TAUOLA Universal Interface — general principle and standard benchmark distribution

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T. Pierzchała, E. Richter-Wąs, Z. Wąs, MW, Acta Phys. Pol. B32, 1277 (2001)

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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 $Z/\gamma^* \to \tau^+\tau^-$.
- The τ polarisation from the $Z/\gamma^* \to \tau^+\tau^-$ decay.
- Observables sensitive to the spin correlations in the τ pair production.
- Case of the neutral Higgs boson signatures at LHC.
- Summary and Outlook.

Universal interface for TAUOLA package

- The aim of this interface is to provide a method of calculating/estimating spin effects in cases when spin effects would not be taken care of at all.
- 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 JETSET generator, however it works also with the PYTHIA or HERWIG.
- 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 two body process $f\bar{f} \to (Z/\gamma) \to \tau^+\tau^-$, buried inside multi-body production process such as for example $f\bar{f} \to gZ$, $f\bar{f} \to \gamma Z$, $fg \to fZ$, $f\gamma \to fZ$. Additional particles are grouped/summed into effective quarks and leptons.

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.
- Information from the history part of the event, where the 4-momenta of gluons, quarks are stored, can be used.

τ polarisation from different origins

- Longitudinal polarisation 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 polarisation of the τ leptons.

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

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

τ polarisation 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.

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

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

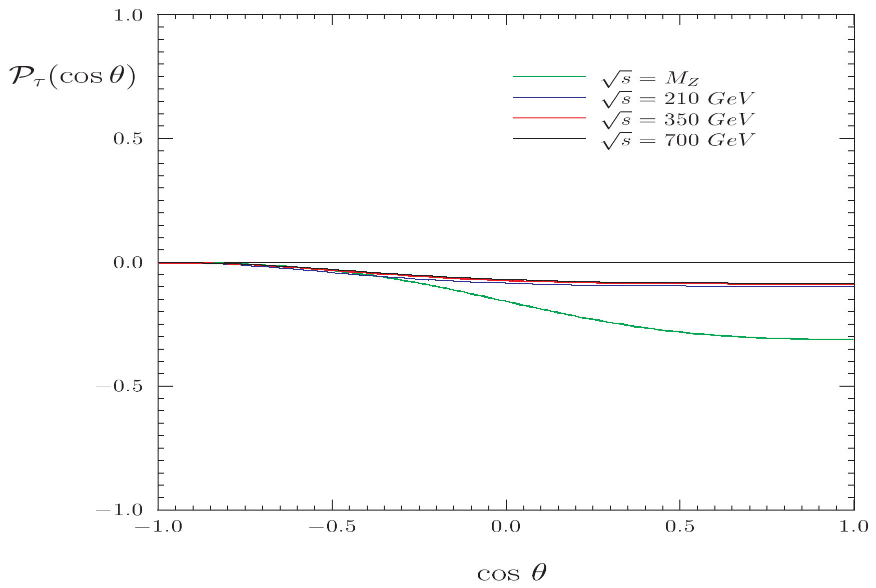
$$\begin{aligned}
F_0(s) &= \tfrac{\pi\alpha^2}{2s}(q_f^2 q_\tau^2 + 2Re\chi(s)q_f q_\tau v_f v_\tau + |\chi(s)|^2(v_f^2+a_f^2)(v_\tau^2+a_\tau^2))\\
F_1(s) &= \tfrac{\pi\alpha^2}{2s}(\qquad 2Re\chi(s)q_f q_\tau a_f a_\tau + |\chi(s)|^2 2v_f a_f 2v_\tau a_\tau)\\
F_2(s) &= \tfrac{\pi\alpha^2}{2s}(\qquad 2Re\chi(s)q_f q_\tau v_f a_\tau + |\chi(s)|^2(v_f^2+a_f^2)2v_\tau a_\tau)\\
F_3(s) &= \tfrac{\pi\alpha^2}{2s}(\qquad 2Re\chi(s)q_f q_\tau a_f v_\tau + |\chi(s)|^2 2v_f a_f(v_\tau^2+a_\tau^2))
\end{aligned}$$

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

- The $q_f, v_f, a_f, q_\tau, v_\tau, a_\tau$ are the charges and Z coupling constants of the fermions and τ respectively.

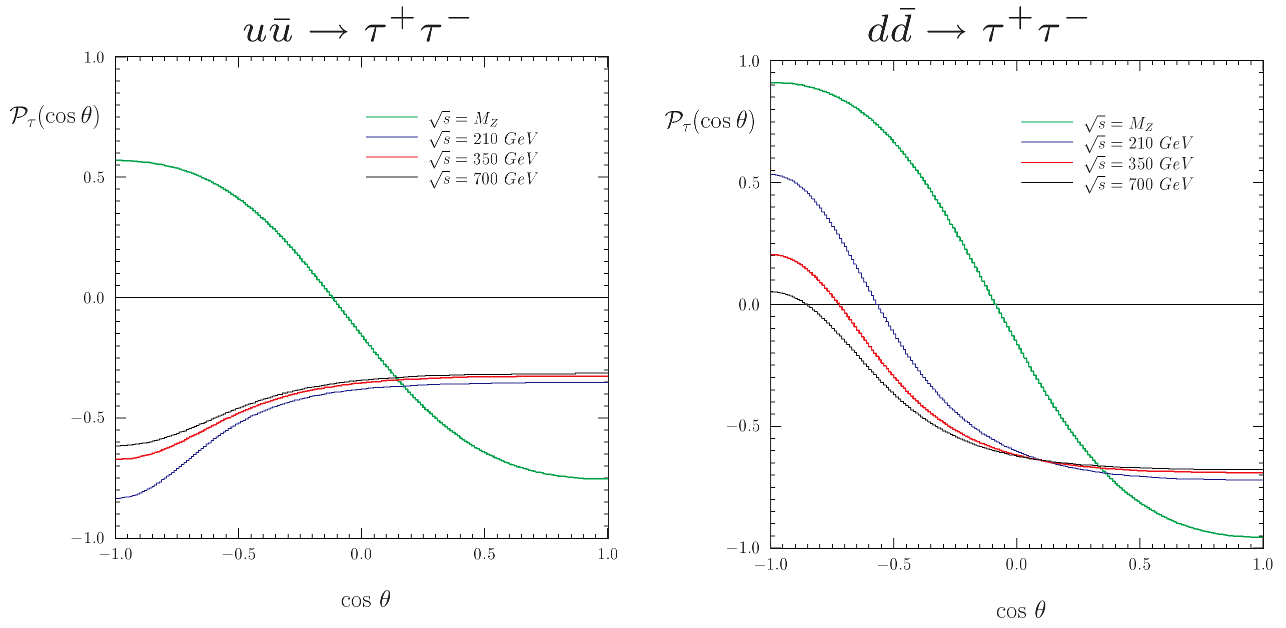
Test of the TAUOLA Universal Interface

$$e^+e^- \to \tau^+\tau^-$$



- The τ polarisation as a function of $\cos\theta$.
- θ – the scattering angle in the Z/γ^* rest frame, calculated with respect to the e^- effective beam.
- τ's are strongly polarised in the forward direction
- τ polarisation changes significantly with the center of mass energy.

Test of the TAUOLA Universal Interface



- τ are strongly polarised in the forward and in the backward directions for CMS energy close to the Z peak.
- The average polarisation 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.

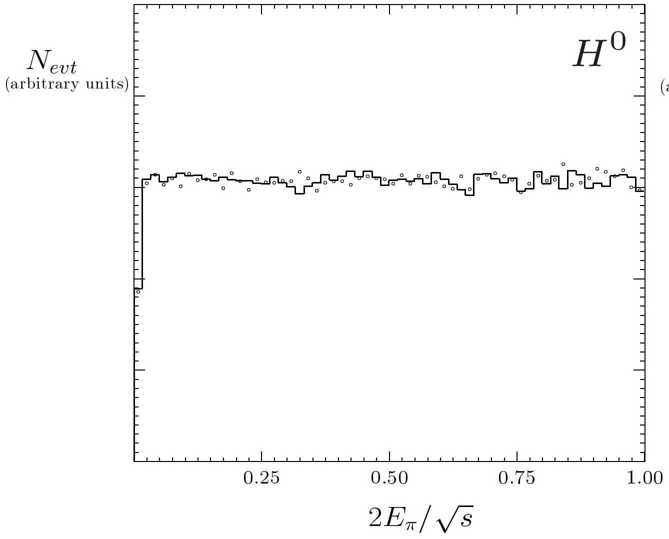
Identification of the H^0 and Z/γ^* states

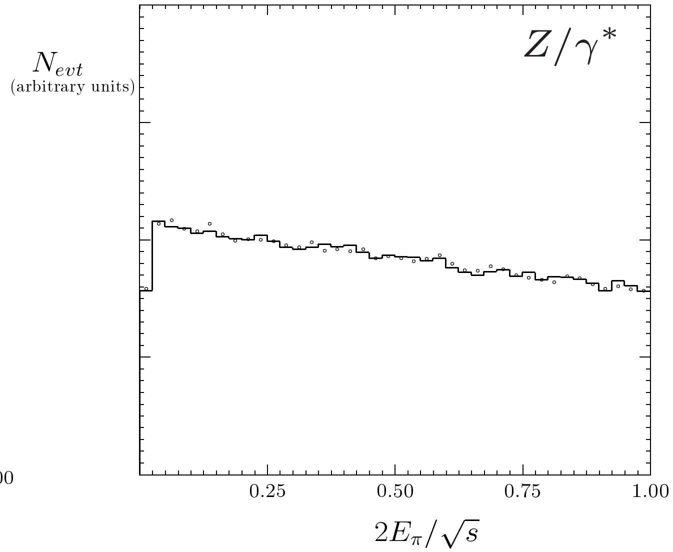
- The polarisation of the τ lepton can be exploited to identify a neutral Higgs bosons via the decay $H^0 \to \tau^+\tau^-$.
- The background is $Z/\gamma^* \to \tau^+\tau^-$ decay.
- There exists a simple polarisation correlation test which will clearly indicate the presence of τ pairs of Higgs origin among the background $Z/\gamma^* \to \tau^+\tau^-$.
- The τ pairs are produced with the well defined spin configurations:

  $+\ +$ or $-\ -$ for vector bosons

  $+\ -$ or $-\ +$ for neutral Higgs boson.
- The polarisation 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.

π energy spectrum from $\tau \rightarrow \pi\nu$ decay

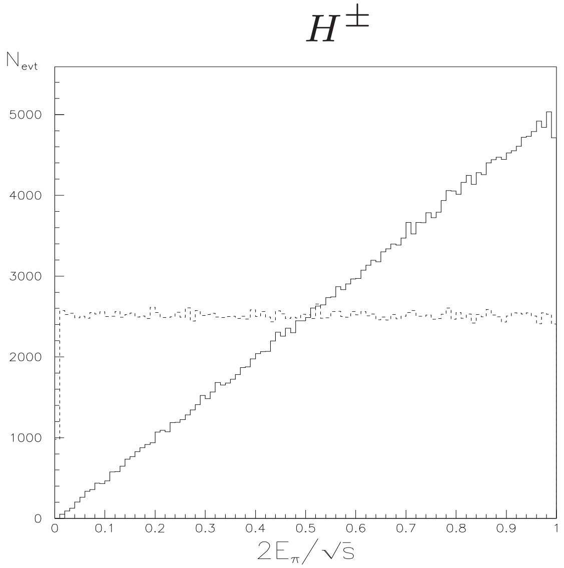


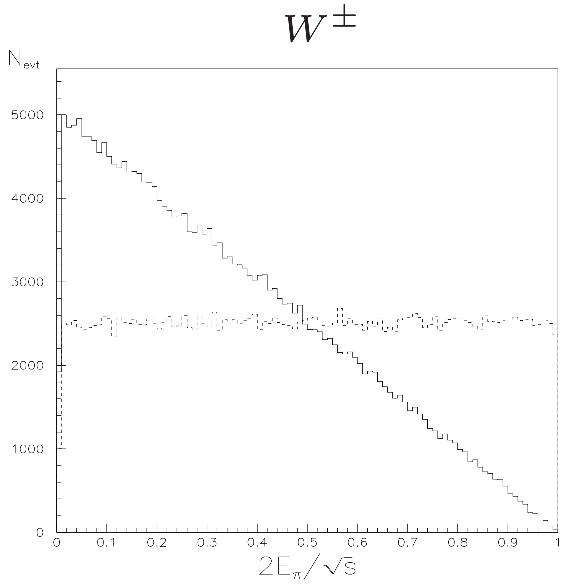


- *Single π energy spectrum in the case of τ produced from H^0 or Z/γ^*. The invariant mass of the pair of two incoming quarks was taken $\sqrt{s} = m_Z = m_H$. Energies are defined in the rest frame of Higgs boson or Z.*
- *The slope of π energy spectrum (in the case of Z) due to the τ polarisation. The slope is proportional to the polarisation.*

$$\frac{d\sigma}{dz_\pm} \sim 1 + \mathcal{P}_\tau \; 2\,(z_\pm - 0.5) \qquad\qquad z_\pm = 2E_{\pi^\pm}/\sqrt{s}$$

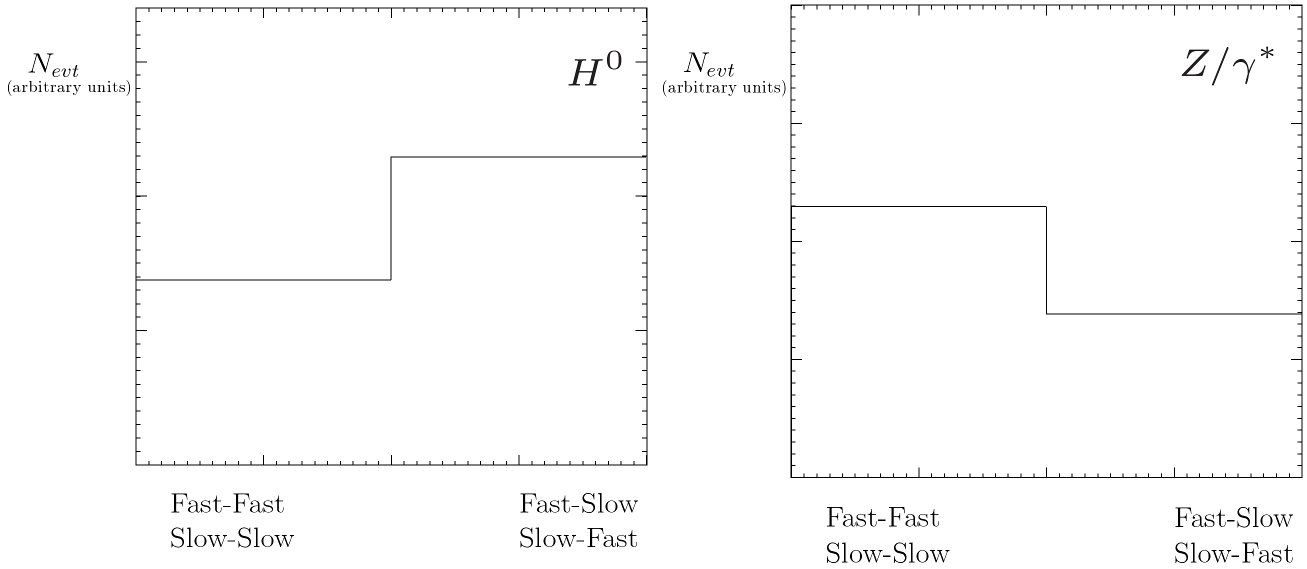
π energy spectrum from $\tau \to \pi\nu$ decay





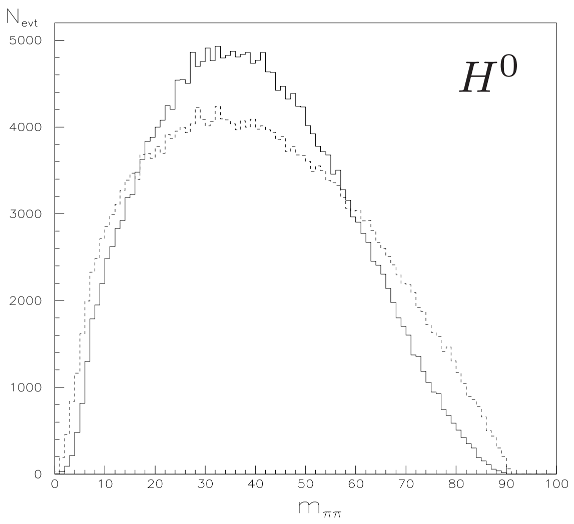
- *Single π energy spectrum in the case of τ produced from $H^{\pm}$ or $W^{\pm}$. The invariant mass of the pair of two incoming quarks was taken $\sqrt{s} = m_{H^{\pm}}$ or $\sqrt{s} = m_{W^{\pm}}$. Energies are defined in the rest-frame of $H^{\pm}$ or $W^{\pm}$.*
- *For $W^{\pm}$ average polarisation is -100% and the distribution slope is maximally negative, touch zero at $z_{\pm} = 1$.*
- *For $H^{\pm}$ average polarisation is 100% and the distribution slope is reversed, touch zero at $z_{\pm} = 0$.*

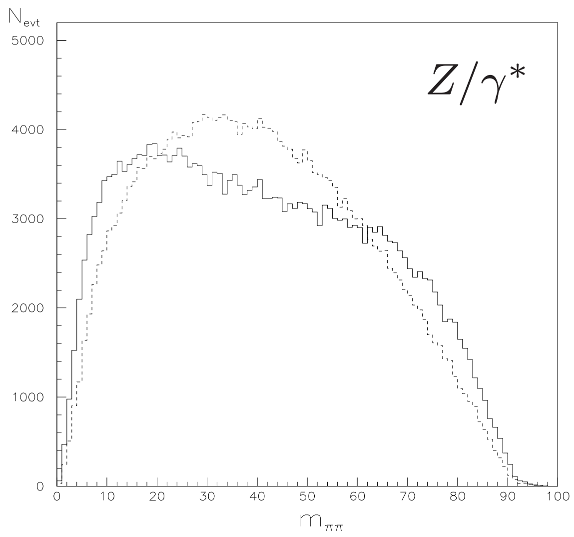
$\pi^+\pi^-$ energy-energy correlations



- $\pi^+\pi^-$ energy-energy correlations, case of $\tau\tau$ produced from H or Z/γ^*.
- $\sqrt{s} = m_H = m_Z$. Energies are calculated in the rest frame of the $\tau\tau$ pair.
- In the $Z/\gamma^* \to \tau^+\tau^-$ decays a Fast (a Slow) $\pi^\pm$ is most likely to be associated with a a Fast (a Slow) $\pi^\mp$; the opposite is for $H^0 \to \tau^+\tau^-$ decays.
- The excess arises from Higgs decay can be recognised in the $\pi^+\pi^-$ mode as a Fast $\pi^\pm$ with a Slow $\pi^\mp$.

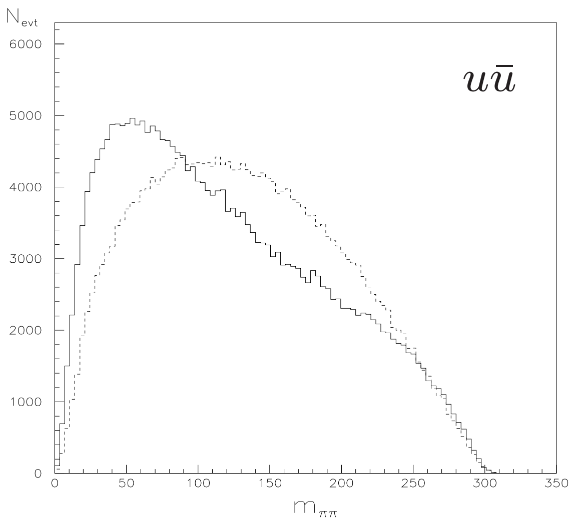
$\pi^+\pi^-$ invariant mass distribution

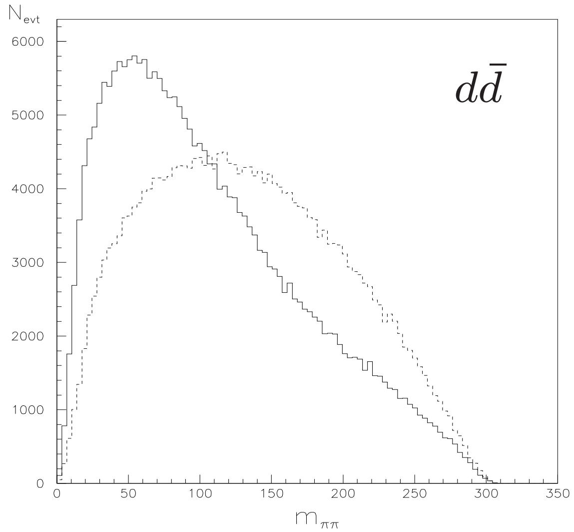




- *The $\pi^+\pi^-$ invariant mass distribution for H^0 and for Z/γ^* . $\sqrt{s} = m_H = m_Z$.*
- *For Higgs boson, the mass distribution is peaked centrally, whereas for Z/γ^* shoulders of the distributions are more profound.*
- *If all polarisation effects are switched off the distributions are identical.*
- *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.*

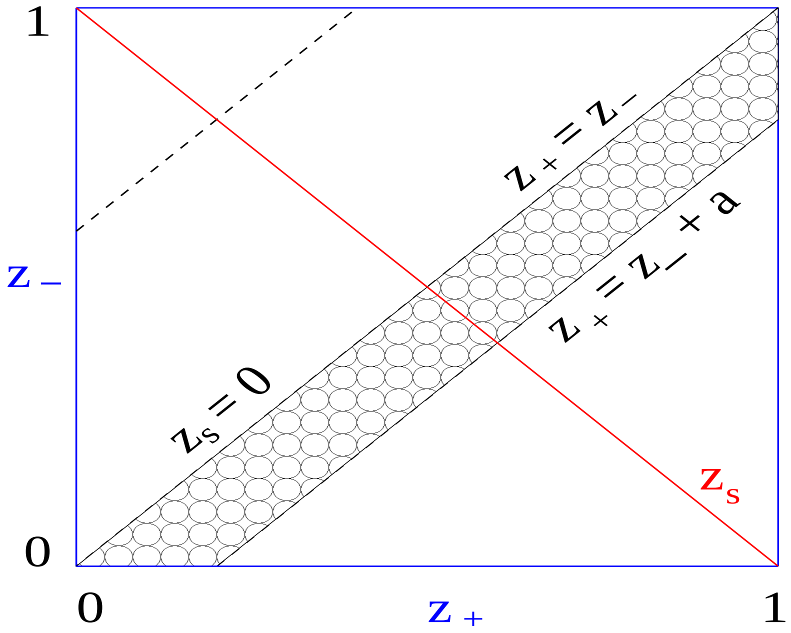
$\pi^+\pi^-$ invariant mass distribution





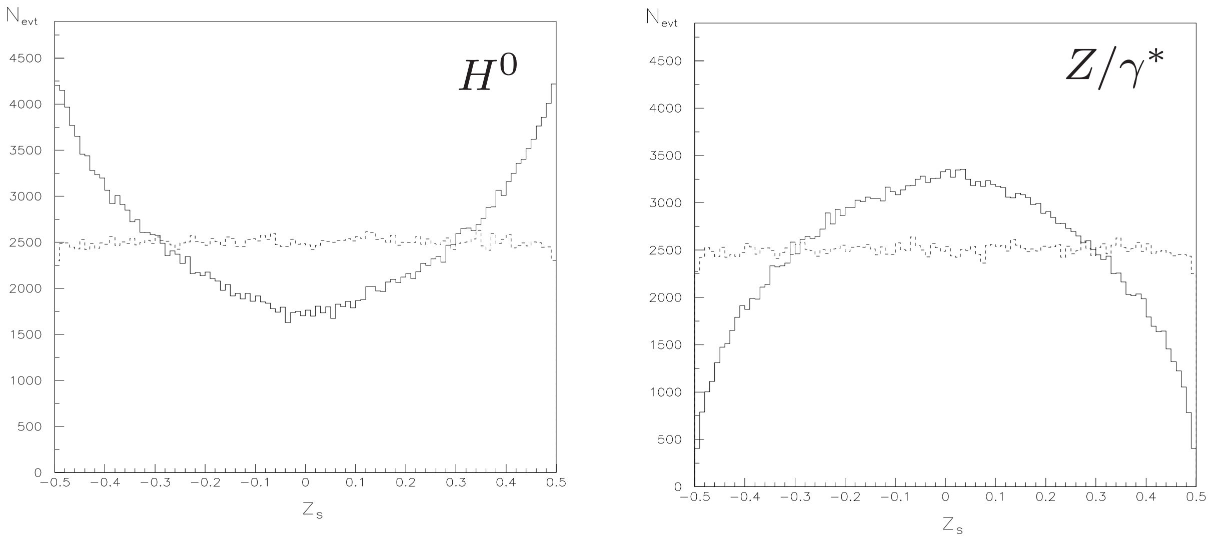
- The $\pi^+\pi^-$ invariant mass distribution for $u\bar{u} \to Z/\gamma^*$ and $d\bar{d} \to Z/\gamma^*$ produced with CMS energy of 300 GeV.
- The average polarisation increases above the Z peak and approaches respectively -35% and -61% in the case of $u\bar{u}$ and $d\bar{d}$ annihilation.
- The shape of the distribution might give the insight to the structure functions of the colliding protons.

Definition of the variable z_s



- Variable z_s defined as signed part of the following phase space part: surface in z_+, z_- variables between lines $z_+ = z_-$ and $z_+ = z_- + a$.
- $z_\pm = 2E_\pm/\sqrt{s}$, $z_\pm$ – the energy fraction carried by the pion.
- The allowable range for this variable is -0.5 $\leq z_s \leq$ 0.5

New observable — z_s



- *Expected number of events as the function of z_s variable.*
- *In the $Z/\gamma^* \to \tau^-\tau^+$ decays a Fast (Slow) $\pi^\pm$ is most likely associated with a Fast (Slow) $\pi^\mp$. The solid line has maximum at $z_s = 0$ and approaches zero for $z_s = \pm 0.5$.*
- *Precisely the opposite is true in the case of $H^0 \to \tau^-\tau^+$. The maximum is now at $z_s = \pm 0.5$ and minimum for $z_s = 0$.*

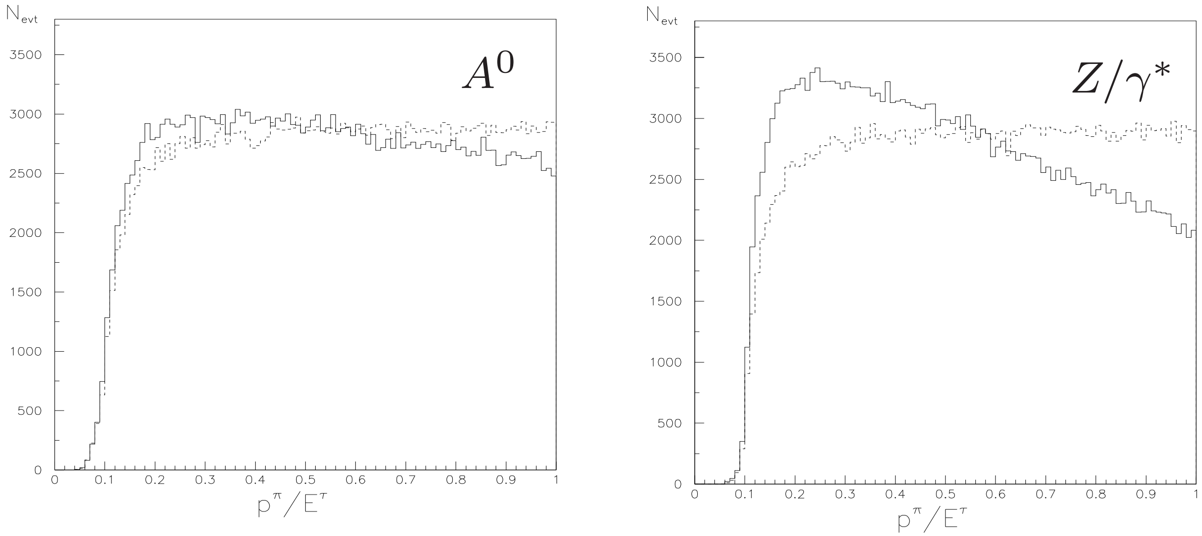
Higgs signatures at LHC

- The τ leptons are considered as a very promising signature for the searches of the Higgs bosons in the MSSM at LHC collider.
- The neutral Higgs bosons H^0 and A^0 decays into $\tau^+\tau^-$ pair, are enhanced for the large values of $\tan\beta$.
- 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 the $Z/\gamma^* \to \tau^+\tau^-$ decay and the reducible backgrounds is the QCD jets, $t\bar{t}$ and W+jets.
- The τ identification is based on the presence of a single hard isolated charged hadron in the jet using tracker information. The 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 or W+jets events.

Monte Carlo setup

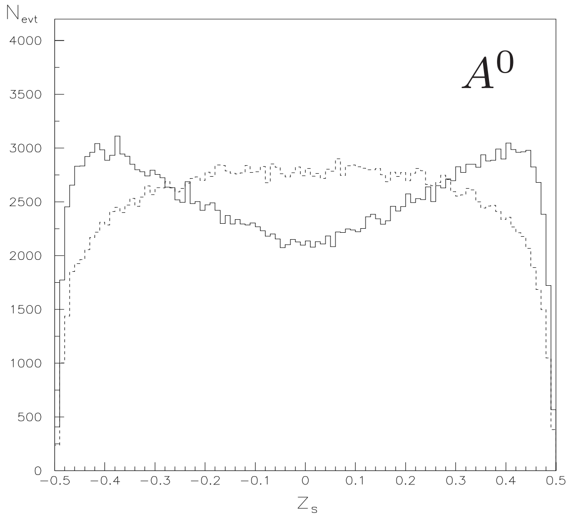
- All Monte Carlo samples have been generated with the TAUOLA library, which can be used to decay $\tau^\pm$ leptons of the fixed helicity state.
- For the production of the $\tau^\pm$ leptons pairs Monte Carlo program PYTHIA was used.
- For the interfacing the τ lepton decay and the production, with full spin effects included, our spin interface was used.
- The case of $\tau^\pm$ decay to $\pi^\pm\bar{\nu}_\tau(\nu_\tau)$ are taken.
- 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 $300 \pm 10\ GeV$.
- The minimal transverse momenta of the $\pi' s$ were required to be above $15\ GeV$ and the pseudorapidity $|\eta|\ <\ 2.5$.

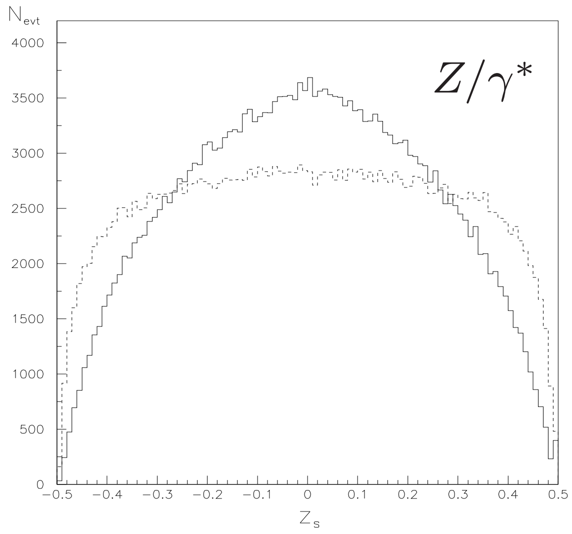
π energy spectrum — case at LHC



- π energy spectrum in the laboratory frame for Higgs boson and for Z/γ^*.
- Spin correlations lead to the softer spectrum of π in Z/γ^* decays.
- Suppress the identification efficiency of the τ with respect to those produced from the Higgs boson decay.

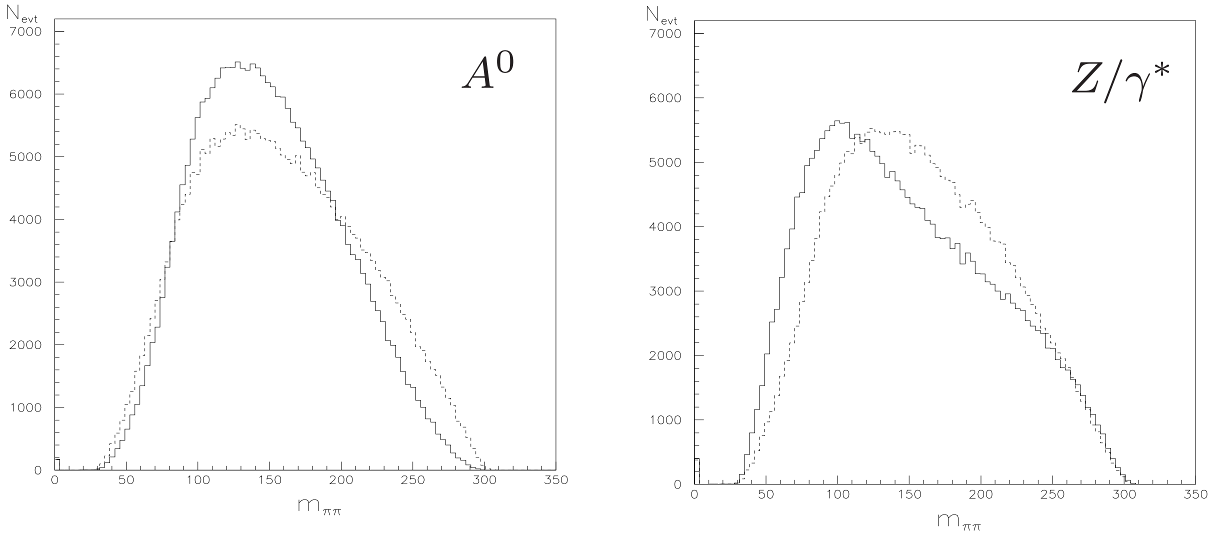
New observable z_s — case at LHC





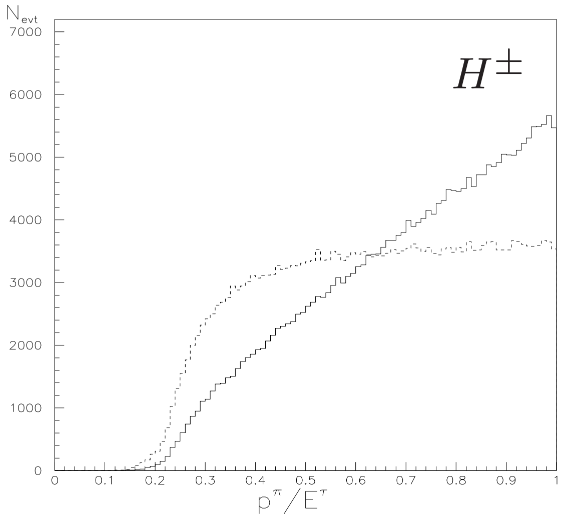
- *The expected number of events as a function of the $\pi^+\pi^-$ Energy-Energy correlation variable z_s.*
- *The effect is strong enough to discriminate between scalar and vector cases.*
- *Exploring this effect would require good experimental reconstruction of the effective CMS frame which might be very difficult.*

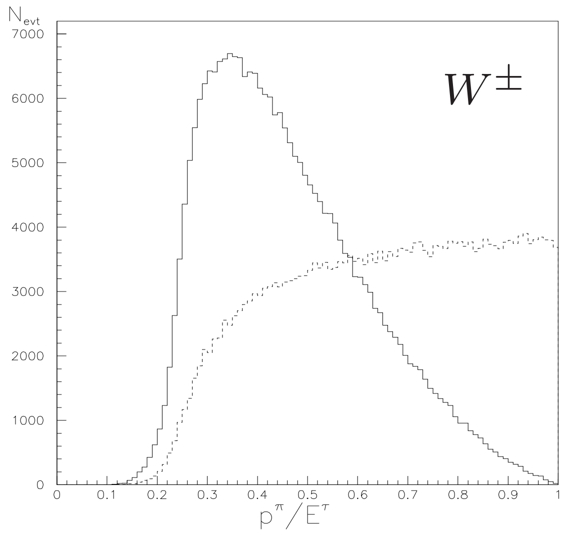
$\pi^+\pi^-$ invariant mass distribution — case at LHC



- The $\pi^+\pi^-$ invariant mass distribution after basic selection for A^0 and Z/γ^*.
- The Higgs boson mass of the 300 GeV. For the Z/γ^*, the CMS energy of the produced $\tau^+\tau^-$ pair was taken in the range 300 $\pm$ 10 GeV.
- In the vector case the correlations lead to the more profound shoulders.
- In the case of the scalar Higgs boson the correlations lead to the narrower distribution, enhancing the fraction of events localised in its central part.

π energy spectrum — case at LHC





- Distribution of p^π/E^τ in the laboratory frame for $H^\pm$ and for $W^\pm$.
- The main background comes from $W^\pm \to \tau^\pm \nu$ decay.
- The Higgs boson mass $m_{H^\pm} = 130\ GeV$ is taken.

Transverse spin correlations

- Extended standard universal interface of the TAUOLA with the complete spin effects for τ leptons originating from the spin zero particle is now available.
- Transverse spin effects may be helpful to distinguish between scalar $(J^{PC} = 0^{++})$ or pseudoscalar $(J^{PC} = 0^{-+})$ nature of the spin zero particle, e.g. Higgs boson.
- The interface is expected to work with any Monte Carlo generator providing Higgs boson production, and subsequent decay into a pair of τ leptons.
- In case of Higgs boson at the LC we devised a very promising method for the measurement of the Higgs boson parity using decay chain $H/A^0 \to \tau^+\tau^- \to \rho^+\bar{\nu}_\tau\rho^-\nu_\tau \to \pi^+\pi^0\bar{\nu}_\tau\pi^-\pi^0\nu_\tau$.

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.
- The Standard Model $Z/\gamma^* \to \tau^+\tau^-$ production process is a dominant background for the MSSM Higgs bosons searches in the $\tau^+\tau^-$ decay channel at the LHC.
- The invariant mass distributions presented here, sensitive to the $\tau^+\tau^-$ 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.
- This code is available from the address: www.home.cern.ch/~wasm