Determination of the CP parity of Higgs bosons in their tau decay channels at the ILC

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Introduction

- A neutral spin-0 resonance (Higgs boson) with mass of ~ 126 GeV has been discovered at the LHC

- Current measurements of its properties are consistent with the prediction of one Standard Model like Higgs boson

- Question:
  What is the CP quantum number of the scalar resonance?
  Is it a CP-eigenstate? CP mixed state?

Introduction

- More involved models might be realized, for instance a general 2-Higgs doublet model leading to 5 physical higgs bosons

- CP is approximately conserved

  2 CP-even states: h^0, H^0

  1 CP-odd state: A^0

  2 charged states: $H^\pm$

- CP is violated, neutral states mix: h_1, h_2, h_3

- How to distinguish degenerated states of definite CP-quantum number from mixed CP states?

Introduction

- $\Phi \to \tau\bar{\tau}$ decay (in general fermion pairs) is especially suitable as tau leptons couple at tree level to scalar and pseudo-scalar components of the Higgs boson

- Large braching fraction of $\Phi \to \tau\bar{\tau}$

- Degenerated states of scalar and pseudo-scalar bosons can be distinguished from a CP-mix state

- Radiative corrections to $\Phi \to \tau\bar{\tau}$ are small

- Method shown here: CP property of scalar bosons can be measured in the tau-tau decay channel, if the Higgs production vertex can be reconstructed ($Z \to e^+e^-$)

Introduction

- CP quantum numbers and possible CP violation of neutral Higgs bosons can be measured in a variety of Higgs decays or Higgs production processes, (*e.g. hep-ph/0608079*)

- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \rho + \nu$ — *(Desch, Was, Worek '03) uses 6.3% of events*

- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \pi + \nu$ — *Kramer et al. '94, Kühn, Wagner '84, Kühn '93)*

- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \text{hadrons}$ — *(A. Rouge, '05) uses 23% of events; small Higgs width*

Higgs decay into tau lepton pairs

- Consider Lagrangian: $\mathcal{L}_Y = -\frac{m_\tau}{v}\,(\,a\cdot\bar{\tau}\tau + b\cdot i\,\bar{\tau}\gamma_5\tau\,)\,\phi^0$

- Higgs decays via $\phi^0 \to \bar{\tau}\tau$, where the $\bar{\tau}\tau$ pair has $P=(-1)^{L+1}$ and $C=(-1)^{L+S}$

- if $\tau\bar{\tau}$ is in $^1S_0$ state :
  $\rightarrow\; J^{PC} = 0^{-+}$
  $\rightarrow\; A^0$
  $\rightarrow \langle s_{\tau^-}\cdot s_{\tau^+}\rangle = -\frac{3}{4}$
  $\rightarrow a=0, b=1$

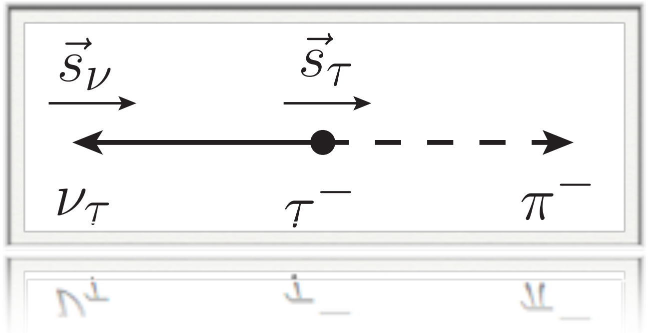
- if $\tau\bar{\tau}$ is in $^3P_0$ state :
  $\rightarrow\; J^{PC} = 0^{++}$
  $\rightarrow\; H^0, h^0$
  $\rightarrow \langle s_{\tau^-}\cdot s_{\tau^+}\rangle = \frac{1}{4}$
  $\rightarrow a=1, b=0$

Higgs decay into tau lepton pairs

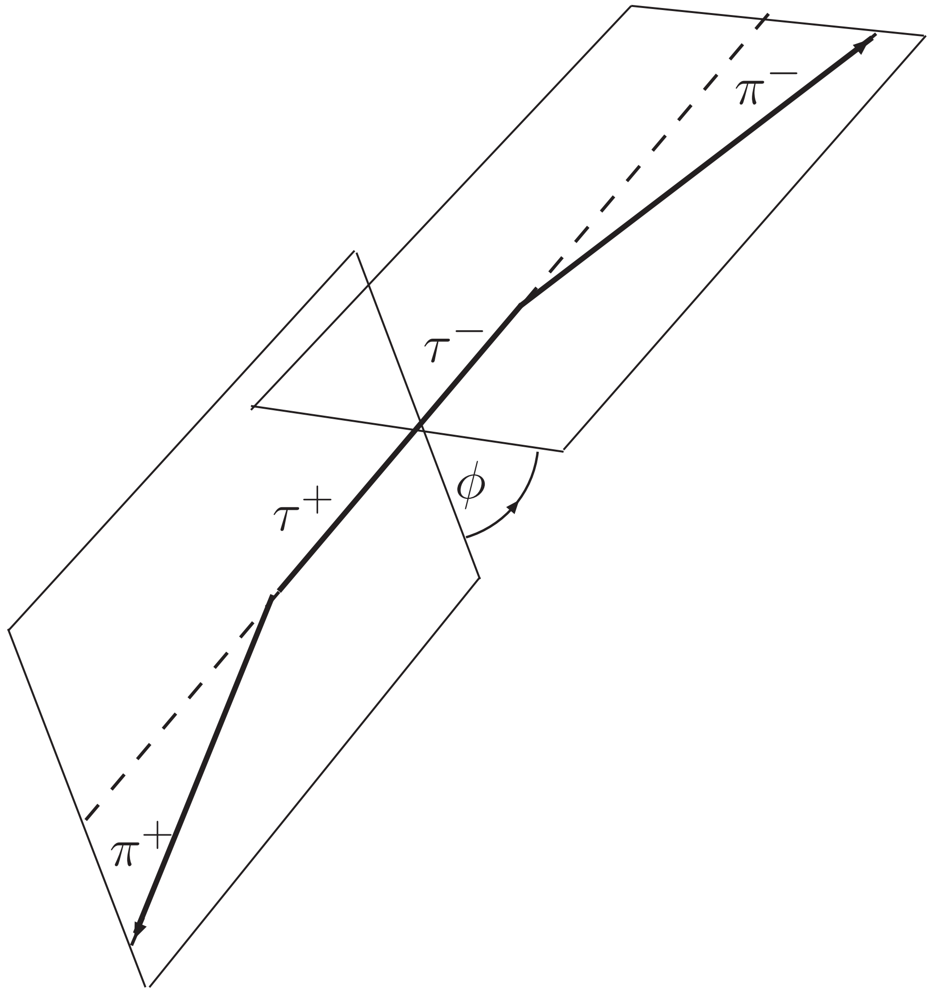
- Consider $\tau^- \to \pi^- + \nu_\tau$:
  Higgs decay probability can be written as *(Barger et al. '79)*

$$\Gamma(H, A \to \tau^-\tau^+) \sim 1 - s_z^{\tau-} s_z^{\tau+} \pm s_T^{\tau^-} s_T^{\tau^+}$$

- Pion is preferably emitted in the direction of the tau-Spin in the tau rest frame

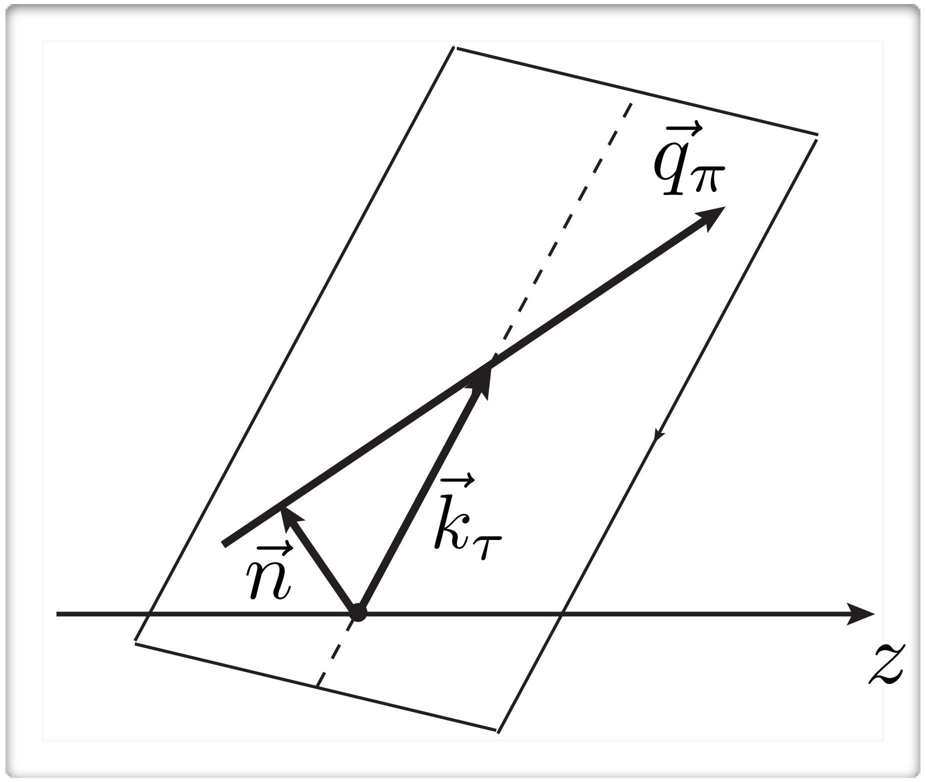


- $\varphi = acos\,(\hat{q}_{\pi^-} \cdot \hat{q}_{\pi^+})$ is sensitive to $\tau\tau$ spin correlation ($\hat{q}_{\pi^\pm}$ defined in $\tau^\pm$ rest frame)



Higgs decay into tau lepton pairs

- No reconstruction of τ rest frames
- Use impact parameter vectors $\hat{n}_-$, $\hat{n}_+$
  $\varphi \sim acos(\hat{n}_- \cdot \hat{n}_+)$
- Boost $\hat{n}_\pm$ into $\pi^-\pi^+$-ZMF (denoted by *)
  $(n^\mu n_\mu = -1)$:
- $\varphi^* = \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$
- Measurement of PV necessary
  (from $Z \to e^+e^-$)



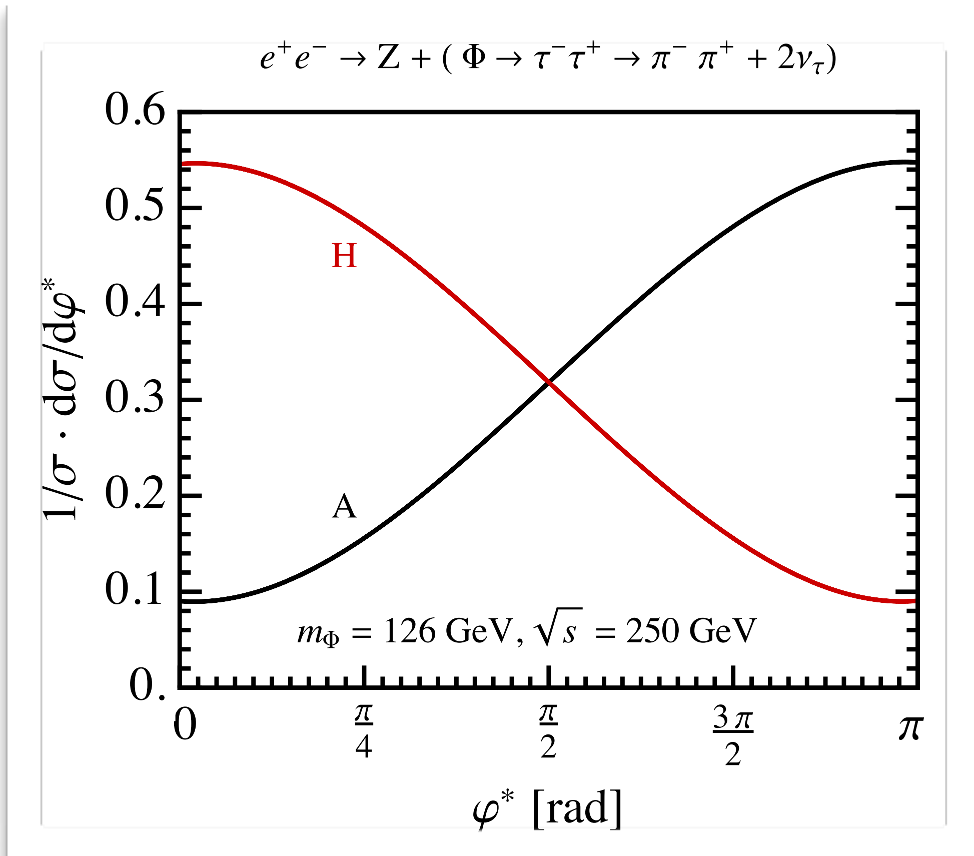
Higgs decay into tau lepton pairs

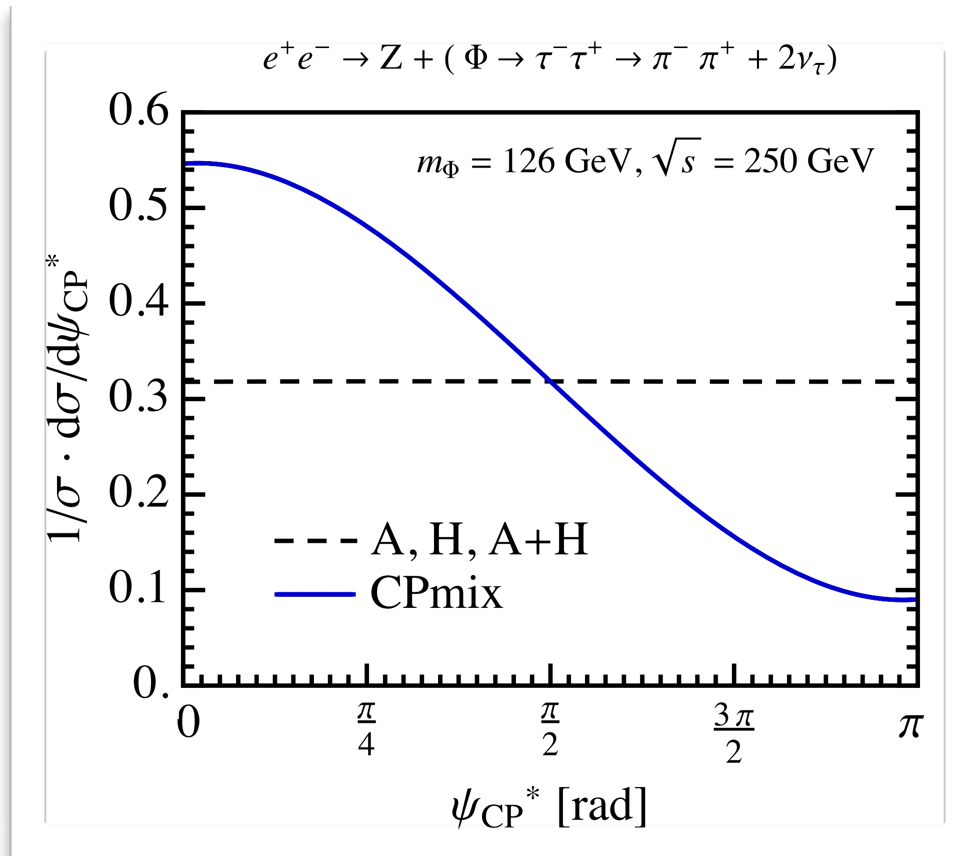
$$\mathcal{O}_3 = s_{\tau^-} \cdot s_{\tau^+}$$

$$\varphi^* = \mathrm{acos}(\,\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp}\,)$$

$$\mathcal{O}_2 = \hat{k}_{\tau^-} \cdot (s_{\tau^-} \times s_{\tau^+})$$

$$\psi^*_{CP} = \mathrm{acos}(\,\hat{q}^*_{\pi^-} \cdot (\hat{n}^*_{-\perp} \times \hat{n}^*_{+\perp})\,)$$

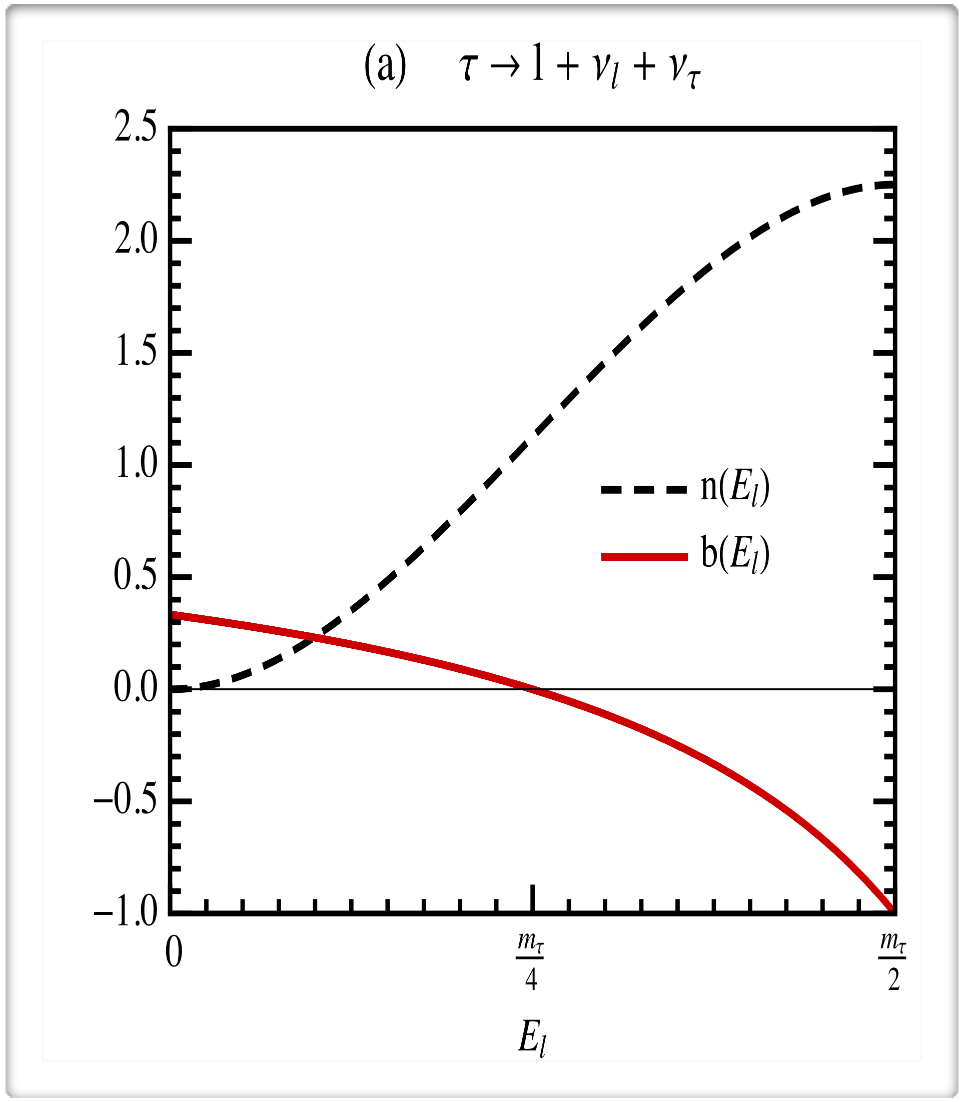




Higgs decay into tau lepton pairs

- Differential decay width: $\frac{d\Gamma(\tau(k,s)\to i(q)+X)}{\Gamma/(4\pi)\ dE_i d\Omega_i} = n(E_i)\,(1+b(E_i)\ \hat{s}\cdot\hat{q})$
- Branching ratios:

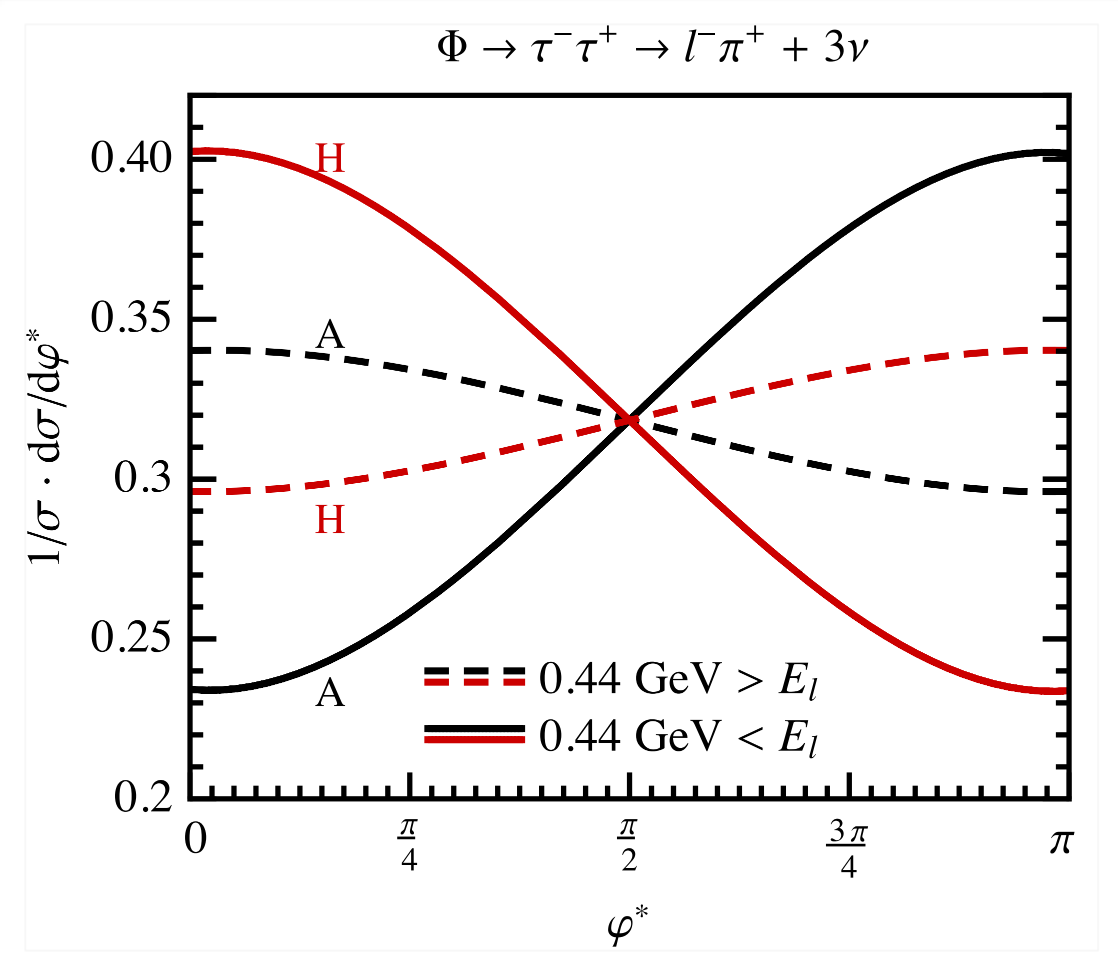
decay mode	BR_{PDG} [%]
$\tau^- \to \pi^-$	11
$\tau^- \to \rho^- \to \pi^-\pi^0$	25.5
$\tau^- \to a_1^- \to \pi^- 2\pi^0$	9.3
$\tau^- \to a_1^- \to \pi^-\pi^+\pi^-$	9
$\tau^- \to e^-, \mu^-$	35.2



- Energy variable in 3-body decay modes: $\tau^\pm \to l^\pm + X$ and $\tau^\pm \to \rho^\pm/a_1^\pm + X \to \pi^\pm + X$
- $b(E)$ determines spin analyzer quality
- $n(E)$ determines relativ contribution to σ

Higgs decay into tau lepton pairs

- Leptonic decay: $\tau^- \to l^- + \nu_\tau + \overline{\nu}_l$
- Assume theoretical cut in τ rest frame at $E_l = \frac{m_\tau}{2} = 0.44$ GeV
- Slopes have opposite sign for $E_l < m_\tau/2$ and $E_l < m_\tau/2$
- Need to separate both regions
- Cancelation even stronger for hadronic $\tau \to a_1/\rho + X$ decay channels



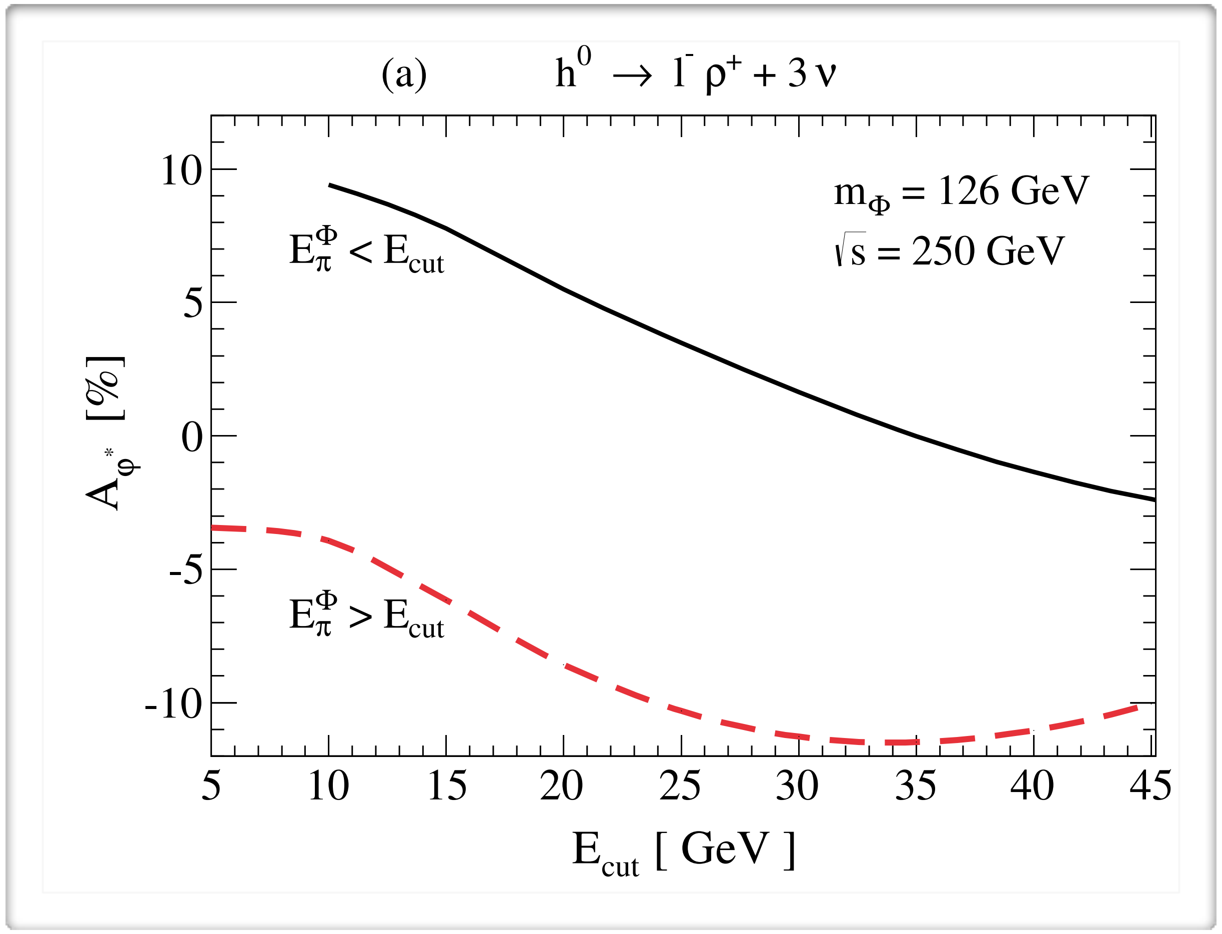
Higgs decay into tau lepton pairs

- Cut on the visible τ-decay particle energy in Higgs rest frame, here: E_π^Φ

- Asymmetry is defined by:
  $$A_{\varphi^*} = \frac{N(\varphi^* > \pi/2) - N(\varphi^* < \pi/2)}{N(\varphi^* > \pi/2) + N(\varphi^* < \pi/2)}$$

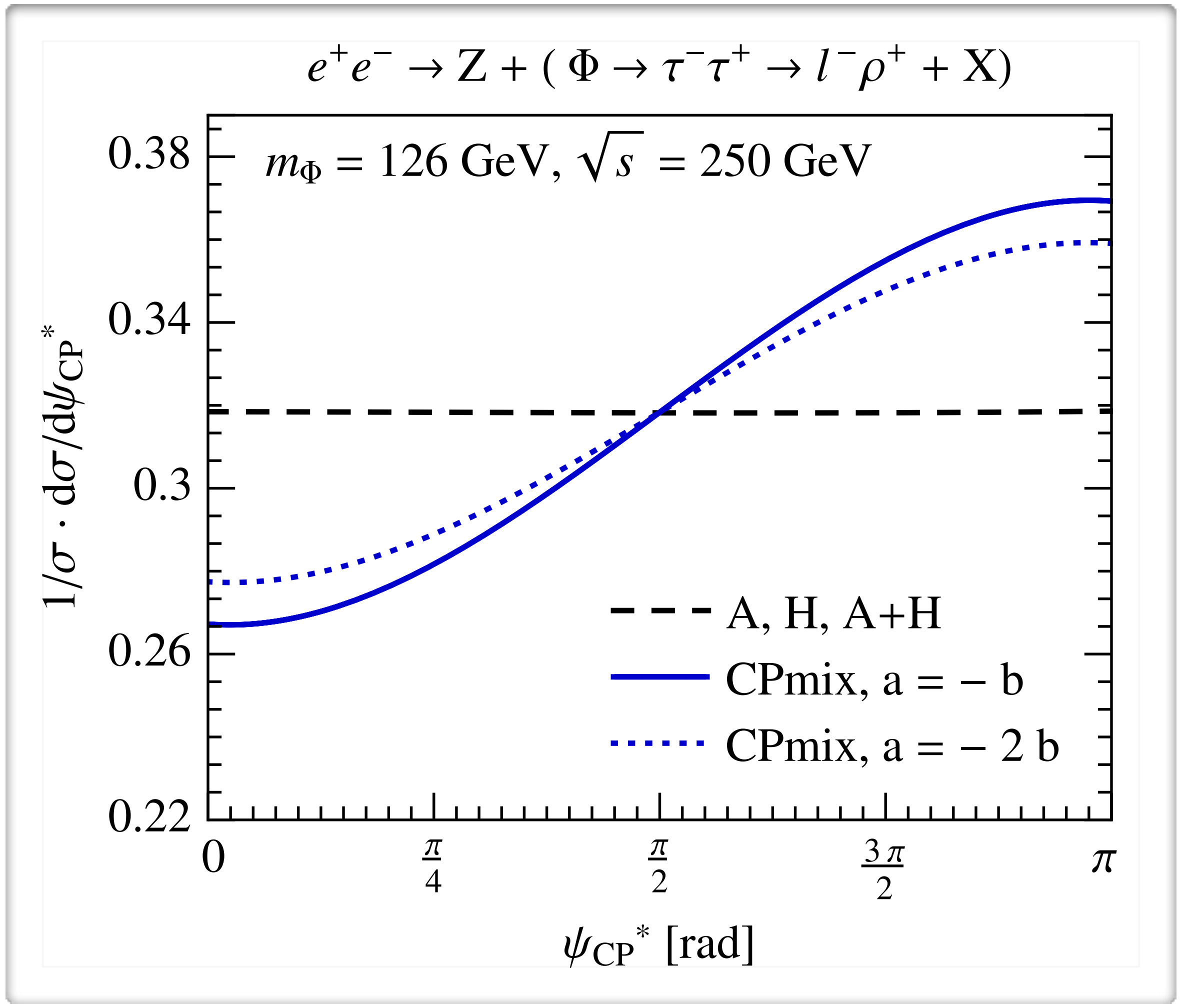
- Optimize separation of events with positive and negative $b(E_\pi)$

- Use both sets to determine the CP nature of the Higgs bosons



Higgs decay into tau lepton pairs

- CP mixed states can be tested using:
  $\psi^*_{CP} = \text{acos}(\hat{q}^*_1 \cdot (\hat{n}^*_{1\perp} \times \hat{n}^*_{2\perp}))$
- Mixing is maximal for $a = -b$
- No asymmetry for CP eigenstates
- Sign of the asymmetry dependes on:
  - tau decay channel
  - sign of a and b



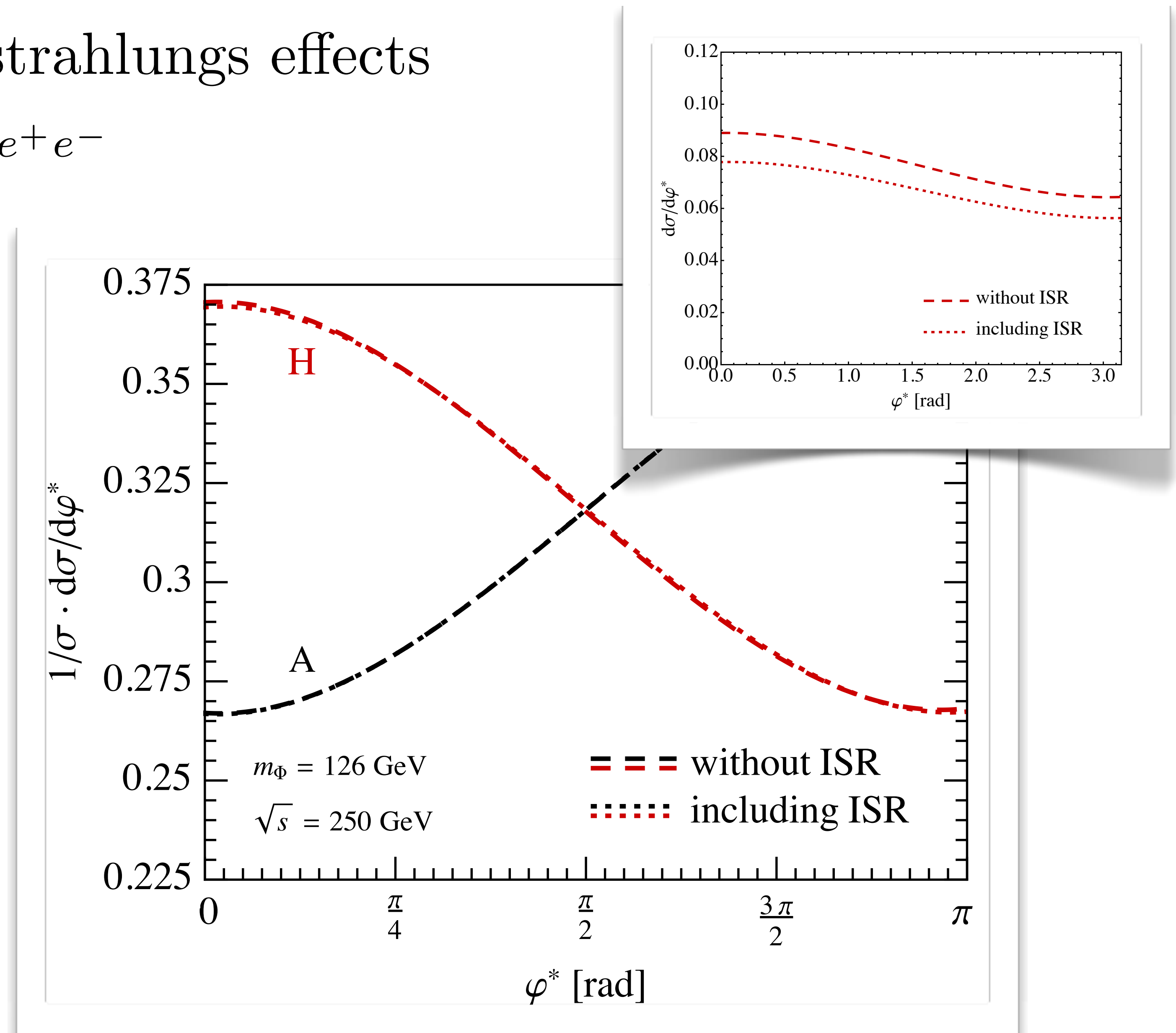
ISR and Beamstrahlung

- Initial state radiation and Beamsstrahlungs effects lower the center of mass energy, $s_{e^+e^-}$

- Assume: $\vec{p}_{\Phi}^{\,Lab} = -\,\vec{p}_{Z}^{\,Lab}$

- Boost lepton and pion into Higgs rest frame $\rightarrow$ cut on E_l^{Φ} and/or E_{π}^{Φ}, here $E_{\pi}^{\Phi} \geq 25$ GeV

- Negligible effect on normalized distributions



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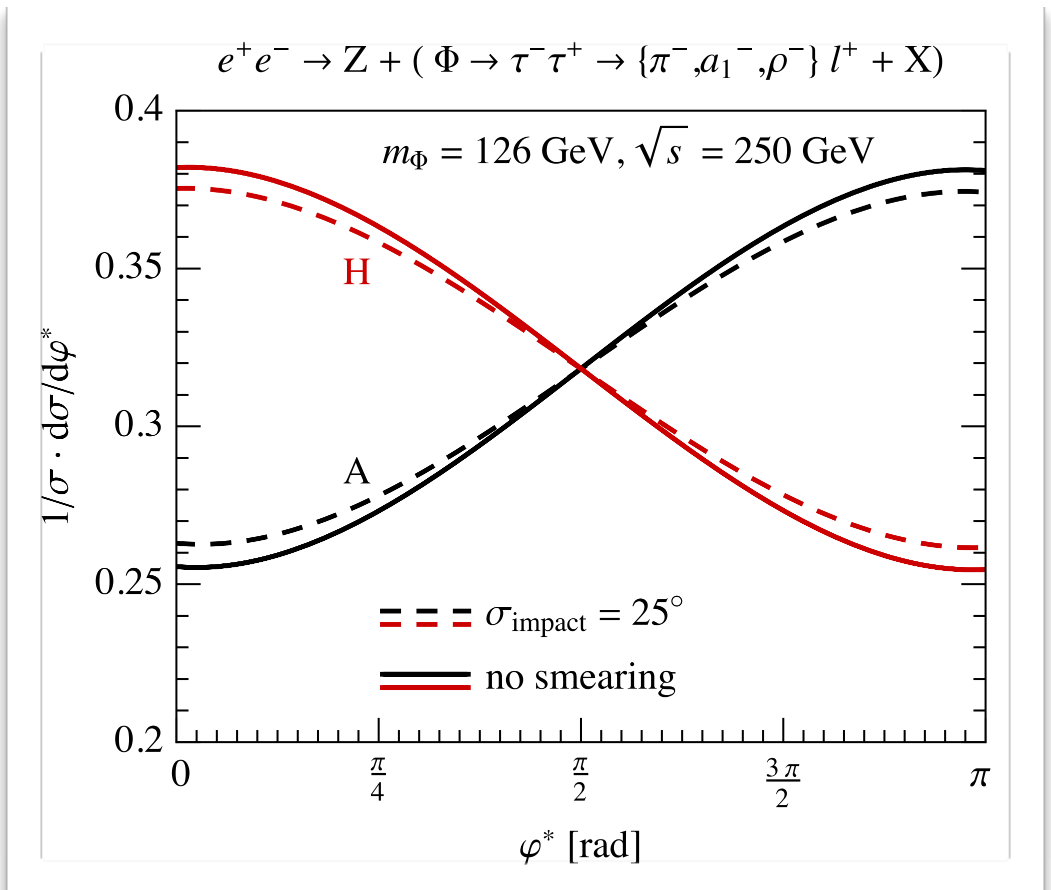
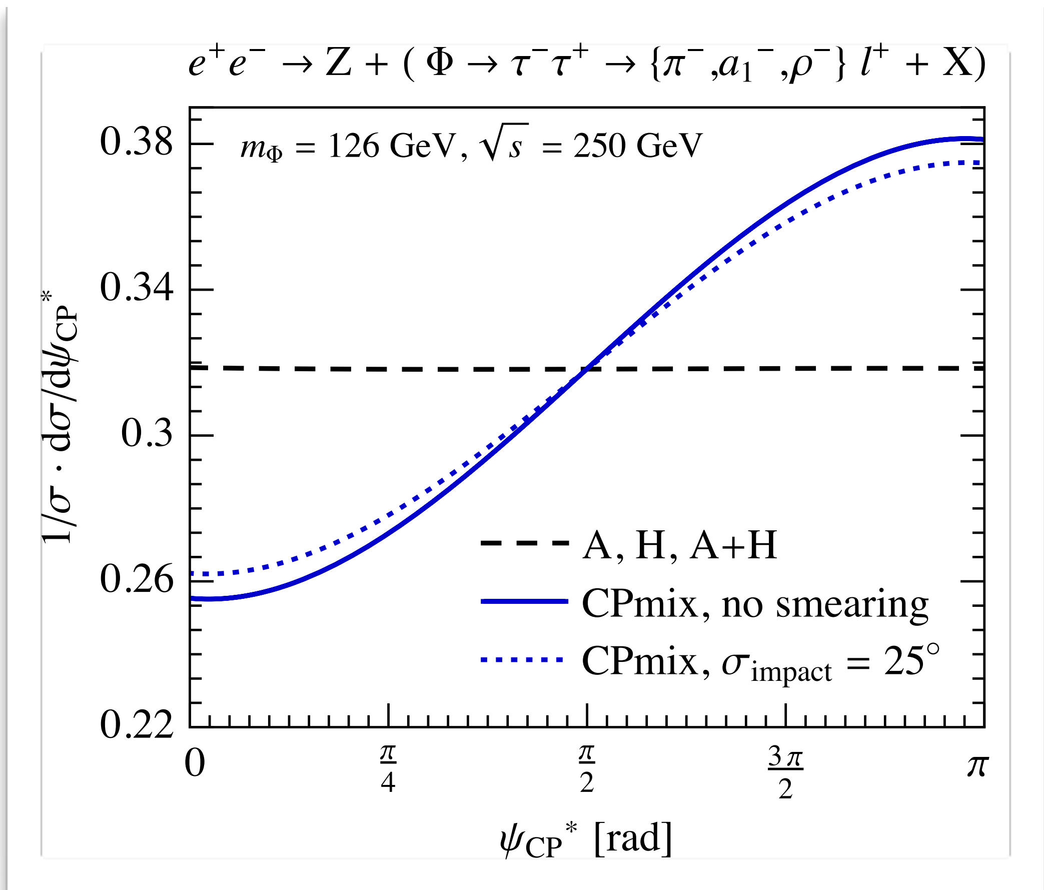
Measurement uncertainties

- Combined hadron-lepton channel with $E^{\Phi}_{\pi_{min}} = 25$ GeV and $E^{\Phi}_{l_{min}} = 15$ GeV
  $\tau^+\tau^- \rightarrow \{a_1, \rho, \pi\}^+ + l^- + X$
- Gaussian smearing of impact parameter measurement
  with $\sigma_{\text{impact}} = 25^o$ as suggested in worek '03





Concluding Remarks

- Determination of the CP quantum numbers of neutral, Spin-0 resonances is possible in the tau decay channel, where all dominant tau-decay channels can be included

- CP-odd and CP-even eigenstates as well as CP mix states can be distinguished in $H \to \tau\bar{\tau}$ using two different observables

- Need to be done:
  Include background, realistic simulation.
  Optimize energy cut of the visible τ decay particle in Higgs rest frame

Higgs decay into tau lepton pairs

- Similar for $\tau \rightarrow \rho + \nu_\tau$

  $\tau \rightarrow a_1 + \nu_\tau$

- $b(E_{a_1,\rho})$ opposite to leptonic decay
- $n(E_{a_1,\rho})$ equally important for small and large pion energies in tau rest frame

- φ^* horizontal line at 0 if integrated over whole spectrum (no cuts)

- Energy for direct decay fixed