TAU POLARISATION AND ITS CORRELATIONS AS A SIGNAL FOR HIGGS BOSONS — UNIVERSAL SPIN INTERFACE FOR TAUOLA PACKAGE* **

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We show how the $\tau^+\tau^-$ spin correlations can be used to improve the recognition of the parent boson spin, and hence to identify scalar boson $H^0 \to \tau^+\tau^-$ events from the vector boson $Z/\gamma^* \to \tau^+\tau^-$ background in high energy accelerator experiments.

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1. Introduction

The most unsatisfactory feature of the Standard Model is our lack of knowledge of the actual mechanism that breaks the electroweak gauge symmetry and generates the particle masses. In the Standard Model the breaking occurs by a complex Higgs boson doublet. Three components of this doublet become the longitudinal polarisation states of the massive vector gauge bosons ($W^\pm$, Z), while the remaining component manifests itself as a neutral massive scalar Higgs particle. On the other hand the minimal supersymmetric model contains two Higgs boson doublets. Three fields are taken by the vector bosons and remaining five become physical particles: a pair of charged boson $H^\pm$, two scalars h^0, H^0 and one pseudoscalar A^0. Many more complicated mass generation models have been proposed, but their common feature is that the couplings of the Higgs bosons to fermions increase with the fermion mass. Thus for leptons the $H\tau^+\tau^-$ coupling dominates over the $H\mu^+\mu^-$, He^+e^- couplings. The experimental observation

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which breaks e, μ, τ, universality by favouring $\tau^+\tau^-$ events could be an indication of the presence of a Higgs scalar. Whenever such a departure from lepton universality is observed a simple helicity correlation test can be performed which will clearly indicate that the $\tau^+\tau^-$ pairs have scalar boson origin as opposed to arising from vector boson decay. We will show that correlation of polarisations of the outgoing τ leptons are very different for $H^0 \to \tau^+\tau^-$ decays from that for $Z/\gamma^* \to \tau^+\tau^-$ decays. The distinction arises because the vector bosons Z/γ^* decay into either $+\,+$ or $-\,-$ whereas the scalar Higgs bosons H into $+\,-$ or $-\,+$, where $+, -$ denotes the τ pairs spin configurations.

2. Universal interface for TAUOLA package

We present the algorithm for the interfacing the τ lepton decay package `TAUOLA` - a library of Monte Carlo programs to simulate decays of τ leptons [1–3] with "any" production generator to include spin effects in the elementary $Z/\gamma^* \to \tau^+\tau^-$ process [4]. The approximate spin correlation are calculated from the information stored in the `HEPEVT` common block [5] filled by "any" τ production program as described in Ref. [6]. As a demonstration example the interface is combined with the `JETSET` generator, however it should work in the same manner with the `PYTHIA` [7], `HERWIG` or `ISAJET` generators as well. In fact, such an interface can be considered as a separate software project, to some degree independent both from the specific problem of τ production and its decay.

The aim of this interface is *not* to replace the matrix element calculations, but rather to provide a method of calculating/estimating spin effects in cases when spin effects would not be taken care of, at all. Such an approach is limited for the treatment of longitudinal spin degrees only and to the case of particle production and decay in the ultra-relativistic limit. The approximation consists of reconstructing information of the elementary $2 \to 2$ body process $f\bar{f} \to (Z/\gamma^*) \to \tau^+\tau^-$, buried inside multi-body production process such as for example $f\bar{f} \to gZ$, $f\bar{f} \to \gamma Z$, $fg \to fZ$, $f\gamma \to fZ$ *etc.* The additional particles are grouped (summed) into effective quarks and leptons to minimise their virtualities. Such an approach is internally consistent in the case of photon or gluon emission within the leading log approximation. The principle of calculating kinematic variables is simple. The 4-momenta of the $2 \to 2$ body process have to be found. The 4-momenta of the outcoming τ's are at present used directly[1]. Initial state momenta are constructed from the incoming and outcoming momenta of particles accompanying production of the Z/γ^* state[2]. Longitudinal po-

[1] This part of the algorithm will be improved in a near future.

[2] The Z/γ^* state does not need to be explicitly coded in the `HEPEVT` common block.

larisation of τ leptons $\mathcal{P}_\tau$ depends on the spin quantum number of the τ mother. It is randomly generated as specified in Table I.

TABLE I

Probability for the configurations of the longitudinal polarisation of the pair of τ leptons from different origins.

Origin	$\mathcal{P}_{\tau^+}$	$\mathcal{P}_{\tau^-}$	Probability
Neutral Higgs bosons: h^0, H^0, A^0	$\mathcal{P}_{\tau^+}=+1$	$\mathcal{P}_{\tau^-}=-1$	0.5
	$\mathcal{P}_{\tau^+}=-1$	$\mathcal{P}_{\tau^-}=+1$	0.5
Charged Higgs boson: H^+ or H^-	$\mathcal{P}_{\tau^+}=+1$	$\mathcal{P}_{\tau^-}=+1$	1.0
Charged vector boson: W^+ or W^-	$\mathcal{P}_{\tau^+}=-1$	$\mathcal{P}_{\tau^-}=-1$	1.0
Neutral vector boson: Z/γ^*	$\mathcal{P}_{\tau^+}=+1$	$\mathcal{P}_{\tau^-}=+1$	P_Z
	$\mathcal{P}_{\tau^+}=-1$	$\mathcal{P}_{\tau^-}=-1$	$1-P_Z$
Other	$\mathcal{P}_{\tau^+}=+1$	$\mathcal{P}_{\tau^-}=+1$	0.5
	$\mathcal{P}_{\tau^+}=-1$	$\mathcal{P}_{\tau^-}=-1$	0.5

The probability P_Z used in the generation, is calculated directly from the squares of the matrix elements of the Born-level $2 \to 2$ process $f\bar{f} \to \tau^-\tau^+$:

$$P_Z = \frac{|\mathcal{M}|^2_{f\bar{f}\to\tau^-\tau^+}(+,+)}{|\mathcal{M}|^2_{f\bar{f}\to\tau^-\tau^+}(+,+) \ + \ |\mathcal{M}|^2_{f\bar{f}\to\tau^-\tau^+}(-,-)}, \tag{1}$$

where $f = e, \mu, u, d, c, s, b$. It can be also expressed (following conventions of Ref. [8]), with help of the couplings of fermions to the γ (and Z) bosons.

$$P_Z(s,\theta) \ = \ \frac{\frac{d\sigma_{\rm Born}}{d\cos\theta}(s,\cos\theta;1)}{\frac{d\sigma_{\rm Born}}{d\cos\theta}(s,\cos\theta;1) + \frac{d\sigma_{\rm Born}}{d\cos\theta}(s,\cos\theta;-1)}, \tag{2}$$

$$\begin{aligned}\frac{d\sigma_{\rm Born}}{d\cos\theta}(s,\cos\theta;p) \ &= \ (1+\cos^2\theta)F_0(s) + 2\cos\theta F_1(s) \\ &\quad -p[(1+\cos^2\theta)F_2(s) + 2\cos\theta F_3(s)]\,. \end{aligned} \tag{3}$$

with the four form-factors

$$\begin{aligned}
F_0(s) \ &= \ \frac{\pi\alpha^2}{2s}\left(q_f^2 q_\tau^2 + 2{\rm Re}\,\chi(s) q_f q_\tau v_f v_\tau + |\chi(s)|^2 \left(v_f^2+a_f^2\right)\left(v_\tau^2+a_\tau^2\right)\right), \\
F_1(s) \ &= \ \frac{\pi\alpha^2}{2s}\left(2{\rm Re}\chi(s) q_f q_\tau a_f a_\tau + |\chi(s)|^2 \, 2v_f a_f \, 2v_\tau a_\tau\right), \\
F_2(s) \ &= \ \frac{\pi\alpha^2}{2s}\left(2{\rm Re}\chi(s) q_f q_\tau v_f a_\tau + |\chi(s)|^2 \left(v_f^2+a_f^2\right) 2v_\tau a_\tau\right), \\
F_3(s) \ &= \ \frac{\pi\alpha^2}{2s}\left(2{\rm Re}\chi(s) q_f q_\tau a_f v_\tau + |\chi(s)|^2 \, 2v_f a_f \left(v_\tau^2+a_\tau^2\right)\right),
\end{aligned} \tag{4}$$

and

$$\chi(s) = \frac{s}{s - M_Z^2 + is\frac{\Gamma_Z}{M_Z}}\,. \tag{5}$$

The q_f, v_f, a_f, q_τ, v_τ, a_τ are the charges and Z coupling constants of the fermions and τ, respectively.

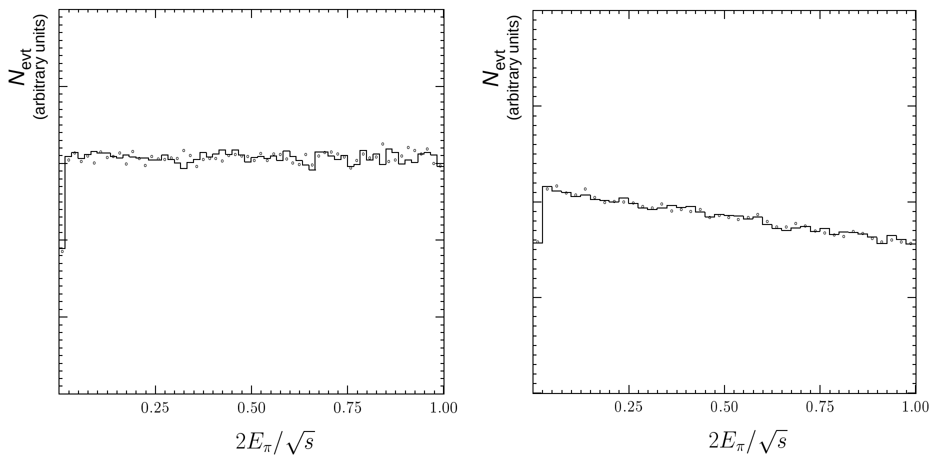


Fig. 1. Single π energy spectrum in the case of τ produced from H (left-hand side) or Z (right-hand side), $\sqrt{s} = m_H$ or $\sqrt{s} = m_Z$ respectively.

3. Spin sensitive observables

The polarisation of the τ lepton can be exploited to identify a neutral Higgs bosons via the decay $H^0 \to \tau^+\tau^-$. Any experimental observation which breaks e, μ, τ universality — the equality of e, μ and τ couplings to the gauge bosons — by favouring $\tau^+\tau^-$ events could be an indication of the presence of a neutral Higgs scalar. The couplings of the "Higgs" particles to fermions increase with the mass of the fermion, thus the τ couples preferentially in comparison with either μ or e. Here the background is $Z/\gamma^* \to \tau^+\tau^-$ decays. Whenever such a departure from lepton universality is observed there exists a simple polarisation correlation test which, if used will help to indicate the presence of τ pairs of Higgs boson origin among the background $Z/\gamma^* \to \tau^+\tau^-$ events. As we can see from Table I, the τ pairs are produced with the well defined spin configurations: $+\,+$ or $-\,-$ for vector bosons $+\,-$ or $-\,+$ for neutral Higgs boson. Thus a polarisation correlation test can be performed using the energy distributions of the final decay products which are sensitive to the admixture of the H^0 to Z/γ^* parentage of the τ pairs. The polarisation correlation can be studied using the various τ decay modes. Let us concentrate on the case of τ decays to $\pi\nu$, most sensitive to the spin correlations. The leptonic decay mode *i.e.* $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ are not very sensitive to the polarisation correlation because of the two missing neutrinos in this decay. In the case of other hadronic τ decay, *e.g.* $\tau^- \to \nu_\tau\rho^- \to \nu_\tau\pi^-\pi^0$, $\tau^- \to \nu_\tau a_1^- \to \nu_\tau\pi^- 2\pi^0$, $\tau^- \to \nu_\tau K^{*-} \to \nu_\tau K^-\pi^0$ *etc.* the reconstruction of π^0 is also necessary. For the production of the τ lepton pairs Monte Carlo program `PYTHIA` was used, and for the decay Monte Carlo program `TAUOLA`, and this spin interface [4]. It was assured, that the invariant mass of the pair of two incoming quarks was $\sqrt{s} = m_Z = m_H$. Energies are defined in the $\tau^+\tau^-$ pair rest-frame. With the help of variables $z_\pm = 2E_{\pi^\pm}/\sqrt{s}$, the spin effects are visualised. Fig. 1 shows the slope of π energy spectrum (in the case of Z) due to the τ polarisation. The slope of the distribution is simply proportional to the polarisation.

$$\frac{d\sigma}{dz_\pm} \sim 1 + \mathcal{P}_\tau \; 2\,(z_\pm - 0.5)\,. \tag{6}$$

In the case of the plot on the left-hand side the spectrum is flat, as would be in the case of scalar neutral Higgs boson where there is no polarisation. As we can see in the Fig. 2 ($\pi^+\pi^-$ energy-energy correlations) in $Z/\gamma^* \to \tau^+\tau^-$ decays a Fast (a Slow) $\pi^\pm$ is most likely to be associated with a a Fast (a Slow) $\pi^\mp$ whereas the opposite is favoured for $H^0 \to \tau^+\tau^-$ decays. Therefore, a excess arising from Higgs boson decay can be recognised in the $\pi^+\pi^-$ mode as a Fast $\pi^\pm$ with a Slow $\pi^\mp$. The quantity which

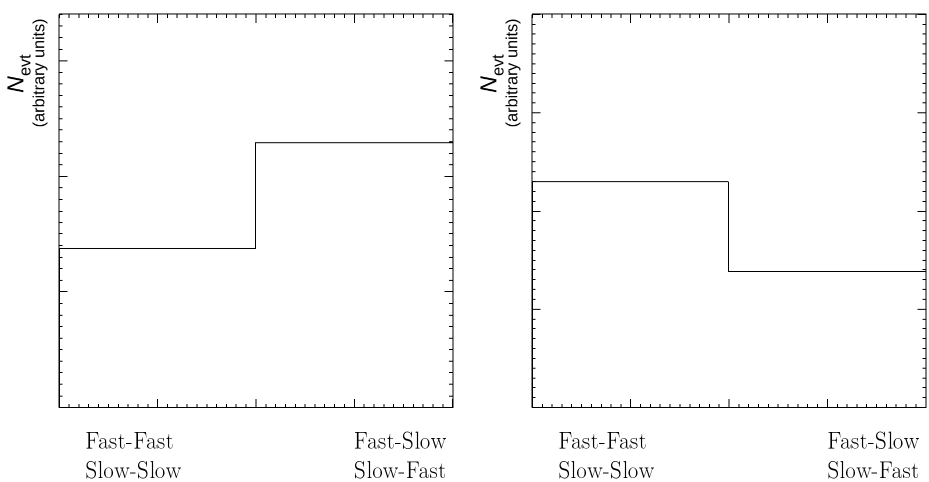


Fig. 2. $\pi^+\pi^-$ energy-energy correlations in the case of τ produced from H (left-hand side) or Z (right-hand side), $\sqrt{s} = m_H$ or $\sqrt{s} = m_Z$, respectively.

can be measured experimentally is the invariant mass distribution. Fig. 3 shows $\pi^+\pi^-$ invariant mass distribution for the Higgs boson and Z cases. Continuous line — with spin effects included, dotted line — with spin effects switched off. Left-hand side plot corresponds to the Higgs boson case, right-hand side to the Z. In the case of Higgs boson, the mass distribution

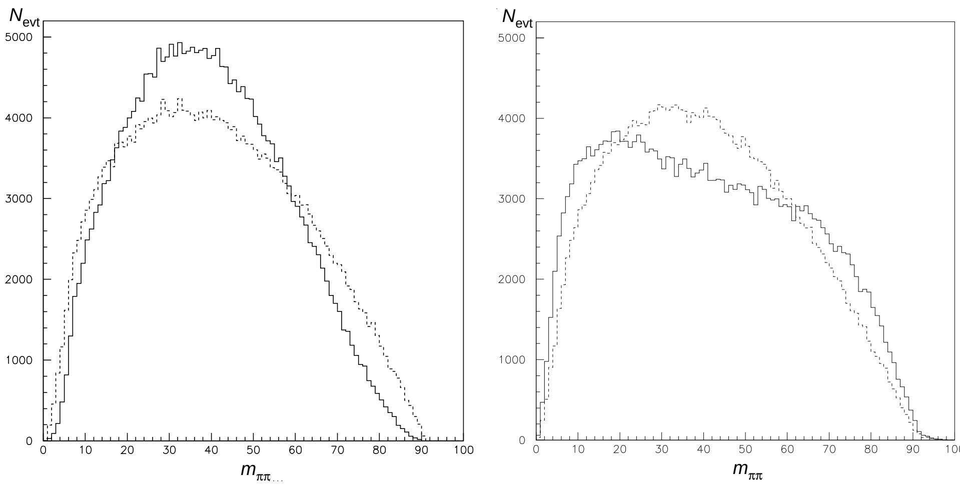
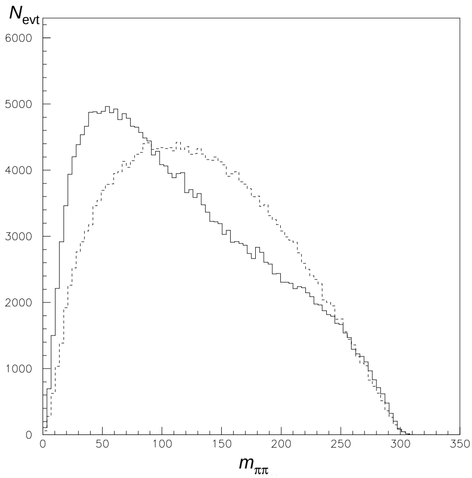


Fig. 3. The $\pi^+\pi^-$ invariant mass distribution. Left-hand side plot for H; right-hand side for Z/γ^*. Continuous line with spin effects included, dotted line with spin effects switched off. In the two cases respectively $\sqrt{s} = m_H = m_Z$.

is peaked centrally, whereas in the case of Z/γ^* shoulders of the distributions are more profound. In the Z/γ^* case the Fast-Fast and Slow-Slow configurations are localised mostly at the shoulders of the $\pi^+\pi^-$ invariant mass distributions, while for the the Higgs boson case the Fast-Slow configurations are localised in the centre of the distributions. If all polarisation effects are switched off (dashed lines) the distributions in the two cases are identical. This observable, *i.e.* a well defined distribution of invariant mass built from the visible decay products of the τ's, can be helpful in separating Higgs boson signal from Z/γ^* background. The same distribution have also been studied for the off-peak production of Z/γ^*, *i.e.* for the larger cms energies. In these cases the average polarisation is large and negative, also distinct for the $u\bar{u}$ and $d\bar{d}$ annihilations. This may open a way for measuring the flavour of the quarks leading to τ pair production. As illustrated in Fig. 4, the effect on the $\pi^+\pi^-$ invariant mass distribution is noticeable. The shape of the distribution might give the insight to the structure functions of colliding protons.



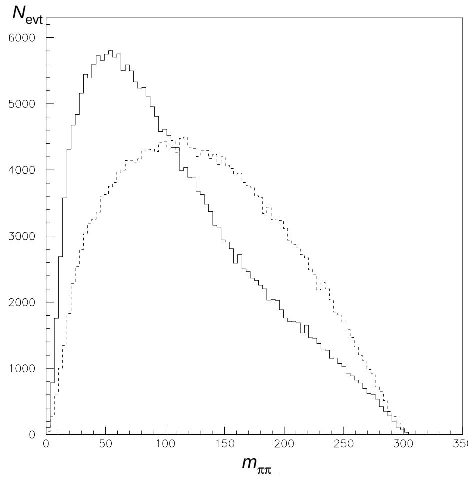


Fig. 4. The $\pi^+\pi^-$ invariant mass distribution for $u\bar{u} \to Z/\gamma^*$ (left-hand plot) and $d\bar{d} \to Z/\gamma^*$ (right-hand plot) produced with cms energy of 300 GeV. Continuous line with spin effects included, dotted line with spin effects switched off.

4. Case of the Higgs boson signatures at LHC

The τ leptons are considered as a very promising signature for the searches of the Higgs bosons in the Minimal Supersymmetric Standard Model (MSSM) at LHC collider [9, 10]. The neutral Higgs bosons H and A decay into $\tau^+\tau^-$ pair, are enhanced for the large values of $\tan\beta$ ($\tan\beta$ denotes the ratio of the vacuum expectation values of the Higgs doublets in the MSSM model), with the branching ratio of about 10% for most of the range of the interesting Higgs boson mass values (150–1000 GeV). The irreducible background to this process is a $Z/\gamma^* \to \tau\tau$ decay and the reducible backgrounds is the QCD jets. In this study the τ identification is based on the presence of a single hard isolated charged hadron in the jet using tracker information. Two hard tracks from τ^- and τ^+ in the signal events have an opposite sign while no strong charged correlation is expected for the QCD jets. Fig. 5 shows the effect of $\pi\pi$ invariant mass distribution. Events were generated with the Monte Carlo `PYTHIA 5.7` [11], the Higgs boson mass of the 300 GeV and the width below 1 GeV (as for $\tan\beta \sim 10$) was assumed. For the Z/γ^*, the cms energy of the produced $\tau\tau$ pair was taken in the range 300 ± 10 GeV. A simple selection was applied. The minimal transverse momenta of the $\pi' s$ were required to be above 15 GeV and the pseudorapidity $|\eta| < 2.5$ [9]. In Fig. 5 we can see the visible effect of spin-correlations. Similarly as in case of Fig. 3, the distribution for the Z/γ^* has more profound shoulders than for the Higgs boson, due to spin correlations.

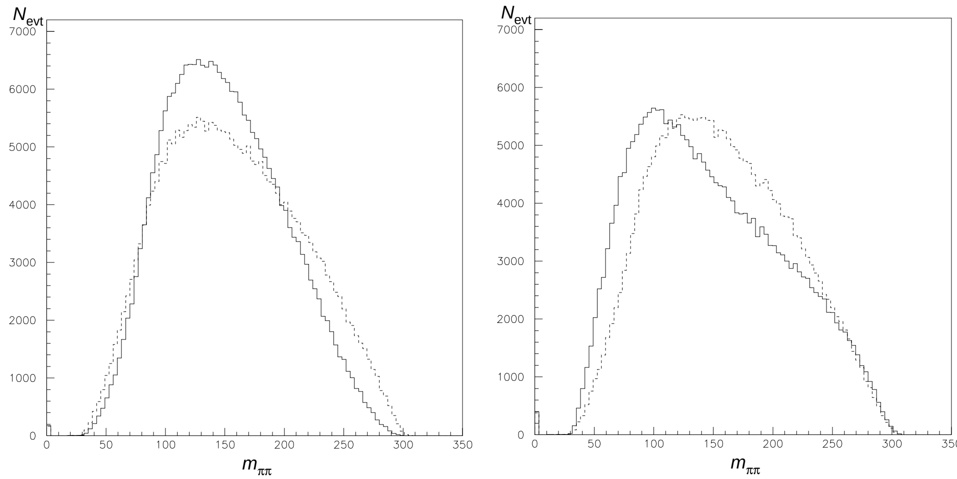


Fig. 5. The $\pi^+\pi^-$ invariant mass distribution after basic selection. On the left for Higgs boson, on the right for Z/γ^*. Continuous line with spin effects included, dotted line with spin effects switched off. The Higgs boson mass was assumed to be 300 GeV.

5. Summary

We have discussed the algorithm for interfacing the τ lepton decay package `TAUOLA` with "any" production generator to include effects due to spin in the elementary $Z/\gamma^* \to \tau^+\tau^-$ process [4]. The invariant mass distributions presented here, sensitive to the $\tau^+\tau^-$ spin correlations, can possibly be used for the MSSM Higgs boson searches at LHC to enhance sensitivity of the signal or to verify the hypothesis of the spin zero nature of the Higgs boson. This code is publicly availale from the address [12].

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