CP Nature Of Higgs Bosons From Decays To τ Leptons

Małgorzata Worek

Institute of Nuclear Physics, Cracow, Poland

G. Bower (SLAC), K. Desch (Hamburg U.), A. Imhof (DESY)

T. Pierzchała (Silesia U.) and Z. Wąs (Cracow, INP & CERN)

Points:

- Interface of TAUOLA τ-lepton decay library with complete spin effects for τ leptons originating from spin zero particle.
- $\tau^{\pm} \rightarrow \pi^{\pm} \bar{\nu}_{\tau} (\nu_{\tau})$ decay channel.
- Physical observable used to distinguish between scalar and pseudoscalar Higgs boson in $\tau^{\pm} \rightarrow \rho^{\pm} \bar{\nu}_{\tau} (\nu_{\tau})$ decay.
- τ flight direction as a probe to optimize the method.
- Properties of the density matrix for $H_{mix} \rightarrow \tau^{+}\tau^{-}$ decay.
- Definition of the observable in $\tau^{\pm} \rightarrow \rho^{\pm} \nu_{\tau} \rightarrow \pi^{\pm}\pi^{0} \nu_{\tau}$ decay chain.
- Monte Carlo set-up.
- Results with an idealized detector set-up and with realistic assumptions.
- Summary and Outlook.

Main References

- *Published Papers:*
  - T. Pierzchała, E. Richter-Wąs, Z. Wąs, M. Worek. Acta Phys. Polon. **B32**, 1277 (2001).
  - Z. Wąs, M. Worek. Acta Phys. Polon. **B33**, 1875 (2002).
  - G. R. Bower, T. Pierzchała, Z. Wąs, M. Worek. Phys. Lett. **B543**, 227 (2002).
  - K. Desch, Z. Wąs, M. Worek. Eur. Phys. J. **C29**, 491 (2003).

- *Article In Press:*
  - K. Desch, A. Imhof, Z. Wąs, M. Worek.
    "Probing the CP nature of the Higgs boson at linear colliders with tau spin correlations; the case of mixed scalar–pseudoscalar couplings".
    Phys. Lett. **B**.

Motivation

Any LC Programme Must Include Higgs Boson Parity Measurement

- Many scenarios of Higgs mechanism: $\mathcal{SM}$, $\mathcal{MSSM}$, $\mathcal{2HDM}$, ...
  - $\mathcal{CP}$ conserving $\Longrightarrow$ mass eigenstates $=$ $\mathcal{CP}$ eigenstates.
  - $\mathcal{CP}$ violating $\Longrightarrow$ mass eigenstates $\neq$ $\mathcal{CP}$ eigenstates.
- Major goal to distinguish among these models.
- Estimate precision of the scalar–pseudoscalar mixing angle.
- Even if one doublet $\mathcal{SM}$ is a good model

  $\Longrightarrow$ determine that the observed Higgs boson is indeed $\mathcal{CP}$ even in nature.

Motivation

- Many possibilities for the measurement.

  $\Longrightarrow$ Model dependent.

  $\Longrightarrow$ Higgs boson production mechanism dependent.

  $\Longrightarrow$ Higgs boson rest frame reconstruction required.

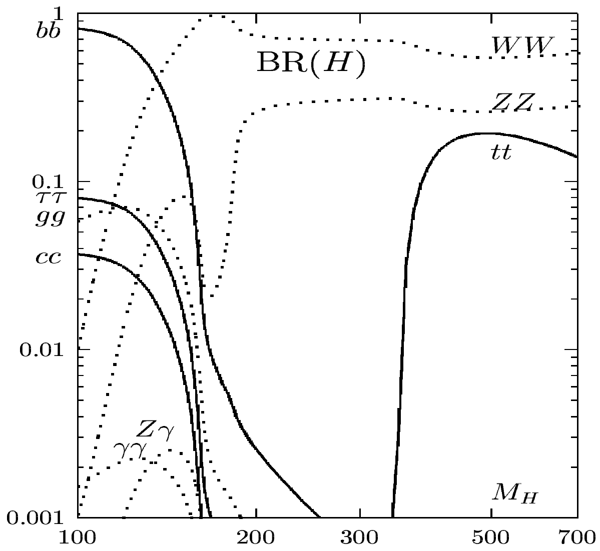
- We will concentrate on $H \to \tau^+\tau^-$ decay.

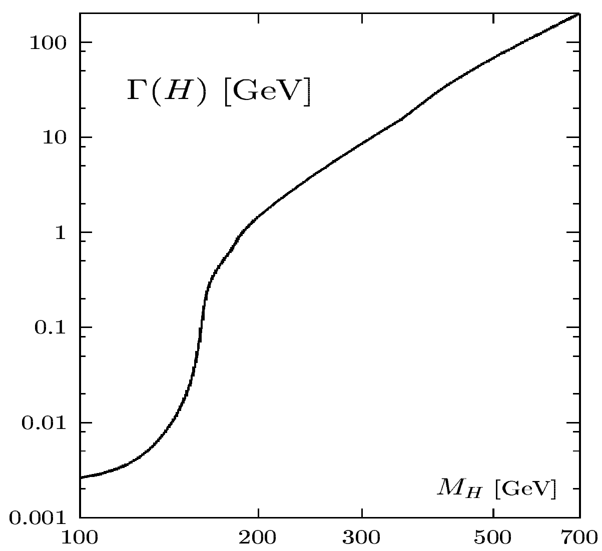
  $\Longrightarrow$ Only measurement of Higgs boson couplings to fermions.

  $\Longrightarrow$ This measurement is to a large degree production independent.

  $\Longrightarrow$ Replace Higgs boson rest frame reconstruction.

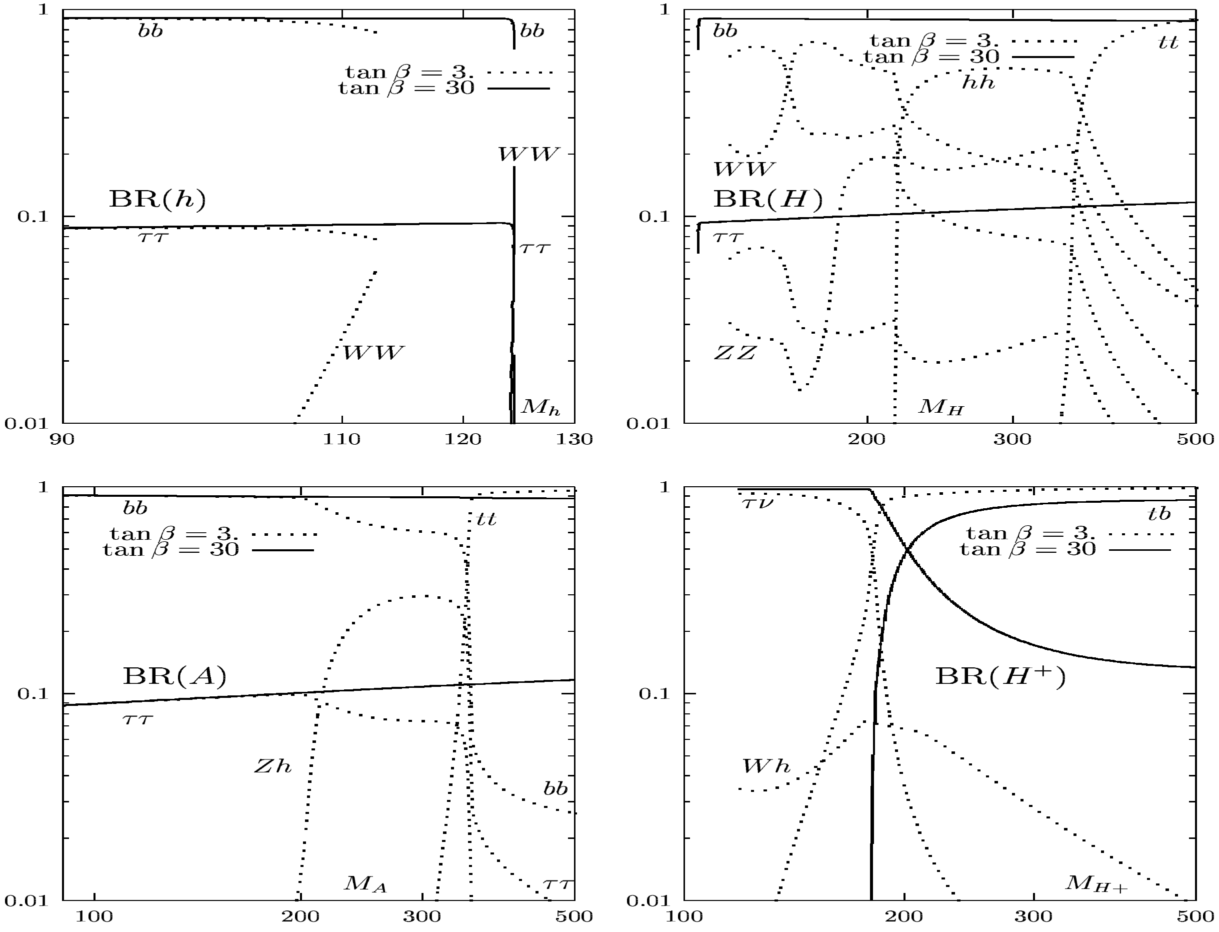
Main Branching Ratios Of SM Higgs Boson





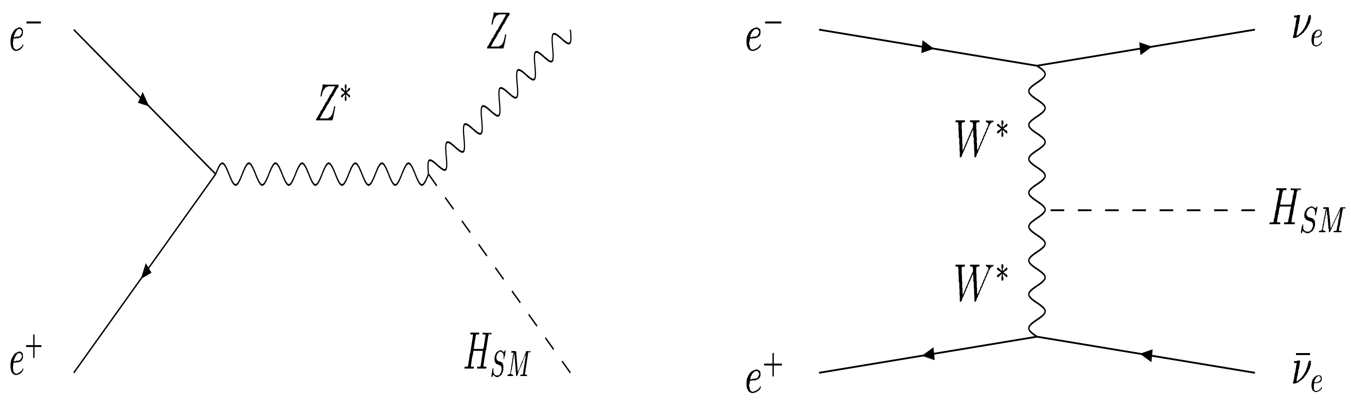
- *The most frequent fermion decay mode is* $b\,\bar{b}$ *channel,* $\mathcal{BR}(H \to b\bar{b}) \sim 90\%$.
- But *fragmentation process destroys the* b *spin informations.*
- *Next available channel is then* $\tau^+\tau^-$, $\mathcal{BR}(H \to \tau^+\tau^-) \sim 9\%$.
- *Useful for* $m_H \sim 140\ GeV$. *Higgs is very narrow,* $\Gamma(H) \leq 10\ MeV$.

Main Branching Ratios Of MSSM Higgs Boson



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

Production Mechanism Of SM Higgs Boson



- *Main production mechanisms of the SM Higgs boson at e^+e^- colliders.*

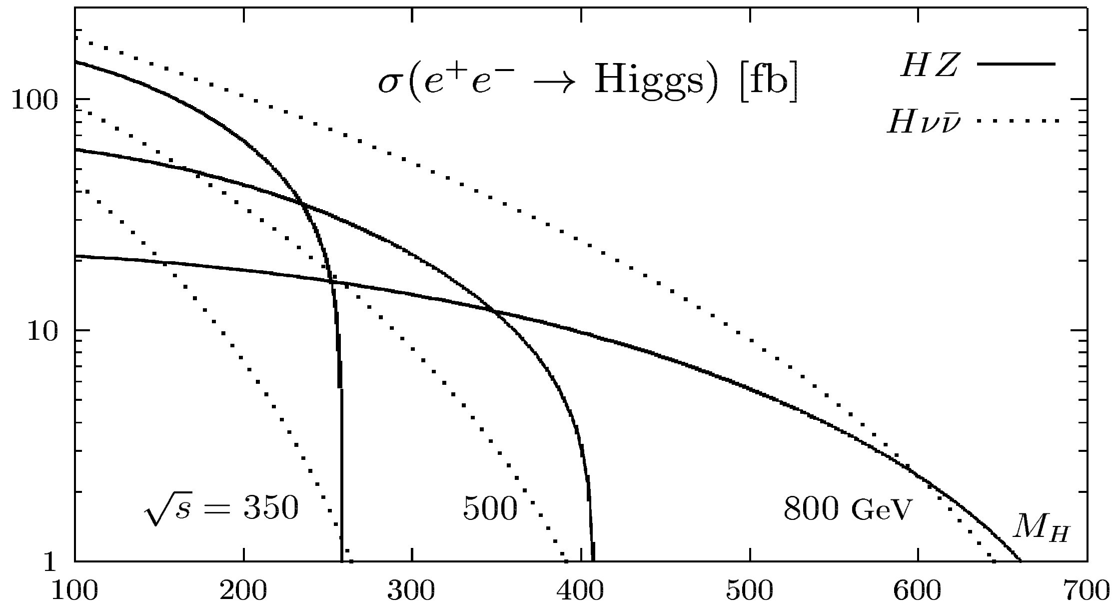
Higgsstrahlung $\longrightarrow$ at low energies.

WW fusion $\longrightarrow$ at high energies.

$$\sigma(e^+e^- \to ZH) \sim 1/s$$

$$\sigma(e^+e^- \to \bar{\nu}_e \nu_e H) \sim \log(s/M_H^2)$$

Production Mechanism Of SM Higgs Boson At LC



- The cross-sections for Higgstrahlung and WW fusion processes for three values of $\sqrt{s}$.
- At $\sqrt{s} = 500$ GeV Higgstrahlung and WW fusion processes have approximately the same cross-section for 100 $GeV \leq M_H \leq 200$ GeV.

Parity Of Higgs Boson

- H/A parity information can be extracted from the correlations between τ^+ and τ^- spin components in the plane transverse to the $\tau^+\tau^-$ axes.

$$\Gamma(H/A^0 \to \tau^+\tau^-) \sim 1 - s_{\parallel}^{\tau^+} s_{\parallel}^{\tau^-} \pm s_{\perp}^{\tau^+} s_{\perp}^{\tau^-}$$

- s^τ is the τ polarization vectors.
- $\parallel / \perp$ denote components parallel / transverse to the Higgs boson momentum.

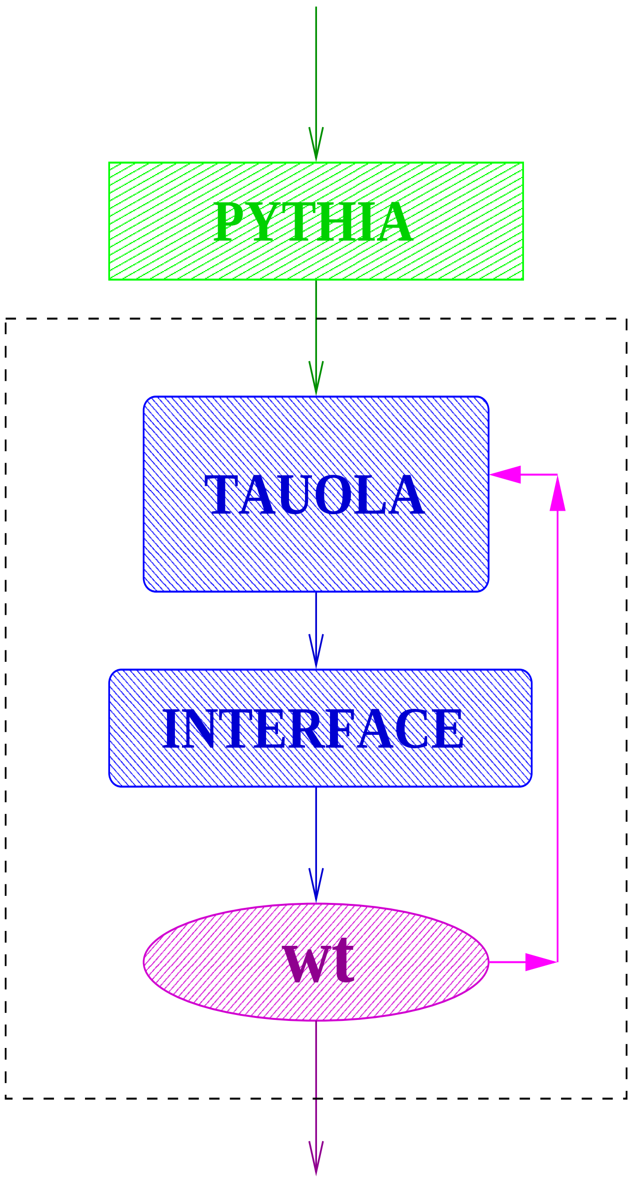
$$wt = \frac{1}{4}\left(1 + \sum_{ij=1}^{3} R_{ij} h^i h^j\right)$$

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

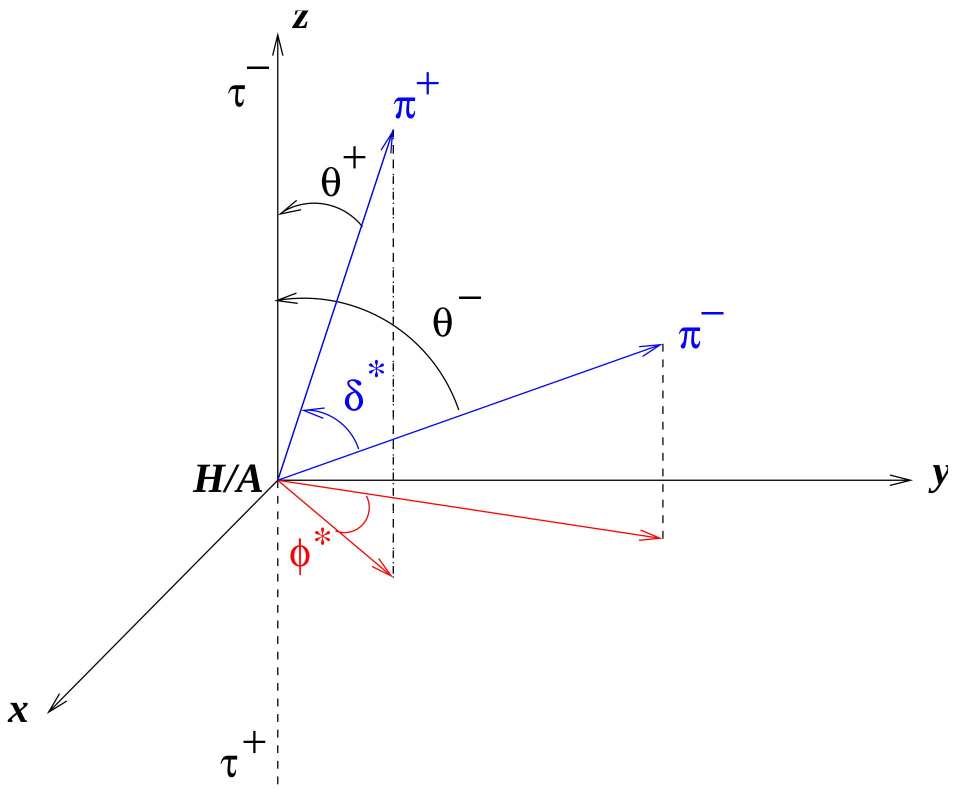
- Components respectively for scalar and pseudoscalar Higgs boson.

Monte Carlo Generation

- The algorithm is organized in two steps:
  1. First Step
     - $\tau^+\tau^-$ lepton pair is generated
     - $\tau^\pm$ leptons decay in their respective rest frames, no spin effects at all
  2. Second Step
     - spin weight is calculated and rejection is performed.
     - If the event is rejected, only the generation of the τ lepton decays is repeated.
- $wt = \frac{1}{4}\left(1 + \sum_{ij=1}^{3} R_{ij} h^i h^j\right)$



Angular Correlation Of Tau Decay Products

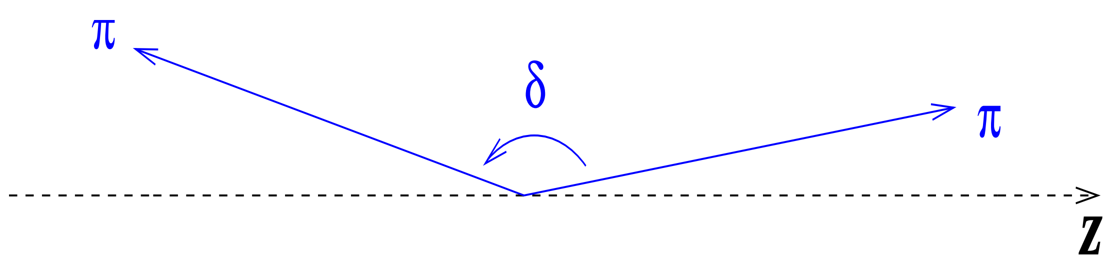


$$\frac{1}{\Gamma}\frac{d\Gamma(H/A^0 \to \pi^+\bar{\nu}_\tau\pi^-\nu_\tau)}{d\cos\theta^+ \, d\cos\theta^- \, d\phi^*} = \frac{1}{8\pi}\left[1 + \cos\theta^- \cos\theta^+ \mp \sin\theta^+ \sin\theta^- \cos\phi^*\right].$$

$$\frac{1}{\Gamma}\frac{d\Gamma(H/A^0)}{d\phi^*} = \frac{1}{2\pi}\left[1 \mp \frac{\pi^2}{16}\cos\phi^*\right].$$

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

- Case of $\tau \longrightarrow \pi\nu_{\tau}$ decay, $\mathcal{BR}(\tau \to \pi\nu_{\tau}) = 11\%$.
- Sensitivity to the parity of the Higgs reflected in angular correlations of secondary decay products.
- The polarimeter vector in the τ rest frame is given by the formula $\tilde{h} = -\tilde{n}_{\pi}$ where $\tilde{n}$ denotes the unit vector into the direction of flight of the pion.



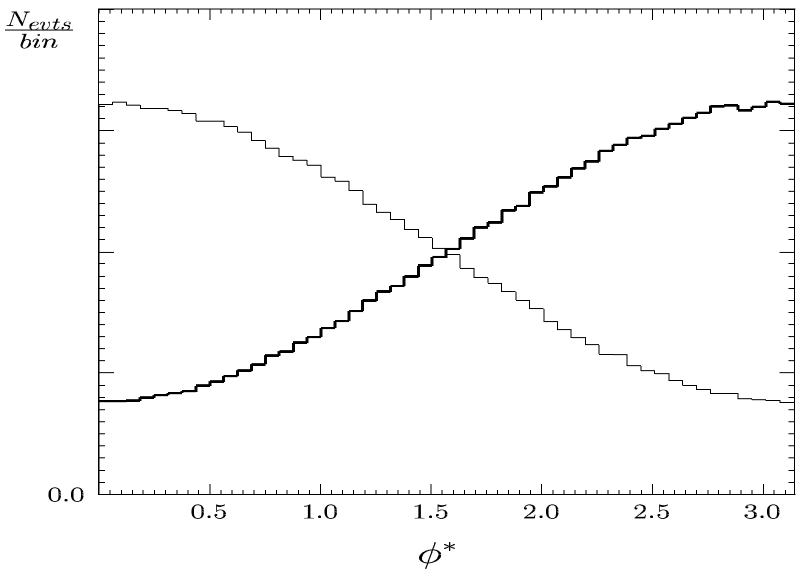
- Useful observable is the angle δ between the two charged pions in the Higgs rest frame (acollinearity distribution of $\pi^{+}\pi^{-}$ from $\tau^{\pm}$ decays).

Monte Carlo Set-up

- Monte Carlo samples $\Longrightarrow$ TAUOLA τ lepton decay library.
- Production of the τ lepton pairs $\Longrightarrow$ PYTHIA.
- Production process $\Longrightarrow$ $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-(q\bar{q})H.$
- Higgs boson mass $\Longrightarrow$ $m_H = 120\ GeV.$
- CMS energy $\Longrightarrow$ $\sqrt{s} = 350\ GeV.$
- The effects of ISR $\Longrightarrow$ in PYTHIA generation.
- τ lepton pair decay with full spin effects in decay chain
  $H \rightarrow \tau^+\tau^-,\ \tau^\pm \rightarrow \pi^\pm\bar{\nu}_\tau(\nu_\tau)$ $\Longrightarrow$
  $\Longrightarrow$ UNIVERSAL INTERFACE FOR TAUOLA PACKAGE.
- Detector effects $\Longrightarrow$ Gaussian spreads of the measured quantities with respect to the generated ones $\Longrightarrow$ verified with SIMDET.

Acoplanarity Distribution For $\tau \to \pi \nu_\tau$

$\mathcal{BR}(\tau \to \pi \nu_\tau) = 11\%.$

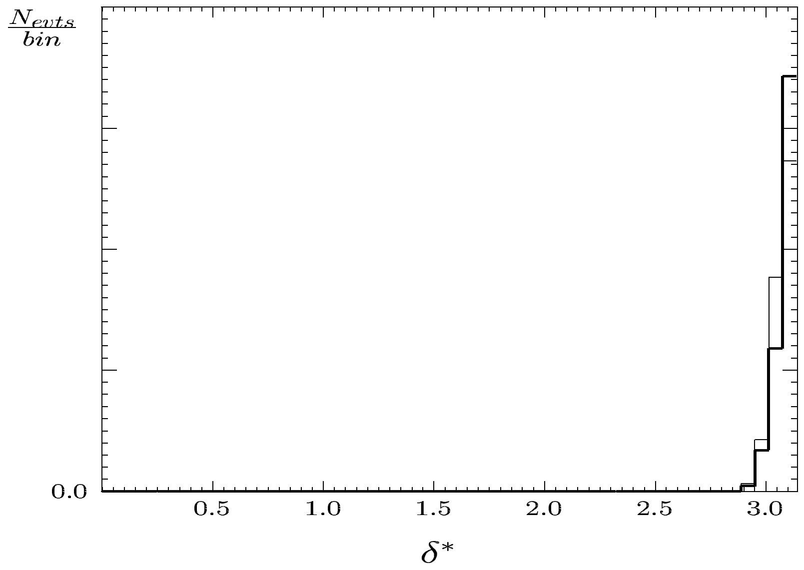


- $\pi^+\pi^-$ acoplanarity distribution in Higgs boson rest frame. Thick line for scalar Higgs boson and thin line for pseudoscalar.

$$\phi^* = \arccos(\tilde{n}^+ \cdot \tilde{n}^-)$$

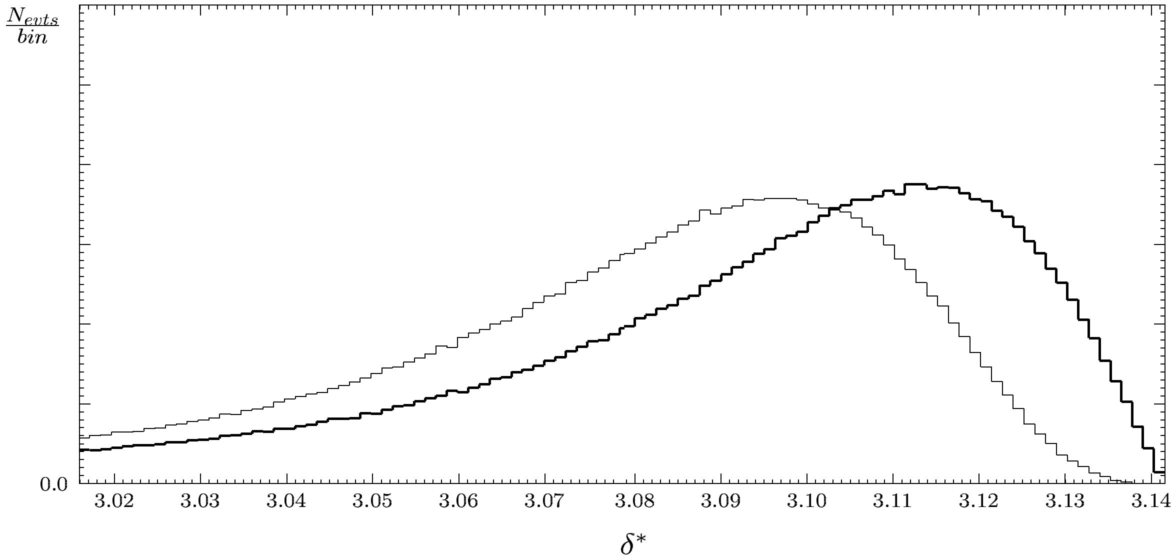
$$\tilde{n}^\pm = \frac{\tilde{p}^{\,\pi^\pm} \times \tilde{p}^{\,\tau^-}}{|\tilde{p}^{\,\pi^\pm} \times \tilde{p}^{\,\tau^-}|}$$

Acollinearity Distribution For $\tau \rightarrow \pi \nu_\tau$



- $\pi^+\pi^-$ acollinearity distribution in Higgs boson rest frame.
- Full angular range $0 < \delta^* < \pi$ is shown.
- Thick line for scalar Higgs boson and thin line for pseudoscalar one.

Acollinearity Distribution For $\tau \to \pi \nu_\tau$

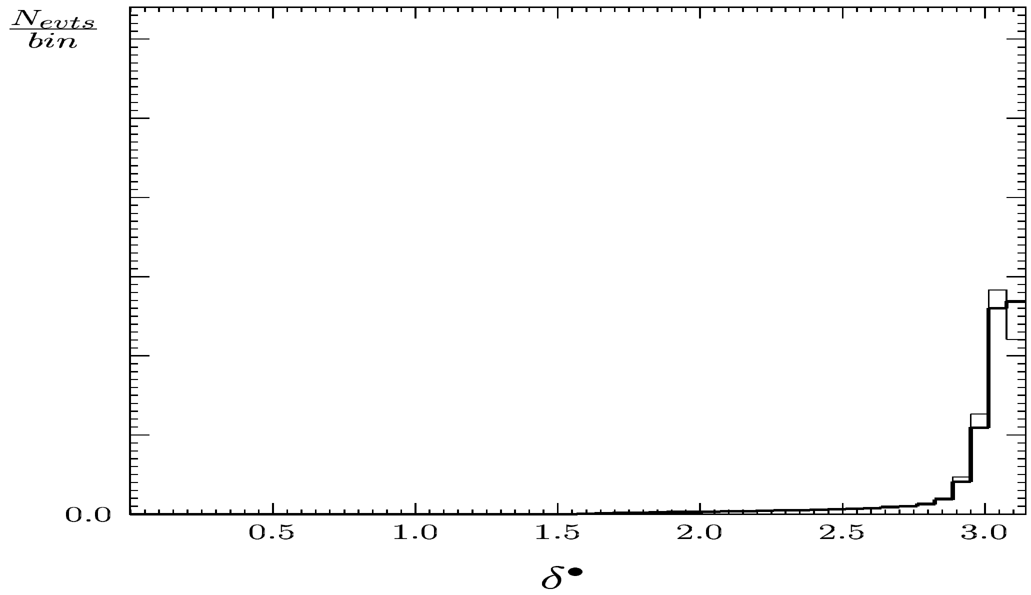


- $\pi^+\pi^-$ acollinearity distribution in Higgs boson rest frame.
- Parts of distribution close to the end of spectrum $\delta^* \sim \pi$.
- Thick line for scalar Higgs boson and thin line for pseudoscalar one.

Detector Effects

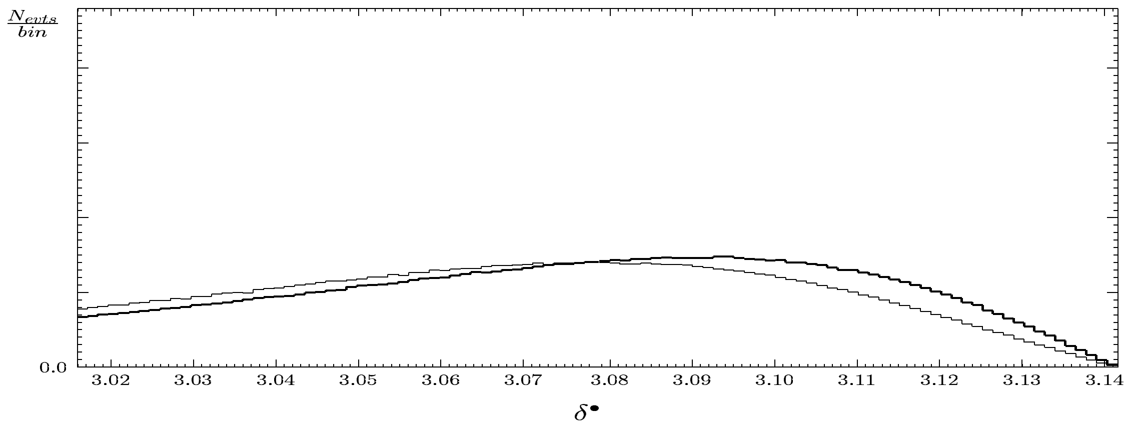
- *Gaussian spreads of 'measured' quantities with respect to generated ones. For charged pion momentum we assume* 0.1% *spread on its energy and direction.*
- *Higgs rest frame reconstructed in Higgsstrahlung production process,* $e^+e^- \to HZ$ – *when* Z *boson decays either into a charged lepton pair or hadronically.*
- *Reconstructed Higgs boson momentum – difference of the sum of beam momenta and momenta of all visible particles, decay products of* Z *and all radiative photons of* $|\cos\theta| < 0.98$.
- *Spread of* $2\ GeV$ *with respect to transverse momentum of reconstructed Higgs boson momentum, and* $5\ GeV$ *for longitudinal component, to mimic beamstrahlung effect.*

Acollinearity Distribution For $\tau \to \pi \nu_\tau$



- $\pi^+\pi^-$ acollinearity distribution in reconstructed Higgs boson rest frame.
- Smearing is included.
- Full angular range $0 < \delta^\bullet < \pi$ is shown.
- The thick line for scalar Higgs boson and thin line for pseudoscalar one.

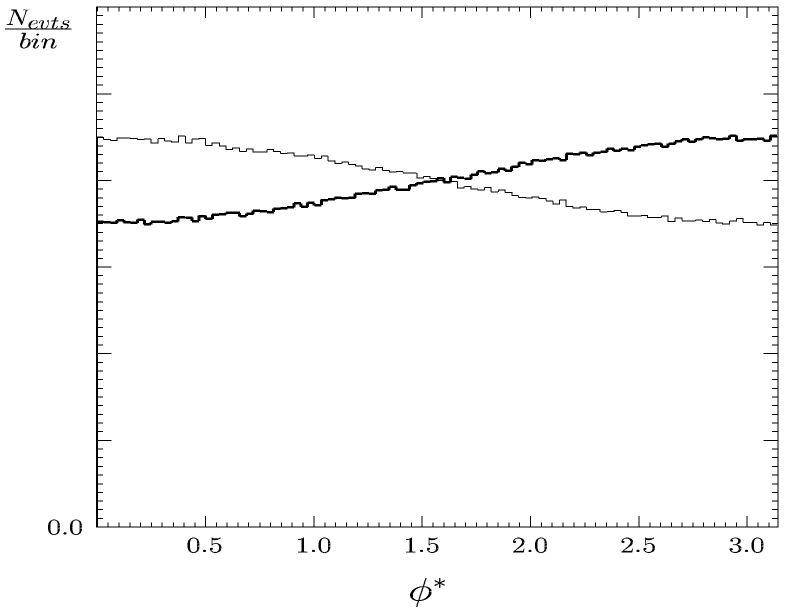
Acollinearity Distribution For $\tau \to \pi \nu_\tau$



- Parts of the distribution close to the end of the spectrum – $\delta^\bullet \sim \pi$.
- Thick line for scalar Higgs boson and thin line for pseudoscalar one.
- 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.

Angular Distribution For $\tau \to \rho \nu_\tau$

$\mathcal{BR}(\tau \to \rho \nu_\tau) = 25\%.$

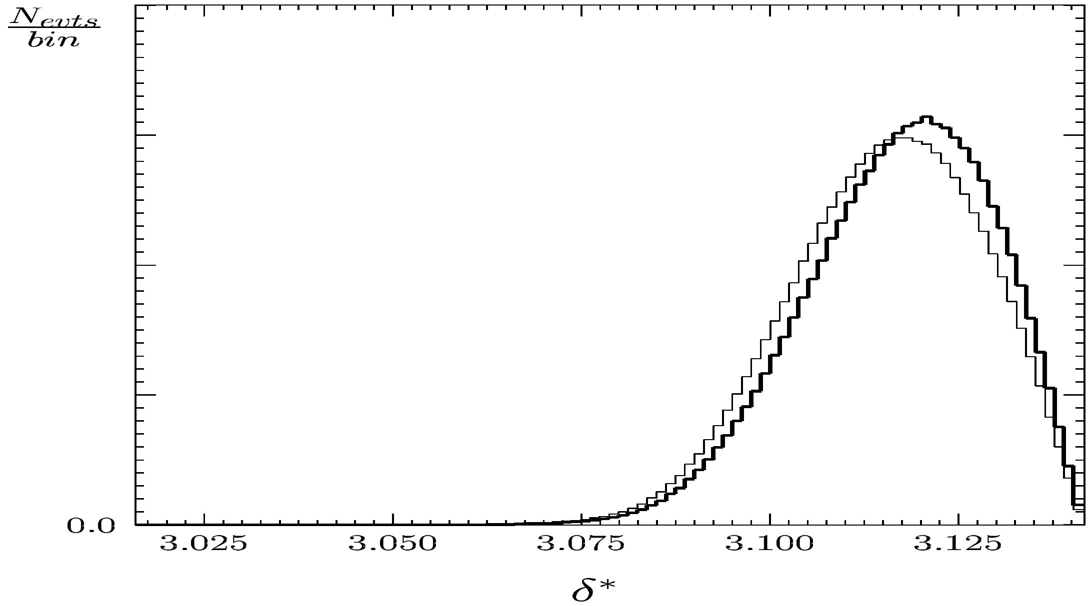


- $\rho^+ \rho^-$ acoplanarity distribution in Higgs boson rest frame.
- Angular correlation term reduced by factor $(m_\tau^2 - 2Q^2)^2/(m_\tau^2 + 2Q^2)^2$.

$$\phi^* = \arccos(\tilde{n}^+ \cdot \tilde{n}^-)$$

$$\tilde{n}^\pm = \frac{\tilde{p}^{\,\rho^\pm} \times \tilde{p}^{\,\tau^-}}{|\tilde{p}^{\,\rho^\pm} \times \tilde{p}^{\,\tau^-}|}$$

Acollinearity Distribution For $\tau \rightarrow \rho\nu_\tau$



- $\rho^+\rho^-$ *acollinearity distribution in Higgs boson rest frame.*
- *Parts of distribution close to the end of spectrum* $\delta^* \sim \pi$.
- *Thick line for scalar Higgs boson and thin line for pseudoscalar one.*

Detector Effects

Gaussian spreads of 'measured' quantities with respect to 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 $\frac{1}{3}\frac{2\pi}{1800}$.
- Replacement τ rest frames:

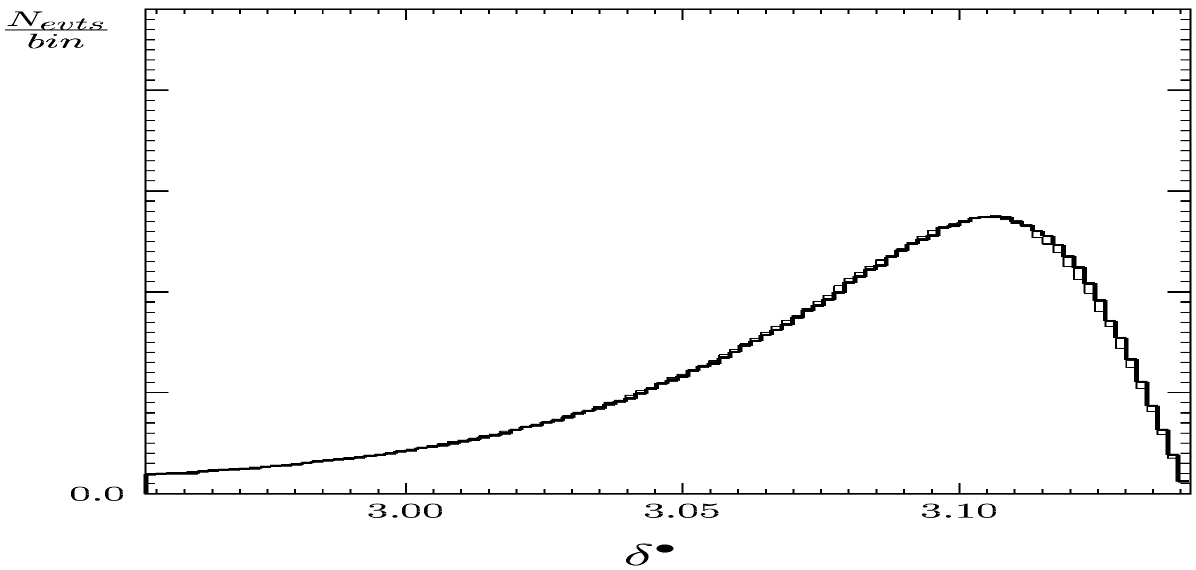
$\Longrightarrow$ In the r.f. of $\rho^+\rho^-$ pair define $\tau^\pm$ momenta along direction of $\rho^\pm$.

$\Longrightarrow$ For $\tau^\pm$ energies take half of the Higgs boson mass.

$\Longrightarrow$ Boost $\pi^+, \pi^0, \pi^-, \pi^0$ momenta to replacement τ rest frames.

$\Longrightarrow$ π energies defined this way are used in energy difference cuts.

Acollinearity Distribution For $\tau \to \rho\nu_\tau$



- $\rho^+\rho^-$ acollinearity distribution in Higgs boson rest frame.
- Thick line for scalar Higgs boson and thin line for pseudoscalar one.
- Difference between scalar and pseudoscalar Higgs practically invisible once detector smearings are introduced.

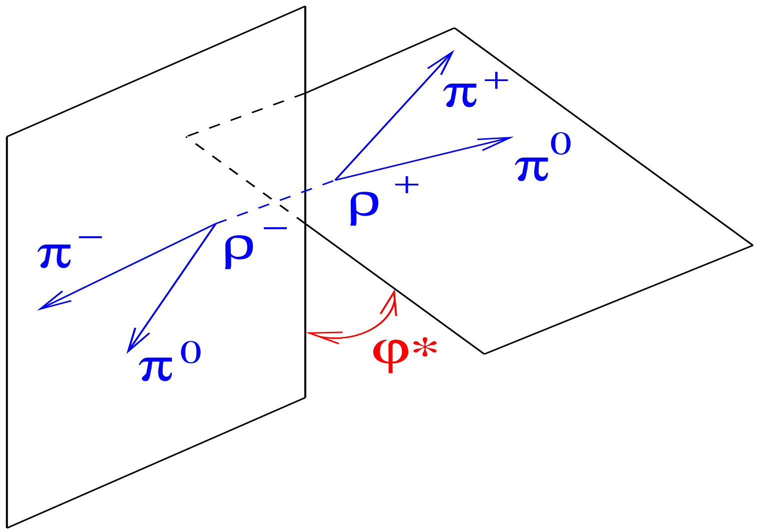
Pure Scalar And Pseudoscalar Higgs Boson

- Case of $\tau \longrightarrow \rho\nu_\tau$ decay, $\mathcal{BR}(\tau \rightarrow \rho\nu_\tau) = 25\%$.
- The polarimeter vector, q for $\pi^{\pm} - \pi^{0}$, N for ν_τ

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

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

- Acoplanarity of the $\rho^{\pm}$ decay products in $\rho^{+}\rho^{-}$ r.f. and events separation.



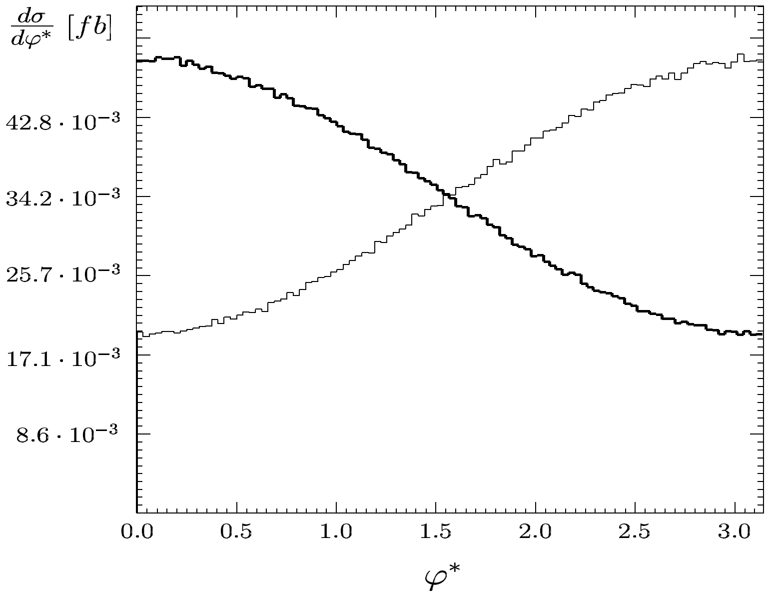
$$y_1 y_2 > 0\,; \qquad y_1 y_2 < 0$$

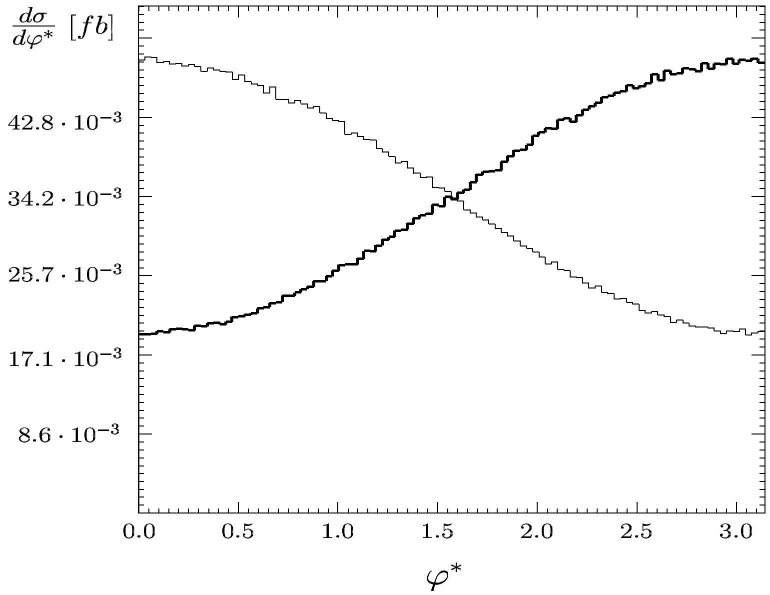
$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}\,; \qquad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}$$

Monte Carlo Set-up

- Monte Carlo samples $\Longrightarrow$ TAUOLA τ lepton decay library.
- Production of the τ lepton pairs $\Longrightarrow$ PYTHIA.
- Production process $\Longrightarrow$ $e^+e^- \to ZH \to \mu^+\mu^-(q\bar{q})H$.
- Higgs boson mass $\Longrightarrow$ $m_H = 120\ GeV$.
- CMS energy $\Longrightarrow$ $\sqrt{s} = 500\ GeV$.
- The effects of ISR $\Longrightarrow$ in PYTHIA generation.
- τ lepton pair decay with full spin effects in decay chain
  $H \to \tau^+\tau^-,\ \tau^\pm \to \rho^\pm\bar{\nu}_\tau(\nu_\tau),\ \rho^\pm \to \pi^\pm\pi^0 \Longrightarrow$
  $\Longrightarrow$ UNIVERSAL INTERFACE FOR TAUOLA PACKAGE.
- Numerical results $\Longrightarrow$ confirmed with second simulation using PANDORA.

Results





- $\rho^+\rho^-$ decay products' acoplanarity distribution in the rest frame of $\rho^+\rho^-$ pair.
- Selection $y_1 y_2 > 0$ for left plot and the opposite $y_1 y_2 < 0$ for right plot.
- Thick lines for scalar Higgs boson and thin lines for pseudoscalar one.

Detector Effects

Gaussian spreads of ‘measured’ quantities with respect to 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 $\frac{1}{3}\frac{2\pi}{1800}$.
- Replacement τ rest frames:

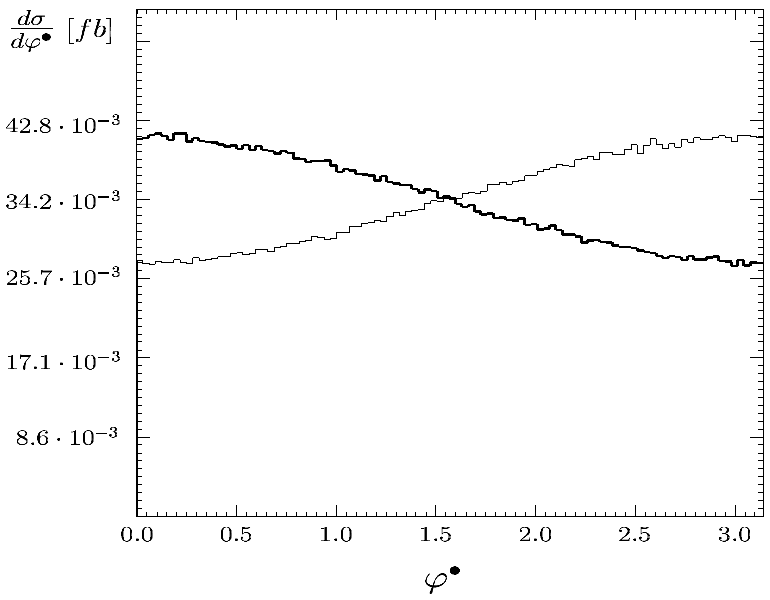
$\Longrightarrow$ In the r.f. of $\rho^+\rho^-$ pair define $\tau^\pm$ momenta along direction of $\rho^\pm$.

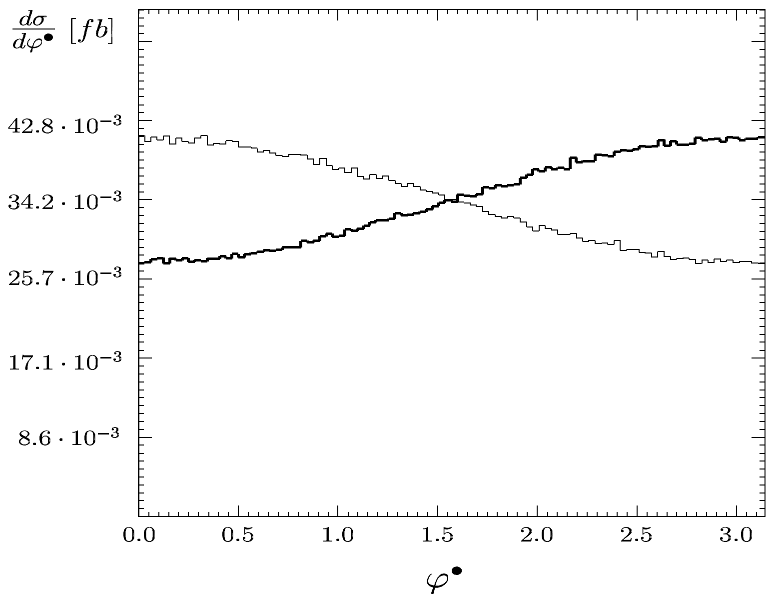
$\Longrightarrow$ For $\tau^\pm$ energies take half of the Higgs boson mass.

$\Longrightarrow$ Boost $\pi^+, \pi^0, \pi^-, \pi^0$ momenta to replacement τ rest frames.

$\Longrightarrow$ π energies defined this way are used in energy difference cuts.

Results After Detector Effects





- $\mathcal{CP}$ of Higgs boson can be measured to a confidence level greater than 95%.

$500\ fb^{-1}$

$m_H = 120\ GeV$

$\sqrt{s} = 500\ GeV$

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- H$

Summary And Outlook

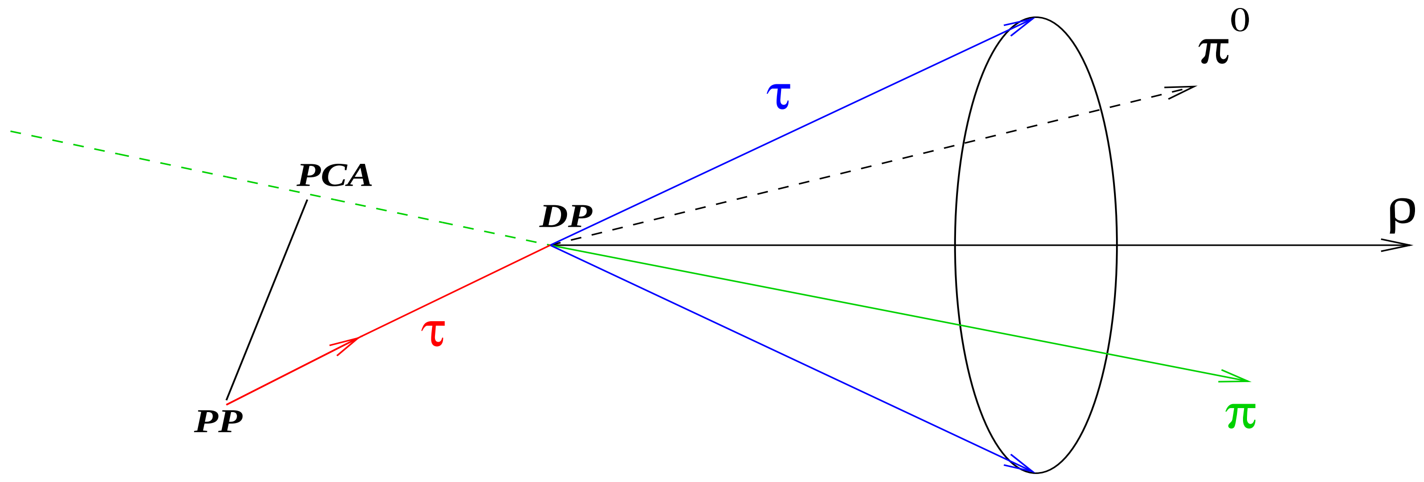
- Extended standard universal interface of the TAUOLA with the complete spin effects for τ leptons originating from the spin zero particle is now available.
- Interface works with any Monte Carlo generator providing Higgs boson production, and subsequent decay into a pair of τ leptons.
- Little hope for the elegant method to check Higgs boson parity using its decay to $\tau^{\pm} \to \pi^{\pm}\bar{\nu}_{\tau}(\nu_{\tau})$.
- 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.

Summary And Outlook

- For $500\ fb^{-1}$ of luminosity at a $\sqrt{s} = 500\ GeV$ $\mathcal{CP}$ of a 120 GeV Higgs boson can be measured to a confidence level greater than 95%.
- To confirm the method we have used two distinct Monte Carlo programs.
- 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.

τ Impact Parameter – Method Optimization

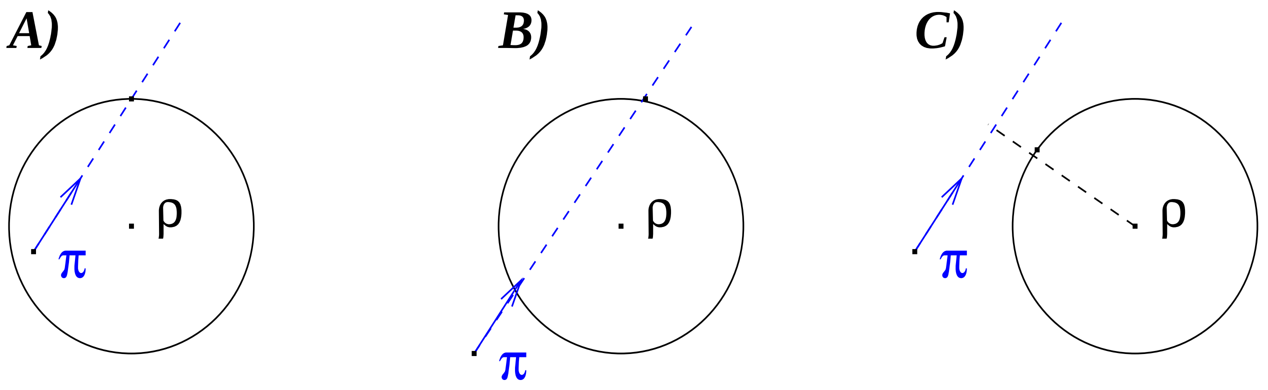
- Distance of closest approach of a decay product track to the τ production point.



- Determination of the direction of the impact parameter, where the production point can be localized with respect to the charged pion tack.
- 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.



- $\mathcal{A}$) π direction inside the circle — the solution is taken as the τ direction.
- $\mathcal{B}$) π direction outside the circle — one of the two solutions is taken on the random basis.
- $\mathcal{C}$) 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.

Details Of Observable

- Acoplanarity of the ρ^+ and ρ^- decay planes:
  - Reconstructed four-momenta of π^+ and π^0 are combined to yield the ρ^+ four-momentum. The same is done for the ρ^-.
  - All reconstructed four-momenta are boosted into the $\rho^+\rho^-$ rest frame.
  - The angle φ between the planes of the ρ^+ and ρ^- decay products in this frame is the acoplanarity.

- Normalized energy differences:
  - Events are divided into two classes depending on value of $y_1 y_2$.
  - $y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}$; $\quad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}$.
  - The energies of $\pi^\pm, \pi^0$ are to be taken in respective $\tau^\pm$ rest frames.

Details Of Observable

- *Higgs boson rest frame:*
  - Higgs boson rest frame can be reconstructed in the Higgsstrahlung production process $e^+e^- \to ZH;\ Z \to \mu^+\mu^-(q\bar{q});\ H \to \tau^+\tau^-$.
  - 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 $|\cos\theta| < 0.98$.
- *τ energy:*
  - In reconstructed Higgs boson rest frame τ four-momenta are estimated in a crude way by assuming the direction of the respective ρ's and an energy of $m_H/2$.
  - The τ momenta are boosted back to laboratory frame and their energies are taken to be reconstructed energies of τ leptons.

Details Of Observable

- τ direction:
  - τ direction in the laboratory system is constrained by two requirements.
  - It has to lie on a cone around the ρ direction with opening angle ψ:

$$\cos\psi = \frac{2E_\tau E_\rho - m_\tau^2 - m_\rho^2}{2\vec{p}_\tau \vec{p}_\rho},$$

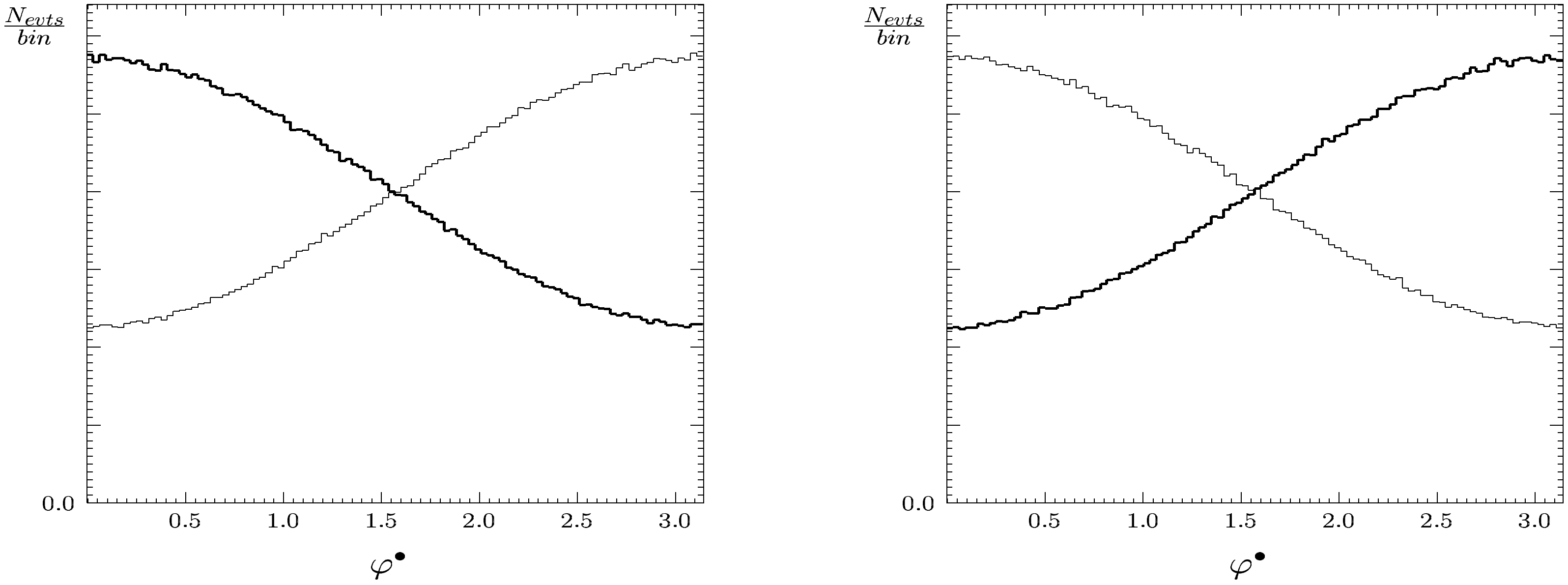
  - It has to lie in the plane spanned by the vector pointing from PP to PCA and the π^+ momentum.

- Impact parameter improved replacement τ-rest frame:
  - With the help of τ energy and τ momentum new impact parameter improved replacement τ rest frame can be defined.
  - Alternative way of estimating difference of $\pi^\pm$, π^0 energies in $\tau^\pm$ rest frames.

Monte Carlo Set-up

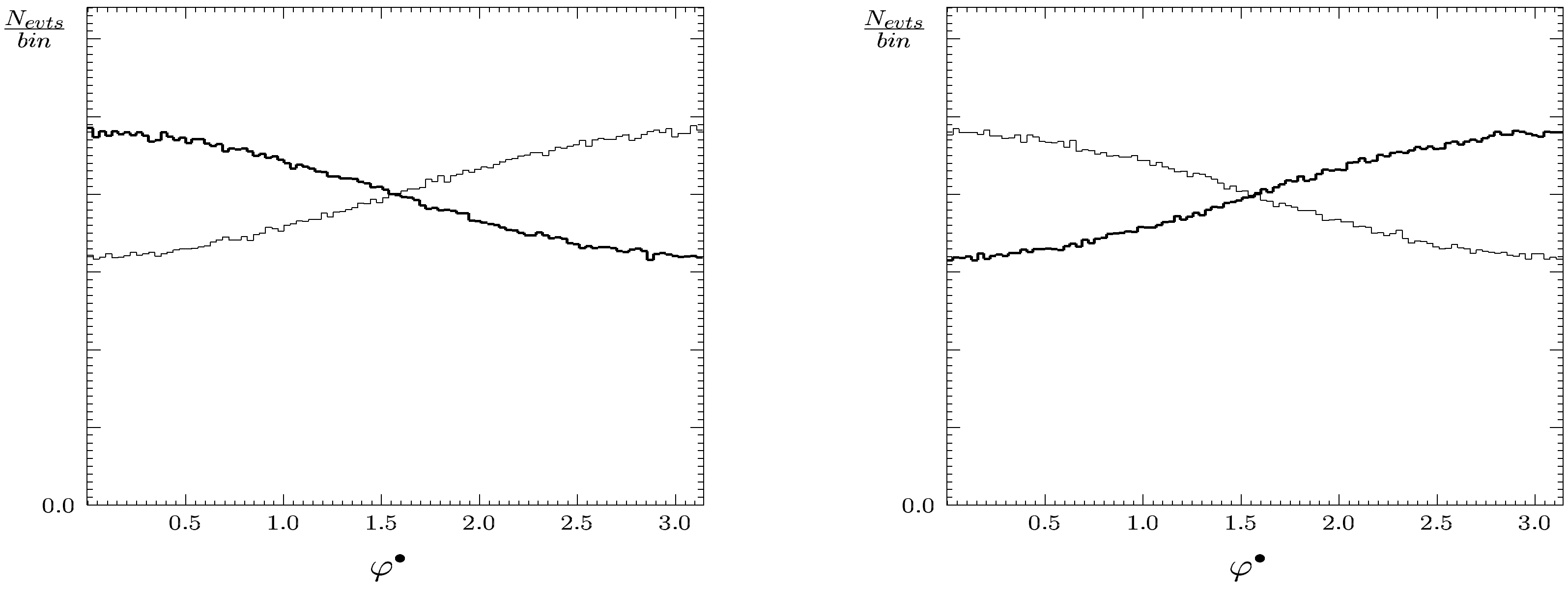
- Monte Carlo samples $\Longrightarrow$ TAUOLA τ lepton decay library.
- Production of the τ lepton pairs $\Longrightarrow$ PYTHIA.
- Production process $\Longrightarrow$ $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-(q\bar{q})H.$
- Higgs boson mass $\Longrightarrow$ $m_H = 120\ GeV.$
- CMS energy $\Longrightarrow$ $\sqrt{s} = 350\ GeV.$
- The effects of ISR $\Longrightarrow$ in PYTHIA generation.
- τ lepton pair decay with full spin effects in decay chain
  $H \rightarrow \tau^+\tau^-,\ \tau^\pm \rightarrow \rho^\pm\bar{\nu}_\tau(\nu_\tau),\ \rho^\pm \rightarrow \pi^\pm\pi^0 \Longrightarrow$
  $\Longrightarrow$ UNIVERSAL INTERFACE FOR TAUOLA PACKAGE.
- Detector effects $\Longrightarrow$ Gaussian spreads of the measured quantities with respect to the generated ones $\Longrightarrow$ verified with SIMDET.

Results With τ Impact Parameter



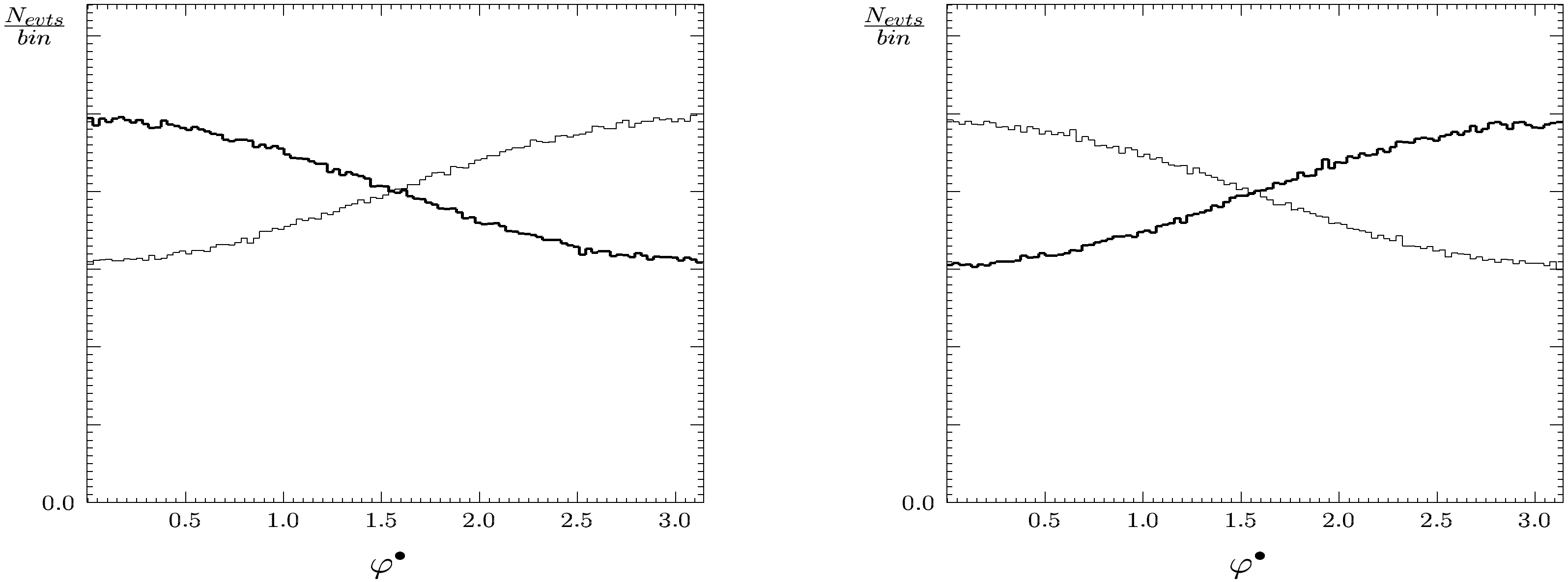
- $\rho^+\rho^-$ decay products' acoplanarity distribution in rest frame of $\rho^+\rho^-$ pair.
- Detector smearing and generator level $\tau^{\pm}$ rest frames.
- The thick for scalar Higgs boson, thin for pseudoscalar one. The left figure with $y_1 y_2 > 0$, right for $y_1 y_2 < 0$.

Results With τ Impact Parameter



- $\rho^+\rho^-$ decay products' acoplanarity distribution in rest frame of $\rho^+\rho^-$ pair.
- Detector smearing and replacement $\tau^{\pm}$ rest frames without τ impact parameter help.
- The thick for scalar Higgs boson, thin for pseudoscalar one. The left figure with $y_1 y_2 > 0$, right for $y_1 y_2 < 0$.

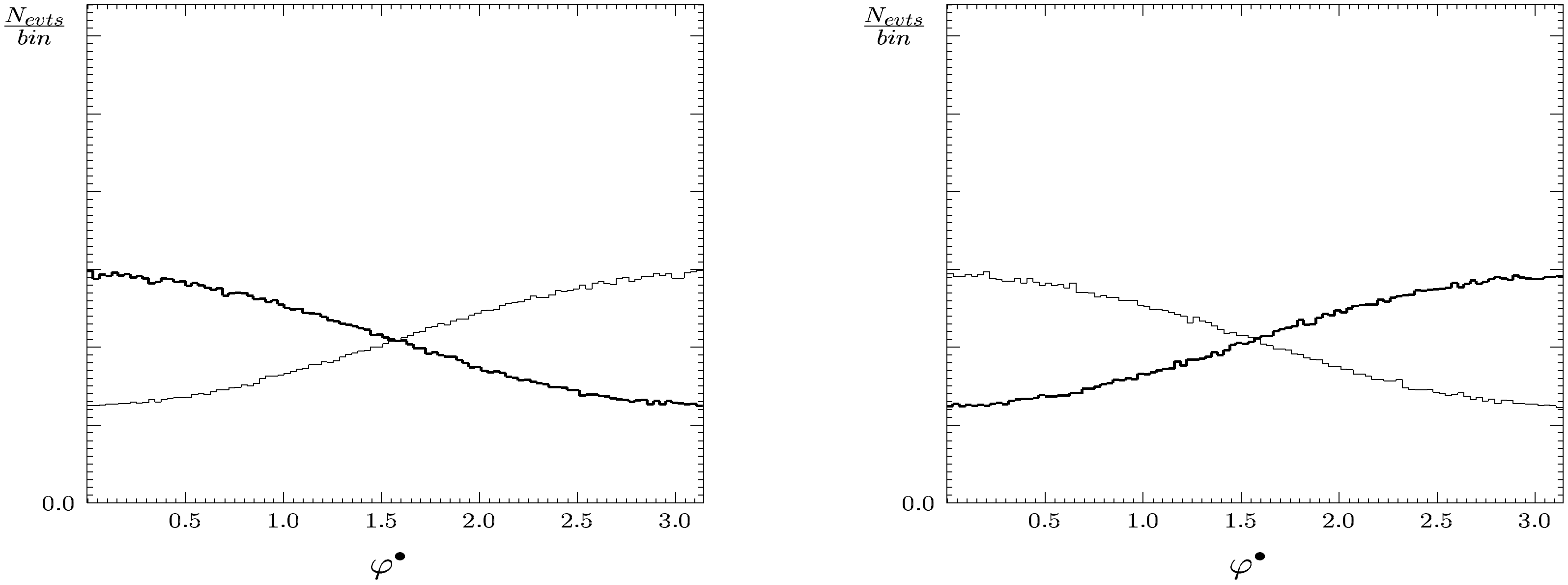
Results With τ Impact Parameter



- τ impact parameter is used in the reconstruction of the $\tau^{\pm}$ rest frames.
- Improvement $\sim$ 12%
- Gaussian spread of impact parameter.

$$\sigma_{IP} = 25^0$$

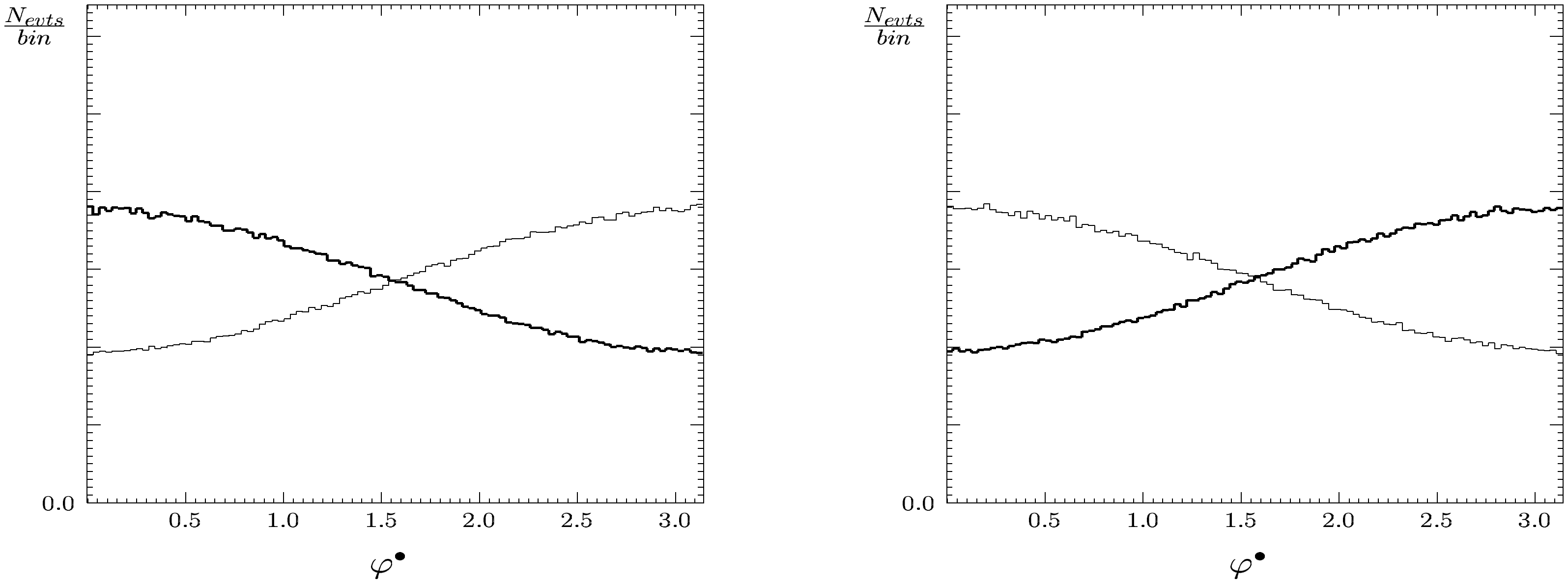
Results With τ Impact Parameter – Additional Cuts



- *Only events where the signs of y1 and y2 are the same whether calculated using the method without or with the help of the τ impact parameter.*
- *Improvement $\sim$ 107%.*
- *Only $\sim$ 52% events are accepted.*

Improvement: $\sim 4.5\sigma$

Results With τ Impact Parameter



- *Cuts depending on the position of the pion with respect to the* τ *cone.*
- *In case of single solution events result from old method ignored.*
- *Improvement* $\sim 67\%$.
- *The number of accepted events* $\sim 72\%$.

Summary And Outlook

- Measurement of impact parameter can be helpful in determination of Higgs boson parity at a future linear collider, using $H/A \to \tau^+\tau^-$; $\tau^\pm \to \rho^\pm \bar{\nu}_\tau(\nu_\tau)$ cascade decay.
- Separation between scalar and pseudoscalar for 120 GeV Standard Model Higgs boson $\sim 4.5\sigma$.
- Angular resolution of vector pointing from PP to PCA has been found to be approximately 25°.

Spin Weight For Mixed Scalar–Pseudoscalar Case

- Mixed scalar and pseudoscalar couplings of the Higgs to $\tau\tau$ are allowed.
- Measurement of the pseudoscalar admixture in the $h\tau\tau$ coupling to $\mathcal{SM}$ Higgs.
- Spin weight and general Higgs boson Yukawa coupling to the τ lepton.

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

$$\bar{\tau}(a + ib\gamma_5)\tau$$

- Non-zero components of spin correlation matrix R_{ij}

$$R_{33} = -1 \qquad R_{11} = R_{22} = \frac{a^2\beta^2 - b^2}{a^2\beta^2 + b^2} \qquad R_{12} = -R_{21} = \frac{2ab\beta}{a^2\beta^2 + b^2}$$

- With

$$\beta = \sqrt{1 - \frac{4m_\tau^2}{m_H^2}}$$

Phenomenology Of General Case

- Higgs boson Yukawa coupling expressed with the help of the scalar–pseudoscalar mixing angle ϕ

$$\bar{\tau} N (\cos\phi + i \sin\phi \gamma_5) \tau$$

- Components of the spin density matrix

$$R_{11} = R_{22} = \frac{\cos\phi^2 \ \beta^2 - \sin\phi^2}{\cos\phi^2 \ \beta^2 + \sin\phi^2} \qquad R_{12} = -R_{21} = \frac{2\cos\phi \sin\phi \ \beta}{\cos\phi^2 \ \beta^2 + \sin\phi^2}$$

- In the obvious limit $\beta \to 1$ — the components of the rotation matrix coincide with matrix for rotation by an angle -2ϕ around z axis:

$$R_{11} = R_{22} = \cos 2\phi \qquad R_{12} = -R_{21} = \sin 2\phi$$

Phenomenology Of General Case

- Decay probability for the mixed scalar–pseudoscalar case

$$\Gamma(H_{mix} \to \tau^+\tau^-) \sim 1 - s_{\|}^{\tau^+} s_{\|}^{\tau^-} + s_{\perp}^{\tau^+} R(2\phi)\, s_{\perp}^{\tau^-}$$

- $R(2\phi)$ – operator for the rotation by an angle 2ϕ around the $\|$ direction.

$$R_{11} = R_{22} = \cos 2\phi \qquad R_{12} = -R_{21} = \sin 2\phi$$

- Pure scalar case is reproduced for $\phi = 0$.
- For $\phi = \pi/2$ we reproduce the pure pseudoscalar case.

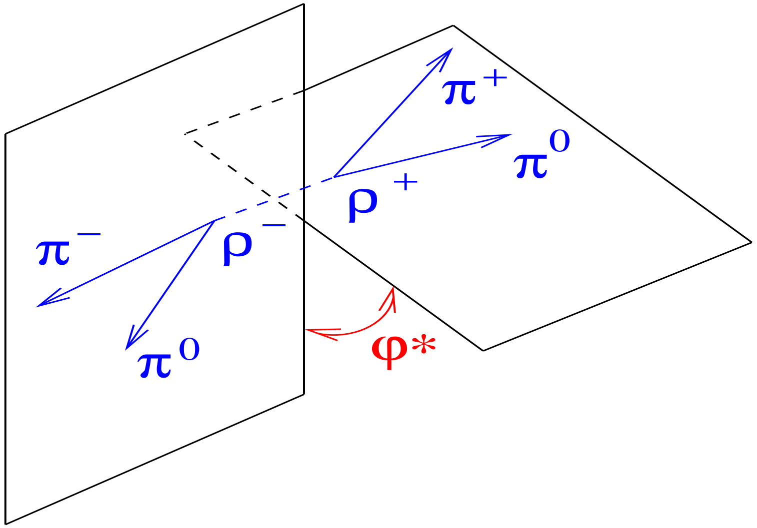
Pure Scalar And Pseudoscalar Higgs Boson

- Case of $\tau \to \rho\nu_\tau$ decay, $\mathcal{BR}(\tau \to \rho\nu_\tau) = 25\%$.
- The polarimeter vector, q for $\pi^\pm - \pi^0$, N for ν_τ

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

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

- Acoplanarity of the $\rho^\pm$ decay products in $\rho^+\rho^-$ r.f. and events separation.

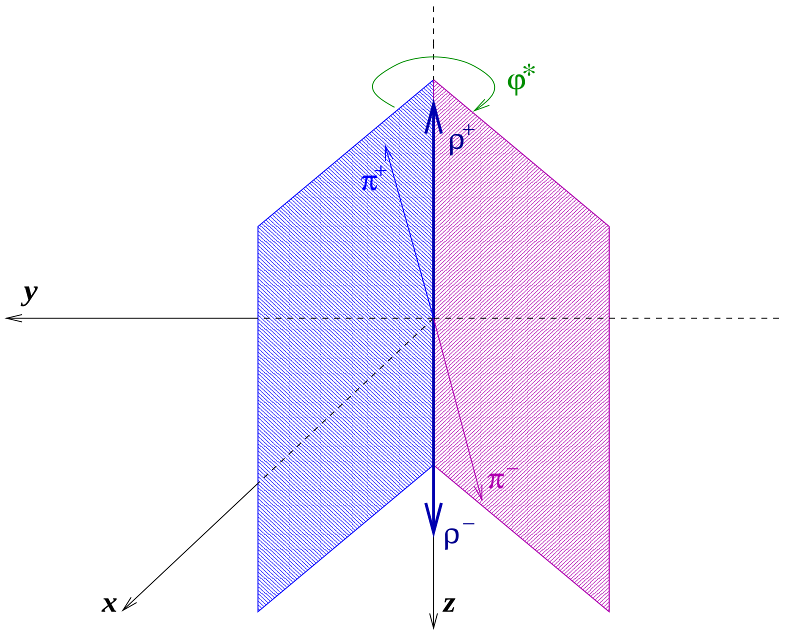


$$y_1 y_2 > 0\,; \qquad y_1 y_2 < 0$$

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

Observable For Mixed Scalar–Pseudoscalar Case

- *For mixing angle ϕ, transverse components of τ^+ spin polarization vector is correlated with the one of τ^- rotated by an angle 2ϕ.*
- *Acoplanarity $0 < \varphi^* < 2\pi$ is of physical interest, not just $\arccos \mathbf{n}_- \cdot \mathbf{n}_+$.*
- *Distinguish between the two cases $0 < \varphi^* < \pi$ and $2\pi - \varphi^*$.*
- *If no separation made the parity effect would wash itself out.*



Normal to planes $\mathbf{n}_\pm = \mathbf{p}_{\pi^\pm} \times \mathbf{p}_{\pi^0}$

Find the sign of $\mathbf{p}_{\pi^-} \cdot \mathbf{n}_+$

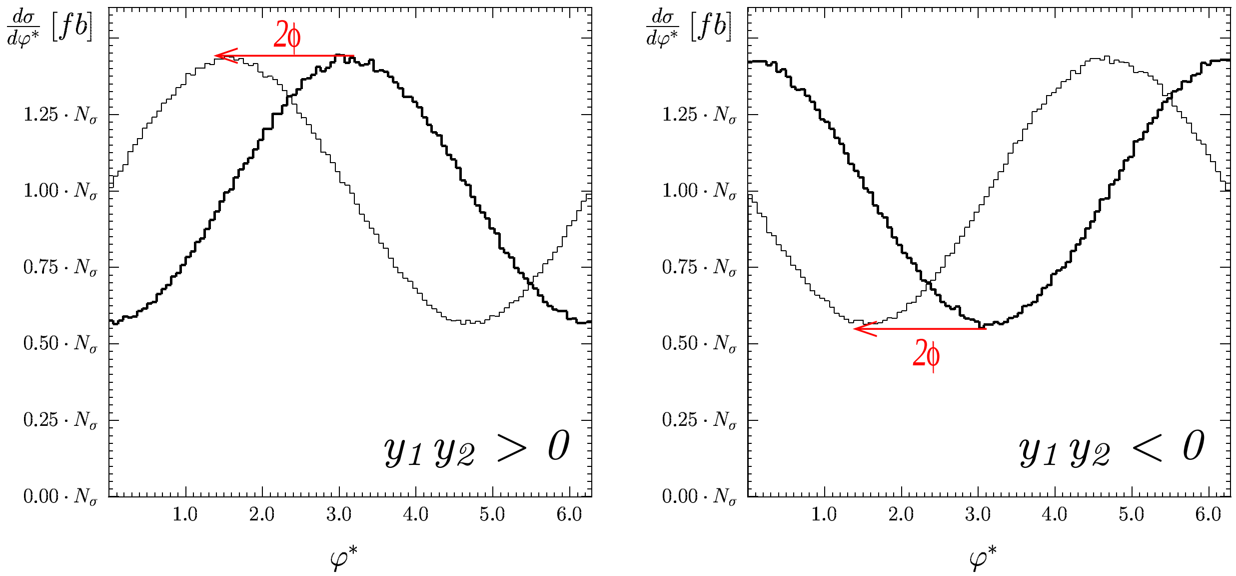
Negative $0 < \varphi^* < \pi$

Otherwise $2\pi - \varphi^*$

Monte Carlo Set-up

- Monte Carlo samples $\Longrightarrow$ TAUOLA τ lepton decay library.
- Production of the τ lepton pairs $\Longrightarrow$ PYTHIA.
- Production process $\Longrightarrow$ $e^+e^- \to ZH \to \mu^+\mu^-(q\bar{q})H.$
- Higgs boson mass $\Longrightarrow$ $m_H = 120\ GeV.$
- CMS energy $\Longrightarrow$ $\sqrt{s} = 350\ GeV.$
- The effects of ISR $\Longrightarrow$ in PYTHIA generation.
- τ lepton pair decay with full spin effects in decay chain
  $H \to \tau^+\tau^-,\ \tau^\pm \to \rho^\pm\bar{\nu}_\tau(\nu_\tau),\ \rho^\pm \to \pi^\pm\pi^0 \Longrightarrow$
  $\Longrightarrow$ UNIVERSAL INTERFACE FOR TAUOLA PACKAGE.
- Detector effects $\Longrightarrow$ Gaussian spreads of the measured quantities with respect to the generated ones $\Longrightarrow$ verified with SIMDET.

Results With An Idealized Detector Set-up



- The acoplanarity distribution in the rest frame of the $\rho^+\rho^-$ pair.
- Generator level $\tau^\pm$ rest frames are used, $N_\sigma = 62.7 \cdot 10^{-3}$ [fb].
- The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.

Replacement τ Rest Frame

- *Take just laboratory frame instead of $\tau^{\pm}$ rest frames.*
- *Better replacement τ rest frames:*

$\Longrightarrow$ *In the r.f. of $\rho^{+}\rho^{-}$ pair define $\tau^{\pm}$ momenta along direction of $\rho^{\pm}$.*

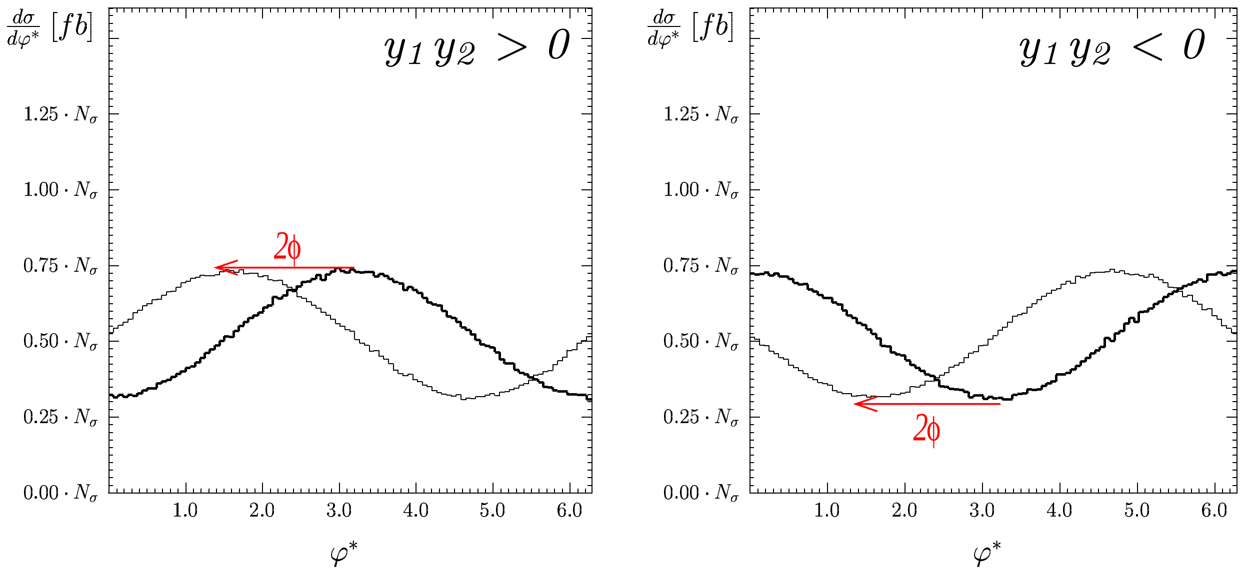
$\Longrightarrow$ *For $\tau^{\pm}$ energies take half of the Higgs boson mass.*

$\Longrightarrow$ *Boost $\pi^{+}, \pi^{0}, \pi^{-}, \pi^{0}$ momenta to replacement τ rest frames.*

$\Longrightarrow$ *π energies defined this way are used in energy difference cuts.*

- *Many more, equally "good" options checked. Problems because of Beamstrahlung.*

Results With Detector-like Set-up



- *Only events where the signs of y1 and y2 are the same whether calculated using the method without or with the help of the τ impact parameter.*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*

Precision on $\phi \sim 6^\circ$ for $1000\ fb^{-1}$ and $\sqrt{s} = 350$ GeV

Summary And Outlook

- Prospects for measurement of pseudoscalar admixture in $h\tau\tau$ coupling to a Standard Model Higgs boson.
- Specific angular distributions in $h \to \tau^+\tau^-, \; \tau^\pm \to \rho^\pm \bar{\nu}_\tau(\nu_\tau)$ decay chain can be used to probe mixing angles of scalar–pseudoscalar $h\tau\tau$ couplings.
- Precision on mixing angle ϕ of approximately 6° can be anticipated for a $\mathcal{SM}$ Higgs cross section using typical properties of a future detector at an e^+e^- linear collider.

τ Production And Decay Process In MC

- The cross section for the process

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

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

- 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

$$d\sigma = |A|^2 |\bar{\mathcal{M}}|^2 |\bar{\mathcal{M}}^{'}|^2 (1 + R_{\mu\nu} h_1^\mu h_2^\nu)$$

$$dLips(p_1 + p_2; q_1, q_2) dLips(q_1; k_1, k_2, k_3) dLips(q_2; k_1^{'}, k_2^{'}, k_3^{'})$$

General Formalism For Semileptonic τ 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:*

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

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

$$\Pi_\mu = 2\left((J^* \cdot N)J_\mu + (J \cdot N)J^*_\mu - (J^* \cdot J)N_\mu\right) \qquad \Pi^{5\mu} = 2\epsilon^{\mu\nu\rho\sigma}\mathcal{I}m J^*_\nu J_\rho N_\sigma$$

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

- *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
$E_{\rm CM}$ (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 linear colliders with center of mass energies of* $350\ GeV$ *and above, beamstrahlung will become of significant physical interest.*
- *Occurs when particles of first beam, or radiating beam, are deflected by electromagnetic field of second (target) beam and emit synchrotron radiation.*
- *Beamstrahlung may carry away substantial fraction of primary beam energy and lead to degradation of effective center of mass energy*