Fermion and boson loops in VBS
(in the context of HEFT)
based on arxiv.2207.01458

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1. Introduction

- Higgs couplings to gauge bosons and **top quark** are still compatible with the SM with deviations of ***O* (10%).** For other fermions (e.g **bottom**) and the triple-Higgs coupling **larger** deviations are not excluded .[1]
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- These deviations may come **from strongly interacting new physics**, where the Higgs boson and the Goldstone Bosons are composite states.

- We address the boson and heavy fermion loop corrections to **VBS, top and bottom quark**. In particular, fermion corrections are often neglected because the bosons dominate at high energy. (~ 3 TeV).

Questions:

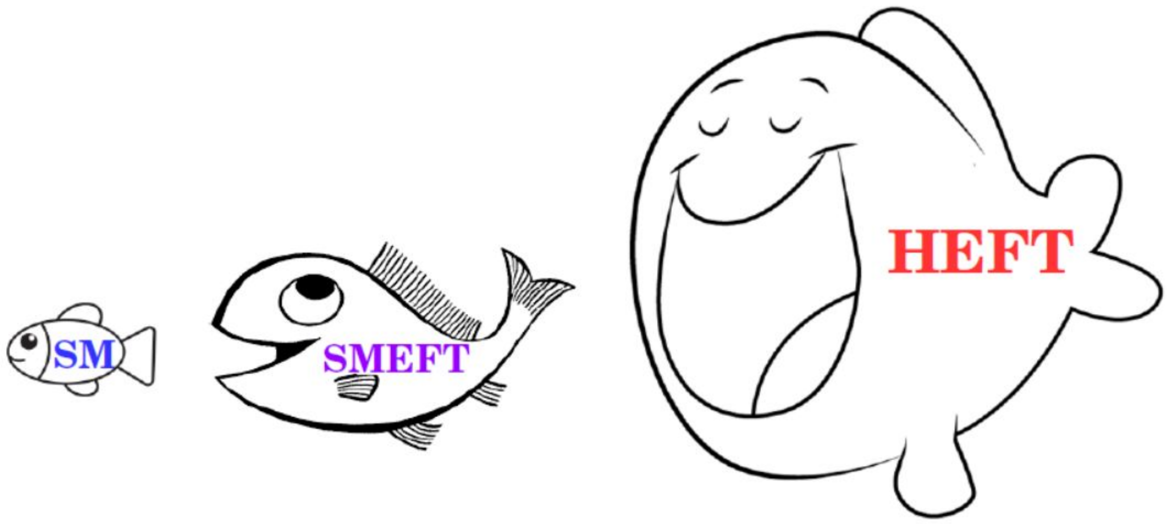
- **What can we do with these strongly interacting amplitudes that break unitarity?**
- **What is the impact of heavy fermions?**

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

2. Quick EFT Recap

- Models (SUSY, MCHM, 2HDM, etc).
- The existence of this desert of new states (energy gap) suggests the use of Effective Field Theories (EFT).

  - Standard Model Effective Field Theory (SMEFT).
  - Higgs Effective Field Theory (HEFT = EChL + Higgs).



[By Felipe llanes-Estrada]

is SMEFT enough? T. Cohen, N. Craig, X. Lu, D. Sutherland. JHEP 03 (2021) 237

R. Alonso, E. Jenkins, A.V Manohar.Phys.Lett.B 754 (2016) 335-342

R. Gómez-Ambrosio, Felipe J. Llanes-Estrada, Alexandre Salas-Bernárdez, J.J. Sanz-Cillero. Phys.Rev.D 106 (2022) 5, 5

3. Higgs Effective Field Theory (HEFT)

HEFT= EChL + Higgs

Spherical parametrization

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

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

$$\mathscr{L}_S = \frac{v^4}{4}\mathscr{F}(h)\mathrm{Tr}\{\partial_\mu U^\dagger \partial^\mu U\} + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)\,,$$

Derivative interactions

$$\mathscr{L}_{\mathrm{kin-F}} = i\bar{t}\partial\!\!\!/\, t \,+\, i\bar{b}\partial\!\!\!/\, b\,,$$

$$\mathscr{L}_{\mathrm{Yuk}} = -\mathscr{G}(h)\Bigg[\sqrt{1 - \frac{\omega^2}{v^2}}(M_t\bar{t}t + M_b\bar{b}b) + i\frac{\omega^0}{v}\left(M_t\bar{t}\gamma^5 t - M_b\bar{b}\gamma^5 b\right) + i\frac{\sqrt{2}\omega^+}{v}\left(M_b\bar{t}P_R b - M_t\bar{t}P_L b\right) + i\frac{\sqrt{2}\omega^-}{v}\left(M_t\bar{b}P_R t - M_b\bar{b}P_L t\right)\Bigg]$$

$$\partial_\mu,\ M_W,\ M_Z,\ M_h \sim \mathcal{O}(p)$$

$$D_\mu U,\ V_\mu,\ g' v \mathcal{T},\ \hat{W}_\mu,\ \hat{B}_\mu \sim \mathcal{O}(p)$$

$$\hat{W}_{\mu\nu}\,,\ \hat{B}_{\mu\nu} \sim \mathcal{O}(p^2)$$

Ordered by chiral dimension

Validity up to ~ 3 GeV = 4 π v

$$\mathscr{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots \qquad \mathscr{G}(h) = 1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \dots \qquad V(h) = v^4 \sum_{n=3}^{\infty} V_n \left(\frac{h}{v}\right)^n$$

for

$$a = b = c_1 = d_3 = 1$$

$$c_2 = c_3 = \dots c_n = 0$$

$$V_2 = \frac{M_h^2}{2v^2}, V_3 = d_3\frac{M_h^2}{2v^2}, \quad V_4 = \frac{M_h^2}{8v^4}, \quad V_{n>4} = 0$$

Recover the SM

NLO lagrangian

R. L. Delgado
doi:10.1007/978-3-319-60498-5

$$
\begin{aligned}
\mathcal{L}_4 = {} & a_4[\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5[\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)^2 \\
& + \frac{d}{v^2}(\partial_\mu h \partial^\mu h)\mathrm{Tr}[(D_\nu U)^\dagger D^\nu U] + \frac{e}{v^2}(\partial_\mu h \partial^\nu h)\mathrm{Tr}[(D^\mu U)^\dagger D_\nu U] + \\
& a_1 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}) + i a_2 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]) - i a_3 \mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu, V^\nu]) \\
& + g_t \frac{M_t}{v^4} \partial_\mu \omega^a \partial^\mu \omega^b t\bar{t} + g'_t \frac{M_t}{v^4} \partial_\mu h \partial^\mu h t\bar{t}
\end{aligned}
$$

The equivalence theorem

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

3.1 Boson-loop contributions to VBS

Tree level

$$A(s,t,u) = \frac{1-a^2}{v^2}s$$
$$M(s,t,u) = \frac{a^2-b}{v^2}s$$
$$T(s,t,u) = 0$$

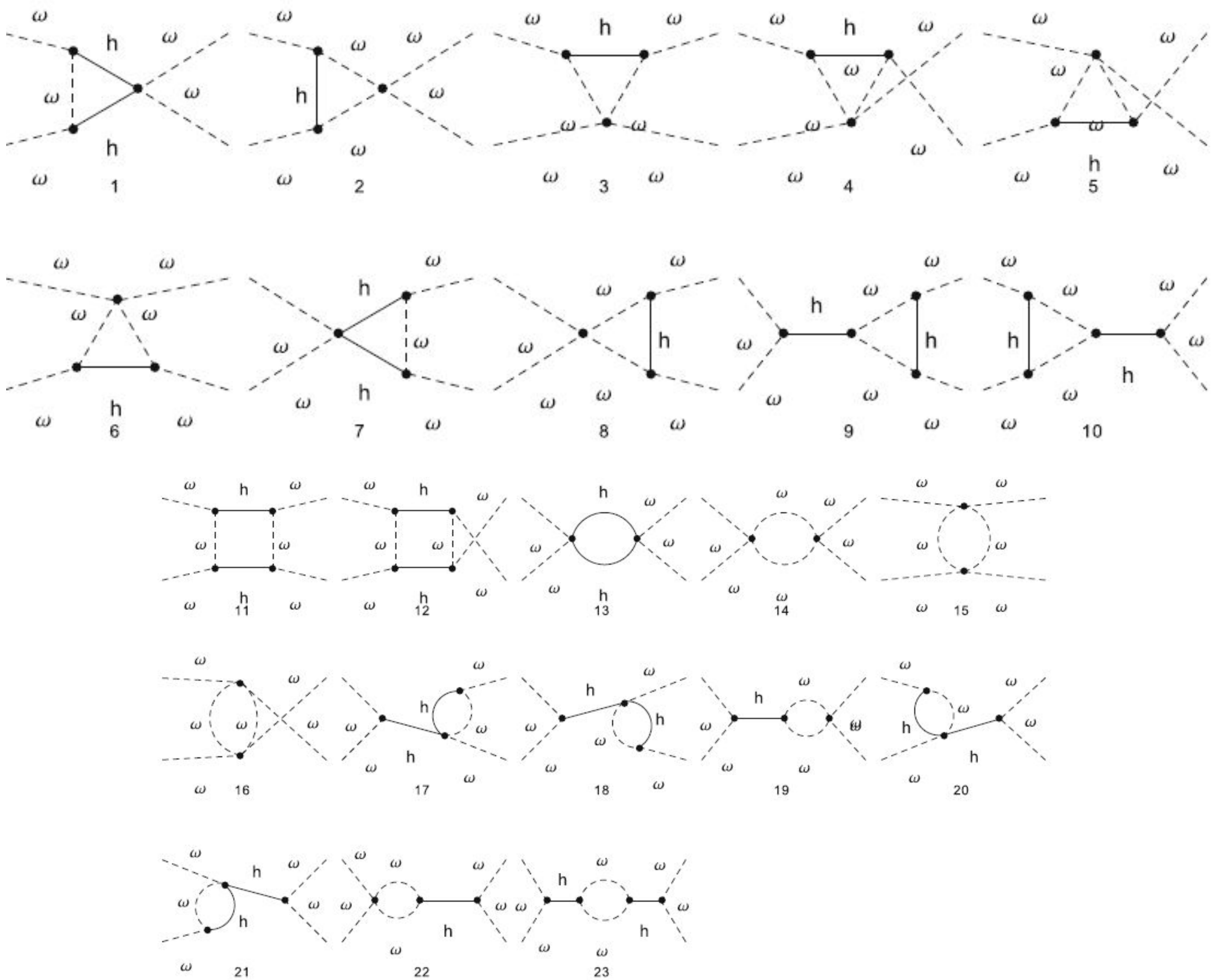
Pure GB scattering

GB GB -> HH

HH -> HH

In the SM these amplitudes are zero but in general they break unitarity

One-loop level for pure GB scattering



We can compute the rest of processes and arrange the Partial Wave Amplitudes (PWA) the interaction matrix

$$A_{IJ} = \mathcal{M}_{IJ}(\omega\omega \to \omega\omega)$$
$$M_J = \mathcal{M}_{0J}(\omega\omega \to hh) = \mathcal{M}_{0J}(hh \to \omega\omega)$$
$$T_J = \mathcal{M}_{0J}(hh \to hh),$$

$$F(s) = \begin{pmatrix} F_{00}(s) & 0 & 0 & 0 & 0 \\ 0 & F_{11}(s) & 0 & 0 & 0 \\ 0 & 0 & F_{20}(s) & 0 & 0 \\ 0 & 0 & 0 & F_{02}(s) & 0 \\ 0 & 0 & 0 & 0 & F_{22}(s) \end{pmatrix}$$

$$F_{0J}(s) = \begin{pmatrix} A_{0J}(s) & M_J(s) \\ M_J(s) & T_J(s), \end{pmatrix}, \; J = 0, 2$$

As we said, in general they break unitarity.
We can apply unitarization procedures like in QCD

$$\text{Im}\,[A_{IJ}(s)] = \sqrt{1 - \frac{4m^2}{s}}[A_{IJ}(s)][A_{IJ}(s)]^*$$

The Inverse Amplitude Method (IAM)

A. Dobado, Maria J. Herrero, Tran N. Truong,.Physics Letters B, Volume 235, Issues 1–2

F^0 tree level , F^1 one-loop

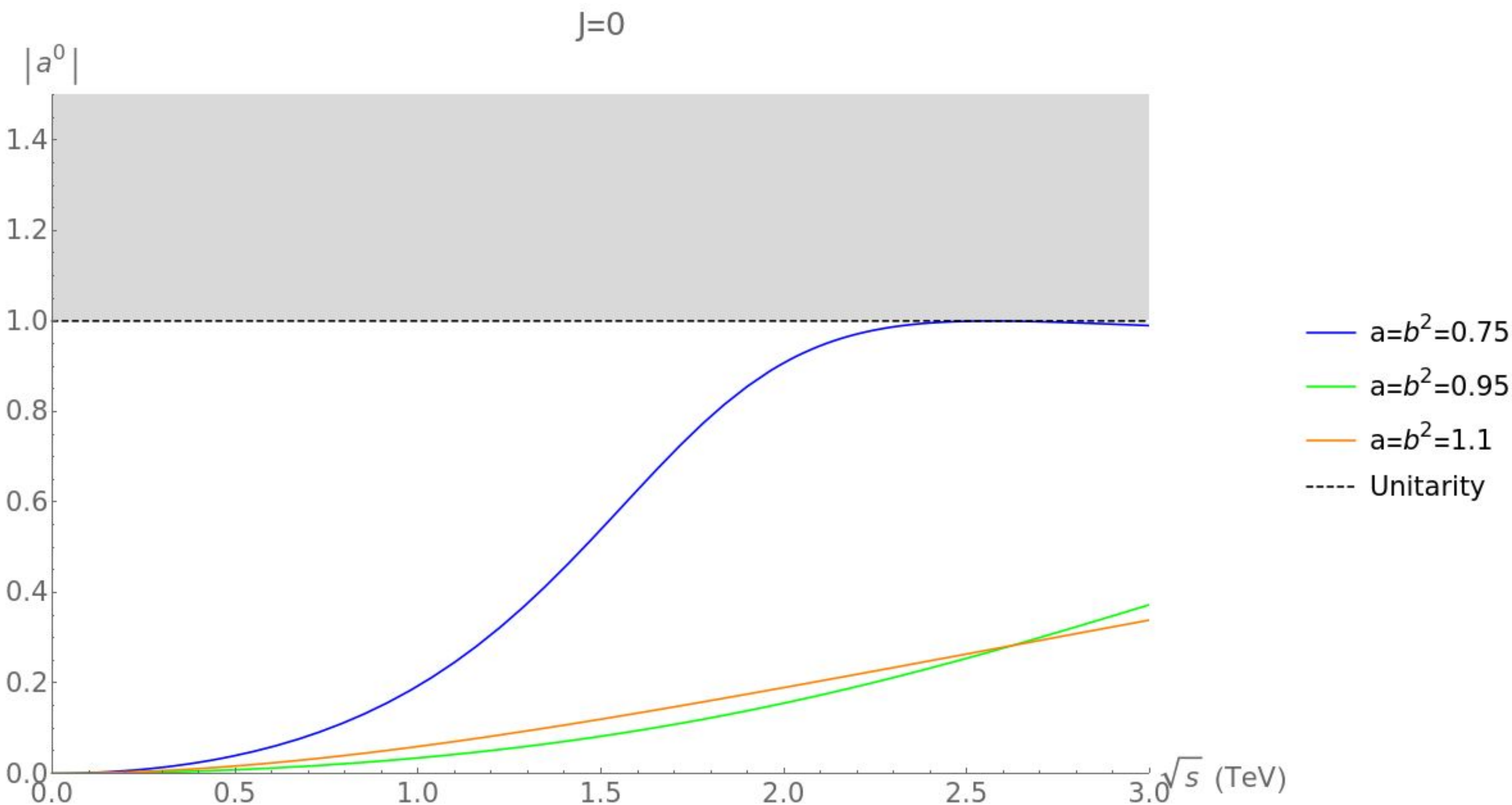
$$F_{\mathrm{IAM}}(s) = [F^{(0)}(s)][F^{(0)}(s) - F^{(1)}(s)]^{-1}[F^{(0)}(s)],$$

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

For a elastic channel

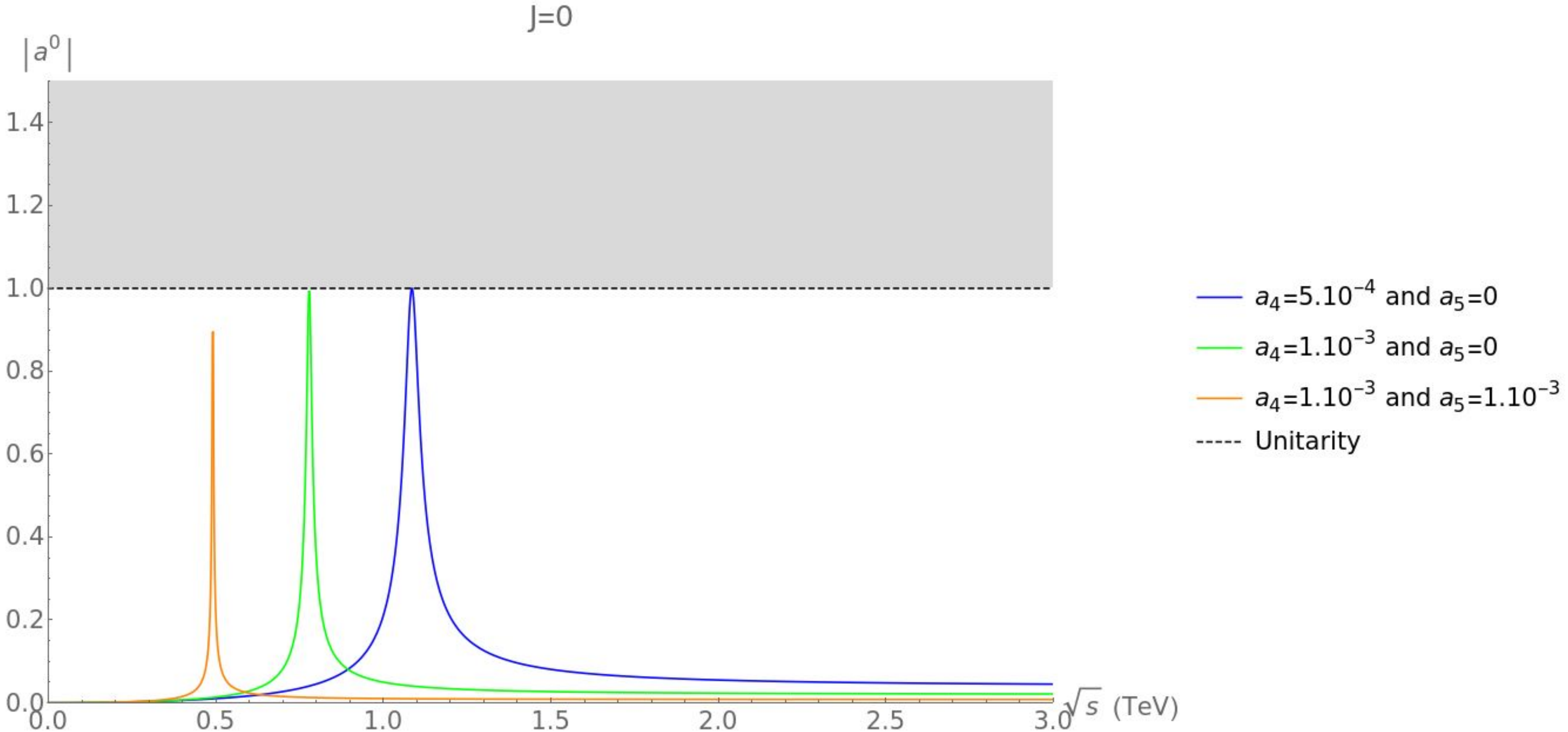
Other methods: N/D method, K matrix/ improved K matrix

Elastic VBS scattering



$a_4 = a_5 = 0$

$a=b^2=0.95$



-Is that all?

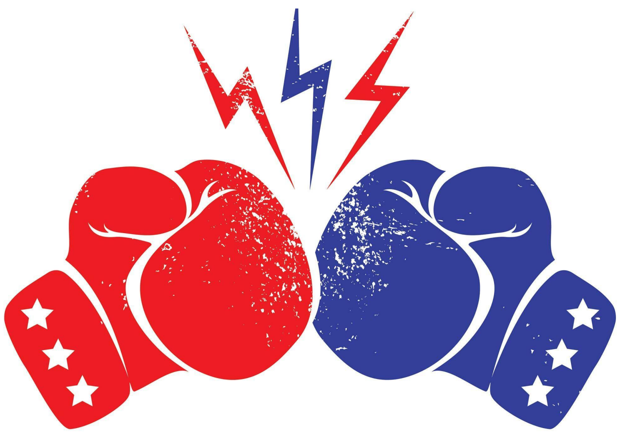
- We have used the naive version of the Equivalence Theorem and neglected all masses.

- What about the fermion loops and Yukawa couplings?

-Are we missing a relevant contribution?

Fermions | **Bosons**

$\mathcal{O}(M_{\mathrm{Fer}}^2 s/v^4)$ **VS** $\mathcal{O}(s^2/v^4)$

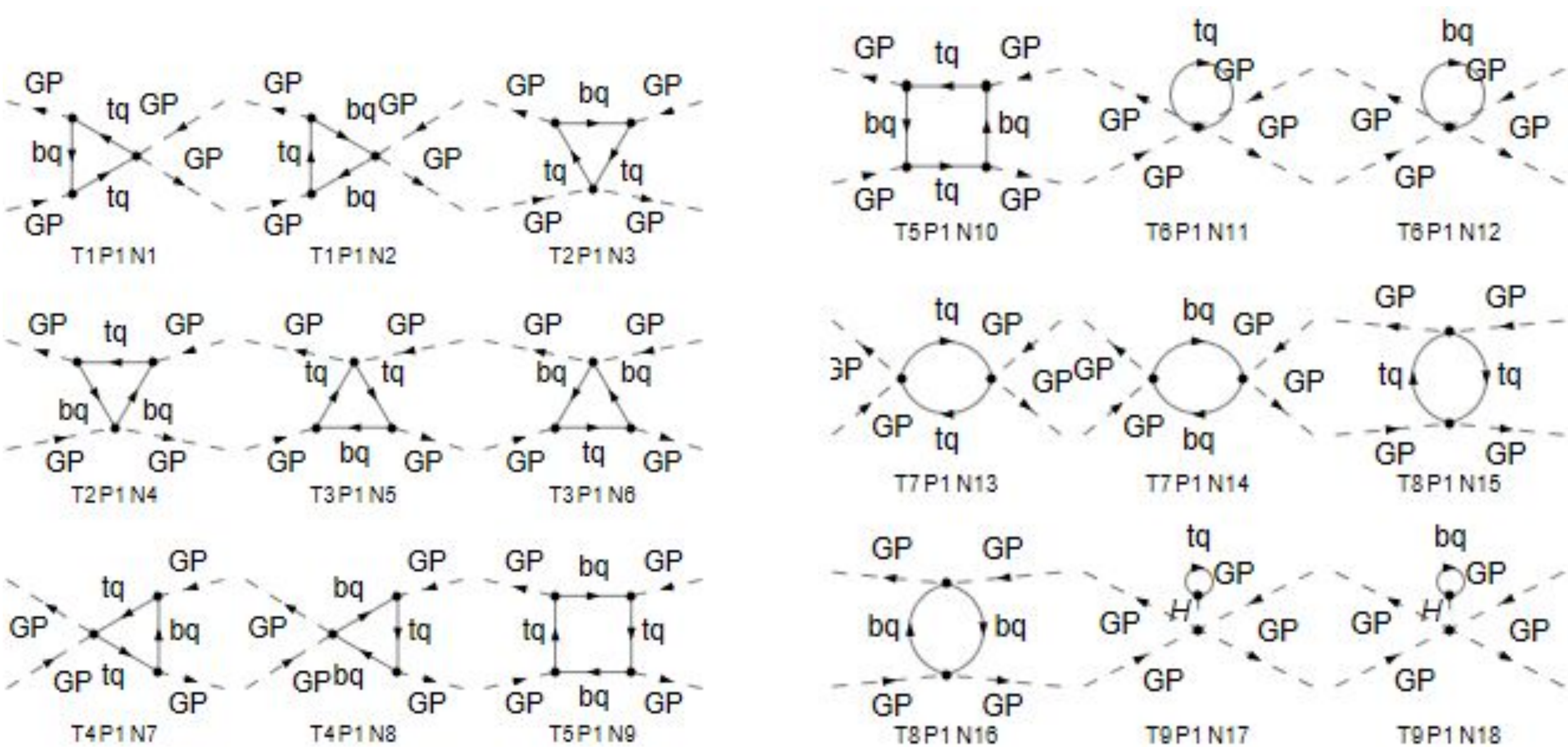


We can expect that bosons will dominate at high energies

3.2 Fermion contributions to VBS

One-loop fermion contribution to $W^+W^- \rightarrow W^+W^-$

Fermions: top and bottom quark



Problems:

-Difficulty to compare directly with the boson-loop contributions in the hard high energy limit without masses and close to the SM.

$$A(s,t,u) = \frac{1-a^2}{v^2}s$$
$$M(s,t,u) = \frac{a^2-b}{v^2}s$$
$$T(s,t,u) = 0$$

- Source of incompatibilities when using a Monte Carlo and failure to yield the crucial cancellations at high energies.

Solution:

-Calculate the real thing (in process).

-Assess the importance of fermion loops through the calculation of the imaginary part of these amplitudes that enters at NLO for the real VBS scattering.

$$\text{Im}\,[T(p_1p_2 \to k_1k_2)] = \sum_{\{a,b\}} \frac{1}{64\pi^2 K_{ab}} \sqrt{1-\frac{4m_{q,ab}^2}{s}} \int d\,\Omega_{\vec{q}}[T(p_1p_2 \to q_{1a}q_{2b})][T(q_{1a}q_{2b} \to k_1k_w)]^*$$

$$Im[Bosons] = Im[a_J]|_{W^+W^-,ZZ,Zh,hh}$$

$$Im[Fermions] = Im[a_J]|_{t\bar{t},b\bar{b}}$$

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

R ~1 → Fermions dominate
R ~0 → Bosons dominate

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

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

$Im[Fermions]$ depend on a and c_1

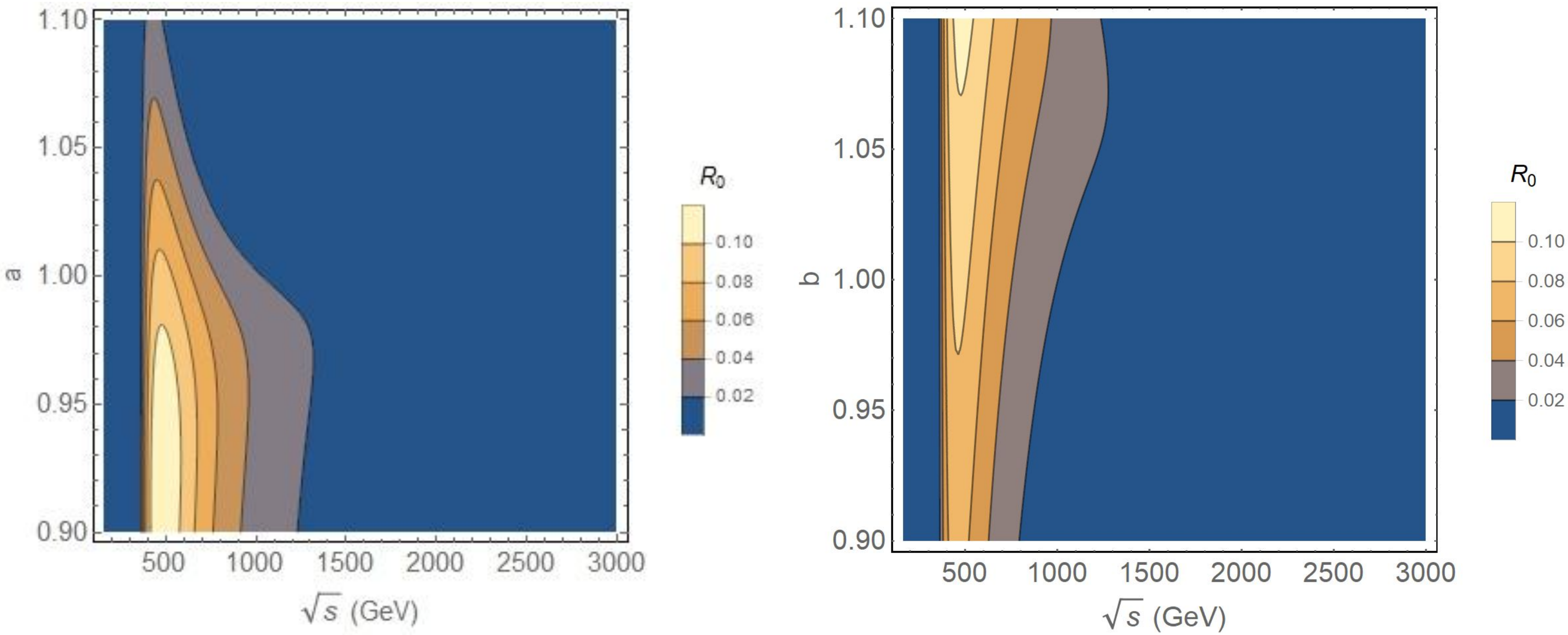
We will alow a 10% deviation from 1

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

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

C.Quezada Calonge, A. Dobado, JJ. Sanz-Cillero arXiv:2207.01458

4.1 Partial wave a_0 (J=0)

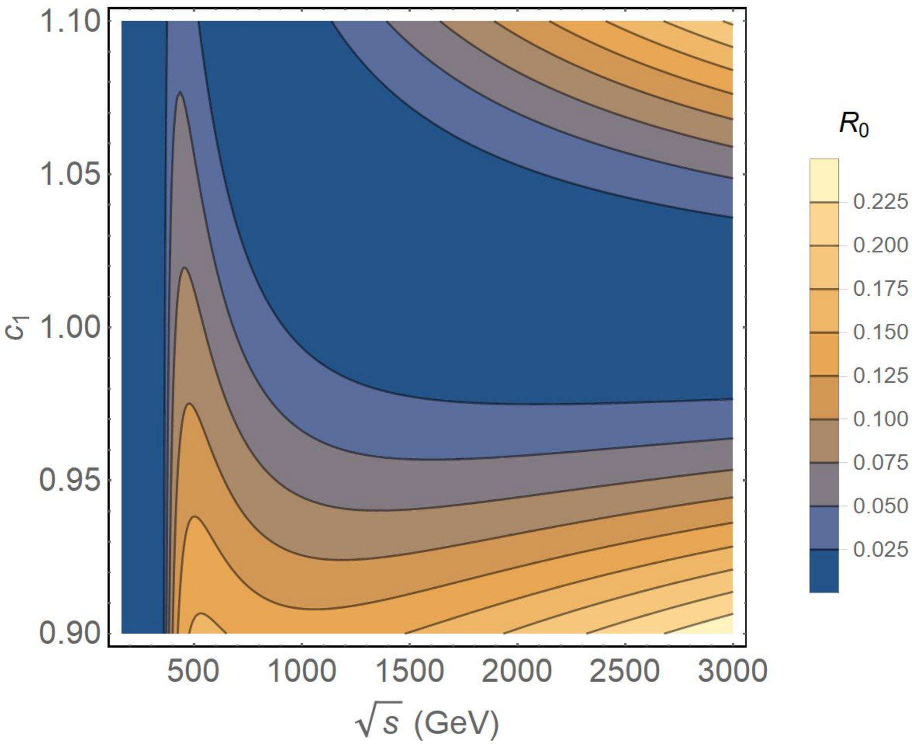


$b = c_1 = d_3 = 1$ $\qquad$ $a = c_1 = d_3 = 1$

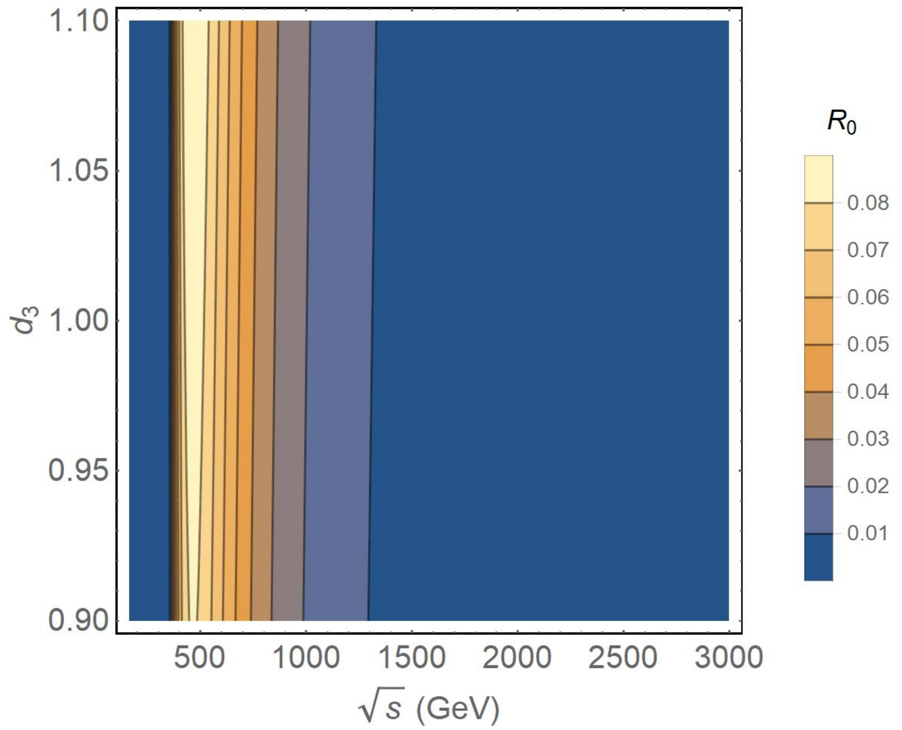
10 % corretions at 500 GeV maximum for *a* =0.9 and *b*=1.1

Bosons completely dominate over 1 TeV for a and b

Expected behavior



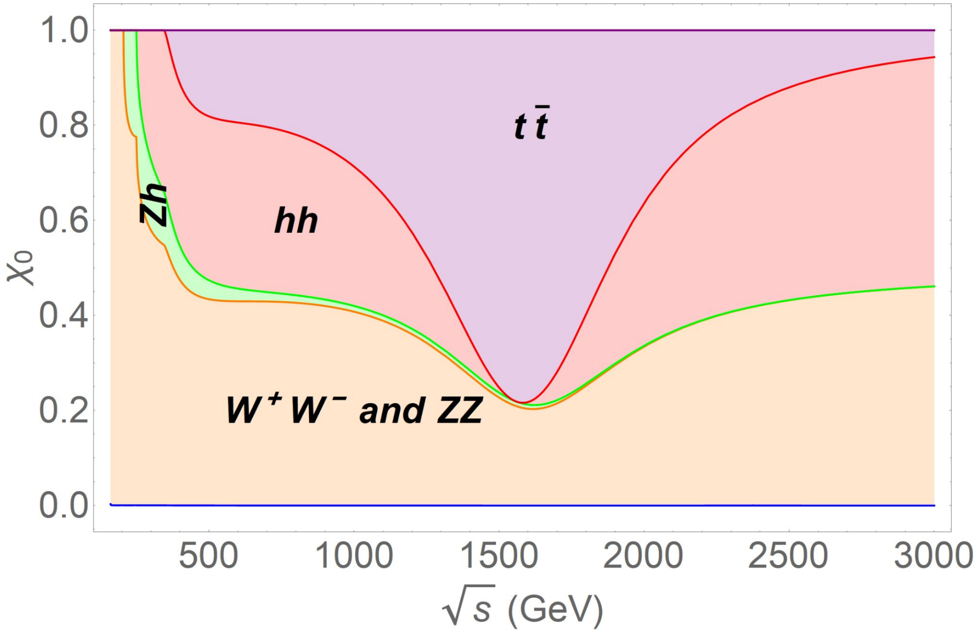
$$a = b = d_3 = 1$$



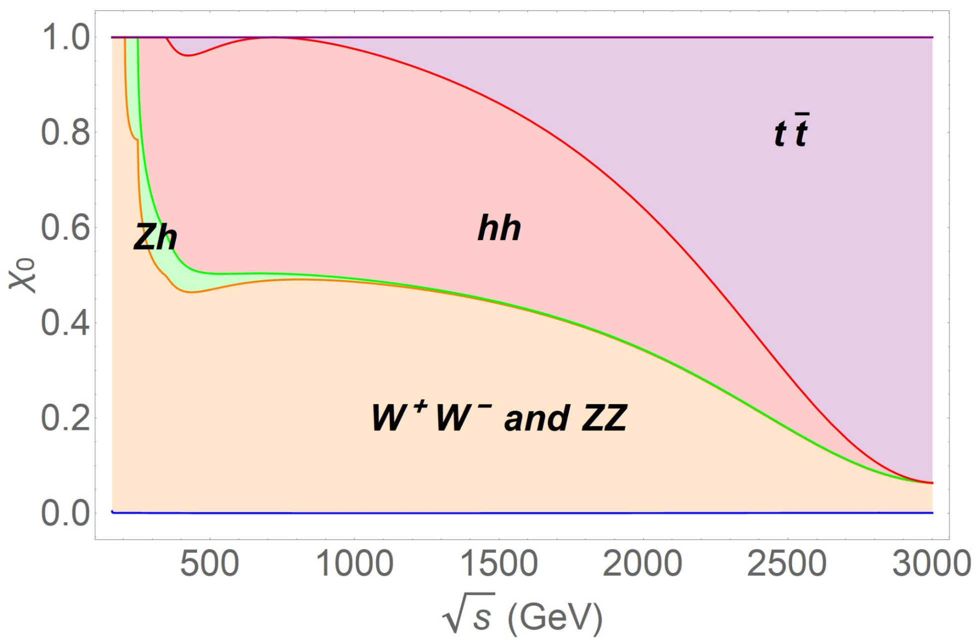
$$a = b = c_1 = 1$$

The value of the triple higgs coupling is not relevant

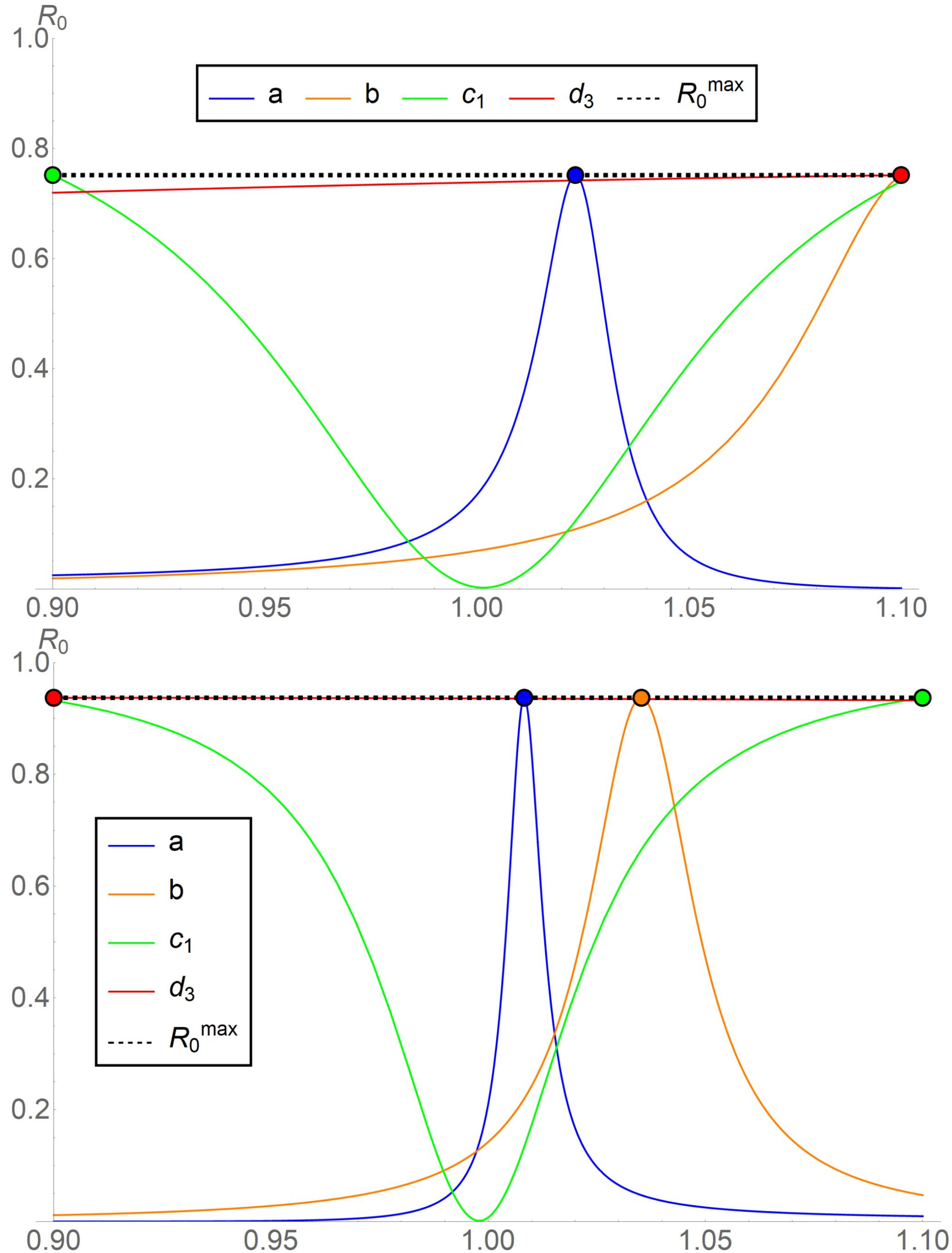
Largest corrections at 1.5 Tev and 3 TeV



$R_0 = 75\%$ for $a = 1.023, b = 1.100$
$c_1 = 0.900, d_3 = 1.100$

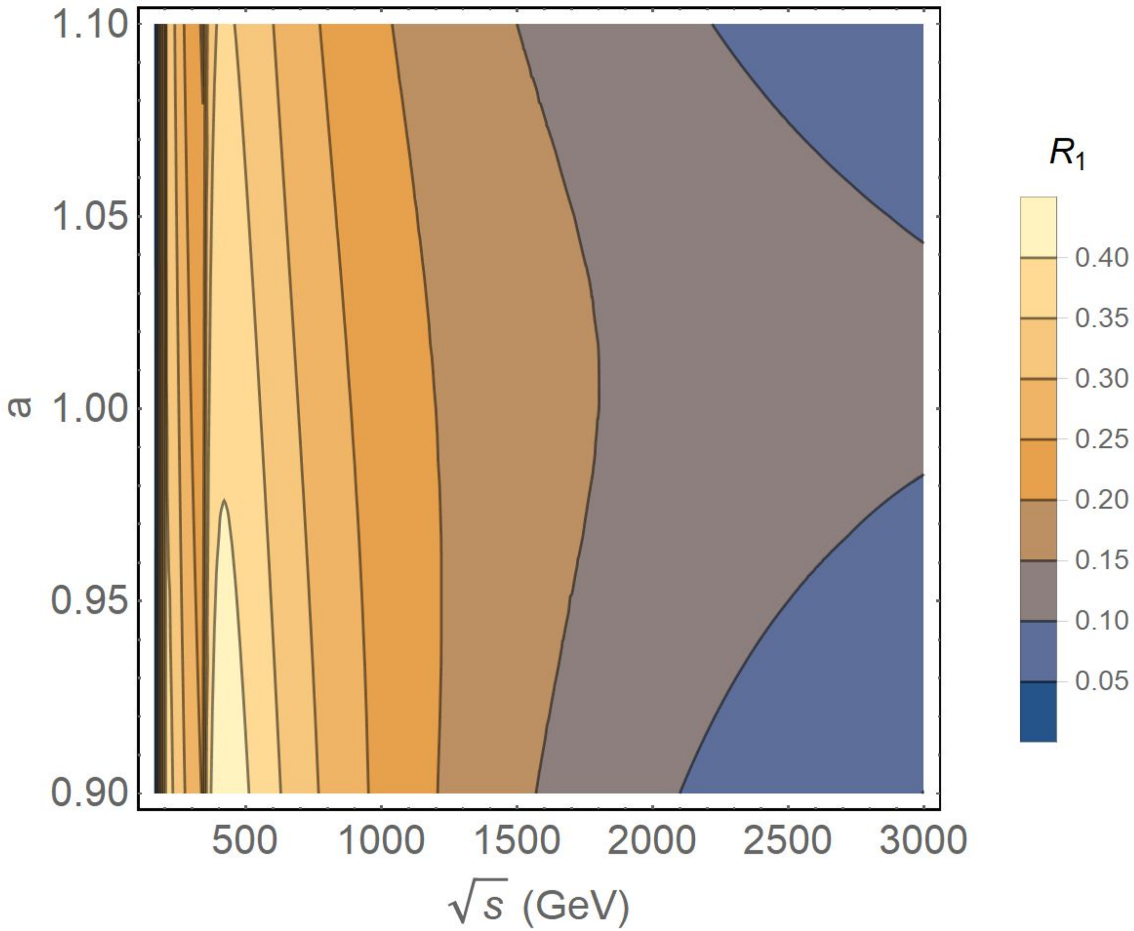


$R_0 = 94\%$ for $a = 1.008, b = 1.035$
$c_1 = 1.100, d_3 = 0.900$



Fine interplay among the couplings

4.2 Partial wave a_1 (J=1)

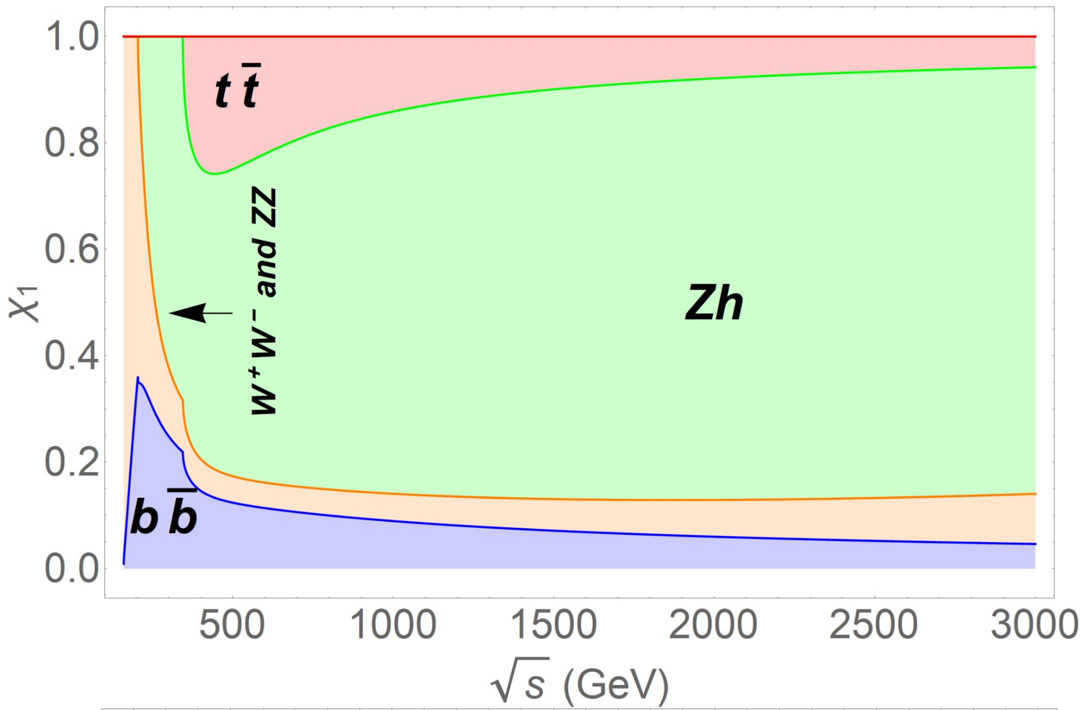


Im[Bosons] = f(a) $\approx \left[\frac{(1-a^2)\string^2s}{96\,\pi v\string^2}\right]^2$

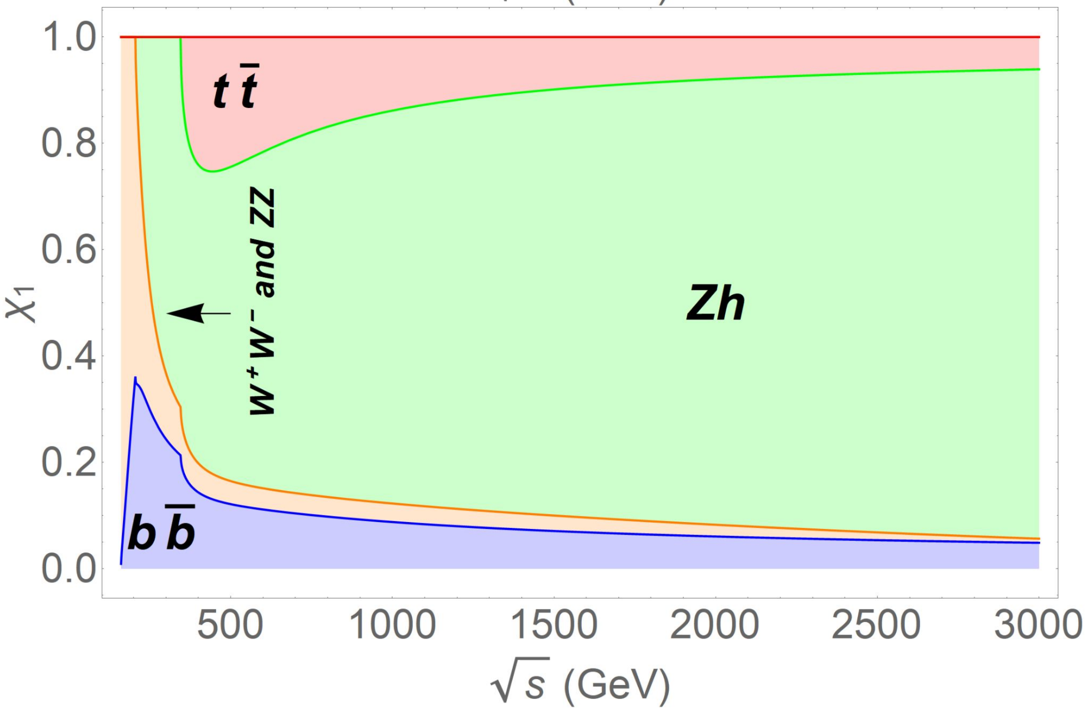
Im[Fermions]=$Im[Fermions]_{SM}$

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

15% corrections for a close to 1



$$R_1 = 17\% \quad \text{for} \quad a = 0.991$$



$$R_1 = 11\% \quad \text{for} \quad a = 1.013$$

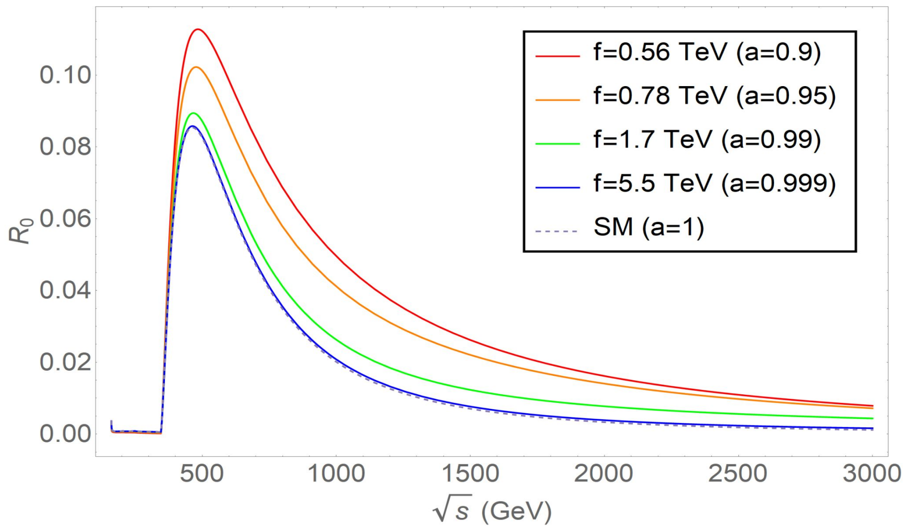
4. Specific Scenarios: Minimal Composite Higgs Model

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

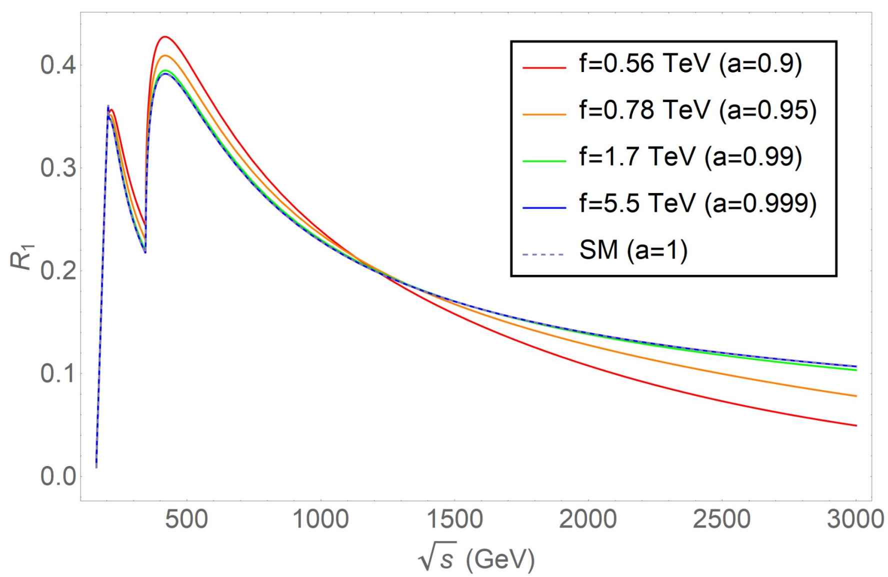
$$\xi = v^2/f^2$$

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

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



Negligible fermion corrections to J=0 in MCHM



10% corrections to J=1 in MCHM

5. Conclusions

- We estimate the imaginary part of fermion corrections to WW scattering: negligible in some of the parameter space but in fact there are regions where fermions dominate over bosons.
- The MCHM shows J=1 is more sensitive to fermion corrections than J=0. J=0 drastically drops when we deal with the MCHM.
- Current work: considering the whole amplitude (real and imaginary) and applying unitarization procedures.

Thank you.