Monte Carlo And τ Leptons For Higgs Boson Parity At The Linear Collider

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Points:

- History
- Interface of the TAUOLA with complete spin effects for $H/A^0 \to \tau^+\tau^-$.
- Case of pure scalar and pseudoscalar Higgs boson.
- Case of mixed scalar and pseudoscalar couplings of the Higgs boson to τ.
- Physical observable for $\tau \to \rho\nu_\tau$.
- Systematic errors.
- Summary and Outlook.

History

It is a great pleasure for me to talk about the subject which technically is rooted directly into the work on early versions of TAUOLA and KORALZ, performed here in ALEPH MPI group in years 1987-1989.

Main References

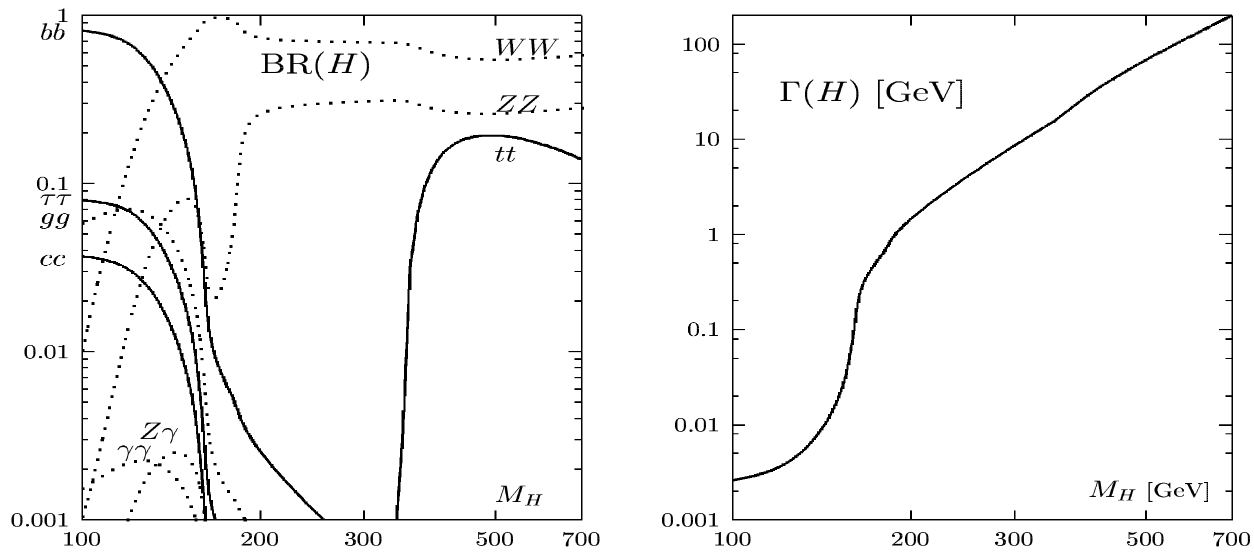
- T. Pierzchala, E. Richter-Was, Z. Was and M. Worek, Acta Phys. Polon. B **32** (2001) 1277
- Z. Was and M. Worek, Acta Phys. Polon. B **33** (2002) 1875
- G. R. Bower, T. Pierzchala, Z. Was and M. Worek, Phys. Lett. B **543** (2002) 227
- K. Desch, Z. Was and M. Worek, Eur. Phys. J. C **29** (2003) 491
- K. Desch, A. Imhof, Z. Was and M. Worek, "Probing the CP nature of the Higgs boson at linear colliders with tau spin correlations: The case of mixed scalar pseudoscalar couplings," arXiv:hep-ph/0307331.

Introduction

Any LC programme must include Higgs boson parity measurement

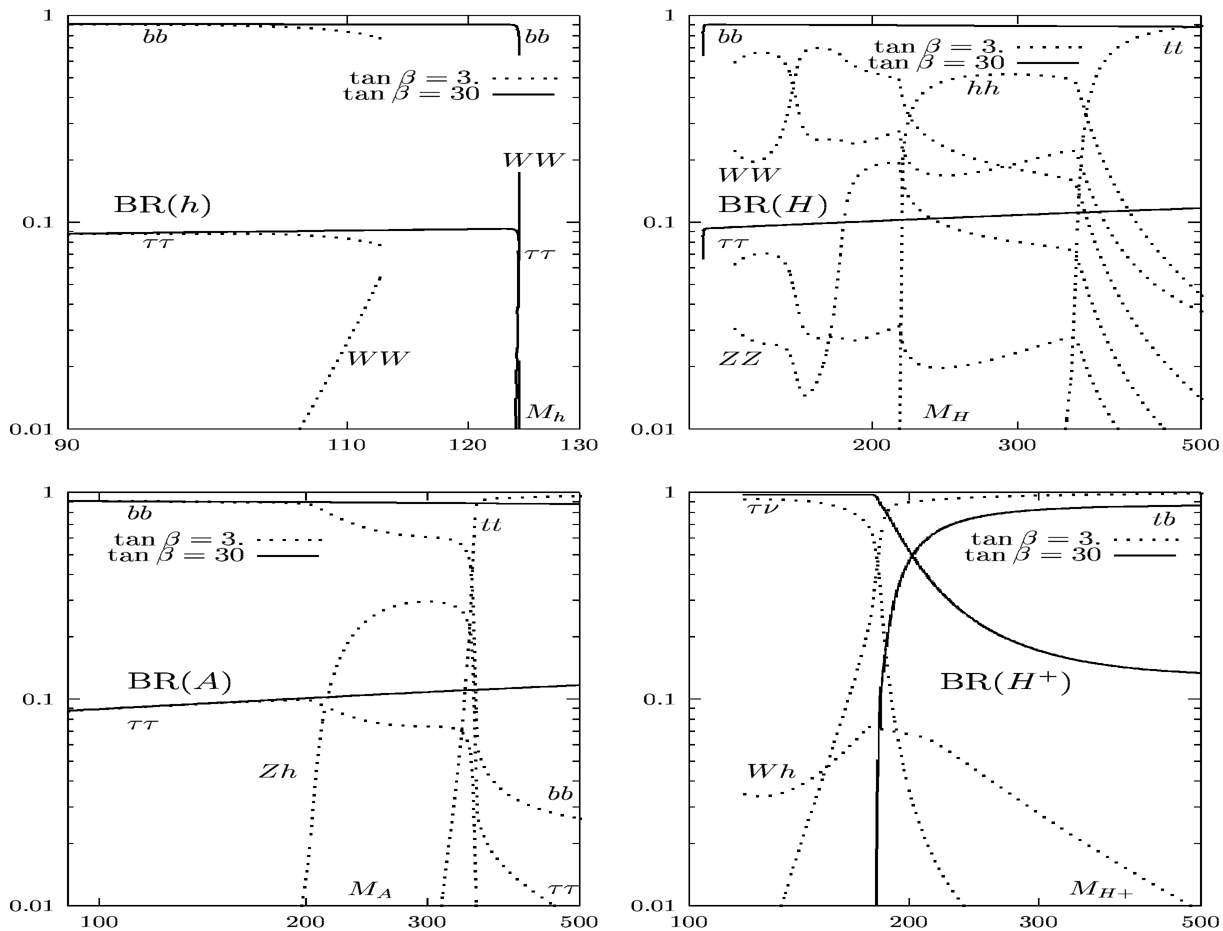
1. There are many possibilities for the measurement.
2. There are many scenarios of Higgs mechanism: SM, MSSM, ...
3. We will concentrate on the measurement using $H \to \tau^+\tau^-$ decay; i.e. the measurement of Higgs boson couplings to fermions.
4. This measurement is to a large degree production independent.

Main Branching Ratios Of Light SM Higgs Boson



- *The most frequent fermion decay mode is the* $b\bar{b}$ *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 Bosons



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

Introduction

τ Production And Decay Process In Our MC's

- *The cross section for the process*

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

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

- *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*

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

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

Introduction

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:*

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

Introduction

Inital State Interactions

- The formalism presented above was explained on the case of $2 \to 2$ production processe (example from TAUOLA documentation).
- This is sufficient for our purpose, even a bit too much; $.1 \to 2$ would be enough.
- If higher order effect are included, picture changes a little bit,
- we will omit this quite complicated point here.
- Most of details are in references. Transparency No 2.
- Some other, specially those important for future studies of theoretical systematic errors, can be found in references for LEP Monte Carlos KORALZ and KKMC.

Introduction

Higgs Boson Parity

- *Decay probability in formalism of Kramer et al.*

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

- s^τ *is the* τ *polarization vectors.*
- $\parallel / \perp$ *denote components parallel / transverse to the Higgs boson momentum.*
- *The spin weight is given by the following formula*

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

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

- *Components for pure scalar and pseudoscalar Higgs boson respectively.*

Density matrix

Only transverse spin correlations between τ^+ and τ^- are different for scalar and pseudoscalar Higgs

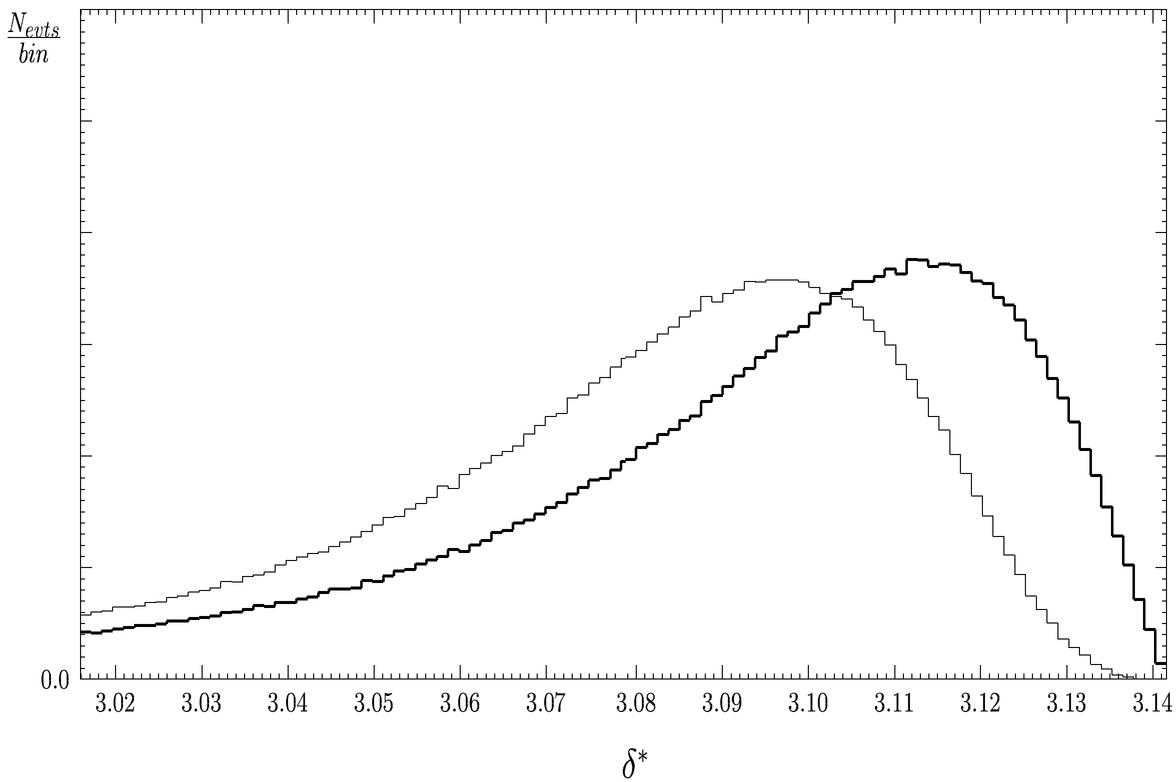
- The correlations can not be measured directly
- One need to measure distributions of τ decay products
- Precisely their transverse (to τ direction in Higgs boson rest frame) momenta
- Most sensitive to spin is $\tau^\pm \to \pi^\pm \nu$
- The largest branching ratio (25 %) has $\tau^\pm \to \pi^\pm \pi^0 \nu$

Classic approach

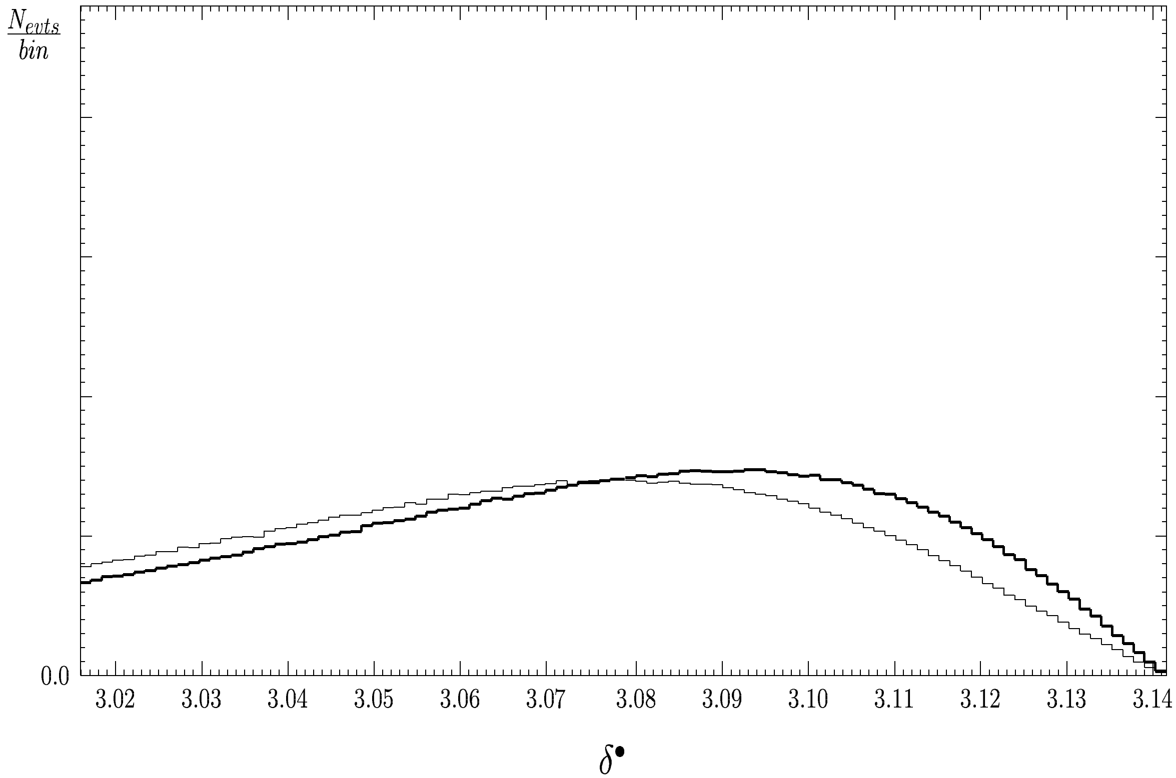
We take the most sensitive to spin $\tau^\pm \to \pi^\pm \nu$ decay channels and we look at $\pi^+\pi^-$ acollinearity in **Higgs boson rest-frame**.

We will reproduce analytical result of Kramer et al first.

Generator level look fine:



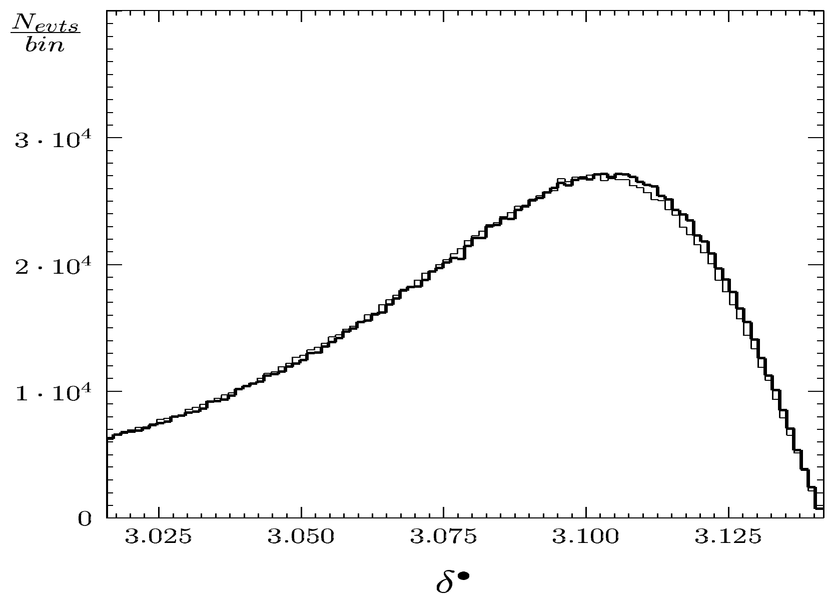
But once **beamstrahlung** and detector smearings are in ...



CMS 350 GeV, $e^+e^- \to ZH$, In LC experiments Higgs boson momentum can be measured from the balance of the total energy momentum conservation. That is why smearing of H momentum: ± 2 GeV for p_T, ± 5 GeV for p_{Long} must be assumed. Largest loss of sensitivity is from beamstrahlung.

$\tau \rightarrow \pi^{\pm}\pi^{0}\nu$

Let us look for $\tau^{\pm}$ decay to $\rho^{\pm}\nu$ for help



Acollinearity for scalar and pseudoscalar look indisguishable

$\tau \rightarrow \pi\nu$-decay channel looks tough

$\tau \rightarrow \rho\nu$-decay channel looks hopeless

Scalar or Pseudoscalar?

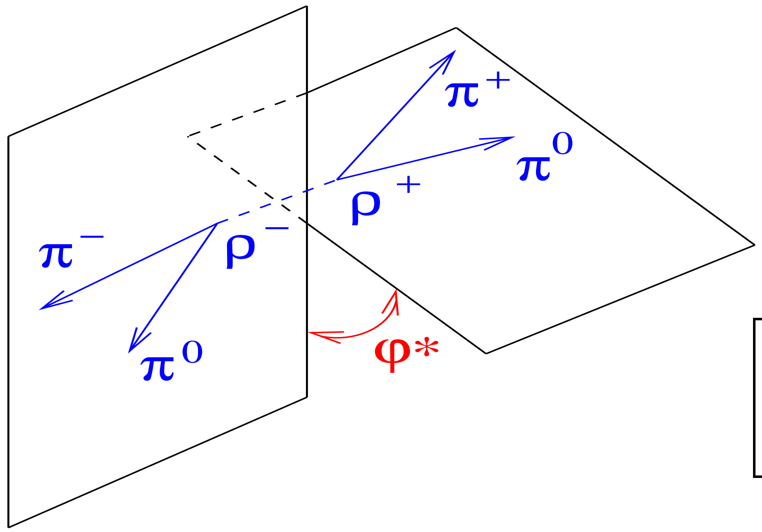
Pure Scalar And Pseudoscalar Higgs Boson

- Case of $\tau \to \rho\nu_\tau$ decay, $\mathcal{BR}(\tau \to \rho\nu_\tau) = 25\%$
- The polarimeter vector is given by the formula where 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 ρ^+ and ρ^- decay prod. (in $\rho^+\rho^-$ r.f.) and events separation.

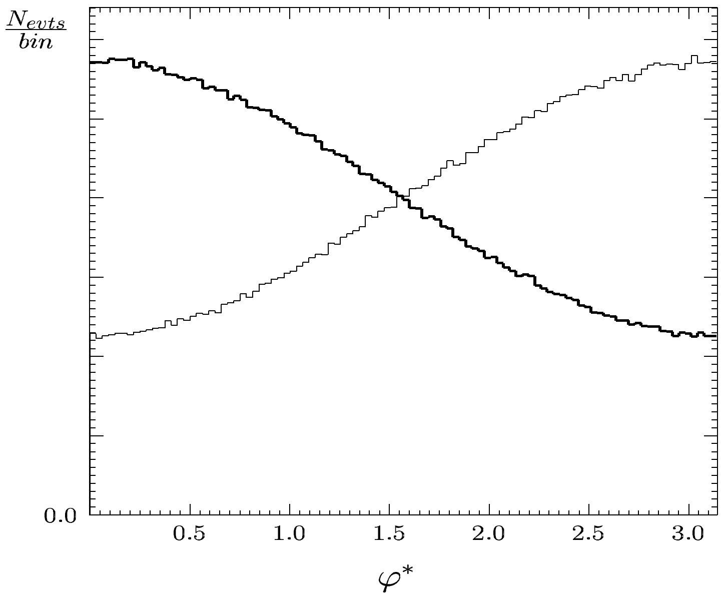


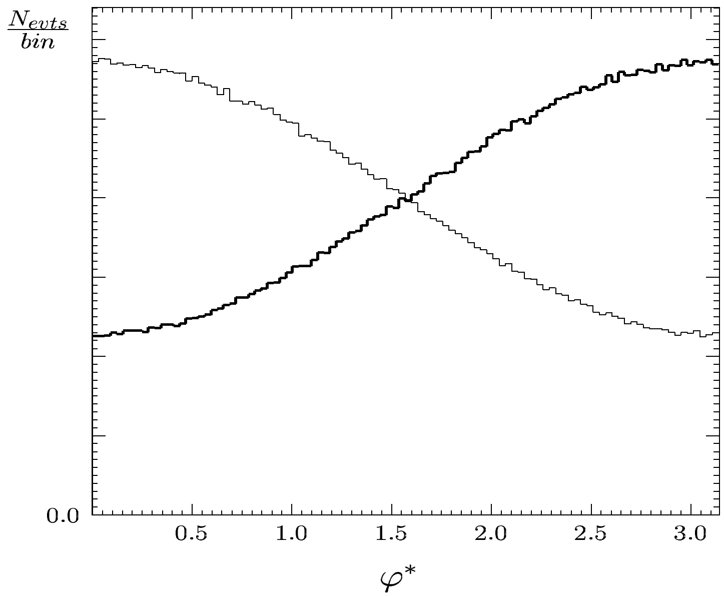
$y_1 y_2 > 0\,;\qquad y_1 y_2 < 0$ (in $\tau^\pm$ r.f.'s)

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

Scalar or Pseudoscalar ?

$\mathcal{R}$esults $\mathcal{W}$ithout $\mathcal{S}$mearing

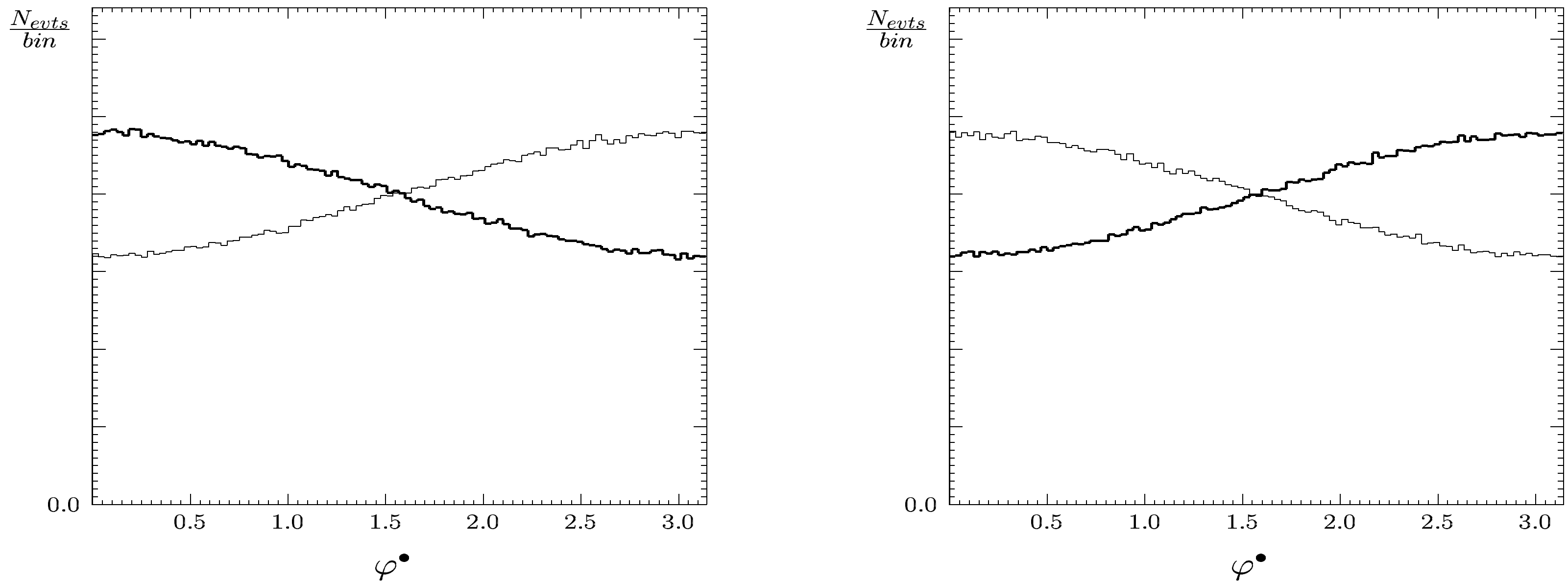




- *The* $\rho^+\rho^-$ *decay products' acoplanarity distribution without any smearing .*
- *Selection* $y_1 y_2 > 0$ *is used in the left plot,* $y_1 y_2 < 0$ *is used for the right plot.*
- *Thick line denote the case of the scalar Higgs and thin lines the pseudoscalar.*
- *Complete spin correlations of* $h \to \tau^+\tau^-$, $\tau^\pm \to \rho^\pm \nu$, $\rho^\pm \to \pi^\pm \pi^0$ *incl.*

Scalar or Pseudoscalar ?

Results With Detector Effects



- *Gaussian spreads of the 'measured' quantities with respect to the generated.*
- *Resolutions verified with SIMDET. Replacement $\tau^{\pm}$ r.f.'s were used for $y_{1,2}$.*
- *Clearly distinguish the different parity states — 3σ effect (0.5 ab^{-1}).*

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- H$ | $m_H = 120\ GeV$ | $\sqrt{s} = 500\ GeV$

Scalar or Pseudoscalar ?

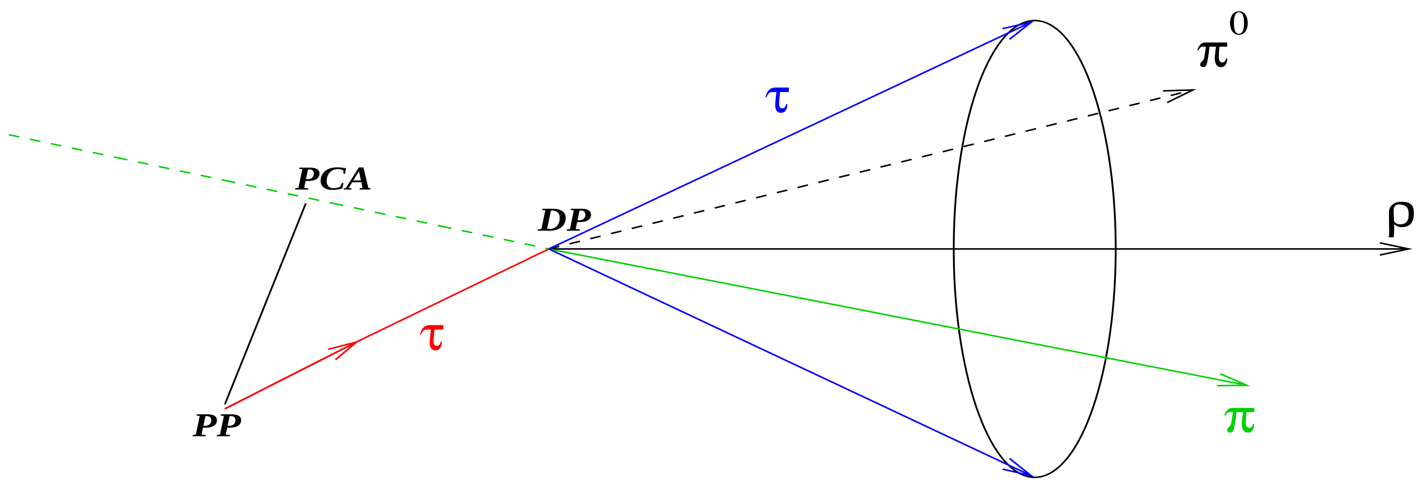
Replacement τ Rest Frame

- Take just laboratory frame instead of $\tau^{\pm}$ r.f.'s.
- Better (but by invisible amount) replacement τ rest frames.
  - In the restframe of $\rho^{+}\rho^{-}$ pair define $\tau^{\pm}$ momenta along direction of $\rho^{\pm}$,
  - For $\tau^{\pm}$ energies take half of the Higgs boson mass.
  - Boost replacement $\tau^{\pm}$ momenta to the lab frame.
- Many more, equally "good" options checked. Problem is that we can not determine direction of ν_{τ} because of Beamstrahlung.

Scalar or Pseudoscalar ?

τ Impact Parameter – Method Optimization

- *To a few GeV τ energy can be determined from CMS and Higgs mass constraints. τ momentum must be localized on a circle around ρ.*

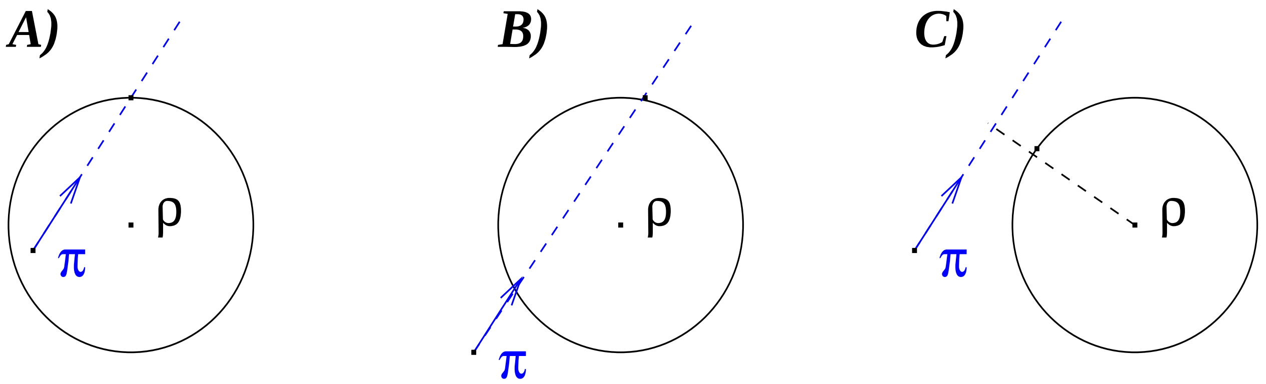


- *Direction of the τ impact parameter, with respect to the $\pi^{\pm}$ track, can help.*
- *Alternative way to find the difference of $\pi^{\pm}$, π^0 energies in $\tau^{\pm}$ rest frames.*

Scalar or Pseudoscalar ?

Candidates For τ Momentum

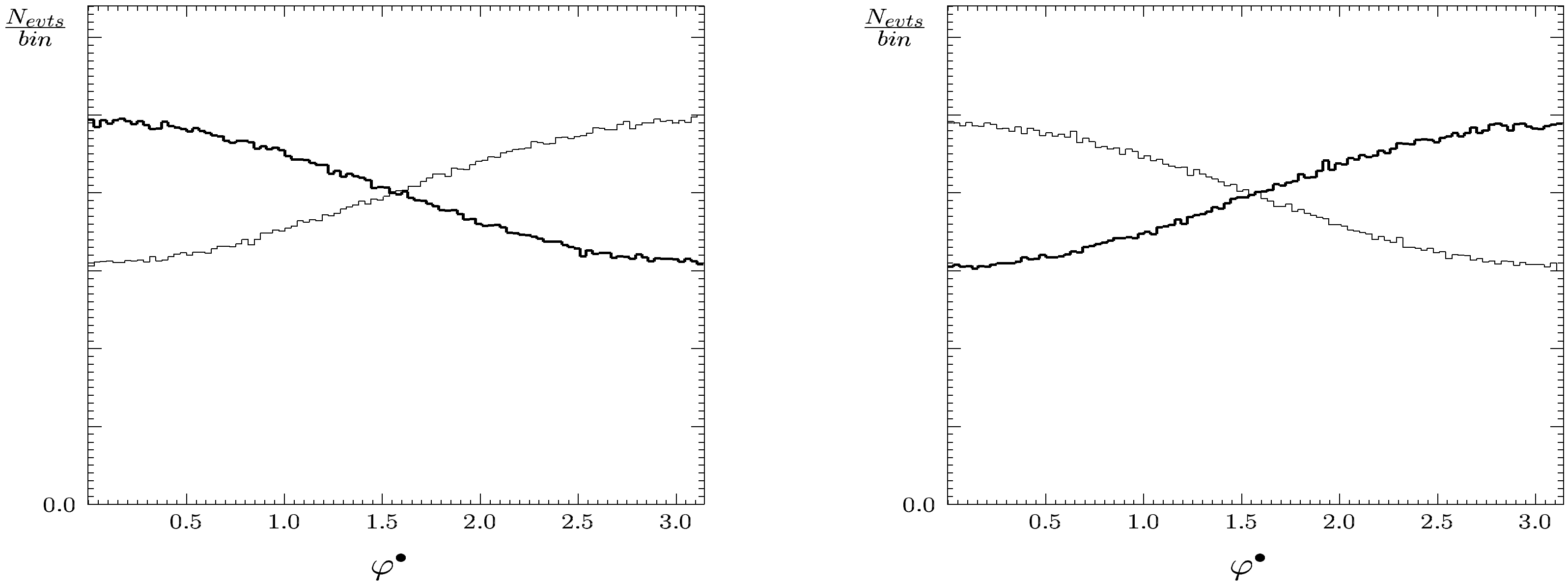
- The intersection of the cone and the plane is calculated numerically.



- $\mathcal{A}$) 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.

Scalar or Pseudoscalar ?

Results With τ Impact Parameter

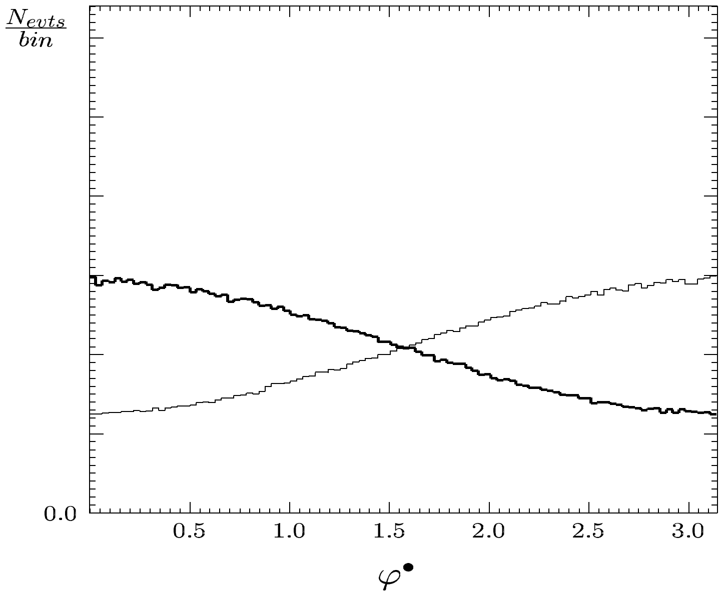


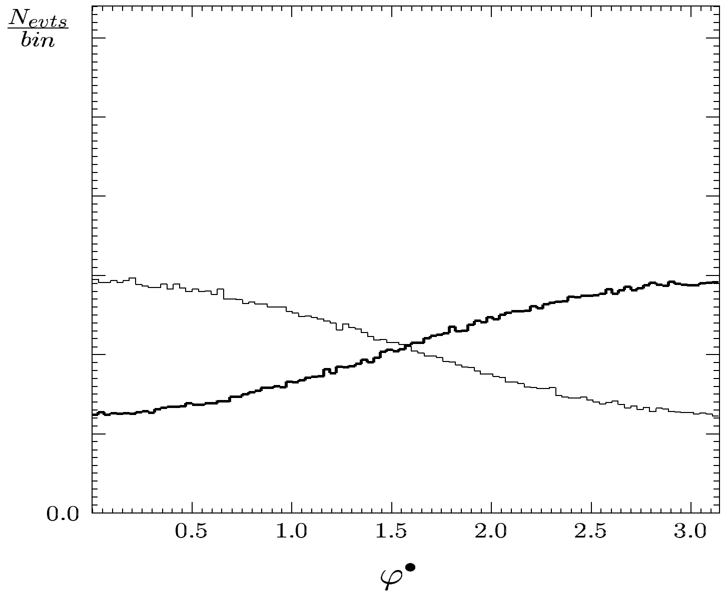
- *The τ impact parameter is used in the reconstruction of the $\tau^{\pm}$ rest frames.*
- *Improvement* $\sim 12\%$
- *Gaussian spread of impact parameter.*

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

Scalar or Pseudoscalar ?

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: $\sim 4.5\sigma$

Scalar or Pseudoscalar ?

Mixed Scalar–Pseudoscalar Coupling Of $h\tau\tau$

- *Both scalar and pseudoscalar couplings of the Higgs to $\tau\tau$ 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}*

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

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

Scalar or Pseudoscalar ?

Spin Weight For Mixed Scalar–Pseudoscalar Case

- Higgs boson Yukawa coupling expresed 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 density matrix coincide with matrix for rotation by an angle -2ϕ around z axis:

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

Scalar or Pseudoscalar ?

Phenomenology Of General Case

- *Decay probability for the mixed scalar–pseudoscalar case*

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

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

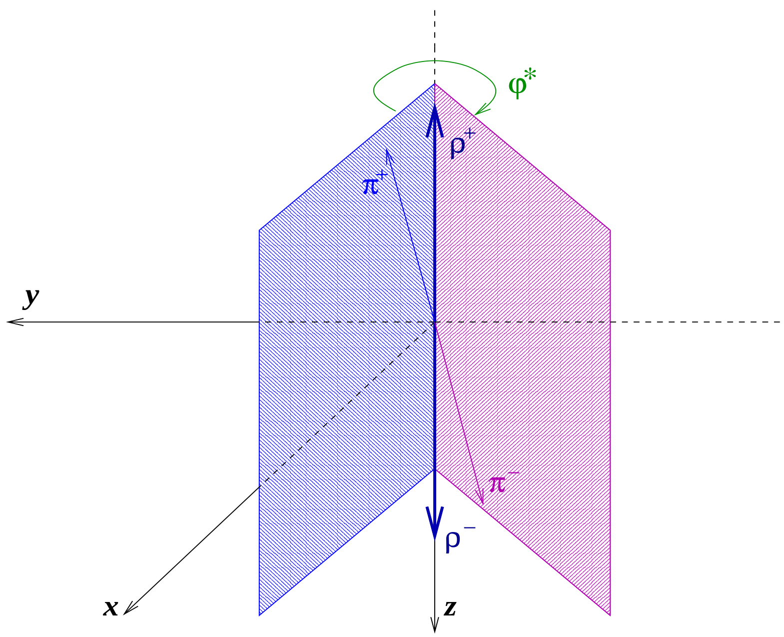
$$R_{11} = R_{22} = \cos 2\phi \qquad R_{12} = -R_{21} = \sin 2\phi$$

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

Scalar or Pseudoscalar ?

Observable For Mixed Scalar—Pseudoscalar Case

- *For mixing angle ϕ, transverse component of τ^+ spin polarization vector is correlated with the one of τ^- rotated by 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: $\mathbf{n}_\pm = \mathbf{p}_{\pi^\pm} \times \mathbf{p}_{\pi^0}$

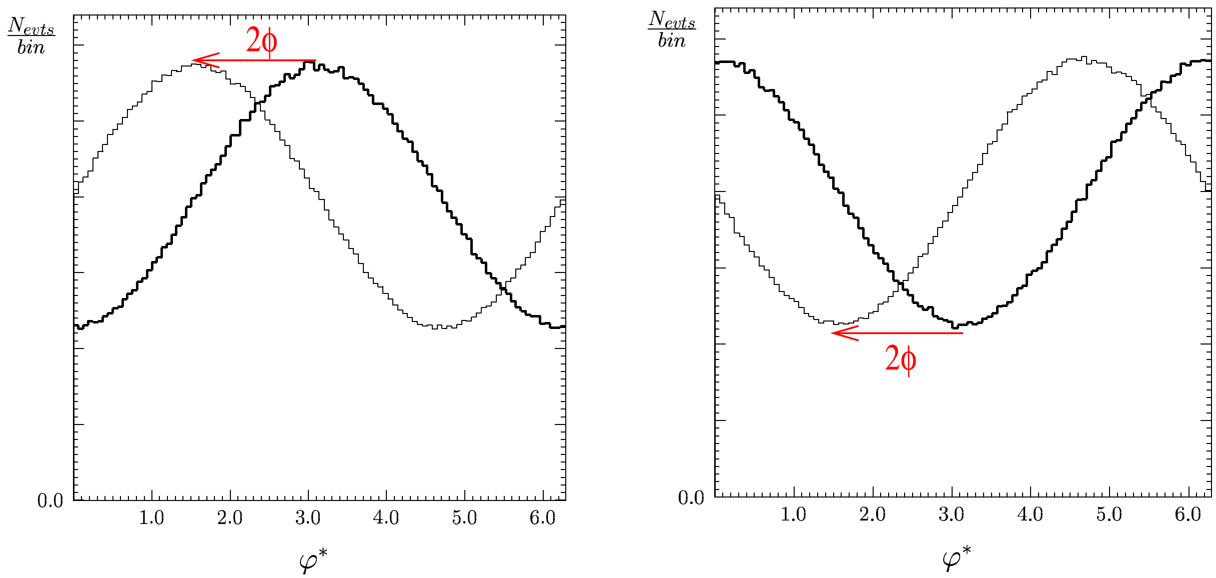
Find the sign of $\mathbf{p}_{\pi^-} \cdot \mathbf{n}_+$

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

Otherwise $2\pi - \varphi^*$

Scalar or Pseudoscalar ?

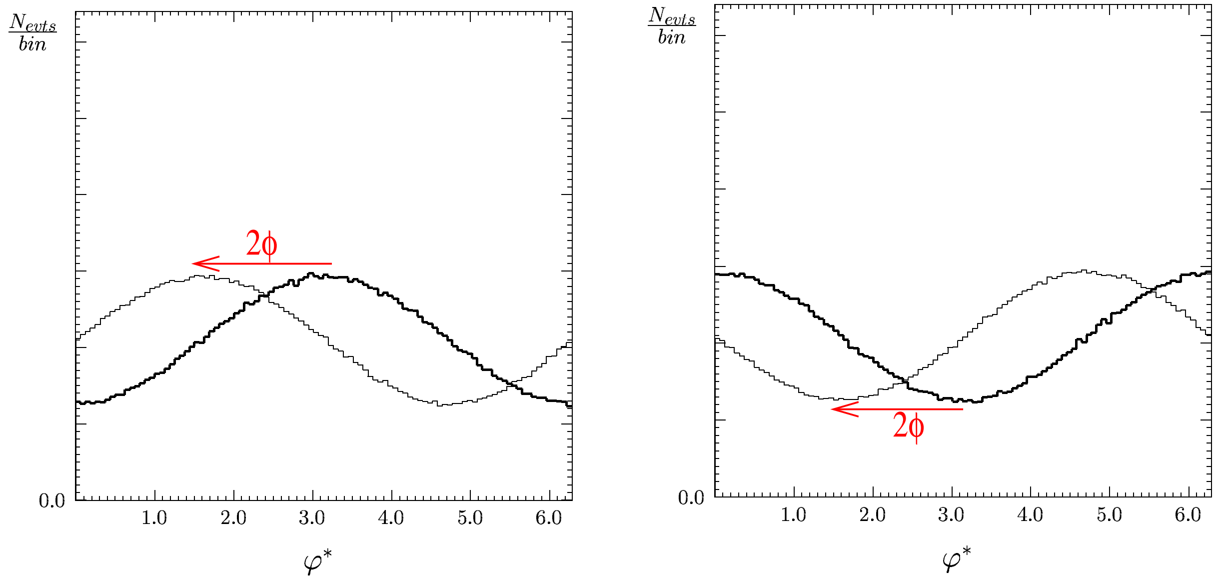
Results For Mixed Scalar–Pseudoscalar Case



- *The acoplanarity distribution in the rest frame of the* $\rho^+\rho^-$ *pair.*
- *Generator level* $\tau^\pm$ *rest frames are used.*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*
- *The left figure contains events with* $y_1y_2 > 0$, *the right one is for* $y_1y_2 < 0$.

Scalar or Pseudoscalar ?

Results For Mixed Scalar–Pseudoscalar Case



- *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.*
- *Detector-like set-up is included (SIMDET).*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*

Precision on $\phi \sim 6^\circ$, for $1ab^{-1}$ and 350 GeV CMS.

Final points

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 available.*
- *Interface works with any Monte Carlo generator providing Higgs boson production, and subsequent decay into a pair of τ leptons.*
- *Promising method for the measurement of the Higgs boson parity using decay chain $H/A^0 \to \tau^+\tau^- \to \rho^+\bar{\nu}_\tau\rho^-\nu_\tau \to \pi^+\pi^0\bar{\nu}_\tau\pi^-\pi^0\nu_\tau$.*
- *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.*

Final points

Summary And Outlook

- This method may be applicable to other production modes including those available at proton colliders as well as at electron colliders.
- Impact parameter method in one prong τ decay is useful for the measurement of the Higgs boson parity $-$ from $\sim 3\ \sigma$ to $\sim 4.5\ \sigma$ (or from $\sim 6\ \sigma$ to $\sim 9\ \sigma$ for 1 ab^{-1} and 350 GeV CMS.
- Precision on mixing angle ϕ of approximately 6° can be anticipated for a SM Higgs cross section using typical properties of a future detector at e^+e^- linear collider.
- 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. But then optimalization becomes tough. Observable is defined from distribution in 32 dimensions.

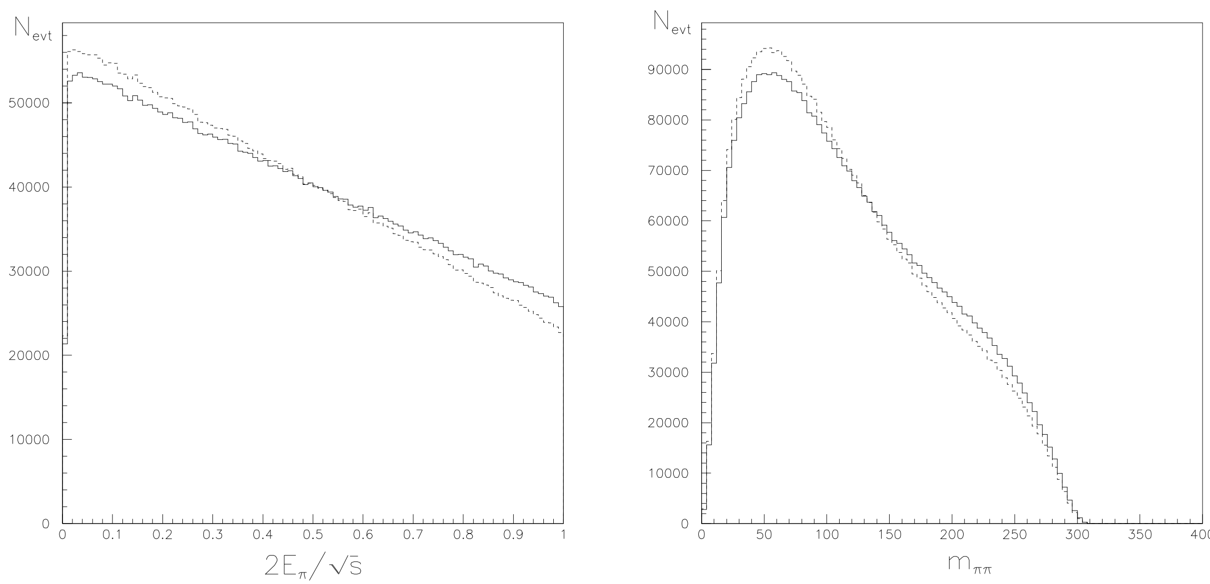
Final points

Systematic Errors

- *There was very little done into that direction*
- *But case is 'nearly' the same as Z decay at LEP. Necessary studies will need to repeat those done for LEP era MC's: KORALZ KKMC*
- *Even though there is plenty of time to LC era, let us provide hint that we DO think about systematics.*
- *Examples will be for LHC and simulation of $Z \to \tau\tau$ background in Higgs boson searches.*

Final points

Plots Indicating Size Of Systematic Error LHC Case



- *In case of LHC simulations it is ambiguous how to reconstruct kinematic of effective $2 \to 2$ hard process used in calulation of spin correlations.*
- *Two options lead to results which are somewhat different, pointing to systematic error.*
- *This must be carefully studied before high precision measurements at LHC (or LC) are to publish their data.*

Final points

Final State Bremsstrahlung

- *Final state bremsstrahlung in H/A/Z/γ^* decays is straighforward to control with the help of* PHOTOS *Monte Carlo.*
- *Other systematic errors due to genuine electroweak and QCD interactions were not studied at all so far.*