Parity of Higgs at a Linear Collider using $H \to \tau^+\tau^-$ decay

Małgorzata Worek

In collaboration with: G. R. Bower, K. Desch, T. Pierzchała, E. Richter-Wąs, Z. Wąs

Goals :

- Interface of the TAUOLA τ-lepton decay library with complete spin effects for τ leptons originating from the spin zero particle.
- The $\tau^\pm \to \pi^\pm \bar{\nu}_\tau(\nu_\tau)$ decay channel.
- Discussion of physical observable which we used to distinguish between the scalar and pseudoscalar Higgs boson in the $\tau^\pm \to \rho^\pm \bar{\nu}_\tau(\nu_\tau)$ decay.
- Measurement of the τ flight direction as a probe to optimize the method.
- Preliminary results for $\tau^\pm \to a_1^\pm \bar{\nu}_\tau(\nu_\tau)$ channel.
- Summary and Outlook

Main References

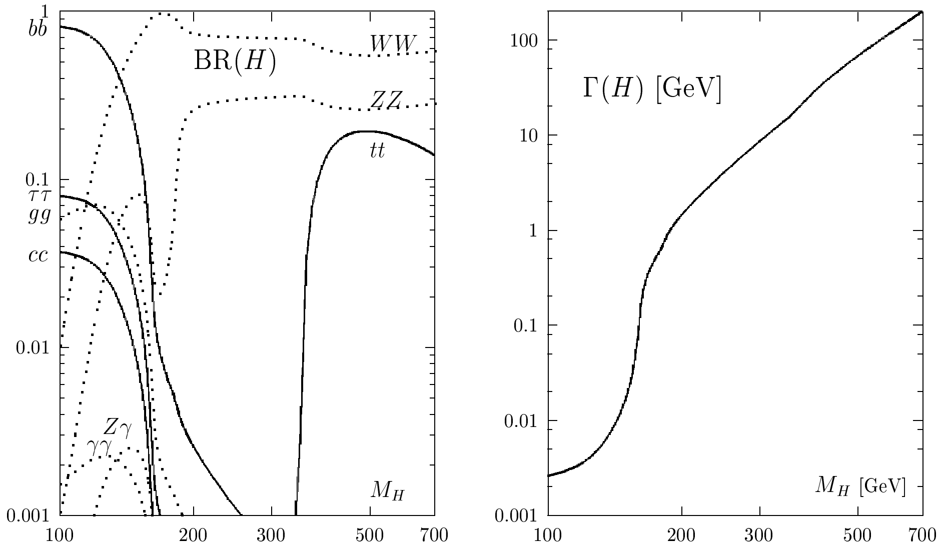
- “ *Spin Effects In τ Lepton Pair Production at LHC* ”.
  By T. Pierzchała, E. Richter-Wąs, Z. Wąs, M. Worek.
  Published in Acta Phys. Polon. B32, 1277-1296, 2001.
  e-Print Archive: *hep-ph/0101311*.

- “ *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*.

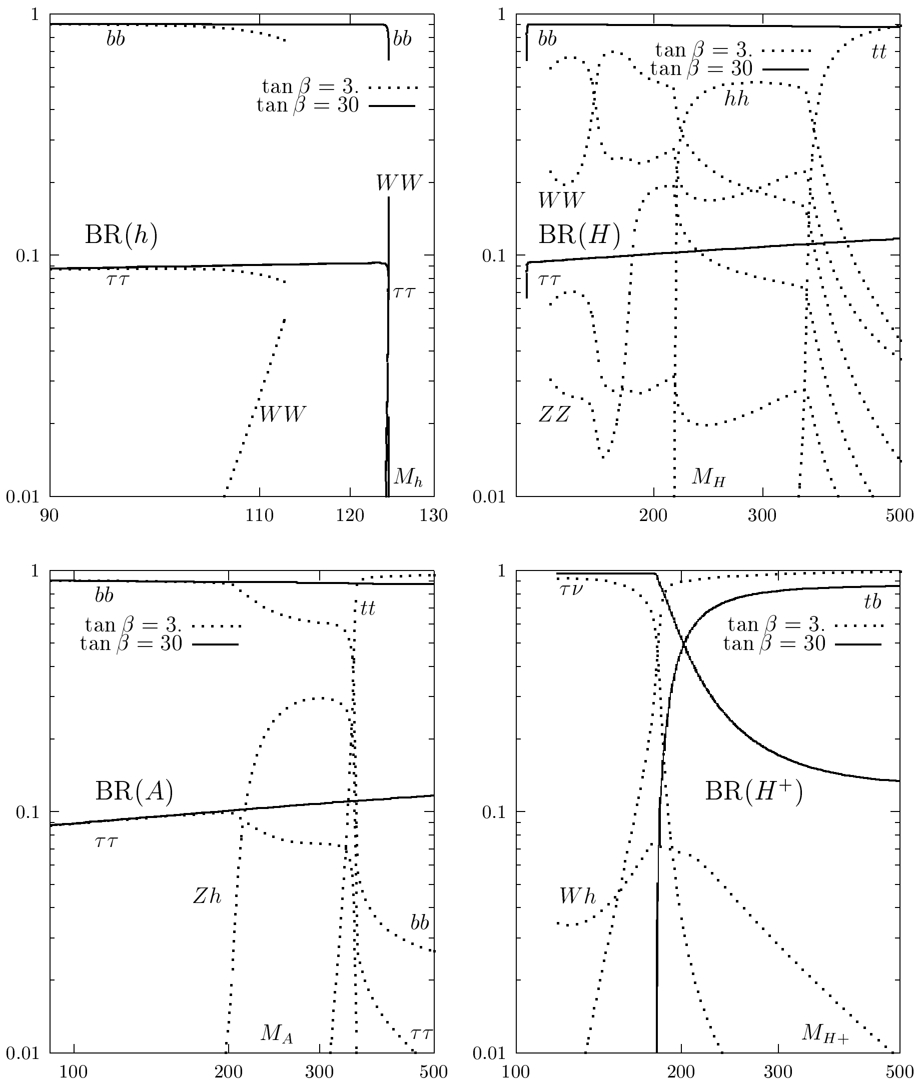
- “ *Measuring Higgs boson parity at a Linear Collider using the τ impact parameter and $\tau \to \rho\nu$ decay* “.
  By K. Desch, Z. Wąs, M. Worek.
  e-Print Archive: *hep-ph/0302046*.

SM Higgs boson main branching ratios



- **The most frequent fermion decay mode of neutral Higgs particles is the $b\bar{b}$ channel, $BR(H \to b\bar{b}) \sim 90\%$.**
- **Very difficult to extract information on the b polarization state, the fragmentation process destroys the b-spin informations.**
- **Cleaner channel is the $\tau^+\tau^-$, $BR(H \to \tau^+\tau^-) \sim 8\%$.**
- **The $\tau^+\tau^-$ channel is useful in the SM for Higgs masses less than $\sim 140\, GeV$. Up to this mass, the Higgs particle is very narrow, $\Gamma(H) \leq 10\, MeV$.**

MSSM Higgs bosons main branching ratios



- In $MSSM$ the $\tau^+\tau^-$ channel is useful over a much larger mass range.

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

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

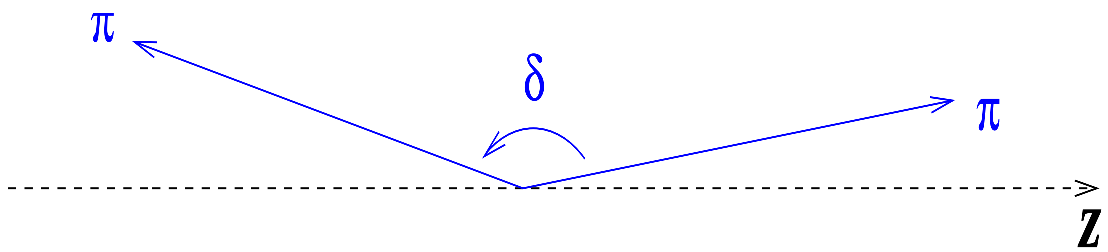
where the components

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

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.

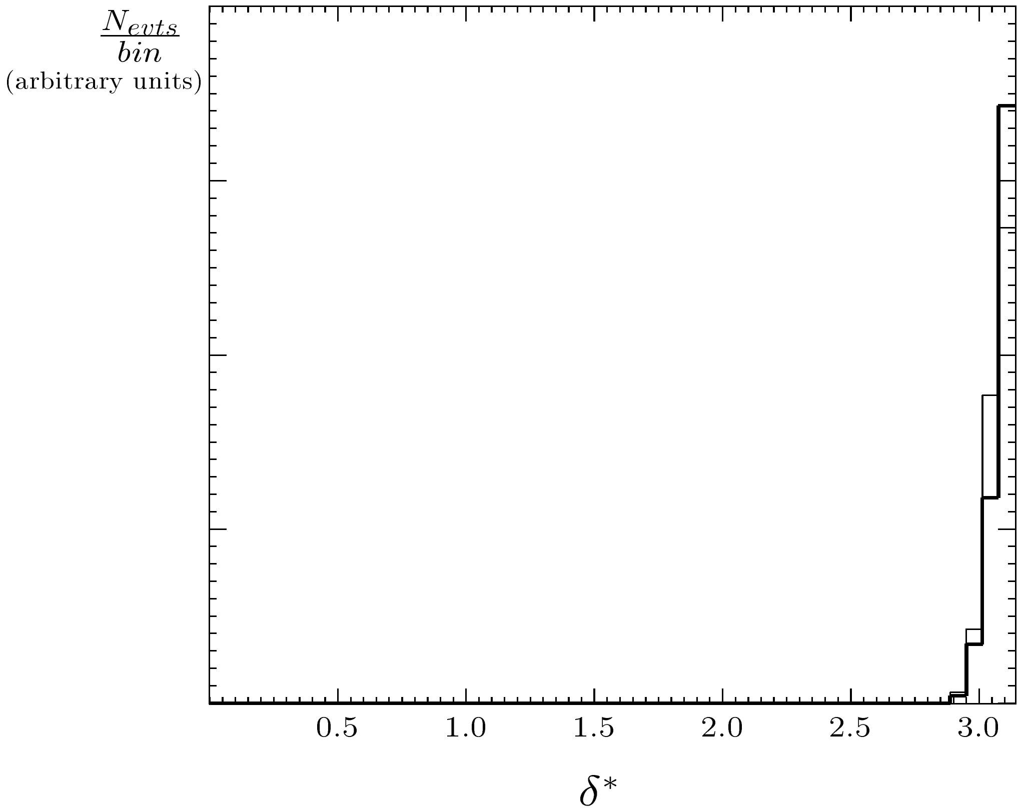


- Useful observable is the angle δ between the two charged pions in the Higgs rest frame (acollinearity distribution of $\pi^{+}\pi^{-}$ from $\tau^{\pm}$ decays).

Monte Carlo set up

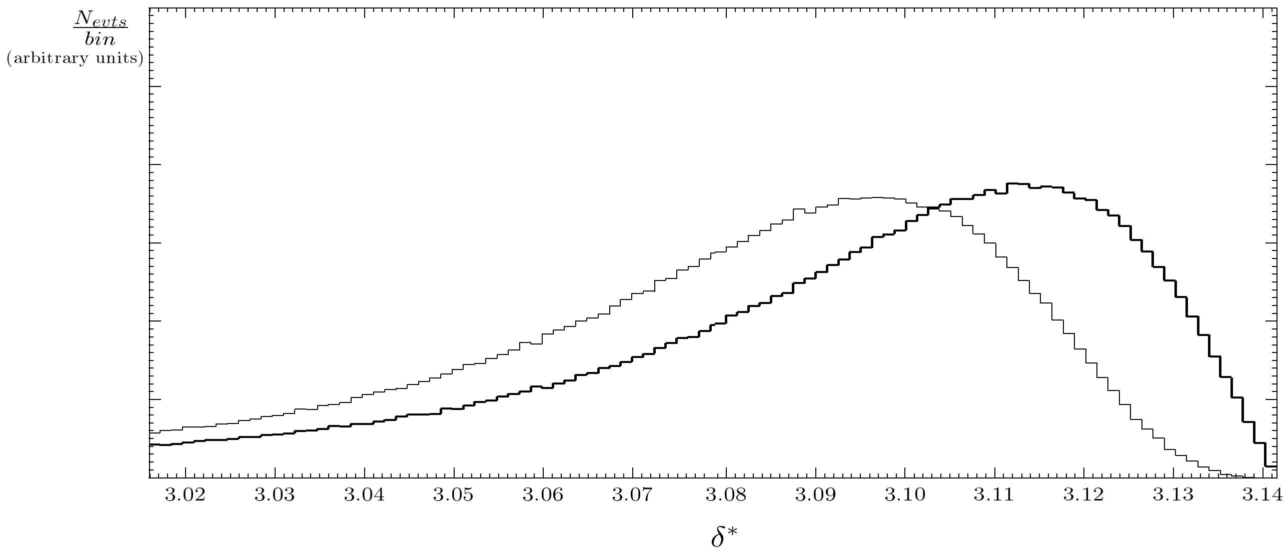
- All the Monte Carlo samples have been generated with TAUOLA — a library of Monte Carlo programs to simulate decays of τ leptons.
- For the production of the τ lepton pairs the Monte Carlo program PYTHIA 6.1 is used.
- The production process $e^+e^- \to ZH \to \mu^+\mu^- H$ has been chosen with a Higgs boson mass of $120\ GeV$ and a center-of-mass energy of $350\ GeV$ or $500\ GeV$.
- 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 $H \to \tau^+\tau^-$, $\tau^\pm \to \pi^\pm \bar{\nu}_\tau(\nu_\tau)$, $\tau^\pm \to \pi^\pm \pi^0 \bar{\nu}_\tau(\nu_\tau)$, $\tau^\pm \to \pi^\pm \pi^- \pi^+ \bar{\nu}_\tau(\nu_\tau)$ 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

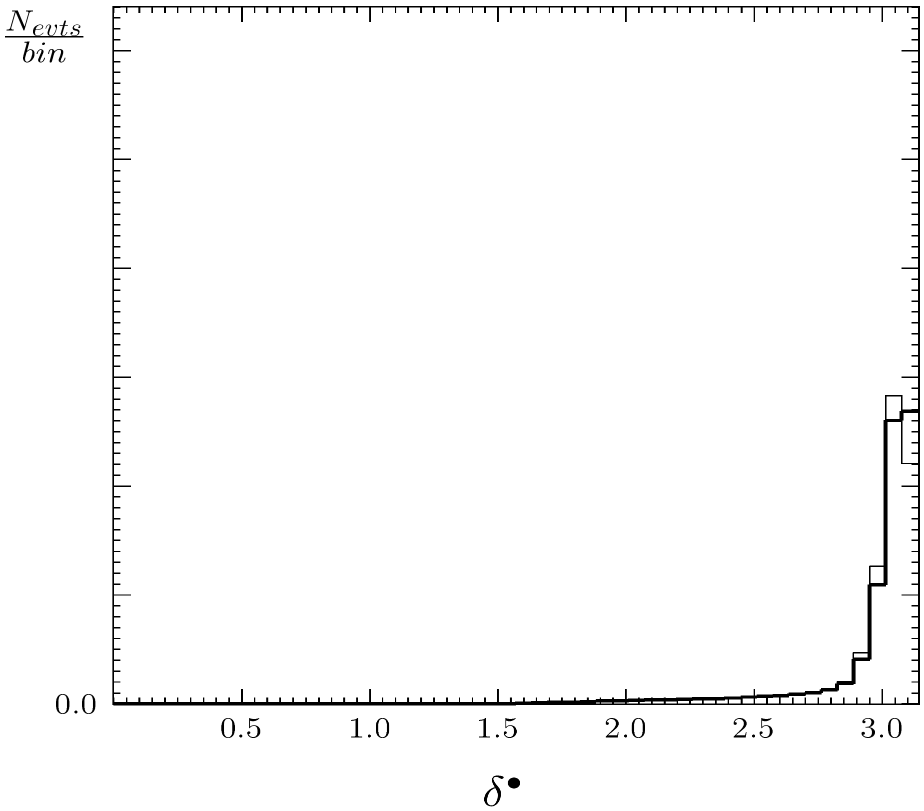


- **The $\pi^+\pi^-$ acollinearity distribution in the Higgs boson rest frame. Parts of the distribution close to the end of the spectrum, $\delta^* \sim \pi$, are shown. The thick line denotes the case of the scalar Higgs boson and the thin line the pseudoscalar one.**

Detector effects

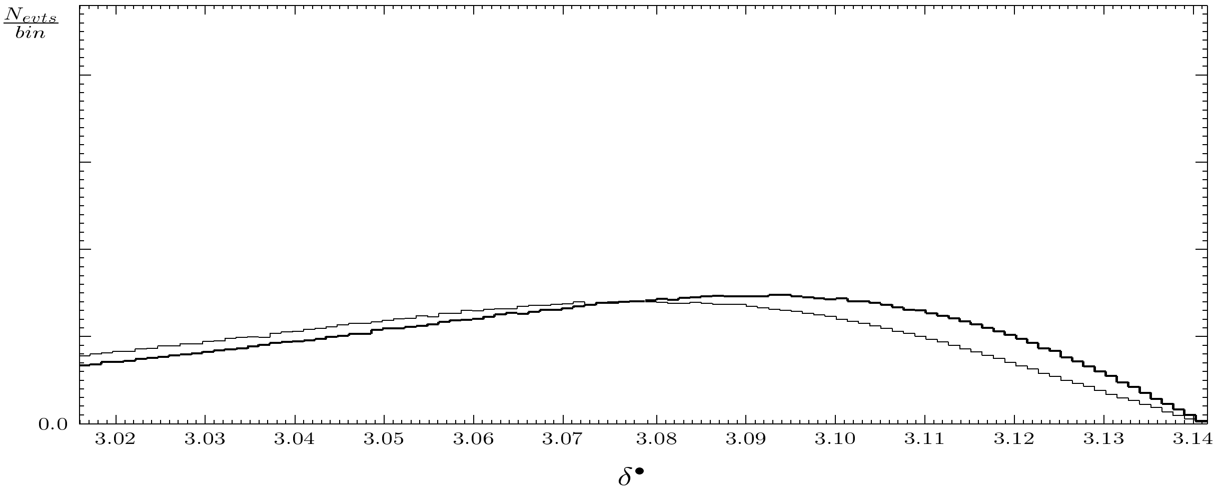
- We assume Gaussian spreads of the ‘measured’ quantities with respect to the generated ones. For charged pion momentum we assume 0.1% spread on its energy and direction.
- The Higgs rest frame can be reconstructed, for instance in the Higgsstrahlung production process, $e^+e^- \to HZ$, when the Z boson decays either into a charged lepton pair or hadronically.
- We define the ‘reconstructed’ Higgs boson momentum as the difference of the sum of beam momenta and momenta of all visible particles, decay products of Z and all radiative photons of $|\cos\theta| < 0.98$.
- We mimic in a very crude way beamstrahlung effects, assuming a $5\ GeV$ Gaussian spread for the longitudinal component of the Higgs boson momentum with respect to the generated one.

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



- The $\pi^+\pi^-$ acollinearity distribution in the reconstructed Higgs boson rest frame. Smearing is included. Full angular range $0 < \delta^\bullet < \pi$ 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 reconstructed Higgs boson rest frame. Smearing is included. Parts of the distribution close to the end of the spectrum, $\delta^{\bullet} \sim \pi$, are shown. The thick line denotes the case of the scalar Higgs boson and the thin line the pseudoscalar one.
- There is little hope to check Higgs boson parity using $H/A \to \tau^+\tau^-; \tau^\pm \to \pi^\pm\bar{\nu}_\tau(\nu_\tau)$ decay chain.

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

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

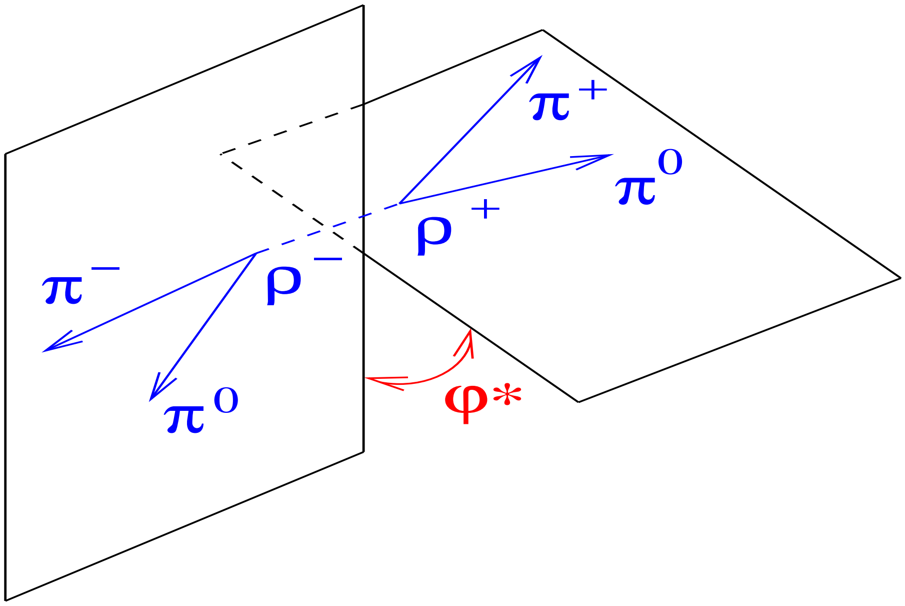
where q is the four-momentum of $\pi^{\pm} - \pi^0$ and N is the four-momentum of ν_{τ}.

- 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.

Optimal variable

- The variable φ^* alone does not distinguish the scalar and psuedoscalar Higgs.
- The $\tau^\pm \to \pi^\pm \pi^0 \bar{\nu}_\tau(\nu_\tau)$ spin sensitivity is proportional to the energy difference of the charged and neutral pion in the τ rest frame.
- Separate events into two zones:

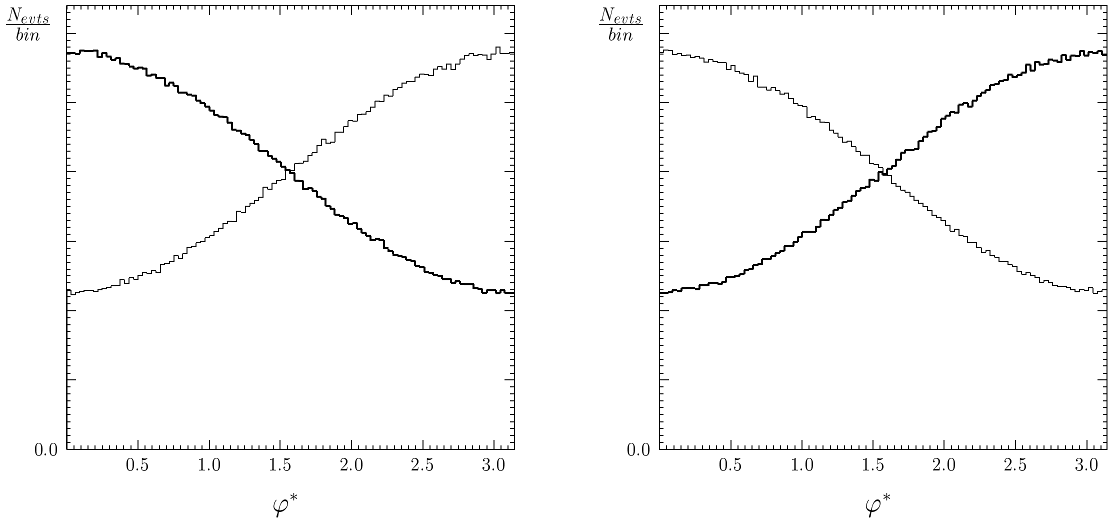
$$y_1 y_2 > 0$$

$$y_1 y_2 < 0$$

$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}; \qquad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}.$$

- $E_{\pi^\pm}$ and E_{π^0} are the $\pi^\pm, \pi^0$ energies in the respective $\tau^\pm$ rest frames.

Results

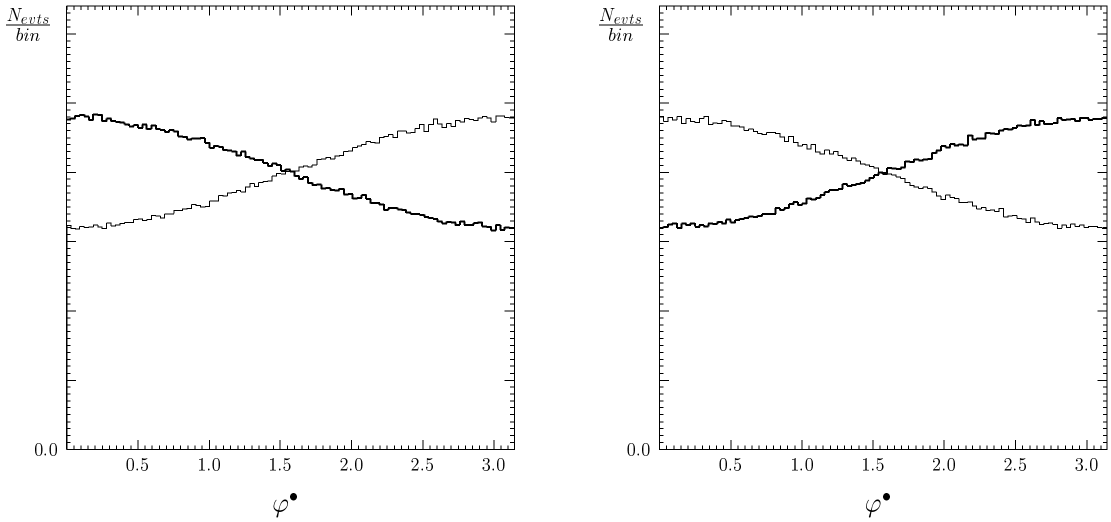


- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Selection $y_1y_2 > 0$ is used in the left plot and the opposite sign selection $y_1y_2 < 0$ is used for the right plot. No smearing is done. Thick lines denote the case of the scalar Higgs boson and thin lines the pseudoscalar one.**

Detector effects

- **We assume Gaussian spreads of the 'measured' quantities with respect to the generated ones.**
- **Charged pion momentum:**
  0.1% spread on its energy and direction.
- **Neutral pion momentum:**
  energy spread of $\frac{5\%}{\sqrt{E_\pi[GeV]}}$**. For the** θ **and** ϕ **angular spread we assume** $\frac{1}{3}\frac{2\pi}{1800}$**.**
- **The replacement** τ **lepton rest frames and the** $\pi^\pm$ **and** π^0 **energy differences:**
  define replacement four-momenta, $p_\pm$**, for the unmeasurable** $\tau^\pm$ **four-momenta in the** $\rho^+\rho^-$ **rest frame:**
  a) Define $p_+^0 = p_-^0 = m_H/2$**.**
  b) Define the direction of the p_+ **and** p_- **three-momenta to be the direction of the** ρ^+ **and** ρ^- **three-momenta in the** $\rho^+\rho^-$ **rest frame, respectively.**
  c) Define the magnitude of the $p_\pm$ **three-momenta so that** $p_+^2 = p_-^2 = m_\tau^2$**.**

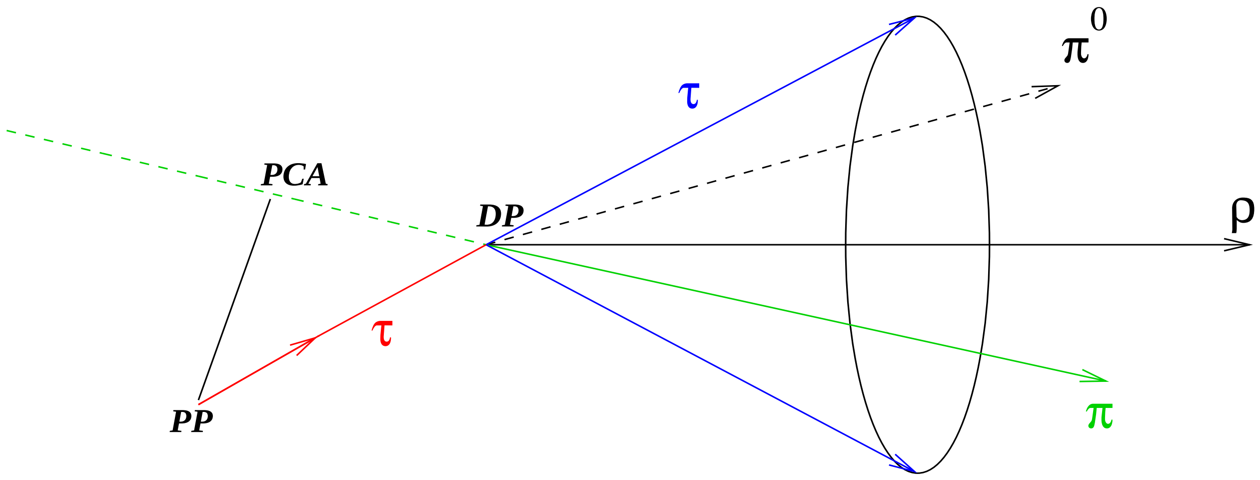
After detector effects ...



- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Selection $y_1 y_2 > 0$ is used in the left plot and the opposite sign selection $y_1 y_2 < 0$ is used for the right plot. All smearing is included. Thick lines denote the case of the scalar Higgs boson and thin lines the pseudoscalar one.**

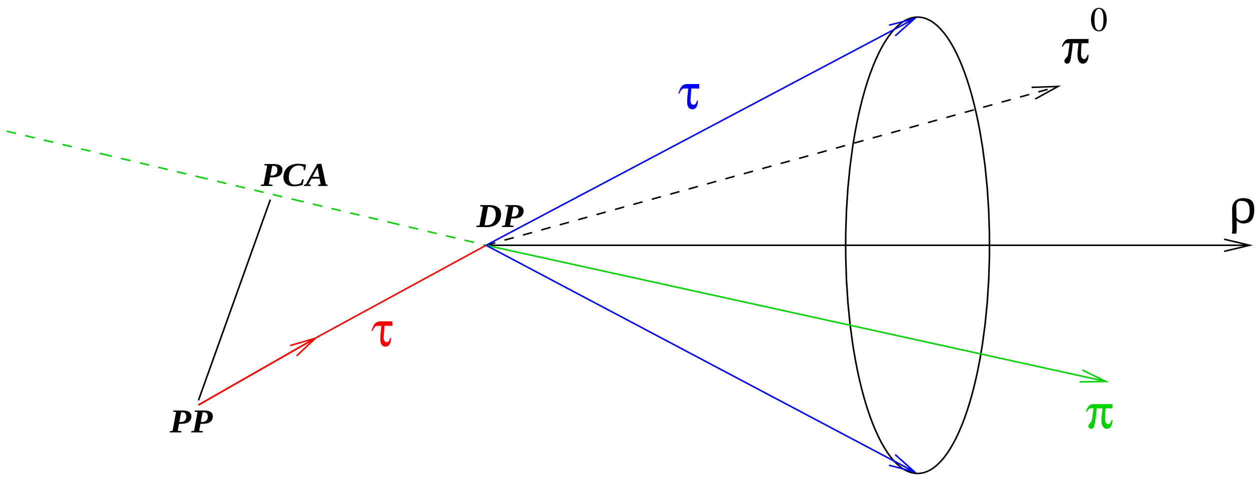
- **Distributions clearly distinguish the different parity states, they are measurable using typical properties of a future detector at an e^+e^- linear collider.**

τ impact parameter



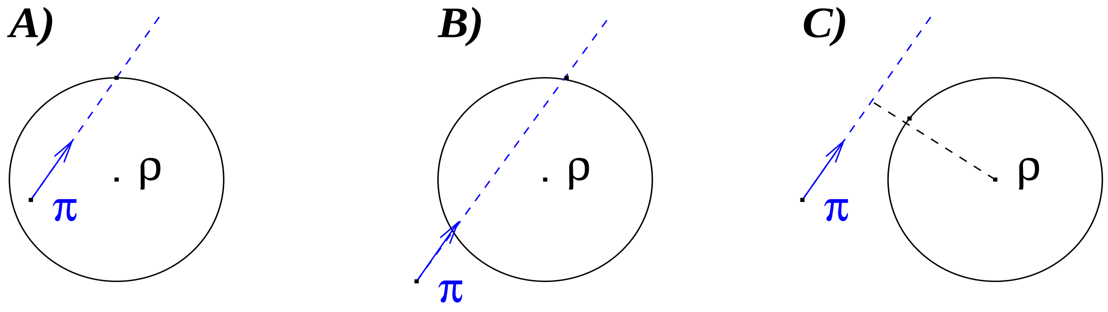
- The τ impact parameter is defined as the distance of closest approach of a decay product track to the τ production point.
- Determination of the direction of the impact parameter (where the production point can be localized with respect to the charged pion tack).
- Investigation of the measurement of the τ lepton impact parameter direction, with precision as expected for future e^+e^- linear collider, can be used to optimize the method.

τ flight direction



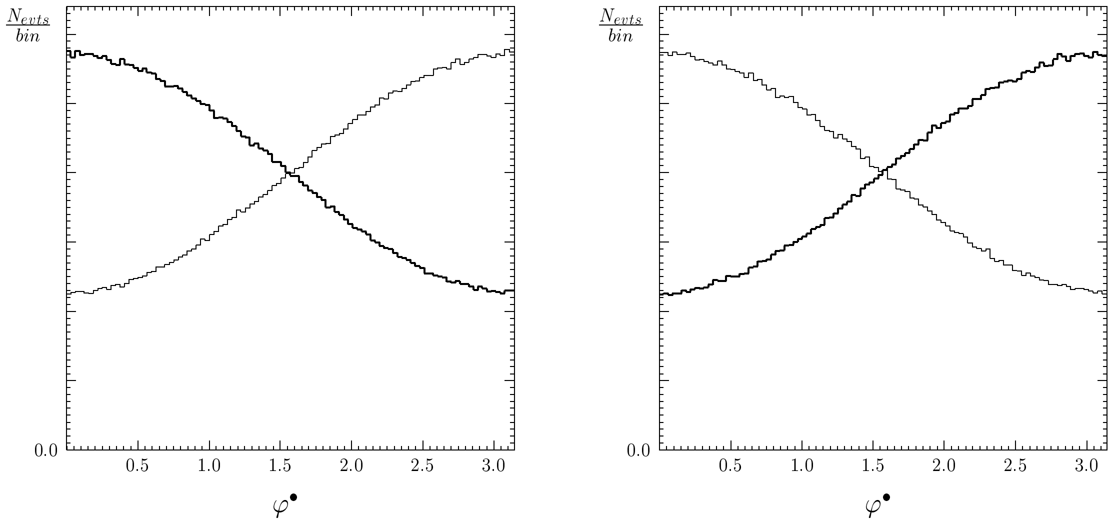
- The τ direction is constrained to lie on a cone around the measured direction of ρ, with opening angle ψ defined as $\cos\psi = \frac{2E_\tau E_\rho - m_\tau^2 - m_\rho^2}{2\vec{p}_\tau \vec{p}_\rho}$
- It has to lie in the plane spanned by the vector pointing from τ production point to point of closest approach and the charged pion momentum.
- New impact parameter τ rest frame can be defined. An alternative way of estimating the difference of $\pi^\pm$, π^0 energies in the $\tau^\pm$ rest frames.

Candidates for τ momentum



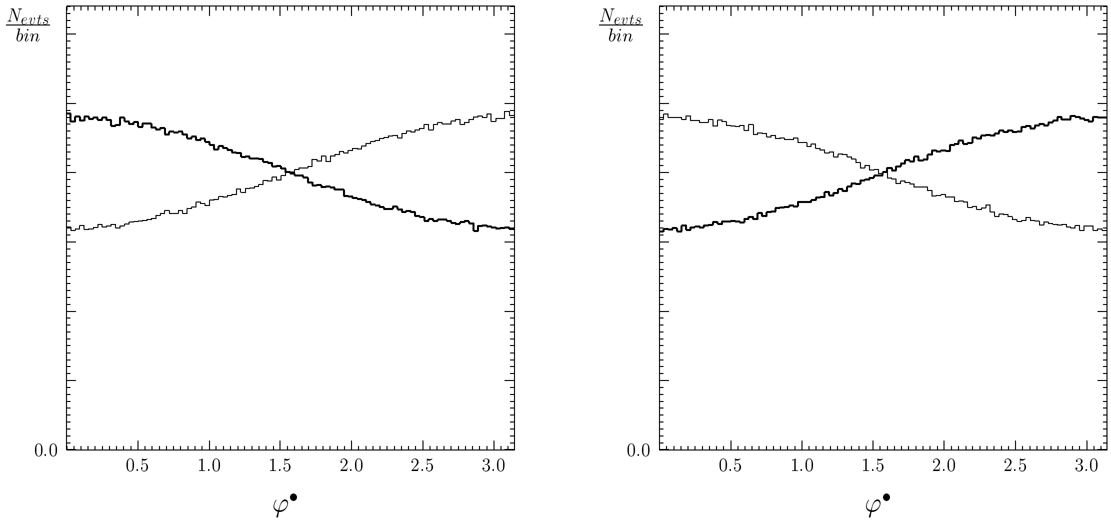
- The intersection of the cone and the plane is calculated numerically. There are 3 cases.
- π direction inside the circle — the solution is taken as the τ direction – case $\mathcal{A}$.
- π direction outside the circle — one of the two solutions is taken on the random basis – case $\mathcal{B}$.
- π direction outside the circle, no crossing of dashed line with the circle due to detection ambiguities of measured angles and energies — the direction on the cone closest to the PCA-π plane is taken – case $\mathcal{C}$.

Results — Generator level $\tau^{\pm}$ rest frames



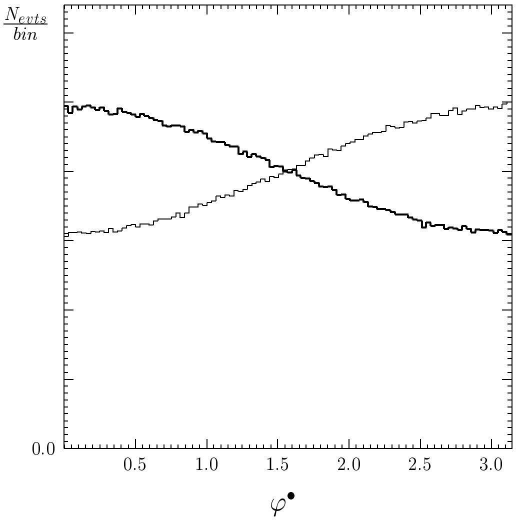
- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Detector smearing is included. Generator level $\tau^{\pm}$ rest frames are used. The thick line corresponds to a scalar Higgs boson, whereas the thin to a pseudoscalar one. The left figure contains events with $y_1 y_2 > 0$, the right is for $y_1 y_2 < 0$.**

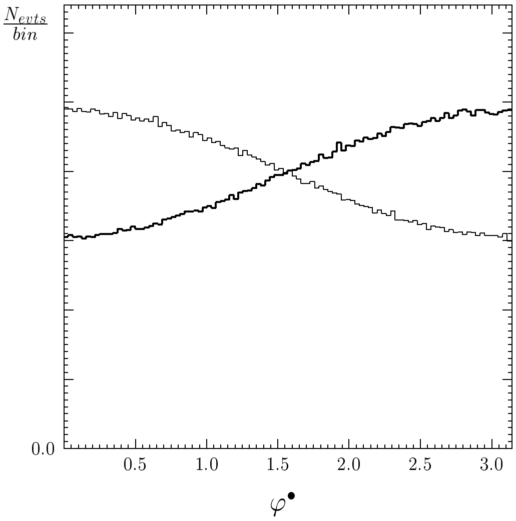
Results — without τ impact parameter help



- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Full smearing is included. Replacement $\tau^\pm$ rest frames are used (without τ impact parameter help). The thick line corresponds to a scalar Higgs boson, whereas the thin to a pseudoscalar one. The left figure contains events with $y_1 y_2 > 0$, the right is for $y_1 y_2 < 0$.**

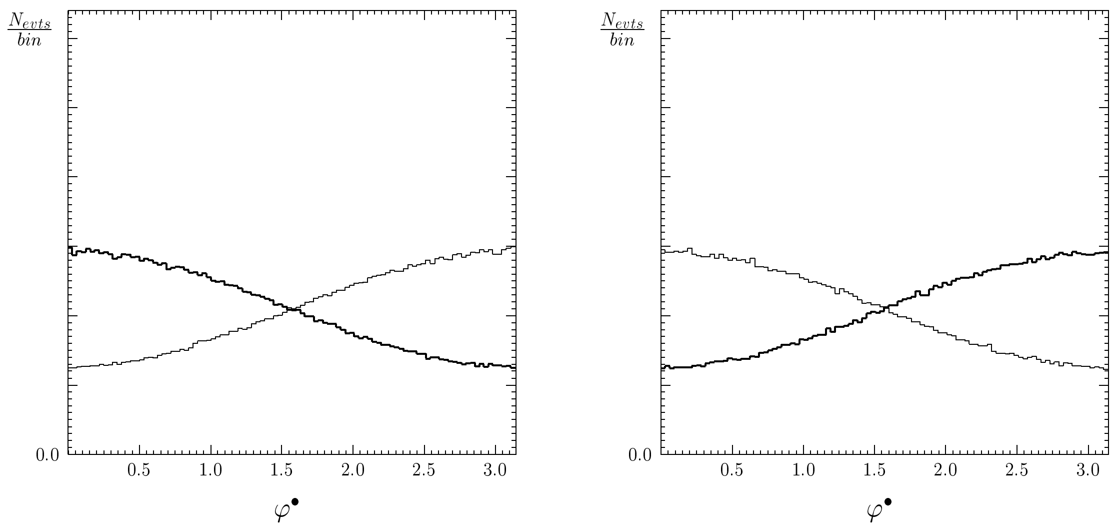
$\tau^{\pm}$ rest frames with impact parameter help





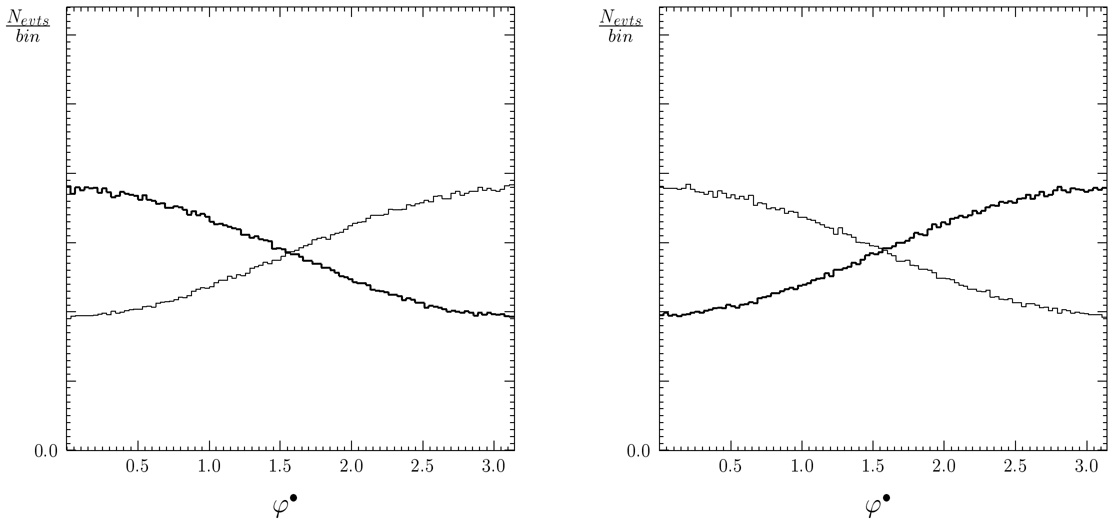
- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Full smearing is included. The τ lepton impact parameter is used in the reconstruction of the $\tau^{\pm}$ rest frames. The thick line corresponds to a scalar Higgs boson, whereas the thin to a pseudoscalar one. The left figure contains events with $y_1 y_2 > 0$, the right is for $y_1 y_2 < 0$.**
- **Improvement $\sim 12\%$**
- **Gaussian spread of impact parameter $\sigma_{IP} = 25^0$**

Results — additional cuts



- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Only events where the signs of the energy differences y1 and y2 are the same whether calculated using the method without or with the help of the τ impact parameter are taken. The thick line corresponds to a scalar Higgs boson, whereas the thin to a pseudoscalar one.**
- **Improvement $\sim 107\%$.**
- **Only $\sim 52\%$ events are accepted.**

Results — additional cuts



- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair, with cuts depending on the position of the pion with respect to the τ cone. The selection is as in previous figure, but in the case of single solution events, the result from the old method is ignored. The thick line corresponds to a scalar Higgs boson, whereas the thin to a pseudoscalar one.**
- **Improvement $\sim 67\%$.**
- **The number of accepted events $\sim 72\%$.**

$\tau^\pm \to \pi^\pm\pi^+\pi^-\nu$ decay

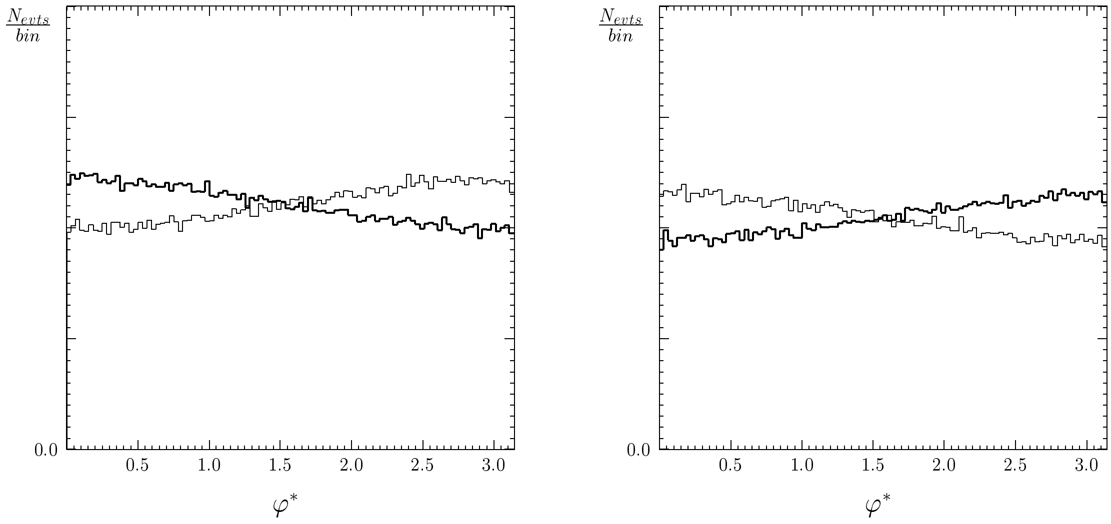
- Branching ratio 9%.
- In comparison to $\tau^\pm \to \pi^\pm \bar\nu_\tau(\nu_\tau)$ decay, its polarimeter force is reduced by the factor $(m_\tau^2 - 2Q^2)^2/(m_\tau^2 + 2Q^2)^2$ where $Q^2 = m_{a_1}^2$.
- For $\tau^-(p,s) \to \pi^-(q_1)\pi^-(q_2)\pi^+(q_3)\nu_\tau(N)$ the polarimeter vector in the τ rest frame reads, $m_{\pi^\pm} = m_{\pi^0}$ is assumed:

$$h^i = \mathcal{N}\Big(Q^i M_\rho^2 + 2q^i(E_{\pi^+} - E_{\pi^-})m_\tau\Big)$$

where where $Q = q_1 + q_2 + q_3$ and $q = q_1 - q_3$.

- As in the $\tau \to \rho\nu$ case first part is proportional to the momentum of the decaying meson a_1 and second one proportional to the difference of the pions, originating from the ρ intermediate states.
- Similar observable like in the $\rho^+\rho^-$ case can be designed if we can find the cuts forcing ρ to be *parallel* to a_1 momentum.

Preliminary results for $\tau \to a_1\nu_\tau$



- **The $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair. Selection $y_1 y_2 > 0$ is used in the left plot and the opposite sign selection $y_1 y_2 < 0$ 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.**
- **The a_1 channel still need many improvements.**

Summary and Outlook

- **There is little hope to check Higgs boson parity using $H/A \to \tau^+\tau^-; \tau^\pm \to \pi^\pm \bar{\nu}_\tau(\nu_\tau)$ decay chain.**
- **The $\rho^+\rho^-$ decay products' acoplanarity distribution clearly distinguish the different parity states $-$ measurable using typical properties of a future detector at an e^+e^- linear collider.**
- **This technique is both model independent and independent of the Higgs production mechanism. Depends only on good measurements of the Higgs decay products.**
- **This method may be applicable to other production modes including those available at proton colliders as well as at electron colliders.**
- **We demonstrated that the impact parameter method in one prong τ decay is useful for the measurement of the Higgs boson parity $-$ from $\sim 3\,\sigma$ to $\sim 4.5\,\sigma$.**
- **Other final states such as $\tau^\pm \to \pi^\pm\pi^+\pi^-\bar{\nu}_\tau(\nu_\tau)$ can be used to increase the statistical samples.**

τ production and decay process in the MC

- **The cross section for the process**

$$e^+(p_1)e^-(p_2) \to \tau^+(q_1,s_1)\tau^-(q_2,s_2)$$

$$d\sigma = |A|^2(1 + R_{\mu\nu}s_1^\mu s_2^\nu)dLips(p_1+p_2;q_1,q_2)$$

$|A|^2$ — **the spin averaged matrix element squared.**

- **The partial width for the $\tau^\pm$ decay is given by**

$$\tau^+(q_1) \to \bar{\nu}_\tau(k_1)\nu_e(k_2)e^-(k_3)$$

$$d\Gamma_e = \frac{1}{2M}|\bar{\mathcal{M}}|^2(1 + h_{1\mu}s_1^\mu)dLips(q_1;k_1,k_2,k_3)$$

$$\tau^-(q_2) \to \nu_\tau(k_1^{'})\bar{\nu}_e(k_2^{'})e^+(k_3^{'})$$

$$d\Gamma_e = \frac{1}{2M}|\bar{\mathcal{M}}^{'}|^2(1 + h_{2\mu}s_2^\mu)dLips(q_2;k_1^{'},k_2^{'},k_3^{'})$$

- **The cross section for the combined production and decay process can therefore be written as follows**

$$d\sigma = |A|^2|\bar{\mathcal{M}}|^2|\bar{\mathcal{M}}^{'}|^2(1 + R_{\mu\nu}h_1^\mu h_2^\nu)$$
$$dLips(p_1+p_2;q_1,q_2)dLips(q_1;k_1,k_2,k_3)dLips(q_2;k_1^{'},k_2^{'},k_3^{'})$$

General formalism for semileptonic decays

- **The matrix element for $\tau(P,s) \to \nu_\tau(N) + X$**

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}(N)\gamma^\mu(v + a\gamma_5)u(P)J_\mu$$

- **The squared matrix element reads:**

$$|\mathcal{M}|^2 = G^2 \frac{v^2 + a^2}{2}(\omega + H_\mu s^\mu)$$

$$\omega = P^\mu(\Pi_\mu - \gamma_{va}\Pi^5_\mu)$$

$$H_\mu = \frac{1}{M}(M^2\delta^\nu_\mu - P_\mu P\nu)(\Pi^5_\nu - \gamma_{va}\Pi_\nu)$$

$$\Pi_\mu = 2\left((J^* \cdot N)J_\mu + (J \cdot N)J^*_\mu - (J^* \cdot J)N_\mu\right)$$

$$\Pi^{5\mu} = 2\epsilon^{\mu\nu\rho\sigma}\, \mathcal{I}m J^*_\nu J_\rho N_\sigma$$

$$\gamma_{va} = -\frac{2va}{v^2 + a^2}$$

- **When $\gamma_{va} = 1$ and $v^2 = a^2$ the polarimeter vector h in the τ rest frame reads:**

$$h_\mu = \frac{H_\mu}{\omega}$$

Beamstrahlung effects

	TESLA	NLC/JLC
E_{CM} (GeV)	500	500
RF frequency (GHz)	1.3	11.4
Repetition rate (Hz)	5	120
Luminosity (10^{34} cm^{-2}sec^{-1})	3.4	2.2
Bunch separation (ns)	337	1.4
Effective gradient (MV/m)	22	50.2
Beamstrahlung (%)	3.3	4.6
Linac length (km)	31	10.8

Table 1: Parameters of TESLA and NLC/JLC accelerator designs.

- **At future linear e^+e^- colliders with center of mass energies of $350\ GeV$ and above, beamstrahlung will become of significant physical interest.**
- **It occurs when particles of the first beam, or radiating beam, are deflected by the electromagnetic field of the second (target) beam and emit synchrotron radiation.**
- **Beamstrahlung may carry away a substantial fraction of primary beam energy and lead to a degradation of the effective center of mass energy for e^+e^- collisions.**
- **The lower energy e^+e^- and γ's contribute to background processes.**