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

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Introduction

- LHC: At least one scalar boson, probably Spin-0, with $m_h = 126$ GeV

- If it is one boson: h^0, H^0 (CP-even), A^0 (CP-odd) or h_1 (CP-mixed)
  - It is not a pure CP-odd state A^0 ($h \to ZZ$: CMS-PAS-HIG-13-002, ATLAS-CONF-2013-013; and 1211.1980)
  - No large anamolous A^0ZZ coupling (because of $h \to ZZ$)

  $\to$ large cross section in $e^+e^- \to hZ$

- If there is more than one Higgs boson (e.g. 2HDM), degenerated in mass
  - E.g. A^0 and H^0: $\to$ H^0 is produced in $ee \to ZH^0$ with large cross section at ILC
  - E.g. h^0 and H^0: or several CPmix: $\to$ $ee \to Zh$ with large cross section at ILC

- Either case: h will be produced with SM like cross section in $e^+e^- \to hZ$

Introduction

- $h \to \tau\bar{\tau}$ 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 branching fraction of $h \to \tau\bar{\tau}$
- $h \to f\bar{f}$: Direct test of the Higgs CP nature possible
- Degenerated states of scalar and pseudo-scalar bosons can be distinguished from a CP-mix state
- Radiative corrections to $h \to \tau\bar{\tau}$ 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 ($Z \to e^+e^-$) (or if one projects onto the transverse plane)

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*)

- $e^+e^- \to Z\,h \to Z + \tau\bar{\tau}$ and $\tau \to$ hadrons — *(Reinhard, Videau, 2009) uses 30% of events*

- $e^+e^- \to Z\,h \to Z + \tau\bar{\tau}$ and $\tau \to \rho + \nu$ — *(Desch, Was, Worek hep-ph/0307331) uses 6.5% of events*

- $e^+e^- \to Z\,h \to Z + \tau\bar{\tau}$ and $\tau \to \rho + \nu$ — *(R. Primulando et al., Phys.Rev. D88 (2013) 076009), 6.5% of events*

- $e^+e^- \to Z\,h \to Z + \tau\bar{\tau}$ and $\tau \to all$ — *(S.B., Bernreuther, Spiesberger, Phys. Lett. B 727 (2013) 488)*

Higgs decay into tau lepton pairs

- Consider Lagrangian: $\mathcal{L}_Y = \, - N \, (\cos\phi \, \bar{\tau}\tau + \sin\phi \, \bar{\tau} i \gamma_5 \tau) \, h$

CP mixing angle

- Higgs decays via $h \to \bar{\tau}\tau$,
  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 :
  $\to \; J^{PC} = 0^{-+}$
  $\to \; A^0$
  $\to \langle s_{\tau^-} \cdot s_{\tau^+} \rangle = -\frac{3}{4}$
  $\to \phi = \frac{\pi}{2}$

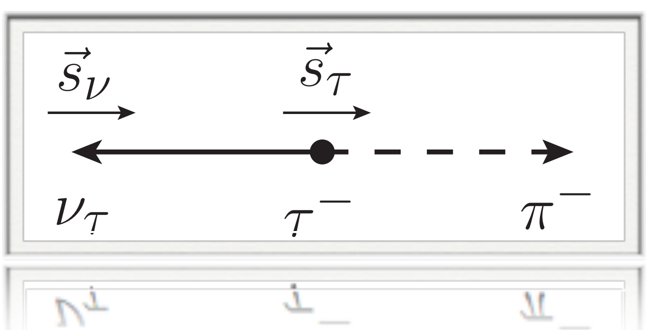
- if $\tau\bar{\tau}$ is in $^3P_0$ state :
  $\to \; J^{PC} = 0^{++}$
  $\to \; H^0, h^0$
  $\to \langle s_{\tau^-} \cdot s_{\tau^+} \rangle = \frac{1}{4}$
  $\to \phi = 0$

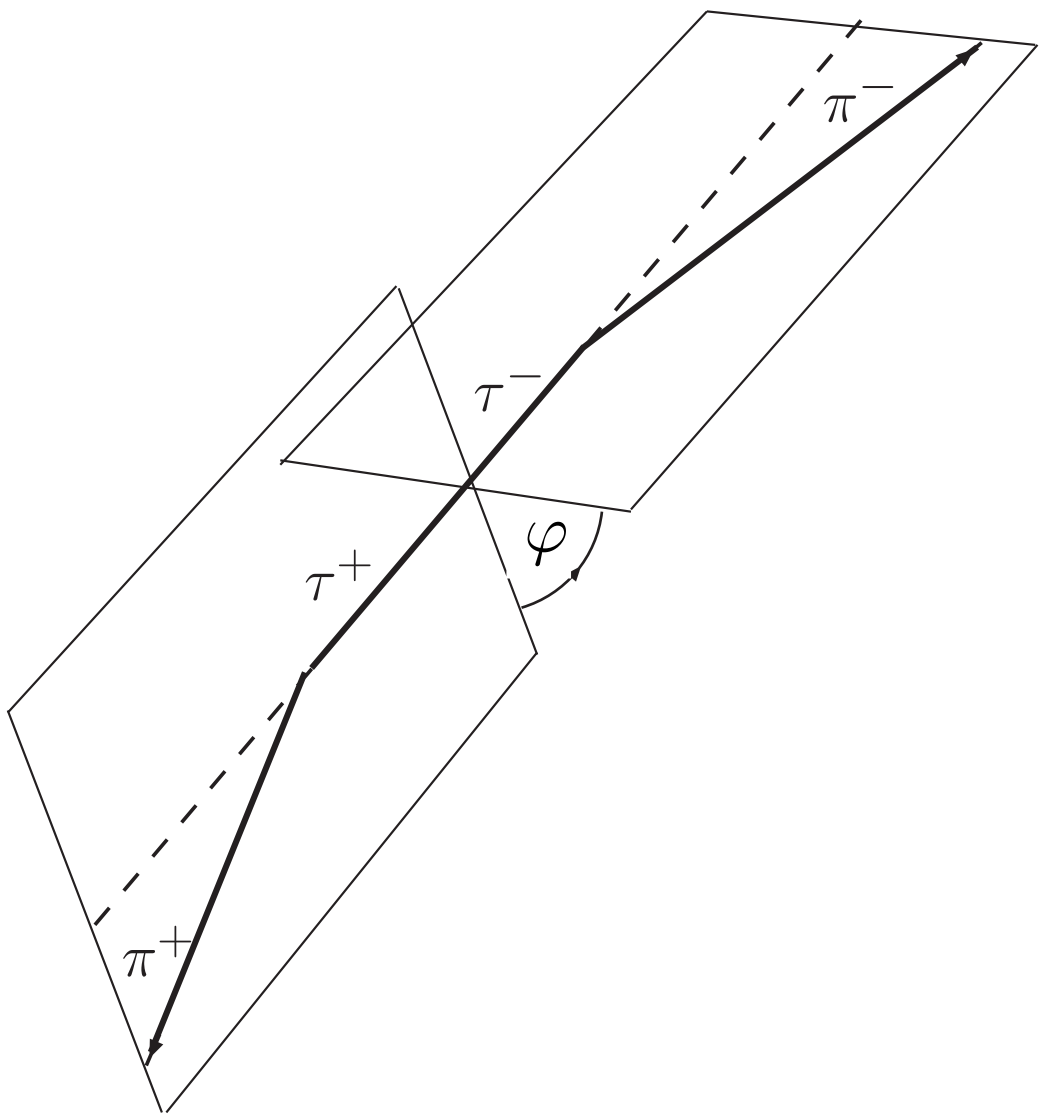
Higgs decay into a pair of tau leptons

- 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





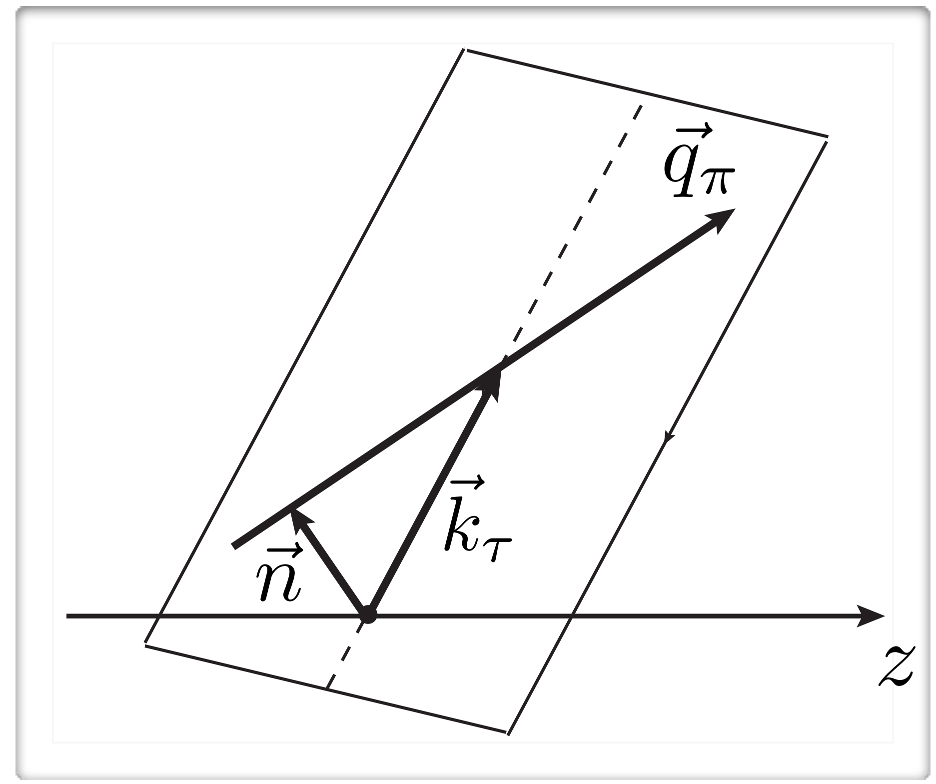
- φ is sensitive to $\tau\tau$ spin correlation

  $\to$ Problem: need to reconstruct τ-momenta

Our Method:

(S.B., Bernreuther; Phys.Lett. B671 (2009) 470-476 [arXiv: 0812.1910])

- No reconstruction of τ momenta necessary
- Use normalized impact parameter vectors $\hat{n}_-$, $\hat{n}_+$, measured in lab frame
- Boost $\hat{n}_\pm$ into $\pi^-\pi^+$-ZMF (denoted by *) $(n^\mu n_\mu = -1)$:
- Define $\varphi^* = \text{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$
- Measurement of Primary Vertex (PV) necessary (e.g. from $Z \to e^+e^-$)



Definition of observables

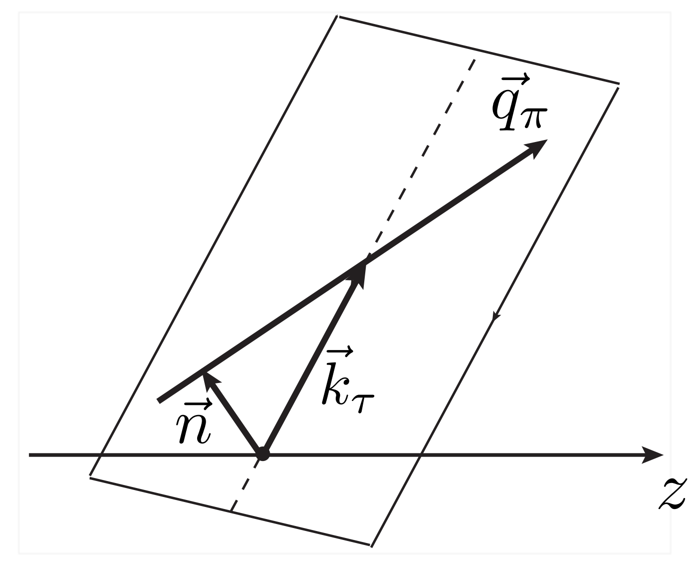
$$\mathcal{O}_3 = s_{\tau^-} \cdot s_{\tau^+}$$

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

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

$$\mathcal{O}^*_{CP} = \hat{q}^*_{\pi^-} \cdot (\hat{n}^*_{-\perp} \times \hat{n}^*_{+\perp}) = \sin\varphi^*_{CP}$$

$$\varphi^*_{CP} = \begin{cases} \varphi^* & if \quad \mathcal{O}^*_{CP} \geq 0 \\ 2\pi - \varphi^* & if \quad \mathcal{O}^*_{CP} < 0 \end{cases}$$



Higgs decay into tau lepton pairs

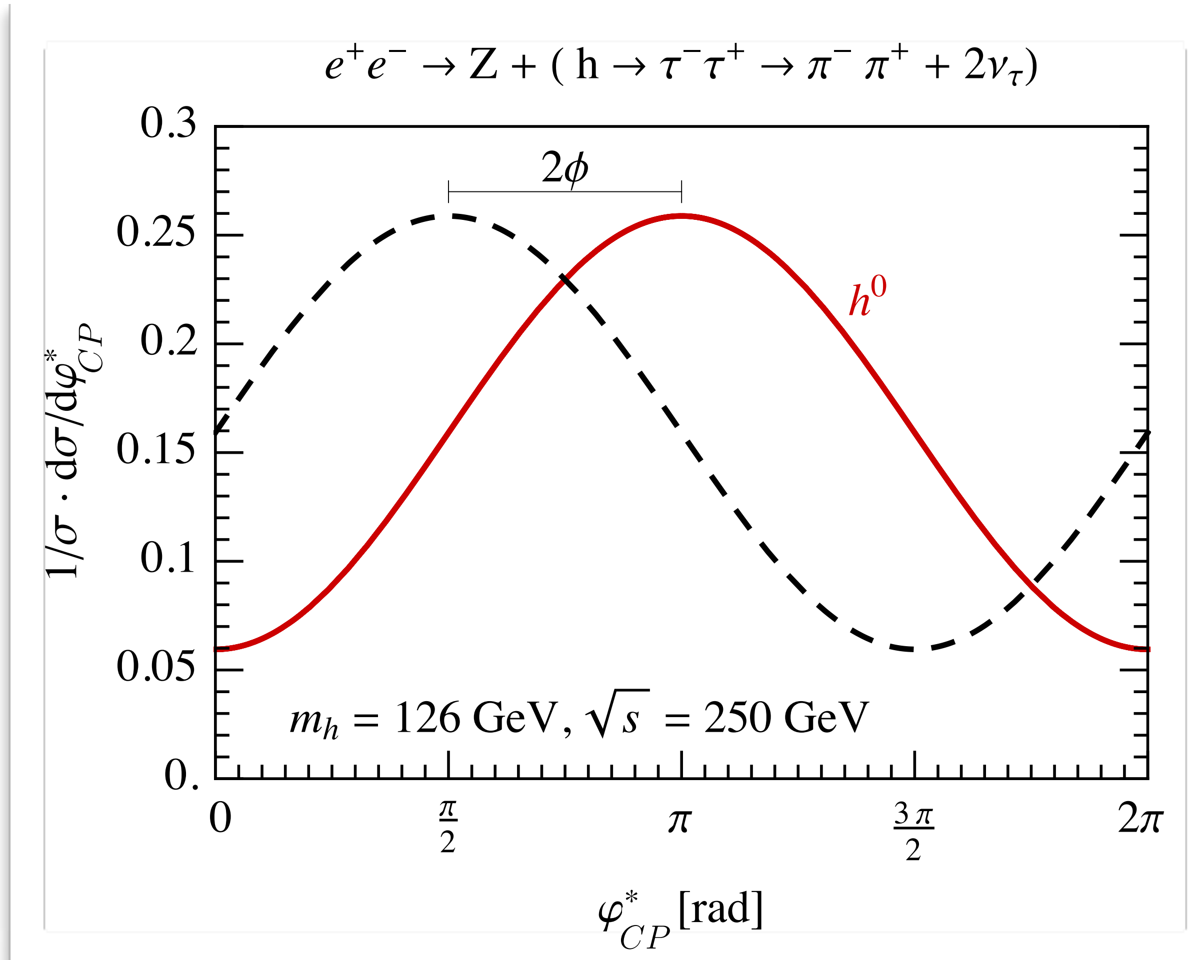
- Example: $h \to \tau\bar{\tau} \to \pi^+\pi^- + \nu_\tau + \bar{\nu}_\tau$ decay:

- $$\frac{1}{\Gamma}\frac{d\Gamma(h \to \pi^+\pi^- + 2\nu)}{d\varphi^*_{CP}} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi)\right]$$

- Define Asymmetry for h^0:

$$A = \frac{\sigma(\cos\varphi^*_{CP} < 0) - \sigma(\cos\varphi^*_{CP} > 0)}{\sigma}$$

E.g. $A(h^0 \to \pi^+\pi^- + 2\nu) = 40\%$

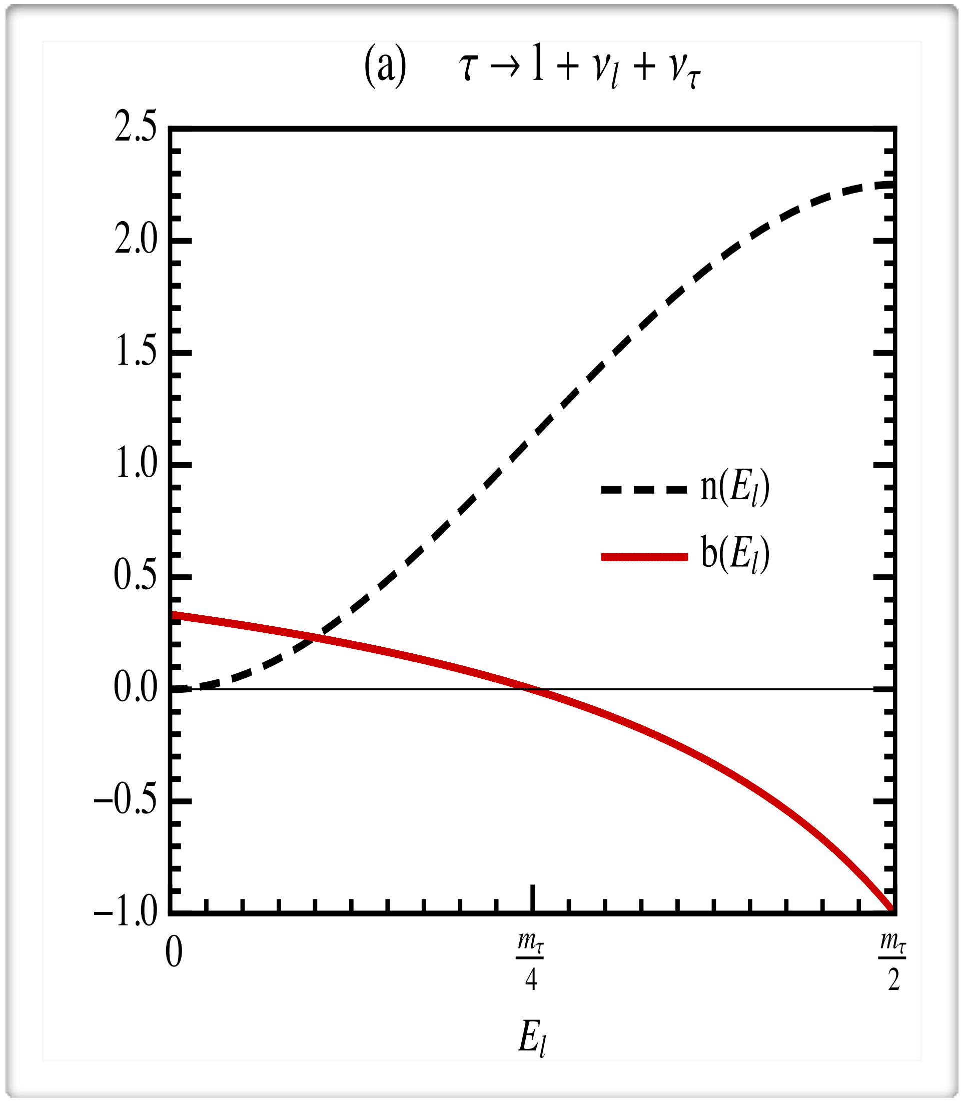


Higgs decay into tau lepton pairs

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

- 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 $\tau^\pm \to \rho^\pm/a_1^\pm + X \to \pi^\pm + X$

- $b(E)$ - spin analyzer quality

- $n(E)$ determines relativ contribution to σ

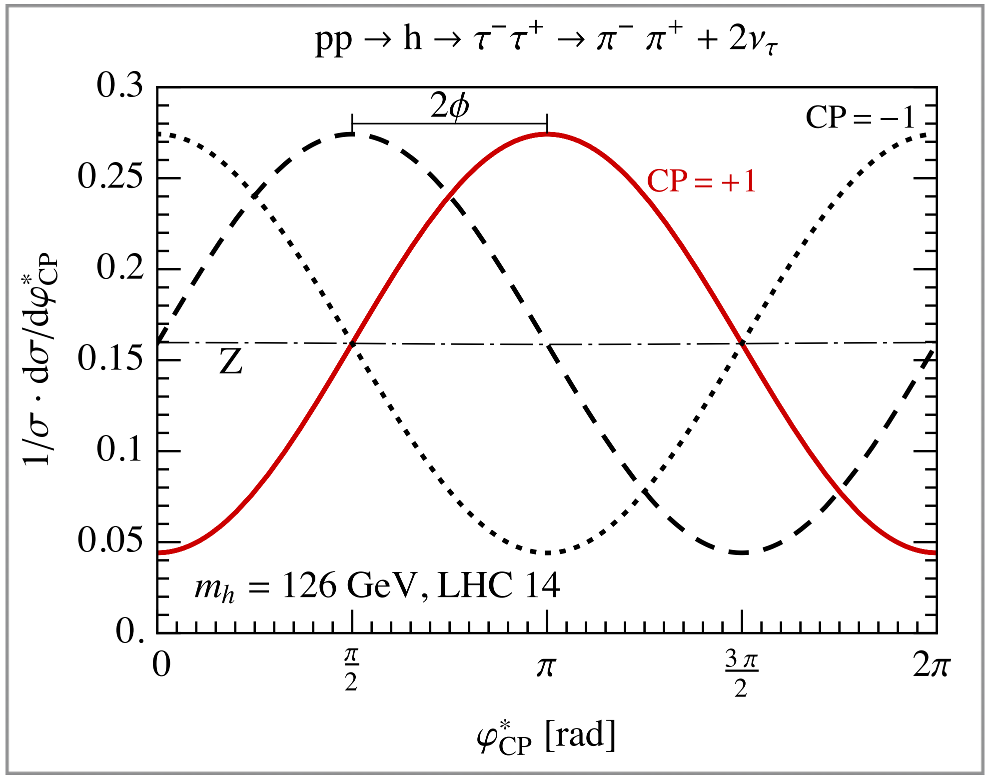
Differential distribution

- Differential cross section:

$$d\sigma \sim d\Omega_\tau \; dE_{a^-} \; dE_{a'^+} d\varphi^*_{CP} \left[v + u \cdot \cos\left(\varphi^*_{CP} - 2\phi\right) \right]$$

$$u = -n\left(E_{a^-}\right) b\left(E_{a^-}\right) n\left(E_{a'^+}\right) b\left(E_{a'^+}\right) \frac{\pi^2 p_h^2}{8} \frac{g_\tau^2}{\sqrt{2} G_F m_\tau^2}$$

$$v = 4n\left(E_{a^-}\right) n\left(E_{a'^+}\right) \; N$$



- Asymmetry, characterizing expected precision:

$$A = \frac{-4u}{2\pi v}$$

$\rightarrow$ Large spin analyzer functions $b(E)$ generate large asymmetries.

$\rightarrow$ Need to separate $b(E) > 0$ and $b(E) < 0$ contributions.

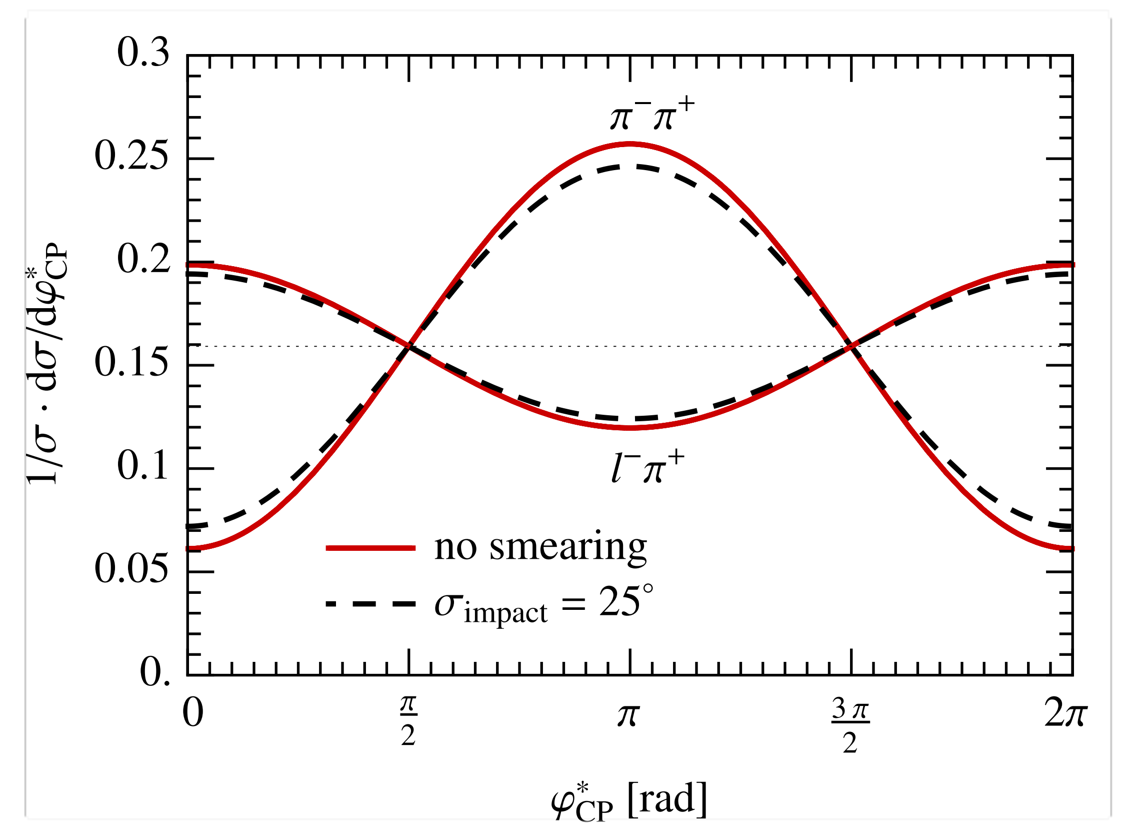
Measurement uncertainties

- Gaussian smearing of impact parameter measurement with $\sigma_{\text{impact}} = 25^o$ as suggested in hep-ph/0307331

  $\rightarrow$ reduction of the asymmetry by a factor of ≈ 0.9

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

  $\rightarrow$ negligible effect on the normalized φ^*_{CP} distribution

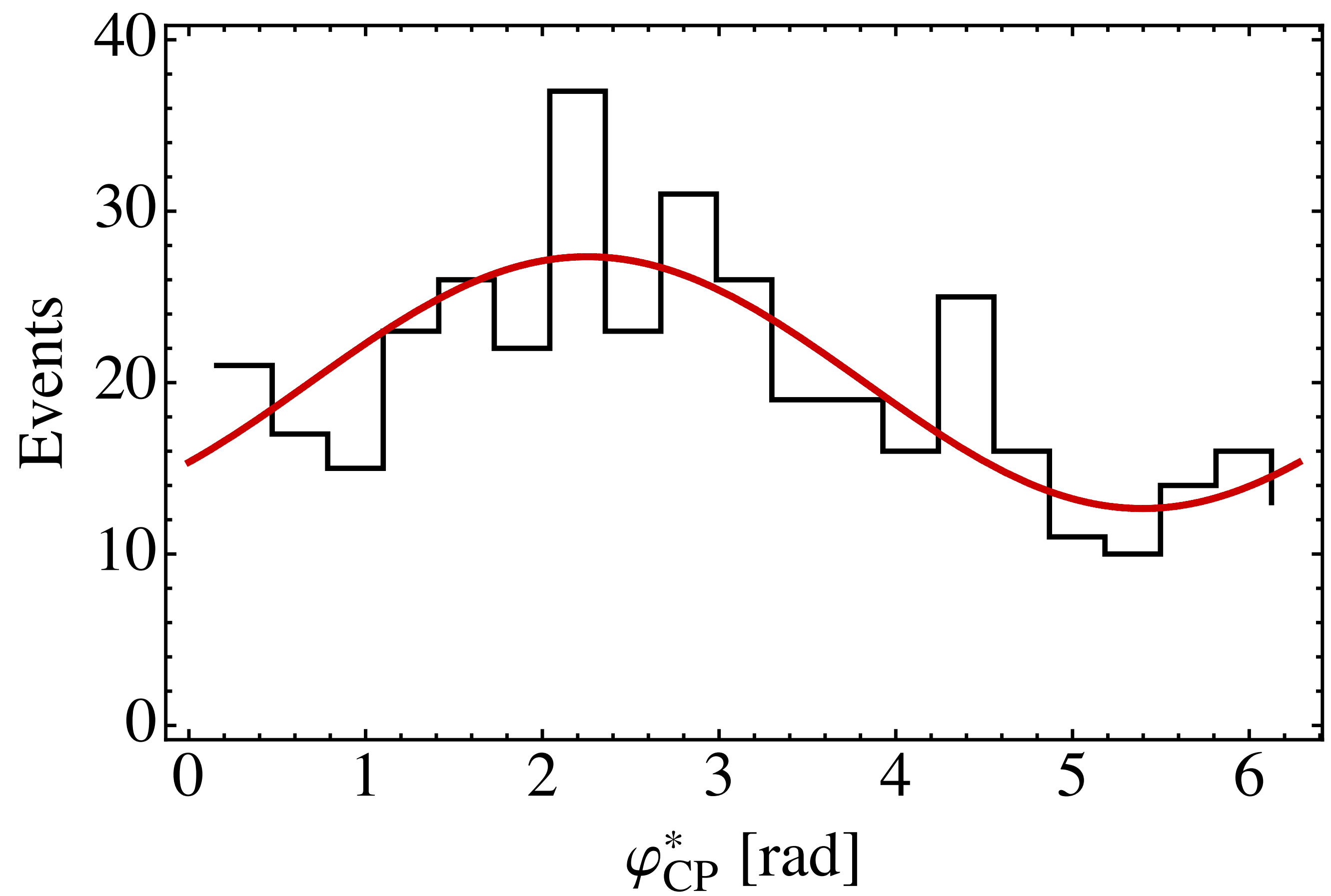


Asymmetry and Precision

- Example: 400 Events
  $A = 20\%$
  20 bins
  $\phi = -\pi/8$

- Fit distribution:
  $u \cdot \cos(\varphi^*_{CP} - 2\phi) + v$

- Expected Precision on ϕ:
  $A = 10\% \quad \rightarrow \quad \Delta\phi = 15.5^\circ$
  $A = 15\% \quad \rightarrow \quad \Delta\phi = 9.0^\circ$
  $A = 20\% \quad \rightarrow \quad \Delta\phi = 6.6^\circ$



- $h\tau\tau$-coupling:
  $\mathcal{L}_Y = \; - N \left(\cos\phi \, \bar{\tau}\tau + \sin\phi \, \bar{\tau} i \gamma_5 \tau \right) h$

Asymmetry and Precision

- Assuming signal to background ratio of $S/B = 4.5$ as suggested in Reinhard'09 with a flat background in φ^*_{CP} for $Z \to \tau\bar{\tau}$
- Taking into account the impact parameter uncertainty by multiplying the theoretical asymmetry by 0.9
- Assuming certain energy cuts for the charged prongs in the Higgs rest frame or the τ rest frame as stated in Phys.Lett. B727 (2013) 488
- Assuming efficiencies for $\tau \to \pi, \rho, a_1$ reconstruction suggested by Reinhard'09 of 0.55

Asymmetry and Precision

$\tau\tau$-decay channel	A [%]	# of events for $\mathcal{L} = 1\,\mathrm{ab}^{-1}$	$\Delta\phi$ [°] $\mathcal{L} = 1\,\mathrm{ab}^{-1}$	$\Delta\phi$ [°] $\mathcal{L} = 500\,\mathrm{fb}^{-1}$
$(\pi + a_1^\lambda)(\pi + a_1^\lambda)$	28.9	269	5.5	7.9
$\rho\rho$	18.0	443	7.0	10
$\rho(\pi + a_1^\lambda)$	22.8	686	4.4	6.3
$a_1(\pi+a_1^\lambda)+\rho a_1+a_1 a_1$	10	638	11	18
all had-had:			3.0	4.3
ll	4.8	454	30	36
$l(\pi + a_1^\lambda)$	11.8	706	8.7	13
$l\rho$	6.0	723	19	27
la_1	3.4	292	38	42
all lep-had:			7.7	11
all:			2.8	4.0

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

- Assuming an integrated luminosity of $1\,\mathrm{ab}^{-1}$ and Higgs-boson production at $\sqrt{s} = 250$ GeV, the mixing angle ϕ can be determined with a statistical uncertainty of $\Delta\phi = 2.8°$.