A Physical Approach to the Study of CP Violation in $H^{\pm} \to W^{\pm} Z$ with 2 Higgs doublets

M. N. Rebelo
CFTP/IST, U. Lisboa

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Our Framework: General 2HDM

Our Work is related to the recent work of Kanemura and Mura:

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S. Kanemura and Y. Mura,
``Loop induced H$^{±}$W$^{∓}$Z vertices in the general two Higgs doublet
model with CP violation,'' JHEP (10} (2024), 041 [arXiv:2408.06863 [hep-
ph]].
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In our work, we allow for generic Yukawa couplings and cover both explicit and spontaneous CP violation. Furthermore, we express the amplitudes in terms of physical couplings making them more transparent.

Motivation

Although the Two-Higgs-Doublet-Model cannot address all shortcomings of the SM it allows to extract useful lessons

Some Pioneering works involving the study of the vertex $W^{\mp}ZH^{\pm}$ in 2HDM

J. A. Grifols and A. Mendez, *The $WZH^{\pm}$ Coupling in $SU(2) \times U(1)$ Gauge Models*, *Phys. Rev. D* **22** (1980) 1725.

(in the context of the possible production of charged Higgs bosons)

A. Mendez and A. Pomarol, *One loop induced $H^{+}W^{-}Z$ vertex in the minimal supersymmetry model*, *Nucl. Phys. B* **349** (1991) 369–380.

A. Mendez and A. Pomarol, *Signals of CP violation in the Higgs sector*, *Phys. Lett. B* **272** (1991) 313–318.

(also for 2HDM but not for the process we considered)

Many authors have studied in the past similar effects involving charged Higgs bosons without emphasis on CP violation:

Capdequi Peyranère, Haber & Irulegui (1991) A. Arhrib, R. Benbrik, M. Chabab (2007)

R. Enberg, W. Klemm, S. Moretti, S. Munir and G. Wouda (2025);

Two Higgs doublets

Most general gauge invariant renormalisable scalar potential

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 \quad [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$

$$+\lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}$$

eleven independent parameters out of a total of fourteen

we may rotate away m_{12}^2 and rephase the doublets making one of the lambdas real

Three neutral states and one pair of charged states: $H_1 \quad H_2 \quad H_3 \quad H^+ \quad H$

Masses and couplings among scalars are given by vevs and parameters of the potential

Two Higgs doublets

Kinetic terms for the scalars

$$\mathcal{L}_k = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2)$$

Covariant derivative in terms of the physical gauge bosons:

$$D_\mu \equiv \partial_\mu + i\left(\frac{1}{\sqrt{2}} g (T_- W_\mu^- + T_+ W_\mu^+) + eQA_\mu + g \sec\theta_W [T_3 - \sin^2\theta_W Q] Z_\mu\right)$$

The couplings $(H_i VV)$, $(H_i H^+ H^-)$ and $(H^+ H^- H^+ H^-)$ can be denoted by e_i, q_i and q respectively and expressed in terms of the parameters of the Lagrangian

B. Grzadkowski, O. M. Ogreid and P. Osland, JHEP (2014), 084
[arXiv:1409.7265 [hep-ph]]

Convenient to introduce “Physical parameter set”:

$$\mathcal{P} \equiv \{M^2_{H^\pm}, M_1^2, M_2^2, M_3^2, e_1, e_2, e_3, q_1, q_2, q_3, q\}$$

Yukawa couplings

General formulas, flavour structure

Yukawa interactions (quark sector)

$$\mathcal{L}_Y = -\overline{Q_L^0}\ \Gamma_1 \Phi_1 d_R^0 - \overline{Q_L^0}\ \Gamma_2 \Phi_2 d_R^0 - \overline{Q_L^0}\ \Delta_1 \tilde{\Phi}_1 u_R^0 - \overline{Q_L^0}\ \Delta_2 \tilde{\Phi}_2 u_R^0$$

quark mass matrices generated after spontaneous gauge symmetry breaking

$$M_d = \frac{1}{\sqrt{2}}(v_1\Gamma_1 + v_2 e^{i\alpha}\Gamma_2), \quad M_u = \frac{1}{\sqrt{2}}(v_1\Delta_1 + v_2 e^{-i\alpha}\Delta_2)$$

$$U_{dL}^\dagger M_d U_{dR} = D_d \equiv diag\ (m_d, m_s, m_b)$$
$$U_{uL}^\dagger M_u U_{uR} = D_u \equiv diag\ (m_u, m_c, m_t)$$

Expansion around the vev's

$$\Phi_j = \begin{pmatrix} \phi_i^+ \\ \frac{e^{i\alpha_j}}{\sqrt{2}}(v_j + \rho_j + i\eta_j) \end{pmatrix}, \qquad j = 1, 2$$

We perform the following transformation:

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = U \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}; \quad \begin{pmatrix} G^0 \\ I \end{pmatrix} = U \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}; \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$U = \frac{1}{v} \begin{pmatrix} v_1 e^{-i\alpha_1} & v_2 e^{-i\alpha_2} \\ v_2 e^{-i\alpha_1} & -v_1 e^{-i\alpha_2} \end{pmatrix}; \qquad v = \sqrt{v_1^2 + v_2^2} = (\sqrt{2} G_F)^{-\frac{1}{2}} \simeq 246\text{GeV}$$

U singles out

H^0 with couplings to quarks proportional to mass matrices

G^0 neutral pseudo-Goldstone boson

G^+ charged pseudo-Goldstone boson

Physical neutral fields are combinations of $H^0 \; R \quad I$

Neutral and charged Higgs Interactions for the quark sector

$$\begin{aligned}\mathcal{L}_Y(\text{quark, Higgs}) = & -\overline{d_L^0}\frac{1}{v}\left[M_d H^0 + N_d^0 R + iN_d^0 I\right] d_R^0 \\ & -\overline{u_L^0}\frac{1}{v}\left[M_u H^0 + N_u^0 R + iN_u^0 I\right] u_R^0 \\ & -\frac{\sqrt{2}H^+}{v}(\overline{u_L^0} N_d^0\, d_R^0 - \overline{u_R^0} N_u^{0\dagger}\, d_L^0) + \text{h.c.}\end{aligned}$$

$$N_d^0 = \frac{1}{\sqrt{2}}(v_2\Gamma_1 - v_1 e^{i\theta}\Gamma_2), \quad N_u^0 = \frac{1}{\sqrt{2}}(v_2\Delta_1 - v_1 e^{-i\theta}\Delta_2).$$

Flavour structure of quark sector of 2HDM characterised by:

four matrices $M_d,\ M_u,\ N_d^0,\ N_u^0$.

Likewise for Leptonic sector, Dirac neutrinos:

$$M_\ell,\ M_\nu,\ N_\ell^0,\ N_\nu^0$$

Yukawa Couplings in terms of quark mass eigenstates

for H^+, H^0, R, I

$$\mathcal{L}_Y(\text{quark, Higgs}) =$$
$$-\frac{\sqrt{2}H^+}{v}\bar{u}\left(VN_d\gamma_R - N_u^\dagger\, V\gamma_L\right)d + \text{h.c.} - \frac{H^0}{v}\left(\bar{u}D_u u + \bar{d}D_d\, d\right) -$$
$$-\frac{R}{v}\left[\bar{u}(N_u\gamma_R + N_u^\dagger\gamma_L)u + \bar{d}(N_d\gamma_R + N_d^\dagger\gamma_L)\, d\right] +$$
$$+ i\frac{I}{v}\left[\bar{u}(N_u\gamma_R - N_u^\dagger\gamma_L)u - \bar{d}(N_d\gamma_R - N_d^\dagger\gamma_L)\, d\right]$$

$$\gamma_L = (1-\gamma_5)/2 \qquad\qquad \gamma_R = (1+\gamma_5)/2$$

$$V = V_{CKM}$$

Flavour changing neutral currents controlled by:

$$N_d = \frac{1}{\sqrt{2}} U_{d_L}^{\dagger} \left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2 \right) U_{d_R}$$

$$N_u = \frac{1}{\sqrt{2}} U_{u_L}^{\dagger} \left(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2 \right) U_{u_R}$$

For generic two Higgs doublet models

N_u, N_d non-diagonal arbitrary

For definiteness rewrite N_d:

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}$$

$\frac{v_2}{v_1} D_d$: conserves flavour

$U_{d_L}^{\dagger} e^{i\alpha} \Gamma_2 U_{d_R}$: leads to FCNC

Valid in framework of the most general 2HDM

Yukawa couplings

In our study we express the couplings of the fermions making use, when applicable, of the physical parameter set introduced before and following the notation and results of:

B. Grzadkowski, H. E. Haber, O. M. Ogreid and P. Osland, JHEP (2018), 056 [arXiv:1808.01472 [hep-ph]]

For numerical illustrations only diagonal $\tilde{\rho}$ matrices were considered:

Diagonal couplings to the neutral scalars

$$H_j \bar{u}_k u_k : \quad \frac{i m_{u_k}}{v^2}\, e_j \qquad \frac{i}{\sqrt{2}\, v}\left[(\tilde{\rho}^U_{kk})^* P_L f^*_j + \tilde{\rho}^U_{kk} P_R f_j\right]$$

$$H_j \bar{d}_k d_k : \quad \frac{i m_{d_k}}{v^2}\, e_j \qquad \frac{i}{\sqrt{2}\, v}\left[(\tilde{\rho}^D_{kk})^* P_R f^*_j + \tilde{\rho}^D_{kk} P_L f_j\right]$$

$$H_j \bar{\ell}_k \ell_k : \quad \frac{i m_{\ell_k}}{v^2}\, e_j \qquad \frac{i}{\sqrt{2}\, v}\left[(\tilde{\rho}^L_{kk})^* P_R f^*_j + \tilde{\rho}^L_{kk} P_L f_j\right]$$

Yukawa couplings

Diagonal couplings to the charged-Higgs and Goldstone fields

$$H^+ d_k \bar{u}_m : \quad iV_{mk}[(\tilde{\rho}^U_{mm})^* P_L \quad (\tilde{\rho}^D_{kk})^* P_R], \qquad H \quad \bar{d}_k u_m : \quad iV^*_{mk}[\tilde{\rho}^U_{mm} P_R \quad \tilde{\rho}^D_{kk} P_L],$$

$$H^+ \ell_k \bar{\nu}_k : \quad i(\tilde{\rho}^L_{kk})^* P_R, \qquad H \quad \bar{\ell}_k \nu_k : \quad i\tilde{\rho}^L_{kk} P_L,$$

$$G^+ d_k \bar{u}_m : \quad \frac{i\sqrt{2}\, V_{mk}}{v}[m_{u_m} P_L \quad m_{d_k} P_R], \qquad G \quad \bar{d}_k u_m : \quad \frac{i\sqrt{2}\, V^*_{mk}}{v}[m_{u_m} P_R \quad m_{d_k} P_L],$$

$$G^+ \ell_k \bar{\nu}_k : \quad \frac{i\sqrt{2}}{v} m_{l_k} P_R, \qquad G \quad \bar{\ell}_k \nu_k : \quad \frac{i\sqrt{2}}{v} m_{l_k} P_L.$$

Feynmam rules proportional to the factor e_i parametrising the H_iVV couplings

B. Grzadkowski, O. M. Ogreid and P. Osland, JHEP (2014), 084
[arXiv:1409.7265 [hep-ph]]

$$H_iH_jZ_\mu: \quad \frac{g}{2v\cos\theta_{\rm W}}\epsilon_{ijk}e_k(p_i \quad p_j)_\mu, \qquad H_iH_jG_0: \quad i\frac{m_i^2 \quad m_j^2}{v^2}\epsilon_{ijk}e_k,$$

$$H_iZ_\mu Z_\nu: \quad \frac{ig^2}{2\cos^2\theta_{\rm W}}e_i\, g_{\mu\nu}, \qquad H_iW_\mu^+W_\nu \;: \quad \frac{ig^2}{2}e_i\, g_{\mu\nu},$$

$$H_iG_0G_0: \quad \frac{im_i^2e_i}{v^2}, \qquad H_iG^+G \;: \quad \frac{im_i^2e_i}{v^2},$$

$$H_iG^+Z_\mu W_\nu \;: \quad \frac{ig^2}{2v}\frac{\sin^2\theta_{\rm W}}{\cos\theta_{\rm W}}e_i\, g_{\mu\nu}, \qquad H_iG \;\; Z_\mu W_\nu^+: \quad \frac{ig^2}{2v}\frac{\sin^2\theta_{\rm W}}{\cos\theta_{\rm W}}e_i\, g_{\mu\nu},$$

$$H_iG_0Z_\mu: \quad \frac{g}{2v\cos\theta_{\rm W}}e_i(p_i \quad p_0)_\mu,$$

$$H_iG^+W_\mu \;: \quad i\frac{g}{2v}e_i(p_i \quad p^+)_\mu, \qquad H_iG \;\; W_\mu^+: \quad i\frac{g}{2v}e_i(p_i \quad p \;\;)_\mu.$$

$$e_1^2+e_2^2+e_3^2=v^2$$

$$H_i H^+ H \quad : \qquad i q_i .$$

Feynman rules proportional to f_i or f_i^*

$$H_i H^+ W_\mu \; : \quad i\frac{g}{2v} f_i (p_i \quad p_+)_\mu , \qquad H_i H \;\; W_\mu^+ : \qquad i\frac{g}{2v} f_i^* (p_i \quad p \;\;)_\mu ,$$

$$H_i H^+ Z_\mu W_\nu \; : \qquad \frac{ig^2}{2v}\frac{\sin^2\theta_W}{\cos\theta_W} f_i g_{\mu\nu}, \qquad H_i H \;\; Z_\mu W_\nu^+ : \qquad \frac{ig^2}{2v}\frac{\sin^2\theta_W}{\cos\theta_W} f_i^* g_{\mu\nu},$$

$$H_i H^+ G \quad : \qquad \frac{i}{v^2}(m_i^2 \quad m_{H^\pm}^2) f_i , \qquad H_i H \;\; G^+ : \qquad \frac{i}{v^2}(m_i^2 \quad m_{H^\pm}^2) f_i^*$$

Properties:

$$\mathrm{Re}\, f_i f_j^* = v^2 \delta_{ij} \quad e_i e_j ,$$

$$\mathrm{Im}\, f_i f_j^* = v \sum_k \epsilon_{ijk} e_k , \longrightarrow \quad |f_i| = \sqrt{v^2 \quad e_i^2}$$

$$\sum_{i,j,k} \epsilon_{ijk} e_i f_j^* f_k = \quad 2iv^3 , \longrightarrow \text{ there are some relative complex phases among the } f_i$$

$$\sum_i e_i f_i = 0$$

Apart from an overall common phase, they are fully determined by the e_i and v.

In the alignment limit $e_1 = v, \qquad e_2 = e_3 = 0$

Let $\kappa = \dfrac{e_1}{v}$ refer to the degree of alignment

then we have

$$|f_1| = v\sqrt{1 \quad \kappa^2} = \sqrt{e_2^2 + e_3^2}.$$

Away from alignment, one finds

$$f_2 = \frac{f_1(e_1 e_2 + i e_3 v)}{e_2^2 + e_3^2},$$

$$f_3 = \frac{f_1(e_1 e_3 \quad i e_2 v)}{e_2^2 + e_3^2},$$

whereas, in the limit $e_1 \to v \quad (e_2 \to 0 \text{ and } e_3 \to 0)$ one has

$f_1 \to 0, \; f_2 \to i f_3$ and $\left(|f_{2,3}| \to v\right)$

Couplings involving gauge bosons and fermions

$$
\begin{aligned}
W_\mu^+ l\bar{\nu}_l : &\qquad \frac{ig}{\sqrt{2}}\gamma^\mu P_L \equiv a_W \gamma^\mu P_L, \\
W_\mu\, \bar{l}\nu_l : &\qquad a_W \gamma^\mu P_L, \\
W_\mu^+ \bar{u}_m d_k : &\quad a_W V_{mk} \gamma^\mu P_L, \\
W_\mu\, u_m \bar{d}_k : &\qquad a_W V_{mk}^* \gamma^\mu P_L, \\
Z_\mu \bar{f} f : &\qquad \frac{ig}{2\cos\theta_W}\gamma^\mu [Z_L^f P_L + Z_R^f P_R] \equiv a_Z \gamma^\mu [Z_L^f P_L + Z_R^f P_R],
\end{aligned}
$$

with the product

$$
a_W a_Z = \quad \frac{g^2}{2\sqrt{2}\cos\theta_W}.
$$

Then, we have for the quarks

$$
\begin{aligned}
Z_L^u &= 1 \quad (4/3)\sin^2\theta_W, & Z_R^u &= \quad (4/3)\sin^2\theta_W, \\
Z_L^d &= \quad 1 + (2/3)\sin^2\theta_W, & Z_R^d &= (2/3)\sin^2\theta_W,
\end{aligned}
$$

and for the leptons

$$
\begin{aligned}
Z_L^\nu &= 1, & Z_R^\nu &= 0, \\
Z_L^\ell &= \quad 1 + 2\sin^2\theta_W, & Z_R^\ell &= 2\sin^2\theta_W.
\end{aligned}
$$

CP Violation in the process $H^{\pm}(p_1) \to W^{\pm}(p_2)Z(p_3)$

Study of the asymmetry

$$\delta = \frac{(H^+ \to W^+Z) \quad (H \quad \to W \quad Z)}{(H^+ \to W^+Z) + \quad (H \quad \to W \quad Z)}$$

(different decay rates)

The decay rate can be expressed as:

$$= \frac{1}{2M}\sum_{\text{spin}}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}|\mathcal{M}|^2\,(2\pi)^4\delta^{(4)}(p_1+p_2+p_3)$$

$$= \frac{1}{16\pi M}\sum_{\text{spin}}\frac{\sqrt{\lambda}}{M^2}|\mathcal{M}|^2.$$

$\lambda(m_{H^\pm}^2, m_W^2, m_Z^2)$, with $\lambda(x,y,z) = x^2 + y^2 + z^2 \quad 2xy \quad 2yz \quad 2zx.$ Källén function

Our work focused on:

$$\mathcal{M}(H^{\pm} \to W^{\pm}Z)$$

In extensions of the SM with N Higgs doublets there is no tree level coupling $W^{\mp}ZH^{\pm}$

Kinetic terms for the scalars do not mix different doublets;

$$\mathcal{L}_k = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2)$$

$H^{\pm}$ is associated to the doublet that does not acquire vev in the Higgs basis
therefore, triple couplings involving it cannot be generated by the kinetic term

Grifols and Mendez 1980

Likewise, the coupling $H^{\pm}W^{\mp}\gamma$ cannot be generated **Gunion and Haber 2005**

However the couplings $H_i H^{\pm} Z_\mu W^{\mp\mu}$ are allowed whereas $H_i H^{\pm} \gamma_\mu W^{\mp\mu}$ are not

$$D_\mu \equiv \partial_\mu + i\left(\frac{1}{\sqrt{2}} g(T_- W_\mu^- + T_+ W_\mu^+) + eQA_\mu + g \sec\theta_W [T_3 - \sin^2\theta_W Q] Z_\mu\right)$$

$H_i H^{\pm} Z_\mu W^{\mp\mu}$ = ($H^{\pm} W^{\mp\mu}$) ($H_i Z_\mu$)

$$T^- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \quad T^+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad Q = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad T_3 = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & -\frac{1}{2} \end{pmatrix}$$

It is convenient to split the one loop amplitudes into a bosonic and a fermionic part

$$\mathcal{M} = \mathcal{M}^{\text{boson}} + \mathcal{M}^{\text{fermion}}$$

The superscript refers to the loop fields that couple to the external fields

Different phase dependent couplings contribute to each term. For this reason fermionic tadpoles are included in the "boson" term

The phase dependent couplings in the boson term are all proportional to quantities referred to as f_i or f_i^*

Apart from an overall common phase these are fully determined by the e_i and v_i

In the limit of alignment there is no CP violation in the purely bosonic sector under the assumption that the SM-like Higgs boson is the lightest of the neutral scalars.

However, alignment does not imply that there is no CP vilation in the bosonic sector since H2 and H3 may still mix.

The CKM phase does not contribute to CP violation at the one loop level in this process since the elements of the matrix appear in mutually conjugated pairs

The asymmetry can be thought as consisting of three parts: a bosonic part a fermionic part and interference,

$$\delta = \delta^{\text{bosonic}} + \delta^{\text{fermionic}} + \delta^{\text{interference}}.$$

In general we found a contribution to the charge asymmetry from CP violation in the purely bosonic sector as well as from CP violation in the purely fermionic sector

There is a charge asymmetry even in the alignment limit, it originates from the amplitudes of the quark and lepton loops, as well as their interference with bosonic loops

Complex quantities relevant for CP violation in this process

CP violation results from the interplay of different complex quantities

* Loop integrals become complex when invariant mass of the external field at a particular vertex exceeds the sum of the masses of the two particles at that vertex. (These phases do not change in the amplitude for the corresponding charge-conjugated processes)

* Bosonic amplitudes are proportional to the complex couplings f_i **or** f_i^*

relative phases among them are physical, given in terms of couplings e_j

* Fermionic amplitudes are proportional to complex quantities $\tilde{\rho}$, phase differences among $\tilde{\rho}^U$, $\tilde{\rho}^D$ and $\tilde{\rho}^L$ are physical and play a role

* The bosonic and fermionic amplitudes may interfere. This interference is most easily illustrated by the product $f_i \tilde{\rho}^f$ appearing in the fermionic tadpole amplitudes

Cutkosky cuts

Cutkosky (1960):
A loop integral will develop a non-trivial imaginary part
if it has a vertex ABC where A is an external field
whose invariant mass exceeds $m(B) + m(C)$

Counting of independent CP violating phases relevant for this process

With three complex couplings f_i in the bosonic sector (associated with the three neutral states h_i) and three complex couplings $\tilde{\rho}^f$ in the fermion sector (associated with up- and down-type quarks and charged leptons), we have a total of six phases. Only differences are physical, so the number of physical phases (arising from these fields) is five. Rather than picking five relative phases between fermion and boson fields, we define two relative phases in the bosonic sector (phases of f_2 and f_3 relative to the reference phase of f_1), two in the fermionic sector (phases of $\tilde{\rho}^U$ and $\tilde{\rho}^D$ with respect to $\tilde{\rho}^L$) and one phase relating $\tilde{\rho}^L$ to f_1.

We define θ_{BF} to be the difference betwen the phase of $\tilde{\rho}^L_{33}$ and the phase of f_1

The computation is performed in the Feynman 'T Hooft gauge

Automated one loop calculations including the generation of Feyman Graphs and Amplitudes were used:

T. Hahn and Perez-Victoria , Comput. Phys. Commun. 118 (19990

T. Hahn Comput. Phys. Commun. 140 (2001) 418

J. Kublbeck, M. Bohm and A. Denner, 60 (1990) 165

Feynman Graphs and Amplitudes were also checked by hand

Different types of Feynman diagrams

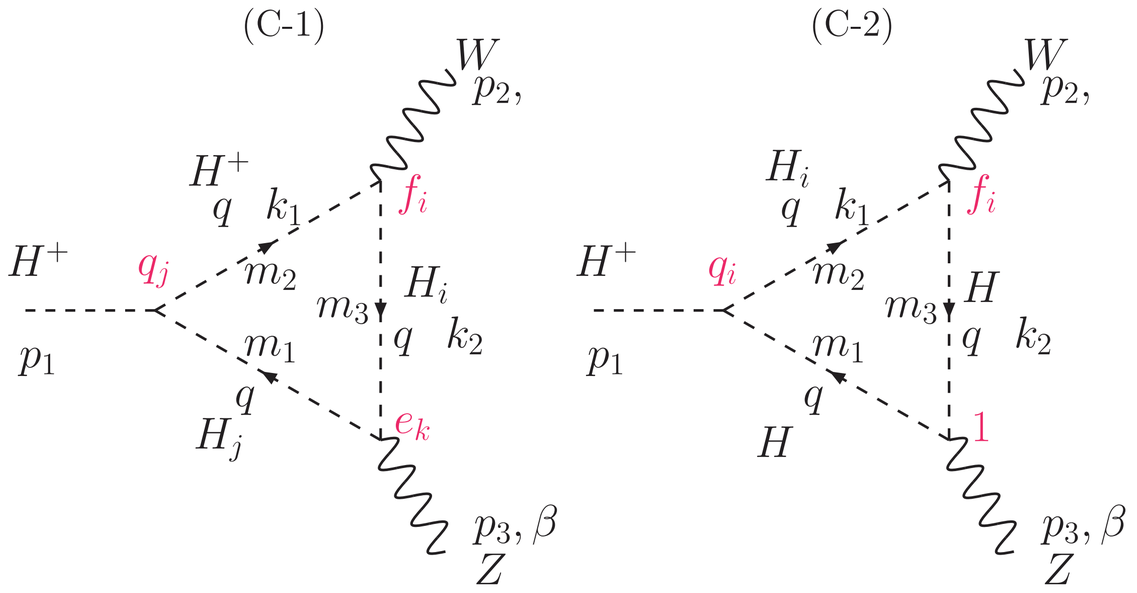


Figure 2: Boson triangle diagrams involving the q_i (or q_j) couplings.

Different types of Feynman diagrams

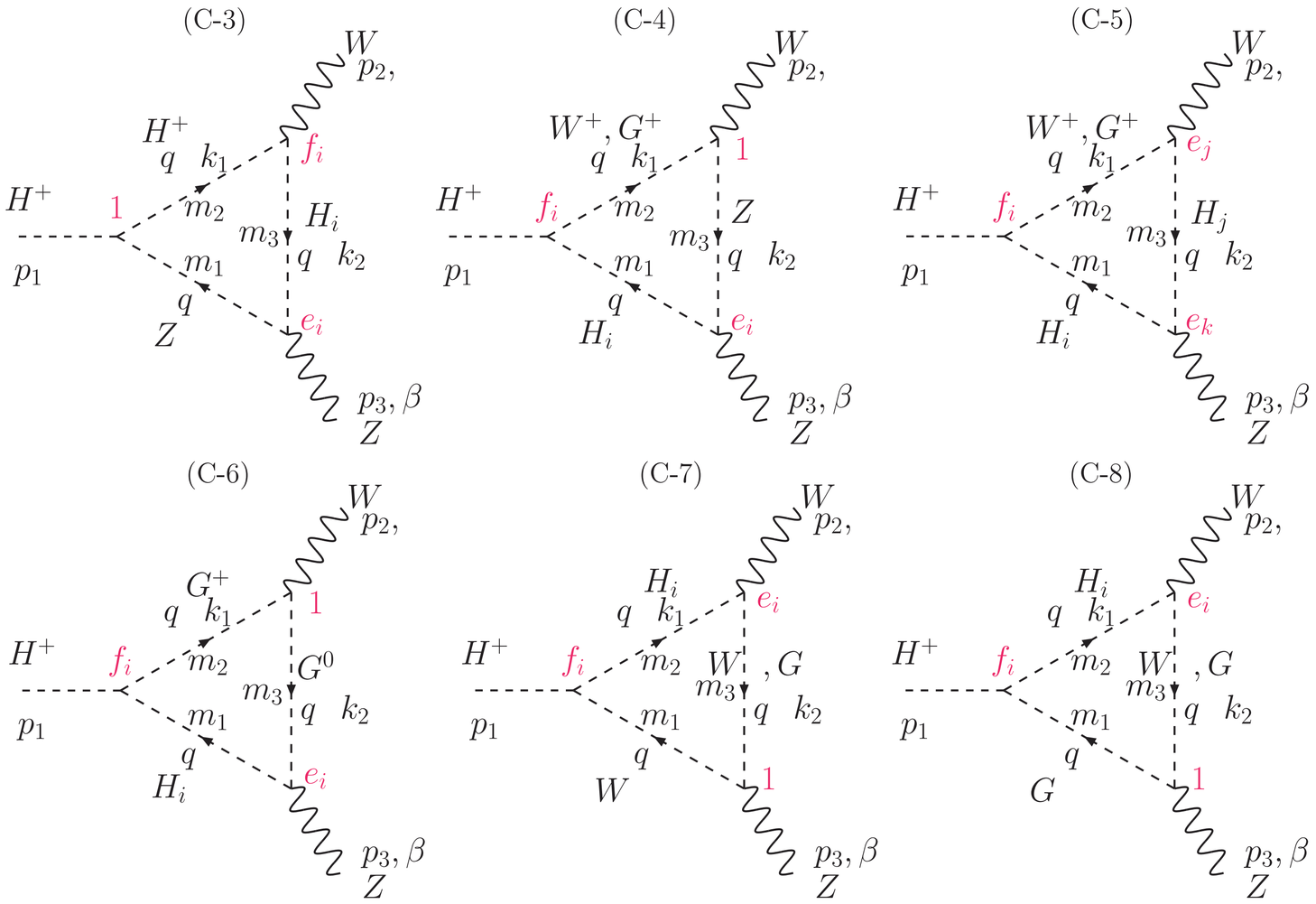


Figure 3: Other boson triangle diagrams. Some represent two cases, with a $W^{\pm}$ or a $G^{\pm}$.

Different types of Feynman diagrams

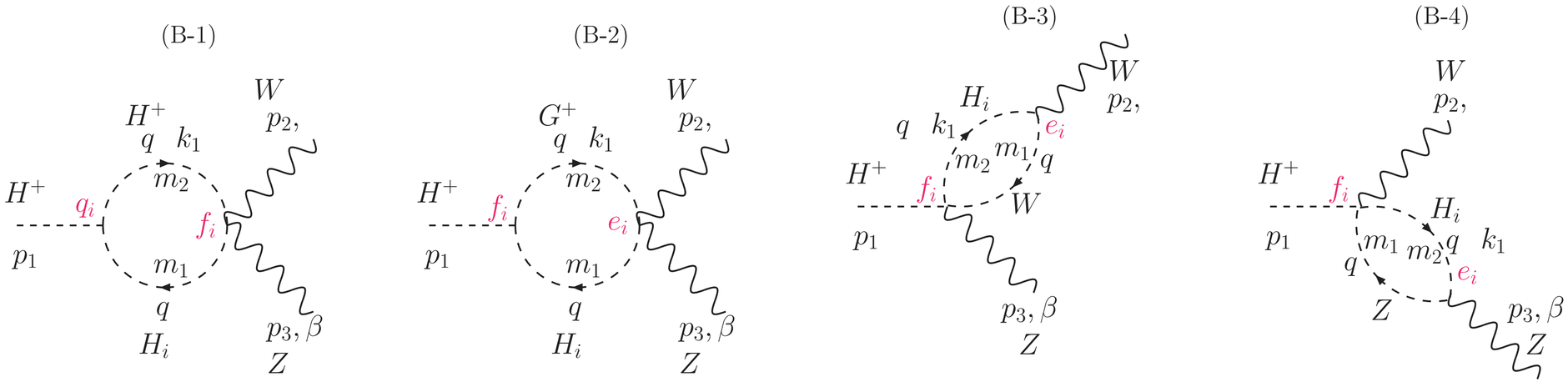


Figure 4: Boson loops—parts (B-1)–(B-4).

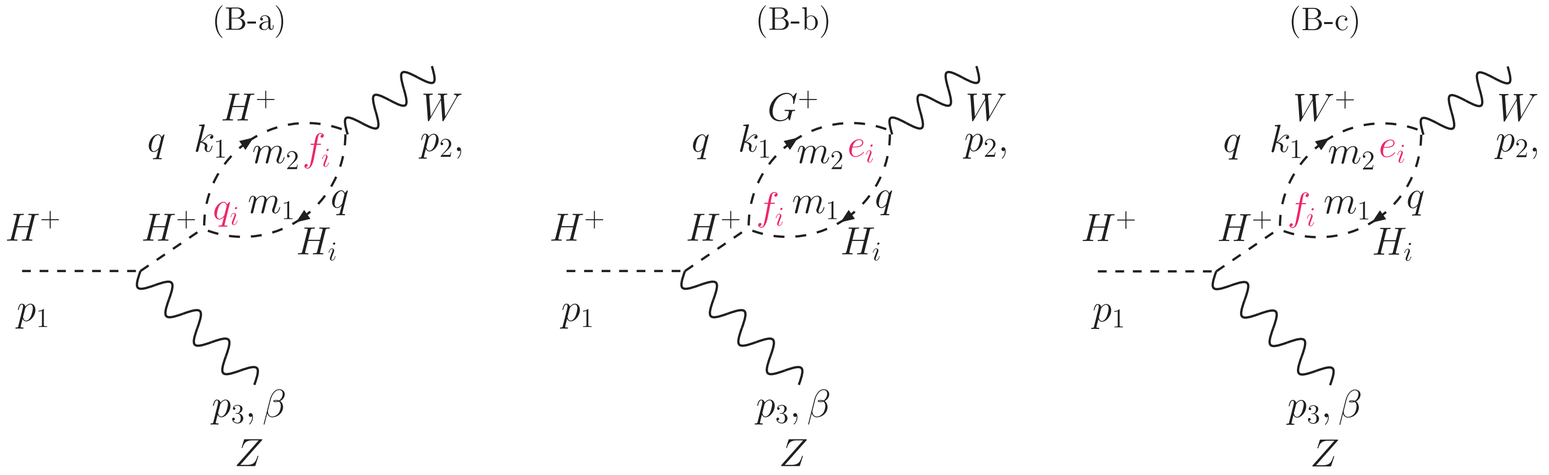


Figure 6: Boson loops—parts (B-a) to (B-c).

Different types of Feynman diagrams

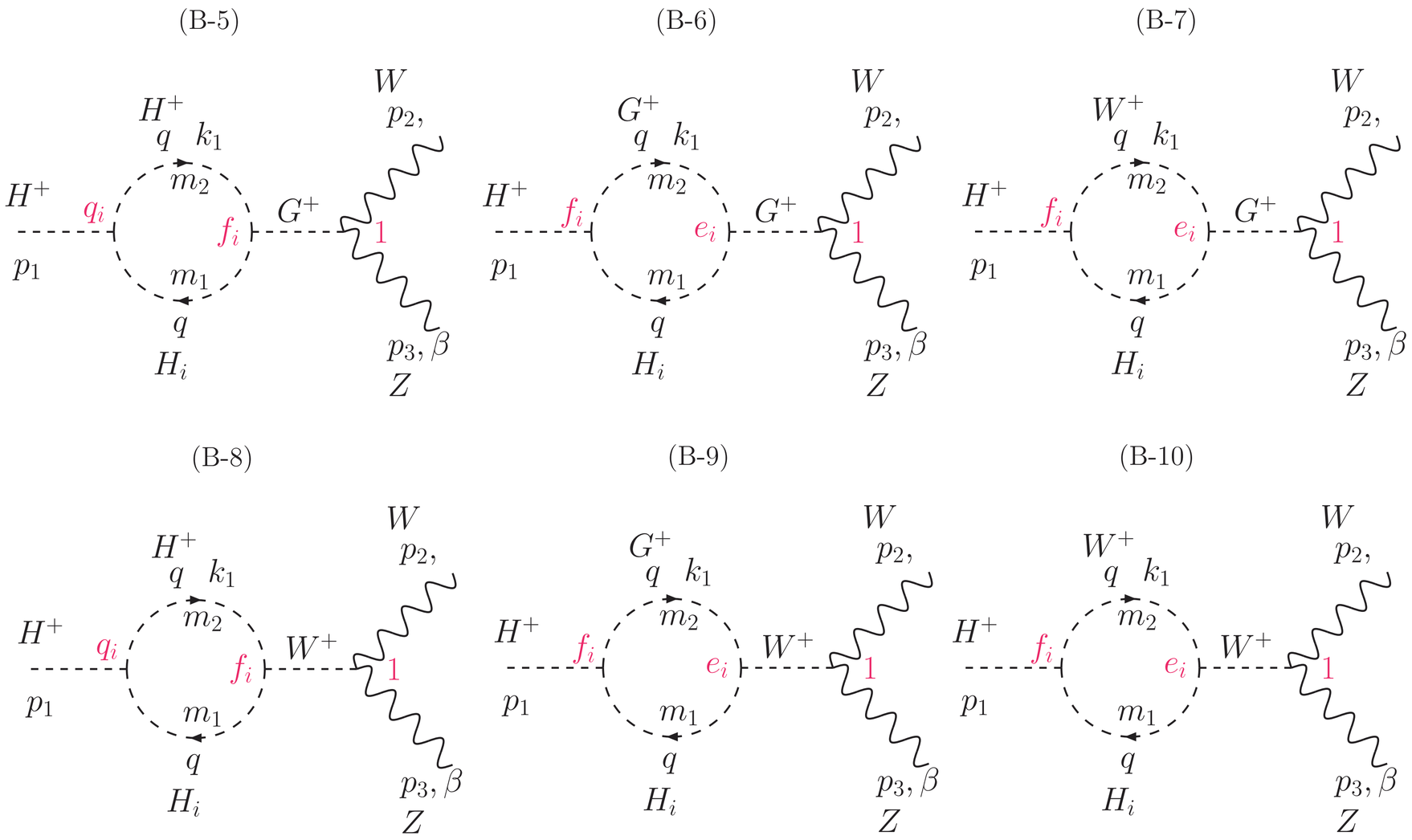


Figure 5: Boson loops—parts (B-5)–(B-10).

Different types of Feynman diagrams

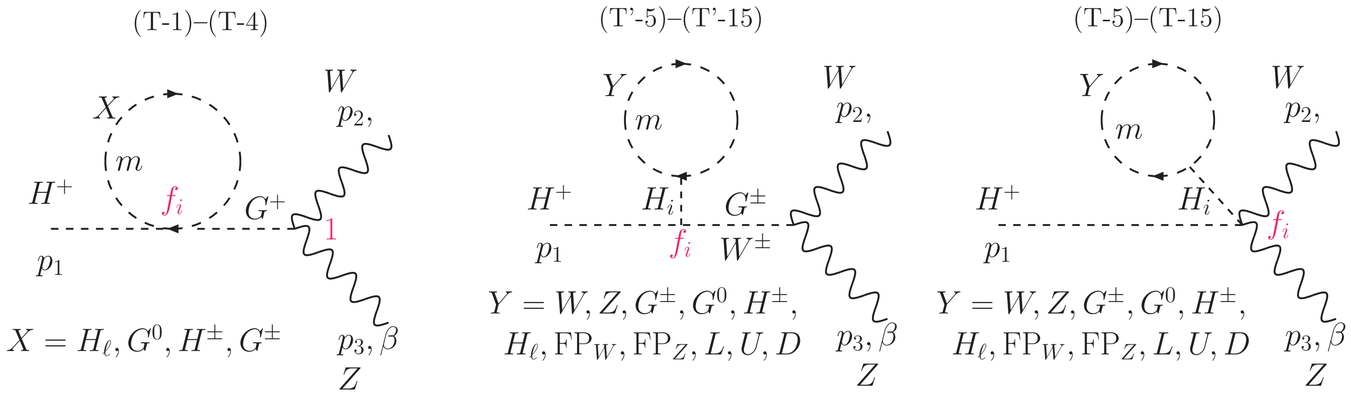


Figure 7: Boson/fermion tadpole diagrams. Left: parts (T-1)–(T-4). Centre and right: parts (T-5)–(T-15).

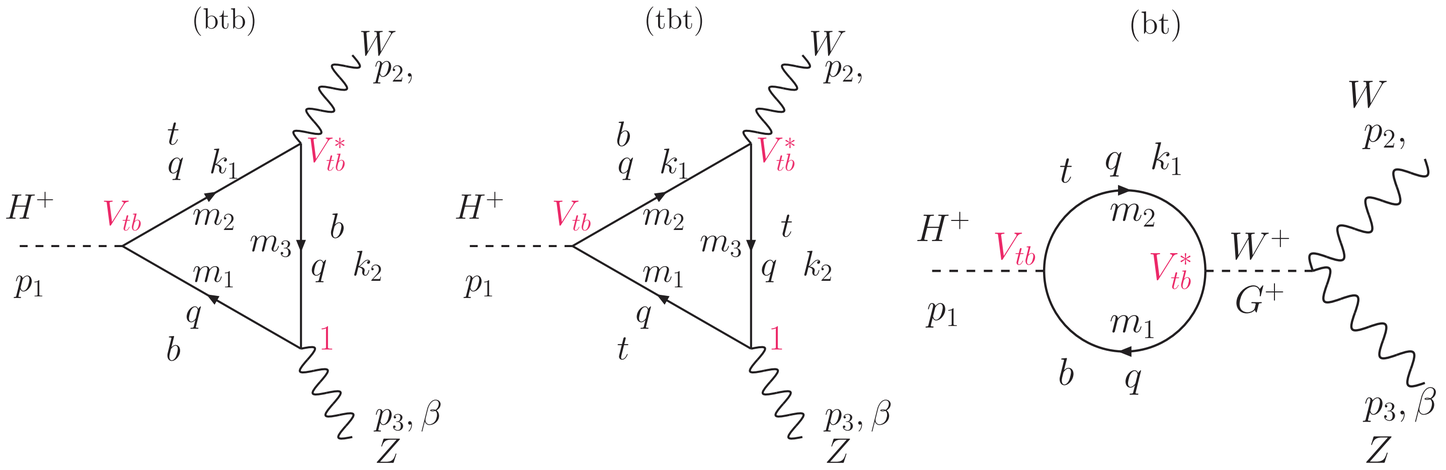


Figure 12: Quark loops. The arrows indicate momentum flow, not charge flow.

Some illustrative examples

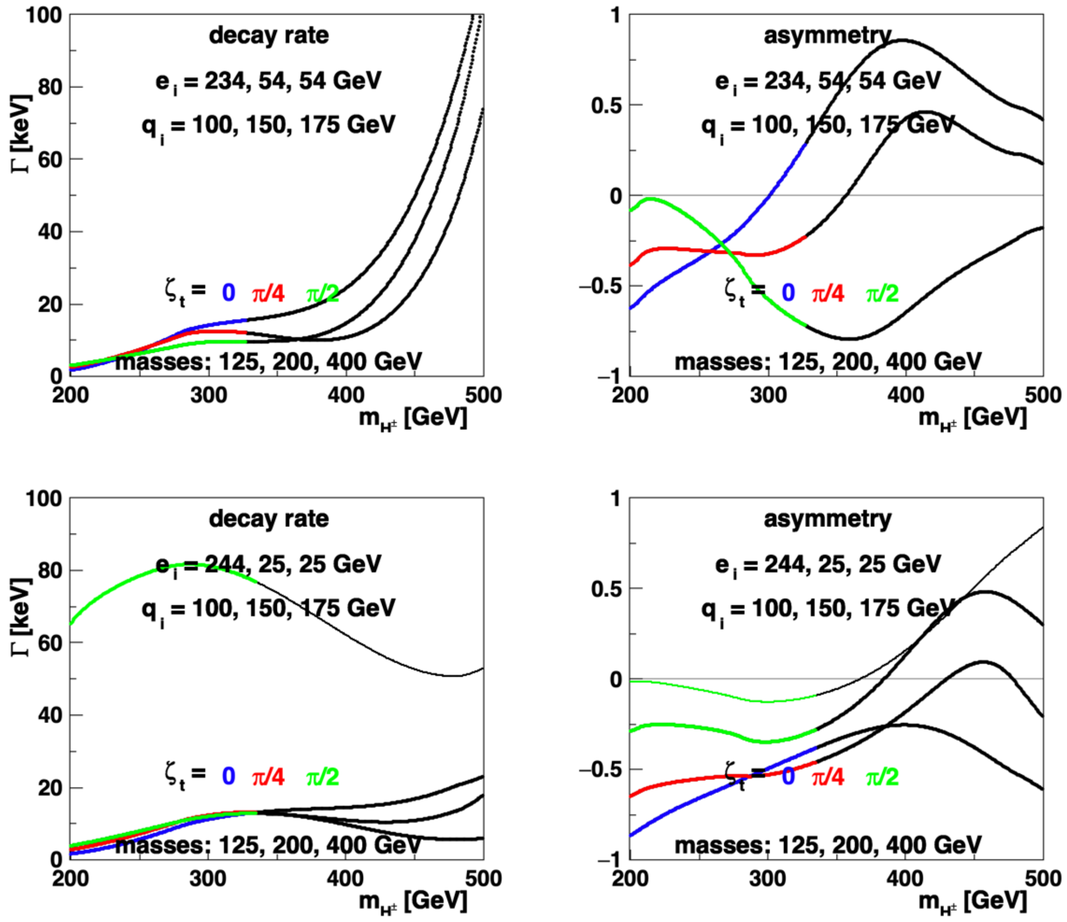


Figure 15: Decay rate and asymmetry resulting from bosonic and fermionic loops (t and b quarks and tau leptons) for limits near alignment. For the bosonic amplitudes, we consider two degrees of alignment, upper row: $e_1 = 0.95v$, lower row: $e_1 = 0.99v$. For the fermionic loops, we consider $\tilde{\rho}^X_{33} = 0.1 \times \exp(i\zeta_X)$, where X is t, b, τ with $\zeta_b = \zeta_\tau = 0$ and three values of ζ_t. Thin, green curves in lower panels: no fermion tadpole contributions.

Some illustrative examples

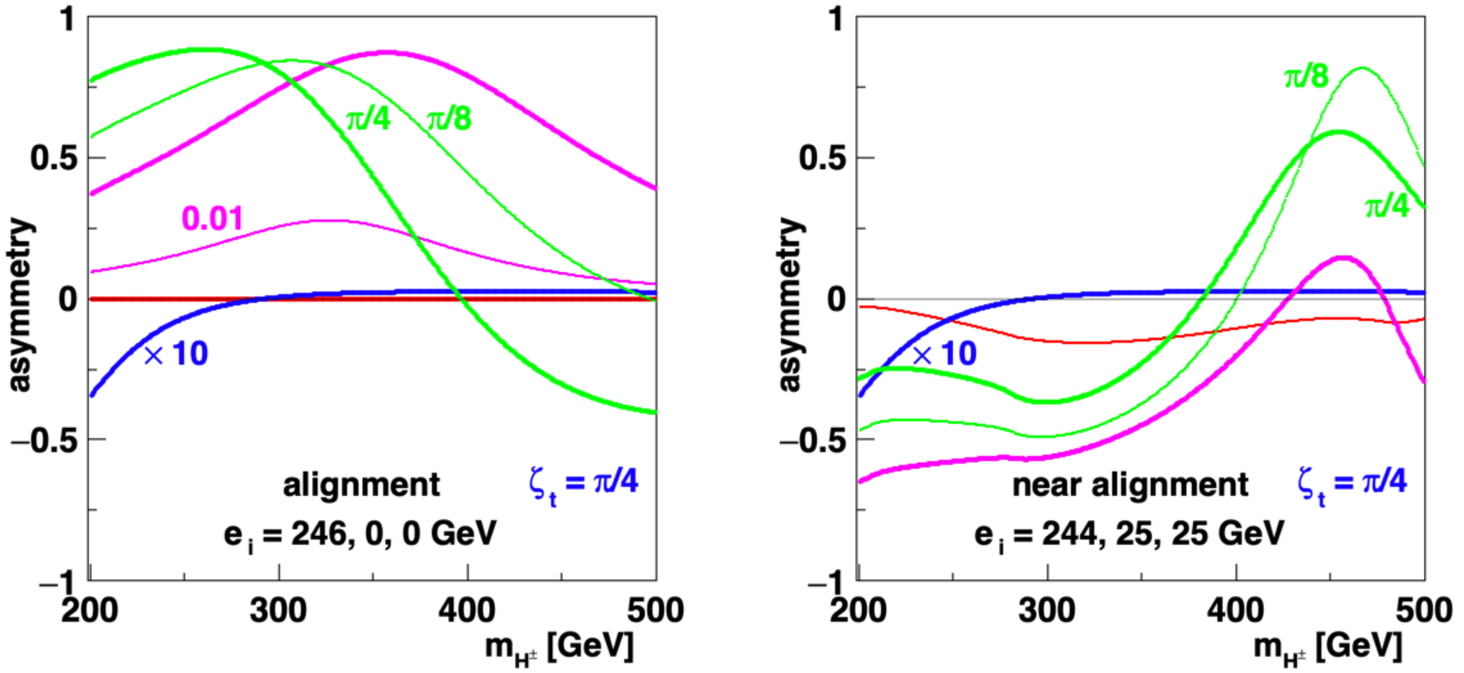


Figure 19: Bosonic sector (red): $m_i = \{125,\ 200,\ 400\}$ GeV; Left (alignment), $e_1 = v$, $e_2 = e_3 = 0$; Right: $e_1 = 0.99v = 244$ GeV, $e_2 = e_3 = 25$ GeV; Both: $q_i = \{100, 150, 175\}$ GeV; Fermionic sector (blue): $m_t = 172$ GeV, $m_b = 4.7$ GeV, $m_\tau = 1.78$ GeV, $\tilde{\rho}^X_{33} = 0.1 \times \exp(i\zeta_X)$, $\zeta_t = \pi/4$, $\zeta_b = \zeta_\tau = 0$; Purple curves show overall asymmetry (bosonic plus fermionic sectors); Cross-relation (see section 2.5): $\theta_{\rm BF} = \pi/8$, $\pi/4$ (green curves).

Final Comments

Experimentally we are close to the alignment limit. The exact alignment limit is not excluded.

In the alignment limit there is no CP violation in the purely bosonic sector under the assumption that the Higgs that was already discovered is the lightest of the neutral ones.

The CKM matrix, although being complex, does not contribute to CP violation in this process at one loop, it is the phases in the new matrices Nd and Nu, here denoted as $\tilde{\rho}$ that play an important role for CP violation via fermionic loop amplitudes.

A sizable charge asymmetry is possible even in the limit of alignment

CP violation in the process we considered would be confirmed experimentally by the observation of different decay rates to W and Z for opposite charges of the Higgs