TRANSVERSE SPIN EFFECTS IN $H/A \to \tau^+\tau^-$; $\tau^\pm \to \nu X^\pm$ MONTE CARLO APPROACH * **

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The transverse spin effects may be helpful to distinguish between scalar ($J^{\mathrm{PC}} = 0^{++}$) or pseudoscalar ($J^{\mathrm{PC}} = 0^{-+}$) nature of the spin zero (Higgs) particle once discovered in future accelerator experiments. The correlations can manifest themselves *e.g.* in the distribution of acollinearity angle of $X^\pm$ in the decay chain $H/A \to \tau^+\tau^-$; $\tau^\pm \to \nu X^\pm$. This delicate measurement will require, however, reconstruction of the Higgs boson rest-frame. Then, questions of the combined detection-theoretical effects may be critical to establish the reliability of the method. An appropriate Monte Carlo program is essential. To make such studies possible we have extended the standard universal interface of the `TAUOLA` τ-lepton decay library to include the complete spin effects for τ leptons originating from the spin zero particle. The interface is expected to work with any Monte Carlo generator providing Higgs boson production and subsequent decay into a pair of τ leptons. Examples of numerical results and cross checks of the program will be also given. In particular, we find that effects of beamstrahlung may be critical to the quality of the measurement of the Higgs boson, unless some improvements of the method can be found.

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One of the main goals for future high energy experiments is to measure properties of the Standard Model (SM) Higgs sector. Proton-(Anti)Proton Colliders, such as TEVATRON [1] or LHC [2,3] are expected to discover the Higgs boson, if the (SM) or one of its MSSM extensions is true. Otherwise the spectrum of possibilities is practically unlimited and discovery cannot be guaranteed. The comprehensive precise measurements of all Higgs boson properties are expected to be left for future experiments on high energy e^+e^- linear colliders such as JLC [4], NLC [5], or TESLA [6].

One of the important measurement, just after establishing that the newly discovered particle has indeed spin zero, is to check if it is a scalar or pseudoscalar. Depending on the mass of the (to be) discovered Higgs boson, and if it is of Standard Model or one of its numerous extensions, different observables can give access to this information. Already a long time ago, see *e.g.* [7], it was argued that exploring transverse spin correlations in the Higgs boson decay $H/A \to \tau^+\tau^-; \tau^\pm \to \nu_\tau X^\pm$ can in some cases provide a *model independent* test. The method relies on the properties of the Higgs boson Yukawa coupling to the τ lepton, which in the general case can be written as $\bar{\tau}(a_\tau + ib_\tau\gamma_5)\tau$ (for a discussion of the Higgs boson models, see *e.g.* [8] page 123). The method, at least in principle, does not depend on the Higgs boson production mechanism at all.

There are many reasons why this process may turn out not to be interesting. The cross section may be too small for the luminosity of the future collider, the mass of the Higgs boson may be heavy and other Higgs boson decay channels better suited for the parity measurement. Finally, the parity of the Higgs boson may be measurable from the properties of its production. However, it is generally accepted that the $H/A \to \tau^+\tau^-$ offers a very interesting signature. Its feasibility needs to be studied especially in the context of decisions to be taken on properties of the future LC detectors which may be taken soon. The proposed measurement [7] is *experimentally* involved. It requires reconstruction of the acollinearity angle (δ^*) between τ^+ τ^- decay products *in the H/A rest-frame*. Note that in case of $H/A \to \tau^+\tau^-$ the four momentum of the Higgs boson is not directly measurable as we have the unobservable ν_τ among its decay products; it needs to be reconstructed from the constraints of energy momentum conservation for the whole event. The distribution in angle (δ^*) is sensitive to the transverse $\tau^+\tau^-$ spin correlations, which are different for the scalar, pseudoscalar or the mixed state (we will take into considerations only the extreme cases corresponding to choosing either b_τ or a_τ equal zero). Precise enough reconstruction of the H/A *rest-frame* is important. Many effects, theoretical (*e.g.* QED bremsstrahlung), or experimental (uncertainty on beam energies, not sufficient hermeticity of the detector, angular/energy resolution for all particles and jets *etc.*) may invalidate the method. In the following, we will concentrate on the feasibility of the method, taking into account properties of the $H/A \to \tau^+\tau^-$ decay, and simple assumptions on bremsstrahlung and beamstrahlung in reconstructing Higgs boson rest-frame, leaving out from the considerations all other limitations and constraints, be it theoretical or experimental.

It is generally expected that the Monte Carlo method is the only way to estimate whether the measurement can be realized in practice, and which features of the future detection setup may turn out to be crucial. Our paper is organized as follows. First, an algorithm for generating decays of $\tau^\pm$ leptons produced in $H/A \to \tau^+\tau^-$ including full spin correlations for the Higgs boson production mechanism is explained, and some numerical examples testing the correctness of the program are given. Later, results taking into account inaccuracies in reconstructing the Higgs boson rest-frame are shown and conclusions are given.

Since the Higgs boson spin is zero, the spin correlations of its decay products *do not* depend at all on the mechanism of the Higgs boson production. Technical difficulties, related to the choice of τ^+ and τ^- spin quantization frames, present in the case of $e^+e^- \to Z/\gamma \to \tau^+\tau^-$ [9, 10] (bremsstrahlung effects included or not), are not present. The analytical form of the density matrix is simple. To calculate the density matrix for the pair of τ leptons it is thus enough to: know their four momenta, know that they indeed originate from the Higgs boson and, assume the type of the Yukawa interaction. Such information is stored in the event data structure called `HEPEVT` common block [11] used by practically all Monte Carlo generators for Higgs boson production.

In Refs. [12, 13], the algorithm was developed where all τ leptons found in the `HEPEVT` common block can be decayed with the help of the `TAUOLA` library [14–16] and the τ decay products are appended to the `HEPEVT` as well. The kinematical information on the momenta of all particles forming an event was used to calculate, in some approximation, the longitudinal spin state of the τ. For our purpose that solution had to be extended, to incorporate the full density matrix of the $\tau^+\tau^-$ pair, in the case when it is originating from the Higgs boson decay. The following changes had to be introduced to the algorithm explained in Ref. [12]:

1. The quantization frames for the spin states of τ^+ and τ^- need to be properly oriented with respect to each other. In our solution they are simply connected by the boost along τ lepton momenta as defined in the Higgs boson rest-frame. At the technical level this is enforced by the `TRALOR` routine [14] defining the relation of the $\tau^\pm$ spin quantization frames and the laboratory frame. As an intermediate step this routine uses the Higgs boson rest-frame.

2. The density matrix was taken from Ref. [7] and adapted to the quantization frames as specified in previous point. Only two cases of purely scalar or pseudoscalar Higgs boson were implemented. Any further extension is, however, straightforward.

3. Generation of τ^+ and τ^- decays is then performed following the method explained in Ref. [14] and used in `KORALB` [10] for a long time.

4. We have assumed that production generator provides two-body Higgs boson decays to τ leptons only, in particular, that it does not provide any bremsstrahlung corrections. Instead, `PHOTOS` [17, 18] can be used for that purpose, once generation of $\tau^{\pm}$ decays is completed.

5. More complete inclusion of bremsstrahlung corrections would require a substantial re-write and extension of the program to the solution as in Ref. [19] or a similar one.

Once we have explained the main principles of our calculation, let us turn to the discussion of numerical results. As an example we will take a Higgs boson of 120 GeV. In the first two plots, which will be constructed for the quantities defined in the Higgs boson rest-frame we are totally independent of the production mechanism. We will study the predictions for the scalar and pseudoscalar cases, essentially to provide the test of our generator. Thick lines will denote predictions for the scalar Higgs boson and thin lines for the pseudoscalar one. As in Ref. [7], we take the $\tau^{\pm} \to \nu\pi^{\pm}$ decay mode only.

Fig. 1 presents the distribution in the angle $\phi^* = \arccos(\vec{n}^+ \cdot \vec{n}^-)$, where $\vec{n}^{\pm} = \frac{\vec{p}^{\;\pi^{\pm}} \times \vec{p}^{\;\tau^-}}{|\vec{p}^{\;\pi^{\pm}} \times \vec{p}^{\;\tau^-}|}$, *i.e.* the non-observable acoplanarity angle. The distribution is indeed, as it should be [7], proportional to $\sim 1 \mp \frac{\pi^2}{16} \cos\phi^*$, respectively, for scalar and pseudoscalar Higgs. In Fig. 2 we plot the distribution of the $\pi^+\pi^-$ acollinearity angle (δ^*). The difference between the case of a scalar and a pseudoscalar Higgs is clearly visible, especially for acollinearities close to π (see Fig. 3).

Let us now turn to the distributions defined for the semi-realistic case. We need thus to take into consideration the combined process of decay and production of the Higgs boson. As an example[1], for the production mechanism we took the process $e^+e^- \to ZH$; $Z \to \mu^+\mu^-(\bar{q}q)$; $H \to \tau^+\tau^-$ (only the scalar H can be produced in this process in (SM)), at Center-of-Mass system energy of 350 GeV simulated with `PYTHIA 6.1` Monte Carlo program [20], effects due to initial state bremsstrahlung were taken into account. As in

[1] We have checked that in case of other production processes and center-of-mass system energies, the results, presented later in the paper, remain similar or are slightly less sensitive to the transverse spin (*i.e.* Higgs boson parity) effects.

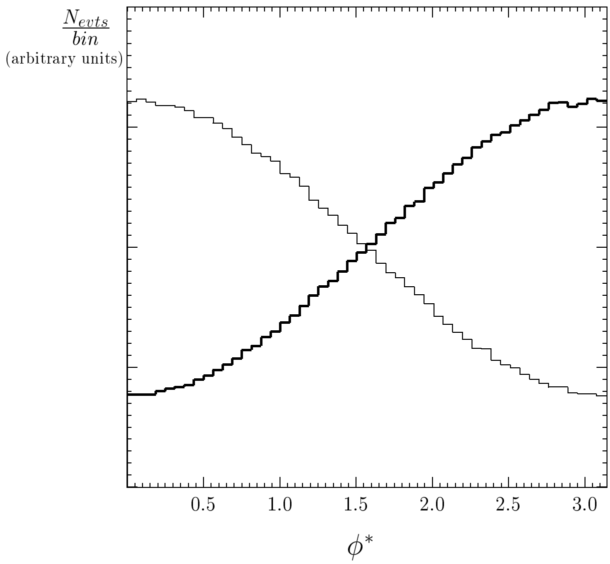

Fig. 1. The $\pi^+\pi^-$ acoplanarity distribution (angle ϕ^*) in the Higgs boson rest-frame. The thick line denotes the case of the scalar Higgs boson and thin line the pseudoscalar one.

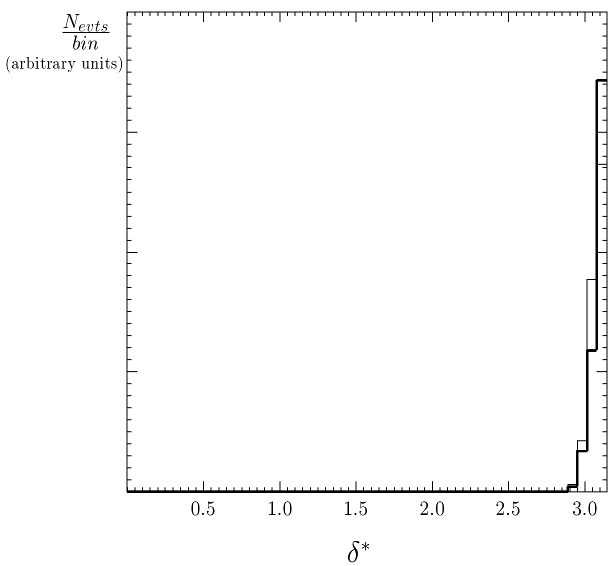

Fig. 2. The $\pi^+\pi^-$ acollinearity distribution (angle δ^*) in the Higgs boson rest-frame. Full angular range $0 < \delta^* < \pi$ is shown. The thick line denotes the case of the scalar Higgs boson and thin line the pseudoscalar one.

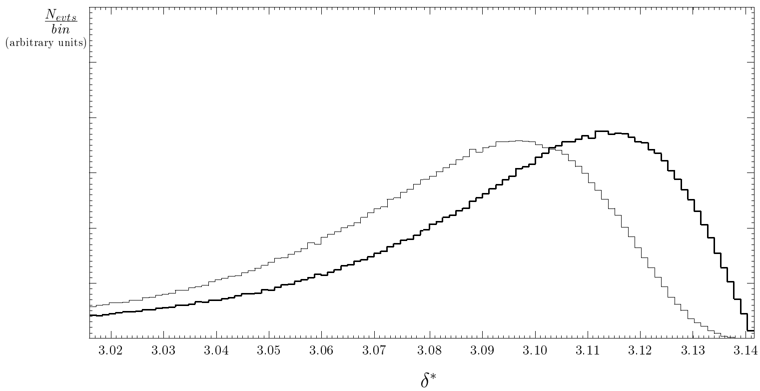

Fig. 3. The $\pi^+\pi^-$ acollinearity distribution (angle δ^*) in the Higgs boson rest-frame. Parts of the distribution close to the end of the spectrum; $\delta^* \sim \pi$ are shown. The thick line denotes the case of the scalar Higgs boson and the thin line the pseudoscalar one.

this case production of the pseudoscalar Higgs boson is excluded, to quantify the size of the spin effect we will compare the predictions when all spin effects are included (thick lines on the following plots), with the case when only longitudinal spin correlations are included (thin lines). The difference between the two lines visualizes the size of the transverse spin effects.

If we could compare predictions for scalar and pseudoscalar, the difference would be roughly a factor of two larger[2]. Then however, we could not limit our discussion to the properties of the Higgs boson decay. Many possibilities due to generally distinct, and model dependent, production mechanisms for the scalar and pseudoscalar Higgs boson would make the picture more involved and not suitable for our discussion.

As we can see in Fig. 4, the $\pi^+\pi^-$ acollinearity angle (δ) distribution in the laboratory frame looks quite different than in the Higgs boson rest-frame, the two cases of different spin treatments are indistinguishable, distribution is not peaked at $\delta \sim \pi$ at all.

If information on the beam energies and energies of all other observed particles (high p_{T} initial state bremsstrahlung photons, decay products of Z *etc.*) are taken into considerations the Higgs rest-frame can be reconstructed. We may define the "reconstructed" Higgs boson momentum as the difference of sum of beam energies and momenta of all visible particles, that is, for example, decay products of the Z and all radiative photons of $|\cos\theta| <$

[2] By numerical accident, the case when only longitudinal spin correlations are included is equivalent to the case of non-coherent sum of scalar and pseudoscalar Higgs boson contributions of the equal proportions. This holds, of course, if the same production mechanism could be applied for the two cases.

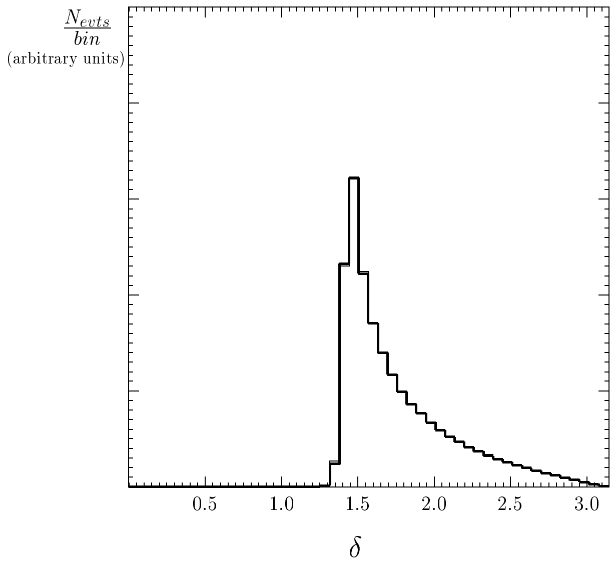

Fig. 4. The $\pi^+\pi^-$ acollinearity distribution (angle δ) in the laboratory frame. Full angular range $0 < \delta < \pi$ is shown. The thick line denotes the case when all spin effects are included in the decay of the scalar Higgs boson, while only longitudinal spin correlations are included for thin line. The two lines are nearly indistinguishable.

0.98. In our study we will mimic in a very crude way beamstrahlung effects only, assuming a flat spread over the range of $\pm$ 5 GeV for the longitudinal component of the Higgs boson momentum with respect to the generated one[3]. This assumption means, that the detection effect which is practically independent of the Higgs boson production mechanism is only included. As we can see (Figs. 5 and 6) in the distribution of the acollinearity angle ($\delta^\bullet$) defined in reconstructed Higgs boson rest-frame, the effects due to transverse spin effects are only barely visible.

We should stress that, in this very simple example, we have not discussed at all other effects potentially degrading the method, such as limited statistics, backgrounds, uncertainties in reconstruction of the energies and directions for the particles and jets, which may lead to systematic errors comparable in size to the parity effect, remaining after beamstrahlung effect is taken into account. Alone, this ambiguity in reconstruction of the Higgs boson four-momentum degraded the method of measuring the Higgs boson parity using the decay chain $h \to \tau^+\tau^-$, $\tau^\pm \to \pi^\pm\nu$ in a decisive way.

[3] The typical spread for the beam energy in linear collider is of the order of few percent [4] or even worse.

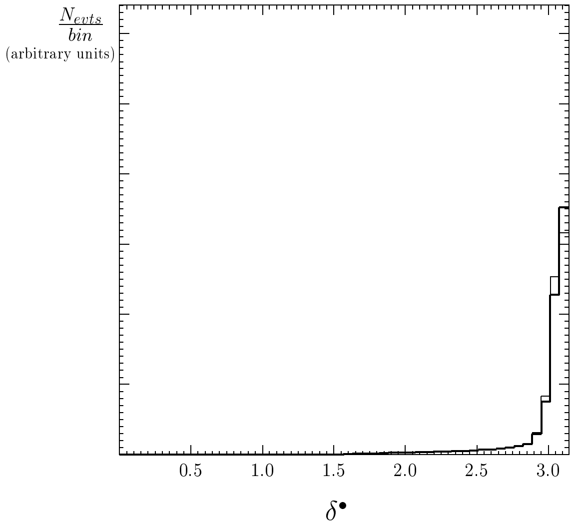

Fig. 5. The $\pi^+\pi^-$ acollinearity distribution (angle $\delta^\bullet$) in the scalar Higgs boson reconstructed rest-frame. Full angular range $0 < \delta^\bullet < \pi$ is shown. The thick line denotes the case when all spin effects are included, while only longitudinal spin correlations are taken for thin line.

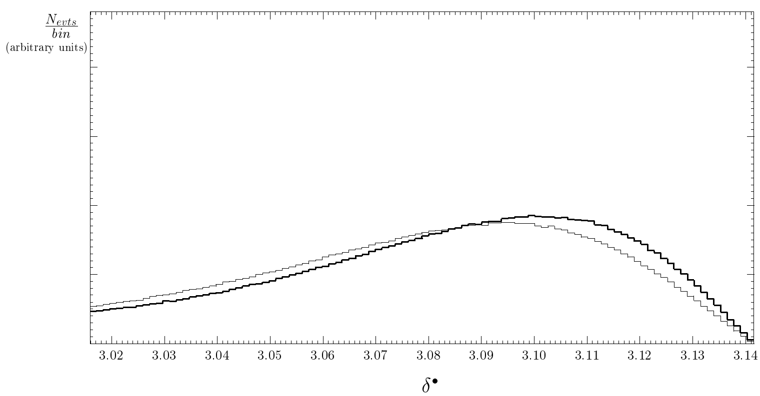

Fig. 6. The $\pi^+\pi^-$ acollinearity distribution (angle $\delta^\bullet$) in the scalar Higgs boson reconstructed rest-frame. Parts of the distribution close to the end of the spectrum; $\delta^\bullet \sim \pi$ are shown. The thick line denotes the case when all spin effects are included, while only longitudinal spin correlations are taken for thin line.

We have studied several mechanisms of the Higgs boson productions, in all cases depletion of the acollinearity distribution sensitivity to the transverse spin effect was quite similar. We can conclude that our results are thus independent from the production mechanism.

Recently some work was started on detector effects, see [21] for details. We can nonetheless conclude that, due to the beamsstrahlung effect, there is little hope, for the elegant method of reference [7] to check Higgs boson parity using its decay to τ leptons (whatever the luminosity of future Linear Collider), unless, may be, other, unfortunately less sensitive to spin than $\tau^\pm \to \pi^\pm \nu$ decay modes are used as well. We may hope, also that methods similar to the fruitful ones for measurement of τ polarization at LEP 1, or for the study of CP parity and known for a long time, see *e.g.* [22, 23], may become available for our case as well. Definitely, realistic studies, combining accelerator, detector and theoretical effects are needed to settle the matter.

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