Anomalous ZZZ coupling as a sign of dark CP violation in the Three-Higgs Doublet Model

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with
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work in progress

Motivation

- **Standard Model:**
  - Higgs particle found at the LHC in 2012
    $\rightarrow$ very SM-like
  - no signal for New Physics as of 2019
  - several issues are still not explained by the SM
- **Dark Matter:**
  - if Standard Cosmological Model correct: 85% mass missing
  - only gravitational interaction observed
  - nature of DM unknown
- **CP violation:**
  - CPv in the SM not enough to explain BAU
- **...**
- **Many competing models on the market**
  - what are distinct signatures?

3HDM

Three-Higgs Doublet Models:

- three $SU(2)$ doublets, ϕ_1, ϕ_2, ϕ_3
- richer symmetry groups than the 2HDMs
- richer particle spectrum
- stable DM candidate and CP violation
  $\rightarrow$ unlike the 2HDM
- in this talk

Z_2-symmetric 3HDM with Two Inert and One Higgs doublet:

I(2+1)HDM

I(2+1)HDM

Z_2-symmetry in I(2+1)HDM:

$$\phi_1 \to -\phi_1,\ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3,\ \text{SM fields} \to \text{SM fields}$$

Z_2-invariant potential:

$$V = \sum_i^3 \left[-|\mu_i^2|(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2\right] + \sum_{ij}^3 \left[\lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)\right]$$
$$+ \left(-\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.\right)$$
$$+ \Big(\lambda_4(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_5(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_6(\phi_1^\dagger\phi_2)(\phi_1^\dagger\phi_1)$$
$$+ \lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_2) + \lambda_8(\phi_3^\dagger\phi_1)(\phi_3^\dagger\phi_2) + h.c.\Big)$$

- 21 parameters in V
- explicit CP violation: $\mu_{12}^2, \lambda_1, \lambda_2, \lambda_3$ are complex
  $\to$ 3 independent CPv phases
- Yukawa interaction: "Model I"-type (only ϕ_3 couples to fermions)
- explicit Z_2-symmetry

Particle Content

Z_2-invariant vacuum state:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

- ϕ_3 – SM-like doublet with SM-like Higgs h
- Z_2-odd (inert) doublets ϕ_1 and ϕ_2 mix:

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix} = R_{4\times 4} \begin{pmatrix} H_1^0 \\ H_2^0 \\ A_1^0 \\ A_2^0 \end{pmatrix}, \quad \begin{pmatrix} S_1^\pm \\ S_2^\pm \end{pmatrix} = R_{2\times 2} \begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix}$$

- 4 neutral Z_2-odd particles

  mixing between states of opposite CP-parity

- S_1 – **DM candidate**, other dark particles heavier

  $\rightarrow$ interesting DM phenomenology

CPV in the Dark Sector

- inert scalars do not couple to fermions

  → CKM matrix as in the SM

- inert scalars have mixed CP-parity

  → different interaction with Z compared to CPc 3HDM:

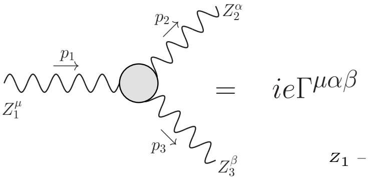
  - CPv 3HDM: $ZS_1S_2,\ ZS_1S_3,\ ZS_1S_4,\ ZS_2S_3,\ ZS_2S_4,\ ZS_3S_4$
  - CPc 3HDM: $ZH_1A_1,\ ZH_2A_1,\ ZH_1A_2,\ ZH_2A_2$

  → but how does it differ from CPc 3HDM+singlet?:

  - $ZH_1A_1,\ ZH_1A_2,\ ZH_2A_1,\ ZH_2A_2,\ ZH_3A_1,\ ZH_3A_2$

- **what is a clear signature of dark CP violation?**

ZZZ vertex



Z_1 – off-shell, Z_2, Z_3 – on-shell

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

vertices forbidden by Z_2 symmetry:

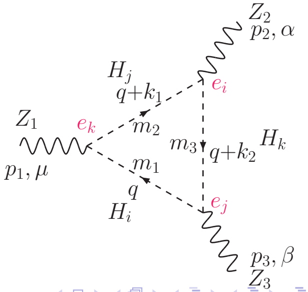
$ZZS_i, G^0ZS_i \Rightarrow$

no SG^0Z, SSZ triangle/bubble diagrams

vertices allowed by Z_2 symmetry:

$ZS_iS_j \Rightarrow$

only SSS triangle diagrams remain



Formula for f_4

in the LoopTools notation

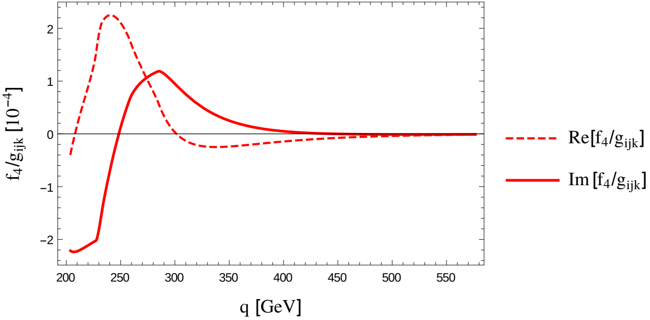
$$f_4 = \frac{1}{e}\,\frac{1}{2\pi^2}\,\frac{M_Z^2}{q^2 - M_Z^2}\sum_{i,j,k}^{4} g_{ijk}\epsilon_{ijk}C_{002}(M_Z^2, M_Z^2, q^2, m_i^2, m_j^2, m_k^2)$$

g_{ijk} is given by scalar-Z couplings:

$$g_{ijk} = |g_{ZS_iS_j}|\,|g_{ZS_jS_k}|\,|g_{ZS_kS_i}| \sim R_{ij}R_{jk}R_{kj}$$

where R_{ij} are elements of the rotation matrix

$\Rightarrow$ if there is no CP mixing then $g_{ijk} \to 0$



$$m_1 = 72\,\mathrm{GeV}, m_2 = 103\,\mathrm{GeV}, m_3 = 129\,\mathrm{GeV}, m_4 = 155\,\mathrm{GeV}$$

Asymmetries

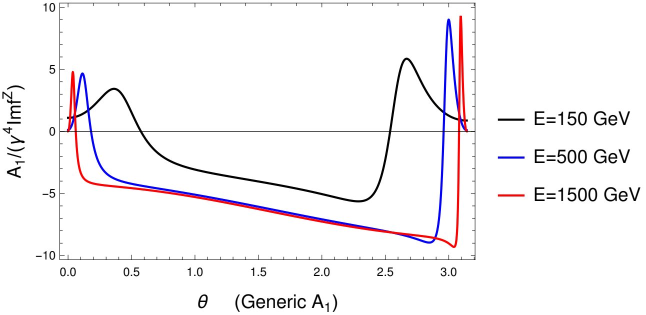
ZZ production at e^+e^- colliders: $e^-(\sigma)e^+(\bar{\sigma}) \to Z(\lambda)Z(\bar{\lambda})$

$\lambda, \bar{\lambda}$ – helicities of Z, $\sigma, \bar{\sigma}$ – helicities of e^-, e^+

$$A_1 = \frac{\sigma_{+,0} - \sigma_{0,-}}{\sigma_{+,0} + \sigma_{0,-}} \qquad \sigma_{\lambda,\bar{\lambda}} = \sum_{\sigma,\bar{\sigma}} \mathcal{M}_{\sigma,\bar{\sigma};\lambda,\bar{\lambda}}(\theta)\mathcal{M}^*_{\sigma,\bar{\sigma};\lambda,\bar{\lambda}}(\theta)$$

Asymmetry depends on the ZZZ coupling:

$$A_1 = -4\beta\gamma^4 \left[(1+\beta^2)^2 - (2\beta\cos\theta)^2\right] \mathcal{F}_1(\beta,\theta)\, \mathrm{Im} f_4$$



f_4 vs masses

21 parameters in the potential $\Rightarrow$ large parameter space to explore

$$f_4 \sim g_{ijk} \sim R_{ij} R_{jk} R_{ki}$$

- amount of CP violation ($\Rightarrow$ size of f_4) related to mixing between states
- this is related to mass splittings

$$\mathcal{M}_N = \begin{pmatrix} \bullet & \bullet & \mathcal{O}(\mathrm{Im}\lambda_3) & 0 \\ \bullet & \bullet & 0 & \mathcal{O}(\mathrm{Im}\lambda_2) \\ \mathcal{O}(\mathrm{Im}\lambda_3) & 0 & \bullet & \bullet \\ 0 & \mathcal{O}(\mathrm{Im}\lambda_2) & \bullet & \bullet \end{pmatrix} \text{ in basis } \begin{pmatrix} H_1^0 \\ H_2^0 \\ A_1^0 \\ A_2^0 \end{pmatrix}$$

- **large mass splittings preferred**
- Problem in CPv 2HDM with h_1, h_2, h_3:

  LHC points towards an alignment limit

  $\Rightarrow h_1 = h_{SM}$ and $R_{12} \to 1, R_{23} \to 0, R_{31} \to 0 \Rightarrow g_{ijk} \to 0$
- no such requirement in the 3HDM

Conclusions and Outlook

- **3HDM** with Z_2 symmetry: I(2+1)HDM
- interesting model with rich phenomenology
- CP violation in the dark sector
- non-zero contribution to ZZZ vertex – test of CP violation
- **large mixing and mass splittings preferred**

References

- 3HDM

[V. Keus, S. King, S. Moretti JHEP 1401 (2014) 052, arXiv:1408.0796; V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP **1411** (2014) 016, JHEP **1511**, 003 (2015), V. Keus, S. F. King, S. Moretti and D. Sokolowska, JHEP 1511, 003 (2015), A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. F. King, S. Moretti, D. Rojas and D. Sokolowska, JHEP 1612 (2016) 014]

- ZZZ in multi-scalar models

[K. Hagiwara, R.D. Peccei, D. Zeppenfeld, K. Hikasa, Nucl. Phys. B282, 253 (1987); C. Gounaris, J. Layssac, F. Renard, Phys. Rev. D61 (2000) 073013; C. Gounaris, J. Layssac, F. Renard, Phys. Rev. D62 (2000) 073012; B. Grzadkowski, O.M. Ogreid, P. Osland, JHEP1605 (2016) 025;]

- Numerical Tools

[LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP 3.4, Comput. Phys. Commun. **184** (2013) 1729; LoopTools, Comput. Phys. Commun. 118 (1999) 153]

BACKUP SLIDES

Asymmetry A_1

$$A_1^{ZZ} = -4\beta\gamma^4 \left[(1+\beta^2)^2 - (2\beta\cos\Theta)^2\right] \mathcal{F}_1(\beta,\Theta)\, \Im f_4^Z ,$$

$$\mathcal{F}_1(\beta,\Theta) = \frac{N_0 + N_1\cos\Theta + N_2\cos^2\Theta + N_3\cos^3\Theta}{D_0 + D_1\cos\Theta + D_2\cos^2\Theta + D_3\cos^3\Theta + D_4\cos^4\Theta}$$

$$N_0 = \left(1+\beta^2\right)\xi_1, \qquad N_1 = -2\beta^2\left(\xi_1 - \xi_2\right), \tag{1a}$$

$$N_2 = \left(\beta^2 - 3\right)\xi_1, \qquad N_3 = 2\left(\xi_1 - \xi_2\right), \tag{1b}$$

$$D_0 = \left(1+\beta^2\right)^2\left(\xi_3 + \xi_4\right), \qquad D_1 = 2\left(1-\beta^4\right)\xi_3, \tag{1c}$$

$$D_2 = -\left(3 + 6\beta^2 - \beta^4\right)\left(\xi_3 + \xi_4\right), \qquad D_3 = -4\left(1-\beta^2\right)\xi_3, \tag{1d}$$

$$D_4 = 4\left(\xi_3 + \xi_4\right), \tag{1e}$$

with

$$\xi_1 = \sin\theta_W \cos\theta_W (1 - 6\sin^2\theta_W + 12\sin^4\theta_W), \tag{2a}$$

$$\xi_2 = 16\sin^7\theta_W\cos\theta_W, \tag{2b}$$

$$\xi_3 = 1 - 8\sin^2\theta_W + 24\sin^4\theta_W - 32\sin^6\theta_W, \tag{2c}$$

$$\xi_4 = 32\sin^8\theta_W. \tag{2d}$$

Other asymmetries