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Fermion Loops in VBS

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1. Introduction

- Higgs couplings to gauge bosons and **top quark** are still compatible with the SM with deviations of $\mathcal{O}$ **(10%).** For other fermions (e.g **bottom**) and the triple-Higgs coupling **larger** deviations are not excluded .[1]

- These deviations may come **from strongly interacting new physics**, where the Higgs boson and the Goldstone Bosons are composite states.

- We will focus on heavy fermion loop corrections (imaginary part) with **top quark** because of its large mass, 175 GeV. Fermion corrections are often neglected because the bosons ones dominate at high energy. (~ 3 TeV)

But how important are fermion loops?

The imaginary parts enter in the NLO counting

Is it possible to find values for the modified couplings that lead to a significant contribution?

[1] Handbook of LHC Higgs Cross Sections: 4. - LHC Higgs Cross SectionWorking Group

2.Electroweak Chiral Lagrangian (EFT)

- Electroweak Chiral Lagrangian : EW GB **transform non-linearly** and a **Higgs-like** field which **transforms linearly** under $SU(2)_L x SU(2)_R$ which breaks to the **Custodial Symmetry** $SU(2)_{L+R}$.

$$SU(2)_L \times SU(2)_R \xrightarrow{SSB} SU(2)_{L+R}$$

- Systematic expansion in **chiral power counting** (different to the SMEFT canonical expansion). **Renormalizable order by order.**

$$\mathscr{L}_{EChL} = \mathscr{L}_2 + \mathscr{L}_4 + \dots$$

- It is often used the Equivalence Theorem [2], where we relate the gauge bosons with the would-be-Goldstones at high energies.

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

- Because of exact cancellations of some amplitudes we need go beyond the ET.

[**2] P.B. Pal,** What is the equivalence theorem really? (1994)

The lagrangian at lowest order (chiral dimension 2)

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

GB + h + Yukawa sector

Spherical parametrization

$$U = \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\bar{\omega}}{v}$$

GB $\bar{\omega} = \tau^a \omega^a$

Just the top for this case

$$Q^{(\prime)} = \begin{pmatrix} \mathscr{U}^{(\prime)} \\ \mathscr{D}^{(\prime)} \end{pmatrix} \quad \mathscr{U}' = (u,c,t)' \quad \mathscr{D}' = (d,s,b)'$$

Quarks

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

$$V(h) = v^4 \sum_{n=3}^{\infty} V_n \left(\frac{h}{v}\right)^n$$

for $V_2 = V_3 = \frac{M_h^2}{2v^2}$, $V_4 = \frac{M_h^2}{8v^4}$, $V_{n>4} = 0$ ⇒ **Recover the SM**

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

Modifications on the Higgs SM couplings and beyond!

$a = b = 1$

$c_1 = 1$

$c_2 = c_3 = \ldots c_n = 0$

3. Loops

We have calculated the contribution of top quark loops via the generating functional, obtaining the scattering for gauge bosons. Renormalized the relevant couplings and fields and compared to the existing literature [3].

We have obtained the real and imaginary part of the PWA.

But how important are fermion loops?

The imaginary parts enter in the NLO counting.
In general the bosons dominate at high energy. ($\sqrt{s}$ ~ 3 TeV)

$$Im[Bosons] = Im[a_J]\Big|_{W^+W^-, ZZ, HH, \gamma\gamma}$$
$$Im[Fermions] = Im[a_J]\Big|_{t\bar{t}}$$

$$R_J = \frac{Im[Fermions]}{Im[Boson] + Im[Fermions]}$$

R ~ 1 $\rightarrow$ Fermions dominate
R ~ 0 $\rightarrow$ Bosons dominate

We will inspect this ratio for the PWA of the process $W^+W^- \rightarrow W^+W^-$

[3] G. Buchalla et al. LMU-ASC 13/20 [4] D. Espriu and J. Matías Phys. Rev. D **52**, 6530
[5] T. Bahnik hep-ph/9710265 [6] A. Denner et al Phys. Rev. D **51**, 4738
[7] E. Arganda, C. Garcia-Garcia and M.J Herrero *Nucl.Phys.B* 945 (2019) 114687

$Im[Bosons]$ depend on a, b and and d_3

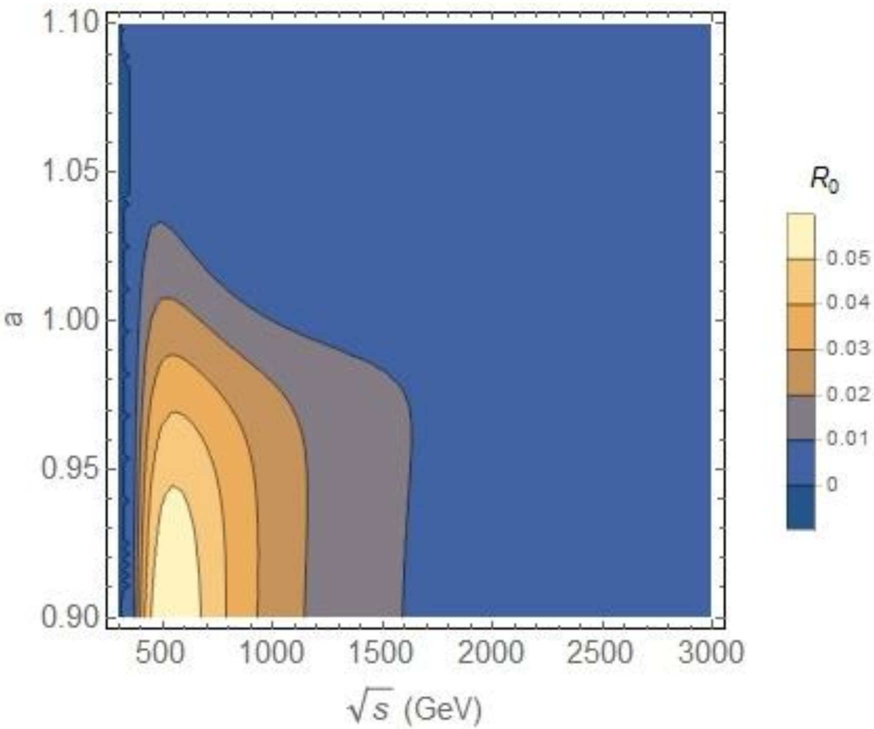
$Im[Fermions]$ depend on a and c_1

We will alow a 10% deviation from 1

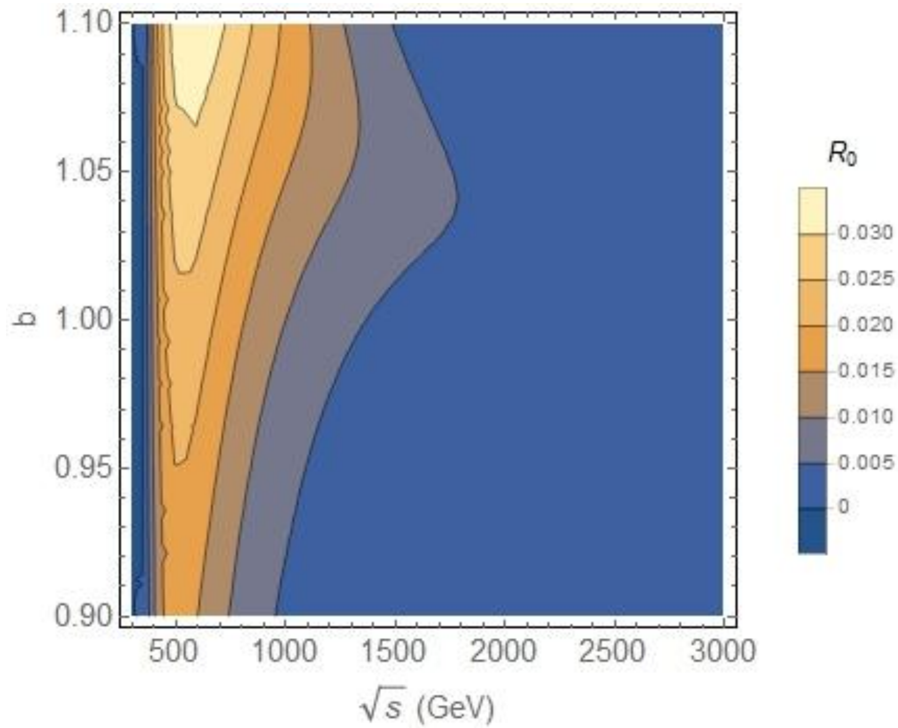
[1] Handbook of LHC Higgs Cross Sections: 4. - LHC Higgs Cross SectionWorking Group

4. Results for $W^+W^- \rightarrow W^+W^-$

4.1 Partial wave a_0 (J=0)



$b = c_1$



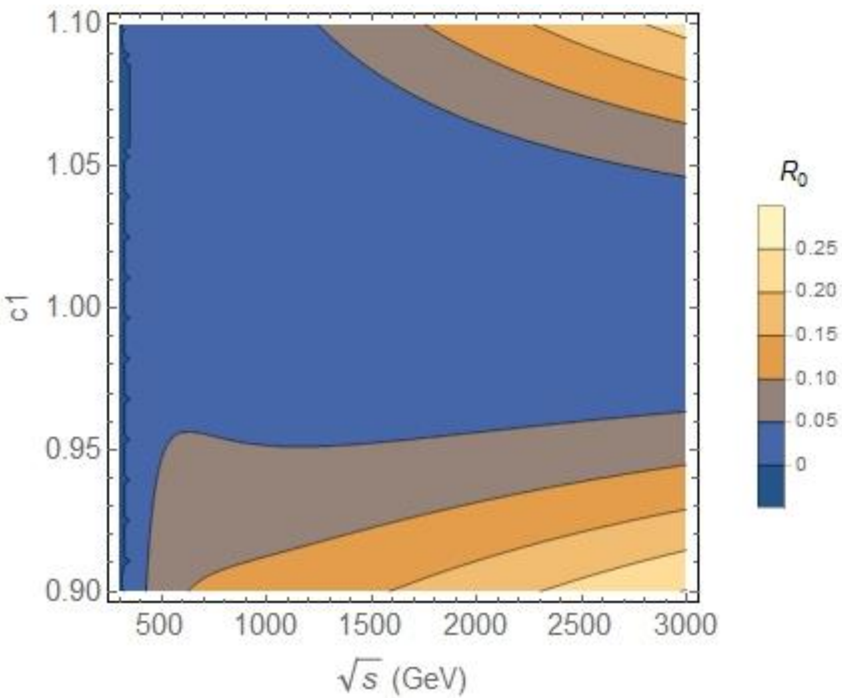
$a = c_1 = 1$

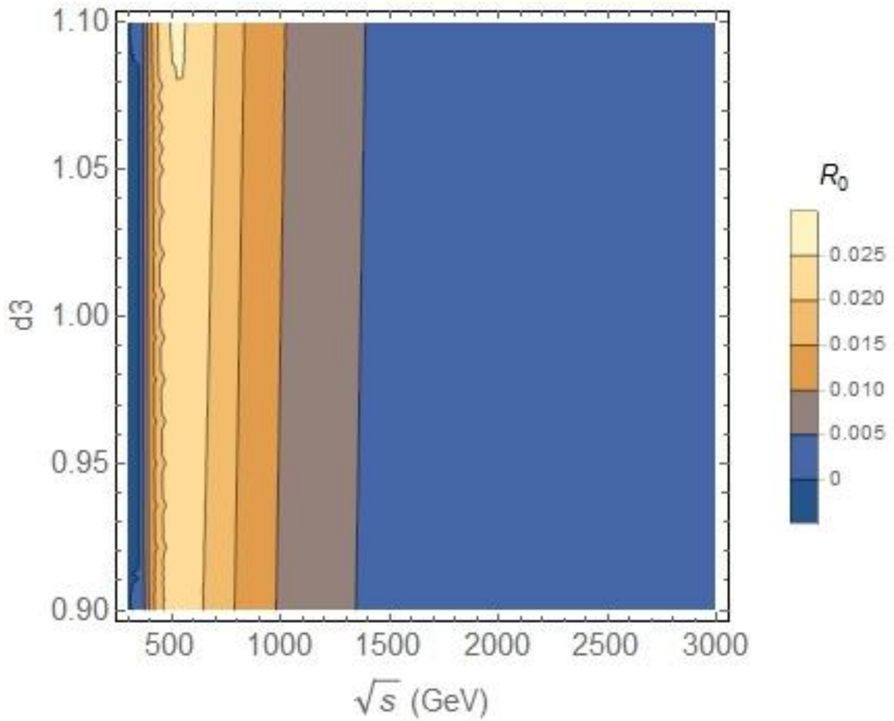
5 % corretions at 500 GeV
máximum for *a* around 0.9

3 % correction at 500 GeV
for ***b*** around 1.1

Bosons completely dominate over 1 TeV for a and b

$a = b = 1$





We find corrections of 25% at high energies around c_1=0.90 and c_1=1.1

Again 2% corrections. Neglibible

Parameter scan for a_0

We inspect a, b, c_1 and d_3 ∈[0.90,1.10] [1]

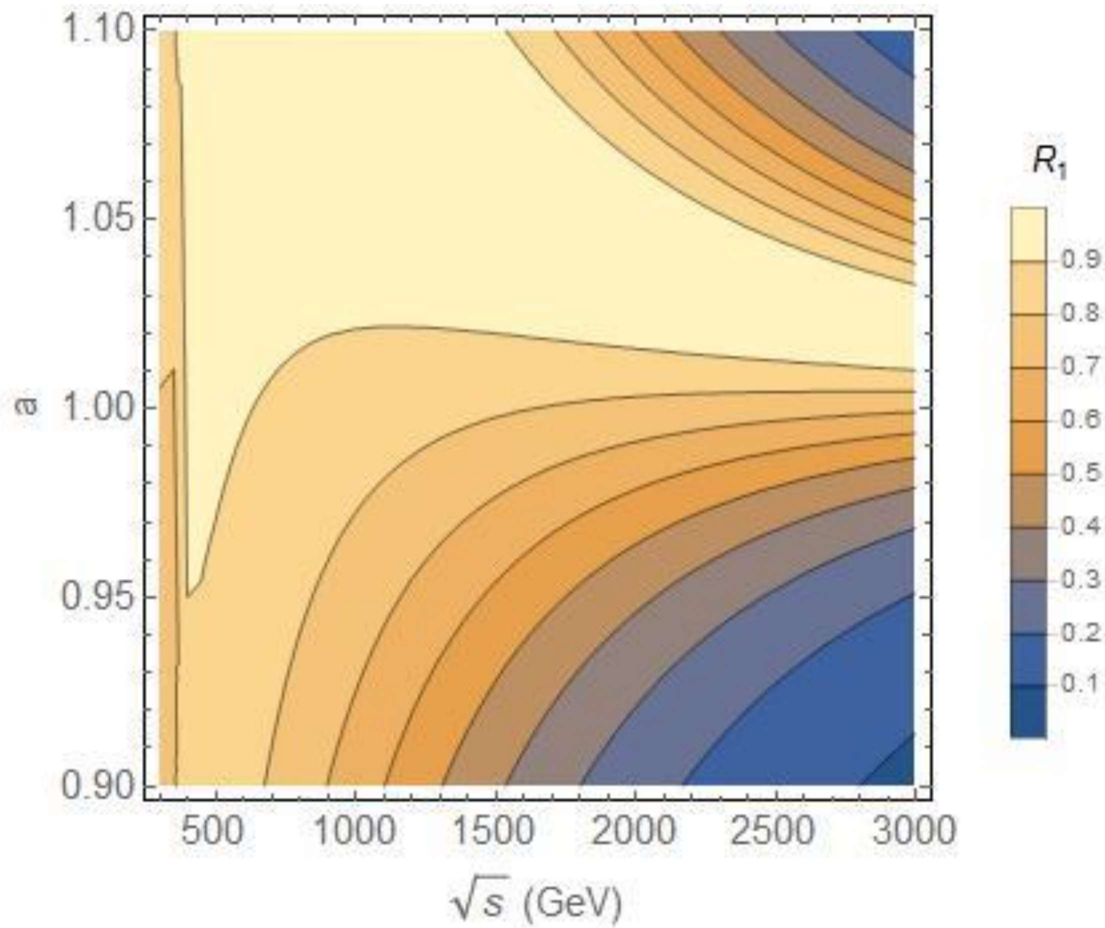
$\sqrt{s}$ (Tev)	a	b	c_1	d_3	R_0
1.5	0.95	0.95	0.9	0.95	0.07
1.5	1.05	1.1	1.1	1.1	0.16
3.0	1.0	1.0	0.9	1.0	0.25
3.0	1.0	1.0	1.1	1.0	0.22

Highest R

Clearly c_1 is the most important parameter for **J=0**

[1] Handbook of LHC Higgs Cross Sections: 4. - LHC Higgs Cross SectionWorking Group

4.2 Partial wave a_1 (J=1)



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

Im[Fermions]=$Im[Fermions]_{SM}$

Does not depend on b, c_1 or d_3 , just a

High corrections for a close to 1

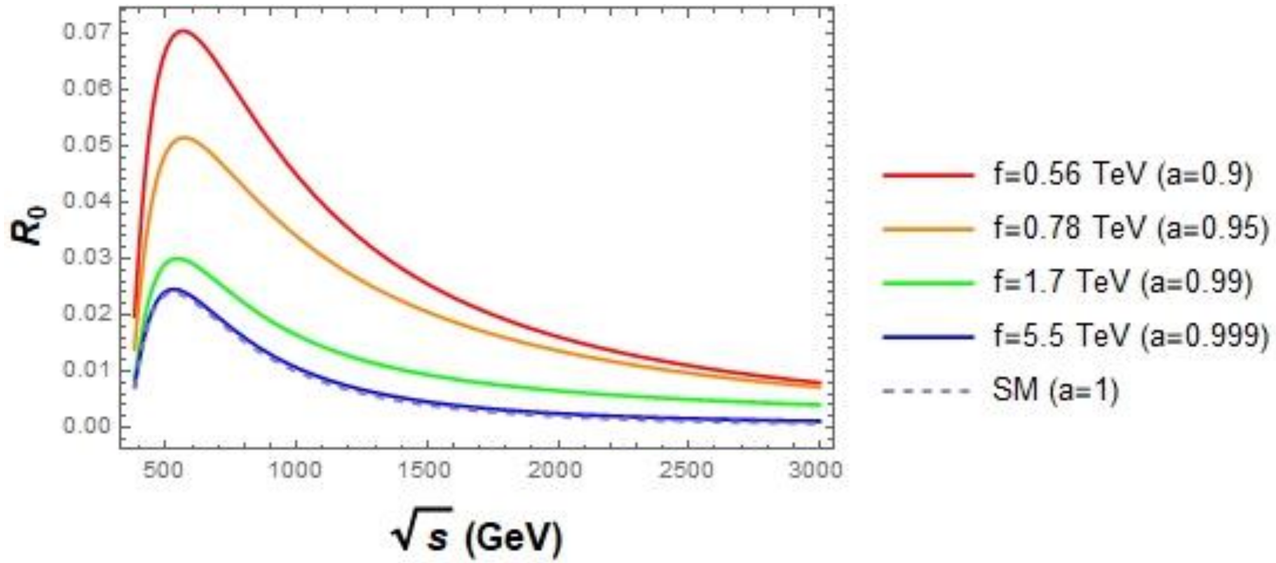
4. Specific Scenarios: Minimal Composite Higgs Model

Agashe, Contino, Pomoral *Nucl.Phys.B* 719 (2005) 165-187

$$\xi = v^2/f^2$$

$$b^* = 1 - 2\xi$$

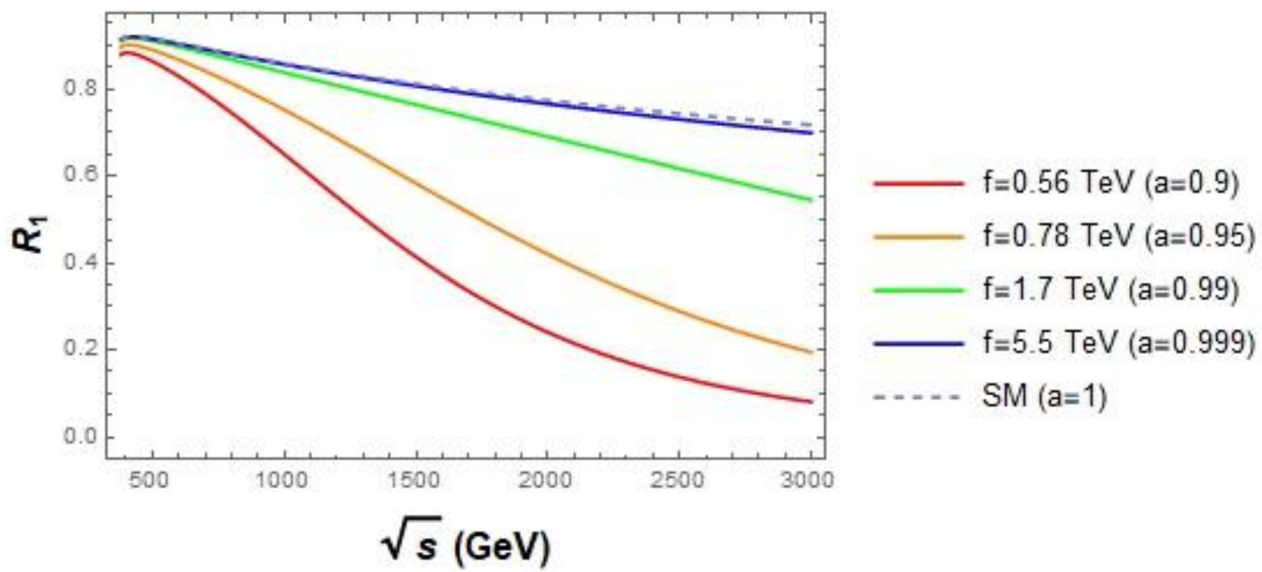
$$a^* = c_1^* = \sqrt{1-\xi}$$



R1 is significally larger than R0

a1 more sensitive to fermion corrections

80% corrections at Low energy



5. Conclusions

- We estimate fermion corrections to WW scattering: negligible in most of the parameter space but not always.
- For instance, the PWA's:

R_0	1.5 - 3 TeV	$a = b = d_3 = 1$and c_1=0.9	15-25%
R_1	1.5- 3 TeV	a $\in$[0.95, 1.95]	60-90%

- The MCHM shows R1 than R0 hence its more sensitive to the fermion corrections.
- Future work: considering the whole amplitude (real and imaginary) and unitarizing.

Thank you.