Higgs CP measurement

First FCC-ee Workshop on Higgs Physics

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Higgs quantum numbers

$$J^{CP}$$

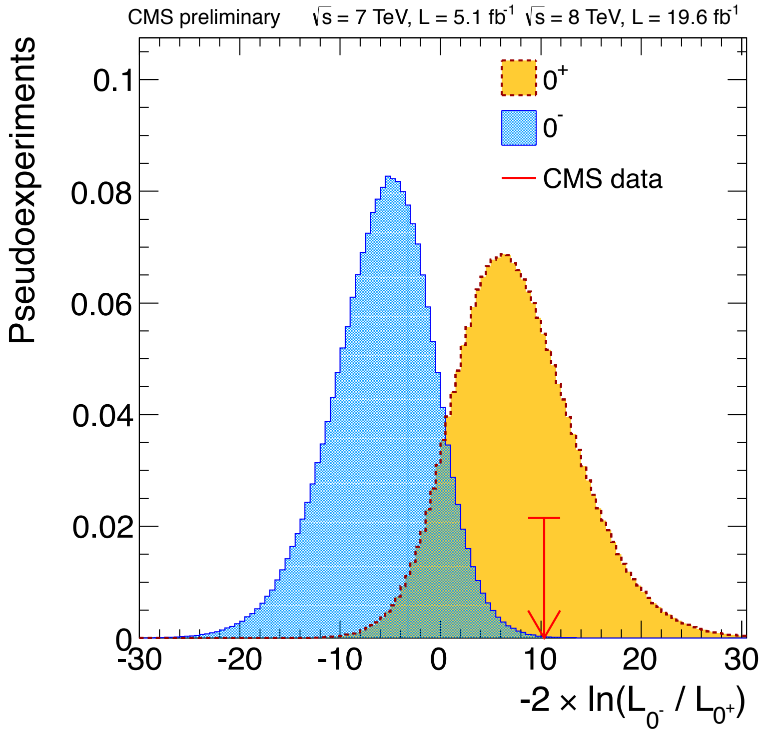
Very sure that the Higgs Boson is spin-0

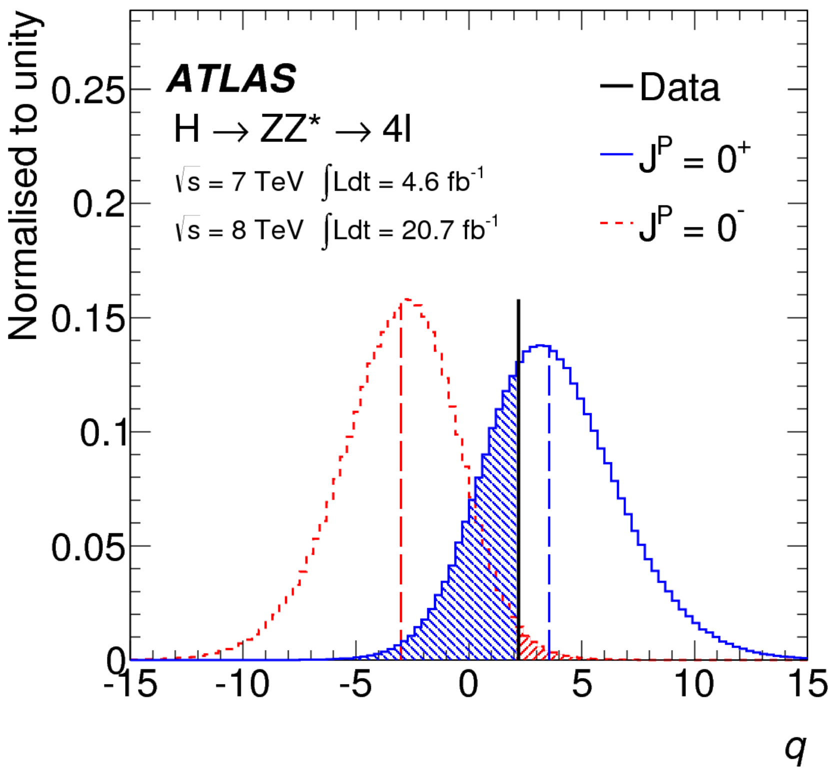
CP measurement

- Group setting up delphes studies on fcc-ee Higgs studies
- Higgs CP measurement as a starting point

Run 1 measurements

- What do we know from LHC Run 1?
  - Pure pseudo-scalar tested against SM Higgs
  - Excluded at 98% (ATLAS) and 99.9% (CMS)





Anomalous couplings

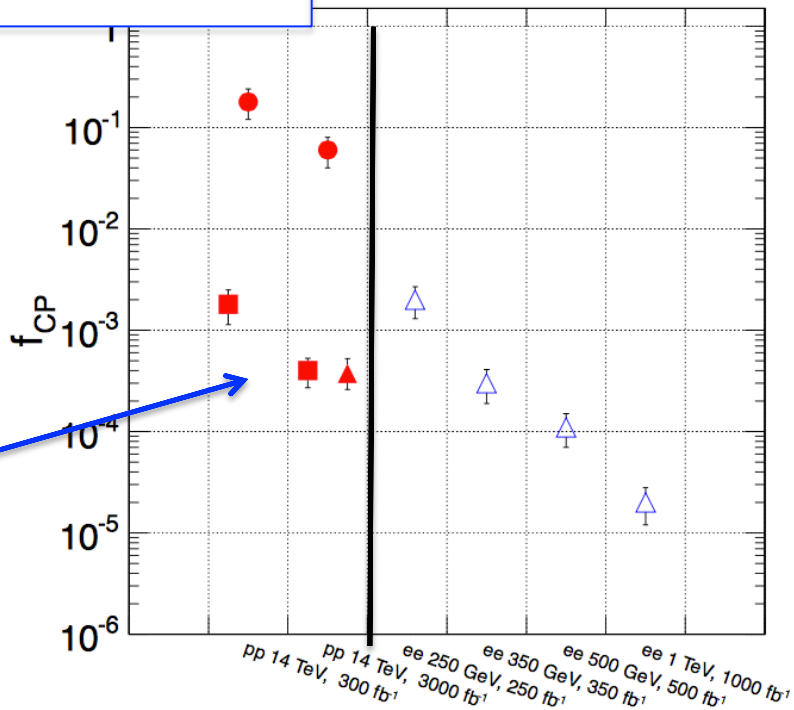
- Mixture of scalar and pseudo-scalar
- Considering H->ZZ coupling structure

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- Fraction of CP-odd contribution

$$f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

- Snowmass Higgs Paper [1310.8361]
  - Circles: H->VV
  - Triangles: HZ
  - Squares: VBF



Fermionic couplings

- Pseudo-scalar term arises from a higher dimension operator

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

  - Pseudo-scalar coupling is expected to be subdominant
- Tree level couplings to quarks and leptons
  - CP-even and CP-odd couplings induced at the same order

$$\mathcal{L}_{h\bar{f}f} = \cos\alpha y_f \bar{\psi}_f \psi_f h + \sin\alpha \tilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h.$$

- H->ττ decay is a promising channel to study the CP violation

CP violation in h->ττ decays

- CP violation can be probed through τ polarization
  - τ decays clean enough that the spin information is not washed out by hadronization effects
  - Pion is preferably emitted in the direction of the τ spin in rest frame
- Existing studies for both pp and ee colliders
  - τ->ρν and τ->aν decays considered
  - More difficult for pp colliders

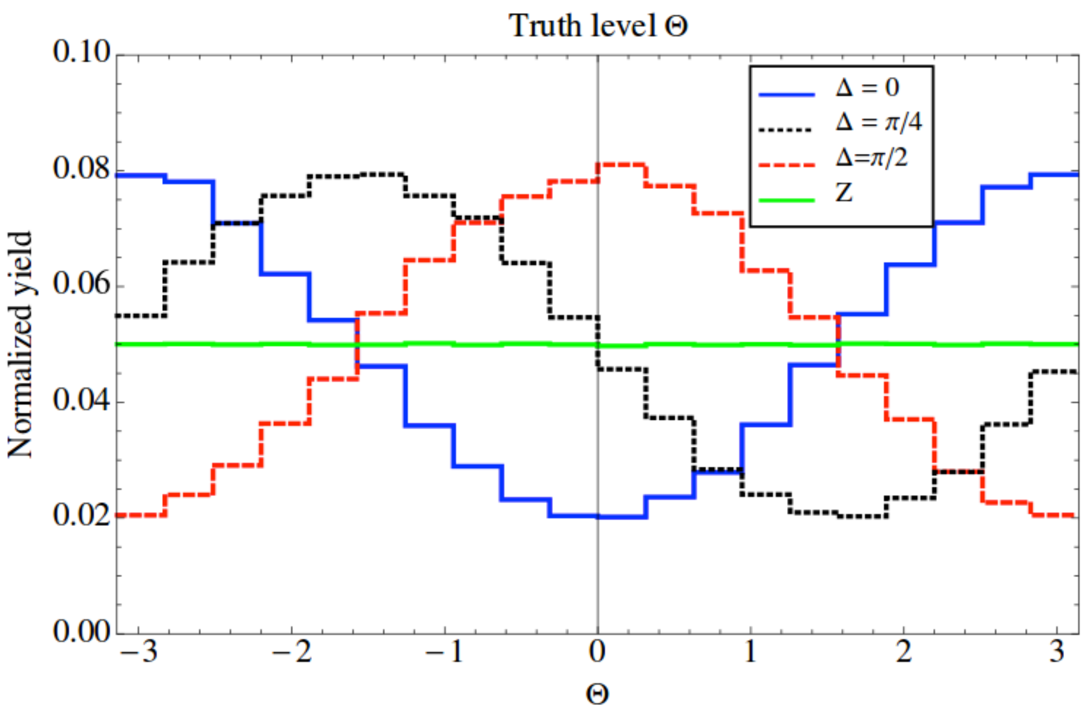
Theta variable

- An observable [Θ] variable constructed using momenta of the tau decay products [arxiv:1308:1094]
  - ρ is predominantly longitudinal and polarized in the direction of tau polarization [rest frame]
  - Difference between charged and neutral pion 3 momenta is roughly parallel to the ρ polarization

- For e+e-: decay h->ττ->ρρνν can be constructed up to a two-fold ambiguity
- For pp: collinear approximation can be used for example

Theta variable 2

- An observable [Θ] variable constructed using momenta of the tau decay products [arxiv:1308:1094]
- CP phase can be read off directly from the distribution



Results

[arxiv:1308:1094]

τ_h efficiency	50%	70%
3σ	$L = 550\ \mathrm{fb}^{-1}$	$L = 300\ \mathrm{fb}^{-1}$
5σ	$L = 1500\ \mathrm{fb}^{-1}$	$L = 700\ \mathrm{fb}^{-1}$
Accuracy($L = 3\,\mathrm{ab}^{-1}$)	11.5°	8.0°

e^+e^- results
$\sqrt{s}$=250 GeV
1 ab^{-1} integrated lum.

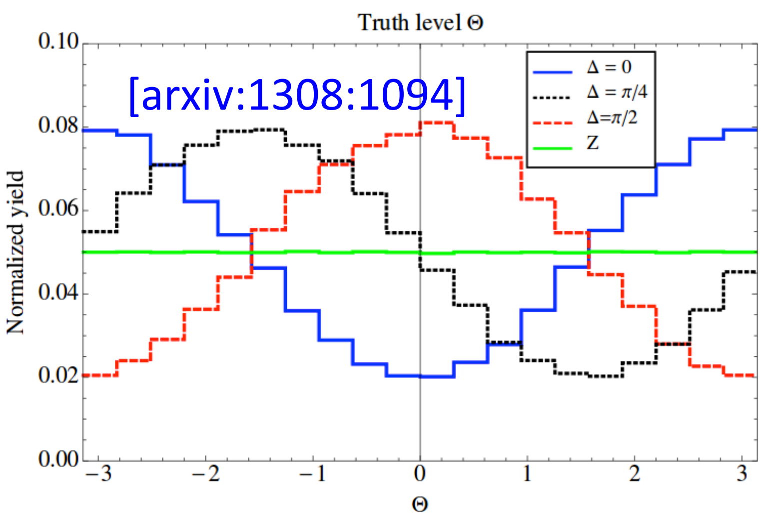
$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z \to \mathrm{visibles})$	80%
N_{events}	990
Accuracy	4.4°

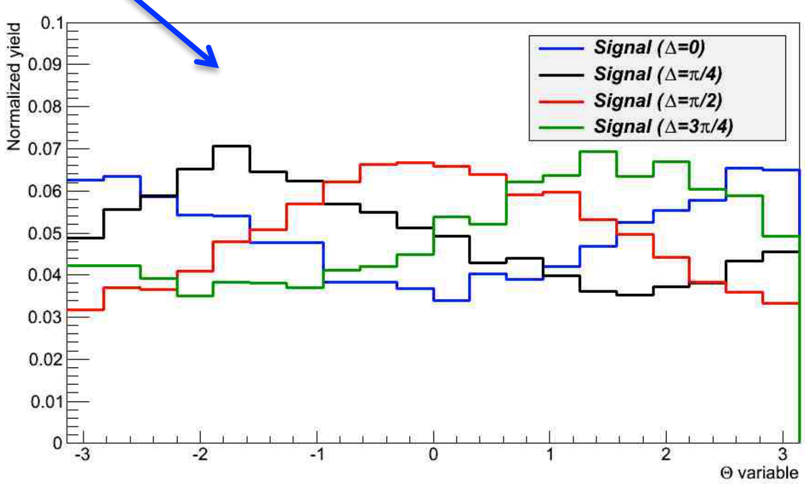
Background/detector effects

- Previous studies do not consider detector effects
  - Missing energy resolution is critical for pp studies for example
    - Z->ττ contamination is important [1501:0315]
- Plan to include detector simulation and backgrounds
  - Finite tracking and calorimeter resolution
  - Distinguishing the charged and neutral pions with overlap
- Effect of the systematic uncertainties on the measurement
- Plan to use Delphes for detector simulation
  - Delphes cards for ILC have been released recently
  - Based on [1306.6329]

Delphes distributions

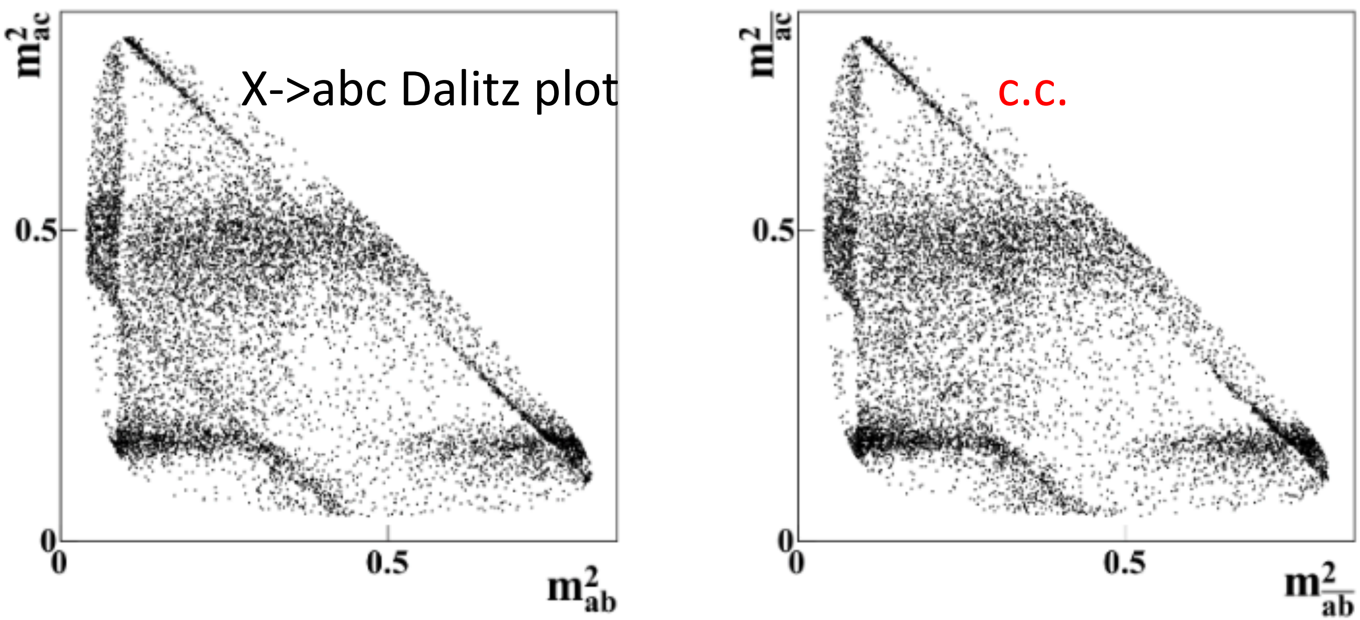
- Signal and background Delphes samples were produced
  - DY, ZZ, Zll, and di-jet samples
- Signal selection was optimized
- The amplitude of Θ variable is degraded using Delphes simulation
- Studies are ongoing





Additional approaches

- Model independent method for observing CP violation in many-body decays proposed [arxiv:1105.5338]
- Unbinned multivariate two-sample test [X->abc decay and c.c. decay]
    - Define a test statistic and distance in the multivariate space
    - Sensitivity of the method is significantly larger than binned χ^2 test when systematic effects are important



Summary

- Summary of current Higgs CP results for ee colliders
- H->ττ decay very promising for CP measurement
  - ~5 degrees uncertainty for 1 ab^{-1} integrated luminosity at $\sqrt{s}$=250 GeV
- Additional studies using H->ττ decays are underway
  - Delphes simulation used to understand the impact of the detector effects

BACKUP

Theta variable 2

$$\Theta = \mathrm{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \mathrm{Arccos}\left[\frac{\vec{E}_+ \cdot \vec{E}_-}{\left|\vec{E}_+\right| \left|\vec{E}_-\right|}\right]$$

where

$$\vec{E}_\pm = \frac{m_h}{2}\left[(y_\pm - r)\,\vec{p}_{\pi^\pm}\Big|_0 - (y_\pm + r)\,\vec{p}_{\pi^{0\pm}}\Big|_0\right]^\perp$$

$$y_\pm \equiv \frac{2q_\pm \cdot p_{\tau^\pm}}{m_\tau^2 + m_\rho^2} = \frac{q_\pm \cdot p_{\tau^\pm}}{p_{\rho^\pm} \cdot p_{\tau^\pm}} \qquad r \equiv \frac{m_\rho^2 - 4m_\pi^2}{m_\tau^2 + m_\rho^2} \approx 0.14 \qquad q_\pm \equiv p_{\pi^\pm} - p_{\pi^{0\pm}}$$

Object selection

The objects are selected in the following way:

- The two oppositely-charged hadrons with P>500GeV and separated by dR > 2.25. The number of charged pions is taken as the number of tracks with P > 500 MeV within dR < 0.3 of the selected tracks.
- For each charged hadron take the photons with P > 500 MeV within dR of 0.4. The reconstructed objects from the photons are taken as the neutral pions. The number of neutral pions is taken as $N_{photon}/2$.
- Look for oppositely-charged pairs of electrons/muons (P > 10 GeV and iso < 0.4) and reconstruct the Z. If none are found reconstruct the Z by adding all other objects separated by dR > 0.2 of the previously selected objects.

Object selection

- The events are pre-selected in the following way:
  - Require $|M_Z - 91.2| < 5$ GeV and $|M_H - 125| < 5$ GeV.
  - Check whether the neutrino momenta solution is good by requiring $M_\nu > -5$ GeV.
  - Require that there only be one charged pion for each tau.
- Events are split into two categories. Here are the cuts applied to each category.
  - Z reconstructed from leptons
    - There should be exactly 2 leptons, and they must have opposite charge
  - Z reconstructed from other objects
    - Require $M_\tau > 0$ GeV
    - For Z, require $p_T > 10$ GeV and $|P - 51.6| < 3$