The TauSpinner program for studies on spin effect in tau production at the LHC.

Z. Czyczula, T. Przedzinski, Z. Was

Abstract

Final states involving tau leptons are important components of searches for new particles at the Large Hadron Collider (LHC). A proper treatment of tau spin effects in the Monte Carlo (MC) simulations is important for understanding the detector acceptance as well as for the measurements of tau polarization and tau spin correlations. In this note we present a TauSpinner package designed to simulate the spin effects. It relies on the availability of the four-momenta of the taus and their decay products in the analyzed data. The flavor and the four-momentum of the boson decaying to the $\tau^- \tau^+$ or $\tau^+ \nu$ pair need to be known. In the $Z/\gamma^*$ case the initial state quark configuration is attributed from the intermediate boson kinematics, and the parton distribution functions (PDF’s). TauSpinner is the first algorithm suitable for emulation of tau spin effects in tau-embedded samples. It is also the first tool that offers the user the flexibility to simulate a desired spin effect at the analysis level. An algorithm to attribute tau helicity states to a previously generated sample is also provided.

(Submitted to Eur. Phys. J. C)
1 Introduction

Tau leptons are an excellent signature with which to probe new physics at the LHC. As the heaviest leptons, they have the largest coupling to the Higgs boson both in the Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM). Their short-enough lifetime and parity-violating decays allow for their spin information to be preserved in the decay product kinematics recorded in the detector. They are therefore the only leptons suitable for measuring longitudinal polarization and its correlations, which provide important constraints on the nature of the observed resonance.

In this note we present a TauSpinner package, which is a MC program designed to generate tau spin effects in any tau sample provided their origin is known. This tool has two important applications:

Data driven analysis of $Z/\gamma^* \rightarrow \tau^- \tau^+$ and $W^\pm \rightarrow \tau^\pm \nu$ backgrounds. In the case of the algorithms for embedding taus on measured light lepton samples the TauSpinner may represent a third step. The first step is to construct the tau four-momenta from the four-momenta of the measured lighter leptons (and accompanying photons) while the second step comprises the decay of unpolarized taus using Tauola e.g. Taucola [2, 3, 4]. Omission of the last step leaves the kinematics of the tau decay particle different from what is expected from the polarized taus that appear in nature. This could lead to a mis-modeling of the shapes of various observables and hence a mis-measurement of the acceptance of a given set of cuts.

MC studies. Since the tau spin effects affect the overall acceptance of the taus in the detector, a proper treatment of these effects is of great importance for the interpretation of the results as well as feasibility studies of new models. It is also key for measurements of tau polarization and tau spin correlations. The TauSpinner algorithm allows one to create samples with different tau polarizations from an initial sample by re-weighting events to give the desired distributions as a function of the decay mode of the tau. Furthermore, the helicity states of the taus can be attributed to the previously generated sample (with spin effect included or introduced with the TauSpinner weight).

This letter is organized as follows. In Sec. 2 we present the algorithm while in Sec. 3 we discuss its performance as compared to the standard Tauola MC package. The results are summarized in Sec. 4. All relevant technical details are provided in App. A and B.

2 The TauSpinner algorithm

The TauSpinner algorithm relies on a leading order approximation in which spin amplitudes are used to calculate the spin density matrices for hard $2 \rightarrow 2$ or $1 \rightarrow 2$ Born level processes [5]. TauSpinner is constrained to the longitudinal tau spin degrees only. It starts with identifying the flavor of the intermediate boson: $W^\pm, Z/\gamma^*, H$ or $H^\pm$. The information on the four-momenta of the outgoing taus and their decay products as well as the intermediate boson four-momentum is then used to determine the polarimetric vectors. The longitudinal tau polarization ($P_\tau$) is randomly generated as specified in Tab. 1 and set to $\pm 1$ which correspond to pure tau helicity states. Probability of the helicity states is a constant for taus originating from the $W^\pm, H^\pm$ and $H$ bosons. In $Z/\gamma^* \rightarrow \tau^- \tau^+$ events, the probability, denoted $p^Z_\tau$, is a function of the $\tau^-$ scattering angle, $\theta$, and the center of mass squared of the hard process, $s$. At the Born level, and in the ultrarelativistic limit, $p^Z_\tau$ is, following notations of [5], given by:

\[ p^Z_\tau = \frac{\sin^2 \theta}{\pi s} \]

In order to enhance statistics for the spin analysis, the decay of unpolarized taus can be performed multiple times.
\[ p_{\tau}^Z(s, \theta) = \frac{\frac{d\sigma}{d\cos\theta}(s, \cos\theta, P_\tau = 1)}{\frac{d\sigma}{d\cos\theta}(s, \cos\theta, P_\tau = 1) + \frac{d\sigma}{d\cos\theta}(s, \cos\theta, P_\tau = -1)} \]  

(1)

where

\[ \frac{d\sigma}{d\cos\theta}(s, \cos\theta, P_\tau) = (1 + \cos^2\theta)F_0(s) + 2\cos\theta F_1(s) - P_\tau[(1 + \cos^2\theta)F_2(s) + 2\cos\theta F_3(s)] \]  

(2)

and \( F_i(s) \)'s are four form factors which depend on the initial and the final state fermion couplings to the Z boson and the propagator. The dependence on the \( \tau^- \) longitudinal polarization \( P_\tau \) is taken into account (note that in this case \( P_\tau = \pm 1 \), also \( P_{\tau_1} = P_{\tau_2} = P_\tau \)). In [5] the probability \( p_{\tau}^Z \) is calculated using the information on the initial state quarks stored at the generation level. In Tau\( \text{Spinner} \) the initial state quark configuration is attributed stochastically from the intermediate boson kinematics and PDFs in the following steps:

1. The invariant mass of the \( Z/\gamma^* \) is calculated from the intermediate boson four-vector. Note that it does not need to coincide with the sum of \( \tau^- \tau^+ \) four-momenta as it may include photons of final state bremsstrahlung.

2. The scattering angle, \( \cos\theta \), is calculated in the \( \tau^- \tau^+ \) pair rest frame from the angle between the direction of the first beam (1,0,0,1) boosted to this frame and the direction of the \( \tau^+ \) or from the angle between the direction of the second beam (1,0,0,-1) boosted to this frame and the direction of the \( \tau^- \). In the final step the average of the two \( \theta \).

3. The fraction of momenta taken by partons of the proton: \( x_1 \) and \( x_2 \) are resolved from constraints \( x_1 x_2 E_{\text{CM}}^2 = s \) and \( (x_1 - x_2) E_{\text{CM}} = p_z \), where \( E_{\text{CM}} \) and \( p_z \) denote the collision center of mass energy and the longitudinal component of the \( Z/\gamma^* \) momentum, respectively.

4. Probabilistic choice on the basis on the leading order \( 2 \to 2 \) Born level cross sections and PDF's is performed to attribute the flavors to the incoming quarks and sign of \( \theta \).

The probability \( p_{\tau}^Z \) is calculated as a weighted average over all possible initial state quark configurations. This solution is only implemented for the case of proton-proton (\( pp \)) collisions. For other types of collision events the functionality of Tau\( \text{Spinner} \) for \( Z/\gamma^* \to \tau^- \tau^+ \) process is restricted to longitudinal spin correlation only (\( p_{\tau}^Z = 0.5 \)).

Note that the calculation of the momentum fractions \( x_1 \) and \( x_2 \) is performed within a collinear approximation where the initial state radiation quarks and gluons are assumed to have no transverse momentum. Furthermore the final state radiation photons are taken into account at collinear level only: they are omitted from the boson decay vertex. Any deviation from the energy-momentum conservation in the boson decay vertex is attributed to the presence of the photons. As shown in Sec. 3 these approximations have practically no impact on the implemented spin effects.

### 2.1 Calculation of the spin weight

The outcome of running the Tau\( \text{Spinner} \) program is a spin weight attributed to each event separately. In the \( \tau^\pm\nu \) final state, for any decay of a polarized tau, the spin weight is defined as [2 3 4]:

\[ \text{In Sec. 3 this angle is referred to as } \theta^* \text{ is taken [10]} \]
Table 1: Probability for the configuration of the longitudinal polarization of taus from different origins [5].

| Origin | \( P_{\tau_1} \) | \( P_{\tau_2} \) | Probability |
|--------|-----------------|-----------------|-------------|
| Neutral Higgs bosons: \( H \) | +1 | –1 | 0.5 |
| | –1 | +1 | 0.5 |
| Neutral vector boson: \( Z/\gamma^* \) | +1 | +1 | \( p_Z^2 \) |
| | –1 | –1 | 1 – \( p_Z^2 \) |
| Charged Higgs: \( H^\pm \) | +1 | – | 1.0 |
| Charged vector boson: \( W^\pm \) | –1 | – | 1.0 |

\[ w_T = 1 + s \cdot h \] (3)

where \( s \) is the tau polarization vector, and \( h \) is the polarimetric vector constructed using hadronic currents. In our \( W^\pm \) and \( H^\pm \) decays the exact expression reduces to:

\[ w_T = 1 + \text{sign} \ h_z \] (4)

where \( \text{sign} \) equals one for left-handed taus from \( W^\pm \) bosons and minus one for right-handed taus from the charged Higgs boson. \( h_z \) is the \( z \) component of the polarimetric vector.

In the \( \tau^- \tau^+ \) final state, the weight is defined as [2, 3, 4]:

\[ w_T = R_{ij} h^i h^j \] (5)

where \( R_{ij} \) is a matrix describing the full spin correlation between the two taus as well as the individual spin states of the taus. \( h^i \) and \( h^j \) are the time (\( t \)) and space (\( x, y, z \)) components of the two taus’ polarimetric vectors. The \( t \) component of \( h \) and \( R_{tt} \) are by convention set to 1.

Neglecting the transverse spin degree, and in the ultrarelativistic limit, for \( Z/\gamma^* \to \tau^- \tau^+ \) events the expression reduces to:

\[ w_T = 1 + \text{sign} \ h_z + h_z - P_{\tau} h_z + P_{\tau} h_z \] (6)

where \( P_{\tau} \) denotes the polarization of the single tau in a mixed quantum state. Within this approximation, \( P_{\tau} \) is a linear function of the probability \( p_Z^2 \):

\[ P_{\tau} = 2p_Z^2 - 1. \] (7)

In an event of a neutral and spin zero Higgs boson decaying to \( \tau^- \tau^+ \), the expression simplifies to:

\[ w_T = 1 + \text{sign} \ h_z h_z \] (8)

The \( \text{sign} \) equals one for the \( Z/\gamma^* \) boson and minus one for the neutral Higgs boson, reflecting the opposite spin correlations in the two samples.

Each tau decay channel requires a distinct method to calculate the polarimetric vector [6]. The tau decay modes implemented in TauSpinner are listed in Tab. [2]. For the remaining channels, involving five pions in the final state and multi-prong decays with kaons, the effect of tau polarization is neglected and \( h_z \) is set to zero.

2.2 Application of the spin weight

The event weight can be used at the analysis level for:

Simulating tau spin effects e.g., in a sample generated without spin effects. The event weight equals \( w_T \). It takes values between (0,2), except for the case of \( Z/\gamma^* \to \tau^- \tau^+ \) when the range is (0,4).
Table 2: Summary of tau decay modes implemented in the TauSpinner. Branching fraction is given for each decay mode [11].

| Tau decay mode          | Branching fraction % |
|-------------------------|----------------------|
| $e^- \bar{\nu}_e \nu_\tau$ | 17.85                |
| $\mu^- \bar{\nu}_\mu \nu_\tau$ | 17.36                |
| $\pi^- \nu$             | 10.91                |
| $\pi^- \pi^0 \nu$       | 25.51                |
| $\pi^- \pi^0 \pi^0 \nu$, $\pi^- \pi^+ \pi^- \nu$ | 9.29, 9.03 (incl. $\omega$) |
| $K^- \nu$               | 0.70                 |
| $K^- \pi^0 \nu$, $\pi^- K^0 \nu$ | 0.43, 0.84          |
| $\pi^- \pi^+ \pi^- \pi^0 \nu$ | 4.54 (incl. $\omega$) |
| $\pi^- \pi^0 \pi^0 \pi^0 \nu$ | 1.04                 |
| Other                   | 2.5                  |

Removing tau spin effects from a sample generated with spin effects. The event weight equals $1/w_T$. Then, it is greater than zero with no upper limit.

Reverting tau spin effects in a sample generated with certain longitudinal tau polarization (and/or correlations) to the different one. The weight equals $(2-w_T)/w_T$ for the $\tau^\pm \nu$ final state corresponding to the $W^\pm \rightarrow H^\pm$ or $H^\pm \rightarrow W^\pm$ replacement, and $w_T(H)/w_T(Z/\gamma')$ or $w_T(Z/\gamma')/w_T(H)$ for the $\tau^- \tau^+$ final state corresponding to $Z/\gamma' \rightarrow H$ or $H \rightarrow Z/\gamma'$ replacement. It is greater than zero without an upper limit.

2.3 Attributing tau helicity states in the $Z/\gamma' \rightarrow \tau^- \tau^+$ decays

The helicity states of the taus are attributed stochastically by comparing a random number with the probability, $p_Z \tau_w T(p_Z \tau_w T = 1)/w_T$, of the right-handed configuration to occur. This method is valid for events generated with spin effects or emulated using the spin weight provided by the TauSpinner. An average over all possible initial state configuration is taken. Presentation of the method principle can be found in Ref. [6].

3 Performance of the TauSpinner algorithm

The performance of the TauSpinner algorithm is studied based on the MC simulated $Z/\gamma' \rightarrow \tau^- \tau^+$ and $W^\pm \rightarrow \tau^\pm \nu$ events. The samples were generated using the general purpose event generator Pythia [12] assuming the $pp$ collision at center of mass energy of 7 TeV. The taus were then made to decay using the Tauola package. Two sets of events were simulated:

No spin effects. In these events the taus were decayed by Tauola as if they had been produced with no polarization. They were used for emulation of spin effects later, with the TauSpinner package.

Tauola. In these events tau spin effects were properly accounted for at the time of tau event generation and decay.

Event generation and simulation of the spin effects in the TauSpinner were performed with the modified LO parton distribution function (PDF) MRSTLO* [13].

3.1 Simulation of the tau polarization in $\tau^\pm \nu$ final state

For all tau decay modes, the main observables that are sensitive to the tau polarization are the tau momentum fraction taken by the hadronic system [14], $x$, and the relative difference between the charge and
the neutral energy in the tau decay, $\Upsilon$.\cite{15}.

Plots a)–c) in Figure 1 demonstrates the performance of TauSpinner for the channels where the tau polarization is extremal. The observable $x$ is plotted in Fig. 1(a) for the combined $\pi^-\nu$ and $K^-\nu$ channels. The observable $Y$ is plotted in Fig. 1(b) and 1(c) for the $\pi^+\pi^0\nu$ and combined $\pi^-\pi^0\pi^0\nu$ and $\pi^-\pi^+\pi^+\nu$ channels, respectively. The sample with no spin effects refers to $W^{\pm} \rightarrow \tau^\pm\nu$ events generated with flat $P_\tau$ value. The $H \rightarrow \tau^\pm\nu$ and $W^{\pm} \rightarrow \tau^\pm\nu$ configurations were obtained by applying an appropriate spin weight to the sample with no spin effects. The weighted observables exhibit the expected behavior indicating a proper implementation of the $P_\tau$ in the TauSpinner package.

Note that the TauSpinner algorithm requires that the decays of unpolarized taus via $\rho$ or $a_1$ preserve the spin correlation between the production and decay of these mesons. This feature is missing if the taus are made to decay using Pythia 6.425. Although a bulk of spin effects are reconstructed, a significant systematic uncertainty arises as demonstrated in Fig. 1(d).

\subsection{Simulation of tau polarization in $Z/\gamma^* \rightarrow \tau^-\tau^+$ events}

In $Z/\gamma^* \rightarrow \tau^-\tau^+$ events, the single tau polarization $P_\tau$ depends on the intermediate boson virtuality, the flavor of the incoming quark and the scattering angle. The complexity of this dependence is shown in Fig. 2 where the tau polarization is drawn as a function of $\cos \theta$, for two different ranges of the invariant mass of the boson. In these plots, the quark flavor configuration is fixed at the level of simulation of the spin weight in the TauSpinner.

In the next step, a degree of polarization is studied for different configurations of the incoming quarks.
The virtuality of the intermediate boson is constrained to lie within ±3 GeV of the $Z$ boson mass and both taus are set to decay to $\pi^\pm \nu$ or $K^\pm \nu$. The forward-backward spin asymmetry is accessed by choosing the $\tau^-$ to be emitted in the forward region by requiring the longitudinal momentum of $\tau^-$ to be greater than that of $\tau^+$. Figure 3 shows the observable $x$ for the up and down type quarks entering along the positive or negative $z$ axis. The results are consistent with those of reference [5], and therefore reassure a proper transmission of spin effects from the hard process to the tau decay products.

In the last step, the degree of polarization is studied inclusively for all initial state quark configurations and the results are compared to those simulated using the Tauola package. The $Z/\gamma^*$ virtuality is constrained to lie within ±3 GeV of the $Z$ boson mass. The fraction of the tau momentum taken by the hadron in the $\pi^\pm \nu$ channel is plotted in Fig. 4. Expecting the $Z$ boson to be emitted in the direction of the incoming quark (as compared to the direction of the anti-quark from the sea) these plots can be compared to those in Fig. 3.

Figure 5 shows the fraction of the tau momentum taken by the hadron in the combined $\pi^\pm \nu$ and $K^\pm \nu$ channels for the left-handed and the right-handed taus from the $Z/\gamma^* \to \tau^\pm \tau^\mp$ decays. Helicity states are attributed by the TauSpinner in the sample without and with spin effects simulated at the generation level. The distributions exhibit the expected shapes for properly attributed pure helicity states.
Fig. 4: Fraction of the tau momentum taken by the hadron in the $\pi^- \nu$ channel. Taus with negative charge emitted in the forward hemisphere are chosen.

Fig. 5: Fraction of the tau momentum taken by the hadron in the combined $\pi^- \nu$ and $K^- \nu$ channels. $\tau_R$ and $\tau_L$ denote right-handed and left-handed taus, respectively.
The intrinsic tau polarization arising from parity violation in the weak interactions is attributed on the basis of intermediate \(d\) and \(d\) boson kinematics and PDF’s. For the first algorithm suitable for emulating the spin effects in the tau-embedded samples. The intrinsic tau when the information on the incoming quarks entering the hard process is not available. This is therefore limited to the leading order accuracy and the longitudinal spin degrees only. As compared to the algorithm developed in Ref. [5], the functionality is extended to allow one to estimate the spin effects is restricted to the longitudinal spin degrees, the frame-

\[\text{TauSpinner}\]

4 Summary and outlook

The \text{TauSpinner} package designed to emulate tau spin effects has been introduced. The algorithm is limited to the leading order accuracy and the longitudinal spin degrees only. As compared to the algorithm developed in Ref. [5], the functionality is extended to allow one to estimate the spin effects when the information on the incoming quarks entering the hard process is not available. This is therefore the first algorithm suitable for emulating the spin effects in the tau-embedded samples. The intrinsic tau polarization arising from parity violation in the weak interactions is attributed on the basis of intermediate boson kinematics and PDF’s. For the \(Z/\gamma^* \rightarrow \tau^-\tau^+\) process its complete functionality is limited to \(pp\) collisions and otherwise restricted to conservation of total angular momentum.

Comparisons of \text{Tauola} and \text{TauSpinner} for various spin observables presented in Sec. 3 demonstrate that no additional systematic uncertainty in simulation of tau spin effects has been introduced in the \text{TauSpinner}. This claim should, however, be validated in a sample where the number of high transverse momentum jets is enhanced.

A complete discussion of the theoretical uncertainties is common for the \text{Tauola}, the \text{TauSpinner} and, to a large extent the KORALZ \[8\] MC programs. Some aspects of these uncertainties have been addressed through the work published in Refs. \[2, 3, 4, 7, 9, 16\]. A rigorous evaluation of theoretical effects and in particular a comparison with results based on the next-to-leading order matrix element calculations simultaneous for scattering processes and for spin density matrices is referred to a future work.

Although the current version of the \text{TauSpinner} is restricted to the longitudinal spin degrees, the framework is prepared to simulate the complete spin effects. This extension is planned for the future version of the algorithm. The code of \text{TauSpinner} is publicly available, with all relevant details given in App.
A and B.

5 Acknowledgements

We would like to thank A. Buckley, S. Demers, C. Gwenlan, E. Richter-Was and S. Tsuno for valuable discussions.

References

[1] ATLAS Collaboration, Phys. Lett. B 705, 174 (2011).
[2] S. Jadach et al., Comput. Phys. Commun. 64, 275 (1990).
[3] M. Jezabek, et al., Comput. Phys. Commun. 70, 69 (1992).
[4] R. Decker, et al., Comput. Phys. Commun. 76, 361 (1993).
[5] T.P. et al., Acta Phys. Pol. B 32, 1277 (2001).
[6] N.D. et al., arXiv:1002.0543 (2010).
[7] S. Jadach and Z. Was, Comput.Phys.Commun. 36, 191 (1985).
[8] S. Jadach, B. Ward and Z. Was, Comput.Phys.Commun. 79, 503 (1994).
[9] S. Jadach, B. Ward and Z. Was, Comput.Phys.Commun. 130, 260 (2000).
[10] Z. Was and S. Jadach, Phys. Rev. D 41, 1425 (1990).
[11] K. Nakamura et al., J. Phys. G 37, 260 (2010).
[12] T. Sjostrand, Comput. Phys. Commun. 82, 74 (1994).
[13] A. Sherstnev, R.S. Thorne, Eur. Phys. J. C Part. Fields 55, 553 (2008).
[14] K. Hagiwara, A.D. Martin, D. Zeppenfeld, Phys. Lett. B 235, 198 (1990).
[15] ATLAS Collaboration, ATLAS-CONF-2012-009 (2012).
[16] A. van Hameren and Z. Was, Eur. Phys. J. C 61, 33 (2009).
[17] Z. Czyzula, T. Przedzinski, Z. Was ,
    http://wasm.web.cern.ch/wasm/Welcome.html
    http://hibiscus.if.uj.edu.pl/~przedzinski/tau-reweight
[18] M.R. Whalley, D. Bourilkov and R.C. Group, arXiv:hep-ph/0508110 (2005).
[19] M. Dobbs and J.B. Hansen, Comput. Phys. Commun. 134, 41 (2001).
A Requirements for data files

Data files generated by a MC event generator (or constructed using the tau-embedding method) need to fulfill the following requirements:

1. Four-momenta of the intermediate boson, the taus and the flavor and the four-momenta of the tau decay products need to be available.
2. Flavor of the intermediate boson needs to be available or set by the user.
3. For all types of hard processes, but $Z/\gamma^{*} \rightarrow \tau^{-}\tau^{+}$, the four-momenta can be defined in an arbitrary but common frame. For the $Z/\gamma^{*} \rightarrow \tau^{-}\tau^{+}$ process, the four-momenta have to be given in the laboratory frame in order to be consistent with the PDFs.
4. The four-momenta of the taus and their decay products need to be known with sufficient precision in order to ensure numerical stability of the algorithm. Six significant digits are recommended.

Note that different MC generators may store the truth information in different ways. It is the responsibility of a user to make sure that all these requirements are fulfilled.

B Public version

A generic version of the package can be found in [17]. The main code is written in C++ and relies upon two libraries: Tauola and LHAPDF [18]. A method for reading input information stored using the HepMC [19] format is prepared. Support for any other input format is available upon request.

B.1 Project organization

The TauSpinner package is organized in the following manner:

- src/tau_reweight_lib.c, src/tau_reweight_lib.h - the core of the algorithm.
- src/Tauola_wrapper.h - wrapper for TAUOLA FORTRAN routines.
- src/SimpleParticle.h - definition of class SimpleParticle used as a bridge between the event record (or data file) and the algorithm.
- src/Particle.h - definition of class Particle used for boosting and rotation of the particles.
- src/read_particles_from_TAUOLA.c, src/read_particles_from_TAUOLA.h - interface to the HepMC::IO::GenEvent data files used by the example program.
- README - a short manual.

B.2 The algorithm sequence

The TauSpinner takes the following sequence of steps:

Initialization of Tauola. It is ensured by invoking:

```
Tauc::initialize();
```

Initialization of TauSpinner. It is performed by executing:

```
void initialize_spinner(bool Ipp, int Ipol, double CMSENE)
```

where the argument Ipp passes the information on the type of collision events (Ipp = true sets
In $pp$ collisions, $Ipol$ passes the information on the spin effects included in the input sample ($Ipol=0, 1, 2$ corresponds to no spin effects, complete spin effects and spin correlations only, respectively) and $CMSENE$ sets the collision center of mass energy.

**Reading the data files.** Information on the four-momenta and the flavor of the boson, the final state taus or tau and neutrino pair and the tau decay products is filled and stored in instances of `SimpleParticle` class by the use of the function:

```cpp
void readParticlesFromTAUOLA_HepMC(HepMC::IO::GenEvent &input_file, SimpleParticle &boson,
SimpleParticle &tau, SimpleParticle &tau2, vector<SimpleParticle> &tau_daughters,
vector<SimpleParticle> &tau2_daughters);
```

This function should be modified if the input files are not in the `HepMC::IO::GenEvent` format.

**Calculation of the spin weight.** It is performed by the use of the following functions:

```cpp
double calculateWeightFromParticlesWorHpn(SimpleParticle &boson, SimpleParticle &tau,
SimpleParticle &tau2, vector<SimpleParticle> &tau_daughters) for the $W^\pm \rightarrow \tau^\pm \nu$ and $H \rightarrow \tau^- \tau^+$ processes
double calculateWeightFromParticlesH(SimpleParticle &boson, SimpleParticle &tau,
SimpleParticle &tau2, vector<SimpleParticle> &tau_daughters,
vector<SimpleParticle> &tau2_daughters) for the $Z/\gamma^* \rightarrow \tau^- \tau^+$ and $H \rightarrow \tau^- \tau^+$ processes.
```

**Attributing tau helicity states.** For $Z/\gamma^* \rightarrow \tau^- \tau^+$ process, the tau helicity states are attributed at the stage of calculation of the spin weight. The information can obtained by calling `getTauSpin()` function.

**B.3 Calculation of the spin weight**

For the $\tau^\pm \nu$ final states, the spin weight is calculated in the following steps:

1. The parent boson, the tau, the tau neutrino and the list of tau daughters are identified and boosted to the $\tau^\pm \nu$ rest frame in which the tau is aligned along the $z$ axis.
2. The tau daughters are boosted to the tau rest frame. Two angles of spacial orientation of the neutrino from the tau decay, $\theta2$ and $\phi2$, are calculated and stored. The tau daughters are rotated by these angles in order to align the neutrino along the $z$ axis.
3. The Tauola decay channel is identified.
4. The Tauola FORTRAN subroutine is called to perform calculation of the polarimetric vector $h$.
5. The polarimetric vector $h$ is rotated back using the $\theta2$ and $\phi2$ angles.
6. The spin weight is calculated using eq. [4] and returned to the main program.

For the $\tau^- \tau^+$ final states, the spin weight is calculated in the following steps:

1. The parent boson, the taus and their tau daughters are identified and boosted to the $\tau^- \tau^+$ rest frame in which the taus are aligned along the $z$ axis.
2. For each tau:
   Its identified daughters are boosted to its rest frame. Two angles of spacial orientation of the neutrino from the tau decay, $\theta_2$ and $\phi_2$, are calculated and stored. The tau daughters are rotated by these angles to align the neutrino along the $z$ axis.
   The Tauola decay channel is identified.
   The Tauola FORTRAN subroutine is called to perform calculation of the polarimetric vector $h$.
   The polarimetric vector $h$ is rotated back using the $\theta_2$ and $\phi_2$ angles.

3. In case of the $Z/\gamma^* \rightarrow \tau^- \tau^+$ decays:
   The probability $p_Z^\tau$ is calculated using eqs 1-2.
   The spin weight is calculated using eq. 6 and returned to the main program.

4. In case of the $H \rightarrow \tau^- \tau^+$ decays:
   The spin weight is calculated using eq. 8 and returned to the main program.

B.4 The LHAPDF library wrapper

The evolution of the PDF’s is invoked from the wrapper for PDF’s:

```c
double f(double x, int ID, double SS, double cmsene)
```

where function $f$ calls the evolution function $x_f f(x, SS, ID)$ [13]. The PDF sets need to be available locally. They can be obtained from the LHAPDF project website.