Universal Spin Interface for TAUOLA Package

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Goals :

- **Presentation of the algorithm for matching τ lepton decay and its production, with some control over spin effects in the case of $Z/\gamma \to \tau^+\tau^-$ production mechanism.**
- **The τ polarization from the $Z/\gamma \to \tau^+\tau^-$ decay.**
- **Interface of the TAUOLA τ-lepton decay library with complete spin effects for τ leptons originating from the spin zero particle.**
- **Discussion of physical observables sensitive to the longitudinal and transverse spin correlations in the τ pair production.**
- **Summary and Outlook**

Main References

- “ *Spin Effects In τ Lepton Pair Production at LHC* ”.
  By T. Pierzchała, E. Richter-Wąs, Z. Wąs, M. Worek.
  Published in Acta Phys. Polon. B32, 1277-1296, 2001.
  e-Print Archive: *hep-ph/0101311*.

- “ *Transverse spin effects in $H/A \to \tau^+\tau^-; \tau^\pm \to \nu X^\pm$, Monte Carlo approach* ”.
  By Z. Wąs, M. Worek.
  Published in Acta Phys. Polon. B33, 1875-1884, 2002.
  e-Print Archive: *hep-ph/0202007*.

- “ *Measuring the Higgs boson's parity using $\tau \to \rho\nu$* “.
  By G. R. Bower, T. Pierzchała, Z. Wąs, M. Worek.
  Published in Phys. Lett. B543, 227-234, 2002.
  e-Print Archive: *hep-ph/0204292*.

Universal interface for TAUOLA package

- 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.
- This 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 approximate spin correlation are calculated from the information stored in this HEPEVT common block filled by "any" τ production program.
- As a demonstration example the interface is combined with the PYTHIA generator, however it work in the same manner with the HERWIG generators as well.
- Such an approach is limited for the spin treatment to the longitudinal spin degrees only and to the case of the particles 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. Such an approach is consistent in the case of photons or gluons emission within the leading log approximation.**

The principle of calculating kinematic variables

- **The 4-momenta of the $2 \to 2$ body process have to be found.**
- **The 4-momenta of the outcoming τ's are used directly.**
- **Initial state momenta are constructed from the incoming and outcoming momenta of the particles accompanying production of the Z/γ state.**
- **The Z/γ state does not need to be explicitly coded in the `HEPEVT` common block.**

Some details of the universal interface

- The interface uses as an input, the HEPEVT common block and operates on its content only.
- The τ lepton should be forced to be stable in the package performing generation of the τ production.
- The content of the HEPEVT common block is searched for all τ leptons and τ neutrinos.
- It is checked if there are τ flavour pairs (two τ leptons or τ lepton and τ neutrino) originating from the same mother.
- The decays of the τ flavour pairs are performed with the subroutine TAUOLA.
- Longitudinal spin correlations are generated in the case of the τ produced from decay of: $W \to \tau\nu$, $Z/\gamma \to \tau\tau$, the neutral Higgs boson $H \to \tau\tau$, and the charged Higgs boson $H^{\pm} \to \tau\nu$.

Some details of the universal interface

- **Parallel or anti-parallel spin configurations are generated, before calling on the τ decay, and then the decays of 100 % polarised τ's are executed.**
- **In the case of the Higgs boson (for the spin correlations to be generated) the identifier of the τ mother must be that of the Higgs boson. Here, the particle code convention as that used by the `PYTHIA` Monte Carlo is adopted.**
- **In case of the W and Z/γ it is not necessary. If from the same mother as that of the τ, a ν_τ is also produced, the W is assumed as the mother of the τ. Similarly, if from the same mother another τ with opposite charge is produced, the Z/γ is assumed to be the mother of the τ pair.**
- **The `TAUOLA` interface is organized in a modular form to be used conveniently in "any environments".**

The τ polarization from different origins

Longitudinal polarization of τ leptons $\mathcal{P}_\tau$ depends on the spin quantum number of the τ mother. It is randomly generated as specified in Table 1.

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

Table 1: Probability for the configurations of the longitudinal polarization of the τ leptons.

The τ polarization from $Z/\gamma \to \tau^+\tau^-$ decay

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 $f\bar{f} \to \tau^-\tau^+$:

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

The τ polarization from $Z/\gamma \to \tau^+\tau^-$ decay

It can be also expressed with the help of the couplings of fermions to the γ (and Z) bosons.

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

$$\frac{d\sigma_{Born}}{d\cos\theta}(s,\cos\theta;p) =$$
$$(1+\cos^2\theta)F_0(s)+2\cos\theta F_1(s)-p\big[(1+\cos^2\theta)F_2(s)+2\cos\theta F_3(s)\big]$$

$$F_0(s) = \frac{\pi\alpha^2}{2s}(q_f^2 q_\tau^2+2Re\chi(s)q_f q_\tau v_f v_\tau+|\chi(s)|^2(v_f^2+a_f^2)(v_\tau^2+a_\tau^2))$$
$$F_1(s) = \frac{\pi\alpha^2}{2s}(\quad 2Re\chi(s)q_f q_\tau a_f a_\tau + |\chi(s)|^2 2v_f a_f 2v_\tau a_\tau)$$
$$F_2(s) = \frac{\pi\alpha^2}{2s}(\quad 2Re\chi(s)q_f q_\tau v_f a_\tau + |\chi(s)|^2(v_f^2 + a_f^2)2v_\tau a_\tau)$$
$$F_3(s) = \frac{\pi\alpha^2}{2s}(\quad 2Re\chi(s)q_f q_\tau a_f v_\tau + |\chi(s)|^2 2v_f a_f(v_\tau^2 + a_\tau^2))$$

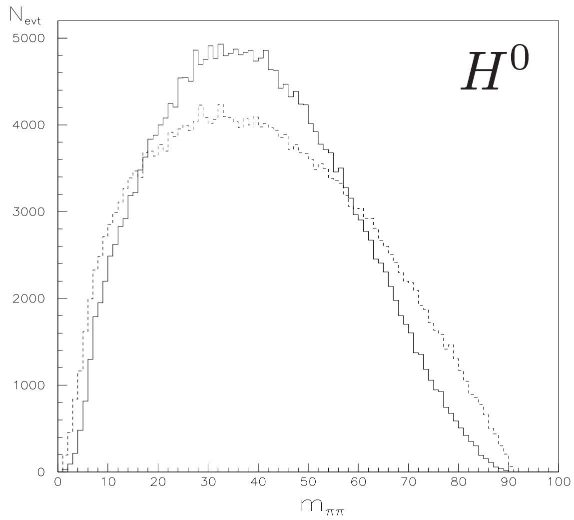
$$\chi(s) = \frac{s}{s-M_Z^2+is\Gamma_Z/M_Z}$$

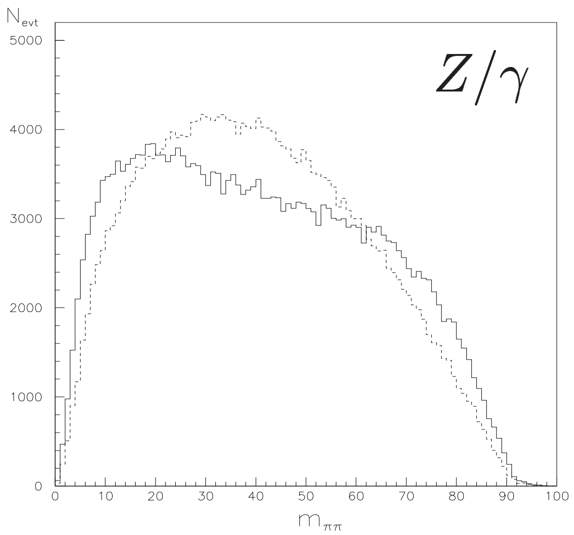
The q_f, v_f, a_f, q_τ, v_τ, a_τ are the charges and Z coupling constans of the fermions and τ respectively.

Identification of the H^0 and Z/γ states

- **The polarization of the τ lepton can be exploited to identify a neutral Higgs bosons via the decay $H^0 \to \tau^+\tau^-$.**
- **The background is $Z/\gamma \to \tau^+\tau^-$ decay.**
- **There exists a simple polarization correlation test which will clearly indicate the presence of τ pairs of Higgs origin among the background $Z/\gamma \to \tau^+\tau^-$ events.**
- **The τ pairs are produced with the well defined spin configurations:**
  $+\ +$ **or** $-\ -$ **for vector bosons**
  $+\ -$ **or** $-\ +$ **for neutral Higgs boson.**
- **The polarization correlation test can be performed using the distributions of the final decay products which are sensitive to the admixture of the H^0 and Z/γ parentage of the τ pairs.**
- **The case of τ decays to $\pi\nu$ is the most sensitive to the spin correlations.**

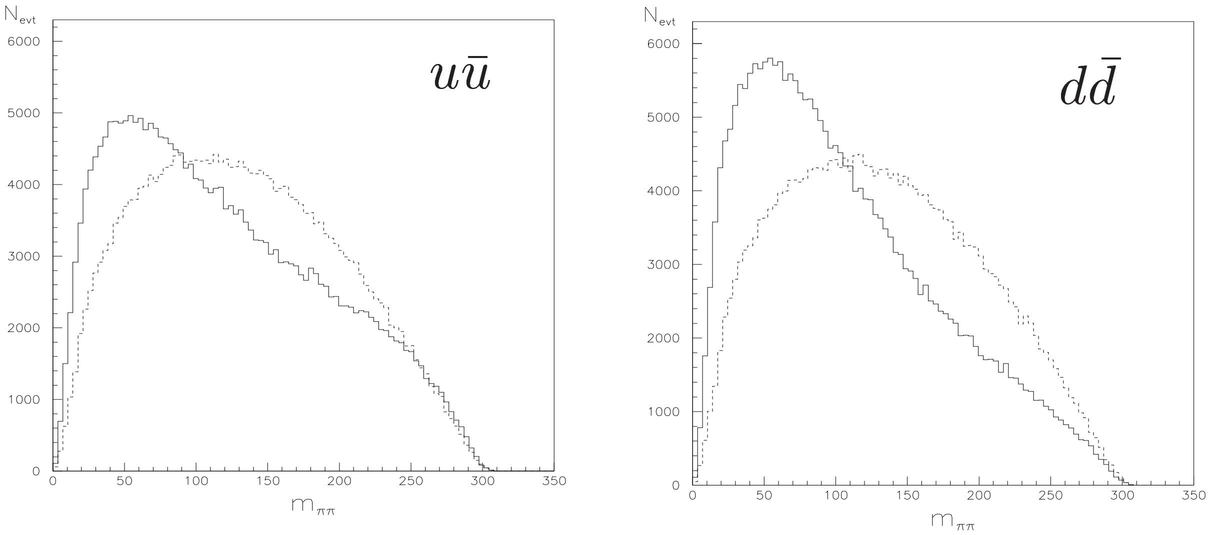
The $\pi^+\pi^-$ invariant mass distribution





- **The $\pi^+\pi^-$ invariant mass distribution for H and for Z/γ state. In the two cases respectively $\sqrt{s} = m_H = m_Z$.**
- **In the case of Higgs boson, the mass distribution is peaked centrally, whereas in the case of Z/γ shoulders of the distributions are more profound.**
- **If all polarization effects are switched off (dashed lines) the distributions in the two cases are identical.**
- **The 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 $\pi^+\pi^-$ invariant mass distribution



- **The $\pi^+\pi^-$ invariant mass distribution for $u\bar{u} \to Z/\gamma$ and $d\bar{d} \to Z/\gamma$ produced with cms energy of 300 GeV.**
- **The average polarization increases above the Z-peak and approaches respectively -35% and -61% in the case of $u\bar{u}$ and $d\bar{d}$ annihilation.**
- **This may open the way for measuring the flavour of the quarks leading to τ pair production.**
- **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 the colliding protons.**

Transverse spin effects

- **The transverse spin effects are helpful to distinguish between scalar $(J^{PC} = 0^{++})$ or pseudoscalar $(J^{PC} = 0^{-+})$ 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 $H/A \to \tau^{+}\tau^{-}$; $\tau^{\pm} \to \nu X^{\pm}$.**
- **An appropriate Monte Carlo program is essential to make such study.**
- **We have extended the standard universal interface, of the $\mathtt{TAUOLA}$ 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.**

Transverse spin effects

- **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 $e^+e^- \to Z/\gamma \to \tau^+\tau^-$, 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 used by practically all Monte Carlo generators for Higgs boson production.**

Higgs boson's parity

- H/A parity information can be extracted from the correlations between τ^+ and τ^- spin components which are further reflected in correlations between the τ decay products in the plane transverse to the $\tau^+\tau^-$ axes.
- The decay probability

$$\Gamma(H/A \to \tau^+\tau^-) \sim 1 - s_{\parallel}^{\tau^+} s_{\parallel}^{\tau^-} \pm s_{\perp}^{\tau^+} s_{\perp}^{\tau^-}$$

is sensitive to the $\tau^\pm$ polarization vectors s^{τ^-} and s^{τ^+} (defined in their respective rest frames). The symbols $\parallel$,$\perp$ denote components parallel/transverse to the Higgs boson momentum as seen from the respective $\tau^\pm$ rest frames.
- This suggests that the experimentally clean $\tau^+\tau^-$ final state may be the proper instrument to study the parity of the Higgs boson.

The algorithm

- The algorithm is organized in two steps. In the first step, the τ lepton pair is generated and the τ leptons are decayed in their respective rest frames as if there were no spin effects at all.
- In the second step, the spin weight is calculated and rejection is performed.
- If the event is rejected, only the generation of the τ lepton decays is repeated.
- The spin weight is given by the following formula

$$wt = \frac{1}{4}\Big(1 + \sum_{i,j=1,3} R_{ij} h^i h^j\Big)$$

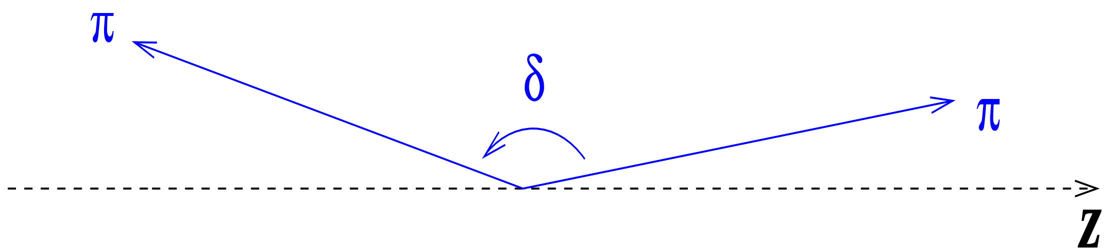
where the components

$$R_{33} = -1, \quad R_{11} = \pm 1, \quad R_{22} = \pm 1$$

respectively for scalar and pseudoscalar Higgs boson and all other components are zero.

$\tau^\pm \to \pi^\pm \bar{\nu}_\tau (\nu_\tau)$ decay

- **Branching ratio 11%.**
- **Sensitivity to the parity of the Higgs is reflected in angular correlations of secondary decay products.**
- **The polarimeter vector in the τ rest frame is given by the formula $\vec{h} = -\vec{n}_\pi$ where $\vec{n}$ denotes the unit vector into the direction of flight of the pion.**

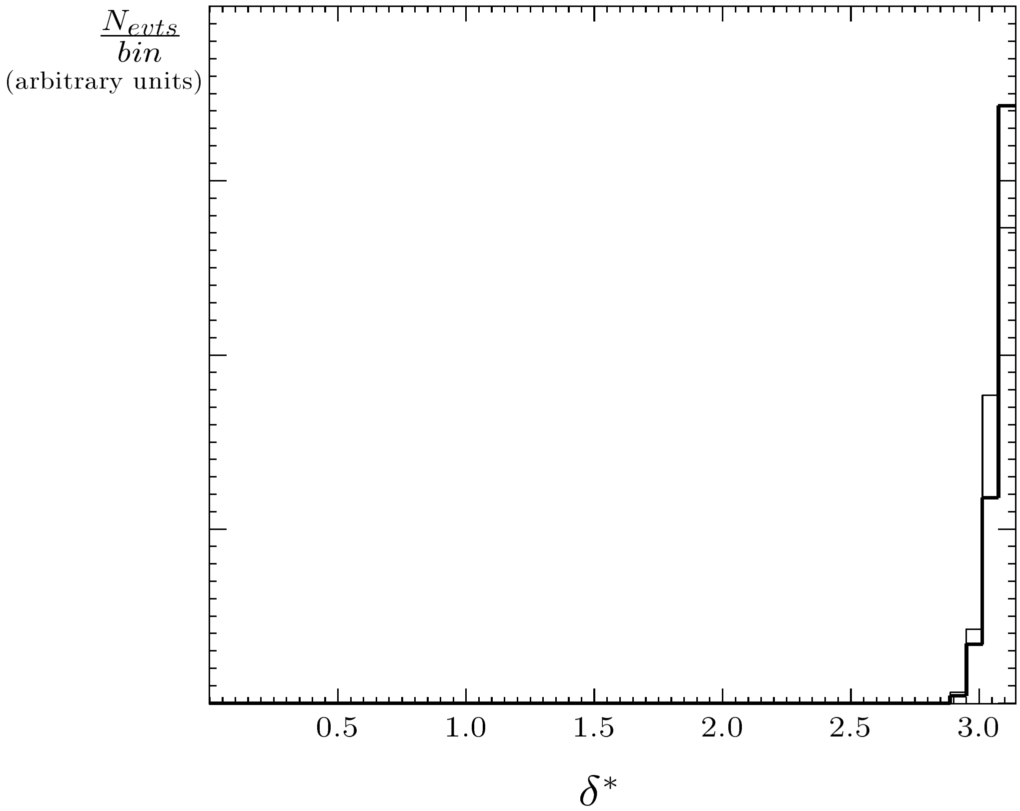


- **Useful observable is the angle δ between the two charged pions in the Higgs rest frame (acollinearity distribution of $\pi^+\pi^-$ from $\tau^\pm$ decays).**

Monte Carlo set up

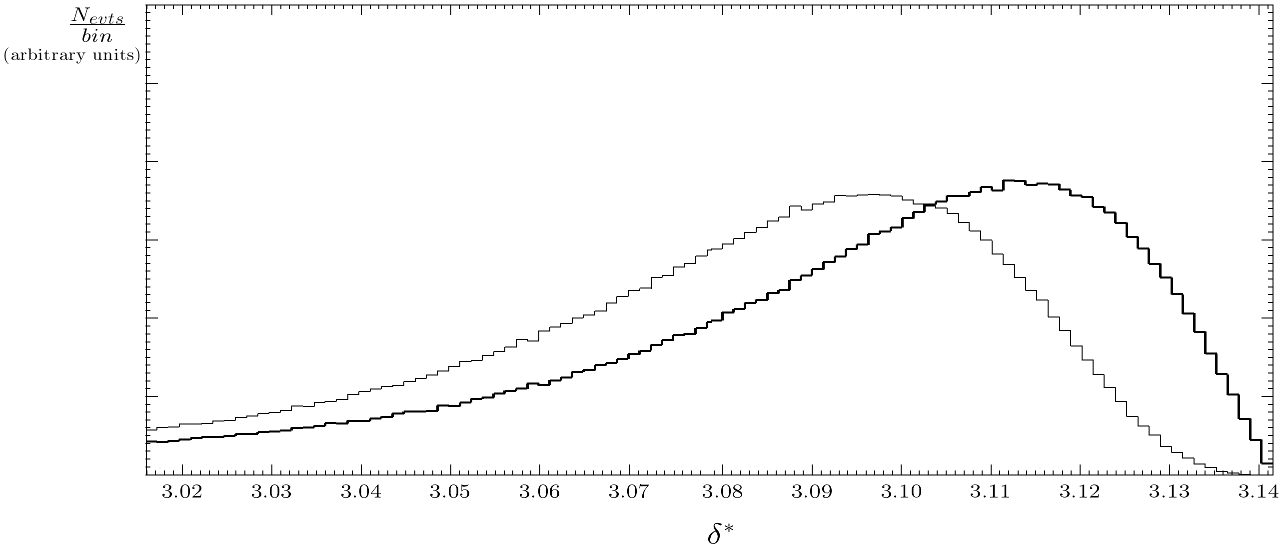
- All the Monte Carlo samples have been generated with TAUOLA – a library of Monte Carlo programs to simulate decays of τ leptons.
- For the production of the τ lepton pairs the Monte Carlo program PYTHIA 6.1 is used.
- The production process $e^+e^- \to ZH \to \mu^+\mu^- H$ has been chosen with a Higgs boson mass of $120\ GeV$ and a center-of-mass energy of $500\ GeV$.
- The effects of initial state bremsstrahlung were included in the PYTHIA generation.
- For the τ lepton pair decay with full spin effects included in the $H \to \tau^+\tau^-$, $\tau^\pm \to \pi^\pm \bar{\nu}_\tau(\nu_\tau)$, $\tau^\pm \to \pi^\pm \pi^0 \bar{\nu}_\tau(\nu_\tau)$ chains, our interface was used.

$\pi^+\pi^-$ acollinearity distribution



- **The $\pi^+\pi^-$ acollinearity distribution 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.**

$\pi^+\pi^-$ acollinearity distribution



- The $\pi^+\pi^-$ acollinearity distribution 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.

$\tau^\pm \to \rho^\pm \bar{\nu}_\tau(\nu_\tau)$ decay

- Branching ratio 25%.
- In comparison to $\tau^\pm \to \pi^\pm \bar{\nu}_\tau(\nu_\tau)$ decay, its polarimeter force is more than a factor of 2 smaller but in many cases this can be improved if the information on the ρ decay products are used.
- The polarimeter vector is given by the formula

$$h^i = \mathcal{N}\Big(2(q\cdot N)q^i - q^2 N^i\Big)$$

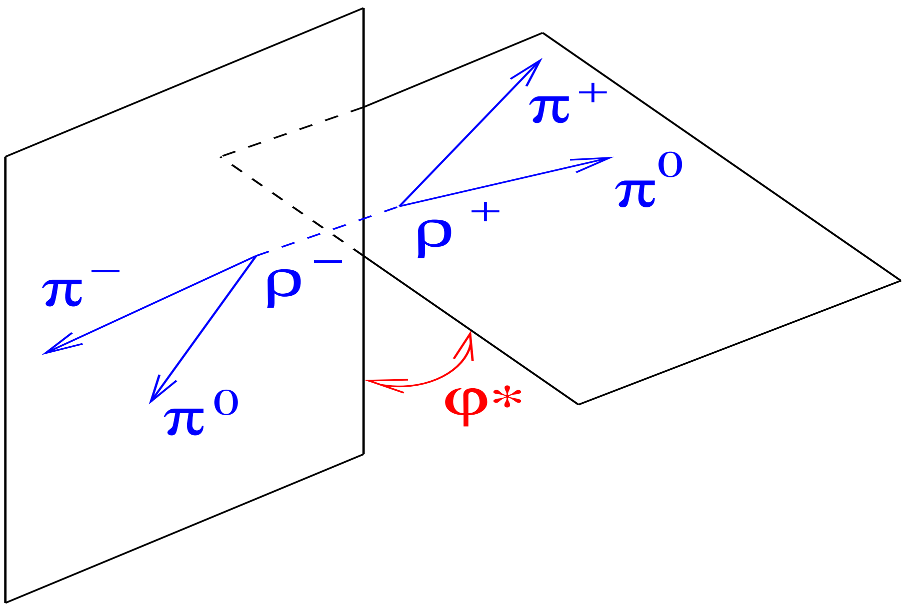
where q is the four-momentum of $\pi^\pm - \pi^0$ and N is the four-momentum of ν_τ.

- In the τ lepton rest frame, when $m_{\pi^\pm} = m_{\pi^0}$ is assumed we have

$$q \cdot N = (E_{\pi^\pm} - E_{\pi^0})m_\tau.$$

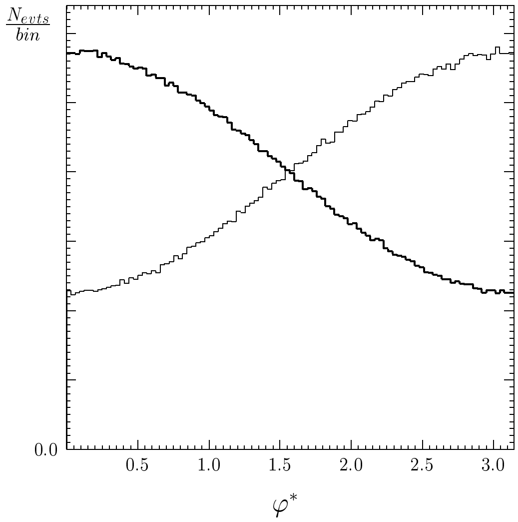
- To exploit this part of the polarimeter vector, we need to have some handle on the difference of the $\pi^\pm$ and π^0 energies in their respective τ leptons rest frames.

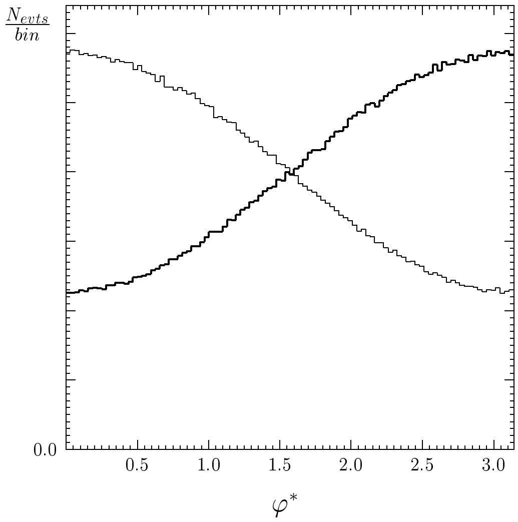
Acoplanarity of the ρ^+ and ρ^- decay products



- In the Higgs rest frame the ρ momentum represents a larger fraction of the Higgs's energy than the neutrino.
- Instead of the reconstruction of the Higgs boson rest frame we use the $\rho^+\rho^-$ rest frame which has the advantage that it is built only from directly visible decay products of the ρ^+ and ρ^-.
- In the rest frame of the $\rho^+\rho^-$ system we define the acoplanarity angle, φ^*, between the two planes spanned by the immediate decay products of the two ρ's - the $\pi^\pm$ and π^0.

Results





- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Selection $(E_{\pi^+} - E_{\pi^0})(E_{\pi^-} - E_{\pi^0}) > 0$ is used in the left plot and the opposite sign selection $(E_{\pi^+} - E_{\pi^0})(E_{\pi^-} - E_{\pi^0}) < 0$ is used for the right plot. No smearing is done. Thick lines denote the case of the scalar Higgs boson and thin lines the pseudoscalar one.**

Summary and Outlook

- The algorithm for the interfacing of the τ lepton decay package TAUOLA with “any” production generator including spin effects in the elementary $Z/\gamma \to \tau^+\tau^-$ process is available.
- The interface is based on the information stored in the HEPEVT common block only.
- The invariant mass distributions sensitive to the longitudinal $\tau^+\tau^-$ spin correlations, can be possibly 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.
- The interface of the TAUOLA τ-lepton decay library with complete spin effects for τ leptons originating from the spin zero particle is also available.
- The transverse spin effects are helpful to distinguish between scalar or pseudoscalar nature of the spin zero Higgs particle at future LC.