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Top quark loop corrections to WW scattering in EChL

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1. Introduction

- Higgs couplings to gauge bosons and **top quarks** 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.**

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

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

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

[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

Just the top for this case

Spherical parametrization

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

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

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

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

$$\underbrace{\mathscr{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots \qquad \mathscr{G}(h) = 1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \ldots}_{\text{Modifications on the Higgs SM couplings and beyond!}}$$

$a = b = 1$

$c_1 = 1$

$c_2 = c_3 = \ldots c_n = 0$

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.

It is important to note that for **ZZ** and **HH** intermediate state we have used the **Equivalence Theorem.**

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)

$$Im[Bosons] = Im[a_J]\Big|_{W^+W^-,ZZ,HH} \quad [4],[5].$$
$$Im[Fermions] = Im[a_J]\Big|_{t\bar{t}}$$

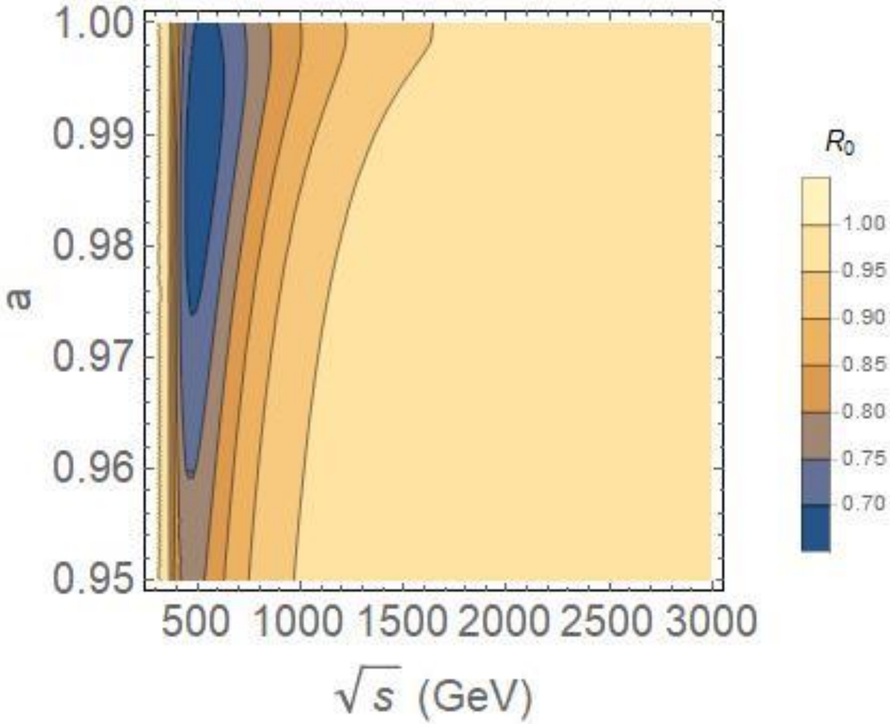
$$R_J = \frac{Im[Bosons]}{Im[Boson] + Im[Fermions]}$$

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

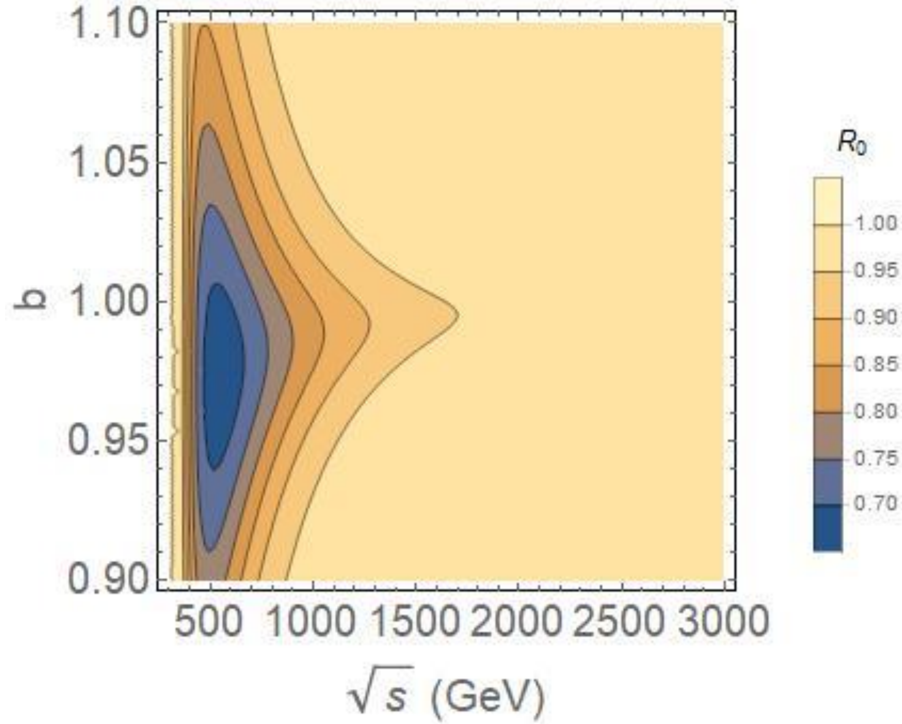
[3] G. Buchalla et al. LMU-ASC 13/20
[4] D. Espriu and J. Matías Phys. Rev. D **52**, 6530
[5] R. Delgado, A. Dobado, F.J. Llanes-Estrada J. Phys. **G41**, 025002

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

Partial Wave a_0

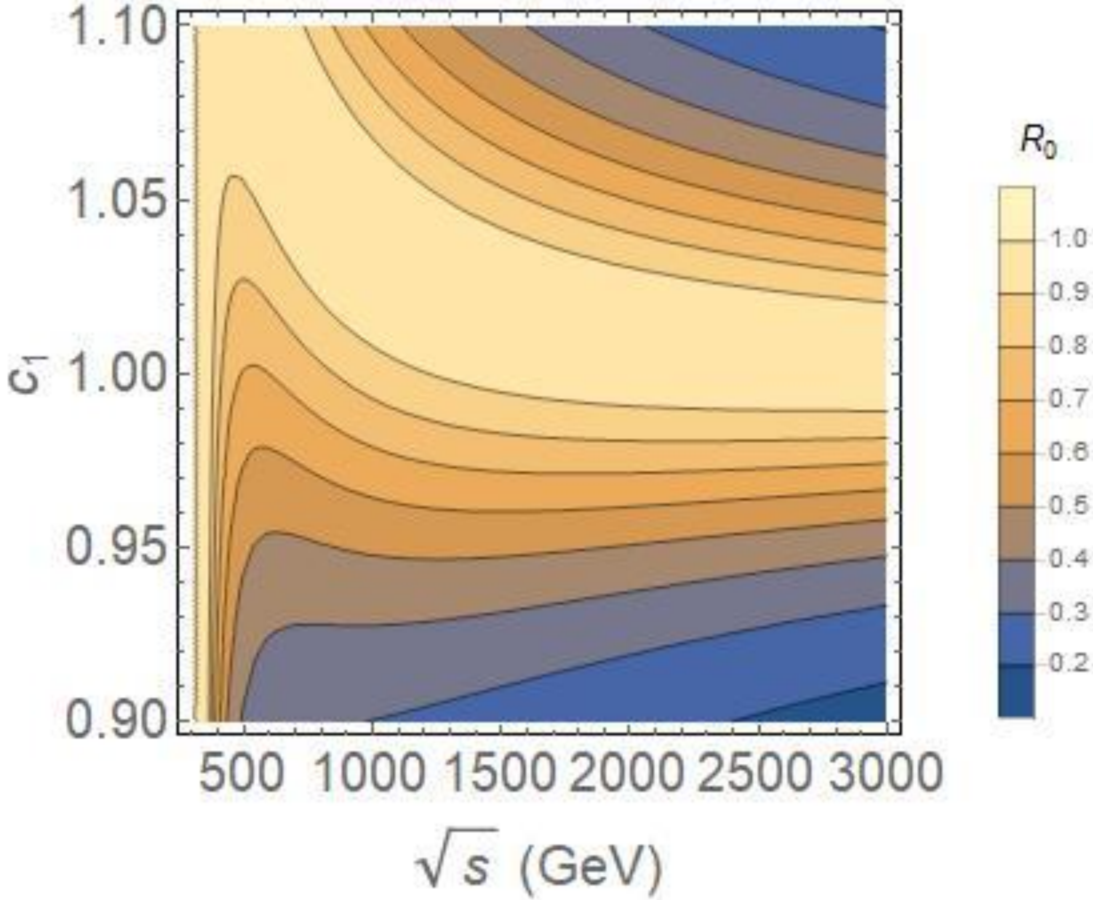


$b = c_1 = 1$



$a = c_1 = 1$

We find corrections of a 30% at energies around 500 GeV. Over 1.5 TeV the bosons contributions dominate



$$a = b = 1$$

We find corrections of 80% at high energies.

Parameter scan for a_0

We inspect a,b,c1 ∈[0.90,1.10] [1]

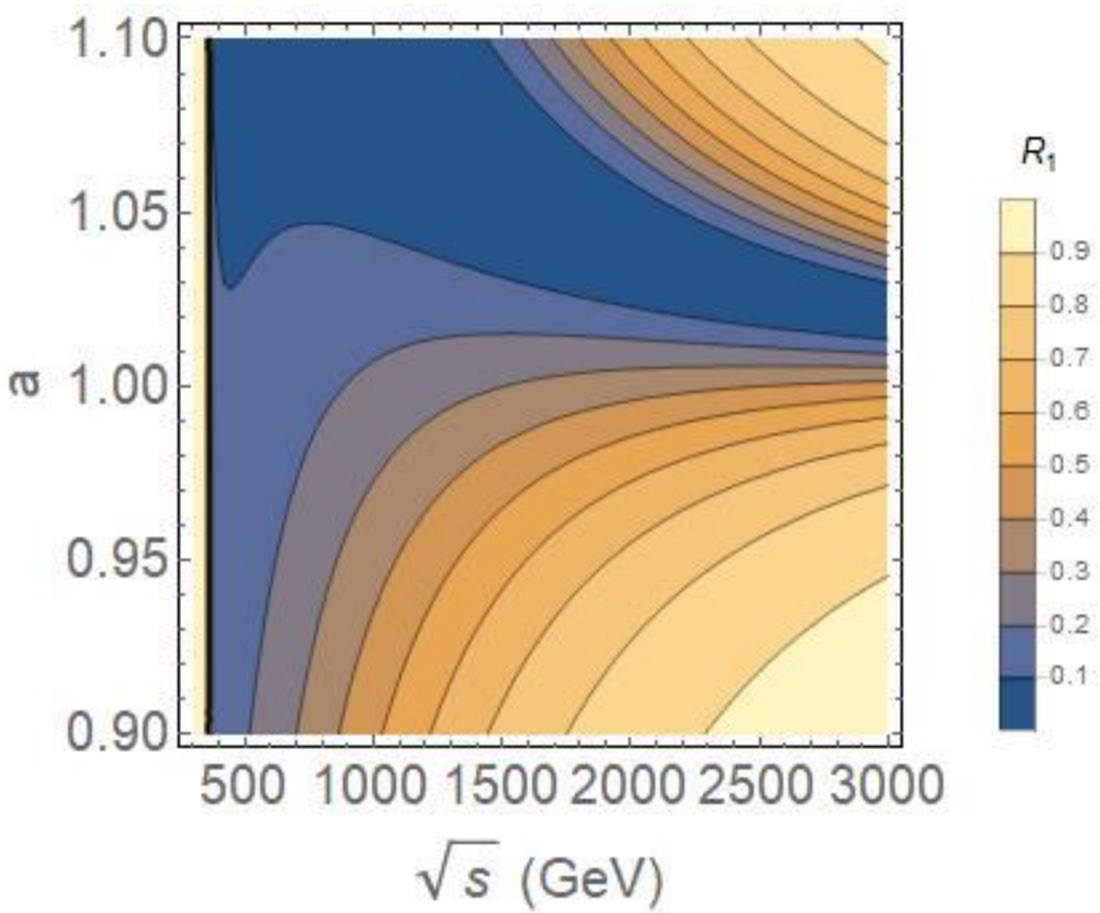
$\sqrt{s}$ (TeV)	a	b	c_1	R
1.5	1	1	0.9	0.26
3	1	1	0.9	0.16
1.5	1	1	1.1	0.42
3	1	1	1.1	0.19

Lowest R

Values of c_1 under 1 yield the lowest rate.

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

Partial Wave a_1

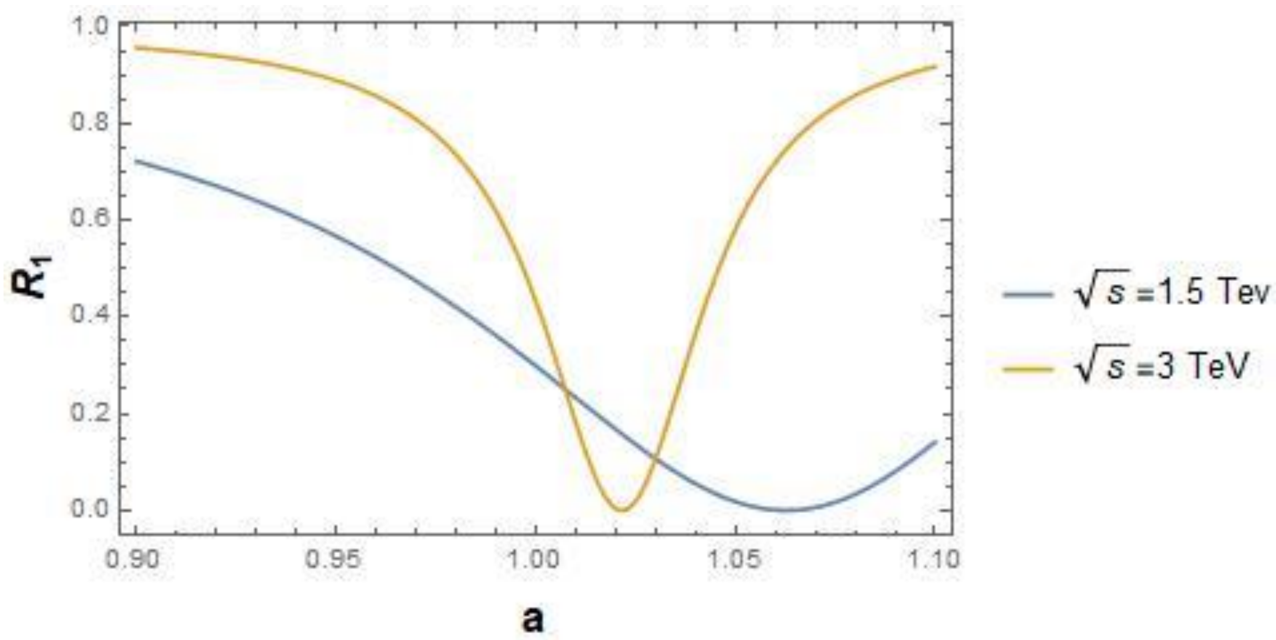


Im[Bosons] = f(a) $\approx \left[\frac{(1-a^2)\text{^}2s}{96\,\pi v\text{^}2}\right]^2$

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

Does not depend on b or c1

Fixing the energy



For this PWA values of a over 1 yiel the lowest R

We can see corrections even of 99% for a=1.06 at 1.5 TeV and a=1.02 for 3 TeV.

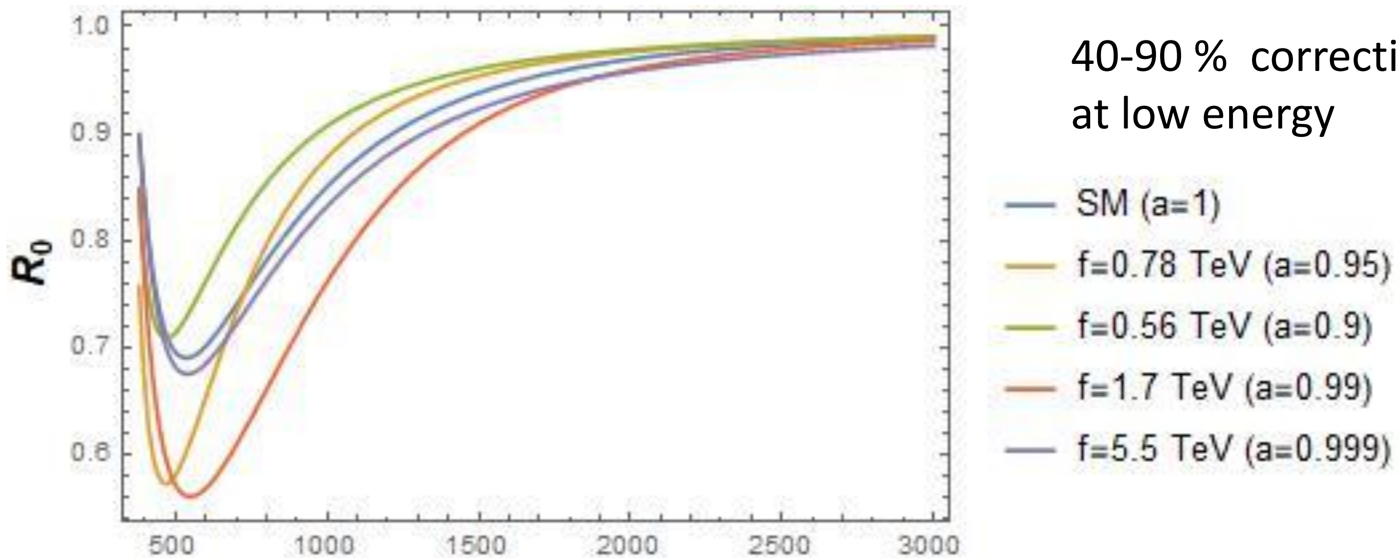
4. Specific Scenarios: Minimal Composite Higgs Model

Referencia MCHM

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

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

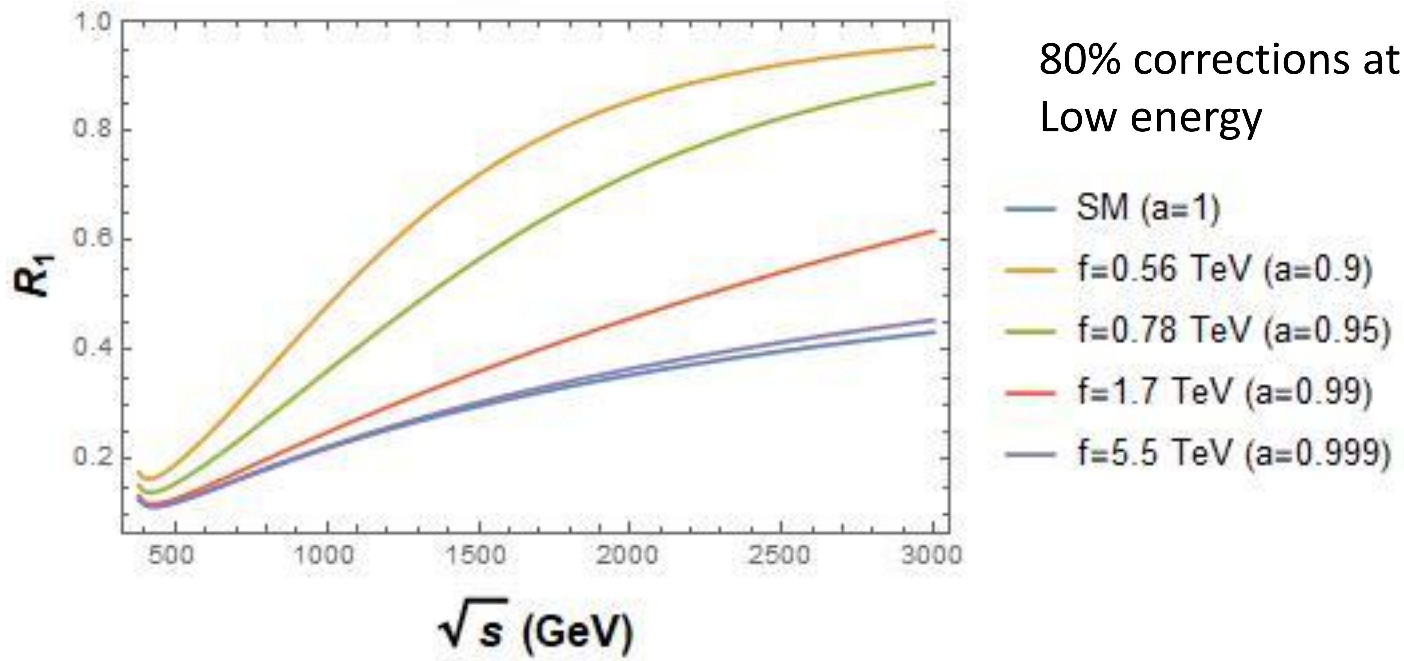
$$a^* = c_1^* = \sqrt{1-\xi}$$



40-90 % corrections at low energy

R1 is significally smaller than R0

a1 more sensitive to fermion corrections



80% corrections at Low energy

5. Conclusions

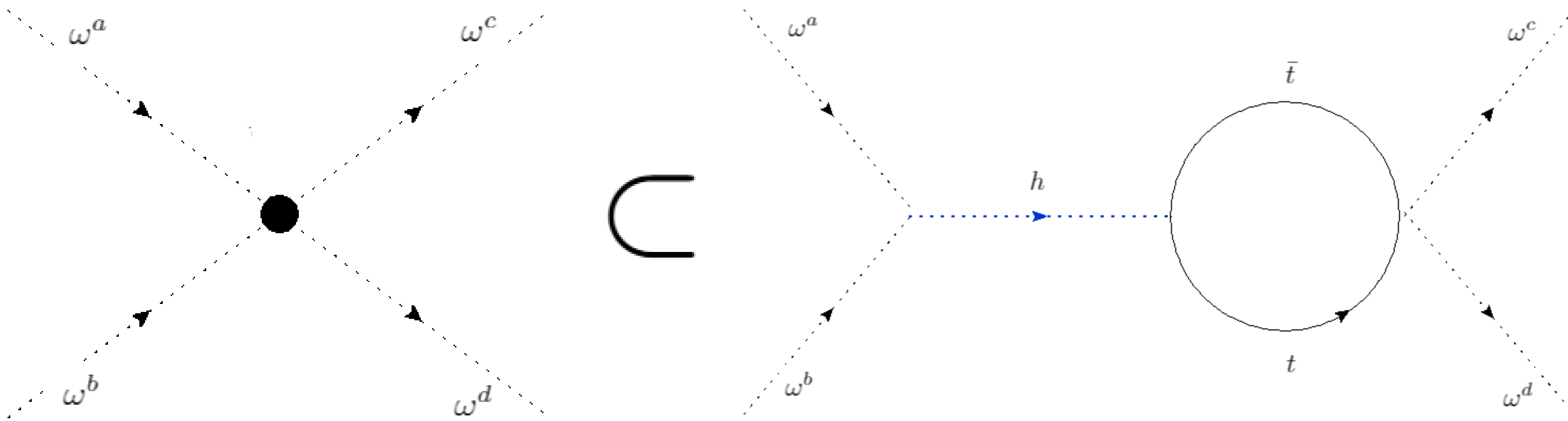
- We estimate fermion corrections to WW scattering: negligible in most of the parameter space but not always.
- For instance, the PWA's:

a_0	70-85% %	a=b=1, c_1=0.9 $\pm$0.01	$\sqrt{s}$ $\in$ [1.5,3]TeV
a_1	85-99%	a=1.02 $\pm$0.01	$\sqrt{s}$ $\in$ [1.5,3]TeV

- The MCHM shows R1 significally smaller than R0 and its more sensitive to the fermion corrections.
- Future work: HH and ZZ intermediate states beyond the Equivalence Theorem.

Thank you.

Backup slides



The scattering includes loops with different point functions (3-point above)

- We will do this by using a Electroweak Chiral Lagrangian **(Effective Field Theory)** introducing new Higgs couplings and modifying the existing ones.
- Scattering and other processes will depend on these effective couplings.

3. One-loop contributions

- <u>Effective action</u>

$$\delta[\omega, h, \bar{Q}, Q] = \delta_0[\omega, h] + S_{YK}[\omega, h, \bar{Q}, Q]$$

Integrating out the quarks field

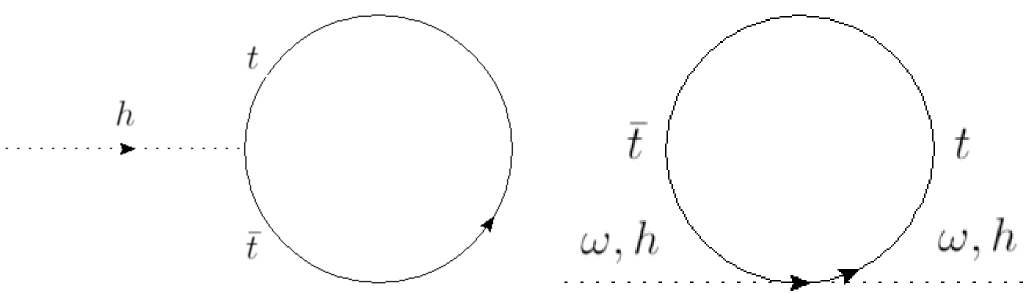
$$e^{i\Gamma[\omega,h]} = \int [d\bar{Q}][dQ] e^{i\delta[\omega,h,\bar{Q},Q]} = e^{i\delta_0} \int [d\bar{Q}][dQ] e^{<\bar{Q}AQ>} = e^{i\delta_0} \det \mathrm{A}$$

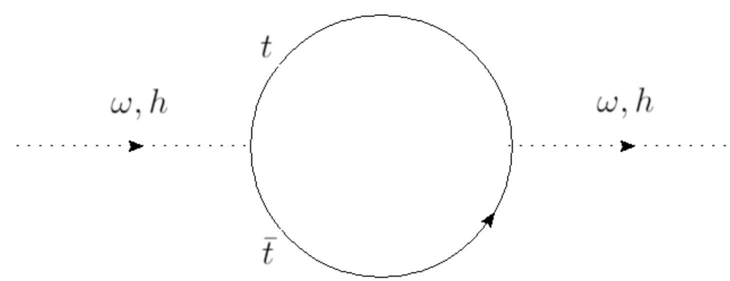
$$\Delta\Gamma = -i\mathrm{Tr}\,(\log \mathrm{A})$$

Systematic expansion of one loop functions depending on numbers of points

$$\Delta\Gamma = \Delta\Gamma^{(1)} + \Delta\Gamma^{(2)} + \ldots$$

- <u>By computing the relevant Feynman diagrams</u> (up to two-points)





$\Delta\Gamma^{(1)}$

1-point

$\Delta\Gamma^{(2)}$

2-point

The lagrangian for our case is

$$V(h) = \lambda_1 v^3 h + \frac{1}{2} m_h^2 h^2$$

$$\mathscr{L}_2 = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{1}{2}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right)\partial_\mu \omega^i \partial^\mu \omega_j \left(\delta_{ij} + \frac{\omega_i \omega_j}{v^2}\right)$$

Higgs + GB

$$- \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2}\right)\Bigg[\sqrt{1 - \frac{\hat{\omega}^2}{v^2}}(M_t\bar{t}t + M_b\bar{b}b) + i\frac{\omega^0}{v}\left(M_t\bar{t}\gamma^5 t - M_b\bar{b}\gamma^5 b\right)$$
$$+ i\frac{\omega^1}{v}\left(\bar{t}(M_b P_R - M_t P_L)b + \bar{b}(M_t P_R - M_b P_L)t\right)$$
$$\frac{\omega^2}{v}\left(\bar{t}(M_b P_R - M_t P_L)b + \bar{b}(M_b P_L - M_t P_R)t\right)\Bigg]$$

Yukawa sector

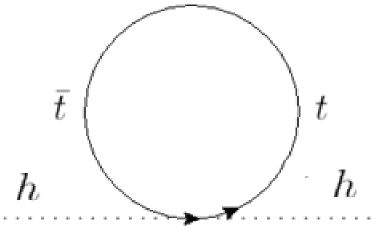
Effective couplings c_1 and c_2

$$\sqrt{1 - \frac{\hat{\omega}^2}{v^2}} \simeq 1 - \frac{\hat{\omega}^2}{2v^2}$$

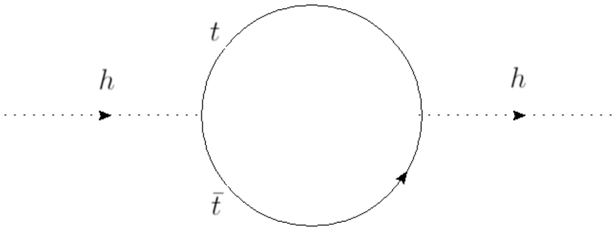
No mass terms for the ω's-> GB behaviour

Expand up to $\overline{\omega}^2$

Different coupling of ω to t and b ⇒ Custodial Symmetry is broken



$$= -i\frac{c_1 M_t}{v}\int \frac{d^4k}{2\pi^4}\frac{\mathrm{Tr}[i(\not{k}+M_t)]}{k^2-M_t^2}$$



$$= \left(\frac{-ic_1 M_t}{v}\right)^2\int \frac{d^4k}{2\pi^4}\frac{\mathrm{Tr}[i(\not{k}+\not{p}+M_t)i(\not{k}+M_t)]}{[(k+p)^2-M_t^2][k^2-M_t^2]}$$

These diagrams lead to divergences. They are computed with the help of the well known Passarino-Veltman functions

$$A_0(M^2) = \frac{2\pi\mu^{(4-D)}}{i\pi^2}\int d^Dk\frac{1}{k^2-M^2}$$

$$B_0(p^2, M_1^2, M_2^2) = \frac{2\pi\mu^{(4-D)}}{i\pi^2}\int d^Dk\frac{1}{k^2-M_1^2}\frac{1}{(k+p^2)-M_2^2}$$

μ^2 regulator

$$\Delta = \frac{2}{\epsilon} + \ln 4\pi - \gamma_E$$

The divergent part is

$$\Gamma^{(1)+(2)}_{Div} = \frac{M_t^2+Mb^2}{(4\pi)^2}\Delta\left[\frac{{c_1}^2}{v^2}h(-\Box)h+\frac{\omega^i}{v}(-\Box)\frac{\omega^i}{v}\right]-\frac{M_t^4+Mb^4}{(4\pi)^2}\Delta\left[(4c_2+6{c_1}^2)\frac{h^2}{v^2}+4c_1\frac{h}{v}\right]$$

No GB mass terms present

[3] **Complete One-Loop Renormalization of the Higgs-Electroweak Chiral Lagrangian** -G. Buchalla, O. Cata, A. Celis, M. Knecht, C. Krause (2017)

4. Corrections

Operators we use for renormalization

$$\mathscr{L}_2 = \frac{1}{2} h(-\Box - m_h^2)h + \frac{1}{2}\omega^i(-\Box)\omega^i - \lambda v^3 h$$

Renormalization method

$$Z_h = 1 - 3\frac{(M_t^2 + M_b^2){c_1}^2}{8\pi^2 v^2}\Delta$$

$$Z_\omega = 1 - 3\frac{(M_t^2 + M_b^2)}{8\pi^2 v^2}\Delta$$

$$\delta m_h = -3\frac{(M_t^4 + M_b^4)}{4\pi^2 v^2}(2c_2 + 3{c_1}^2)\Delta$$

<u>Corrections to Higgs mass</u>

(M_b=0)

$$M_{0h}^2 = M_h^2\left(1 + \frac{M_t^2 c_1^2}{8\pi^2 v^2}\Delta\right) - \frac{M_t^4}{4\pi^2 v^2}(2c_2 + 3{c_1}^2)\Delta$$

Dependence on the new Higgs couplings from the EFT c_1 and c_2

$$\rho = \frac{M_W^2}{M_Z^2 \cos{\theta_W}^2} \Rightarrow \rho = \frac{Z^{1,2}}{Z^0} \simeq 1 + 3\frac{M_b^4 - 2M_b^2 M_t^2 \log(M_b^2/M_t^2) - M_t^4}{16\pi^2 v^2\left(M_b^2 - M_t^2\right)}$$

[4] W. Hollik, Precision tests of the electroweak theory, Part I, CERN-TH 5661/90

When M_b is different from M_t, → Custodial Symmetry is broken

In particular for M_b-> 0

$$\rho \simeq 1 + 3\frac{M_t^2}{16\pi^2 v^2}$$

[5] Top quark effects on WW scattering – Dawson and Valencia (1990)

ω^0 and $\omega^{1,2}$get different contributions. →

$$\underbrace{a_0 \frac{v^2}{4}\partial_\mu \omega^0 \partial^\mu \omega_0}_{\mathscr{L}_4}$$

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

$\mathscr{L}_4$ New operator of chiral dimension 4

[5] Effective Field Theory – A.Pich (1994)

The finite one-loop contribution in the limit M_b-> 0 is

$$\begin{aligned}\mathscr{L}_2^{loop} = & -4c_1 M_t^4 \left(\ln(\mu^2/M_t^2)+1\right)\frac{h}{v} - 2M_t^4\left[2{c_1}^2\Lambda(p^2,M_t,M_t) + (3{c_1}^2+2c_2)\ln(\mu^2/M_t^2) + 5{c_1}^2+2c_2\right]\frac{h^2}{v^2} \\ & + h\frac{{c_1}^2 M_t^2(-\Box)(\Lambda(p^2,M_t,M_t)+\ln(\mu^2/M_t^2)+2)}{v^2}h \\ & + w_a \frac{M_t^2(-\Box)(\ln(\mu^2/M_t^2)))}{v^2} w^a + (\omega_1+\omega_2)\frac{M_t^2(-\Box)}{2v^2}(\omega^1+\omega^2)\end{aligned}$$