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

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Plan

- Introduction and motivations
- 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 of the Higgs interaction with top quarks
- A possible non-Hermiticity of Yukawa interaction of the Higgs field with τ-lepton. Higgs-boson decays $h \to \tau^- \tau^+ \to \mu^- \mu^+ + 4\nu$ and $h \to \pi^- \pi^+ \nu_\tau \bar{\nu}_\tau$
- Brief information on National Science Center "Kharkiv 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 its detailed properties will be further studied at the LHC, future electron positron linear colliders ILC and CLIC, and other facilities.

In particular, it is necessary to verify whether the Higgs-boson interaction with the fermions (quarks and leptons) 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). Why is this important?

1. This is closely related with the origin of CP-violation in the Universe. In the SM the source of violation of CP symmetry is unremovable phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Moreover, all the existing data indicate that this phase is the dominant source of CP violation in the flavor changing processes. However, theoretical calculations show that CP violation in the SM is too small (by many orders of magnitude) to explain the matter-antimatter asymmetry in the Universe.

Therefore there should be other sources of *CP* violation beyond the CKM mechanism. Thus the search for new sources of *CP* violation is one of the main directions in the particle physics. One of possibilities is that additional *CP* violation appears in the Higgs sector.

2. Another interesting aspect is a possibility to test the fundamental *CPT* symmetry in the Higgs-boson interaction with fermions.

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 can appear due to various reasons, e.g. violation of Lorentz symmetry in models with extra dimensions, nonlocality in the string theory or, in particular, due to deviations from the standard quantum mechanical evolution of states because of violation of Hermiticity. It is thus legitimate to test Hermiticity of the Higgs-boson interaction with fermions (it is also called Yukawa interaction).

In this talk the Higgs *CP* properties, as well as a possible violation of Hermiticity of the Yukawa interaction, 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

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

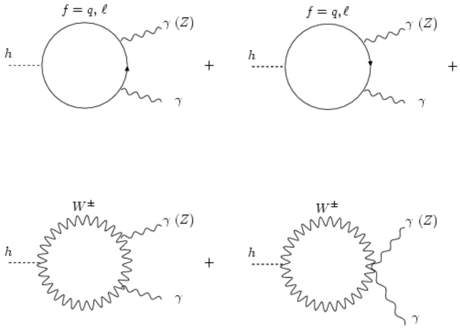
$$\mathcal{L}_{\rm eff}^{h\gamma Z} = \frac{e\,g}{16\,\pi^2\,v}\Big(\underbrace{c_{1Z}\,Z_{\mu\nu}F^{\mu\nu}\,h - c_{2Z}\,(\partial_\mu h\,Z_\nu - \partial_\nu h\,Z_\mu)\,F^{\mu\nu}}_{CP\ even} - \underbrace{\tilde{c}_Z\,Z_{\mu\nu}\widetilde{F}^{\mu\nu}\,h}_{CP\ odd}\Big)$$

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

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

Lowest-order diagrams for $h \to \gamma + \gamma\,(Z)$ in the SM

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 is 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:

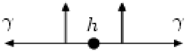
$$\xi_1 = \frac{2\,\mathrm{Re}(c_\gamma \tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2}, \qquad \xi_2 = \frac{2\,\mathrm{Im}(c_\gamma \tilde{c}_\gamma^*)}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2} \leq 1\,,$$
$$\xi_3 = \frac{|\tilde{c}_\gamma|^2 - |c_\gamma|^2}{|c_\gamma|^2 + |\tilde{c}_\gamma|^2} \leq 1\,.$$

The parameters have the following meaning:

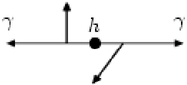
ξ_2 is degree of circular polarization, or average photon helicity,
ξ_1, ξ_3 describe correlation of linear polarizations of two photons.

- 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 would be 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).

$CP = +1$



$CP = -1$

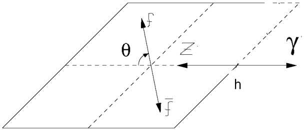


- If Higgs is a mixture of $CP = +1$ and $CP = -1$ states, then these parameters can take any values, provided $\xi_1^2 + \xi_2^2 + \xi_1^2 = 1$.

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

Deviation from these values would mean New Physics. Then 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 boson is on the mass shell and behaves here as a photon):



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

A convenient for measurement is the so-called forward-backward asymmetry $A_{\rm FB}$

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

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

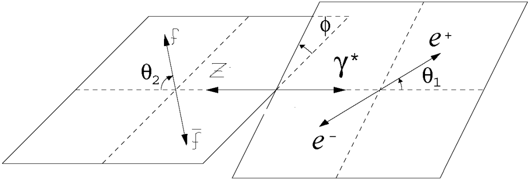
which is proportional to the parameter ξ_2:

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

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

This means that with the b-quarks asymmetry is easier to measure, although there can be experimental difficulties ('tagging', etc.).

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:

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

where

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

Conclusions to Part I

1. We calculated polarization parameters*) in two models of new physics: (i) scalar+pseudoscalar Higgs-fermion coupling, and (ii) effective Lagrangian of dimension 6. In these models 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 interesting because of

   - 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 would 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, Physical Review D **88** (2013) 036009;
Acta Physica Polonica 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 the decay $h \to \gamma\, \ell^+\, \ell^-$ $(\ell = (e,\, \mu,\, \tau))$.

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

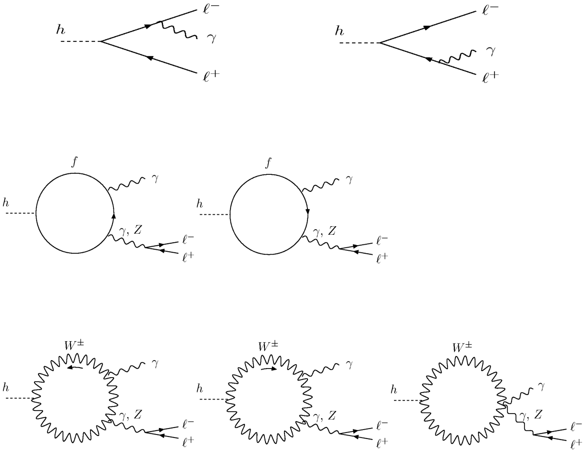
$$\mathcal{L}_{hff} = -\sum_{f=\ell,\, q} \frac{m_f}{v} \big(\underbrace{a_f\, h\, \bar{\psi}_f\, \psi_f}_{CP\ even} + \underbrace{i\, b_f\, h\, \bar{\psi}_f\, \gamma_5\, \psi_f}_{CP\ odd} \big)$$

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-diagram contributions

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

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

and $\sqrt{q^2}$ is the invariant mass of the lepton pair.

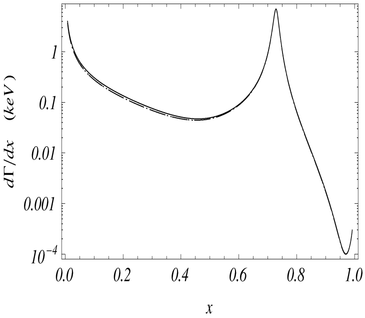
We prove*) that in the Standard model the FB asymmetry is identically zero,

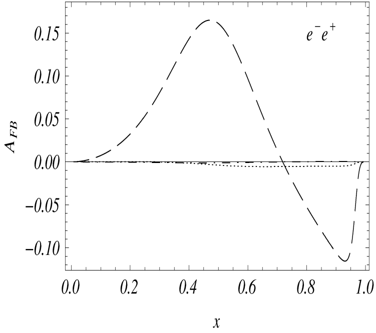
$$A_{\mathrm{FB}}(q^2)_{SM} = 0.$$

The proof is similar to the proof of the Furry theorem in QED.
Therefore any nonzero value of FB asymmetry in experiment can arise in models beyond the SM !

*) A.Yu. Korchin and V.A. Kovalchuk, European Physical Journal C **74** (2014) 3141; Ukrainian Journal of Physics **62** (2017) 557

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

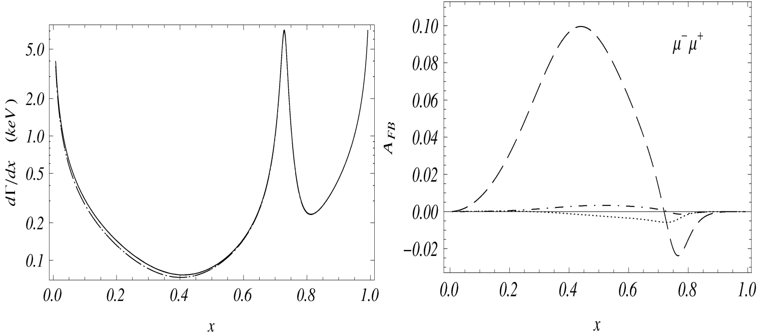




Differential decay width (left) and asymmetry (right) for $h \to e^+ e^- \gamma$ decay as functions of $x \equiv \sqrt{q^2}/m_h$, where $\sqrt{q^2}$ is invariant mass of lepton pair.

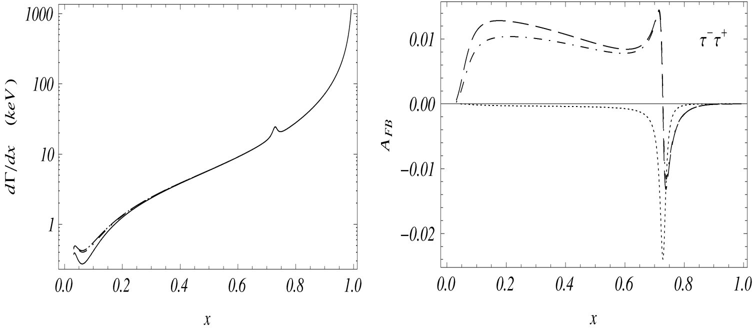
Solid line – SM, dotted – model NP1 (Hermitian), dashed – model NP2 ($h f \bar{f}$ – non-Hermitian), dash-dotted – model NP3 (only $h \ell \bar{\ell}$ – non-Hermitian).
Here "NP" means New Physics.

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.

In decays $h \to \tau^+\tau^-\gamma$ tree-level diagrams dominate which results in small values of asymmetry $\sim$1.5 % (models NP2 and NP3).

Conclusions to Part II

- In the Standard Model the forward-backward asymmetry of the leptons is identically zero.
- For real $hf\bar{f}$ parameters a_f and b_f, the 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 Higgs interaction with the top quark in the loops.
- Therefore the FB asymmetry for e^+e^- and $\mu^+\mu^-$ pairs could be a sensitive probe of the CP properties of the Higgs boson, and even possible non-Hermiticity of its interaction with the top quark.
- Since Hermiticity lies in the proof of the CPT theorem, a non-zero asymmetry would be a sensitive test of the fundamental CPT symmetry.

Part III. A non-Hermiticity of the Yukawa interaction

In the SM the Lagrangian describing interaction between the fermions and the scalar fields, $\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yuk}}$ (Yukawa interaction), in addition to the gauge invariance under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, is Hermitian, that is

$$\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yuk}} = \mathcal{L}^{\mathrm{SM}\,\dagger}_{\mathrm{Yuk}}$$

.

Unlike the other interactions in the SM, e.g. those with the gauge bosons, which are naturally Hermitian, the Yukawa interaction $hf\bar{f}$ has **"acquired" Hermiticity**, which may not be necessary.

Here we study this aspect in the Higgs decay to a pair of τ leptons. Main attention is paid to observables sensitive to properties of the $h\tau^-\tau^+$ interaction, and which can be measured at the LHC.

These observables can be studied, for example, in the processes

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

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

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

Assume again that the interaction Lagrangian for any fermion 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 for unpolarized fermions will be close to value in the SM, and any possible non-Hermiticity does not affect the decay width

$$\Gamma(h \to f\,\bar{f})_{unpol} \;=\; m_h\,\beta_f\,\frac{G_F\; m_f^2}{4\sqrt{2}\pi}\,\left(|a_f|^2\beta_f^2 \;+\; |b_f|^2\right)$$

with β_f being the fermion velocity in the Higgs-boson rest frame ($\beta_f \approx 1$ for any lepton or quark).

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

However, let us consider the case of polarized fermions and calculate the angular distribution of τ's

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

where $\vec{\zeta}_1$ ($\vec{\zeta}_2$) is the polarization vector of f ($\bar{f}$) in its rest frame, and $\vec{n}$ is the unit vector in the direction of 3-momentum of fermion f.
We also introduced the longitudinal component $\zeta_L = \vec{n}\cdot\vec{\zeta}$ and the transverse one $\vec{\zeta}_T = \vec{\zeta} - \vec{n}\,\zeta_L$ for each polarization vector.

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

It is seen that the fermion can be longitudinally polarized with degree of polarization

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

To have a non-zero longitudinal polarization of fermion one needs
(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 would mean non-Hermiticity of the Lagrangian $\mathcal{L}_{hff}$.

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

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

which is also CP violating observable but exists for Hermitian interaction.

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

Direct measurement of fermion polarization is difficult because of the very short lifetime of the τ lepton, $\sim 10^{-13}$ s.

Then one can study the decay to $\tau^- \,\tau^+$ with consequent decay of τ's into the lepton channels

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

and test distribution of μ^- and μ^+ energies:

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

with $x_1 \equiv 2E_1/m_h$, $\;x_2 \equiv 2E_2/m_h$ being the fractions of energies of μ^-, $\;\mu^+$. Here $f(x_1, x_2)$, $g(x_1, x_2)$, $a(x_{1,2})$ are known calculated functions. This distribution is normalized to unity.

Muon energy asymmetries

One can construct observables which are directly 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

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

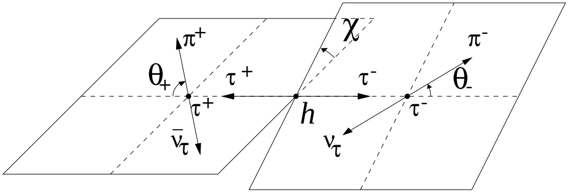
It is nonzero only for a non-Hermitian $h\,\tau^-\,\tau^+$ interaction. Its value essentially depends on the choice of the energy area in which μ^- and μ^+ energies vary. We have found the optimal muon energies for measurement of this asymmetry.

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

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

Higgs-boson decay to the pions

Let us consider somewhat simpler decay to a pair of the τ leptons with their consequent decay to the pions, namely $h \to \tau^-\tau^+ \to \pi^-\nu_\tau\,\pi^+\bar{\nu}_\tau$.



We study the angular distribution of the pions in the so-called helicity frame

$$\frac{d^3\,W}{d\cos\theta_-\,d\cos\theta_+\,d\chi} = \frac{1}{8\pi}\Big[1 - \cos\theta_-\,\cos\theta_+ - \frac{2\,\mathrm{Im}(a_\tau\,b_\tau^*)}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\,\beta_\tau\,(\cos\theta_- - \cos\theta_+)$$
$$-\frac{|a_\tau|^2\beta_\tau^2 - |b_\tau|^2}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\sin\theta_-\,\sin\theta_+\cos\chi - \frac{2\,\mathrm{Re}(a_\tau\,b_\tau^*)}{|a_\tau|^2\beta_\tau^2 + |b_\tau|^2}\beta_\tau\,\sin\theta_-\,\sin\theta_+\sin\chi\Big]$$

Angular distribution of the pions

Instead of parameters a_τ, b_τ let us introduce two angles: the CP violating $\phi_{\rm CP}$, and Hermiticity violating angle $\phi_{\rm H}$, defined via

$$|b_\tau|/|a_\tau| \equiv \tan\phi_{\rm CP}$$

$$\frac{2\,\mathrm{Im}(a_\tau\, b_\tau^*)}{|a_\tau|^2+|b_\tau|^2} = \sin 2\phi_{\rm CP}\ \sin\phi_{\rm H} \qquad \frac{2\,\mathrm{Re}(a_\tau\, b_\tau^*)}{|a_\tau|^2+|b_\tau|^2} = \sin 2\phi_{\rm CP}\ \cos\phi_{\rm H}$$

Then taking into account that the τ's are ultrarelativistic with velocity $\beta_\tau \approx 0.9996$

$$\frac{d^3 W}{d\cos\theta_- d\cos\theta_+ d\chi} = \frac{1}{8\pi}\Big[1-\cos\theta_-\cos\theta_+ - \sin 2\phi_{\rm CP}\sin\phi_{\rm H}(\cos\theta_- - \cos\theta_+) \\ -\Big(\cos 2\phi_{\rm CP}\cos\chi + \sin 2\phi_{\rm CP}\cos\phi_{\rm H}\sin\chi\Big)\sin\theta_-\sin\theta_+\Big]$$

For Hermitian $h\tau\tau$ interaction, $\phi_{\rm H}=0$ or $\phi_{\rm H}=\pi$, this simplifies

$$\frac{d^3 W}{d\cos\theta_- d\cos\theta_+ d\chi} = \frac{1}{8\pi}\Big[1-\cos\theta_-\cos\theta_+ - \cos(\chi\pm 2\phi_{\rm CP})\sin\theta_-\sin\theta_+\Big]$$

Azimuthal angle correlation

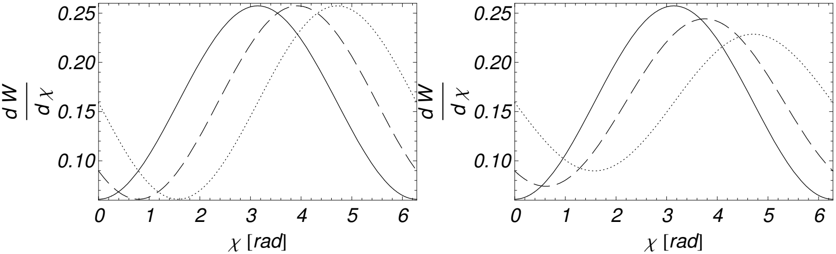
One observable with a maximal sensitivity to the correlations of the τ spins is the azimuthal angle correlation [Hagiwara, 2016]

$$\frac{dW}{d\chi} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos\left(\chi \pm 2\phi_{\rm CP}\right)\right]$$

While for a non-Hermitian $h\tau\tau$ interaction, this angular correlation includes the Hermiticity violating angle $\phi_{\rm H}$

$$\frac{dW}{d\chi} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\left(\cos 2\phi_{\rm CP}\cos\chi + \sin 2\phi_{\rm CP}\cos\phi_{\rm H}\sin\chi\right)\right]$$

Azimuthal angle correlation

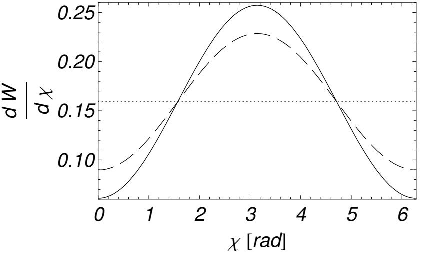


Solid lines correspond to the SM, dashed – $\phi_{\rm CP} = \frac{\pi}{8}$, dotted – $\phi_{\rm CP} = \frac{\pi}{4}$. Left panel is for Hermitian interaction, i.e. $\phi_{\rm H} = 0$, right panel – for non-Hermitian interaction with $\phi_{\rm H} = \frac{\pi}{4}$.

For Hermitian interaction one can measure violation of $\mathcal{CP}$ symmetry via the phase shift in the distribution of χ.
If the interaction is non-Hermitian, then the azimuthal correlation differs from the SM case, and the differences strongly depend on the parameter $\phi_{\rm H}$.

Polar-angle distribution

The differences become especially pronounced for the parameter $\phi_{\rm H} = \frac{\pi}{2}$



Solid line – SM, dashed – $\phi_{\rm CP} = \frac{\pi}{8}$, dotted – $\phi_{\rm CP} = \frac{\pi}{4}$, and $\phi_{\rm H} = \frac{\pi}{2}$.

Finally, there is another observable – the polar-angle distribution of pions

$$\frac{dW}{d\cos\theta_\pm} = \frac{1}{2}\Big(1 \pm \sin 2\phi_{\rm CP} \sin\phi_{\rm H} \cos\theta_\pm\Big)$$

For Hermitian interaction ($\phi_{\rm H} = 0$ or $\phi_{\rm H} = \pi$) the distribution of $\cos\theta_\pm$ is uniform. Therefore any deviation of a measured distribution from 1/2 will point to a non-Hermiticity of the Yukawa interaction and violation of $\mathcal{CP}$ symmetry in the Higgs boson decay to a pair of τ leptons.

Conclusion to Part III

- To search for the fermion longitudinal polarization in $h \to \tau^- \tau^+$ decay, the two-step processes $h \to \tau^- \tau^+ \to \mu^- \bar{\nu}_\mu \nu_\tau \, \mu^+ \nu_\mu \bar{\nu}_\tau$ and $h \to \tau^- \tau^+ \to \pi^- \pi^+ \nu_\tau \bar{\nu}_\tau$ are analyzed $^{*)}$. We proposed observables which are sensitive to the *CP* violation and possible non-Hermiticity in the $h \tau^- \tau^+$ interaction.
- Non-Hermiticity is connected with violation of the fundamental $\mathcal{CPT}$ symmetry. The longitudinal polarization of fermion in $h \to f \bar{f}$ is an example of the $\mathcal{CPT}$-violating observable in the model which is explicitly Lorentz invariant (the related aspects see in the preprint hep-ph/0210052 of L.B. Okun']).
- We constructed $^{*)}$ such a non-Hermitian and Lorentz invariant model for a particle with real physical mass (this is beyond the scope of the talk).
- Comment: a non-Hermitian Lagrangian /Hamiltonian can lead to violation of unitarity of the $\mathcal{S}$-matrix, which seems of course unusual. But in any case measurement of the longitudinal polarization of fermion (in particular, τ lepton) would be an easier task than direct tests of the unitarity violation.

$^{*)}$ A.Yu. Korchin and V.A. Kovalchuk, Physical Review D **94** (2016) 076003, Acta Physica Polonica B **53** (2022) 1-A2.

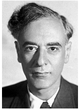
Brief information on NSC KIPT

- National Science Center "Kharkiv Institute of Physics and Technology" is the oldest and largest research center in physics in Ukraine. It was founded in 1928.

- In 1932 the disintegration of the lithium nucleus was carried out for the first time in the Soviet Union (and second in the world).

Brief information on NSC KIPT

- During 1932-1937 the future Nobel Prize Laureate Lev Landau was Head of theoretical department.



- In 1937-1938 the institute suffered heavily from the "Big Terror" in the USSR. In framework of the so-called "Case of UFTI" many scientists were arrested (including L.D. Landau) and some were executed: L.V. Shubnikov ("Shubnikov–de Haas" effect), L.V. Rozenkevich, V.S. Gorsky, ...
- At present there are various directions of research at KIPT:
  – nuclear and high-energy physics;
  – solid-state physics, materials and technologies;
  – plasma physics and controlled thermonuclear fusion;
  – theoretical physics;
  – accelerator physics and new methods of particle acceleration, and some others.
- The institute is damaged by shelling since Feb. 24th 2022 after the invasion of Russia.

Thank you for attention
and hospitality in Krakow !