Search for effects beyond the Standard model in some decays of the Higgs boson

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International Conference "New Trends in High-Energy Physics", 12-18 May 2019, Odessa

Outlook

- Introduction and motivation
- Search for effects of CP violation in the Higgs-boson decays $h \to \gamma\gamma$ and $h \to \gamma Z$
- Higgs-boson decay $h \to \gamma\ell^-\ell^+$: search for violation of CP symmetry and non-Hermiticity
- A possible non-Hermiticity of Yukawa interaction of the Higgs field with fermions in decay $h \to \tau^-\tau^+ \to \mu^-\mu^+ + 4\nu$

In collaboration with Vladimir Kovalchuk (Kharkov Institute of Physics and Technology)

Introduction and motivation

Main properties of the discovered at the LHC boson are consistent with the Higgs boson of the Standard model (SM), however the detailed properties of this boson will be further studied at the LHC and future electron positron linear colliders ILC and CLIC.

In particular, it is necessary to verify whether the Higgs-boson interaction with fermions is $\mathcal{CP}$ symmetrical. There are extensions of the SM with a more complicated Higgs sector, where some of the Higgs bosons may not have definite CP-parity.

Thus any observation of $\mathcal{CP}$ odd or $\mathcal{CP}$ violating effects will indicate unambiguously New Physics (NP).

Whys is this so important? This aspect is closely related with the origin of CP-violation in the Universe. All calculations in the SM show that CP violation due to the complex phase in the CKM matrix is far too small to explain matter-antimatter asymmetry in the Universe. There should be additional sources of the CP violation, and one of them can be in the Higgs sector.

Introduction and motivation

It can be that *CP*-violating effects in the Higgs sector can be discovered only in high-energy processes with creation of Higgs boson, or bosons (and not in the low-energy and high-precision experiments).

Another interesting and unexpected aspect is a possibility to test the fundamental *CPT* symmetry.

The *CPT* symmetry, or *CPT* theorem, is one of the deepest results of Quantum Field Theory [G. Luders 1952, W. Pauli 1957]. Nevertheless there exist extensions of the SM in which *CPT* violation appear due to in particular, deviations from the standard quantum mechanical evolution of states because of violation of Hermiticity (or unitarity).

The Higgs *CP* properties, as well as a possible violation of Hermiticity of the Higgs interaction with fermions, will be addressed for several decays of the Higgs boson.

The most general effective Lagrangians for $h \to \gamma\gamma$ and $h \to \gamma Z$ interaction

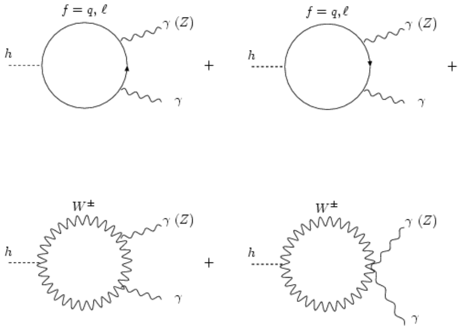
$$\mathcal{L}_{\rm eff}^{h\gamma\gamma} = \frac{e^2}{32\,\pi^2\,v}\Big(\underbrace{c_\gamma\, F_{\mu\nu} F^{\mu\nu}\, h}_{CP\ even} - \underbrace{\tilde{c}_\gamma\, F_{\mu\nu} \widetilde{F}^{\mu\nu}\, h}_{CP\ odd}\Big)$$

$$\mathcal{L}_{\rm eff}^{h\gamma Z} = \frac{e\,g}{16\,\pi^2\,v}\Big(\underbrace{c_{1Z}\, Z_{\mu\nu} F^{\mu\nu}\, h - c_{2Z}\,(\partial_\mu h\, Z_\nu - \partial_\nu h\, Z_\mu)\, F^{\mu\nu}}_{CP\ even} - \underbrace{\tilde{c}_Z\, Z_{\mu\nu} \widetilde{F}^{\mu\nu}\, h}_{CP\ odd}\Big)$$

e is electric charge, $g = e/\sin\theta_W$ – weak coupling constant, $v \approx 246$ GeV is VEV of scalar field, and field tensors are defined as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \qquad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu \qquad \widetilde{F}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta} F^{\alpha\beta},$$

In the SM the processes $h \to \gamma + \gamma$ or $h \to \gamma + Z$ come from one-loop diagrams



The coupling constants consist of the SM and New Physics contributions:

$$c_\gamma = c_\gamma^{\rm SM} + c_\gamma^{\rm NP}, \qquad c_{1Z} = c_Z^{\rm SM} + c_{1Z}^{\rm NP}$$

$$\tilde{c}_\gamma = \tilde{c}_\gamma^{\rm NP}, \qquad c_{2Z} = c_{2Z}^{NP}, \qquad \tilde{c}_Z = \tilde{c}_Z^{NP}$$

Photon polarization parameters

The study of the total decay widths $\Gamma(h \to \gamma\,\gamma)$ or $\Gamma(h \to \gamma\, Z)$ is not very informative.

It would be more interesting to measure the polarization states of the photon.

If the two photons in $h \to \gamma\gamma$ originate from one source (in our case it is the Higgs boson), the polarizations of the photons are correlated ! [L. Landau 1948, C.N. Yang 1950].

This correlation is reflected in the two-photon density matrix

$$\rho^{(\gamma\gamma)} = \frac{1}{4}\,(1 \otimes 1 - \sigma_3 \otimes \sigma_3 + \xi_1\,(\sigma_1 \otimes \sigma_2 - \sigma_2 \otimes \sigma_1)$$

$$+ \quad \xi_2\,(\sigma_3 \otimes 1 - 1 \otimes \sigma_3) - \xi_3\,(\sigma_1 \otimes \sigma_1 + \sigma_2 \otimes \sigma_2)) \neq \rho_1^{(\gamma)} \otimes \rho_2^{(\gamma)}$$

The parameters of the density matrix in terms of the $h\gamma\gamma$ couplings are:

$$\xi_1 = \frac{2\,\mathrm{Re}(c_\gamma\,\tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2}, \qquad \xi_2 = \frac{2\,\mathrm{Im}(c_\gamma\,\tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2} \leq 1\,,$$

$$\xi_3 = \frac{|\tilde{c}_\gamma|^2 - |c_\gamma|^2}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2} \leq 1\,.$$

Polarization parameters of the photon

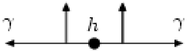
Physical meaning of parameters:

ξ_2 is degree of circular polarization, or average photon helicity,
ξ_1, ξ_3 describe correlation of linear polarizations of two photons.

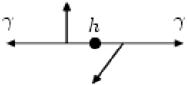
- In the SM the Higgs boson is pure scalar with $CP = +1$, then $\tilde{c}_\gamma = 0 \implies \xi_1^{SM} = 0$, $\xi_3^{SM} = -1$ (linear polarizations are parallel), and $\xi_2^{SM} = 0$ (no circular polarization)

- If the Higgs boson is pure pseudoscalar with $CP = -1$, then $c_\gamma = 0 \implies \xi_1 = 0$, $\xi_3 = 1$ (linear polarizations are orthogonal), and $\xi_2 = 0$ (no circular polarization).

$CP = +1$



$CP = -1$

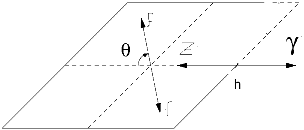


- If Higgs is a mixture of $CP = +1$ and $CP = -1$ states, then these parameters can take any values, provided $\xi_1^2 + \xi_2^2 + \xi_1^2 = 1$.

In the SM $\xi_1^{SM} = \xi_2^{SM} = 0, \ \ \xi_3^{SM} = -1$

Deviation from these values means physics beyond the SM. How to measure ξ_i?

The circular polarization ξ_2 can be measured in the decay $h \to \gamma\, Z \to \gamma\, f \bar{f}$ (Z decays on-mass-shell):



Angular distribution in the polar angle θ between fermion momentum (in rest frame of Z) and direction of Z momentum (in rest frame of h) allows one to find ξ_2:

$$\frac{1}{\Gamma} \frac{d\Gamma(h \to \gamma\, Z \to \gamma\, f \bar{f})}{d\cos\theta} = \frac{3}{8}\Big(1 + \cos^2\theta - 2\, A^{(f)}\, \xi_2\, \cos\theta\Big)$$

$$A^{(f)} \equiv 2\, g_V^f\, g_A^f \,/\, [(g_V^f)^2 + (g_A^f)^2]$$

Forward-backward asymmetry and circular polarization

Measurement of forward-backward asymmetry A_{FB}

$$A_{\mathrm{FB}} \equiv \frac{F-B}{F+B}$$

$$F \equiv \int_0^1 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}\, d\cos\theta, \qquad B \equiv \int_{-1}^0 \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}\, d\cos\theta$$

will allow one to find the parameter ξ_2:

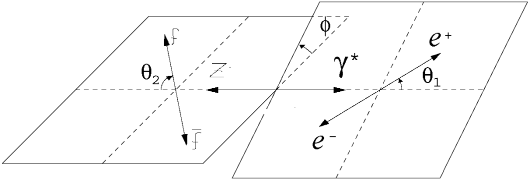
$$A_{\mathrm{FB}} = -\frac{3}{4}\, A^{(f)}\, \xi_2\,,$$

For example, for muons $A^{(\mu)} = 0.142 \pm 0.015$ and $\max(A_{\mathrm{FB}}) = 0.11$, and for b quarks $A^{(b)} = 0.923 \pm 0.020$ and $\max(A_{\mathrm{FB}}) = 0.70$.

This means that with the b-quarks asymmetry is easier to measure, although there may be experimental difficulties (‘tagging’).

How to measure parameters ξ_1 and ξ_3?

ξ_1 and ξ_3 can be found in a more complicated process $h \to \gamma^* Z \to \ell^+\ell^- Z \to \ell^+\ell^- \bar{f} f$:



Distribution over dilepton invariant mass $q^2 = (k_{\ell^+} + k_{\ell^-})^2$ and azimuthal angle ϕ between planes of decay $\gamma^* \to \ell^+\ell^-$ and $Z \to \bar{f} f$ allows one to find ξ_1 and ξ_3:

$$\frac{d\Gamma(h \to \ell^+\ell^- Z)}{dq^2\, d\phi} \Big/ \frac{d\Gamma}{dq^2} = \frac{1}{2\pi}\Big(1 - \frac{1}{4}\,(1 - F_L(q^2)) \times \left(\xi_3(q^2)\cos 2\phi + \xi_1(q^2)\sin 2\phi\right)\Big).$$

where

$$\xi_{1,3}(q^2) \to \xi_{1,3} \quad at\ q^2 = 0$$

Conclusions to Part I

1. We calculated polarization parameters*) in two models of new physics: (i) $S + PS$ Higgs-fermion coupling, and (ii) effective field theory and effective Lagrangian of dimension 6. Circular polarization ξ_2 in $h \to \gamma Z$ and $h \to \gamma\gamma$ turns out to be very small, of the order 10^{-3}.

2. Nevertheless, measurement at the LHC of ξ_2 in the decay $h \to \gamma\, Z \;\to \gamma\, f\, \bar{f}$ will be very interesting:

   - if $\xi_2 = 0 \;\Rightarrow$ no deviation from the SM,
   - if $\xi_2 \neq 0 \;\Rightarrow$ clear signature of CP violation in the Higgs sector and "New Physics",
   - if $\xi_2 \neq 0$ and considerably big, say $\gg 10^{-3}$, this can indicate violation of the fundamental CPT symmetry!

3. In addition, a non-zero value of parameter ξ_1 (correlation of spins) will also mean violation of CP symmetry.

*) A. Korchin, V. Kovalchuk, Phys. Rev. D **88** (2013) 036009; Acta Phys. Polon. B **44** (2013) 2121.

Part II: Decay of the Higgs boson $h \to \gamma \ell^+ \ell^-$

Next we study effects of CP violation and possible non-Hermiticity of the Higgs-boson interaction with leptons and quarks in decay $h \to \gamma\, \ell^+\, \ell^-$ $(\ell = (e,\, \mu,\, \tau))$.

Suppose that interaction of Higgs h with fermions includes scalar and pseudoscalar parts

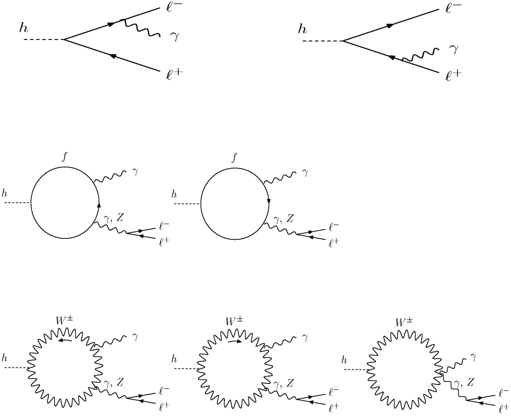
$$\mathcal{L}_{hff} = - \sum_{f=\ell,\, q} \frac{m_f}{v} \, (\underbrace{a_f\, h\, \bar{\psi}_f\, \psi_f}_{CP\ even} + \underbrace{i\, b_f\, h\, \bar{\psi}_f\, \gamma_5\, \psi_f}_{CP\ odd})$$

For real a_f, b_f Lagrangian is Hermitian, however, in general a_f and b_f can be complex. In the SM $a_f = 1,\;\; b_f = 0$.
To stay close to experiment we assume that the decay rate of $h \to f\, \bar{f}$ is the same as in the SM. Then

$$|a_f|^2 + |b_f|^2 = 1\,.$$

Tree-level and loop diagrams

Matrix element includes tree-level and loop diagrams



Sensitive observable – forward-backward asymmetry

$$A_{\mathrm{FB}}(q^2) = \left(\frac{\mathrm{d}\Gamma_F}{\mathrm{d}q^2} - \frac{\mathrm{d}\Gamma_B}{\mathrm{d}q^2}\right)\left(\frac{\mathrm{d}\Gamma_F}{\mathrm{d}q^2} + \frac{\mathrm{d}\Gamma_B}{\mathrm{d}q^2}\right)^{-1},$$

where

$$\frac{\mathrm{d}\Gamma_F}{\mathrm{d}q^2} \equiv \int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta\,, \qquad \frac{\mathrm{d}\Gamma_B}{\mathrm{d}q^2} \equiv \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta$$

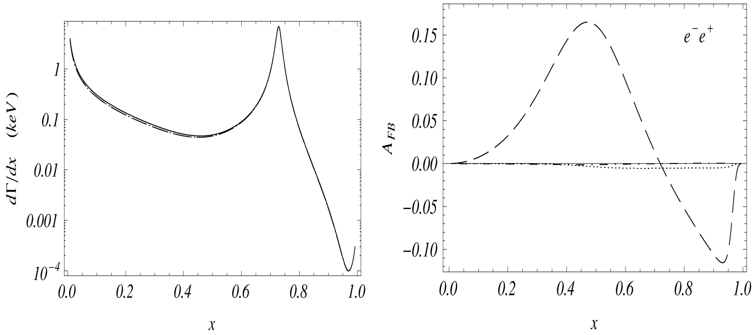
We prove*) that in the Standard model FB asymmetry is identically zero,

$$A_{\mathrm{FB}}(q^2)_{SM} = 0$$

(proof is similar to Furry's theorem in QED). Therefore any non-zero value of FB asymmetry can arise only in models beyond the SM !

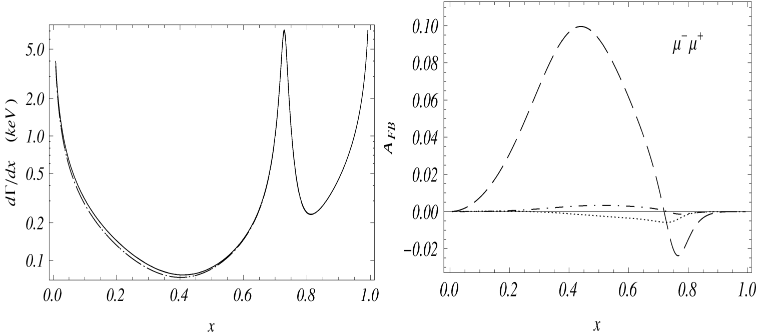
*) A.Yu. Korchin and V.A. Kovalchuk, Eur. Phys. J. C **74** (2014) 3141; Ukr. J. Phys. **62** (2017) 557

Decay rate and asymmetry in $h \to e^+ e^- \gamma$



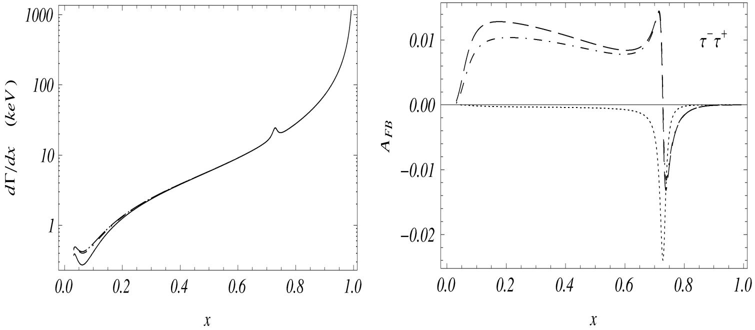
Differential decay width (left) and asymmetry (right) for $h \to e^+ e^- \gamma$ decay as functions of $x \equiv \sqrt{q^2}/m_h$, where $\sqrt{q^2}$ is invariant mass of lepton pair.
Solid line – SM, dotted – model NP1 (Hermitian), dashed – model NP2 ($h f \bar{f}$ – non-Hermitian), dash-dotted – model NP3 (only $h \ell \bar{\ell}$ – non-Hermitian).

Decay rate and asymmetry in $h \to \mu^+\mu^-\gamma$



Differential decay width (left) and asymmetry (right) for $h \to \mu^+\mu^-\gamma$ as functions of $x \equiv \sqrt{q^2}/m_h$. Solid line – SM, dotted – model NP1, dashed – model NP2, dash-dotted – model NP3.

Decay rate and asymmetry in $h \to \tau^+\tau^-\gamma$



Differential decay width (left) and asymmetry (right) for $h \to \tau^+\tau^-\gamma$ decay as functions of $x \equiv \sqrt{q^2}/m_h$. Solid line – SM, dotted – model NP1, dashed – model NP2, dash-dotted – model NP3.

Tree-level diagrams dominates in $h \to \tau^+\tau^-\gamma$ which results in small values of asymmetry about 1.5 % (models NP2 and NP3).

Conclusions to Part II

- In the SM the FB asymmetry $A_{\rm FB}(q^2)$ is identically zero.
- For real a_f and b_f, FB asymmetry for electrons and muons is small, about 1 %.
- For a non-Hermitian $hf\bar{f}$ interaction, FB asymmetry can be larger, $\sim$15 % for e^+e^- and $\sim$10 % for $\mu^+\mu^-$ (model NP2). The largest contribution comes from the $ht\bar{t}$ interaction in the loops
- Therefore the FB asymmetry for e^+e^- and $\mu^+\mu^-$ pairs is a sensitive probe of the CP properties of the Higgs boson, and possible non-Hermiticity of its interaction with the top quarks.
- Since Hermiticity lies in the proof of the CPT theorem, a non-zero asymmetry would be a useful test of the fundamental CPT symmetry.
- There is an interest to our publications from the CMS [PL B 753 (2016) 341, JHEP 1811 (2018) 152, CMS-PAS-HIG-17-007] and ATLAS [PRL 114 (2015) 121801, CERN-PH-EP-2014-294] Collaborations.

Part III. A non-Hermiticity of the Yukawa interaction

In the SM, the Lagrangian describing interaction between the fermions and the scalar fields, $\mathcal{L}_{\rm Yuk}^{\rm SM}$ (Yukawa interaction), is Hermitian, that is $\mathcal{L}_{\rm Yuk}^{\rm SM} = \mathcal{L}_{\rm Yuk}^{\rm SM\,\dagger}$.

Unlike other interactions in the SM, which are naturally Hermitian, the Yukawa interaction has **"acquired" Hermiticity** (put "by hands"), which might not be necessary.

It therefore seems important to verify whether the interaction of the Higgs boson with fermions is indeed Hermitian.

Here we study this aspect in the Higgs decay to the pair of τ leptons. Main attention is paid to observables which are sensitive to non-Hermiticity of the $h\,f\,f$ interaction, and can be measured at the LHC.

These observables can be studied in the two-step process

$$h \to \tau^- + \tau^+ \to \mu^- + \bar{\nu}_\mu + \nu_\tau + \mu^+ + \nu_\mu + \bar{\nu}_\tau$$

Decay $h \to f\,\bar{f}$ with polarized fermions

Assume again that the interaction Lagrangian includes both scalar (CP even) and pseudoscalar (CP odd) parts

$$\mathcal{L}_{hff} = -\sum_{f=\ell,\,q} \frac{m_f}{v}\,(\underbrace{a_f\,h\,\bar{\psi}_f\,\psi_f}_{CP\ even} + \underbrace{i\,b_f\,h\,\bar{\psi}_f\,\gamma_5\,\psi_f}_{CP\ odd})$$

and if $|a_f|^2 + |b_f|^2$ is close to unity, then $h \to f\,\bar{f}$ decay width will be close to value in the SM and any non-Hermiticity does not affect the width.
However, let us consider the case of polarized fermions and calculate the angular distribution

$$\begin{aligned} \frac{d\Gamma}{d\Omega} &= \Gamma(h \to f\bar{f})\frac{1}{16\pi}\Big(1 - \zeta_{1L}\zeta_{2L} + \frac{|a_f|^2\beta_f^2 - |b_f|^2}{|a_f|^2\beta_f^2 + |b_f|^2} \\ &\times (\vec{\zeta}_{1T}\cdot\vec{\zeta}_{2T}) - \frac{2\,\mathrm{Re}(a_f\,b_f^*)}{|a_f|^2\beta_f^2 + |b_f|^2}\beta_f\,\vec{n}\cdot[\vec{\zeta}_{1T}\times\vec{\zeta}_{2T}] \\ &- \frac{2\,\mathrm{Im}(a_f\,b_f^*)}{|a_f|^2\beta_f^2 + |b_f|^2}\beta_f\,(\zeta_{1L} - \zeta_{2L})\Big), \end{aligned}$$

Decay $h \to f\,\bar{f}$ with polarized fermions

where $\vec{\zeta}_1$ ($\vec{\zeta}_2$) is the polarization vector of f ($\bar{f}$) in its rest frame, $\vec{n}$ is the unit vector in the direction of 3-momentum of fermion f in the rest frame of the Higgs.
The fermion f is longitudinally polarized with polarization

$$\alpha_L = \frac{2\,\mathrm{Im}(a_f\, b_f^*)}{|a_f|^2\beta_f^2 + |b_f|^2}\beta_f$$

β_f is velocity of fermion ($\beta_f \approx 1$).

To have a non-zero longitudinal polarization of fermion we need
(i) presence of both a_f and b_f, which means $\mathcal{CP}$ violation,
(ii) complex values of a_f or/and b_f, which means non-Hermiticity of $\mathcal{L}_{hff}$.

In addition, in $\frac{d\Gamma}{d\Omega}$ a non-zero spin-spin correlation term appears:

$$\propto \frac{2\mathrm{Re}(a_f\, b_f^*)}{|a_f|^2\beta_f^2 + |b_f|^2}\,\vec{n}\cdot[\vec{\zeta}_{1T}\times\vec{\zeta}_{2T}]$$

which is also CP violating but does not require non-Hermiticity.

Decay $h \to \mu^- \bar\nu_\mu \nu_\tau \mu^+ \nu_\mu \bar\nu_\tau$

Direct measurement of fermion polarization is difficult.

Then to find parameter α_L we suggest to study decay of Higgs boson to $\tau^- \tau^+$ with their consequent decay into the leptonic channels, i.e. the process

$$h \to \tau^- + \tau^+ \to \mu^- + \bar\nu_\mu + \nu_\tau + \mu^+ + \nu_\mu + \bar\nu_\tau$$

The distribution in muon energies is proportional to

$$\begin{aligned} W(x_1, x_2) \quad &\sim \quad a(x_1)a(x_2)\Big[f(x_1, x_2) + f(x_2, x_1) \\ &+ \quad \frac{2\,\mathrm{Im}(ab^*)}{|a|^2\beta^2 + |b|^2}\big(g(x_1, x_2) - g(x_2, x_1)\big)\Big], \end{aligned}$$

where $x_1 \equiv 2E_1/m_h$, $x_2 \equiv 2E_2/m_h$ are the fractions of energies of μ^-, μ^+, and $f(x_1, x_2)$, $g(x_1, x_2)$, $a(x_{1,2})$ are known functions.

Muon energy asymmetries

We find observables which are proportional to $\mathrm{Im}(ab^*)$.
Define fraction of the number of muons, which corresponds to μ^- in the energy interval $[\varepsilon_1, \varepsilon_1']$ and μ^+ in the energy interval $[\varepsilon_2, \varepsilon_2']$

$$N(\varepsilon_1, \varepsilon_1';\, \varepsilon_2, \varepsilon_2') = \int_{\varepsilon_1}^{\varepsilon_1'} dx_1 \int_{\varepsilon_2}^{\varepsilon_2'} dx_2\, W(x_1,\, x_2)$$

and construct the asymmetry

$$\frac{N(\varepsilon_1, \varepsilon_1';\, \varepsilon_2, \varepsilon_2') - N(\varepsilon_2, \varepsilon_2';\, \varepsilon_1, \varepsilon_1')}{N(\varepsilon_1, \varepsilon_1';\, \varepsilon_2, \varepsilon_2') + N(\varepsilon_2, \varepsilon_2';\, \varepsilon_1, \varepsilon_1')} = \frac{2\,\mathrm{Im}(ab^*)}{|a|^2\beta^2 + |b|^2}\, \Delta(\varepsilon_1, \varepsilon_1'; \varepsilon_2, \varepsilon_2')$$

It is nonzero for a non-Hermitian $h\,\tau^-\,\tau^+$ interaction. Its value essentially depends on the choice of the energy area in which μ^- and μ^+ energies vary. We have found the optimal muon energies for measurement of this asymmetry.

Other observables are asymmetries of the k-th moments of the μ^- and μ^+ energies $(k = 1, 2, 3, ...)$

$$\mathcal{A}_{\mathrm{E^k}} \equiv \frac{\langle E_1^k \rangle - \langle E_2^k \rangle}{\langle E_1^k \rangle + \langle E_2^k \rangle} = \frac{2\,\mathrm{Im}(ab^*)}{|a|^2\beta^2 + |b|^2}\, \delta_{\mathrm{E^k}},$$

Muon energy asymmetries

How to find the most suitable muon energies for measurement of these asymmetries?

(i) the smaller energies the muons have, the bigger number of muons is,
(ii) to have sizable values of asymmetries it is better to choose μ^- and μ^+ with big difference in energies.
Detailed consideration shows that muons should be selected in the intervals of energies

$$E_{\rm min} \,<\, E_1(\mu^-) \,<\, E_0, \qquad E_0 \,<\, E_2(\mu^+) \,<\, E_{\rm max},$$
$$\text{and}$$
$$E_{\rm min} \,<\, E_2(\mu^+) \,<\, E_0, \qquad E_0 \,<\, E_1(\mu^-) \,<\, E_{\rm max}$$

Here $E_{\rm min} = 234$ MeV – minimal muon energy possible, $E_{\rm max} = \frac{1}{2} m_h = 62.53$ GeV – maximal energy, and $E_0 \approx 37.5$ GeV.
For these optimal conditions we find $|\Delta(\varepsilon_{min}, \varepsilon_0; \varepsilon_0, \varepsilon_{max})| \approx 0.5$ and

$$\delta_{\rm E} \approx 0.14, \quad \delta_{\rm E^2} \approx 0.25, \quad \delta_{\rm E^3} \approx 0.33, \ldots$$

Conclusion to Part III

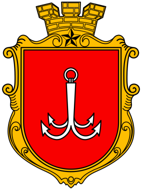
- To search for the fermion longitudinal polarization in $h \to \tau^-\tau^+$ we considered*) two-step process $h \to \tau^-\tau^+ \to \mu^-\bar{\nu}_\mu\nu_\tau\, \mu^+\nu_\mu\bar{\nu}_\tau$. We proposed observables (asymmetries) which take nonzero values only for CP violating and non-Hermitian $h\tau^-\,\tau^+$ interaction.
- These asymmetries are calculated and optimal conditions for their measurement are selected. We hope that the study of these asymmetries will be a useful test of Hermiticity of the Yukawa interaction.
- Important comment: non-Hermiticity is connected with violation of the $\mathcal{CPT}$ symmetry. The longitudinal polarization of fermion in the decay $h \to f\bar{f}$ is an example of the $\mathcal{CPT}$-violating observable in the Lorentz invariant but non-Hermitian model (see also related aspects in L.B. Okun, hep-ph/0210052]).

  In general, non-Hermitian Lagrangian (or Hamiltonian) will lead to violation of the unitarity of $\mathcal{S}$-matrix, which seems strange and unusual. In any case measurement of the longitudinal polarization of a fermion (τ lepton via its decays) can be easier task than the direct tests of the unitarity violation.

*) A.Yu. Korchin and V.A. Kovalchuk, Phys. Rev. D **94** (2016) 076003.

Thank you for attention!

I am especially grateful to the Organizers of the Conference for the kind hospitality in a beautiful city Odessa!



ADDITIONAL SLIDES

Coupling constants in effective Lagrangians

- In the SM in one-loop order:

$$c_\gamma^{\rm SM} \approx -6.60 + 0.08\,i \qquad\qquad c_Z^{\rm SM} \approx -5.540 + 0.005\,i$$

There is a small imaginary part from intermediate on-mass-shell states of leptons and quarks (except top quark), i.e. from processes $h \to f\bar{f} \to \gamma\,\gamma\,(Z)$ with $m_f \leq m_h/2$. Moreover main contribution comes from c, b quarks and τ lepton. As for the real part of $c_\gamma^{\rm SM}$ and $c_Z^{\rm SM}$ – dominant contributions come from $W^\pm$ and t quark loops.

- For a model beyond the SM take, for example, Higgs interaction with fermions including both scalar and pseudoscalar coupling:

$$\mathcal{L}_{hf\bar{f}} = \mathcal{L}_{hf\bar{f}}^{SM} + \mathcal{L}_{hf\bar{f}}^{NP} = -\sum_f \frac{m_f}{v}\, h\,\bar{\psi}_f\,(1 + s_f + i\,p_f\gamma_5)\,\psi_f$$

where s_f, p_f are real for Hermitian $\mathcal{L}_{hf\bar{f}}$, and $s_f = p_f = 0$ correspond to SM.

Model with scalar and pseudoscalar $hf\bar{f}$ coupling

In the one-loop order we find

$$c_{1Z}^{\rm NP} \approx 0.3253 s_t - (8.2 s_b + 1.2 s_c + 0.2 s_\tau)\, 10^{-3} + i\,(4.8 s_b + 0.5 s_c + 0.1 s_\tau)\, 10^{-3}\,,$$

$$\tilde{c}_Z^{\rm NP} \approx -0.4939 p_t + (9.6 p_b + 1.3 p_c + 0.3 p_\tau)\, 10^{-3} - i\,(4.9 p_b + 0.5 p_c + 0.1 p_\tau)\, 10^{-3}\,.$$

How to fix s_f and p_f? Choose parameters satisfying $(1+s_f)^2 + p_f^2 = 1$, for example

$$p_t = p_b = p_c = p_\tau = \pm 1/\sqrt{2}\,, \qquad s_t = s_b = s_c = s_\tau = 1/\sqrt{2} - 1$$

We can show that $\Gamma(h \to f\bar{f}) = \Gamma^{SM}(h \to f\bar{f})$ for any fermion, so that calculated width for $h \to \tau^+\tau^-$ and $h \to b\,\bar{b}$ do not contradict data at the LHC.
The polarization parameters become

$$\xi_1 = \pm 0.121, \qquad \xi_2 = \mp 0.001, \qquad \xi_3 = -0.993$$

and ratio of decay width to the SM width is

$$\mu_{\gamma Z} \equiv \Gamma(h \to \gamma\, Z)\,/\,\Gamma(h \to \gamma\, Z)^{SM} = 1.04$$

General effective field-theory

- New physics is described in terms of higher-order operators in fields of the SM, which are suppressed by inverse powers of a characteristic scale of new physics Λ, such that $\Lambda \gg v = 246$ GeV.

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}, \\
\mathcal{L}_{\rm NP} &= \mathcal{L}_{\rm dim\,6} = -\sum_i \underbrace{c_i\,\mathcal{O}_i}_{CP\ \ even} - \sum_j \underbrace{\tilde{c}_j \widetilde{\mathcal{O}}_j}_{CP\ \ odd}
\end{aligned}
$$

where c_i and $\tilde{c}_j$ are effective couplings, which can be of order unity according to 'naive' dimensional analysis [A. Manohar 1984, H. Georgi 1986], and $\mathcal{O}_i$, $\widetilde{\mathcal{O}}_j$ are $SU(2)_L \otimes U(1)_Y$ gauge-invariant operators of dimension 6.
In the sector of Higgs and two gauge bosons ($\gamma\gamma$, γZ, ZZ, W^+W^-) one has:
5 CP even operators ($i = B, W, BB, WW, WB$):

$$
\begin{aligned}
\mathcal{O}_B &= i\frac{g'}{\Lambda^2}(D_\mu H)^\dagger (D_\nu H) B^{\mu\nu}, \qquad \mathcal{O}_W = i\frac{g}{\Lambda^2}(D_\mu H)^\dagger \tau_k (D_\nu H) W_k^{\mu\nu}, \\
\mathcal{O}_{BB} &= \frac{g'^2}{2\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_{WW} = \frac{g^2}{2\Lambda^2} H^\dagger H W_{k\,\mu\nu} W_k^{\mu\nu}, \\
\mathcal{O}_{WB} &= \frac{g' g}{2\Lambda^2} H^\dagger \tau_k H W_k^{\mu\nu} B_{\mu\nu},
\end{aligned}
$$

Effective field-theory approach

and 3 CP odd operators ($j = BB, WW, WB$):

$$\widetilde{\mathcal{O}}_{BB} = \frac{g'^2}{2\,\Lambda^2}\, H^\dagger\, H\, B_{\mu\,\nu} \widetilde{B}^{\mu\,\nu}, \qquad \widetilde{\mathcal{O}}_{WW} = \frac{g^2}{2\,\Lambda^2}\, H^\dagger\, H\, W_{k\,\mu\,\nu} \widetilde{W}_k^{\mu\,\nu},$$

$$\widetilde{\mathcal{O}}_{WB} = \frac{g'\, g}{2\,\Lambda^2}\, H^\dagger\, \tau_k\, H\, W_k^{\mu\,\nu} \widetilde{B}_{\mu\,\nu},$$

We assume that all constants in $\mathcal{L}_{\dim 6}$ are of order 1: $c_B = c_W = c_{WB} = c_{BB} = c_{WW} = 1$, $\tilde{c}_{WB} = \tilde{c}_{BB} = \tilde{c}_{WW} = 1$.

Choose the scale of new physics $\Lambda = 4\pi v \approx 3.1$ TeV (where $v \approx 246$ GeV). Then it follows that

$$c_{1Z}^{\mathrm{NP}} \sim c_{2Z}^{\mathrm{NP}} \sim \tilde{c}_{Z}^{\mathrm{NP}} \sim 1$$

and polarization parameters are

$$\xi_1 = -0.107, \qquad \xi_2 = 0.0001, \qquad \xi_3 = -0.994, \qquad \mu_{\gamma Z} = 1.12$$

For a smaller scale, $\Lambda = 2$ TeV, deviation from the SM values $\xi_1^{SM} = \xi_2^{SM} = 0$ $\xi_3^{SM} = -1$ is larger:

$$\xi_1 = -0.236, \qquad \xi_2 = 0.0002, \qquad \xi_3 = -0.972, \qquad \mu_{\gamma Z} = 1.31$$

The parameter ξ_2 remains very small.

Choice of parameters of the model

Table: Parameters of $hf\bar{f}$ interaction in SM and in models of NP

$hf\bar{f}$ константы	SM	NP1	NP2	NP3
a_ℓ	1	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
b_ℓ	0	$\frac{1}{\sqrt{2}}$	$\frac{i}{\sqrt{2}}$	$\frac{i}{\sqrt{2}}$
a_q	1	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	1
b_q	0	$\frac{1}{\sqrt{2}}$	$\frac{i}{\sqrt{2}}$	0
a_t	1	1.2	1.2	1
b_t	0	0.37	$0.37\,i$	0

SM and NP1 correspond to Hermitian Lagrangian, models NP2 and NP3 – to non-Hermitian one.

Parameters for the top quark are from A. Kobakhidze et al., Phys. Rev. D **95**, 015016 (2017). In all cases the decay widths to 4 leptons are consistent with experiments of ATLAS and CMS.