6th Red LHC Workshop

09 – 11 May 2022

Juan José Sanz-Cillero

IPARCOS

UNIVERSIDAD COMPLUTENSE MADRID

WW scattering

work in collaboration with A. Dobado & C. Quezada-Calonge:
2102.01976 [hep-ph]; 2012.12242 [hep-ph]; forthcoming.

in person only

Organizers:
J.A. Aguilar-Saavedra
B. Álvarez González
C. Escobar Ibáñez
S. Heinemeyer
C. Santamarina Ríos

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Our WW scattering calculation

FERMION LOOP CONTRIBUTIONS

work in collaboration with A. Dobado & C. Quezada-Calonge:
2102.01976 [hep-ph]; 2012.12242 [hep-ph]; forthcoming.

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Outline

1.) EW Chiral Lagrangian

2.) Loops: bosons vs. fermions

3.) Conclusions

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

EW Chiral Lagrangian (or HEFT)

- 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.

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

- **HOWEVER:** small BSM deviations ~ corrections to naïve-EqTh (if close to SM)

➔ We needed to go beyond naïve Equivalence Theorem: **physical $W_L W_L$ scattering**

O(p^4) Lagrangian:
(x) Buchalla, Cata, JHEP 1207 (2012) 101;
Buchalla,Catà,Krause, NPB 880 (2014) 552-573
(x) Alonso,Gavela,Merlo,Rigolin,Yepes, PLB 722 (2013) 330-335;
Brivio et al, JHEP 1403 (2014) 024
(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041;
JHEP 1704 (2017) 012;
(x) Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

Basic Works:
(*) Apelquist,Bernard '80; Longhitano '80, '81
(*) Feruglio, Int. J. Mod. Phys. A 8 (1993) 4937
(*) Grinstein,Trott, PRD 76 (2007) 073002

Counting:
* Weinberg '79
* Manohar,Georgi, NPB234 (1984) 189
* Georgi,Manohar NPB234 (1984) 189
* Hirn,Stern '05
* Pich,Rosell,Santos,SC JHEP 1704 (2017) 012
* Buchalla,Catá,Krause PLB 731 (2014) 80-86

For a recent SMEFT vs HEFT comparison:
(*) Gomez-Ambrosio,Llanes-Estrada, Salas-Bernardez,SC, 2204.01763 [hep-ph]

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 + YM + matter

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.

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

→ **Recover the SM**

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

↑

$a = b = 1$

$c_1 = 1$

$c_2 = c_3 = \ldots c_n = 0$

Modifications on the Higgs SM couplings and beyond!

Loops: bosons vs. fermions

- We have calculated the contribution of top quark loops to VBS via the generating functional and diagrammatically
- Renormalized the relevant couplings and fields and compared to the existing literature.
- We have obtained the real and imaginary part of the Partial Wave Amplitudes (PWA) or pseudo-PWA's. Here we focus on the imaginary part

$$T(s,t) = \sum_J 16\pi K (2J+1) P_J(\cos\theta)\, a_J(s)$$

But how important are fermion loops?

The imaginary parts enter in the NLO counting.

In general bosons dominate at high energy $(\sqrt{s} \sim 3$ TeV$)$

A small sample of O(p4) HEFT observable computations:
(x) Herrero,Ruiz Morales, NPB 418 (1994) 431-455
(x) Delgado,Dobado,Llanes-Estrada, PRL114 (2015) 22, 221803
(x) Espriu,Mescia,Yencho, PRD88 (2013) 055002
(x) Delgado,Garcia-Garcia,Herrero, JHEP 11 (2019) 065
(x) Fabbrichesi,Pinamonti,Tonero,Urbano, PRD93 (2016) 1, 015004
(x) Corbett,Éboli,Gonzalez-Garcia, PRD 93 (2016) 1, 015005
(x) de Blas,Eberhardt,Krause, JHEP 07 (2018) 048
(x) Quezada,Dobado,SC, PoS ICHEP2020 (2021) 076; in preparation

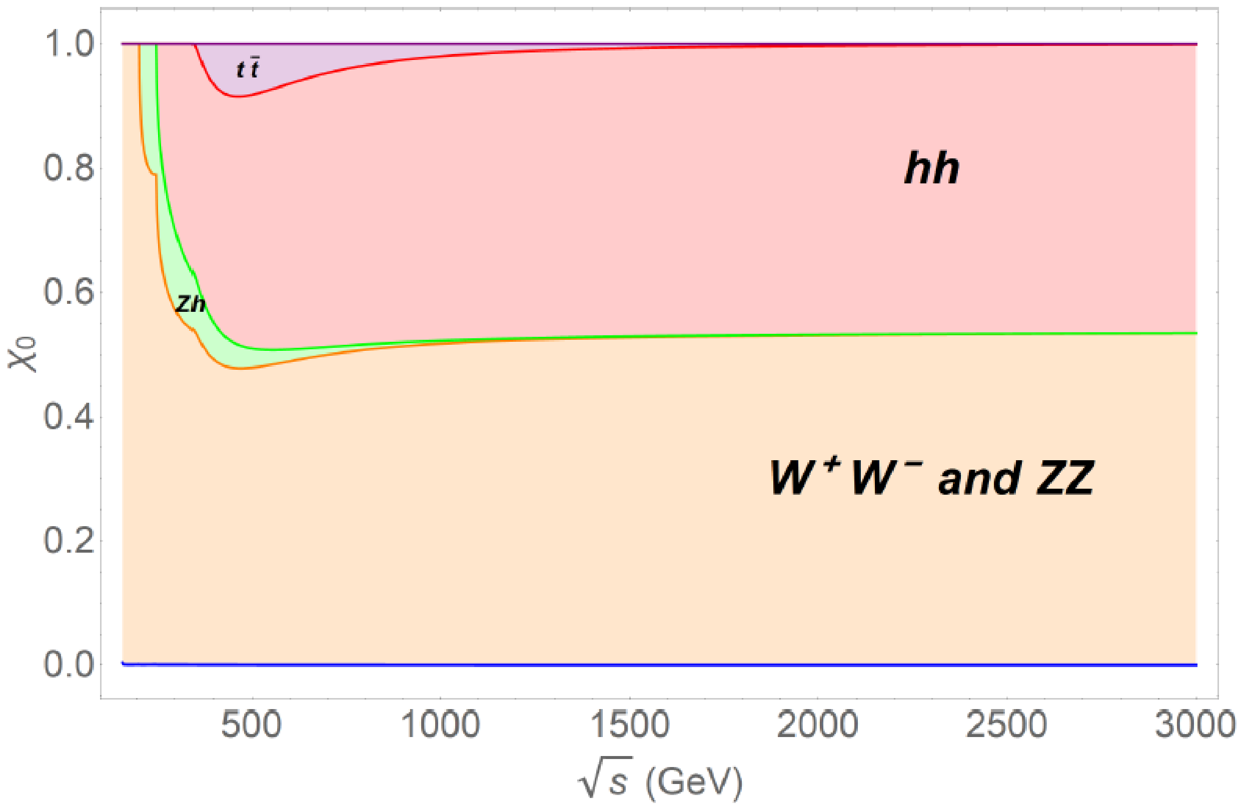
$$\text{Fer}_J = Im[a_J]_{b\bar{b},t\bar{t}}\,,$$
$$\text{Bos}_J = Im[a_J]_{\gamma\gamma,\gamma z,\gamma h,W^+W^-,ZZ,Zh,hh}\,.$$

$$R_J = \frac{\text{Fer}_J}{\text{Bos}_J + \text{Fer}_J} \in [0,1]$$

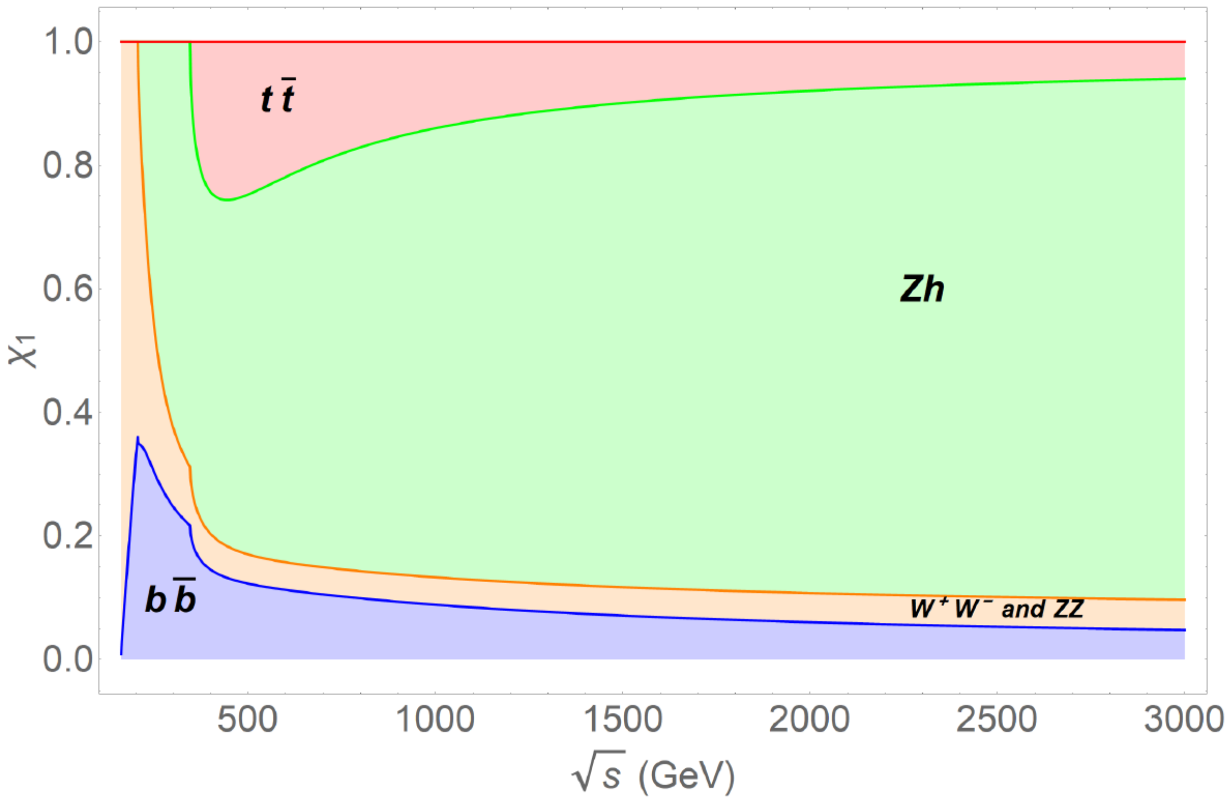
R ~1 → Fermions dominate

R ~0 → Bosons dominate

• SM: small fermion contributions



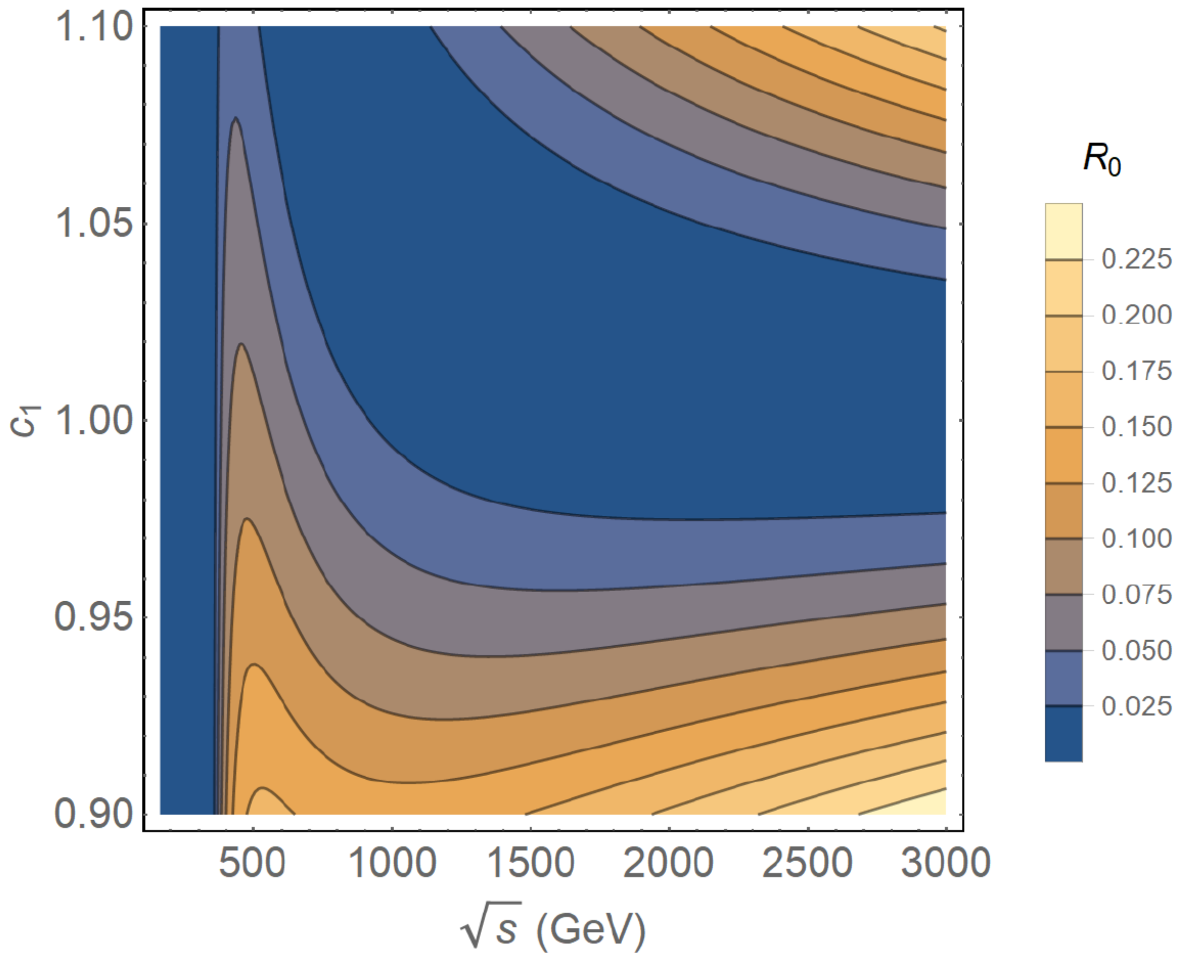
J=0 PWA (g'=0)

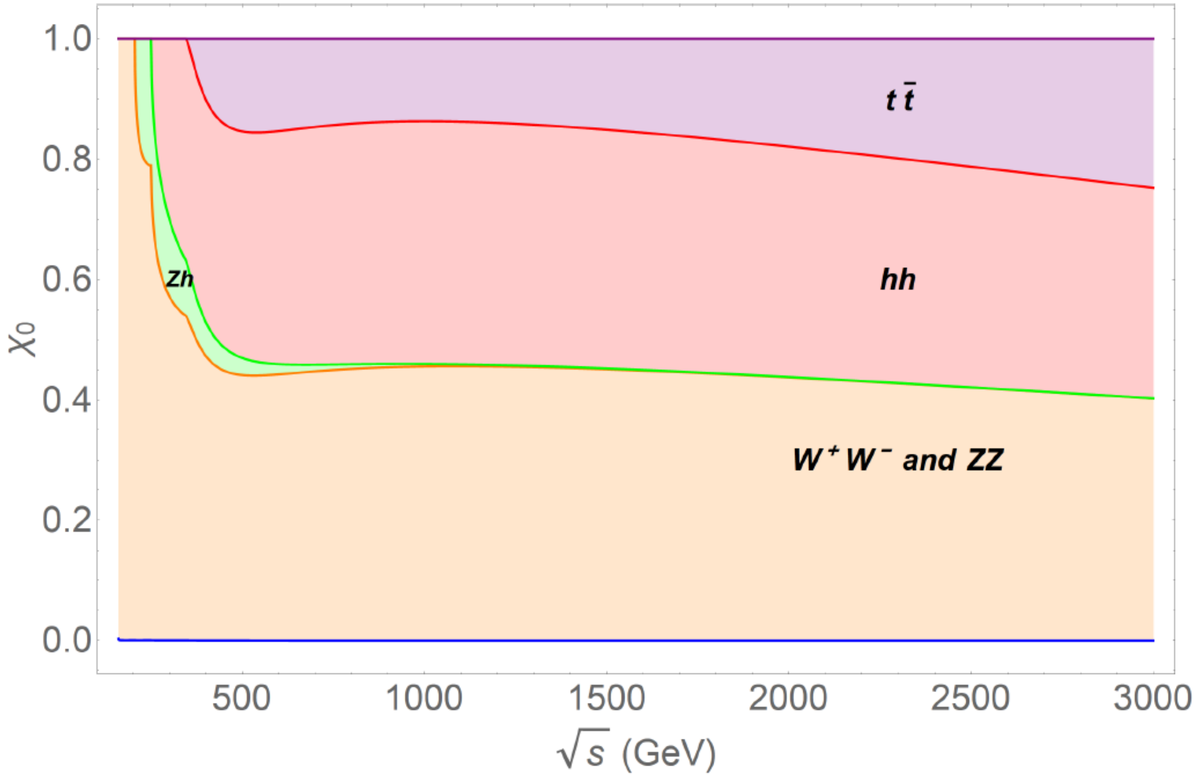


J=1 PWA (g'=0)

• BSM?

J=0 PWA (g'=0)





$a = b = d_3 = 1$ and $c_1 = 0.9$

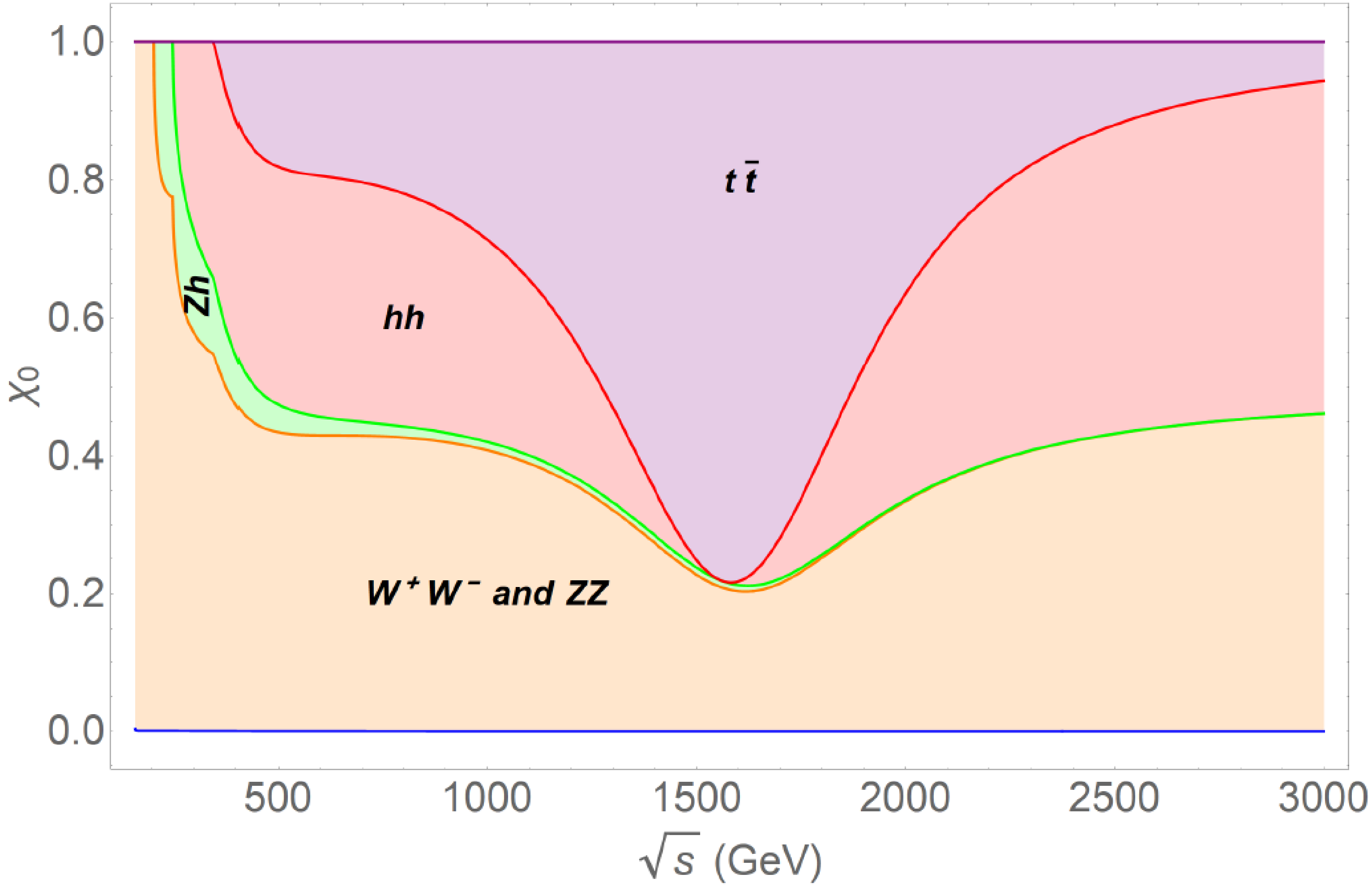
• Also a further detailed analyses of all relevant other variations: a, b, d3, c1

• BSM?

J=0 PWA (g'=0)

- Looking for points of maximal fermion contribution

$E_{opt} = 1.5\ GeV$



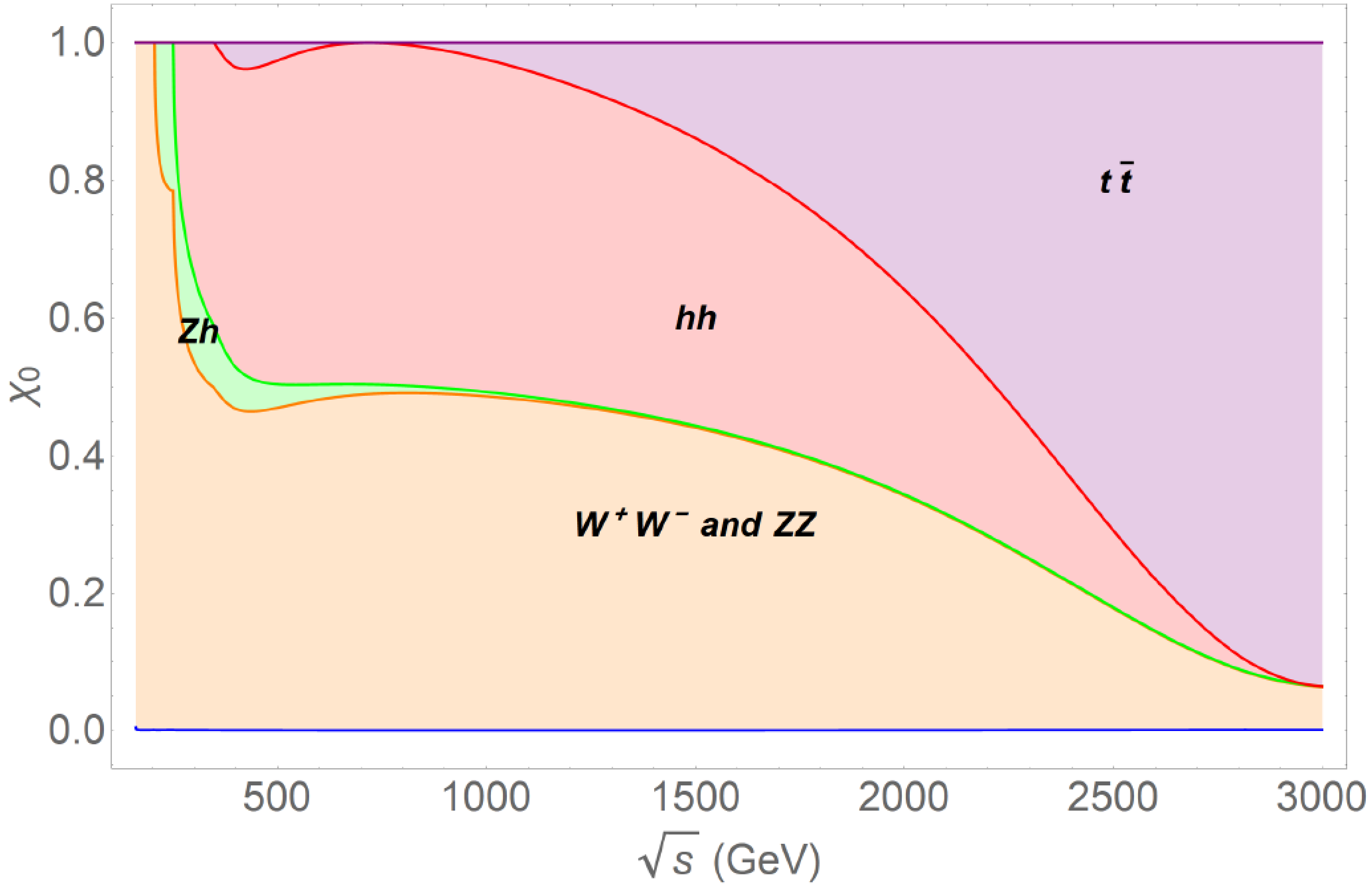
(a) Largest fermion-loop contribution of 75.15% found at 1.5 TeV for J=0 for $a = 1.02$, $b = 1.10$, $c_1 = 0.90$ and $d_3 = 1.1$.

• BSM?

J=0 PWA (g'=0)

- Looking for points of maximal fermion contribution

$E_{opt} = 3\ GeV$

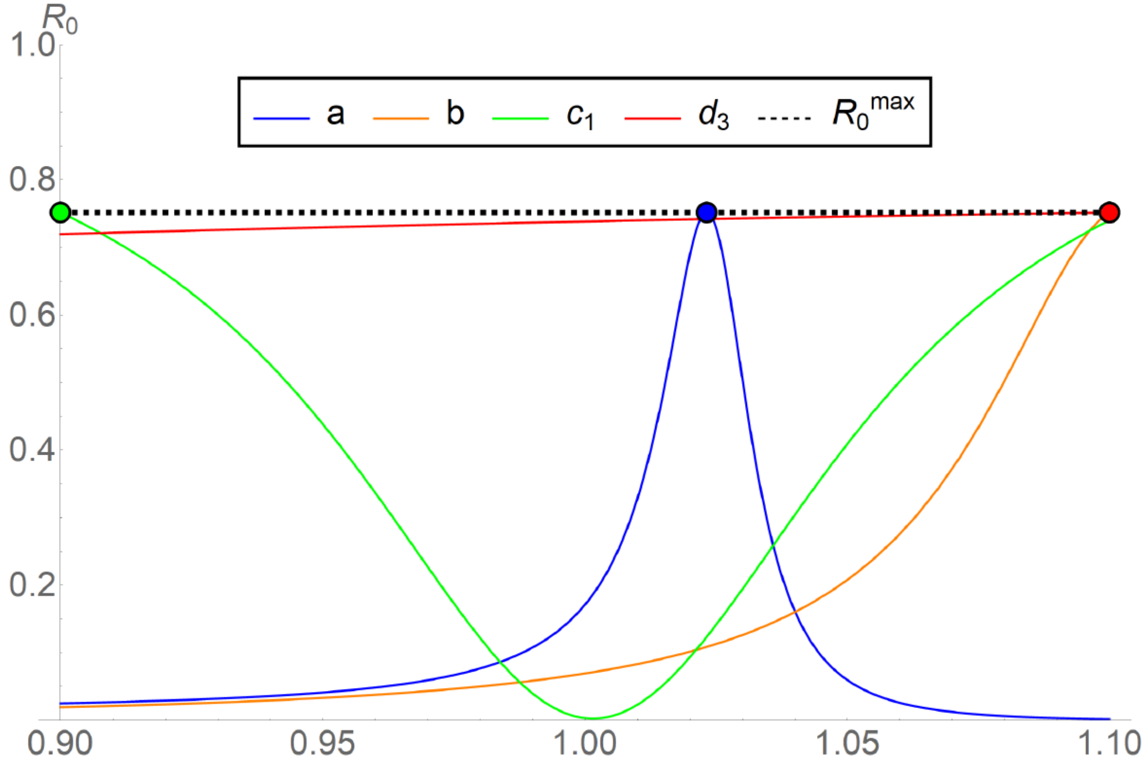


(b) Largest fermion-loop contribution of 93.69% found at 3 TeV for J=0 for $a = 1.01$, $b = 1.06$, $c_1 = 1.10$ and $d_3 = 0.90$.

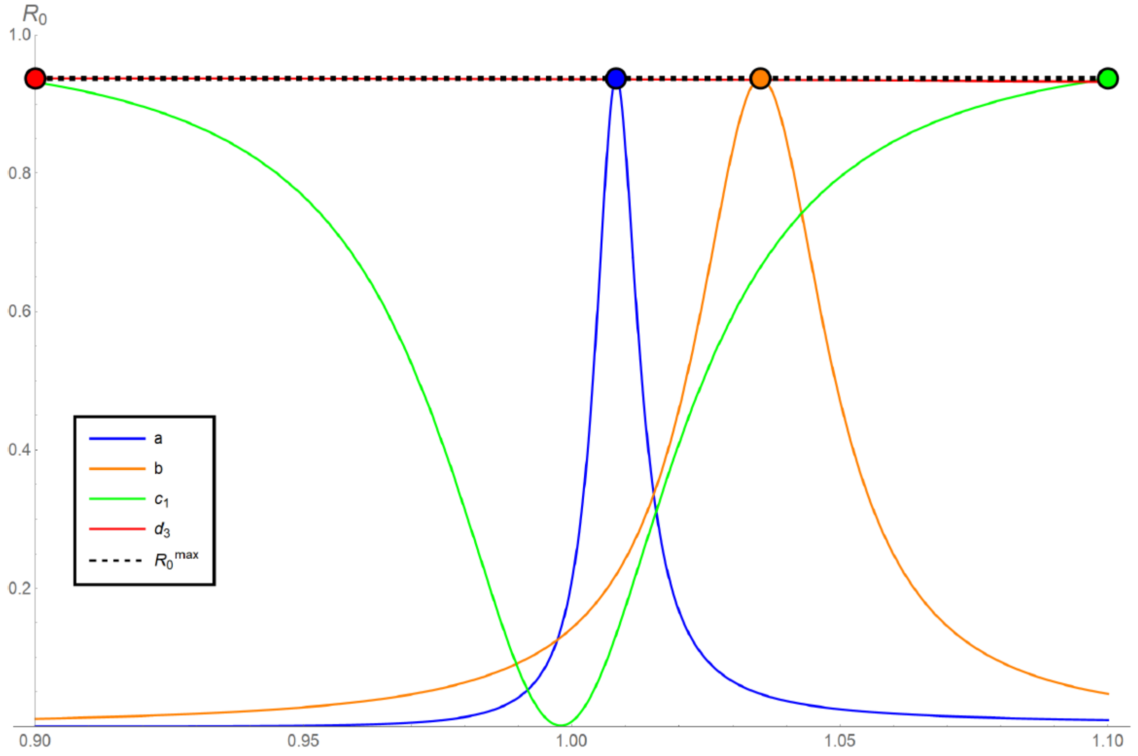
• BSM?

• How sensitive is this to the precise values of the couplings?

J=0 PWA (g'=0)



(a)



(b)

Sensitivity of R_0 to each parameter when the rest are set to the highest correction value at $\sqrt{s}$=1.5 TeV (left side) and $\sqrt{s}$=3 TeV (right side).

- Many additional tests:

  - Variations of all other relevant parameters: a, b, c1, d3 & energy $\sqrt{s}$
  - J=1 PWA (g'=0)
  - beyond g'=0 for J=0 and J=1 ➔ All additional channels computed
  - Study of particular BSM models ➔ MCHM

- Similar results (though here he show most relevant signals)

(*) Quezada-Calonge, Dobado, SC, 2102.01976 [hep-ph]; 2012.12242 [hep-ph]; forthcoming.

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:

  - Varying one coupling at a time ➔ importance ~ 20%
  - A more general search ➔ Fermion importance ~ 70 - 90%

- The MCHM shows R1 is more sensitive to fermion corrections than R0.

- Future work: considering the whole amplitude (real and imaginary) and unitarizing.

BACKUP

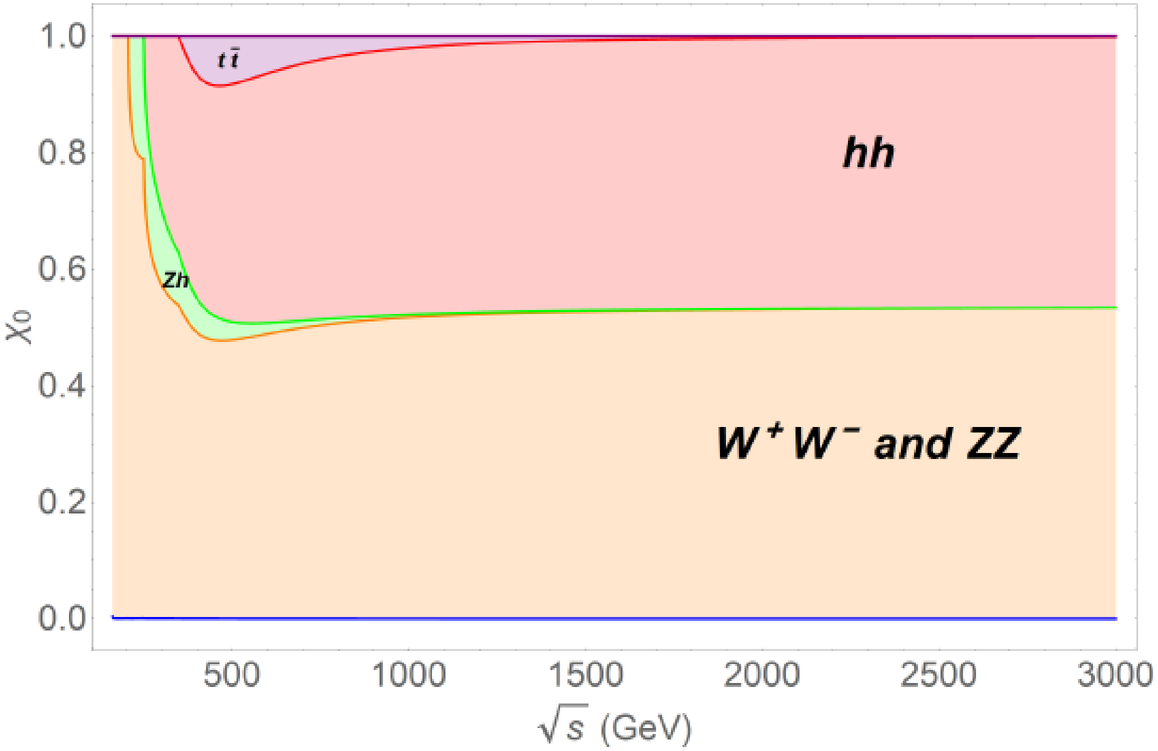
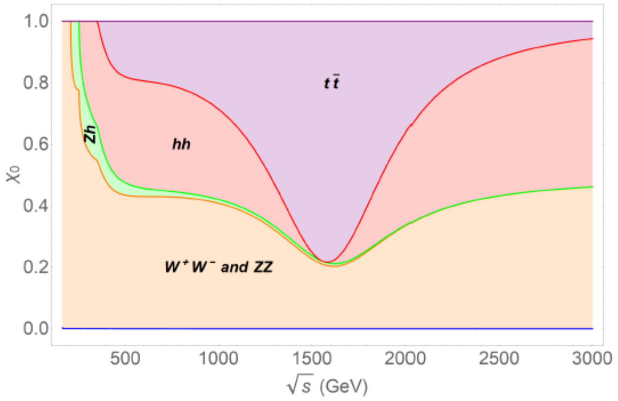
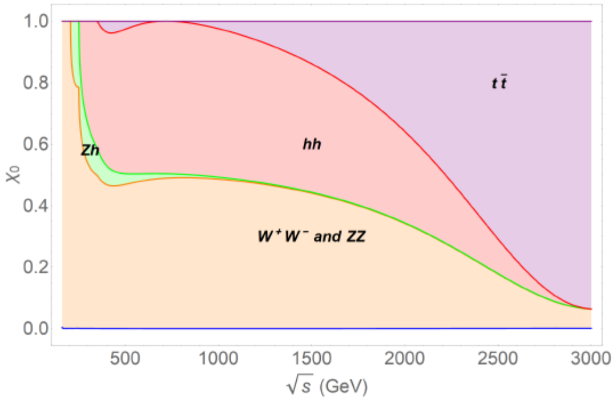


Fig. 4: Cumulative relative contribution of each channel to J=0 PWA in the SM

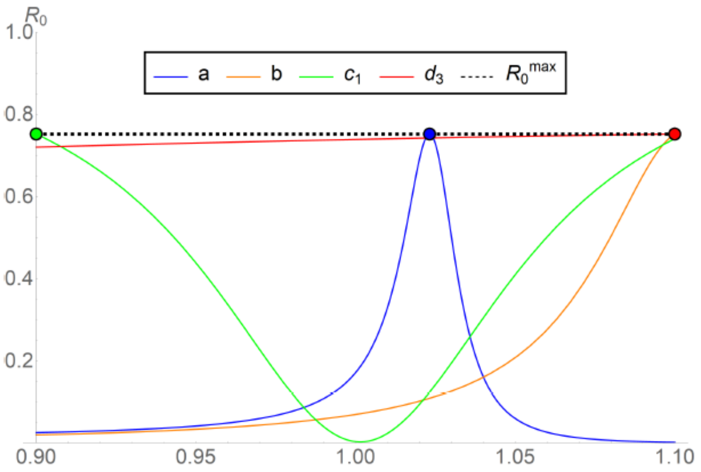


(a) Largest fermion-loop contribution of 75.15% found at 1.5 TeV for J=0 for $a = 1.02$, $b = 1.10$, $c_1 = 0.90$ and $d_3 = 1.1$.

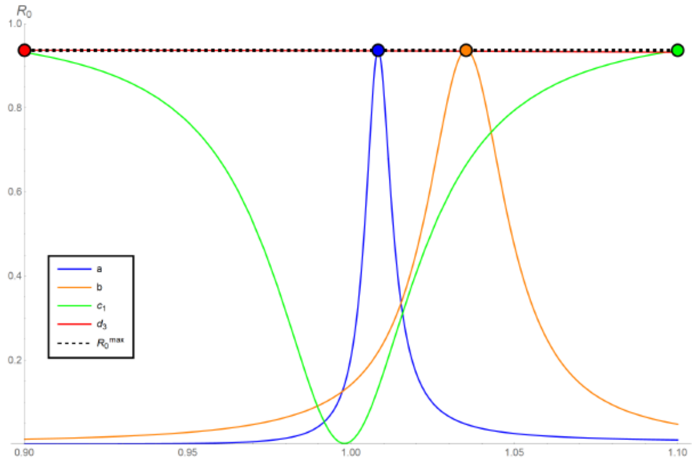


(b) Largest fermion-loop contribution of 93.69% found at 3 TeV for J=0 for $a = 1.01$, $b = 1.06$, $c_1 = 1.10$ and $d_3 = 0.90$.

Fig. 6

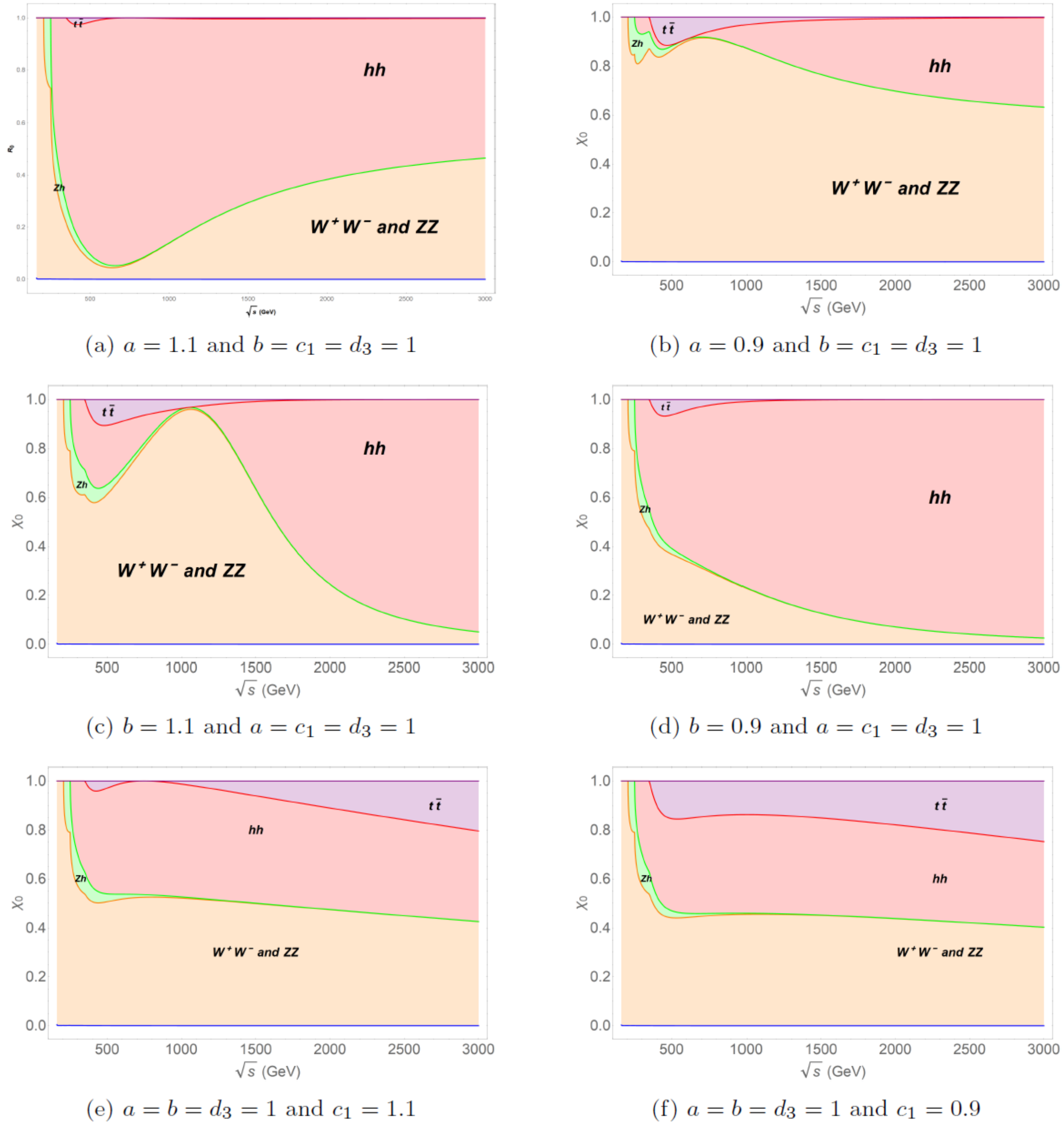


(a)



(b)

Fig. 7: Sensitivity of R_0 to each parameter when the rest are set to the highest correction value at $\sqrt{s}$=1.5 TeV (left side) and $\sqrt{s}$=3 TeV (right side).



(a) $a = 1.1$ and $b = c_1 = d_3 = 1$

(b) $a = 0.9$ and $b = c_1 = d_3 = 1$

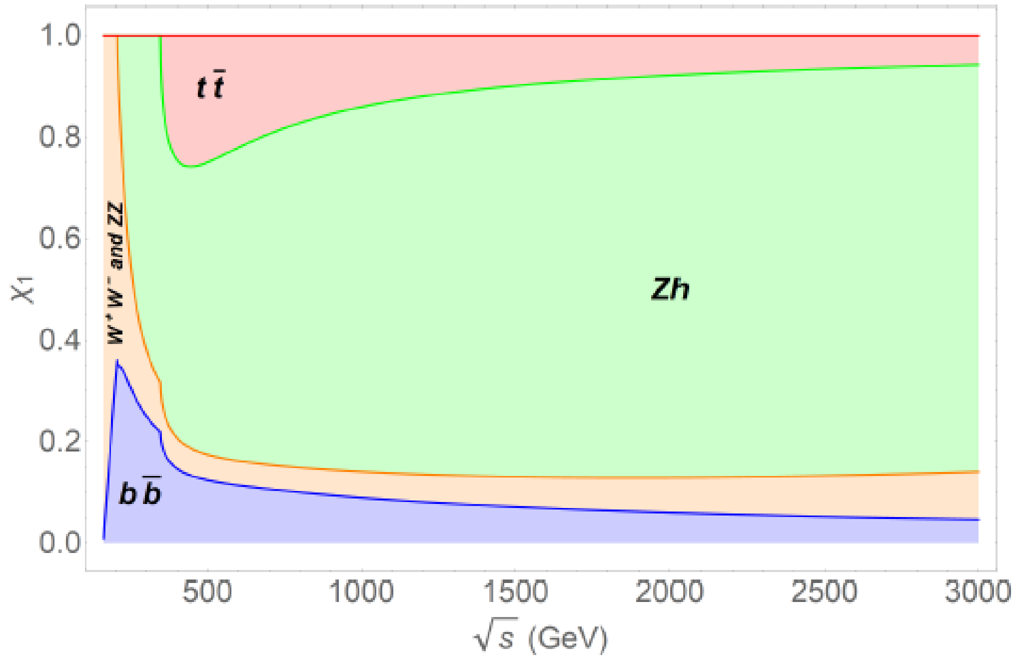
(c) $b = 1.1$ and $a = c_1 = d_3 = 1$

(d) $b = 0.9$ and $a = c_1 = d_3 = 1$

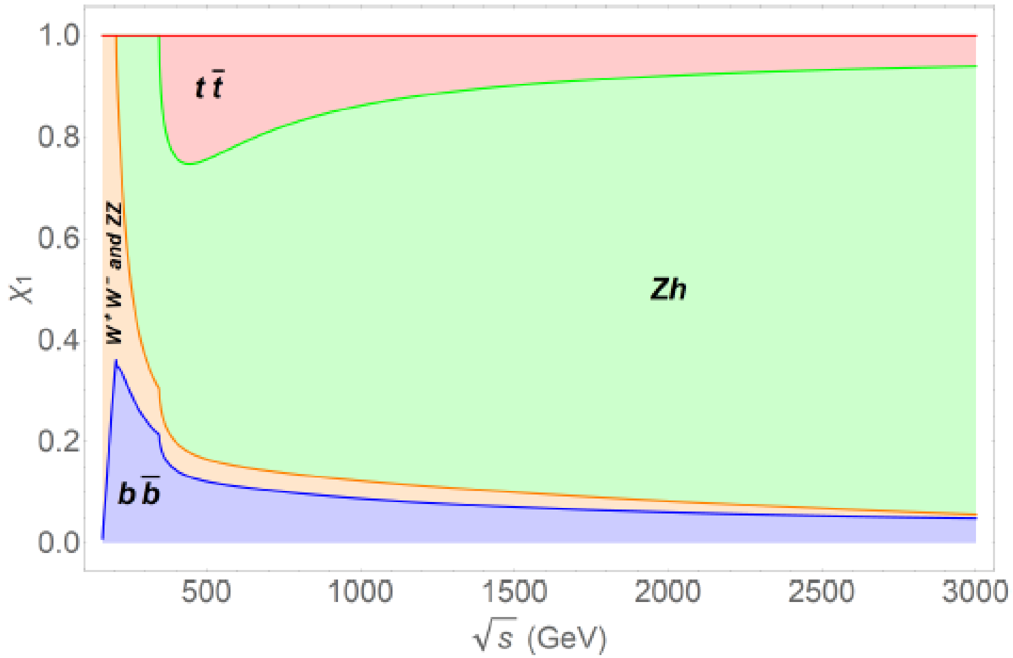
(e) $a = b = d_3 = 1$ and $c_1 = 1.1$

(f) $a = b = d_3 = 1$ and $c_1 = 0.9$

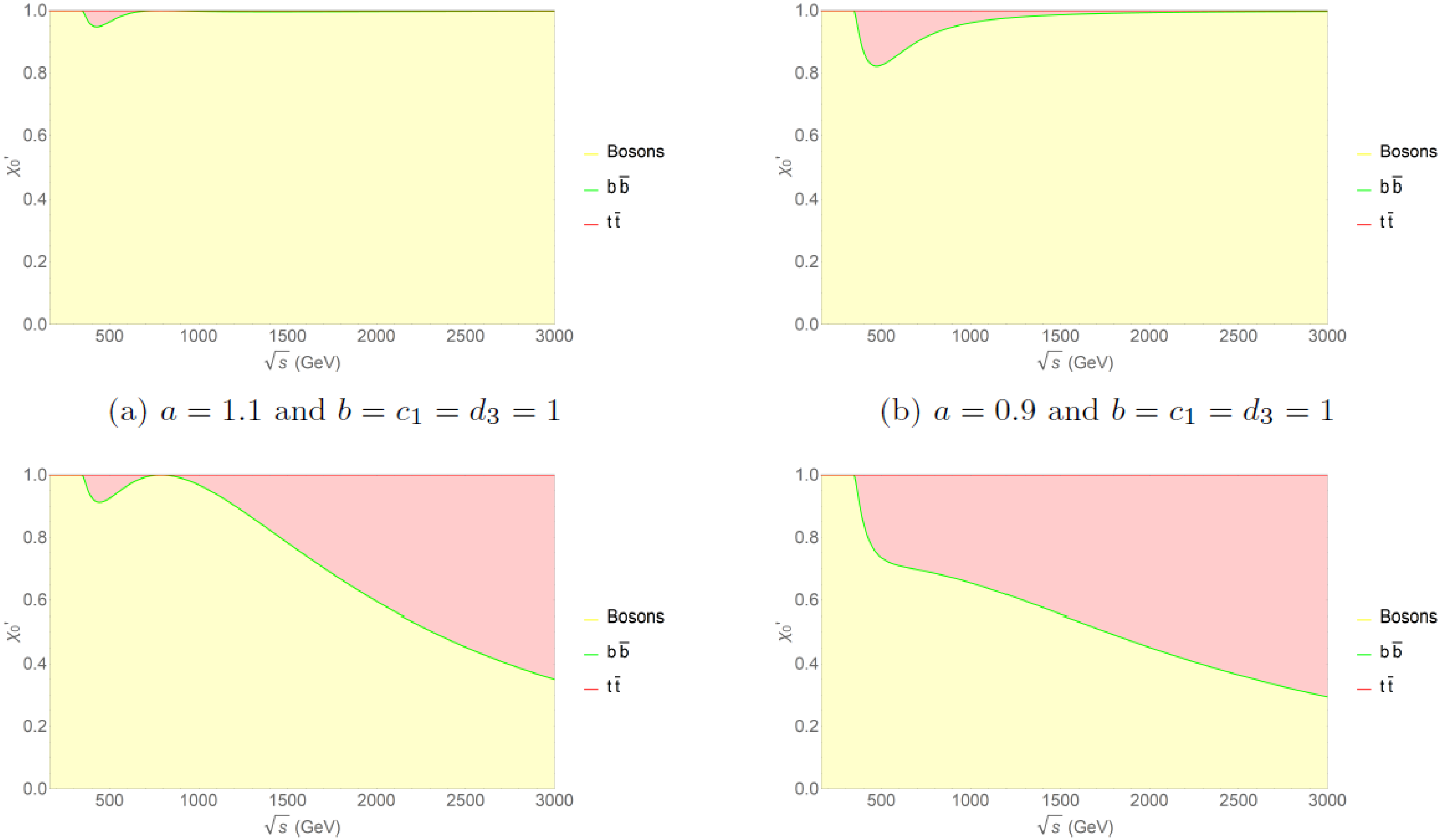
Fig. 5: Cumulative relative contributions of each cut to the J=0 PWA for different set of values. The $b\bar{b}$ is numerically negligible for this PWA.



(a) Largest fermion-loop contribution of 17.05% at 1.5 TeV to J=1 for $a = 0.99$



(b) Largest fermion-loop contribution of 10.94% at 3 TeV to J=1 for $a = 1.01$



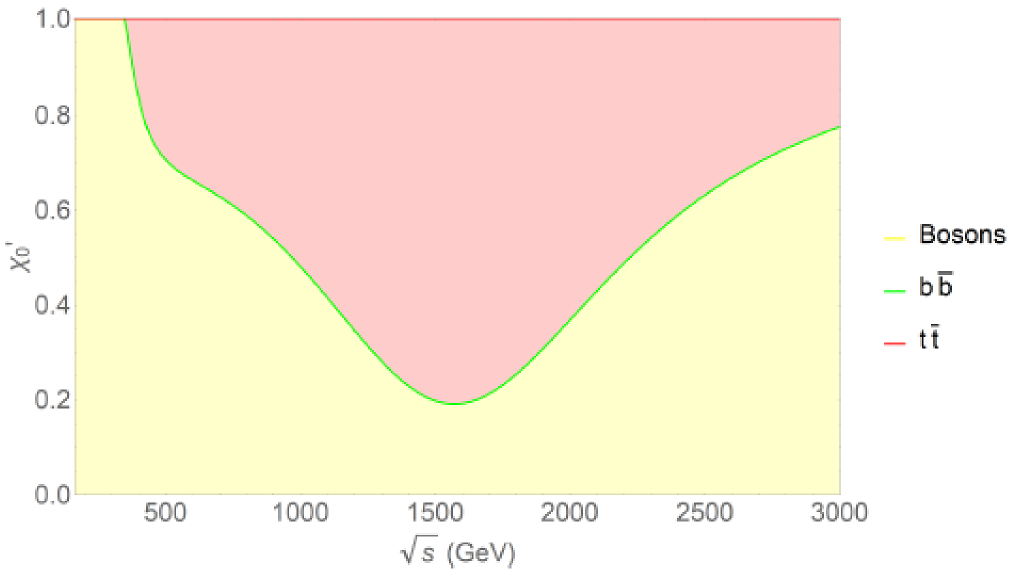
(a) $a = 1.1$ and $b = c_1 = d_3 = 1$

(b) $a = 0.9$ and $b = c_1 = d_3 = 1$

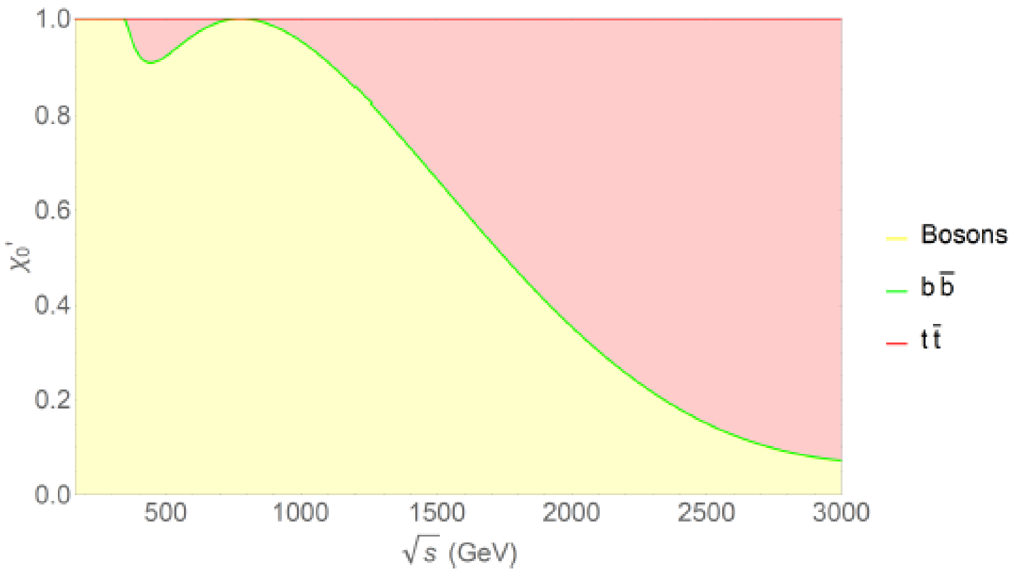
(c) $a = b = d_3 = 1$ and $c_1 = 1.1$

(d) $a = b = d_3 = 1$ and $c_1 = 0.9$

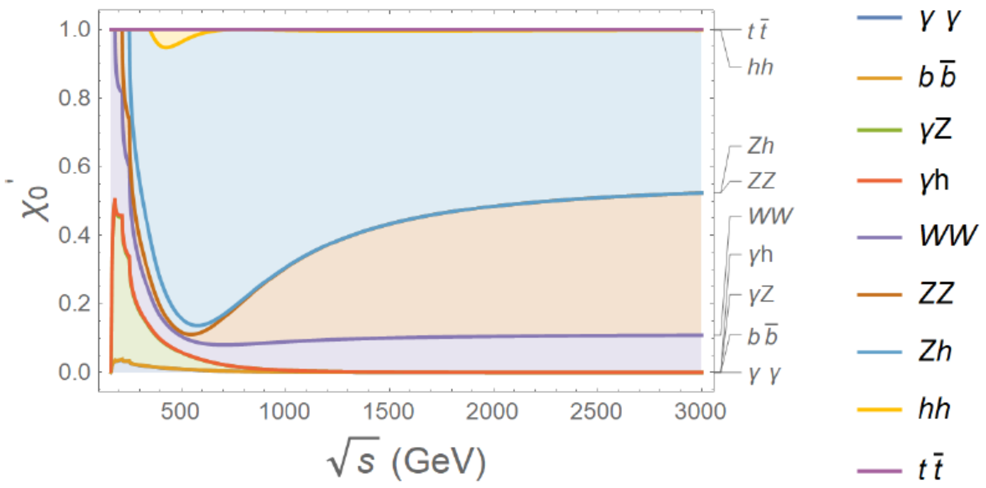
Fig. 16: Cumulative relative contributions of each cut to the J=0 pPWA for different set of values.



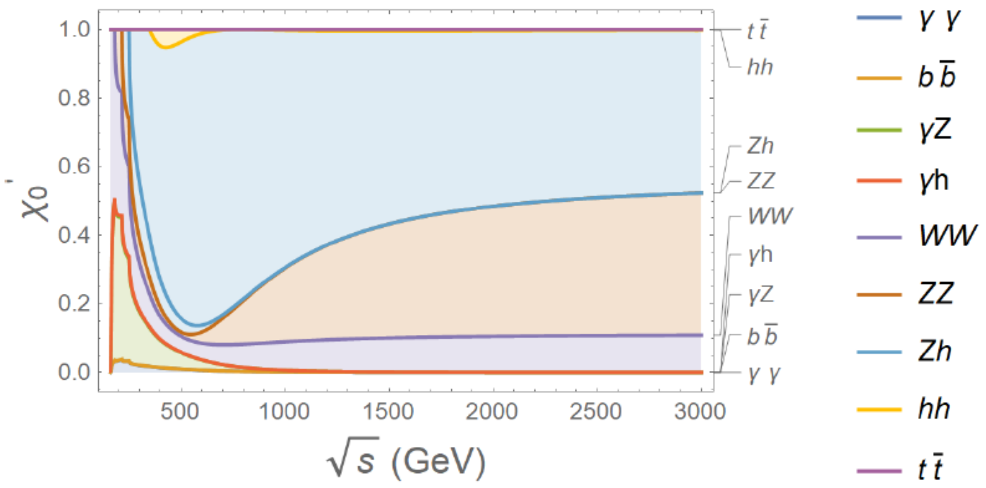
(a) Largest fermion-loop contribution of 80.13% for J=0 at 1.5 TeV for $a = 1.01$, $b = 1.04$, $c_1 = 0.90$ and $d_3 = 1.09$.



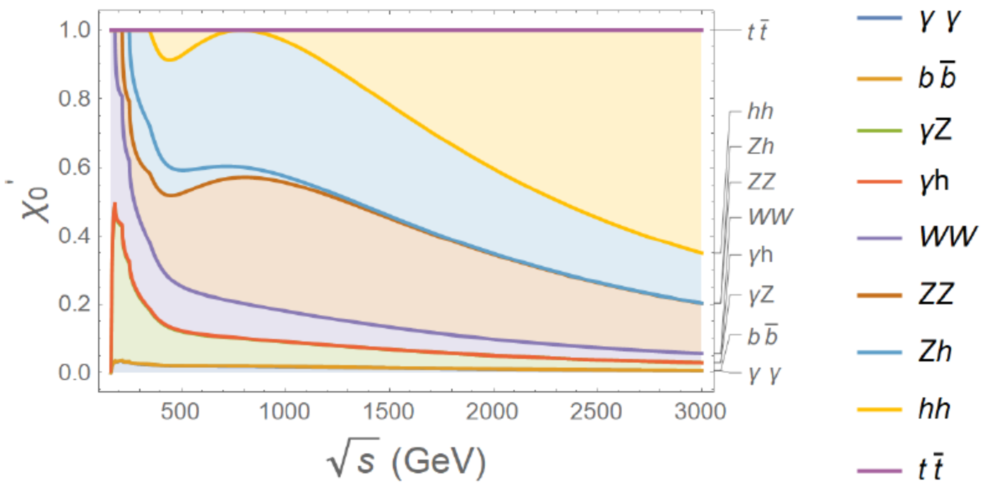
(b) Largest fermion-loop contribution of 92.74% for $J = 0$ at 3 TeV happens for $a = 1.00$, $b = 1.01$, $c_1 = 1.10$ and $d_3 = 1.10$



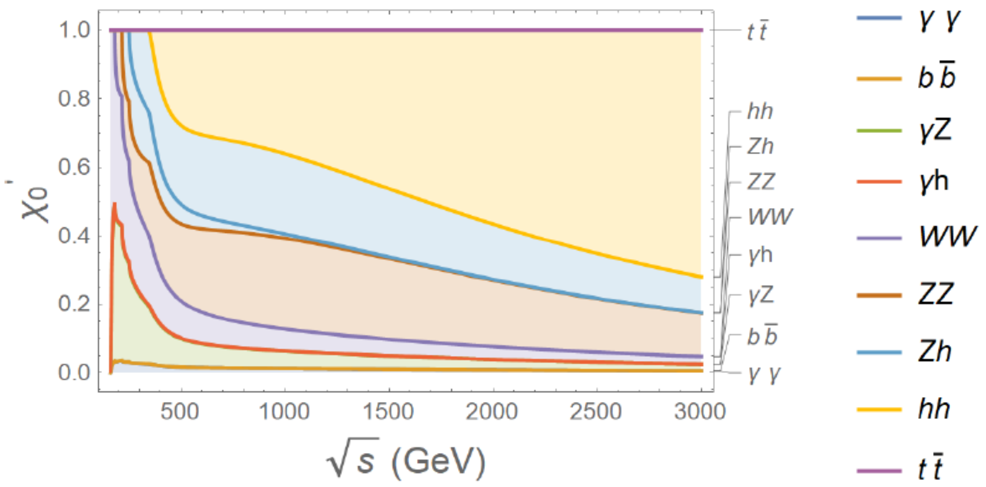
(a) Contribution of each channel for R_0' for $a = 1.1$ and $b = c_1 = d_3 = 1$



(b) Contribution of each channel for R_0' for $a = 0.9$ and $b = c_1 = d_3 = 1$



(c) Contribution of each channel for R_0' for $a = b = d_3 = 1$ and $c_1 = 1.1$



(d) Contribution of each channel for R_0' for $a = b = d_3 = 1$ and $c_1 = 0.9$

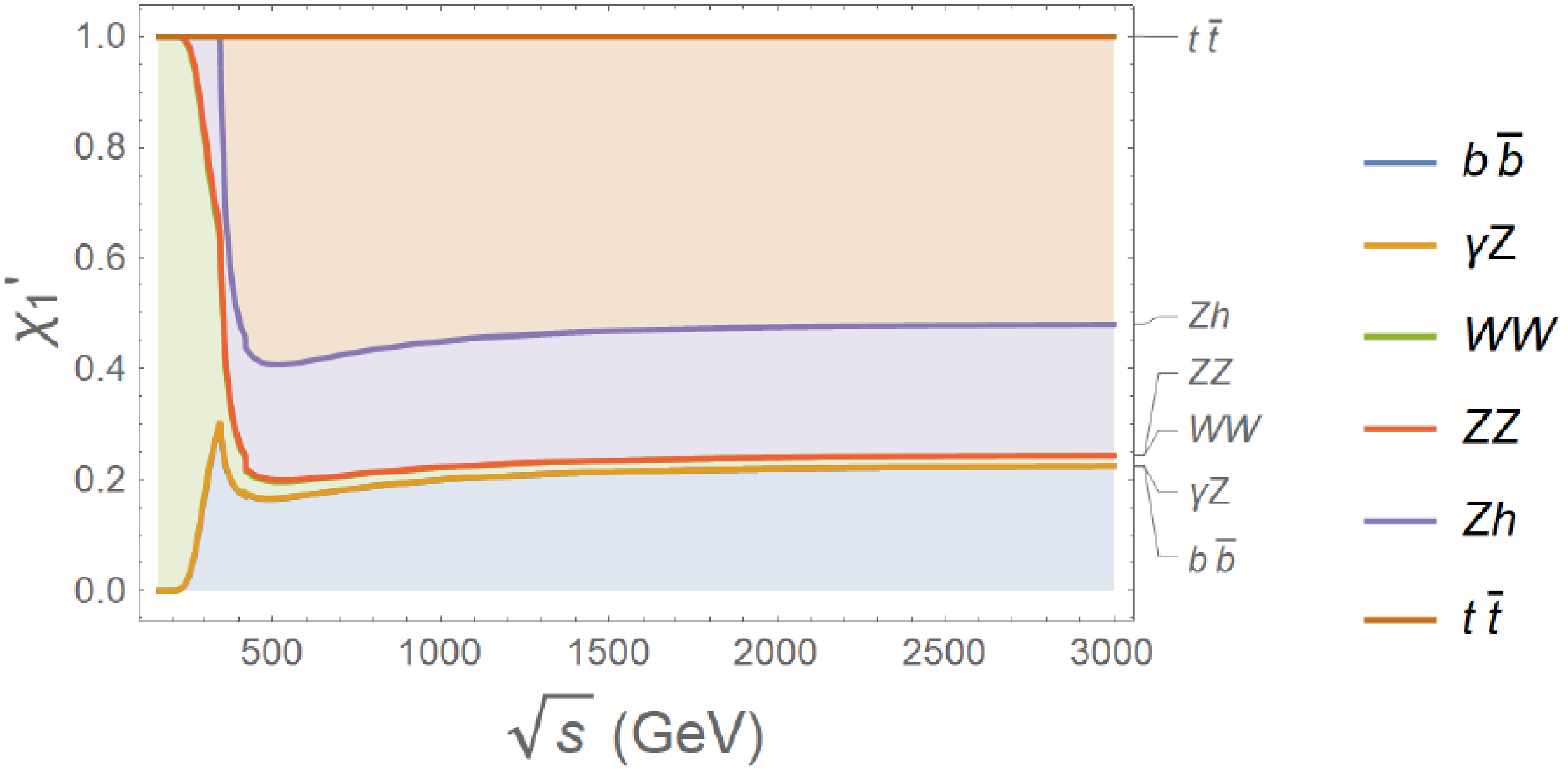


Fig. 31: Ratio for the R_1' pPWA at the SM

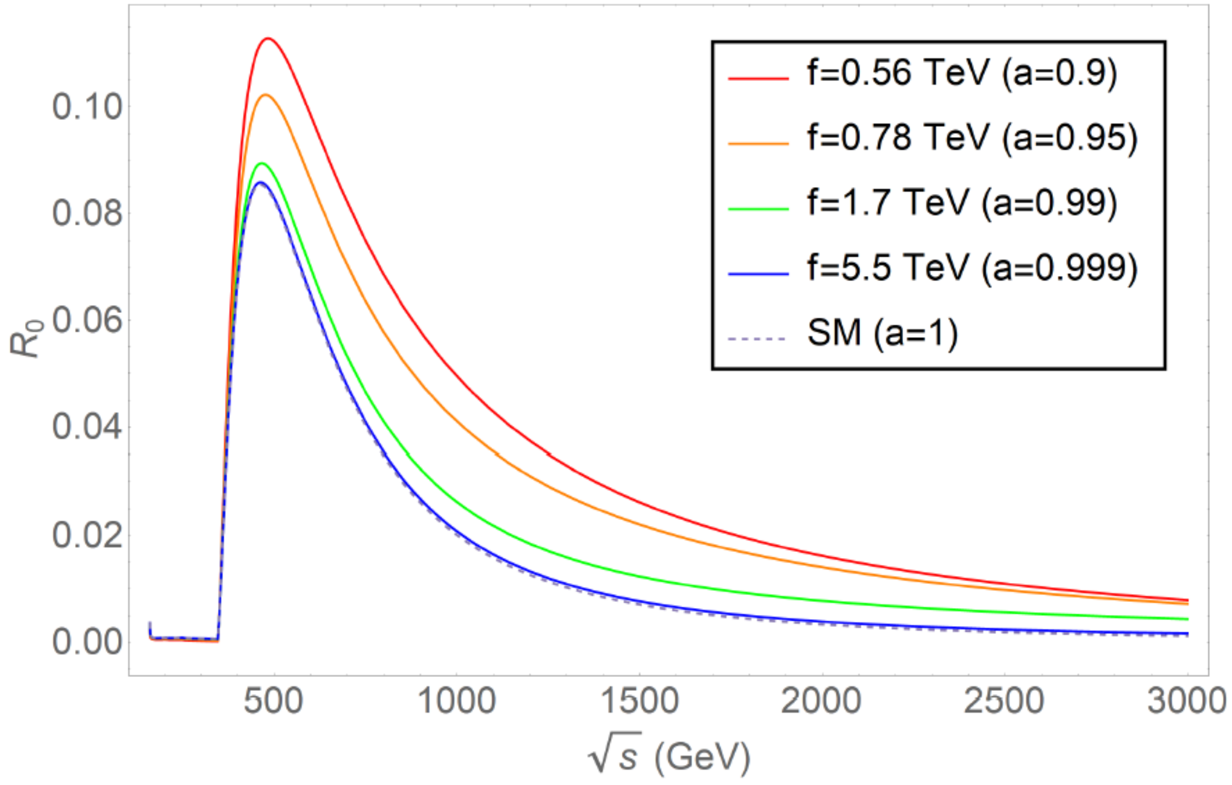


Fig. 24: Ratio for the R_0 PWA in the MCHM

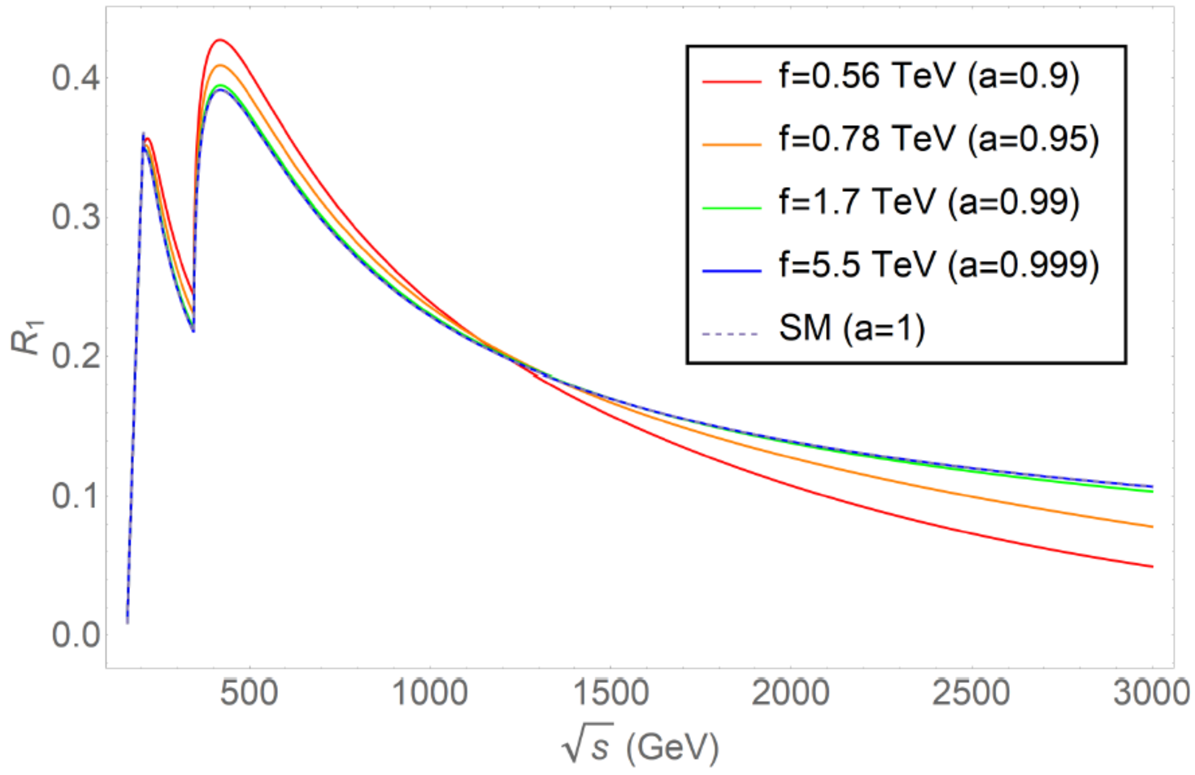


Fig. 25: Ratio for the R_1 PWA in the MCHM

$$a^* = \sqrt{1-\xi}, \quad b^* = 1 - 2\xi, \quad , \quad \text{and} \quad c_1^* = d_3^* = a^*, \quad \text{with} \quad \xi = v^2/f^2$$