CP effects in τ-lepton production and decay: aspects from Monte Carlo simulations

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Main Topics:

- **τ-lepton as a window to new physics**
- **CP in TAUOLA itself**
- **universal interface of TAUOLA: CP.**
- **Observables – examples –**
- **software architecture and F77 $\longrightarrow$ C++ social constraints.**
- **Summary**

My web page is at http://home.cern.ch/wasm

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τ: why window for CP?

- It belongs to the third heaviest family.
- Its spin state can be measured thanks to well known decays.
- Its lifetime is sufficiently large to perfectly separate production from decay.
- Its decay can be controlled with the help of models and other experiment data (fits of model parameters/spectral functions).
- Even its decay vertex can be partly observed.

τ: why difficult?

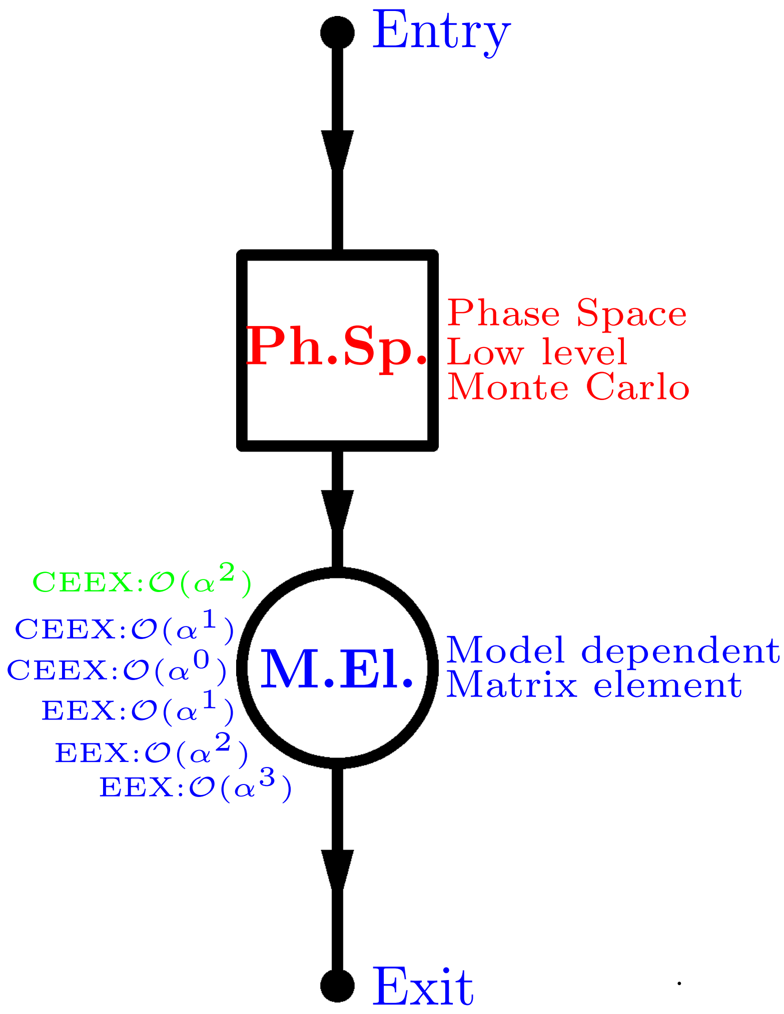
- Complicated signal-background cross-talks.
- Multidimensional distribution need to be controlled.
- Is the software like TAUOLA still useful?
- Wrappers are bad things if one need to dig inside ...

TAUOLA: basic structure

and assumptions

- **Phase space.**
- **Matrix element**
- **Electroweak vertex.**
- **Leptonic decays:** $\tau \to e(\mu)\nu_\tau\nu(\gamma)$**.**
- **Semileptonic decays: Hadronic current.**
- **Spin treatment.**

Textbook principle "matrix element × full phase space" ASSUMED



In the Monte Carlo realization it means that:

- Universal Phase-space Monte Carlo simulator is a separate module producing "raw events" (including importance sampling for possible intermediate resonances)
- Library of several types of hadronic currents provides input for "model weight" which is another independent module
- Electroweak vertex $\tau - \nu_\tau - W$ is a separate sub-part of calculation of the "model weight"
- Caluclation of weights involving anomalous couplings come after of course; approximations are used there.
- This is exactly like in case of KORALZ or KKMC.

General formalism for semileptonic decays

- The differential partial width for the channel under consideration reads

$$d\Gamma_X = G^2 \frac{v^2+a^2}{4M} d\mathrm{Lips}(P; q_i, N)(\omega + \hat{\omega} + (H_\mu + \hat{H_\mu}) s^\mu)$$

- The phase space distribution is given by the following expression where a compact notation with $q_5 = N$ and $q_i^2 = m_i^2$ is used

$$d\mathrm{Lips}(P; q_1, q_2, q_3, q_4, q_5) = \frac{1}{2^{23}\pi^{11}} \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{Q^2_{3,min}}^{Q^2_{3,max}} dQ_3^2$$
$$\int_{Q^2_{2,min}}^{Q^2_{2,max}} dQ_2^2 \quad \times \quad \int d\Omega_5 \frac{\sqrt{\lambda(M^2, Q^2, m_5^2)}}{M^2} \int d\Omega_4 \frac{\sqrt{\lambda(Q^2, Q_3^2, m_4^2)}}{Q^2}$$
$$\times \quad \int d\Omega_3 \frac{\sqrt{\lambda(Q_3^2, Q_2^2, m_3^2)}}{Q_3^2} \int d\Omega_2 \frac{\sqrt{\lambda(Q_2^2, m_2^2, m_1^2)}}{Q_2^2}$$
$$Q^2 = (q_1 + q_2 + q_3 + q_4)^2, \quad Q_3^2 = (q_1 + q_2 + q_3)^2, \quad Q_2^2 = (q_1 + q_2)^2$$
$$Q_{min} = m_1 + m_2 + m_3 + m_4, \quad Q_{max} = M - m_5 \; Q_{3,min} = m_1 + m_2 + m_3, \quad Q_{3,max} = Q - m_4$$
$$Q_{2,min} = m_1 + m_2, \qquad Q_{2,max} = Q_3 - m_3$$

- These formulas if used directly, are inefficient for a Monte Carlo algorithm if sharp peaks due to resonances in the intermediate states are present. The changes affect the program efficiency, but the actual density of the phase space remains intact. No approximations are introduced.

General formalism for semileptonic decays

- Matrix element used in TAUOLA for semileptonic decays (can be changed without touching phase space; used by A.Weinstein and CLEO Phys.Rev.D64:092005,2001)

$$\tau(P,s) \to \nu_\tau(N) X$$

$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}(N)\gamma^\mu (v + a\gamma_5) u(P) J_\mu + \mathcal{M}^{anomalous, \not{C}\not{P}, h, \cdots}$$

- J_μ current depends on all hadrons momenta code prepared on CP dependence.

$$|\mathcal{M}|^2 = G^2 \frac{v^2+a^2}{2} (\omega + H_\mu s^\mu)$$
$$\omega = P^\mu (\Pi_\mu - \gamma_{va} \Pi_\mu^5)$$
$$H_\mu = \frac{1}{M} (M^2 \delta_\mu^\nu - P_\mu P^\nu)(\Pi_\nu^5 - \gamma_{va} \Pi_\nu)$$
$$\Pi_\mu = 2[(J^* \cdot N) J_\mu + (J \cdot N) J_\mu^* - (J^* \cdot J) N_\mu]$$
$$\Pi^{5\mu} = 2 \,\mathrm{Im}\, \epsilon^{\mu\nu\rho\sigma} J_\nu^* J_\rho N_\sigma$$
$$\gamma_{va} = -\frac{2va}{v^2+a^2}$$

- If a more general coupling $v + a\gamma_5$ for the τ current and ν_τ mass $m_\nu \neq 0$ are expected to be used, one has to add the following terms to ω and H_μ

$$\hat{\omega} = 2 \frac{v^2-a^2}{v^2+a^2} m_\nu M (J^* \cdot J), \qquad \hat{H}^\mu = -2 \frac{v^2-a^2}{v^2+a^2} m_\nu \,\mathrm{Im}\, \epsilon^{\mu\nu\rho\sigma} J_\nu^* J_\rho P_\sigma$$

Leptonic and semileptonic decays.

- Complete first order QED corrections can be swithced on/off in $\tau \to e(\mu)\nu_\tau\nu$.
- For multiphoton bremsstrahlung PHOTOS can be used instead to check. See talk by E. Barberio yesterday.
- In semileptonic modes, for up to 5 final state scalars, any current can be easily installed/remodelled. Proper treatment of the rest (phase space, spin, leptonic $\tau - \nu_\tau - W$ current) is assured. Thus many versions !
- For 6 pions or more flat space is only used so far.
- Spin treatment will be discussed later, on decay side H_μ are defined.
- In total well over 20 distinct τ decay modes installed.
- 3 more or less complete versions of formfactors in authors hands: CLEO 1998 ALEPH (lep1) and published CPC plus additional special cases, including prototype version for Belle and BaBar collaborations!
- Such organization of the code is OK if non-factorizable electroweak corrrections of order $\frac{\alpha}{\pi}$ can be neglected. Anomalous terms easy to add.

Main references:

1. R. Decker, S.Jadach, M.Jeżabek, J.H.Kuhn, Z. Was, Comput. Phys. Commun. 76 (1993) 361, ibid. 70 (1992) 69, ibid. 64 (1990) 275
2. P. Golonka, B. Kersevan ,T. Pierzchala, E. Richter-Was, Z. Was, M. Worek (hep-ph/0312240), for τ decays alone, mainly technical stuff.

Also:

1. • Alain Weinstein www home page: http://www.cithep.caltech.edu/˜ajw/korb_doc.html#files
2. • B. Bloch, private communications.
3. R. Decker, M. Finkemeier, P. Heiliger and H.H. Jonsson, Z. Phys. C **70** (1996) 247, now standard 4π formfactors.
4. A. E. Bondar, S. I. Eidelman, A. I. Milstein, T. Pierzchala, N. I. Root, Z. Was and M. Worek, Comput. Phys. Commun. **146**, 139 (2002)
5. P. Abreu et al., Phys. Lett. B426 (1998) 411 (alternative 3π formf.)
6. Sherry Towers alternative formf. in K$\pi\pi$ modes, hep-ex/9908013, Eur. Phys. J. **C13** (2000) 197.

Formfactors secret life

The studies within collaborations were often relying on refits of form-factors, many versions were/are regularly created for more general, or specific purposes. I have seen only some of them. Practical problems with change of language.

Comparison of different parameterizations

- A comparison of CLEO and new Novosibirsk current in TAUOLA. The ω contribution in an old CLEO current is scaled down from *68* $\%$ to *40* $\%$.

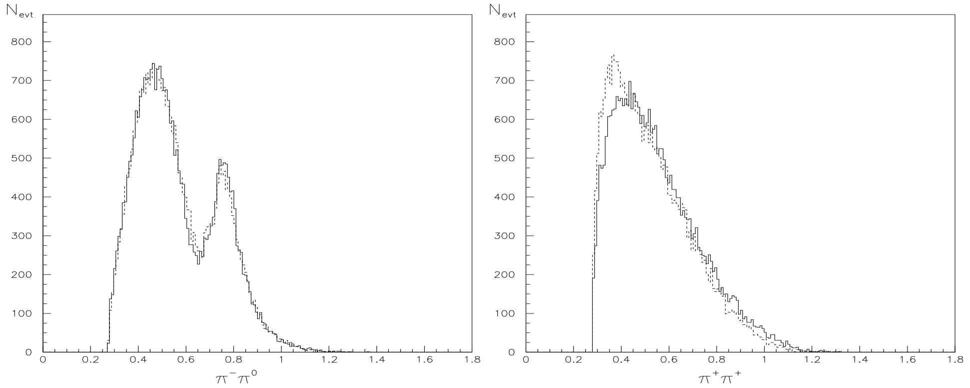


Figure 3: *The $\bar{\nu}_\tau \pi^+\pi^+\pi^-\pi^0$ channel. The Left-hand side plot $\pi^-\pi^0$ invariant mass distribution, right-hand side plot $\pi^+\pi^+$ invariant mass distribution. Continuous line for an old scaled down to 40 % CLEO current, dotted line for a new Novosibirsk current.*

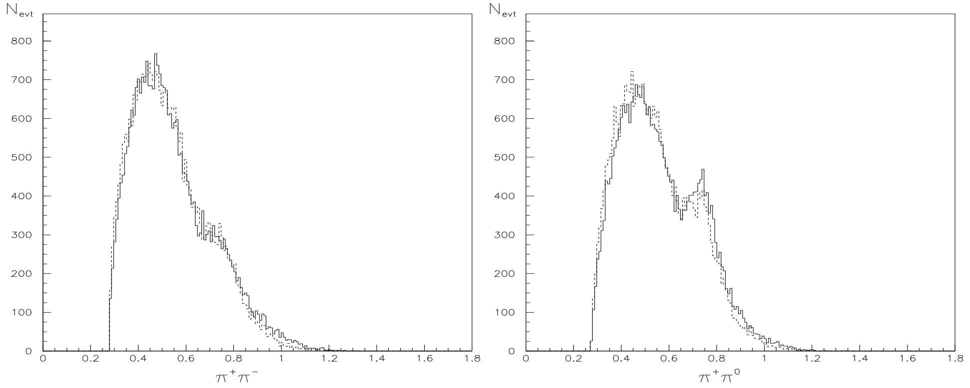


Figure 4: *The $\bar{\nu}_\tau \pi^+\pi^+\pi^-\pi^0$ channel. The Left-hand side plot $\pi^+\pi^-$ invariant mass distribution, right-hand side plot $\pi^+\pi^0$ invariant mass distribution. Continuous line for an old scaled down to 40 % CLEO current, dotted line for a new Novosibirsk current.*

PHOTOS

E. Barberio, B. van Eijk, Z. Was, Comput. Phys. Commun.(1991) ibid. (1994)

See also: P. Golonka et al. hep-ph/0312240, hep-ph/0506026, hep-ph/0508015

- Warning: Radiative corrections in decays may change parity sensitive observables a lot, especially if cut offs are present! F. Sanchez, Z. Was Phys.Lett.B351:562-568,1995
- This subject was covered on yesterday talk by E. Barberio.

TAUOLA universal interface

- To run, generator for tau decays must be combined with the part for tau production.
- In cases of our packages such as KORALB, KORALZ, KKMC host programs provide environment for TAUOLA use.
- I will concentrate on physics points in case when only information from event records is used.
- I will skip technicalities related to the way how HEPEVT common block is filled in 3 versions of PYTHIA conventions and HERWIG.
- also I will skip new developments in domain of event records.
- TAUOLA universal interface reads information from HEPEVT common block, there τ leptons to be decayed are found,
- and their spin states are calculated from kinematical configurations of hard processes leading to τ's.

Formalism for $\tau^+\tau^-$

- Because narrow τ width approximation can be obviously used for phase space , cross section for the process $f\bar{f} \to \tau^+\tau^- Y; \tau^+ \to X^+\bar{\nu}; \tau^- \to \nu\nu$ reads:

$$d\sigma = \sum_{spin} |\mathcal{M}|^2 d\Omega = \sum_{spin} |\mathcal{M}|^2 d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

- This formalism is fine, but because of over 20 τ decay channels we have over 400 distinct processes. Also picture of production and decay are mixed.
- but (only τ spin indices are explicitly written):

$$\mathcal{M} = \sum_{\lambda_1\lambda_2=1}^{2} \mathcal{M}^{prod}_{\lambda_1\lambda_2}\; \mathcal{M}^{\tau^+}_{\lambda_1} \mathcal{M}^{\tau^-}_{\lambda_2}$$

- Formula for the cross section can be re-written (narrow width limit!)

$$d\sigma = \Big(\sum_{spin} |\mathcal{M}^{prod}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^-}|^2\Big) wt\; d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

- where (again thanks narrow width limit!)

$$wt = \Big(\sum_{i,j=0,3} R_{ij} h^i h^j\Big)$$

$$R_{00} = 1, \quad < wt >= 1, \quad 0 \leq wt \leq 4.$$

R_{ij} can be calculated from $\mathcal{M}_{\lambda_1 \lambda_2}$
and h^i, h^j respectively from $\mathcal{M}^{\tau^+}$ and $\mathcal{M}^{\tau^-}$.

- Bell inequalities tell us that it is impossible to re-write wt in the following form

$$wt \neq \Big(\sum_{i,j=0,3} R_i^A h^i\Big)\Big(\sum_{i,j=0,3} R_j^B h^j\Big)$$

that means it is impossible to generate first τ^+ and τ^- first in some given ' quantum state' and later perform separatelly decays of τ^+ and τ^-

- It can be done only if approximations are used !!!
- May be often reasonable, but nonetheless approximations.

Main References for Higgs Boson Parity At The Linear Collider

- 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," Phys. Lett. B **579** (2004) 157

... and for B-meson Decays

- P. H. Chankowski, J. Kalinowski, Z. Was and M. Worek, "CP violation in B0/d $\longrightarrow$ tau+ tau- decays," Nucl. Phys. B **713** (2005) 555
- P. H. Chankowski, J. Kalinowski, Z. Was and M. Worek, hep-ph/0511079.

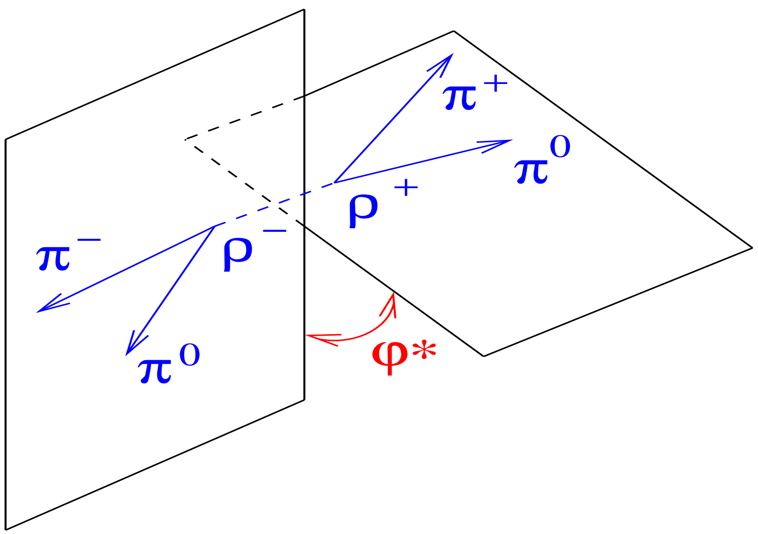
Pure Scalar And Pseudoscalar Higgs Boson

- *Case of* $\tau \longrightarrow \rho\nu_\tau$ *decay,* $\mathcal{BR}(\tau \to \rho\nu_\tau) = 25\%$
- *In def. of polarimeter vector* h^i q *denotes 4-vectors of* $\pi^\pm$ *minus* π^0 *and,* N *of* ν_τ*.*

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

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

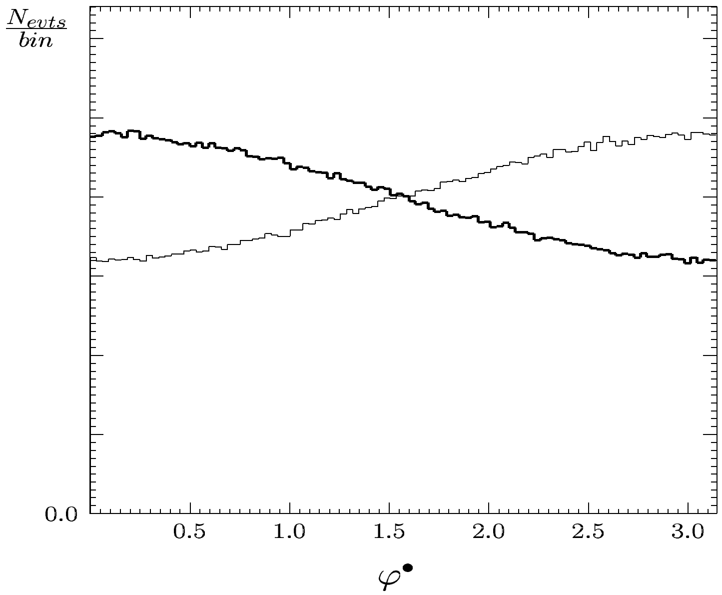
- *Acoplanarity of* ρ^+ *and* ρ^- *decay prod. (in* $\rho^+\rho^-$ *r.f.) and events separation.*

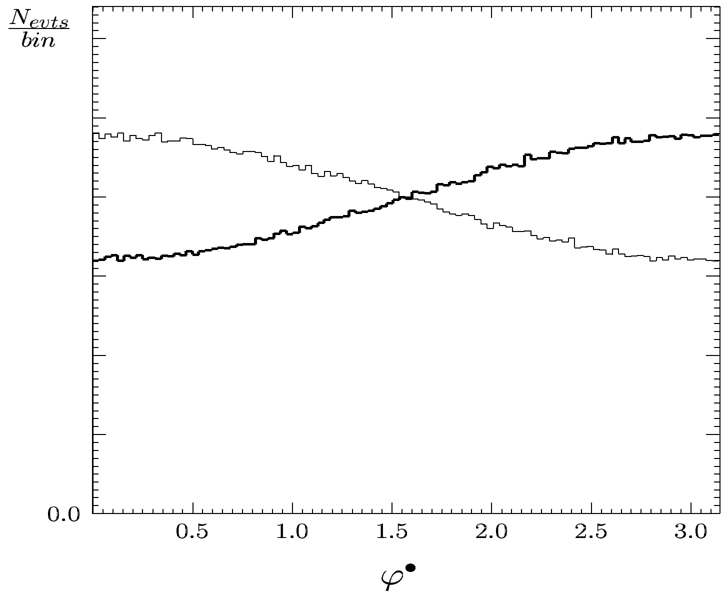


$$y_1 y_2 > 0\;; \qquad y_1 y_2 < 0 \text{ (in } \tau^\pm \text{ r.f.'s)}$$

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

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}).*

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

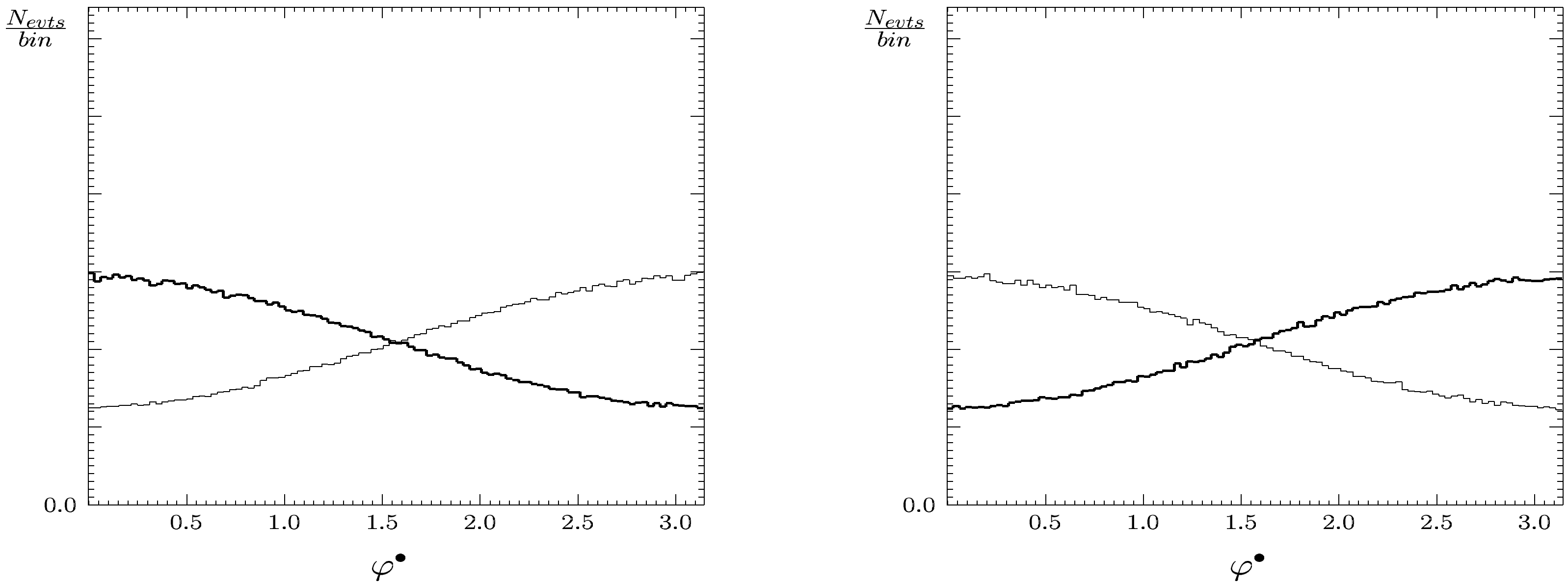
Replacement τ Rest Frame

- Take just laboratory frame instead of $\tau^{\pm}$ r.f.'s.
- Invisibly better 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. The problem is that we can not determine direction of the ν_τ because of Beamstrahlung.

Here we used MC to understand observable build from 24 dimensions

We assumed little knowledge on τ decay vertex

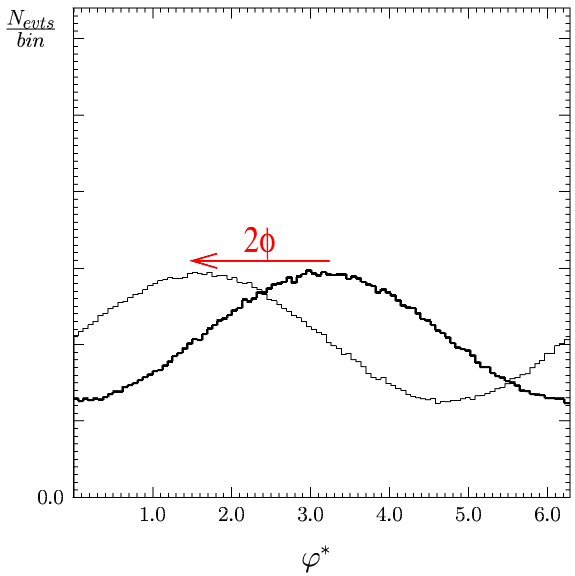
Results With τ Impact Parameter – Additional Cuts

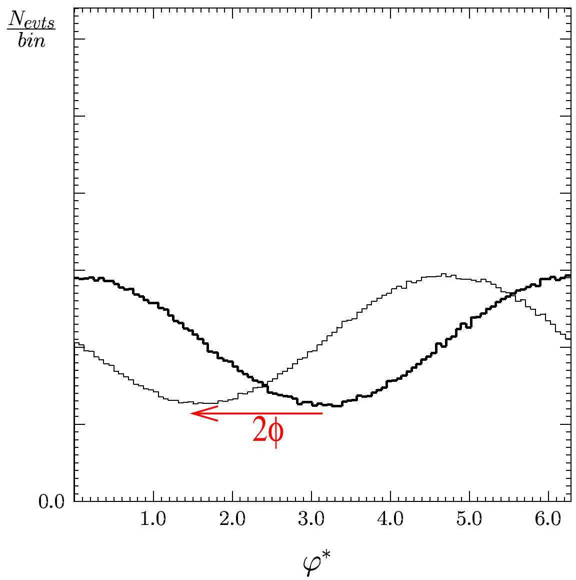


- *Only events where the signs of y1 and y2 are the same whether calculated using the method without or with the help of the τ impact parameter.*
- *Improvement* $\sim 107\%$.
- *Only* $\sim 52\%$ *events are accepted.*

Improvement: $\sim 4.5\sigma$

Results For Mixed Scalar–Pseudoscalar Case

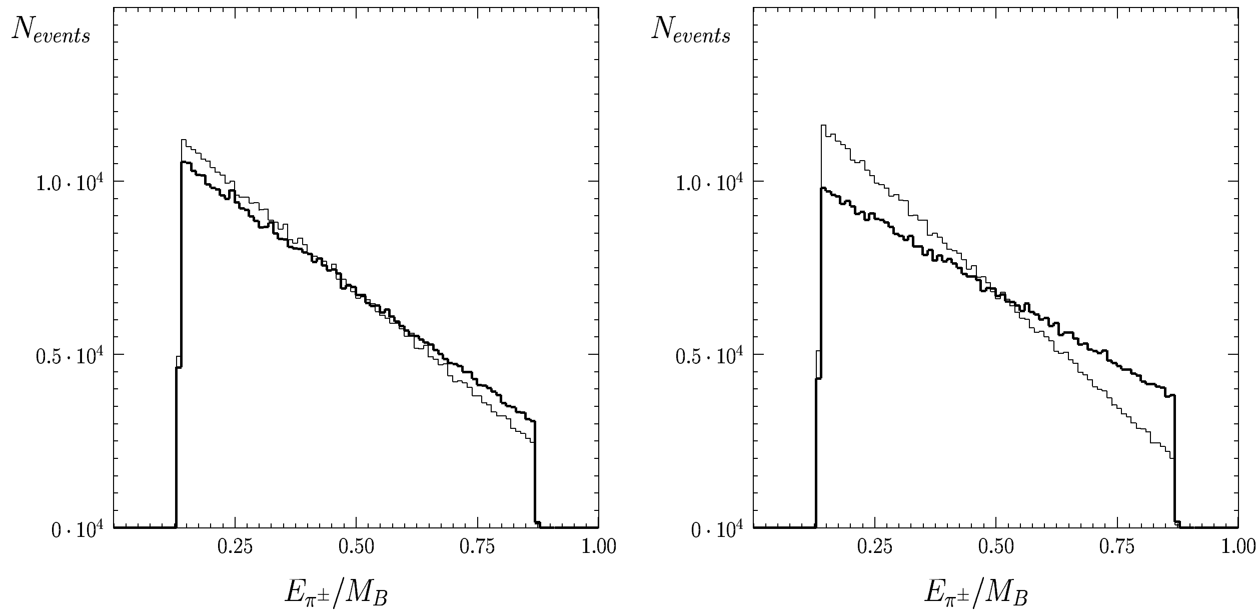




- *Only events where the signs of y1 and y2 are the same whether calculated using the method without or with the help of the τ impact parameter.*
- *Detector-like set-up is included (SIMDET).*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*

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

Most general case for the $a + ib\gamma^5$ coupling



- *In the previous transparency we have used arbitrary but real a and b.*
- *If we assume complex b then height of the wave is proportinal to $\Re(ab)$*
- *The slopes in the plots for pion spectra in $\tau \to \nu\pi$ are proportional to $\Im(ab)$*
- *The two observables are thus complementary (if can be measured).*
- *Only for good LC detectors chances for improvements? Andre Rouge Phys. Lett. B619 (2005) 43.*

Summary

- *We have reviewed tools for simulation of final state physics:*
  - *TAUOLA generator for τ decays*
  - *TAUOLA universal interfaces to implement complete spin correlations for τ decays combined with different production mechanisms.*
  - *We have mentioned importance of radiative corrections in decays and PHOTOS as a mean to generate.*
- *With the help of the tools we have shown specific applications for observables which are CP sensitive :*
  - *Observables are mainly targeted for LC*
  - *But may find their way in applications at BaBar/Belle or LHC as well*
- *Let us turn now to possible future projects.*

Future

- TAUOLA and its associated programs seem to be a living project
- As in the past new parametrizations will be developed within Belle and BaBar. Non-tau experiments like LHC may profit.
- At some time results will be ported to LHC.
- When/if/how translation to C++ should be done?
- Manpower constraints. Struggle with priorities...
- Let us have private discussions now.
- My phone no at CERN till Dec. 5-th is 74146
- I realize how important it isto assure stability of the simulations.
- I am open to technicalities, especially over the next few weeks.