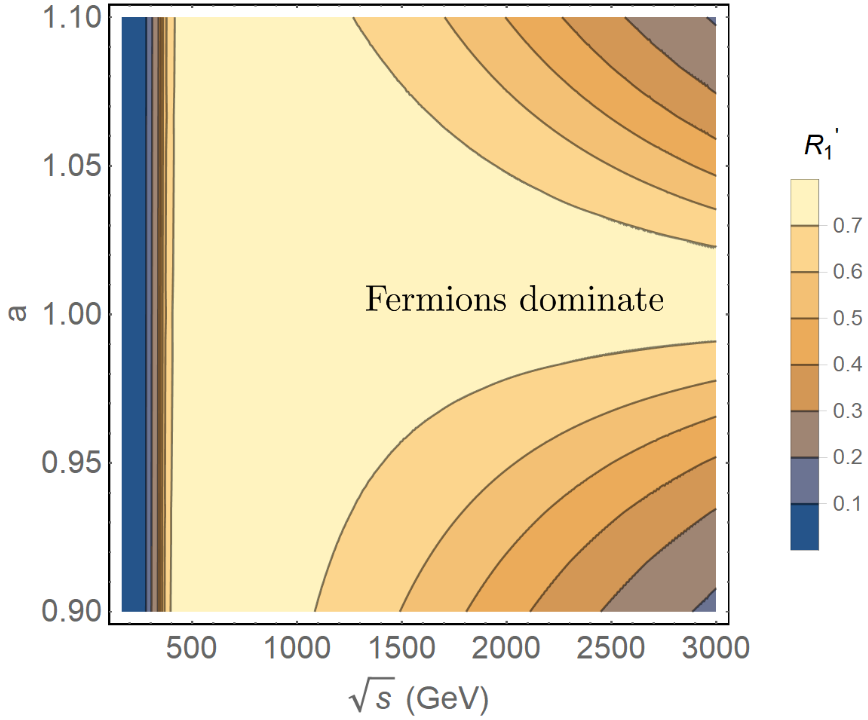
Other combinations of VBS and Higgs show a similar behavior.

Thank you

Backup slides

a_1

[Quezada-Calonge, Dobado, Sanz-Cillero, 22]



High corrections for a $\sim$ 1

$$\text{Im[Bosons]} \sim \left[\frac{(1-a^2)s}{96\pi v^2}\right]^2$$

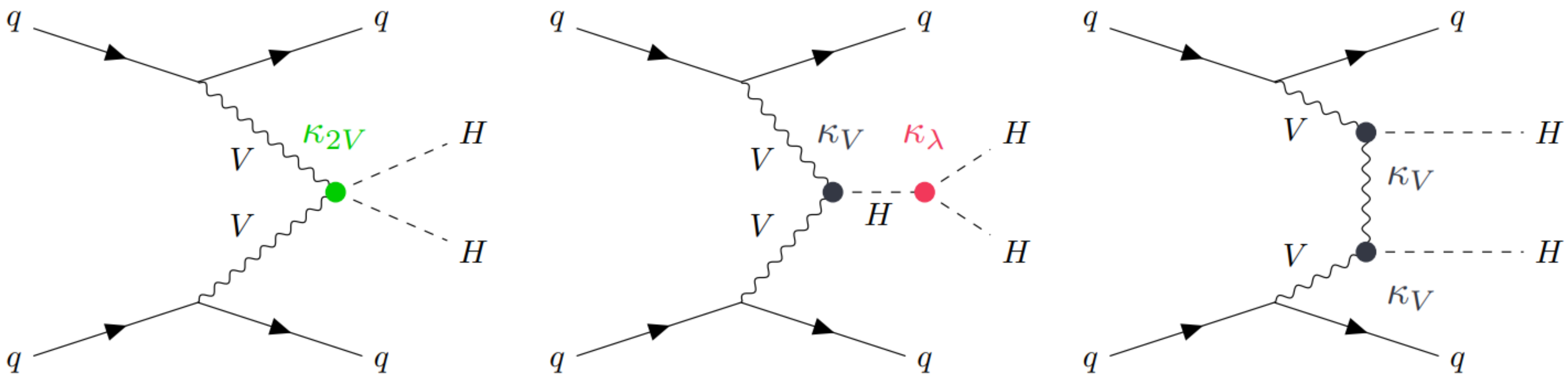
$$\text{Im[Fermions]} = \text{Im[Fermions]}|_{SM}$$

No dependence on HEFT parameters

Parameter scan for a_1

$\sqrt{s}$ (TeV)	$a-1$	$J=1$
1.5 (PWA)	-0.009	R_1=18%
3 (PWA)	0.013	R_1=12%
1.5 (p-PWA)	0.019	R_1'= 66%
3 (p-PWA)	0.007	R_1'= 67%

Ongoing



q
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