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

Stefan Berge
Johannes Gutenberg-University Mainz

Snowmass: Seattle Energy Frontier Workshop
July 1, 2013
University of Washington

PRiSMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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) state
  - 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 $A^0 ZZ$ coupling (because of $h \to ZZ$)

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

- If there is more than one Higgs boson (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 $e^+e^- \to hZ$

  $\to h \to \tau\tau$ ideal channel to measure CP

Higgs decay into tau lepton pairs

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

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 :
    $\to J^{PC} = 0^{-+}$
    $\to A^0$
    $\to \langle s_{\tau^-} \cdot s_{\tau^+} \rangle = -\frac{3}{4}$
    $\to \phi = \frac{\pi}{2}$

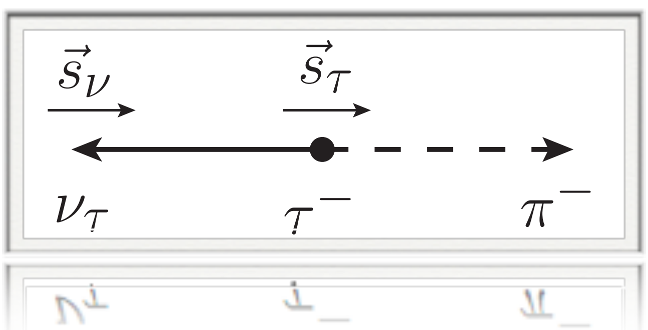
  - if $\tau\bar{\tau}$ is in ${}^3P_0$ state :
    $\to J^{PC} = 0^{++}$
    $\to H^0, h^0$
    $\to \langle s_{\tau^-} \cdot s_{\tau^+} \rangle = \frac{1}{4}$
    $\to \phi = 0$

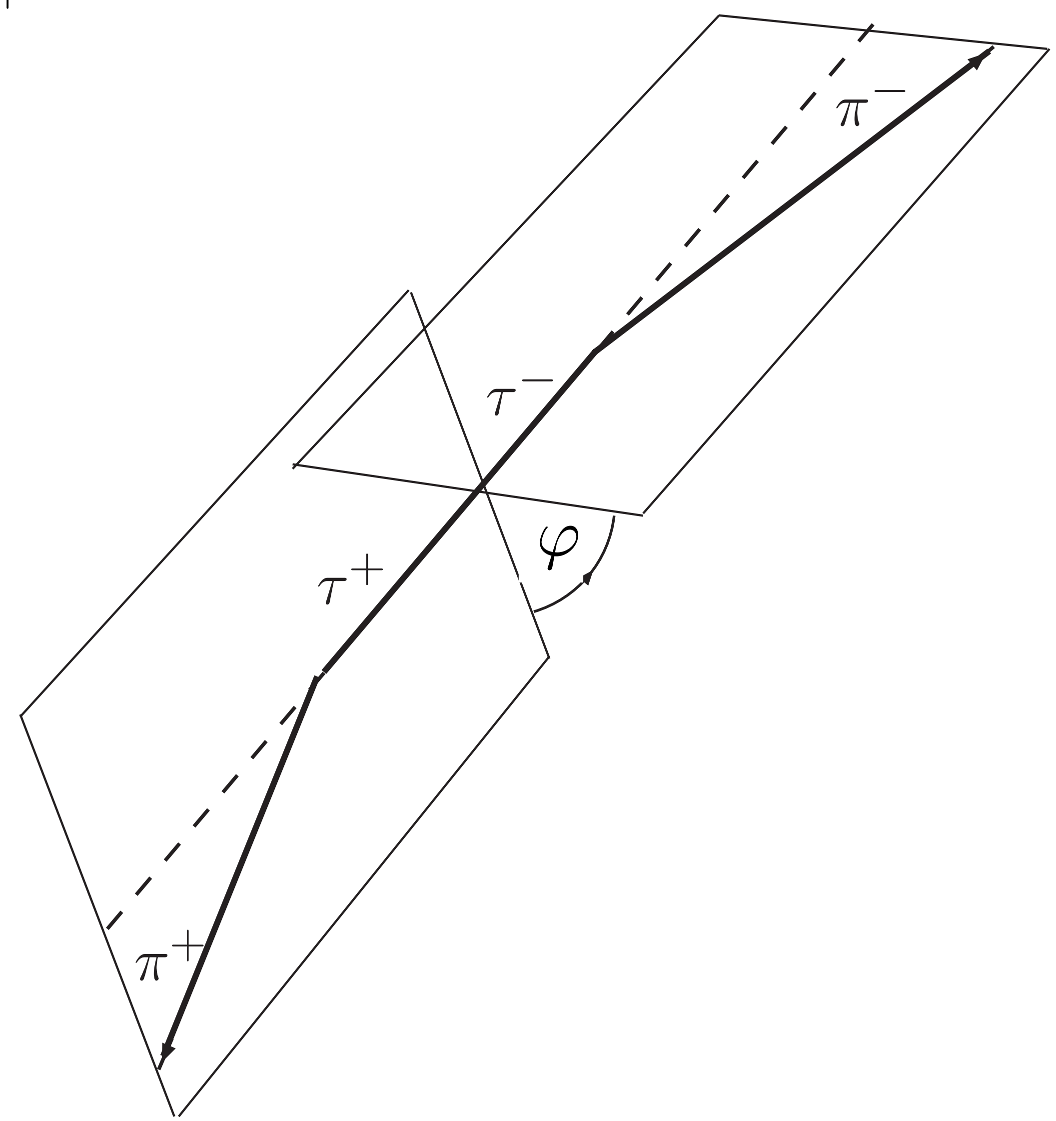
Higgs decay into tau lepton pairs

- 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





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

Higgs decay into tau lepton pairs

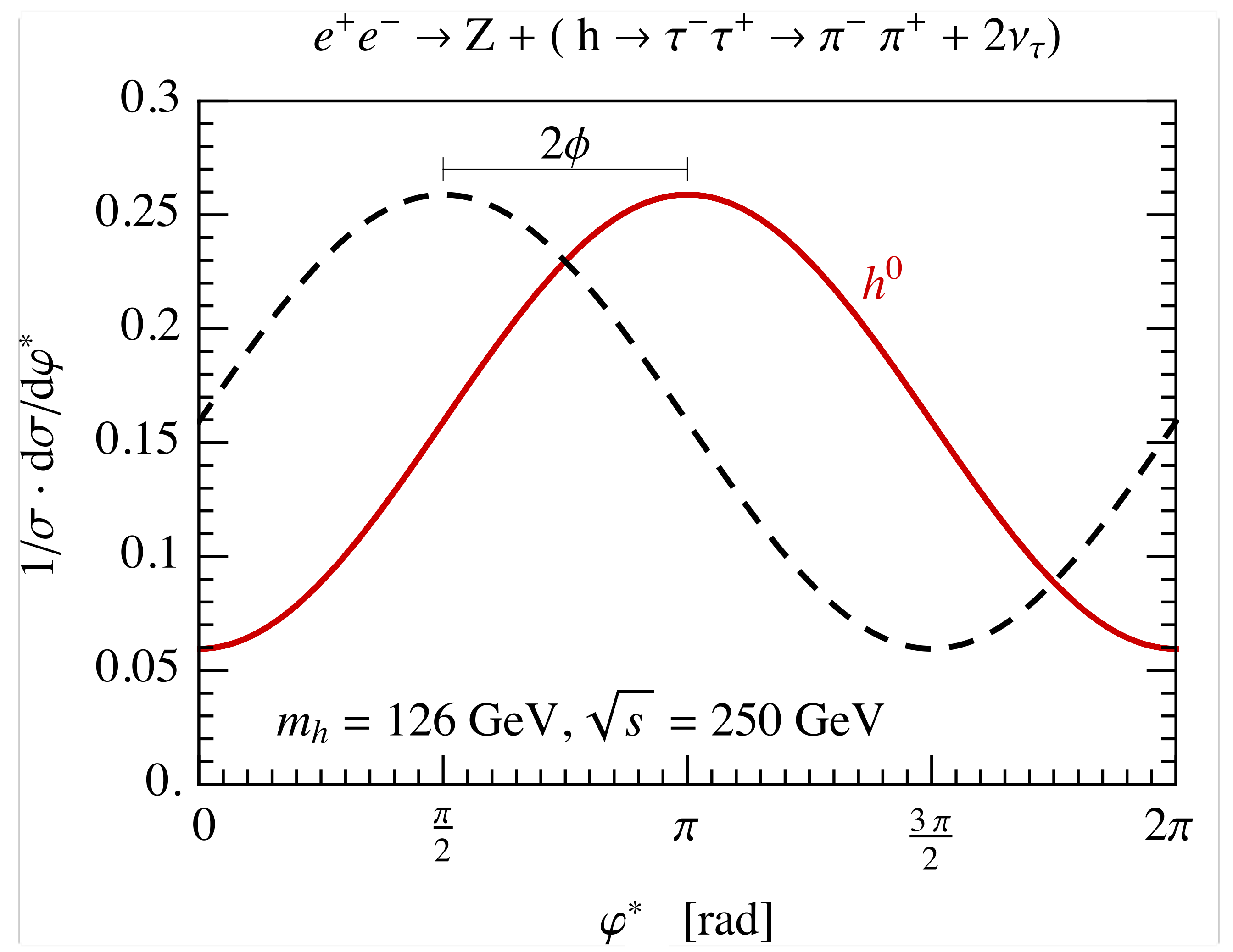
- $$\frac{1}{\Gamma}\frac{d\Gamma(h\to\pi^+\pi^-+2\nu)}{d\varphi^*} = \frac{1}{2\pi}\left[1-\frac{\pi^2}{16}\cos(\varphi^*-2\phi)\right]$$
- $\varphi^* = \varphi^+ - \varphi^-$

  with $\varphi^\pm$ the azimuthal angles of the $\pi^\pm$ defined in their respective $\tau^\pm$ rest frames

- Define Asymmetry:

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

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



PRiSMA
Stefan Berge
Institut für Physik

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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 $\tau \to$ hadrons — *(Reinhard, Videau, 2009) uses 30% of events*

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

- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to all$ — *(S.B., Bernreuther, Spiesberger, arXiv:1208.1507)*

$H \to \tau\tau$: *Reinhard, Videau, talk at Geneve '10*

Polarization: $P(e^-, e^+) = (0.8, 0.3)$

$E_{CM} = 230$ GeV, $m_h = 120$ GeV

$Br(h \to \tau\bar{\tau}) = 0.08\%$

$\sigma(e^-e^+ \to Zh) = 306.8$ fb

$Br(Z \to ee, \mu\mu, u\bar{u}, d\bar{d}, s\bar{s}) = 0.503$

decay mode included	BR [%]
$\tau^- \to \pi^-$	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

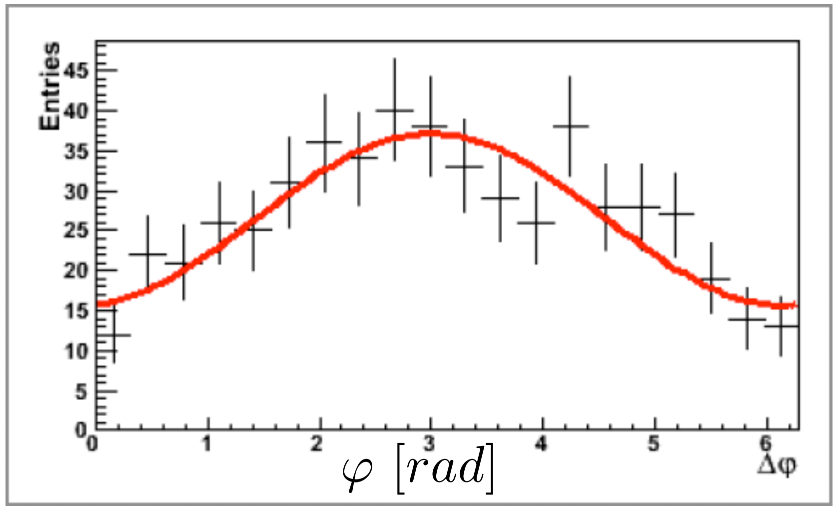
$\to Br^2(\tau \to \text{hadrons}) = 0.3$

- Included ZZ background, beamstrahlung full simulation
- Reconstruction of the τ rest frame, determination of the polarimetric vector

546 Events

$A = 25\%$

$\to \Delta\phi = 4.5°$



Result:
ϕ can be measured using 300 fb^{-1} with a precision of $\Delta\phi = 5^o$

$H \to \tau\tau$: *Desch, Was, Worek, hep-ph/0307331*

Polarization: $P_{e^-} = 0,\ P_{e^+} = 0$

$E_{CM} = 350$ GeV, $m_h = 120$ GeV

$Z \to \mu\mu, q\bar{q};\ \mathcal{L} = 1ab^{-1}$

$\sigma(Zh) \cdot Br_Z \cdot Br_{h\to\tau\bar{\tau}} \cdot Br^2_{\tau\to\rho} = 0.79fb$

decay mode included	BR [%]
$\tau^- \to \rho^- \to \pi^-\pi^0$	25.5

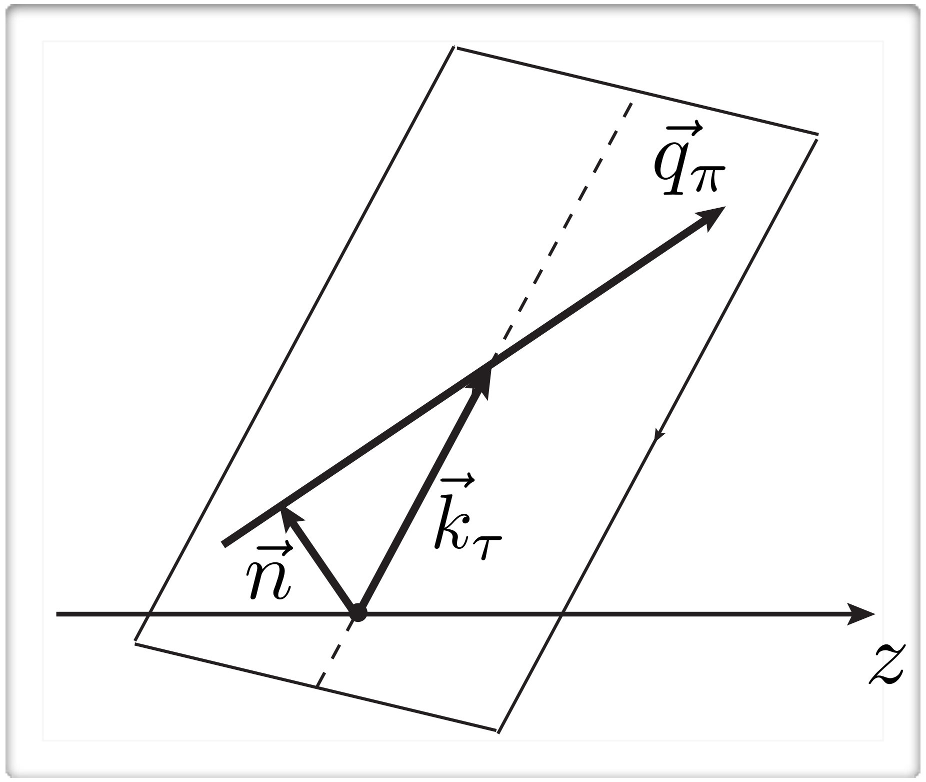
$\to Br^2(\tau \to \rho + \nu_\tau) = 0.065$

- No ZZ background
- Bremsstrahlung included
- SIMDET simulation
- φ^* defined in $\rho\rho$-ZMF
- Reconstruction of τ rest frames only to perform cuts on pion energies

Result:
ϕ can be measured using 620 Events ($A \approx 18\%$) with a precision of $\Delta\phi = 6^\circ$

$H \to \tau\tau$: S.B., Bernreuther, Spiesberger '12

- φ^* is defined without reconstructing the τ rest frames
- Use normalized impact parameter vectors $\hat{n}_-$, $\hat{n}_+$
- Boost $\hat{n}_\pm$ into $\pi^-\pi^+$-ZMF ($n^\mu n_\mu = -1$):
- $\varphi^* \sim \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$
- Measurement of PV necessary (from $Z \to e^+e^-, \mu^+\mu^-, q\bar{q}$)

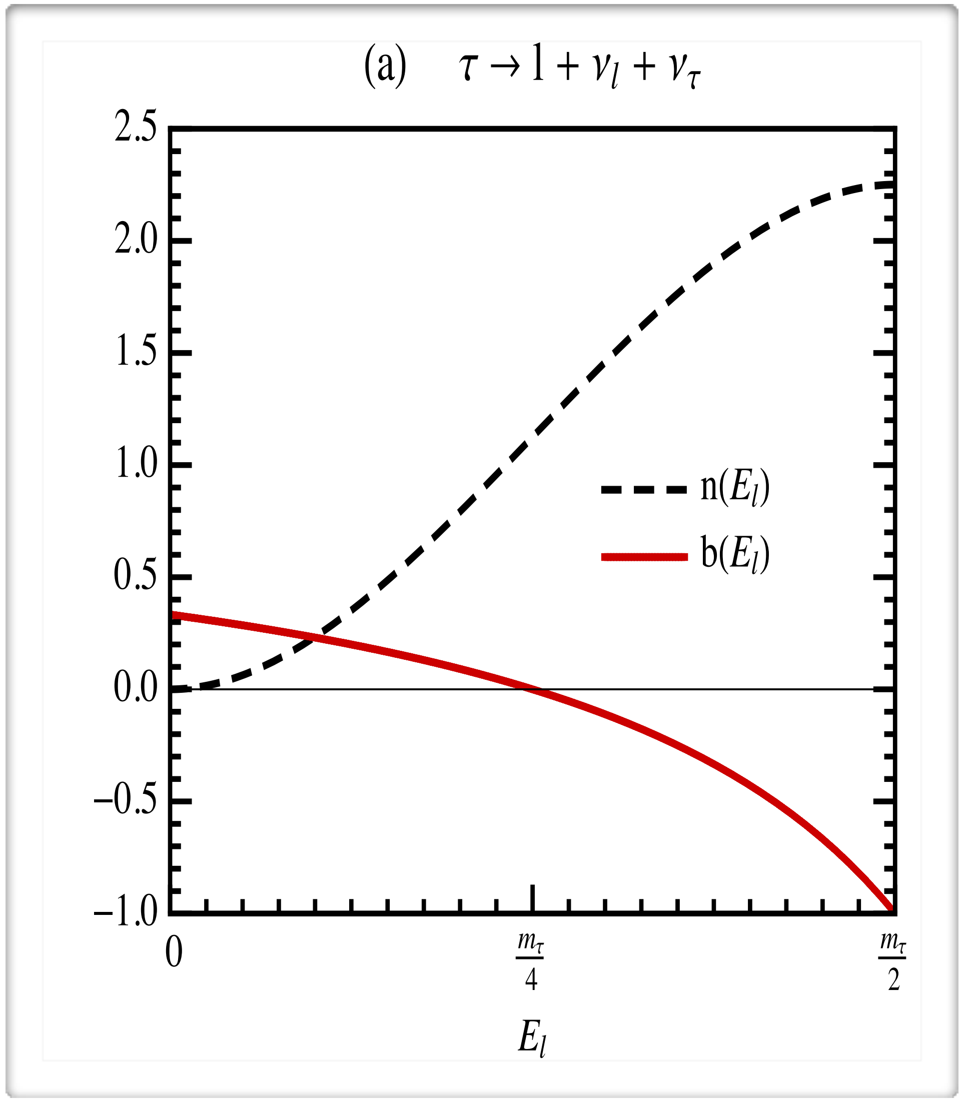


$H \to \tau\tau$: S.B., Bernreuther, Spiesberger '12

- 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 relative contribution to σ

$H \to \tau\tau$: S.B., Bernreuther, Spiesberger '12

$P(e^-, e^+) = (0.8, 0.3)$
$E_{CM} = 250$ GeV
$m_h = 126$ GeV
$\sigma_{Zh} = 303$ fb
$Br_{h\to\tau\bar{\tau}} = 0.062$
$Br_{Z\to ee,\mu\mu,u\bar{u},d\bar{d},s\bar{s})} = 0.503$

$\tau\tau$ decay	$\sigma_{Zh} Br_Z Br_{h\to\tau\bar{\tau}} \cdot Br_\tau Br_{\bar{\tau}}$
had-had	2.8 fb
had-lep	3.6 fb
lep-lep	1.2 fb

Preliminary:

Statistical uncertainty (no background/detector effects included):

$\tau\tau \to (\pi, \rho, a_1^{3\pi^\pm}) + (\pi, \rho, a_1^{3\pi^\pm})$ (cuts in τ-rest frames applied):
$A = 29.7\%$ leading with 472 Events ($\varepsilon = 0.5$, $\mathcal{L} = 500\, fb^{-1}$) to $\Delta\phi \approx 4.1°$

$\tau\tau \to lep + (\pi, \rho, a_1^{3\pi^\pm})$ (h rest frame cuts applied):
$A = 12.2\%$ leading with 565 Events ($\varepsilon = 0.6$, $\mathcal{L} = 500\, fb^{-1}$) to $\Delta\phi \approx 9.5°$

$\tau\tau \to lep + lep$: ($E_l^{h-rest} \geq 15$ GeV):
$A = 7.6\%$ leading with 187 Events ($\varepsilon = 0.8$, $\mathcal{L} = 500\, fb^{-1}$) to $\Delta\phi \approx 32°$

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
- A precision of $\Delta\phi = 5^\circ$ seems achievable with $300 - 500\, fb^{-1}$
- Precision is statistically limited $\rightarrow$ can be estimated for higher luminosities and collider energies based on the number of events available