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How relevant are top loops in VBS searches for new physics?

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Multi-Bosons Interactions 2021

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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 to **VBS** (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.**

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

- It is often used the Equivalence Theorem , 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.

The lagrangian at lowest order (chiral dimension 2)

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

GB + h
+ Yukawa sector

Just the top for this case

Spherical parametrization

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

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

$$Q^{(\prime)} = \begin{pmatrix} \mathscr{U}^{(\prime)} \\ \mathscr{D}^{(\prime)} \end{pmatrix}$$

$\mathscr{U}' = (u,c,t)'$

$\mathscr{D}' = (d,s,b)'$

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

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

$a = b = 1$

$c_1 = 1$

$c_2 = c_3 = \ldots c_n = 0$

Modifications on the Higgs SM couplings and beyond!

3. Loops

We have calculated the contribution of top quark loops to VBS 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 Partial Wave Amplitudes (PWA) or pseudo-PWA's.

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)

[2] G. Buchalla et al. LMU-ASC 13/20

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

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

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

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

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

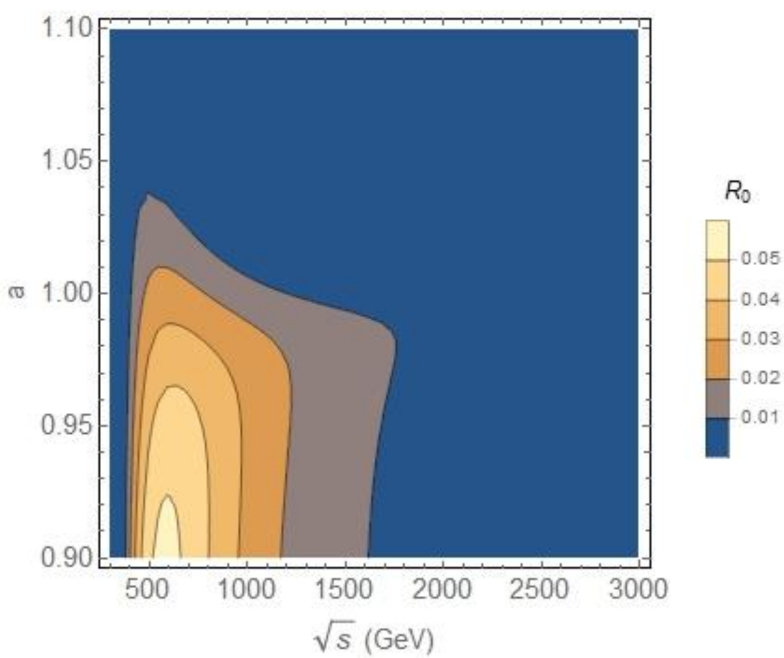
$Im[Fermions]$ depend on a and c_1

We will alow a 10% deviation from 1

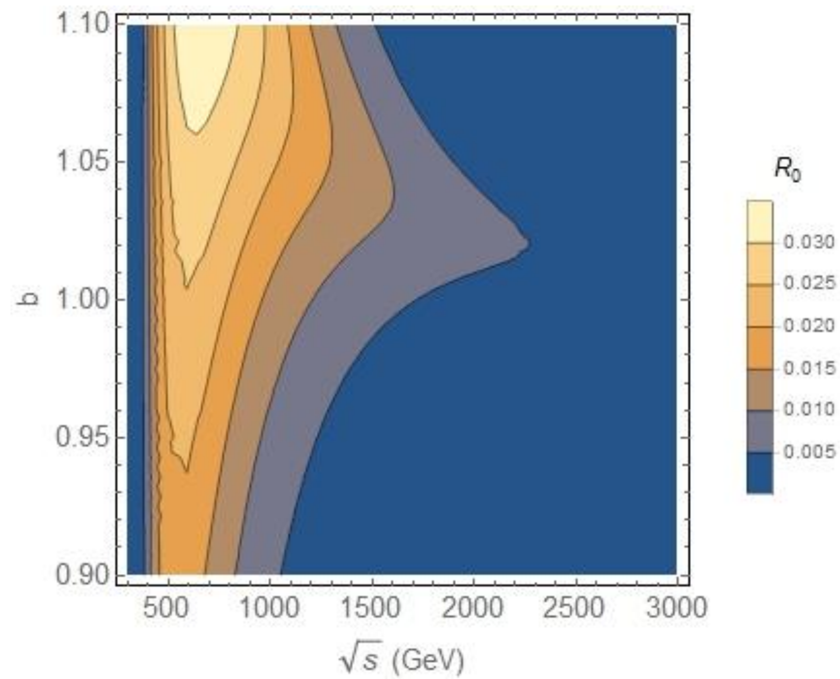
[1] Handbook of LHC Higgs Cross Sections: 4. - LHC Higgs Cross Section Working Group

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

4.1 Partial wave a_0 (J=0)



b = c_1=1



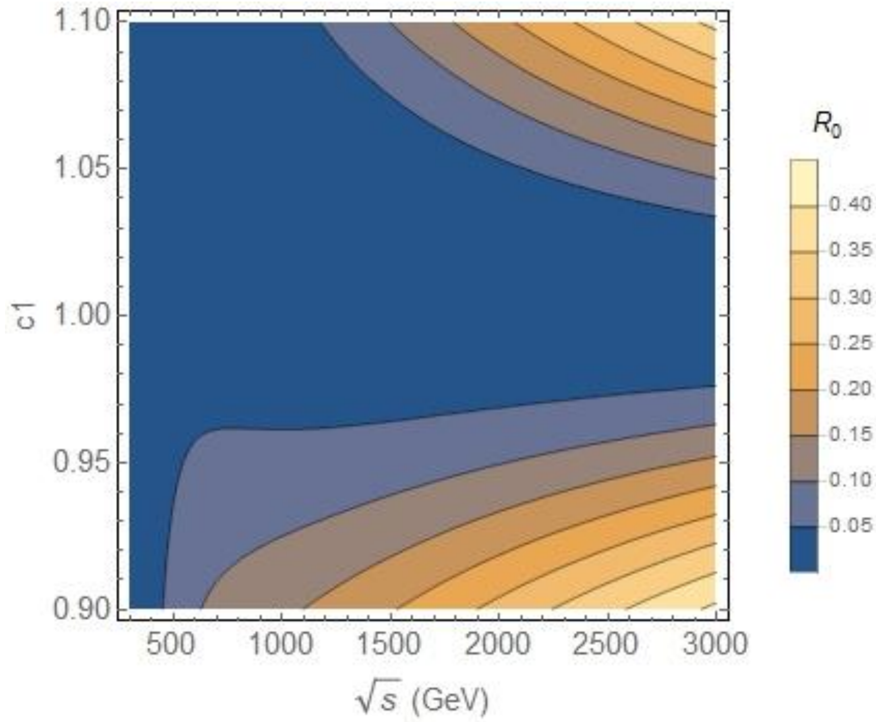
$a = c_1 = 1$

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

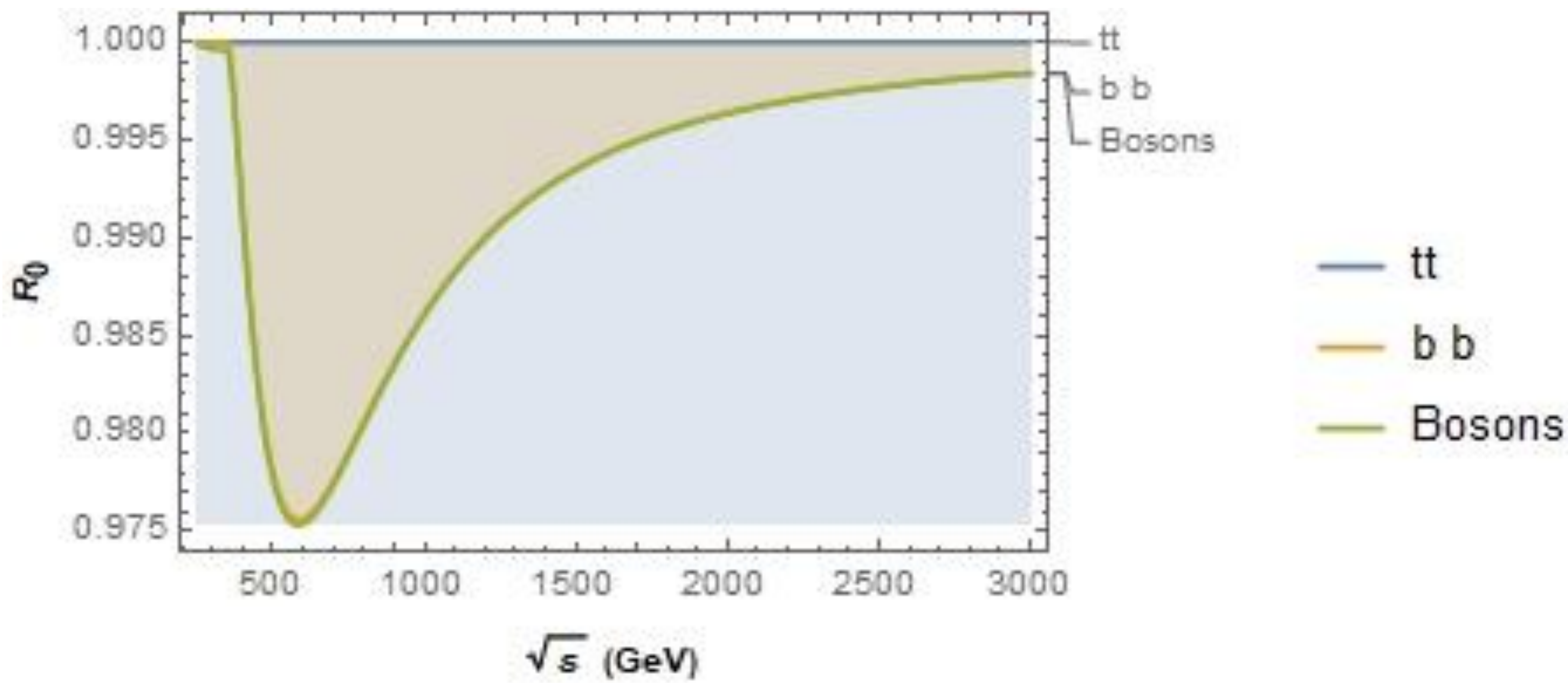
$a = b = 1$



We find corrections of 40% at high energies around c_1=0.90 and c_1=1.1

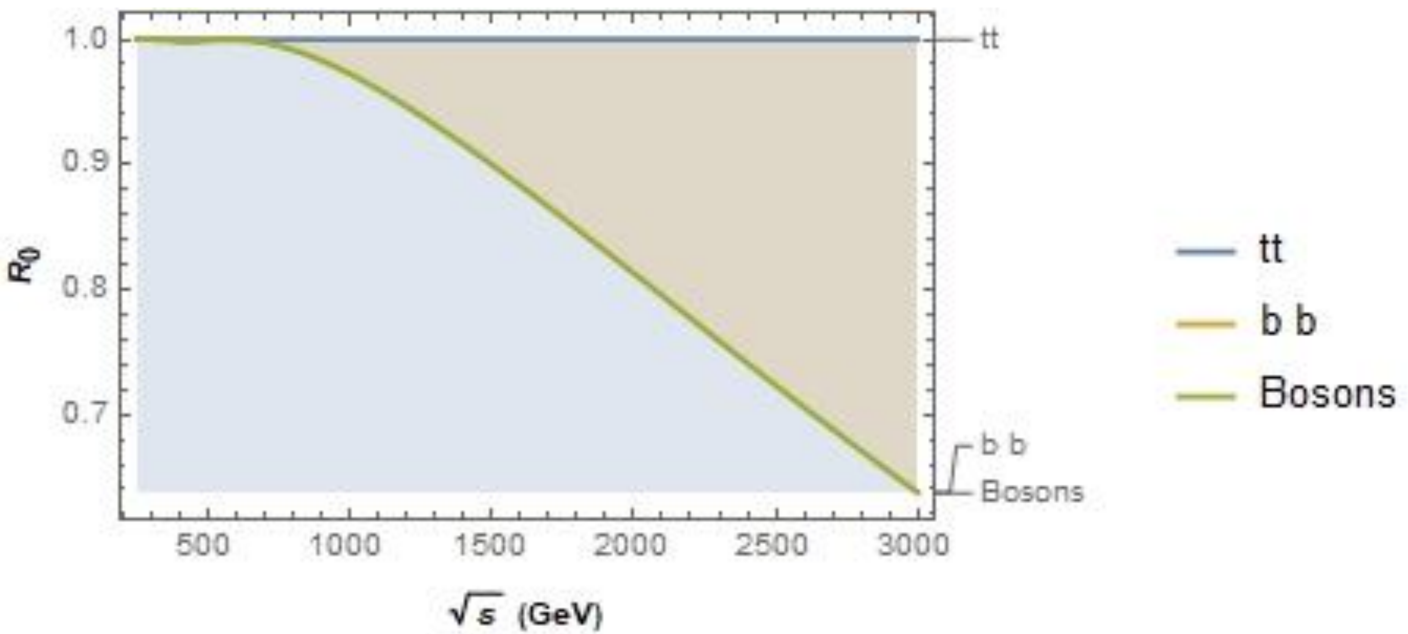
d_3 yields negligible corrections (not worth showing)

At the SM



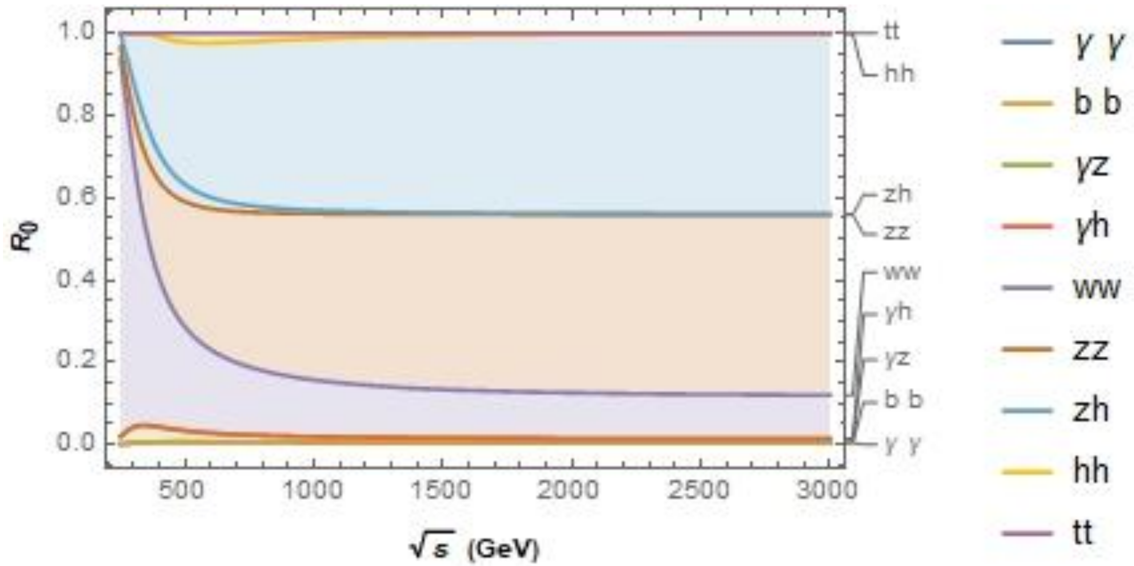
Fermion contributions are not relevant near the SM

c_1=0.9 and c_1=1.1 and rest @SM

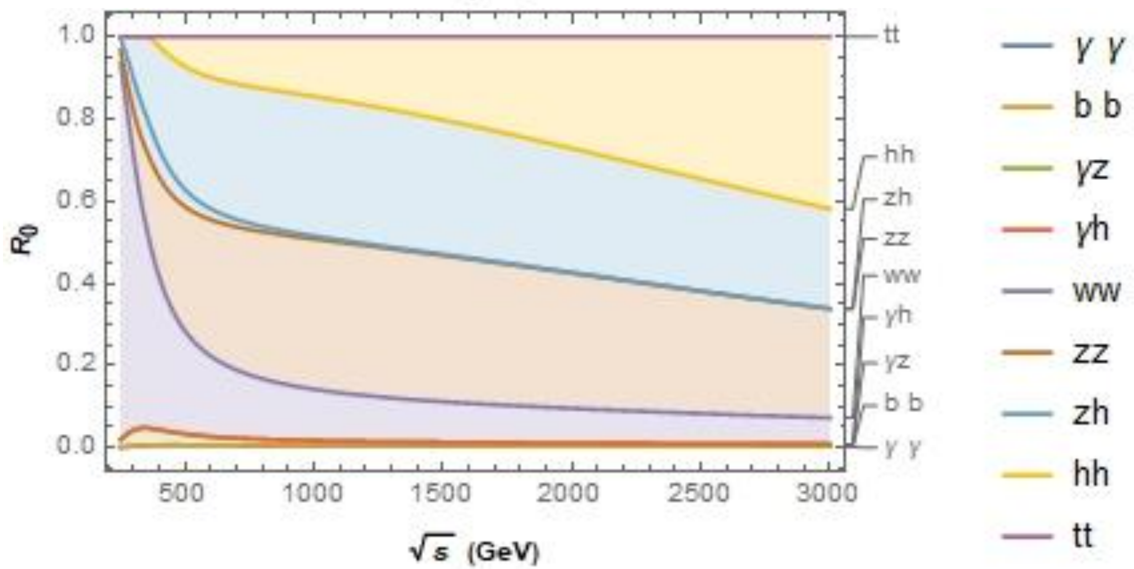


Up to 40% corrections at 3 TeV when c_1 deviates the most from the SM

Showing the contribution of each cut



@SM



c_1=0.9 and c_1=1.1 and rest @SM

Top is the most important one

Fermion contributions are indeed relevant

Parameter scan for a_0

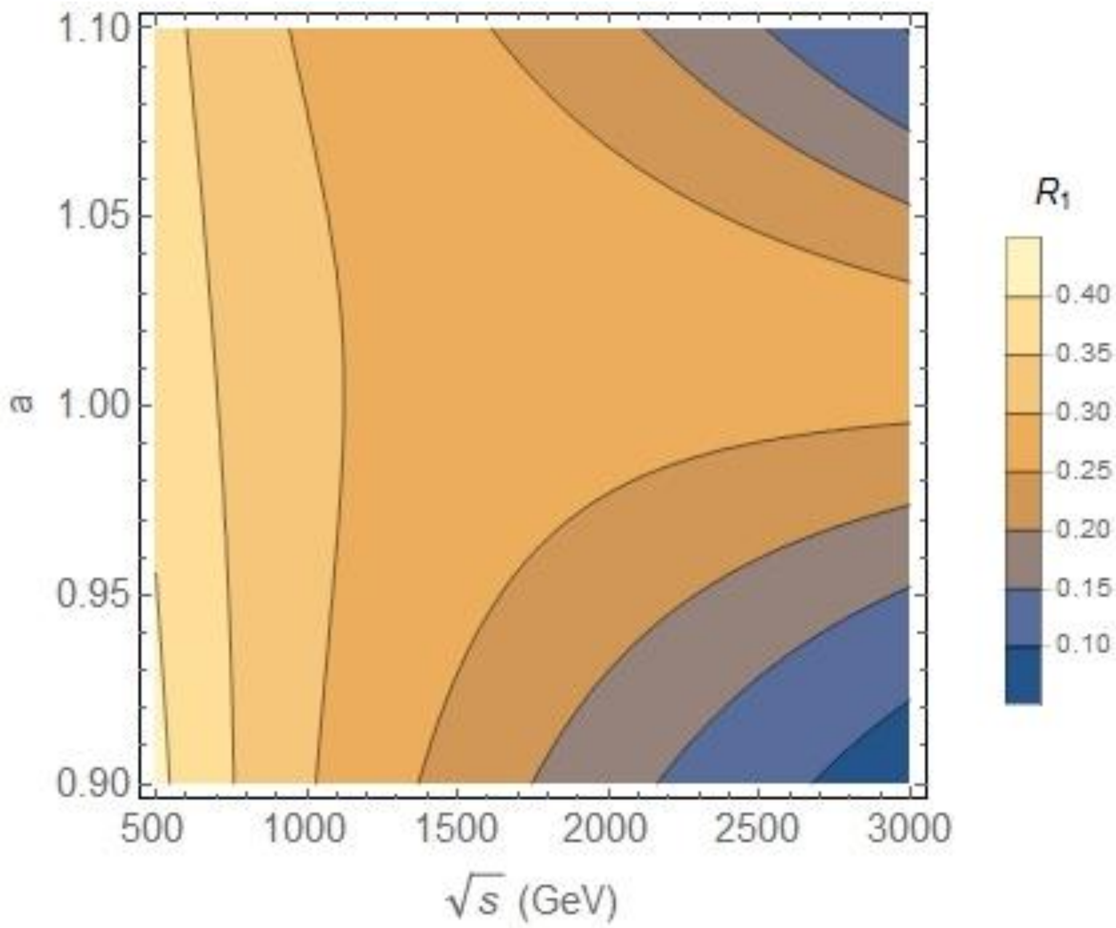
We inspect a, b, c_1 and d_3 ∈[0.90,1.10] [1]

Highest R

$\sqrt{s}$ (TeV)	a	b	c_1	d_3	R_0
1.50	1.00	1.00	0.90	1.10	0.42
3.00	1.00	1.05	0.90	0.90	0.30

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

4.2 Partial wave a_1 (J=1)



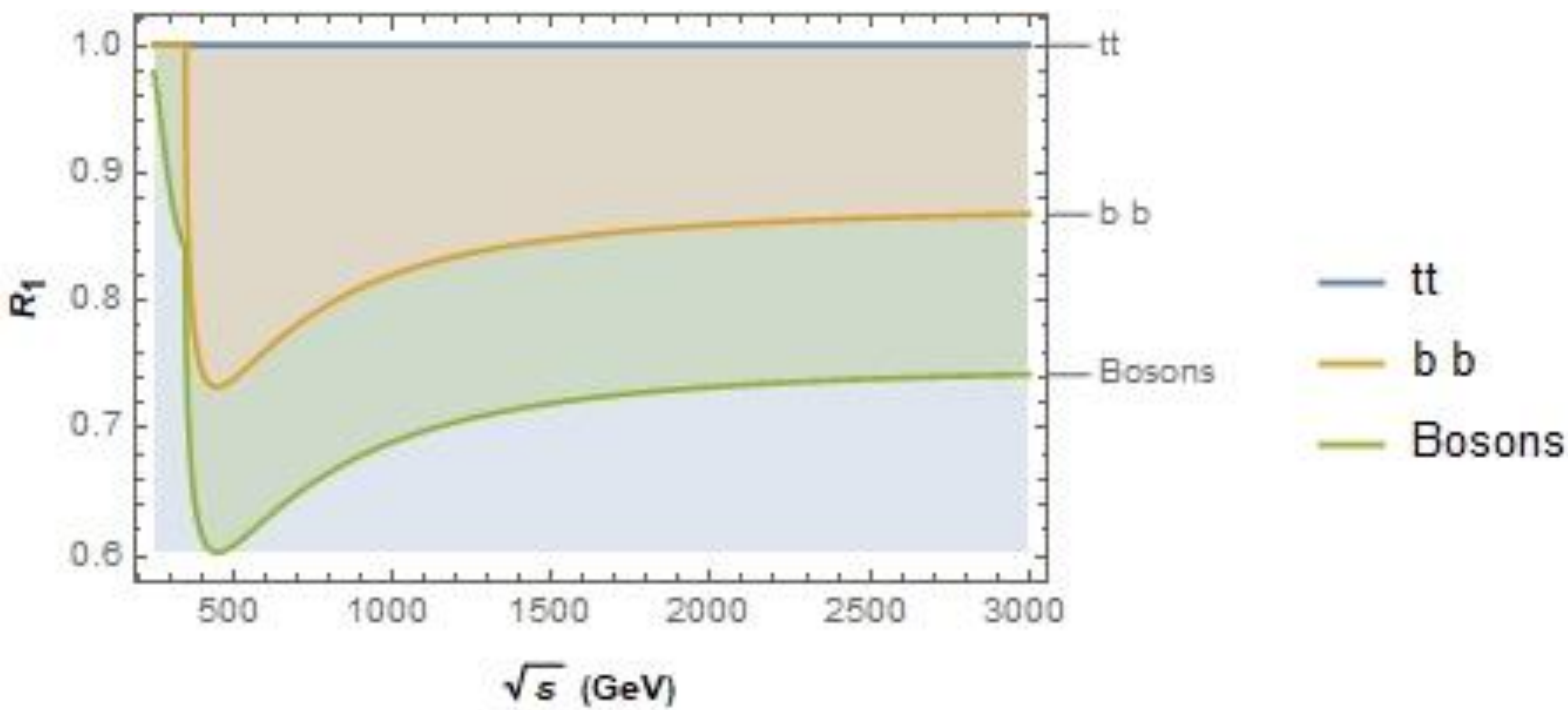
Im[Bosons] = f(a) $\approx \left[\frac{(1-a^2)\hat{}2s}{96\,\pi v\hat{}2}\right]^2$

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

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

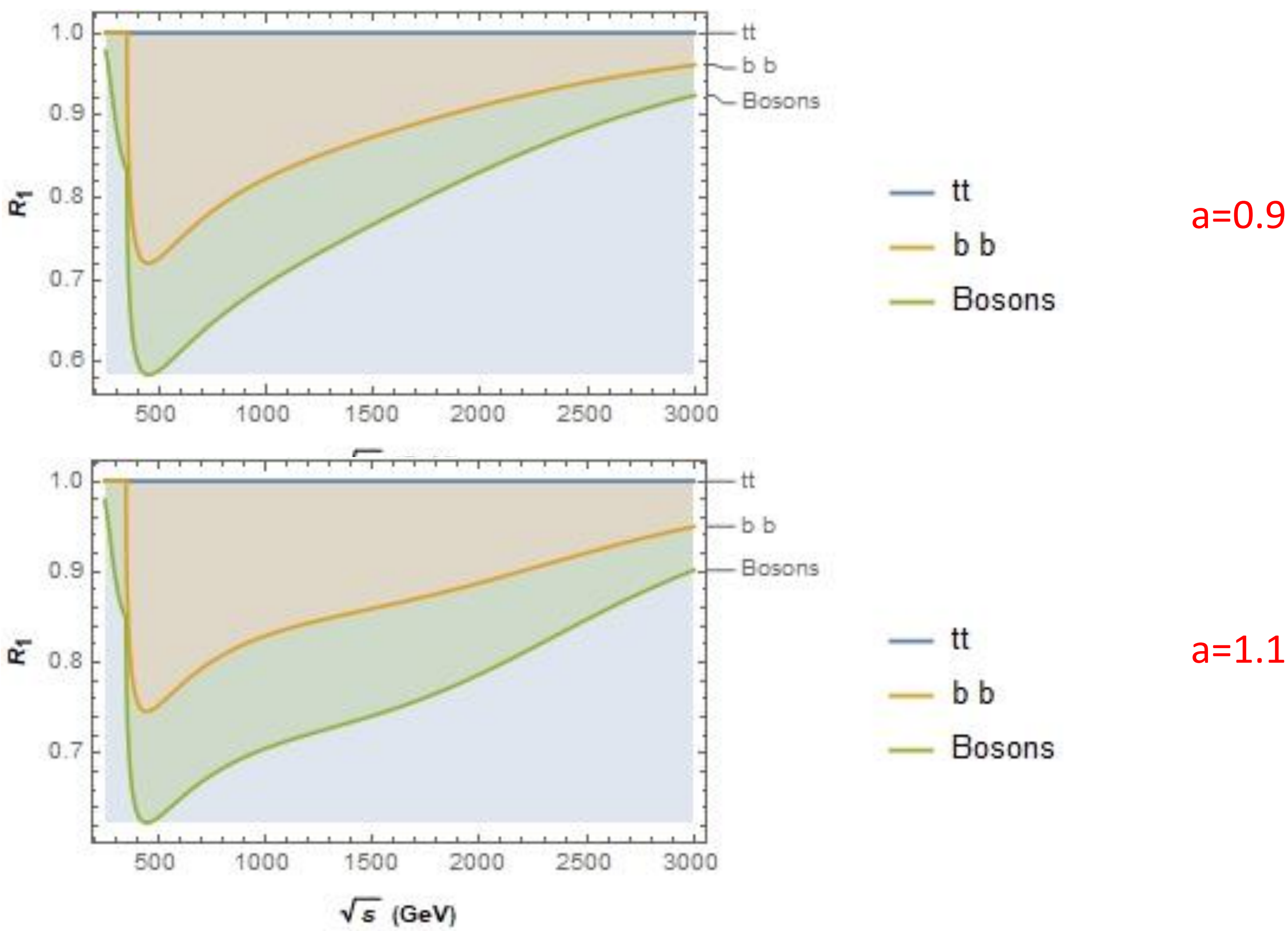
High corrections for a close to 1

At the SM



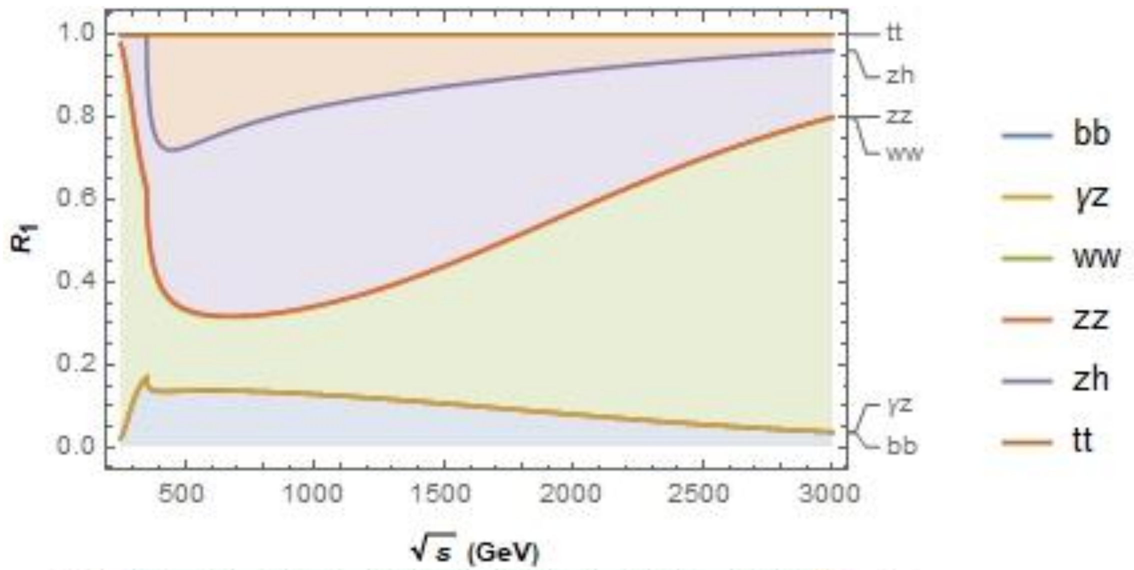
Only one parameter to play with = *a*

When *a* is close to the SM the boson part tends to a constant at large energies and fermions become relevant (30%)

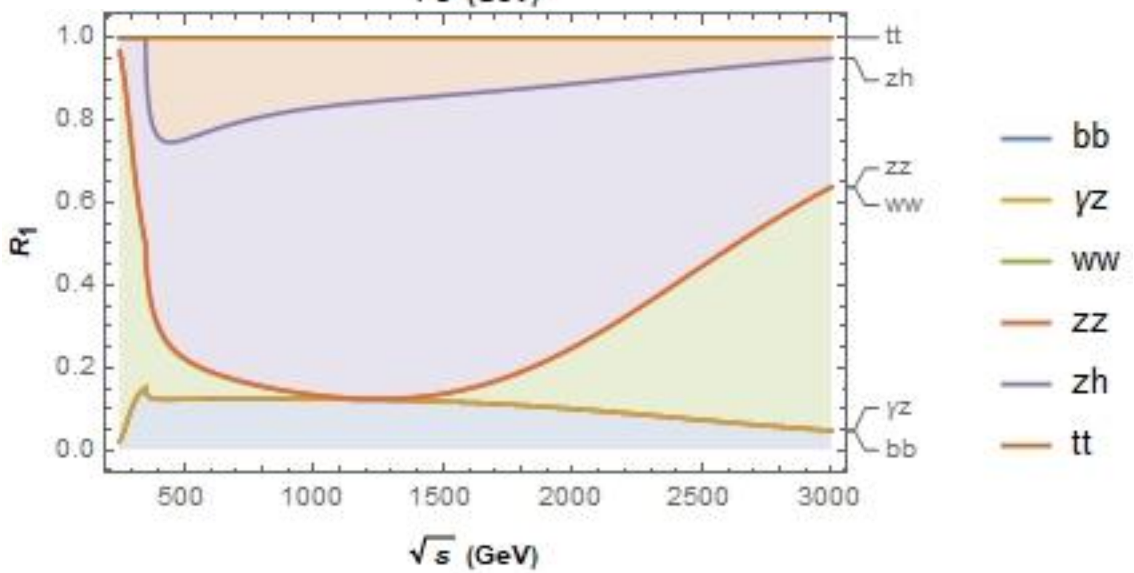


As *a* deviates from the SM the bosons become more important but we still find corrections of a 10% at 3 TeV

Showing the contribution of each cut



a=0.9



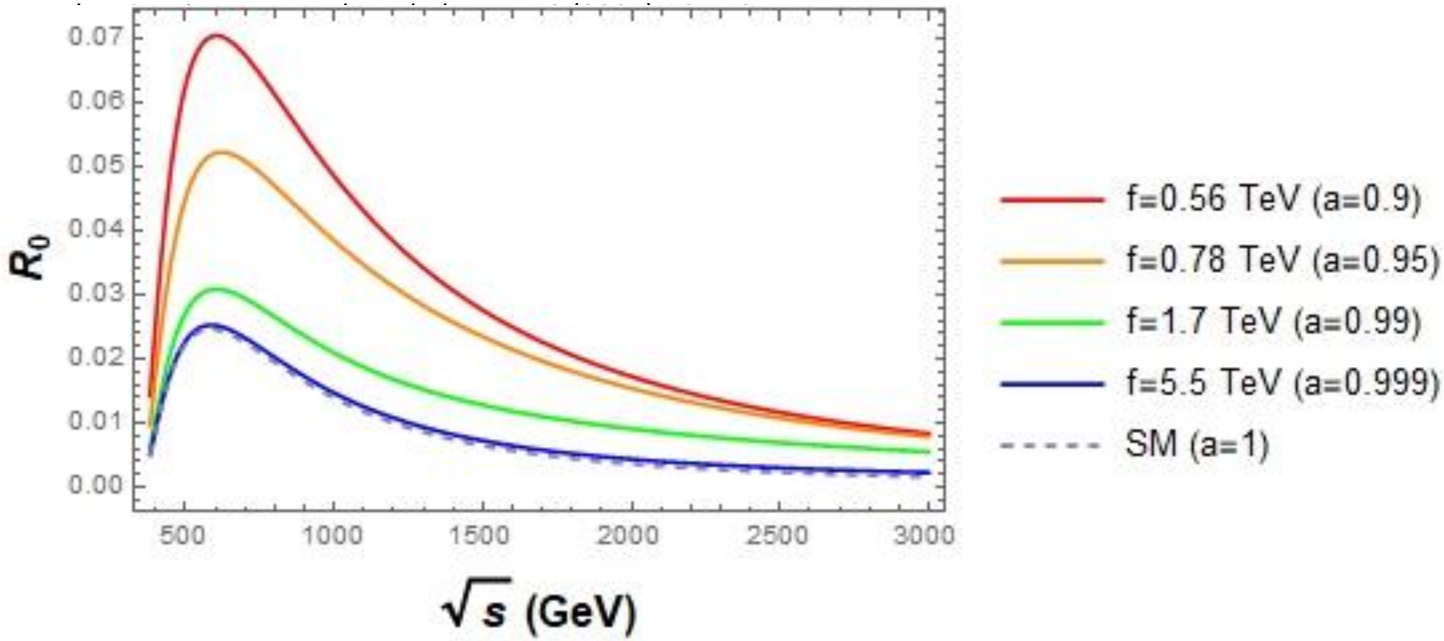
a=1.1

4. Specific Scenarios: Minimal Composite Higgs Model

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

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

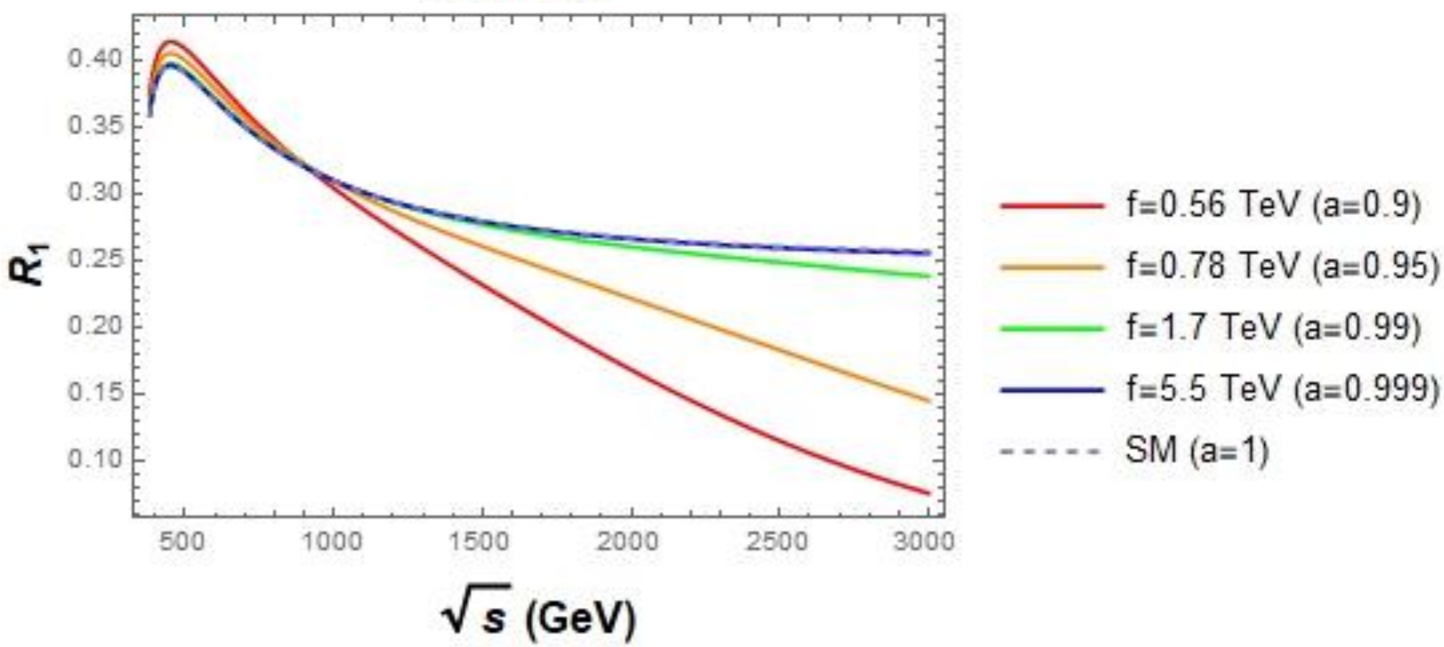
$$a^* = c_1^* = \sqrt{1-\xi}$$



R1 is significally larger than R0

a1 more sensitive to fermion corrections

25% corrections at high energy and for values close to SM



5. Conclusions

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

R_0	1.5-3 TeV	30-40%
R_1	1.5-3 TeV	25-28 %

- The MCHM shows R1 is more sensitive to fermion corrections than R0. R0 drastically drops when we deal with the MCHM.
- Future work: considering the whole amplitude (real and imaginary) and unitarizing.

Thank you.