2HDM: CP VIOLATION IN THE ZZZ AND ZWW COUPLINGS

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Work in collaboration with

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CP violation in the Higgs sector

- Three Weak-basis invariants determine the CP properties of the model.
- First introduced by Lavoura & Silva.
  [L. Lavoura and J.P. Silva*: Fundamental CP-violating quantities in an SU(2)⊗U(1) model with many Higgs-doublets*, Phys. Rev. D **50** (1994) 4619**]**
- Basis-independent description by Gunion & Haber.
  [J.F. Gunion and H.E Haber*: Conditions for CP-violation in the general two-Higgs-doublet model*, Phys. Rev. D **72**(2005) 095002**]**
- Expressed in terms of masses and physical couplings by Grzadkowski et al.
  [B. Grzadkowski, O.M. Ogreid and P. Osland*: Measuring CP-violation in two-Higgs-Doublet models in light of the LHC Higgs data,* JHEP **11** (2014) 084**]**

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The three invariants

$$\mathrm{Im}\, J_2 = 2\frac{e_1 e_2 e_3}{v^9}(M_1^2 - M_2^2)(M_2^2 - M_3^2)(M_3^2 - M_1^2)$$

$$\mathrm{Im}\, J_1 = \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk} M_i^2 e_i e_k q_j$$

$$\mathrm{Im}\, J_{30} = \frac{1}{v^5}\sum_{i,j,k}\epsilon_{ijk} q_i M_i^2 e_j q_k$$

Can be tested before/without discovery of charged Higgs.

Can it be tested before the discovery of additional Higgses?

If all three invariants are zero: CP is conserved

If at least one invariant is nonzero: CP is broken

e_i: H_iVV *or* H_jH_kV couplings

q_i: $H_iH^+H^-$ coupling

The coupling e_i:

$$H_iH_jZ_\mu : \quad \frac{g}{2v\cos\theta_\mathrm{W}}\epsilon_{ijk}e_k(p_i-p_j)_\mu, \quad H_iH_jG_0 : \quad i\frac{M_i^2-M_j^2}{v^2}\epsilon_{ijk}e_k,$$

and

$$\begin{aligned}
H_iZ_\mu Z_\nu &: \quad \frac{ig^2}{2\cos^2\theta_\mathrm{W}}e_i\,g_{\mu\nu}, & H_iW_\mu^+W_\nu^- &: \quad \frac{ig^2}{2}e_i\,g_{\mu\nu},\\
H_iG_0G_0 &: \quad \frac{-iM_i^2e_i}{v^2}, & H_iG^+G^- &: \quad \frac{-iM_i^2e_i}{v^2},\\
H_iG^+A_\mu W_\nu^- &: \quad \frac{ig^2\sin\theta_\mathrm{W}}{2v}e_i\,g_{\mu\nu}, & H_iG^-A_\mu W_\nu^+ &: \quad \frac{ig^2\sin\theta_\mathrm{W}}{2v}e_i\,g_{\mu\nu},\\
H_iG^+Z_\mu W_\nu^- &: \quad -\frac{ig^2}{2v}\frac{\sin^2\theta_\mathrm{W}}{\cos\theta_\mathrm{W}}e_i\,g_{\mu\nu} & H_iG^-Z_\mu W_\nu^+ &: \quad -\frac{ig^2}{2v}\frac{\sin\theta_\mathrm{W}^2}{\cos\theta_\mathrm{W}}e_i\,g_{\mu\nu},\\
H_iG_0Z_\mu &: \quad \frac{g}{2v\cos\theta_\mathrm{W}}e_i(p_i-p_0)_\mu, & &\\
H_iG^+W_\mu^- &: \quad i\frac{g}{2v}e_i(p_i-p^+)_\mu, & H_iG^-W_\mu^+ &: \quad -i\frac{g}{2v}e_i(p_i-p^-)_\mu.
\end{aligned}$$

$$e_i \equiv v_1R_{i1}+v_2R_{i2}$$

$$e_1^2+e_2^2+e_3^2=v^2=(246\,\mathrm{GeV})^2$$

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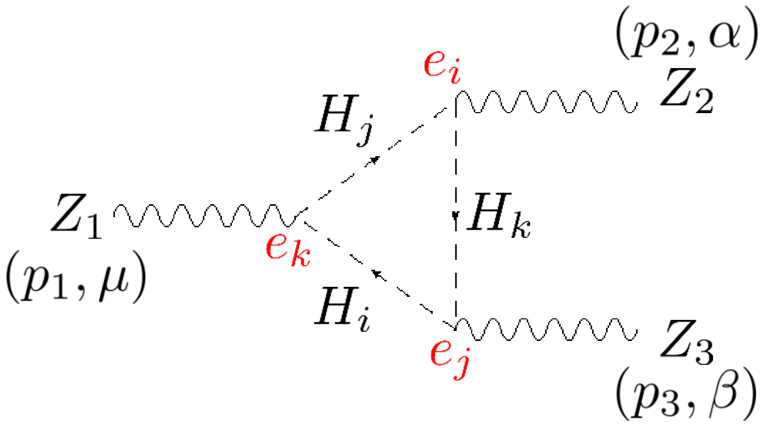
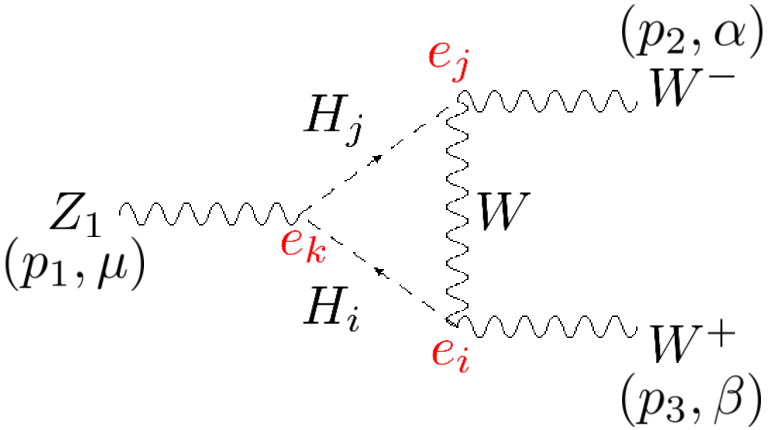
Processes containing Im J_2:

- ZZZ vertex and ZWW vertex





- Summing over all possible combinations of *i*,*j*,*k*, we find $\mathcal{M} \propto \mathrm{Im} J_2$
- Amplitudes directly proportional to Weak-basis invariant. **Ideal** place to discover CPV.

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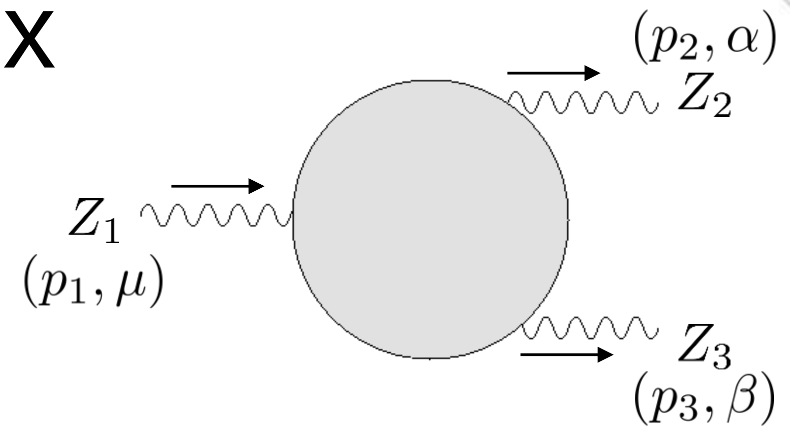
The ZZZ vertex



Does not exist at tree level! Only loop-level effects.

Assuming Z_1 to be off-shell and Z_2 and Z_3 to be on-shell, the general ZZZ vertex can be written as:

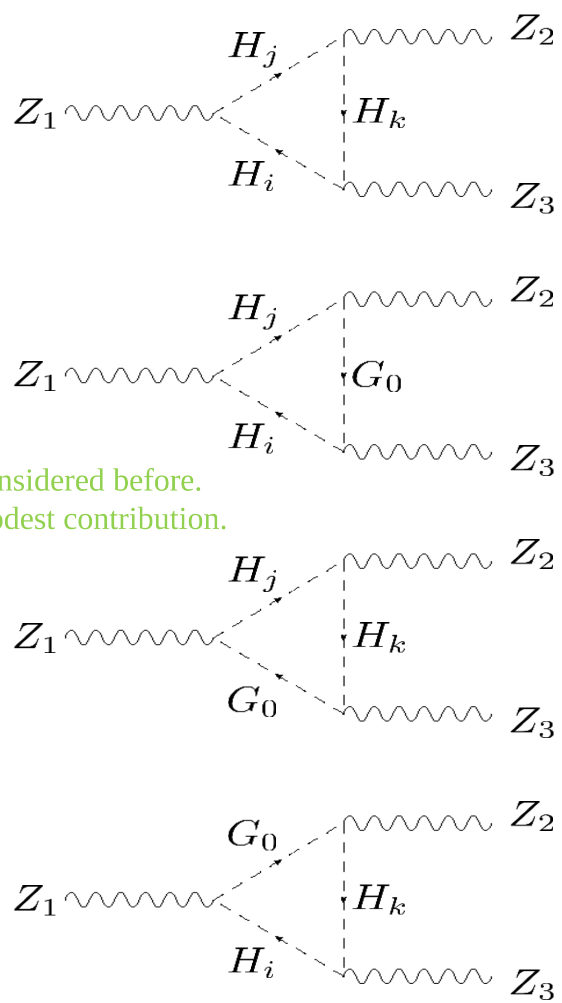
$$e\Gamma^{\alpha\beta\mu}_{ZZZ} = ie\frac{p_1^2 - M_Z^2}{M_Z^2}\left[f_4^Z (p_1^\alpha g^{\mu\beta} + p_1^\beta g^{\mu\alpha}) + f_5^Z \epsilon^{\mu\alpha\beta\rho}(p_2 - p_3)_\rho \right],$$

CP violating form factor.

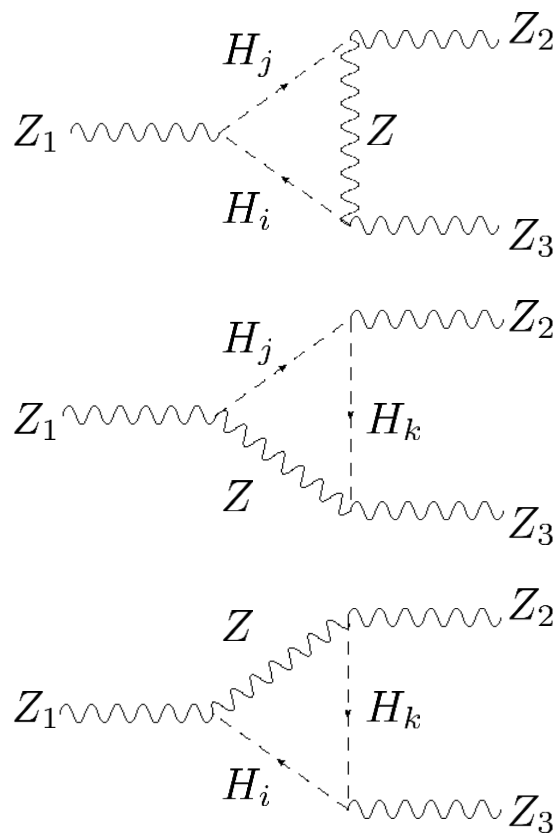
CP conserving form factor.

[K. Hagiwara, R.D. Peccei, D. Zeppenfeld and K. Hikasa: *Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$*, Nucl. Phys. B **282** (1987) 253]

2HDM contributions to f_4^Z



Considered before.
Modest contribution.



Not considered before.
Sizeable contribution.

[D. Chang, W-Y. Keung and P.B Pal: *CP violation in the cubic coupling of neutral gauge bosons*, Phys. Rev. D **51** (1995) 1326]

A total of 42 diagrams contribute to f_4^Z.

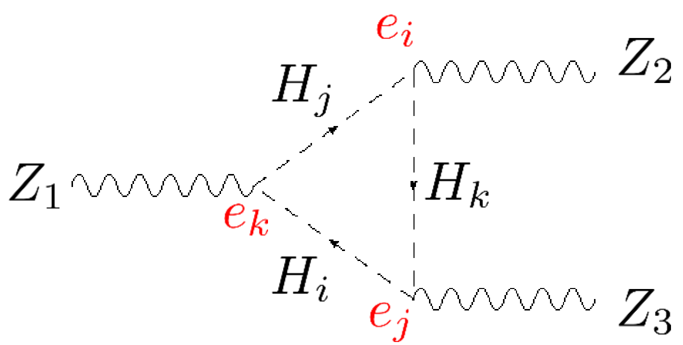
2HDM contributions to f_4^Z

$$f_4^Z = \frac{2\alpha}{\pi\sin^3(2\theta_{\rm W})}\frac{M_Z^2}{p_1^2-M_Z^2}\frac{e_1e_2e_3}{v^3}$$
$$\times\sum_{i,j,k}\epsilon_{ijk}\big[C_{001}(p_1^2,M_Z^2,M_Z^2,M_i^2,M_j^2,M_Z^2)+C_{001}(p_1^2,M_Z^2,M_Z^2,M_Z^2,M_j^2,M_k^2)$$
$$+C_{001}(p_1^2,M_Z^2,M_Z^2,M_i^2,M_Z^2,M_k^2)-C_{001}(p_1^2,M_Z^2,M_Z^2,M_i^2,M_j^2,M_k^2)$$
$$+M_Z^2C_1(p_1^2,M_Z^2,M_Z^2,M_i^2,M_Z^2,M_k^2)\big].$$

Im J_2 is playing hide and seek???

$$\mathrm{Im}\,J_2 \quad = \quad 2\frac{e_1e_2e_3}{v^9}(M_1^2-M_2^2)(M_2^2-M_3^2)(M_3^2-M_1^2)$$

Contribution from



$$f_4^Z = \frac{-2\alpha}{\pi \sin^3(2\theta_{\mathrm{W}})} \frac{M_Z^2}{p_1^2 - M_Z^2} \frac{e_1e_2e_3}{v^3} \sum_{i,j,k} \epsilon_{ijk} \left[C_{001}(p_1^2, M_Z^2, M_Z^2, M_i^2, M_j^2, M_k^2)\right]$$

Im J_2 is playing hide and seek???

$$\mathrm{Im}\, J_2 \quad = \quad 2\frac{e_1e_2e_3}{v^9}(M_1^2 - M_2^2)(M_2^2 - M_3^2)(M_3^2 - M_1^2)$$

Extracting the mass factors of Im J_2

- Express C_{001} in terms of scalar integrals.
- Use known explicit results for scalar integrals (logarithms+dilogarithms).

$$\begin{aligned} x &= \frac{(M_2^2 - M_1^2)}{s_1} \\ y &= \frac{(M_3^2 - M_2^2)}{s_1} \\ x + y &= \frac{(M_3^2 - M_1^2)}{s_1} \end{aligned}$$

- Introduce parameters

$(s_1 = p_1^2)$

$$\mathrm{Im}\, J_2 = 2\frac{e_1 e_2 e_3}{v^9} s_1^3 xy(x+y)$$

Extracting the mass factors of Im J_2

- Substitute
$$\begin{aligned} M_3^2 &= M_1^2 + s_1(x+y) \\ M_2^2 &= M_1^2 + s_1 x \end{aligned}$$

  into
$$\sum_{i,j,k} \epsilon_{ijk} \left[C_{001}(p_1^2, M_Z^2, M_Z^2, M_i^2, M_j^2, M_k^2) \right].$$

  which we have already expressed in terms of logarithms and dilogarithms
- Expand resulting expression for small x and y
- Lowest order term proportional to xy(x+y).
- Im J_2 was «lost», but is now «found»!!!

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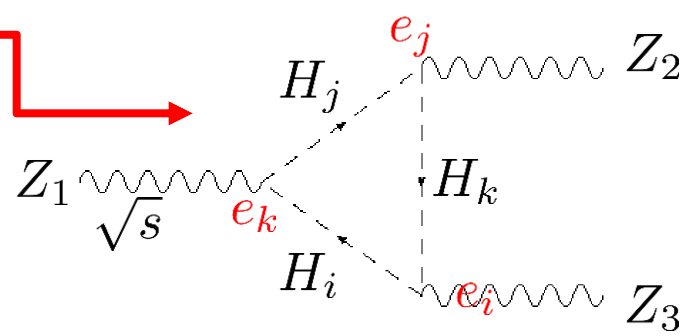
Contribution from in high-energy limit (p_1 is large)



$$
\begin{aligned}
f_4^Z &= \frac{-2\alpha}{\pi \sin^3(2\theta_{\mathrm{W}})} \frac{M_Z^2}{p_1^2 - M_Z^2} \frac{e_1 e_2 e_3}{v^3} \sum_{i,j,k} \epsilon_{ijk} \left[C_{001}(p_1^2, M_Z^2, M_Z^2, M_i^2, M_j^2, M_k^2)\right]. \\
&\simeq \frac{-\alpha}{4\pi \sin^3(2\theta_{\mathrm{W}})} \frac{v^6 M_Z^2}{M_1^2 s_1^2 (s_1 - M_Z^2)} \mathrm{Im} J_2 \\
&\times \left(\log\left(\frac{M_1^2}{s_1}\right) + \frac{i\left(9M_1^2 - 2M_Z^2\right) \log\left(\frac{\sqrt{4M_1^2 - M_Z^2} - iM_Z}{\sqrt{4M_1^2 - M_Z^2} + iM_Z}\right)}{M_Z \sqrt{4M_1^2 - M_Z^2}} + i\pi \right)
\end{aligned}
$$

is proportional to Im J_2

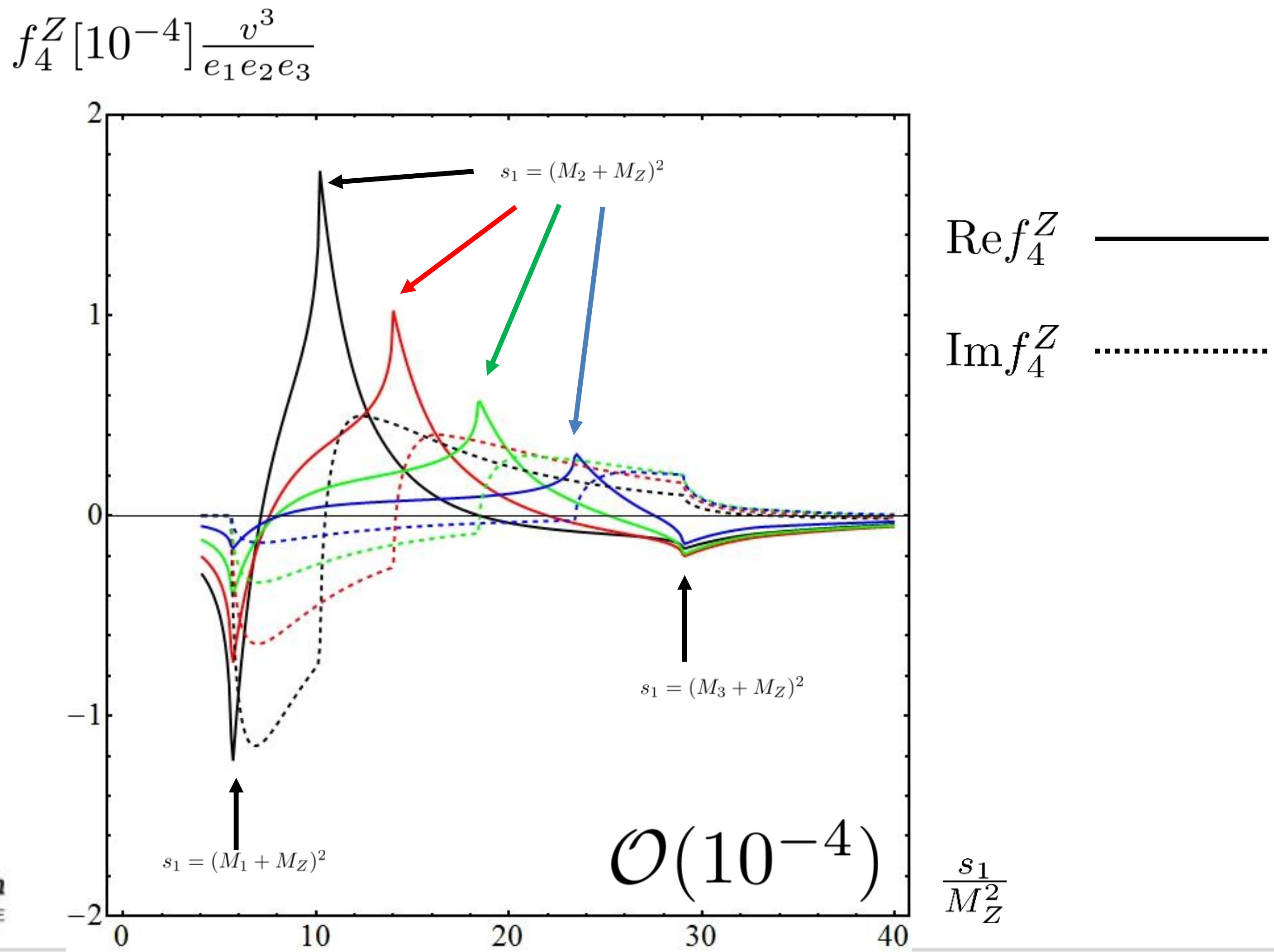
2HDM contributions to f_4^Z

(Contributions from all diagrams)

M_1 = 125 GeV

M_2 = 200 GeV
M_2 = 250 GeV
M_2 = 300 GeV
M_2 = 350 GeV

M_3 = 400 GeV



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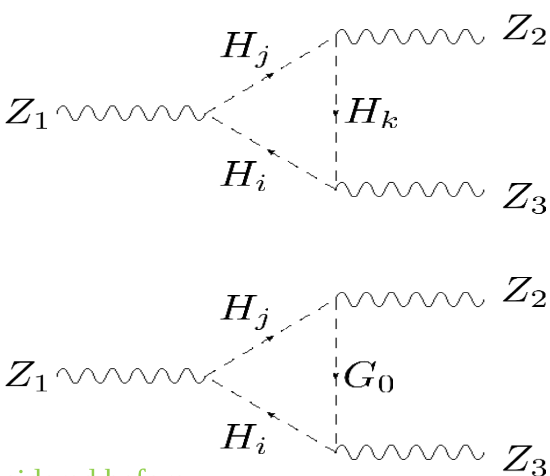
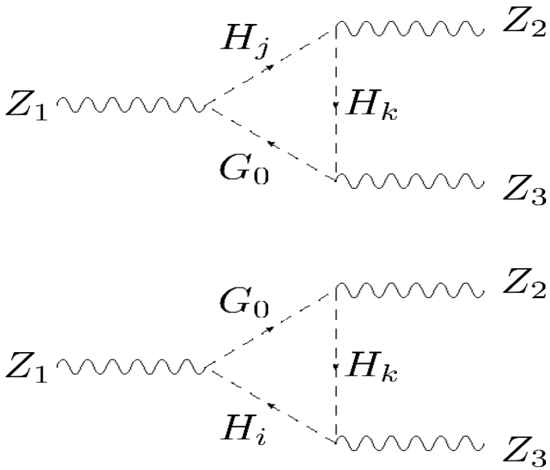
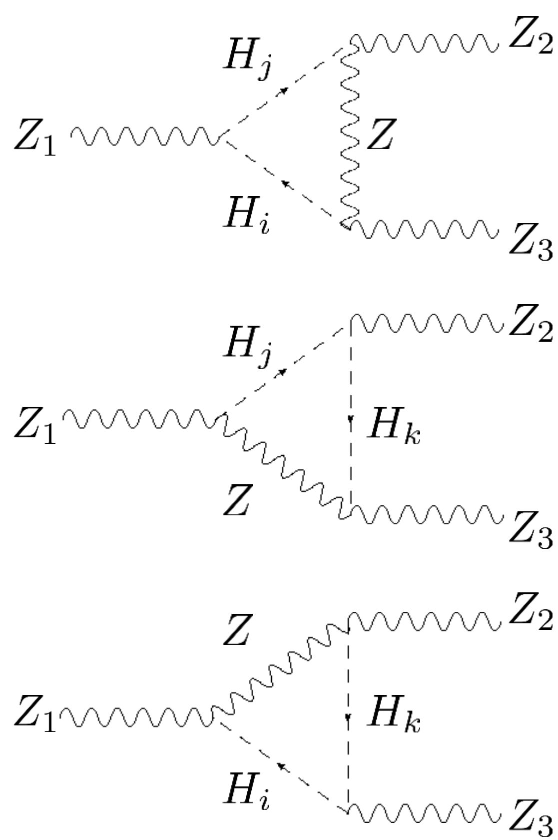
2HDM contributions to f_4^Z



Considered before.
Modest contribution.





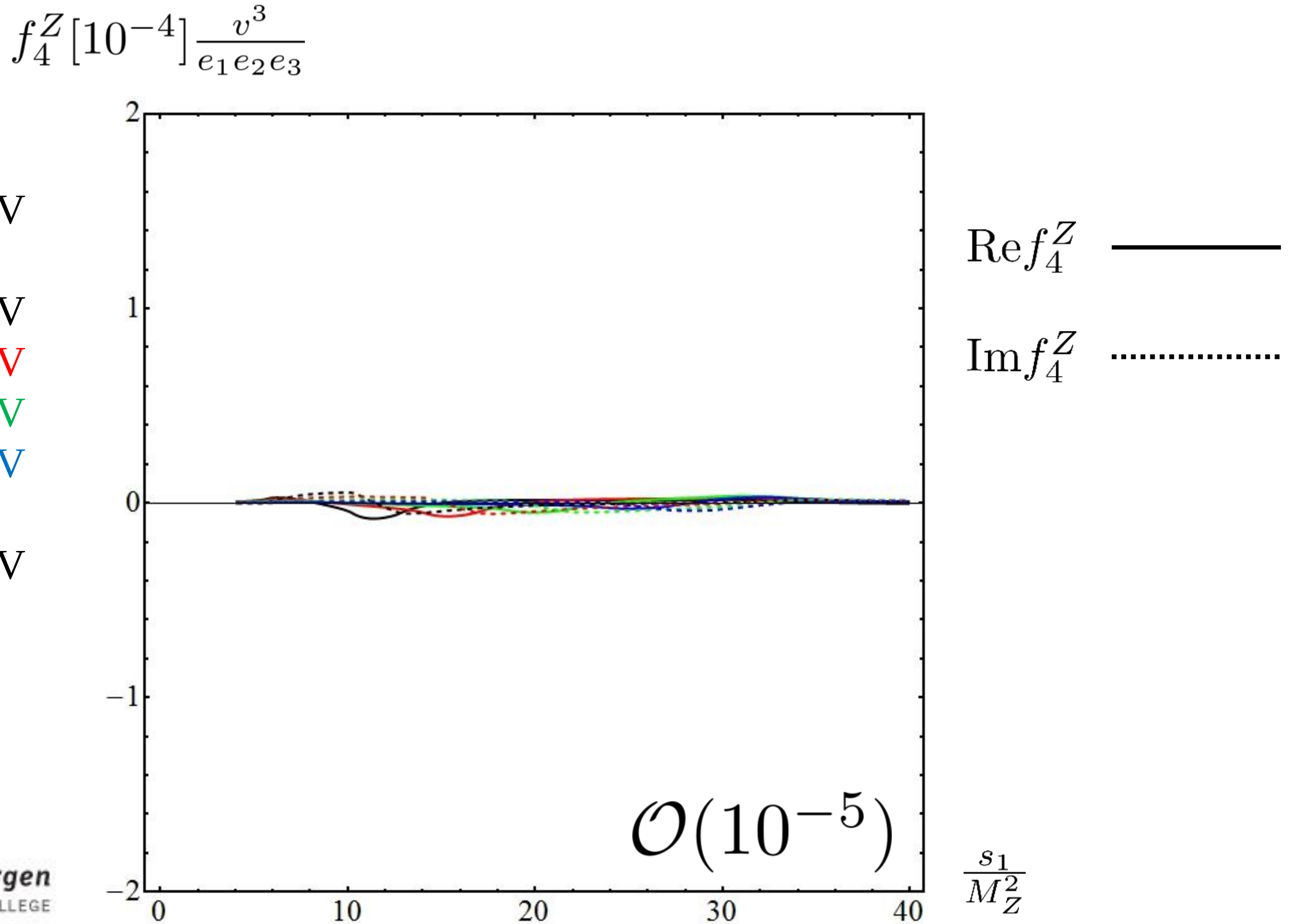
Not considered before.
Sizeable contribution.

[D. Chang, W-Y. Keung and P.B Pal: *CP violation in the cubic coupling of neutral gauge bosons*, Phys. Rev. D **51** (1995) 1326]

A total of 42 diagrams contribute to f_4^Z.

2HDM contributions to f_4^Z

(Diagrams with Z in the loop excluded)



M_1 = 125 GeV

M_2 = 200 GeV
M_2 = 250 GeV
M_2 = 300 GeV
M_2 = 350 GeV

M_3 = 400 GeV

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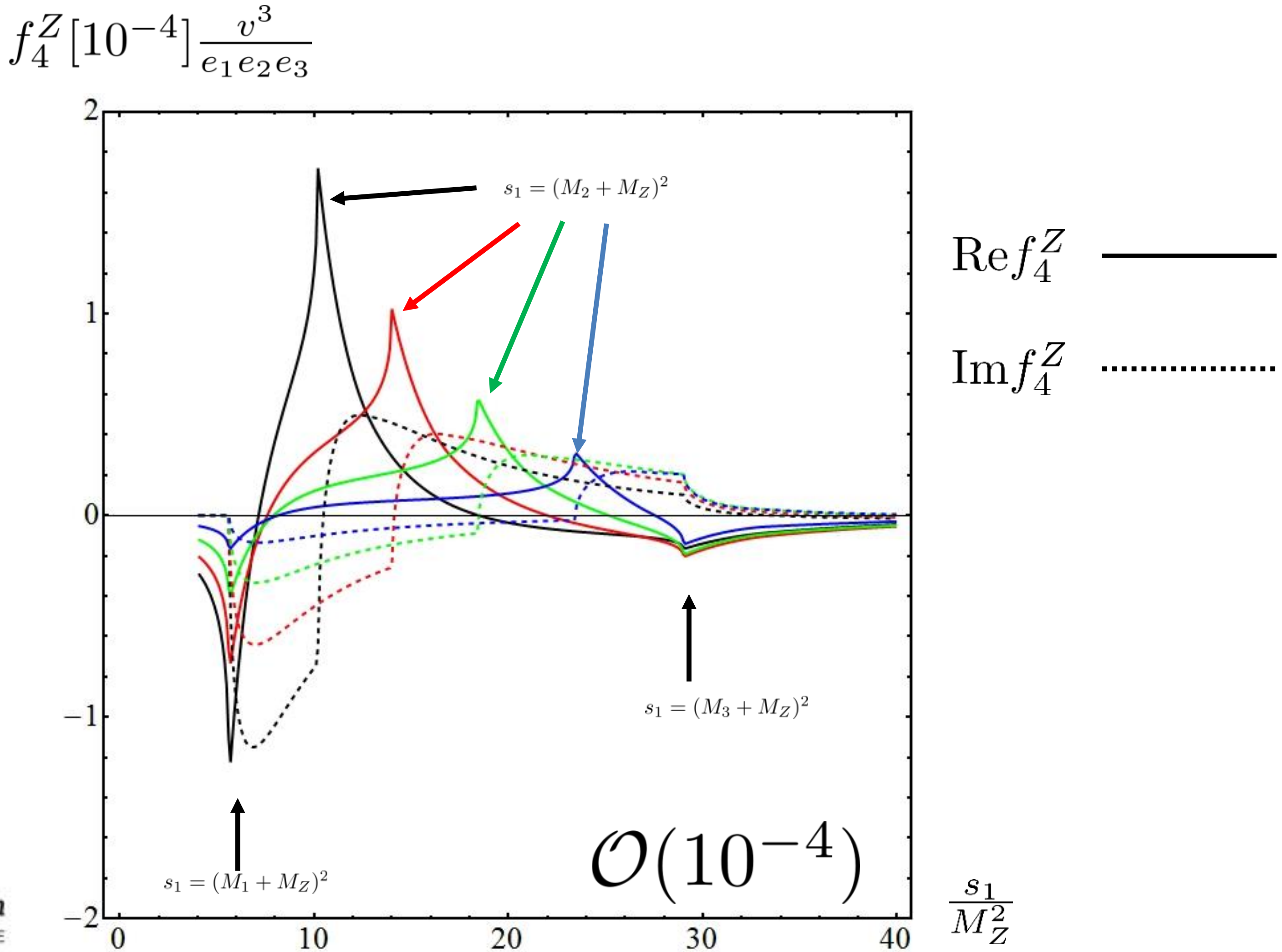
2HDM contributions to f_4^Z
(Contributions from all diagrams)

M_1 = 125 GeV

M_2 = 200 GeV
M_2 = 250 GeV
M_2 = 300 GeV
M_2 = 350 GeV

M_3 = 400 GeV



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CP-sensitive observables

Consider: $e^- e^+ \to Z^* \to Z(\lambda)Z(\lambda')$

Folded asymmetry:

$$\begin{aligned}\mathcal{A}''(\Theta) &= -\frac{1}{\pi}\left[\mathrm{Im}\rho(\Theta)_{+,-} - \mathrm{Im}\rho(\pi-\Theta)_{-,+}\right] \\ &\simeq \frac{\beta(1+\beta^2)\gamma^2[(1+\beta^2)^2 - (2\beta\cos\Theta)^2]\sin^2\Theta\,\xi\,\mathrm{Re}f_4^Z}{\pi[2+3\beta^2-\beta^6-\beta^2(9-10\beta^2+\beta^4)\cos^2\Theta - 4\beta^4\cos^4\Theta]}\end{aligned}$$

to lowest order in f_4^Z .

$\rho(\Theta)$ is the spin-density matrix of the Z boson.

$\gamma^{-2} = 1 - \beta^2 = \frac{4M_Z^2}{s_1}$

$\xi = \xi(\theta_W) \simeq 2.64$

[D. Chang, W-Y. Keung and P.B Pal*: CP violation in the cubic coupling of neutral gauge bosons*, Phys. Rev. D **51** (1995) 1326**]**

CP-sensitive observables

Consider: $e^-e^+ \to Z^* \to Z(\lambda)Z(\lambda')$

Cross section helicity asymmetry:

$$A^{ZZ} \equiv \frac{\sigma_{+,0} + \sigma_{0,+} - \sigma_{0,-} - \sigma_{-,0}}{\sigma_{+,0} + \sigma_{0,+} + \sigma_{0,-} + \sigma_{-,0}}$$
$$= \frac{-2\beta\gamma^4[(1+\beta^2)^2 - (2\beta\cos\Theta)^2][1+\beta^2-(3-\beta^2)\cos^2\Theta]\xi\,\mathrm{Im} f_4^Z}{(1+\beta^2)^2 - (3+6\beta^2-\beta^4)\cos^2\Theta + 4\cos^4\Theta}$$

to lowest order in f_4^Z .

$$\gamma^{-2} = 1 - \beta^2 = \frac{4M_Z^2}{s_1}$$
$$\xi = \xi(\theta_W) \simeq 2.64$$

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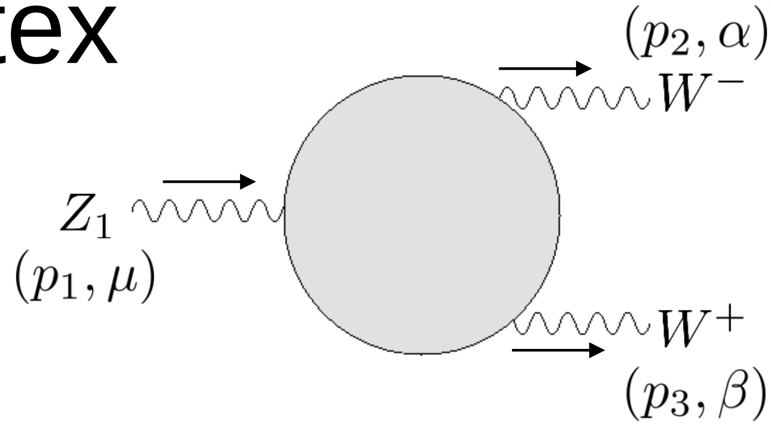
The ZWW vertex

Exists at tree level (CPC)!
Loop-level effects
contribute to CPV.



Assuming Z_1 to be off-shell and W^- and W^+ to be on-shell, the general ZWW vertex can be written as:

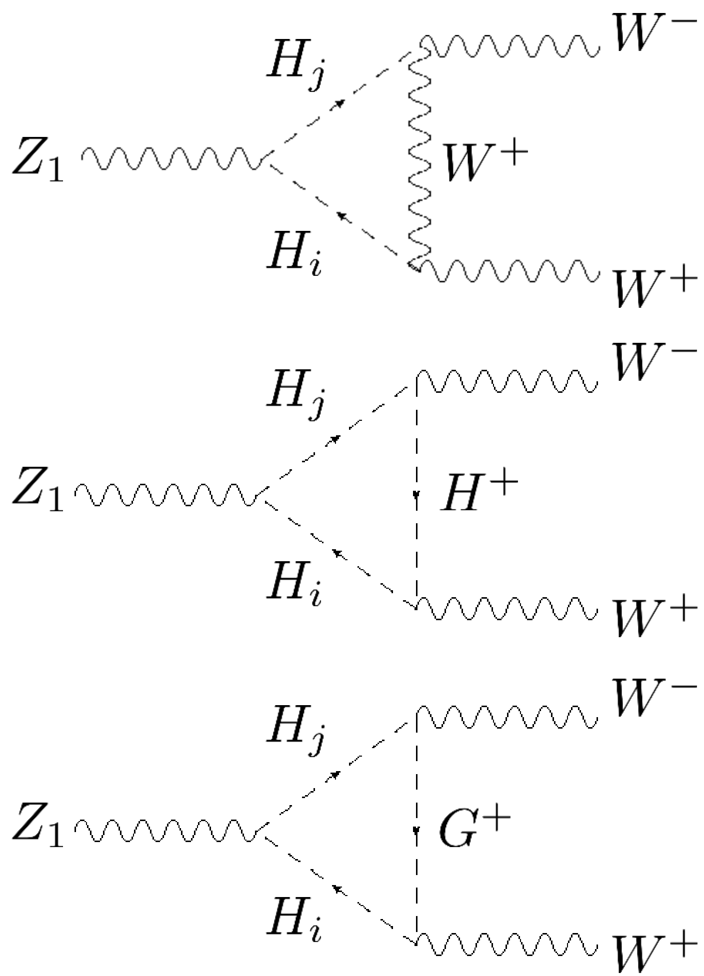
$$\Gamma^{\alpha\beta\mu}_{ZWW} = f_1^Z (p_2 - p_3)^\mu g^{\alpha\beta} - \frac{f_2^Z}{M_W^2}(p_2 - p_3)^\mu p_1^\alpha p_1^\beta + f_3^Z (p_1^\alpha g^{\mu\beta} - p_1^\beta g^{\mu\alpha})$$
$$+ i f_4^Z (p_1^\alpha g^{\mu\beta} + p_1^\beta g^{\mu\alpha}) + i f_5^Z \epsilon^{\mu\alpha\beta\rho}(p_2 - p_3)_\rho$$
$$- f_6^Z \epsilon^{\mu\alpha\beta\rho} p_{1\rho} - \frac{f_7^Z}{M_W^2}(p_2 - p_3)^\mu \epsilon^{\alpha\beta\rho\sigma} p_{1\rho}(p_2 - p_3)_\sigma$$

CP conserving form factors.

CP violating form factors.

[K. Hagiwara, R.D. Peccei and D. Zeppenfeld: *Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$*, Nucl. Phys. B **282** (1987) 253**]**

2HDM contributions to f_4^Z



A total of 18 diagrams contribute to f_4^Z.

2HDM contributions to f_4^Z

$$f_4^Z = \frac{-\alpha}{4\pi\cos^2\theta_{\rm W}\sin^2\theta_{\rm W}}\frac{e_1e_2e_3}{v^3}\sum_{i,j,k}\epsilon_{ijk}\left[C_{001}(p_1^2, M_W^2, M_W^2, M_i^2, M_j^2, M_W^2)\right.$$
$$\left. -C_{001}(p_1^2, M_W^2, M_W^2, M_i^2, M_j^2, M_{H^\pm}^2)\right]$$

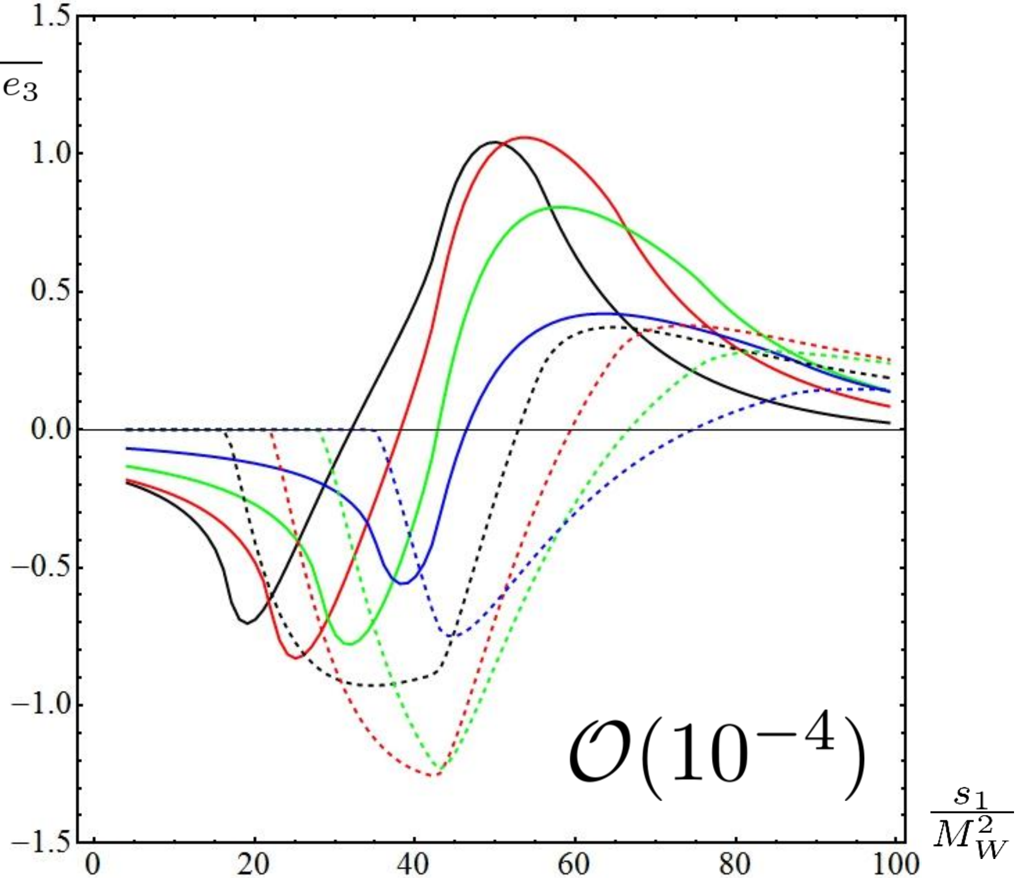
$f_4^Z[10^{-4}]\,\frac{v^3}{e_1e_2e_3}$

M_1 = 125 GeV

M_2 = 200 GeV
M_2 = 250 GeV
M_2 = 300 GeV
M_2 = 350 GeV

M_3 = 400 GeV

M_H = 500 GeV



[X.J. He, J.P Ma and B.H.J McKellar: *CP violating form factors for three gauge boson vertices in the two-Higgs doublet and left-right symmetric models*, Phys. Lett. B **304** (1993) 205]

CP-sensitive observables

Consider: $e^- e^+ \to Z^* \to W^-(\lambda) W^+(\lambda')$

Asymmetries:

$$A_1^{WW} \equiv \frac{\sigma_{+,0} - \sigma_{0,-}}{\sigma_{+,0} + \sigma_{0,-}} \propto \mathrm{Im} f_4^Z$$

$$A_2^{WW} \equiv \frac{\sigma_{0,+} - \sigma_{-,0}}{\sigma_{0,+} + \sigma_{-,0}} \propto \mathrm{Im} f_4^Z$$

to lowest order in f_4^Z .

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Challenges

$$f_4^Z \frac{v^3}{e_1 e_2 e_3} = \mathcal{O}(10^{-4})$$

$$\max\left(\frac{e_1 e_2 e_3}{v^3}\right) = \frac{1}{3\sqrt{3}} = \mathcal{O}(10^{-1})$$

$$\Longrightarrow \; f_4^Z = \mathcal{O}(10^{-5})$$

In the alignment limit $e_1 \simeq v, \quad e_2 \simeq e_3 \simeq 0$
making f_4^Z even smaller.

Challenges

- ZZZ-vertex: CMS-data (2015) from $4l$ and $2l2\nu$ channels at 7 TeV and 8 TeV:

$$\sqrt{s_1} \simeq 4M_Z^2: \quad -0.0022 \leq f_4^Z \leq 0.0026$$

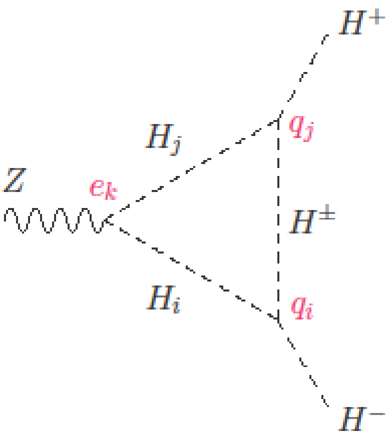
- ZWW-vertex: ?

- Still two orders of magnitude away from the maximal predictions of 2HDM.

Challenges

- If alignment:
$$\begin{aligned}\mathrm{Im}\, J_1 &= \mathrm{Im}\, J_2 = 0 \\ \mathrm{Im}\, J_3 &\neq 0\end{aligned}$$

- We then need to focus on



- Proportional to $\mathrm{Im}\, J_3$ in the alignment limit.

- Will have to await discovery of charged scalar.

Thank you for your attention