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Determination of the Higgs CP-mixing angle in the tau decay channels

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Abstract

The measurement of possible Higgs sector CP-violation in the tau decay channels at the LHC is investigated. A CP-violating effect would manifest itself in these decay modes in characteristic spin-spin correlations of the tau lepton pairs which can be accessed using the momenta and impact parameters of the charged tau decay particles. We examine a CP-sensitive observable for a 125 GeV Higgs boson resonance in the gluon fusion channel at the LHC. Furthermore, we consider the distribution of this observable for the irreducible Drell-Yan background. By splitting these events into two categories we obtain two different distributions which can be used for calibration purposes. Finally, we estimate the achievable precision of the scalar-pseudo-scalar mixing angle of the tau decay channel for Run II and the high luminosity run of the LHC.

Keywords: Higgs bosons, tau leptons, Z boson, spin correlations, parity, CP-violation

1. Introduction

In 2012, the ATLAS and CMS collaborations [1, 2] discovered a new electrically neutral boson h with mass $m_h \simeq 125$ GeV, called Higgs boson. So far experimental results on the properties of h [3, 4, 5, 6, 7, 8, 9, 10, 11] agree within errors with the predictions of the Standard Model (SM). In particular, its couplings to gauge bosons and quarks and leptons also match the SM predictions within the experimental and theoretical uncertainties. The important question concerning the CP-nature of the Higgs boson could not yet be experimentally determined. While it is excluded that the Higgs boson is a pure CP-odd state, a large CP-odd component is still allowed [12, 13, 14].

To establish or exclude possible CP-violating interactions of h, one should investigate all Higgs boson couplings to SM particles because an extended model with Higgs sector CP-violation can generate different impacts on the couplings of SM particles to Higgs bosons. Unfortunately, CP-effects for only a few Higgs couplings will directly be testable at the LHC. CP-sensitive observables in high energy scattering processes can conveniently be constructed in dependence of decay particle momenta of intermediate Higgs bosons. A promising channel is the recently established [8, 10] $h \to \tau^+\tau^-$ decay channel because of its large branching fraction and because CP-violating couplings can already be present at the leading order of the perturbative expansion. In a series of papers [15, 16, 17, 18] we have proposed a method to measure the CP-property of h using the momenta and impact parameters of the charged final particles of the tau decays. Important aspects of our method are that the tau momenta do not need to be reconstructed and all major tau decay channels can be used.

Another method [19] uses the $h \to \tau^+\tau^-$ decay channel at the LHC with subsequent $\tau \to \rho + \nu_\tau$ decay. Furthermore, the proposal [20] investigates the mixing angle of the Higgs-top quark coupling ϕ_t in the $pp \to h + 2jet$ channel with subsequent $h \to \tau^+\tau^-$ decay. Here the τ leptons are used to identify the Higgs boson within the background processes, rather than to extract the mixing angle ϕ_τ with the help of τ spin correlations. This production channel can in principle be used to perform the Higgs CP-measurements of ϕ_t and ϕ_τ at the same time. Finally, if very large luminosities will be available at the LHC, CP-violating effects might be investigated with suitably chosen observables in the $h \to \tau^+\tau^- + \gamma$ decay channel [21].

In addition to the Higgs signal distributions, we also investigated the distribution of our CP-sensitive observable for the irreducible Drell-Yan background $pp \to Z^*/\gamma^* \to \tau^+\tau^-$ including NLO QCD corrections [18]. We further suggest a method how to use these background events at the LHC, to calibrate the measurement of the mixing angle ϕ_τ and to determine experimental uncertainties.

2. Spin correlations in Higgs decay to $\tau^+\tau^-$

We parametrize the Lagrangian for the CP-violating Higgs to tau coupling in dependence of an effective τ-Yukawa interaction strength g_τ and a scalar-pseudo-scalar mixing angle ϕ_τ:

$$\mathcal{L}_Y = -g_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau\right) h\,. \quad (1)$$

The mixing angle ϕ_τ can be accessed using the differential decay width of the Higgs boson into a pair of τ leptons. In the Higgs rest frame the differential decay width can be written in dependence of the τ-spins for the approximation $\beta_\tau = \sqrt{1 - 4m_\tau^2/m_h^2} \approx 1$ as

$$d\Gamma_{h\to\tau^+\tau^-} \sim 1 - s_z^- s_z^+ + \cos(2\phi_\tau)\left(\mathbf{s}_T^- \cdot \mathbf{s}_T^+\right) + \sin(2\phi_\tau)\left[\left(\mathbf{s}_T^+ \times \mathbf{s}_T^-\right)\cdot \hat{\mathbf{k}}^-\right]. \quad (2)$$

Here $\hat{\mathbf{k}}^-$ is the normalized τ^- momentum in the Higgs rest frame pointing in the positive z direction. Furthermore we define by $\hat{\mathbf{s}}^\mp$ the normalized spin vectors of the $\tau^\mp$ in their respective τ rest frames where these rest frames are obtained from the Higgs rest frame by a rotation-free Lorentz boost along the $\tau^\pm$ momenta. Then $s_z^\mp$ denote the z-components of $\hat{\mathbf{s}}^\mp$ and $\mathbf{s}_T^\mp$ the transverse vectors of $\hat{\mathbf{s}}^\mp$. Eq. (2) shows that the longitudinal spin correlation is not sensitive to the mixing angle ϕ_τ and that the scalar product of the third term is CP-even while the triple product in the fourth term is CP-odd. The CP-sensitive information is therefore encoded in the transverse component of the $\tau^+\tau^-$ spin correlation (with respect to $\hat{\mathbf{k}}^-$ in the Higgs rest frame). If φ_s denotes the angle pointing from $\mathbf{s}_T^+$ to $\mathbf{s}_T^-$ in a right handed coordinate system, the differential decay width can be written as

$$d\Gamma_{h\to\tau^+\tau^-} \sim 1 - s_z^- s_z^+ + \left|\mathbf{s}_T^-\right|\left|\mathbf{s}_T^+\right|\cos(\varphi_s - 2\phi_\tau)\,. \quad (3)$$

The τ-spin correlations of $\mathbf{s}_T^+$ and $\mathbf{s}_T^-$ can be measured by investigating the angular correlations of the τ decay products. If one considers the direct $\tau^- \to \pi^- + \nu_\tau$ decay, due to angular momentum conservation, the π^- momentum points in the τ^- rest frame preferably in the same direction as the τ^- spin. Correspondingly for the direct $\tau^+ \to \pi^+ + \bar{\nu}_\tau$ decay, the π^+ momentum points in the τ^+ rest frame preferably in the opposite direction as the τ^- spin. Similar statements can be derived for the other τ decay channels [22].

Our method [16, 15, 17, 23] to access the τ-spin correlation between $\mathbf{s}_T^+$ and $\mathbf{s}_T^-$ is applicable for all major tau decay channels: the leptonic decay channel $\tau \to l + \nu_\tau + \nu_l$, with $l = \{e, \mu\}$, which includes 2 neutrinos for each τ decay and the hadronic decay channels $\tau^- \to \pi^- + \nu_\tau$, $\tau^- \to \rho^- + \nu_\tau$ and $\tau^- \to a_1^- + \nu_\tau$ with subsequent decay of the ρ-meson into a charged and a neutral pion and the decay of the a_1-meson into either one charged pion plus neutral pions or the decay into 3 charged pions.

The momentum vectors of the charged prongs[1] $a^\pm, a'^\pm \in \{e^\pm, \mu^\pm, \pi^\pm, a_1^{L,T,\pm}\}$ of the $\tau^- \to a^- + X$ and $\tau^+ \to a'^+ + X$ decays act as spin analyzers. If $E_\mp$ and $\hat{\mathbf{q}}^\mp$ are the energies and directions of flight of the $a^\mp$ in the respective τ rest frame, the normalized τ-decay distributions are of the form

$$\Gamma_a{}^{-1} \mathrm{d}\Gamma\left(\tau^\mp(\hat{\mathbf{s}}^\mp) \to a^\mp(q^\mp) + X\right) = n(E_\mp)\left[1 \pm b(E_\mp)\,\hat{\mathbf{s}}^\mp \cdot \hat{\mathbf{q}}^\mp\right] dE_\mp \frac{d\Omega_\mp}{4\pi}\,. \quad (4)$$

The spectral functions $b(E_\mp)$ and $n(E_\mp)$ are given in [17]. The function $b(E_\mp)$ describes the τ-spin analyzing power of the decay particle $a^\mp$ and is maximal for the direct decays to pions, $\tau^\mp \to \pi^\mp + \nu_\tau/\bar{\nu}_\tau$, and for the decay[2] $\tau^\mp \to a_1^{L,T,\mp} + \nu_\tau/\bar{\nu}_\tau$. For the other decays, the τ-spin analyzing powers of $l^\mp$ and $\pi^\mp$ depends on the energy $E_\mp$.

Our method to determine the CP-nature of h requires the measurement of the 4-momenta of the charged prongs a^-, a'^+ and their normalized impact parameter vectors $\hat{\mathbf{n}}_\mp$ in the laboratory frame. The 4-vectors $n_\mp^\mu = (0, \hat{\mathbf{n}}_\mp)$ are boosted into the $a^- a'^+$ zero-momentum-frame (ZMF) and their normalized perpendicular[3] components $\hat{n}_\perp^{*\mp}$ define the 'unsigned' angle $\varphi^* = \arccos(\hat{\mathbf{n}}_\perp^{*+} \cdot \hat{\mathbf{n}}_\perp^{*-})$ with $0 \le \varphi^* \le \pi$. If $\hat{\mathbf{p}}_-^*$ is the normalized a^- momentum in the $a^- a'^+$ ZMF and $O_{CP}^* = \hat{\mathbf{p}}_-^* \cdot (\hat{\mathbf{n}}_\perp^{*+} \times \hat{\mathbf{n}}_\perp^{*-})$ is a CP-odd and T-odd triple

[1] $a_1^{L,T,\pm}$ denotes the a_1 meson with subsequent decay into 3 charged pions with $L\,(T)$ longitudinal (transverse) helicity states

[2] The τ-spin analyzing power of a_1^{L-} and a_1^{T-} is +1 and −1, respectively.

[3] Perpendicular with respect to the 3-momentum of a^- and a'^+ in the $a^- a'^+$ ZMF .

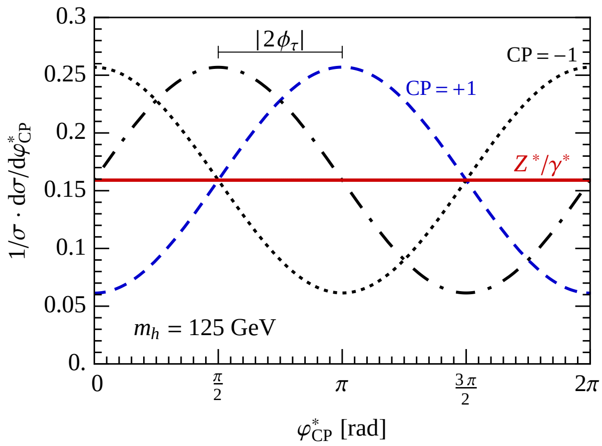

Figure 1: Normalized φ^*_{CP} distribution for $pp \to h/Z^*/\gamma^* \to \tau^+\tau^-$ production at the LHC ($\sqrt{S}$ = 14 TeV) with subsequent $\tau^\pm \to \pi^\pm + \nu_\tau/\bar{\nu}_\tau$ decay. The distribution for a CP-even (CP-odd) Higgs boson is shown by the blue dashed line (black dotted line). For a Higgs boson of CP mixture with $\phi_\tau = -\frac{\pi}{4}$ the distribution is given by the black long-dash dotted line. The distribution for the Drell-Yan background is shown by the solid red line.

correlation, the 'signed' angle φ^*_{CP} with $0 \le \varphi^*_{CP} \le 2\pi$ can be defined by

$$\varphi^*_{CP} = \begin{cases} \varphi^* & if \quad O^*_{CP} \ge 0\,, \\ 2\pi - \varphi^* & if \quad O^*_{CP} < 0\,. \end{cases} \quad (5)$$

Using this definition, the differential Higgs decay width into a pair of τ leptons with respect to φ^*_{CP} at LO can be written as

$$d\Gamma_{h\to\tau^+\tau^-} \approx 1 - b\,(E_+)\,b\,(E_-)\,\frac{\pi^2}{16}\cos\left(\varphi^*_{CP} - 2\phi_\tau\right) . (6)$$

As an example we consider the $h \to \tau^+\tau^-$ with the τ-decay mode $\tau^\mp \to \pi^\mp + \nu_\tau/\bar{\nu}_\tau$. The spin analyzing power for this decay mode is $b(E_\pm) = +1$. The resulting normalized φ^*_{CP}-distributions for the LHC with $\sqrt{S}$ = 14 TeV and a Higgs mass of 125 GeV are shown in Fig. 1. If no cuts are applied on the final state particle momenta as in Fig. 1, the distributions are the same for any Higgs production process. The dashed blue line shows the distribution for a CP-even SM-like Higgs boson, while the dotted black line shows the distribution for a CP-odd Higgs boson. If the discovered Higgs boson is a CP-mixture the dot-dashed black line shows the distribution for the example of a mixing angle $\phi_\tau = -\frac{\pi}{4}$. The shift of the maximum of this distribution with respect to the SM-like distribution corresponds to a shift of φ^*_{CP} by $2\phi_\tau$. If one fits the appropriate function $u \cdot \cos(\varphi^*_{CP} - 2\phi_\tau) + v$ with coefficients u, v to the experimental measurement, one can extract the mixing angle ϕ_τ. Similar distributions are obtained for the other τ-decay channels with a spin analyzing power smaller than one. The maxima and minima of the distributions in Fig. 1 will remain at the current positions. However, the amplitude of the cosine function will be smaller due to the prefactor $b\,(E_+)\,b\,(E_-)$ in Eq. (6). Furthermore, we have shown in Ref. [18] that the distributions are affected by measurement uncertainties in a non-trivial way. It is therefore important to calibrate the measurement and derive reconstruction efficiencies. This can be done by means of the Drell-Yan background process.

3. Tau spin correlations for the Drell-Yan production process

The irreducible and overwhelming background for the $h \to \tau^-\tau^+$ signal process is the Drell-Yan process $pp \to Z^*/\gamma^* \to \tau^-\tau^+$. Because the masses of the Higgs boson and the Z boson are very close and because each τ decay mode includes at least one neutrino, the two reactions can not be separated by simple cuts. We therefore investigated [18] the φ^*_{CP} distribution for the parton level reaction

$$q + \bar{q} \to \gamma^*, Z^* \to \tau^- + \tau^+ \to a^- + a'^+ + X \quad (7)$$

at LO and at NLO QCD. Opposite to Higgs production processes, the matrix element does not factorize into the $pp \to Z^*/\gamma^* + X$ production and $Z^*/\gamma^* \to \tau^+\tau^-$ decay. Instead the full tau-tau spin density matrix has to be calculated and appropriately combined with the spin dependent τ-decay distributions (4). The differential cross section at LO, integrated over the polar angles of the a^- and a'^+ momenta, can be written in the $\tau^+\tau^-$-ZMF as

$$\frac{d\hat{\sigma}^{(0)}_{DY}}{d\phi_+ d\phi_-} \sim 1 + \frac{\pi^2}{32} b(E_+) b(E_-)\,\kappa(B_1, B_2)\,\cos(\phi_+ + \phi_-) \quad (8)$$

where $\kappa(B_1, B_2) = (a^{B_1}_\tau a^{B_2}_\tau - v^{B_1}_\tau v^{B_2}_\tau)/(a^{B_1}_\tau a^{B_2}_\tau + v^{B_1}_\tau v^{B_2}_\tau)$ and $\phi_\pm$ are the azimuthal angles of the a^- and a'^+ momenta in a coordinate system where the direction of the τ^- momentum is chosen to be the z-axis, and the momentum of the initial quark is located in the x,z-plane. If one substitutes in Eq. (8), e.g. ϕ_+ by the difference of the two azimuthal angles, $\varphi = \phi_- - \phi_+$ and integrates over ϕ_- the φ dependence drops out. The corresponding φ^*_{CP} distribution is therefore flat, shown by the red line in Fig. 1. The φ^*_{CP} distribution remains flat if NLO QCD corrections are taken into account.

The signal and background distributions are distorted [18] due to finite experimental resolutions of the charged particle momenta and the impact parameter

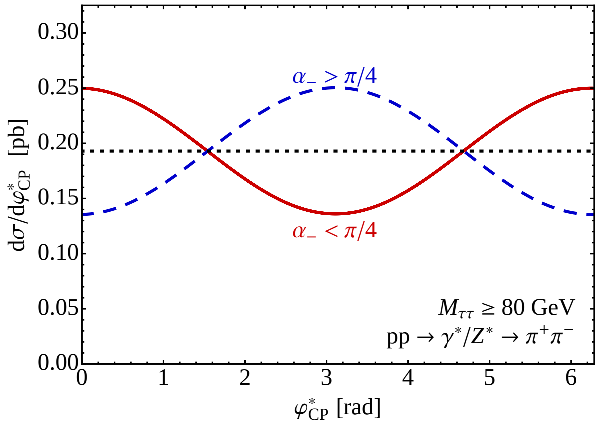

Figure 2: Drell-Yan production of $\tau^-\tau^+$ at the LHC ($\sqrt{S}$ = 14 TeV, $M_{\tau\tau} \geq 80$ GeV, $|\eta_{\pi^\pm}| \leq 1$) with subsequent $\tau^\pm \to \pi^\pm + \nu_\tau/\bar{\nu}_\tau$ decay. Events are split into two categories with π^- 'nearly coplanar' ($\alpha_- < \pi/4$, red solid line) and events with π^- 'nearly perpendicular' ($\alpha_- > \pi/4$, dashed blue line) to the $q\tau$ production plane. The dotted black line indicates the sum of the two distributions divided by two.

measurements. These uncertainties will probably differ for measurements in the beam direction and perpendicular to it. We suggest to calibrate this uncertainties using the Drell-Yan background process in the following way: Eq. (8) shows that a non-uniform distribution is obtained if neither ϕ_- nor ϕ_+ are integrated out. Instead we divide the events into two classes: one class which collects events where the π^- momentum is preferably parallel to the production plane, the second class collects events where the π^- momentum is preferably perpendicular to this plane. The production plane for the scattering reaction Eq. (7) is defined by the beam axis and the τ^- momentum in the laboratory frame. Our method to extract the mixing angle ϕ_τ was, however, specifically defined such that no reconstruction of the τ-momenta needs to be performed. Therefore, we suggest to use the alternative definition in terms of measurable quantities:

$$\cos\alpha_- \quad = \quad \left| \frac{\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}_{L-}}{|\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}_{L-}|} \cdot \frac{\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}_{L-}}{|\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}_{L-}|} \right| . \qquad (9)$$

Here $\hat{\mathbf{p}}_{L-}$ is the π^- direction of flight in the laboratory frame, $\hat{\mathbf{e}}_z$ points along the direction of one of the proton beams and $\hat{\mathbf{n}}_-$ is the impact parameter vector of the π^- in the laboratory frame. With the definition (9) we define events with π^- being 'nearly coplanar' ('nearly perpendicular') by requiring $\alpha_- < \pi/4$ ($\alpha_- > \pi/4$). The resulting distributions for Drell-Yan production at the LHC with $\sqrt{S}$ = 14 TeV and the direct decays $\tau^\mp \to \pi^\mp + \nu_\tau/\bar{\nu}_\tau$ are shown in Fig. (2). The solid red line shows the distribution for $\alpha_- < \pi/4$ and the dashed blue line the distribution for $\alpha_- > \pi/4$. The maximum of the distribution for $\alpha_- > \pi/4$ and the minimum for $\alpha_- < \pi/4$ are located at $\varphi^*_{CP} = \pi$. The form of the curves in Fig. (2) are essentially due to Z^* boson exchange. The resonant Z^* boson peak has been included ($M_{\tau\tau} \geq 80$ GeV) to increase the amplitude. For larger $M_{\tau\tau}$-cuts, the amplitude becomes smaller because the γ^* contribution increases with respect to the Z^* contribution. If one assumes pure γ^* exchange the solid red and dashed blue curves in Fig. (2) would be reversed. This is because the coefficient for Z^* boson exchange in Eq. (8) is $\kappa(Z, Z) \approx 0.98$, while for photon exchange it is $\kappa(\gamma, \gamma) = -1$. Furthermore, the amplitude of the two distributions also depends on the considered rapidities of the two final state pions. Here, the rapidity cuts $|\eta_{\pi^\pm}| \leq 1$ have been applied to enhance the difference between the two curves. As in the case of τ-pair production via Higgs boson exchange, the distributions depend on experimental uncertainties and reconstruction efficiencies. Our numerical simulation shows that both signal and background reactions are affected in a similar way by these uncertainties. The background distributions with its large numbers of events can therefore be used to calibrate the $h \to \tau^+\tau^-$ signal reaction.

4. Concluding Remarks

We have proposed a method to probe for a possible Higgs sector CP-violation in the $h \to \tau^+\tau^-$ decay at the LHC. The corresponding mixing angle ϕ_τ can be extracted by measuring the spin correlations of the τ-lepton pairs. These spin correlations manifest themselves in characteristic distributions of the final τ decay products. Our method uses the momentum directions and the impact parameters of the final charged prongs of the τ decay to reconstruct these τ-spin correlations. We furthermore investigated the largest background to the Higgs boson signal, the Drell-Yan production process. By dividing these background events into two subsets, we proposed a method to calibrate measurement uncertainties of the signal process. Using these results we performed [18] an estimate of the precision of the mixing angle ϕ_τ which might be achievable at the LHC. For this evaluation we included all major τ-decay channels and simulated the φ^*_{CP} distribution by a Monte Carlo program including resolution estimates for the momenta and impact parameters of the final charged prongs [18]. We furthermore assumed signal to background ratios taken from Ref. [8]. For the LHC with $\sqrt{S}$ = 14 TeV we performed simulations for 150 fb^{-1}, 500 fb^{-1} and the high-luminosity LHC upgrade goal of 3 ab^{-1}. The precision of ϕ_τ for these luminosities is estimated to 27°, 14.3°, and 5.1° respectively.

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