Search for CP violation effects in the $h \to \tau\tau$ decay at future e^+e^- colliders

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X. Chen and Y. Wu, arXiv:1703.04855

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Introduction

- After the Higgs was discovered in 2012, understanding its properties, and looking for any possible deviations from the SM prediction, becomes a very important task of LHC

- CP violation is a necessary condition for baryogenesis, a process leading to matter-antimatter imbalance in the universe. Understanding Higgs' CP property is one of the important topics that can be done at the LHC or future e^+e^- colliders, but perhaps with better precision for the latter

    - If Higgs is in a pure CP eigen state: is it CP even or odd ?
    - If Higgs is in a CP mixture: gives rise to CP violation. This is a more exciting scenario, as the current known CP violation source (a single complex phase in CKM) is too small to explain the matter-antimatter imbalance

- Unlike the CP odd Higgs effective coupling to bosons which are dim-6 operators, the CP odd Higgs coupling to fermions is dim-4 and the CP violation effect can be sizable

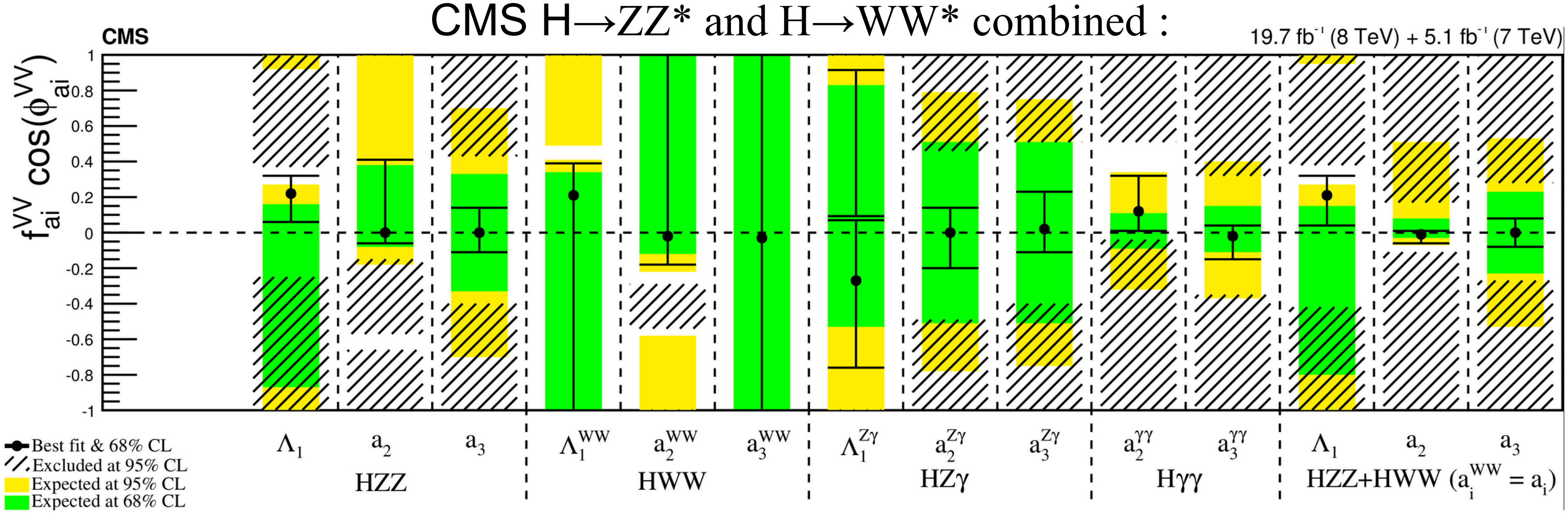
LHC Higgs CP test

[EPJC 75 (2015) 476]
[Phys. Rev. D 92 (2015) 012004]

- ATLAS/CMS considered the mixture of SM and BSM CP even/odd in the HVV tensor structure, using either ME-based variables or templates

$$L(\mathrm{HVV}) \sim \underbrace{a_1 \frac{m_Z^2}{2} \mathrm{HZ}^{\mu}\mathrm{Z}_{\mu}}_{\text{SM}} \underbrace{- \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{HZ}_{\mu}\Box \mathrm{Z}^{\mu} - \frac{1}{2} a_2 \mathrm{HZ}^{\mu\nu}\mathrm{Z}_{\mu\nu}}_{\text{BSM CP-even}} \underbrace{- \frac{1}{2} a_3 \mathrm{HZ}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu}}_{\text{BSM CP odd}} + \ldots$$

CMS H→ZZ* and H→WW* combined :

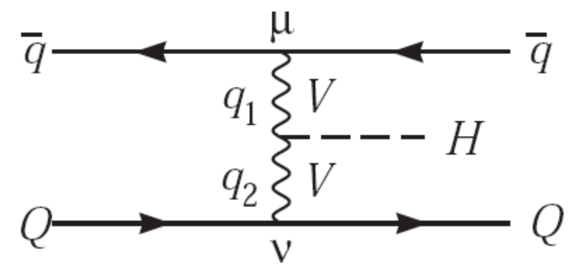


The non-SM tensor couplings are consistent with zero for both ATLAS and CMS

CP test in VBF H→ττ with ATLAS

[arXiv:1602.04516 (accepted to EPJC)]

- The Optimal Observable (OO) is expected to perform better than ΔΦ. It is defined as: $OO = \dfrac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$

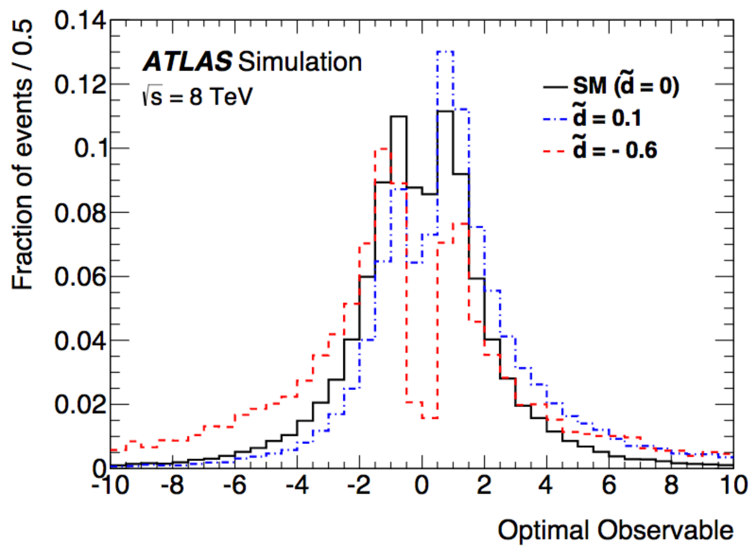


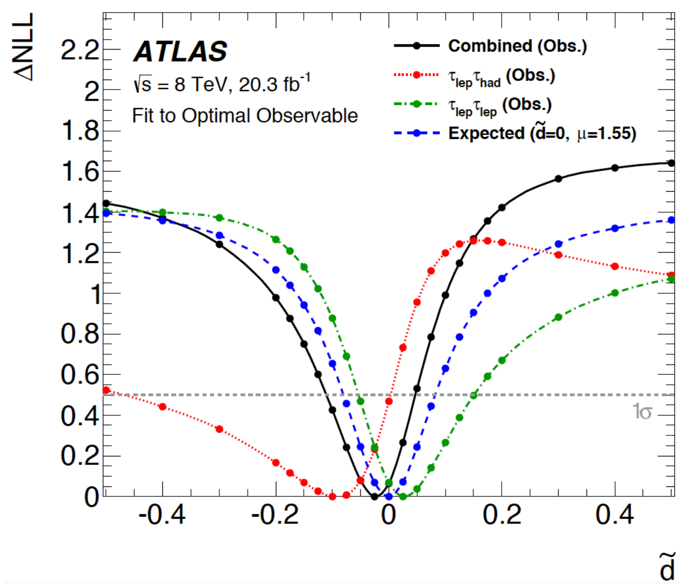
  with the Matrix Element for VBF production being

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\text{CP-odd}}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d}\cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2\cdot|\mathcal{M}_{\text{CP-odd}}|^2$$

- With all 4-momenta of the final state particles (Higgs and two tagging jets) measured (not possible with $H\rightarrow WW^*$), the LO ME of SM and CP-odd can be calculated from HAWK, and then OO can be calculated per event



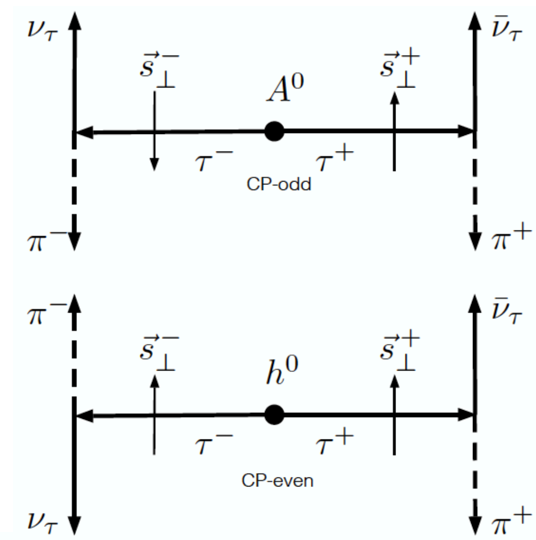


CP test in H→ττ decay

- CP-odd Yukawa coupling can enter the Lagrangian at dim-4, thus sensitive at tree-level rather than with the dim-6 operators in HVV

$$-g_\tau\left(\cos\phi\bar{\tau}\tau+\sin\phi\bar{\tau}i\gamma_5\tau\right)h$$

Φ is the mixing angle. Φ=0 (Φ=π/2) means SM (CP odd)



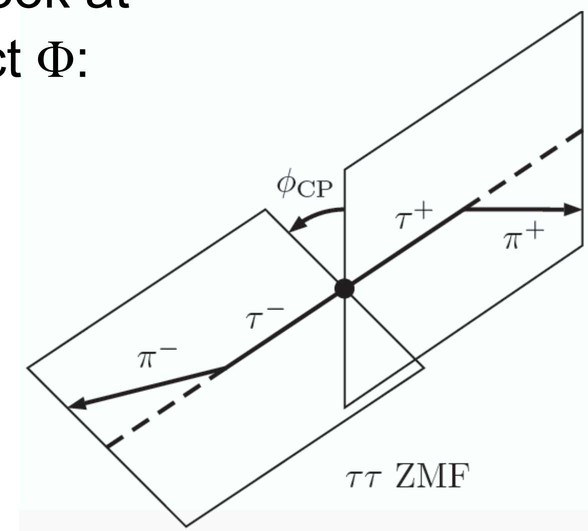
- CP of Hττ coupling can be distinguished by the transverse tau spin correlations

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

Sensitive to CP (H vs A)

- For example, with the τ→πν decay, one can look at the angle between tau decay planes to extract Φ:

$$\frac{d\Gamma\left(h\to\tau\tau\to\pi^+\pi^-+2\nu\right)}{d\phi_{CP}}\propto 1-\frac{\pi^2}{16}\cos\left(\phi_{CP}-2\phi\right)$$



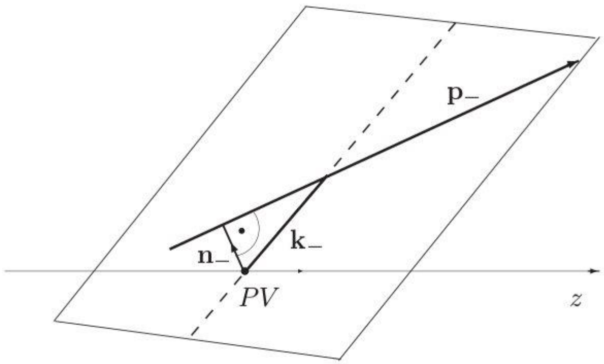
- It is experimentally challenging because the neutrinos are not reconstructed

CP test in H→ττ decay

- There are two methods to extract CP from $H\to\tau\tau$ decay:

Impact Parameter (IP) method:

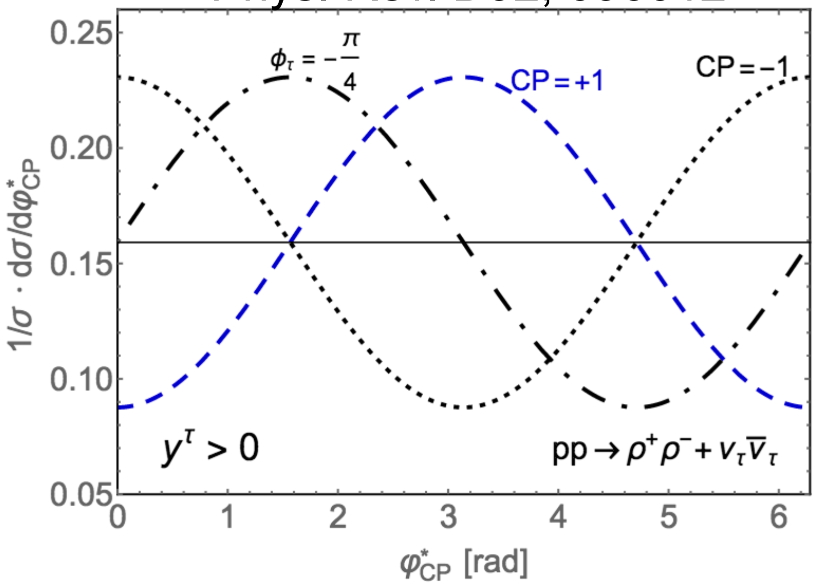
- Approximately reconstruct the tau decay plane from its leading track and IP
- Best for the $\tau\to\pi\nu$ decay. The analyzing power is compromised for other tau decays



Using the $\tau\to\rho\nu\to\pi^{\pm}\pi^{0}\nu$ decay:

- The tau decay plane can be approximately reconstructed by the track and neutral pion
- However, the relative energy of $\pi^{\pm}$, π^{0} need to be classified in order to maximize the analyzing power

Phys. Rev. D92, 096012

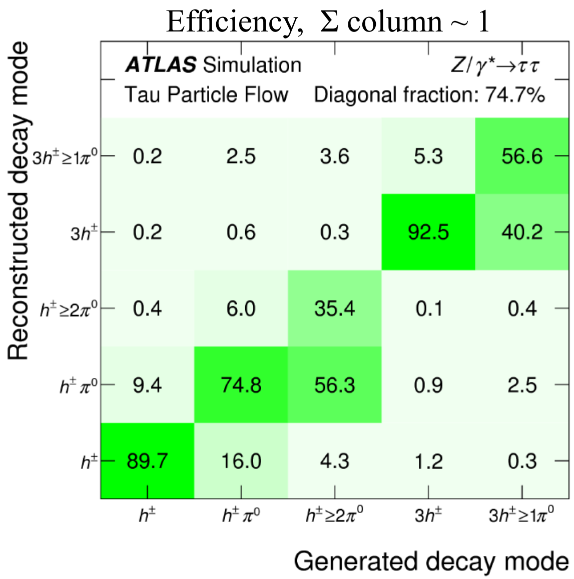


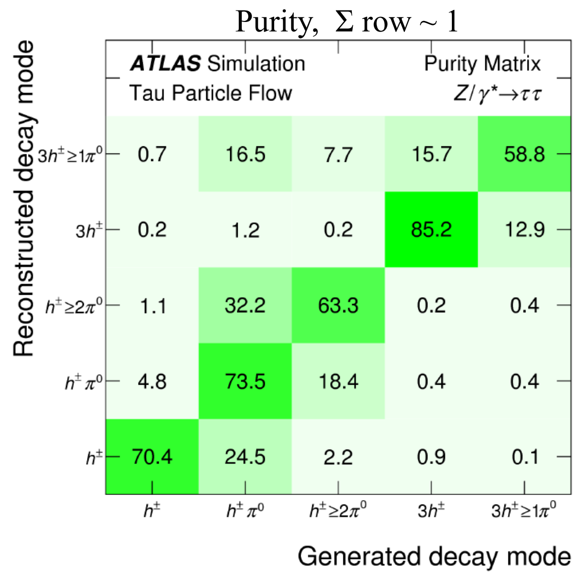
- In order to use the two methods, the tau decay modes (substructure) need to be well differenciated (next few slides)

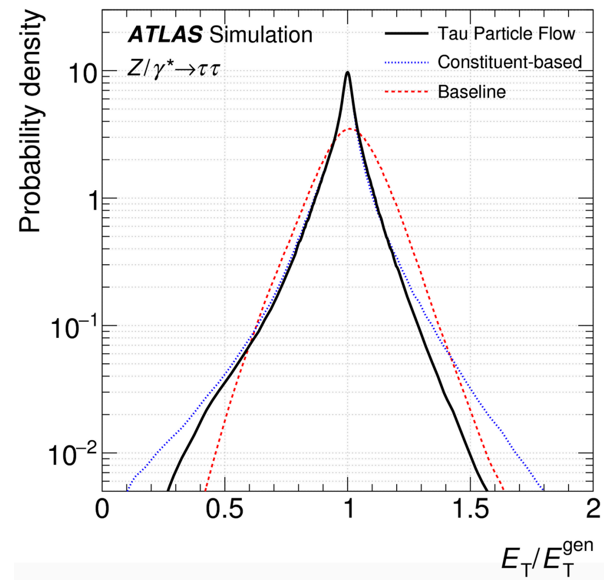
A few extra references:
EPJC 74 (2014) 3164, Phys. Rev. D88 076009,
Phys. Lett. B579 (2004) 157, Phys. Lett. B543 (2002) 227

Tau substructure in ATLAS

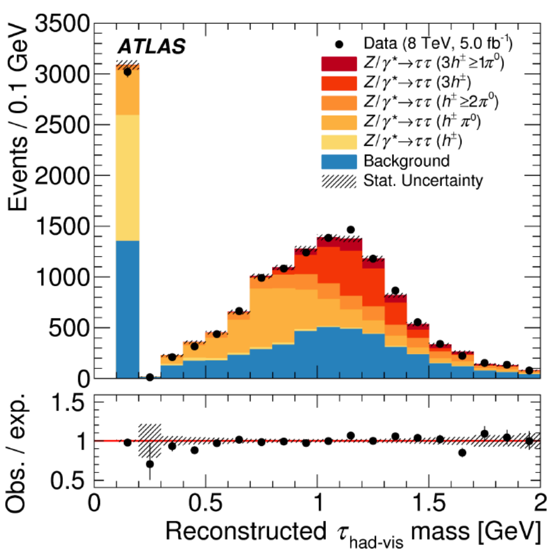
[EPJC 76(5) (2016) 1]



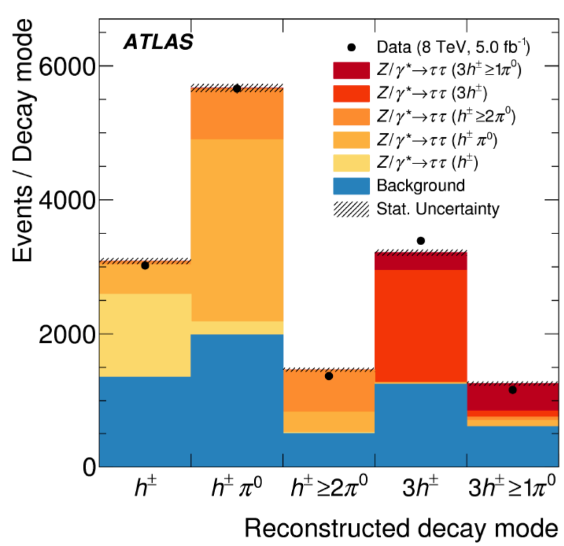




In general, non-negligible fraction of 2/1 π^0 reconstructed as 1/0 π^0



Good reconstruction of tau mass in different decay modes



Good tau decay classification

- With the substructure, a factor of 2 improvement of tau energy w.r.t. the calo-based at low p_T (~0.16 for neutral π^0)
- A factor of 5 improvement in the angular resolution
  - neutral π^0 η : ~0.006
  - neutral π^0 Φ : ~0.012

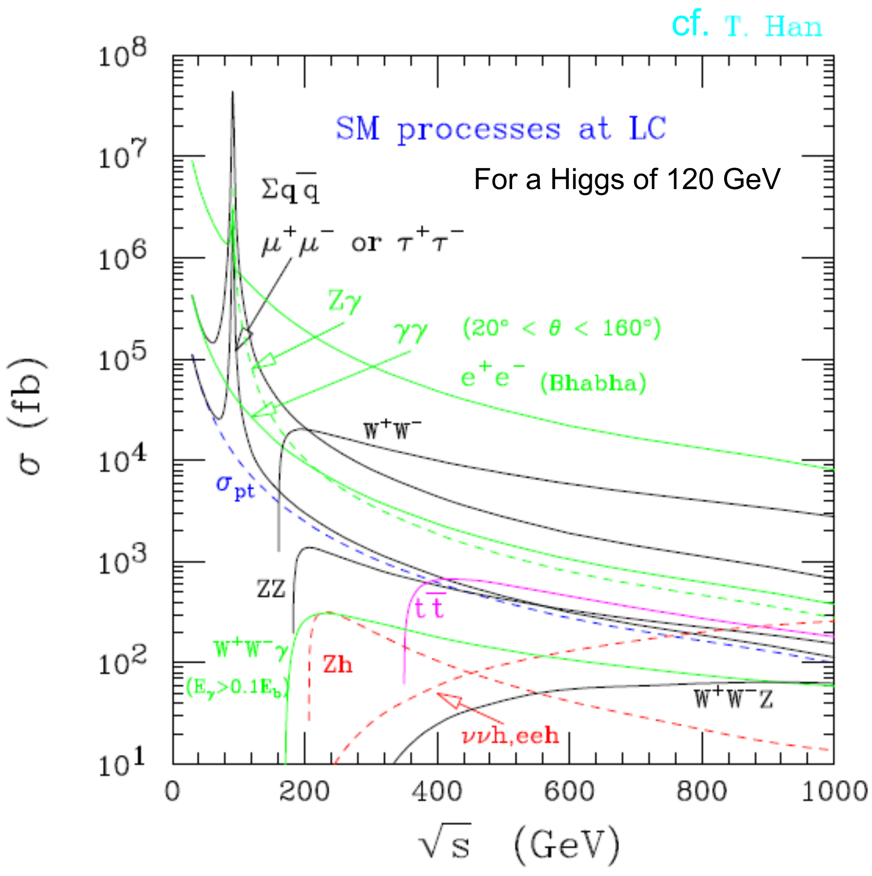
$h \to \tau\tau$ at the e^+e^- collider

- At a e^+e^- collider, the Higgs can be produced via Zh or VBF productions

- We assume a 250 GeV collision energy where the Higgs is mainly produced by the Zh mode. This corresponds to low-energy ILC running

- Three main decay channels are investigated:

Mode	BR (%)
$\nu_\tau l \nu_l$	35.04
$\nu_\tau \pi^\pm$	10.77
$\nu_\tau \pi^\pm \pi^0$	25.37



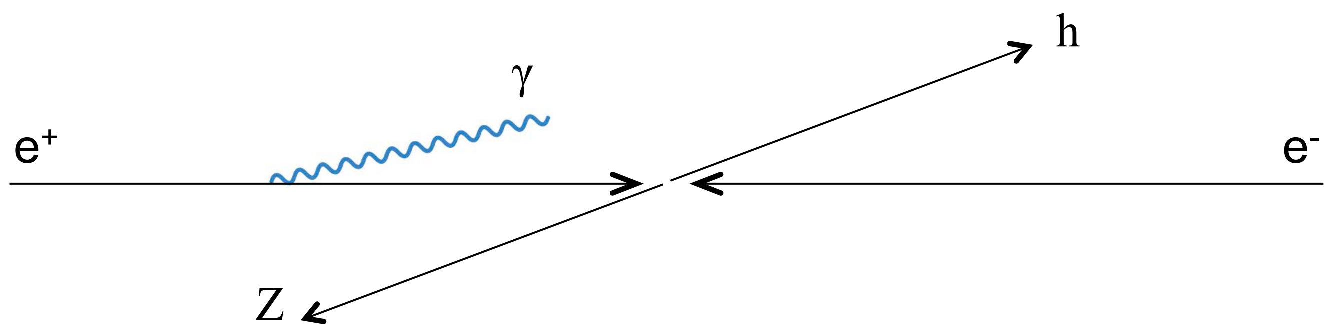
- Encouraged by the tau substructure techniques from ATLAS, it is assumed that π^0 can be resolved with a 10% energy resolution in this analysis. It is further assumed that no cross talk between different modes

$h \to \tau\tau$ simulation

- The Zh process is produced by MG5, the boson decay and parton shower are handled by Pythia8, and detector response are simulated by DELPHES, with the following parametrization
  - A magnetic field of 3.5 T, fiducial tracking up to |η|=2.4. Track direction resolution of 0.001 in η/φ, and momentum resolution of $\sqrt{0.01^2 + (10^{-4} p_T)^2}$. Track efficiency is 99%, ID efficiency for e/μ is 95%
  - The calorimeter energy resolution follows $\sqrt{A^2E^2 + B^2E}$, where A=1.0% (1.5%) and B=15% (50%) for the EM (hadronic) calorimeter. Particle flow (PF) objects are formed from the tracks and calo clusters. A loose relative lepton isolation of <0.7 is applied to reject leptons from jets
  - The hadronic taus (τ_{had}) are tagged on Anti-kt R=0.4 jets from PF objects with an efficiency of 60% (0.5%) for real (fake) taus. For the $Z \to jj$ decay, after masking out the leptons are taus, all remaining PF objects are exclusively clustered into two jets
  - The tracks from tau should have p_T>5 GeV, and the track impact parameter resolution is 5 μm (10 μm) in the transverse (beam) direction

Refined Higgs momentum

- Compared with a hadron collider, the e^+e^- collider has the advantage to resolve the Higgs momentum in z-axis by the recoil of Z, but subject to the ISR photons



- With the known Higgs mass, the fraction of momentum carried away by the collinear photon can be solved, subject to a two-fold ambiguity

$$x = \frac{E_{\mathrm{CM}}^2 - 2E_{\mathrm{CM}}E + m^2 - m_h^2}{\pm E_{\mathrm{CM}}^2 \mp E_{\mathrm{CM}}E + E_{\mathrm{CM}}p_z}$$

E, m and p_z are for the recoiling Z boson. E_{CM}=250 GeV

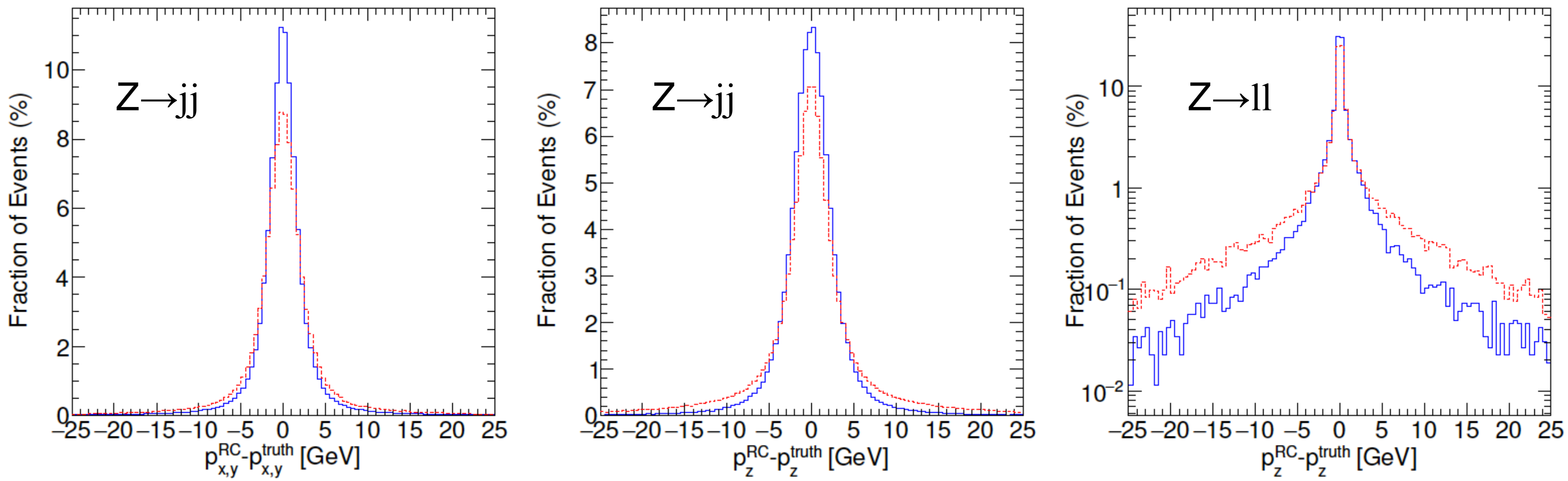
Refined Higgs momentum

- To resolve the ambiguity, collinear approximation (neutrinos from the tau are collinear with the visible products) is used and the following χ^2 is minimized

$$\chi^2 = \sum_{i=0}^{3} \left(\frac{p_{h,i} - p_{h,i}^{\mathrm{RC}}}{0.5}\right)^2 + \left(\frac{m_Z - 91.2}{2.5}\right)^2 + \left(\frac{f_{j1} - 1}{0.06}\right)^2 + \left(\frac{f_{j2} - 1}{0.06}\right)^2$$

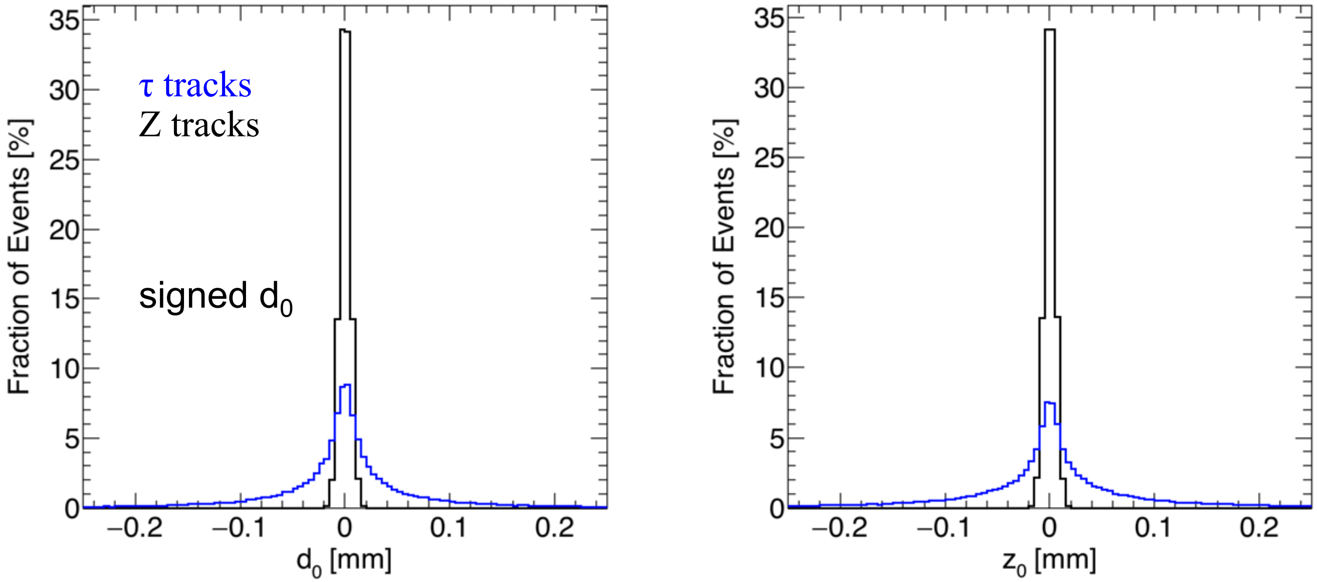
p_h and p_h^{RC} are Higgs 4-momentom from collinear calculation and Z recoil respectively. The $f_{1,2}$ are correction factors for the jets from Z decay

- After minimization, not only the x ambiguity is resolved, but also the Higgs recoil momentum is improved



The impact parameters

- Tracks from taus have broader impact parameter (IP) distributions than the prompt tracks such as the leptons from Z decay

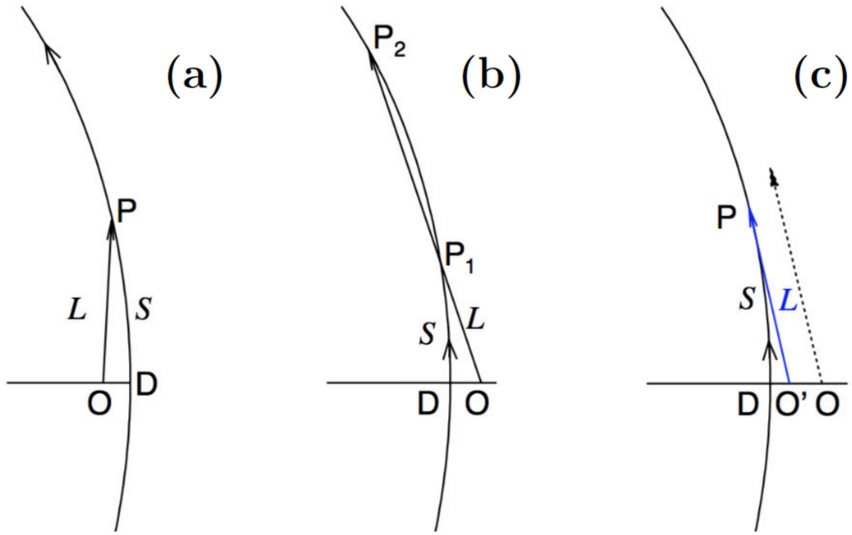


- The impact parameters are additional helpful information to reconstruct the neutrinos from tau decay [A. Rouge hep-ex/0505014; D. Jeans arXiv:1507.01700]. Since the resolution of d_0/z_0 may not be small, we take a less aggressive approach by treating them as extra constraints

  We first find the intersection of tau flight direction with the track trajectory in the transverse plane, and deduce z_0 by $z_0 = L \sinh \eta_\tau - S \sinh \eta_{\mathrm{track}}$

The impact parameters

- The collision point (O) can be inside (a) or outside the track path curvature (b, c)
- In the case of (b), two solutions exist and both are tested. In the case of (c), it is assumed to be from resolution effect



- When the fitted impact parameters are in the physical regime, the χ^2 is

$$\chi^2 = \left(\frac{d_0^{\text{fit}} - d_0}{\sigma_d}\right)^2 + \left(\frac{z_0^{\text{fit}} - z_0}{\sigma_z}\right)^2$$

- Otherwise, in the example case of (c), the χ^2 reads (so that the best-fit perigee point for O' is D)

$$\chi^2 = \left(\frac{d_0^{\text{fit}} + d_0 - 2d_0^{\text{C}}}{\sigma_d}\right)^2 + \left(\frac{z_0^{\text{fit}} - z_0}{\sigma_z}\right)^2$$

Neutrino momentum

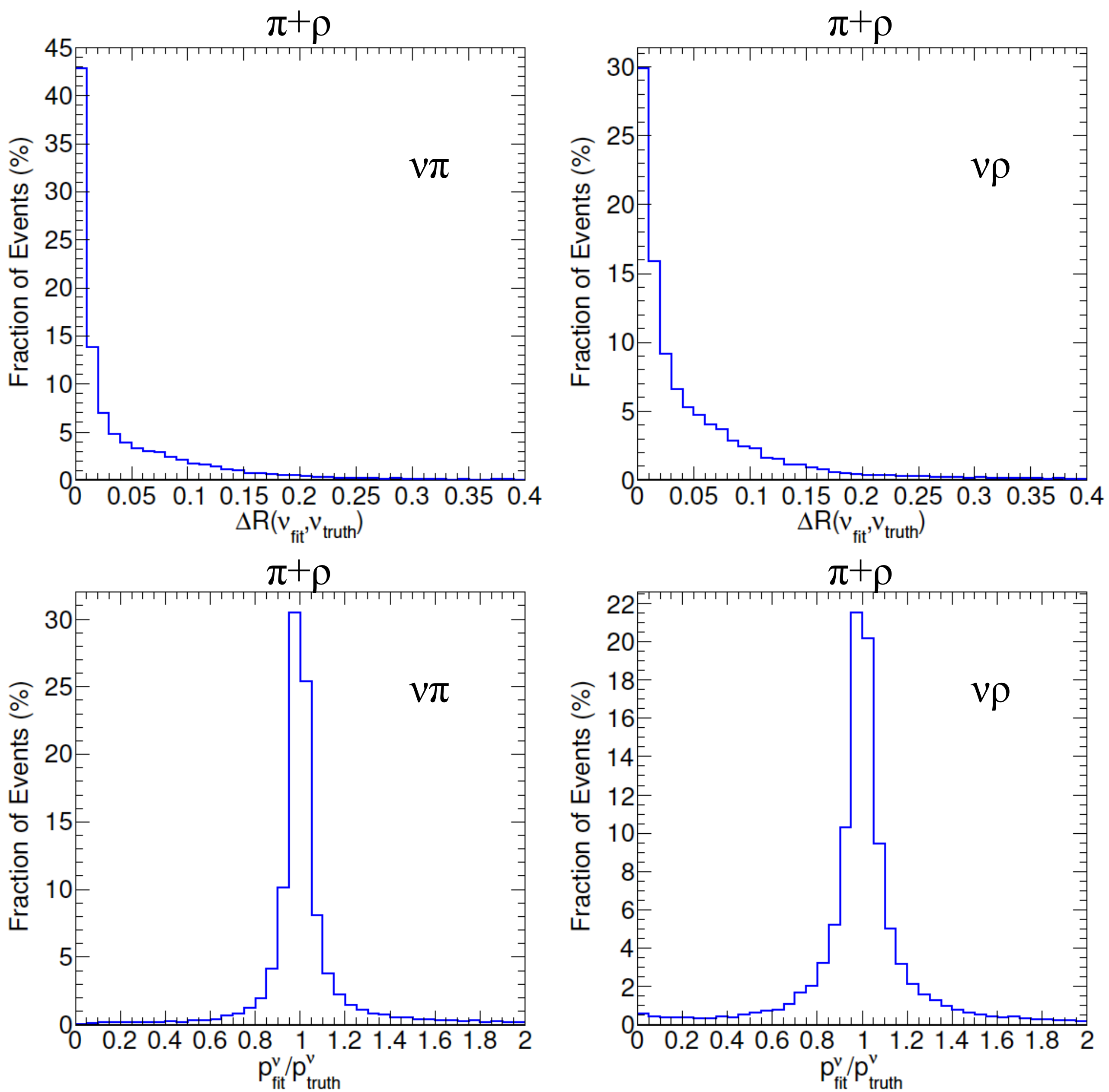
- The momenta of neutrinos from taus can be reconstructed with full constraints in the event

$$\chi^2 = \sum_{i=0}^{3} \left(\frac{p_{h,i}-p_{h,i}^{\mathrm{RC}}}{\sigma_{\mathrm{RC}}}\right)^2 + \left(\frac{m_{\tau 1}-1.777}{\sigma_{\tau 1}}\right)^2 + \left(\frac{m_{\tau 2}-1.777}{\sigma_{\tau 2}}\right)^2 + \chi_{\mathrm{IP}}^2$$

Higgs 4-momentum, tau mass, IP

- For hadronic (leptonic) tau decays, there are 3 (4) unknowns for the neutrinos momenta (less than the constraints)
- We perform the χ^2 minimization by scanning the η/φ of one neutrino, calculate its momentum by the tau mass, and get the other neutrino's information through the total Higgs 4-momentum. The scan is repeated by starting from the other neutrino
- For leptonic taus, the exta unknown, the neutrino pair mass, is also scanned
- After the global minimal point is obtained by scanning, a MINUIT fit is performed for a better estimation

Neutrino momentum



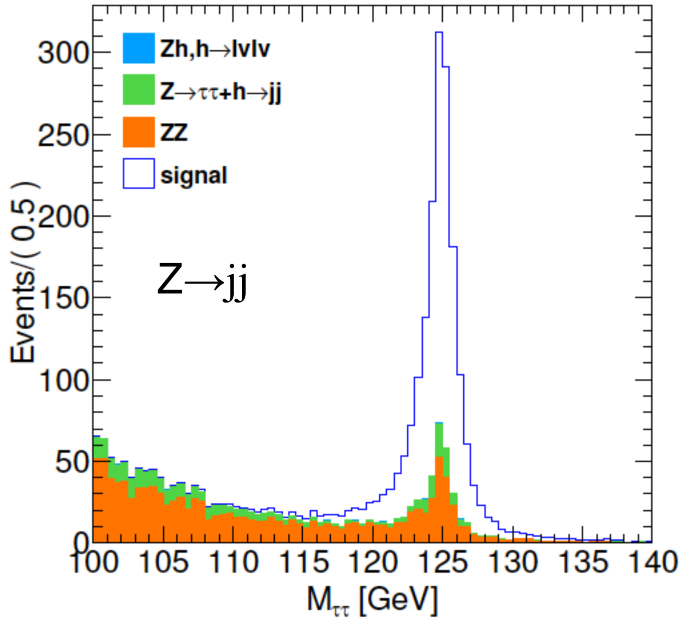
Cleaning cuts

- The combined efficiencies after objects selection (due to jet resolution and neutrino pair, the lepton+Z→jj modes are not considered):

	$\ell+\pi$	$\ell+\rho$	$\pi+\pi$	$\pi+\rho$	$\rho+\rho$
$Z\to ee/\mu\mu$	31.4%	27.2%	19.2%	18.5%	15.7%
$Z\to jj$	~~34.8%~~	~~30.8%~~	24.5%	21.3%	18.9%

- A sequence of cuts are applied to suppress the background, and to purify well reconstructed signal events

$Z\to\ell\ell$	$Z\to jj$
$m_Z > 70$ GeV	$m_Z < 105$ GeV
$m_h^{\rm RC} > 120$ GeV	$m_h^{\rm RC} > 110$ GeV
$m_{h,\rm fit}^{\rm RC} > 122$ GeV	80 GeV$< m_Z^{\rm fit} <$100 GeV
120 GeV$< m_h <$130 GeV	
1.5 GeV$< m_\tau <$2.0 GeV	
$m_\rho >$0.3 GeV (for channels with ρ)	



With 5 ab^{-1} of data, expect to have about 1519 (133) signal (background) events

Higgs CP

- With all final state particles reconstructed, we can perform a Matrix Element based analysis of the underlying Higgs CP mixing angle Φ. The Higgs decay amplitude can be expressed as

$$
\begin{aligned}
|\mathcal{M}|^2 &\propto A + B\cos(2\phi) + C\sin(2\phi), \\
&\propto I_1\cos^2(\phi) + I_2\sin(\phi)\cos(\phi) + I_3\sin^2(\phi)
\end{aligned}
$$

- Two observables can be reconstructed per event for the CP test
  - ❖ Optimal Observable (M. Davier et. al, Phys. Lett. B306,1993, 411): OO = I_2/I_1
  - ❖ ME angle $\Delta\Phi_{ME}$, defined as

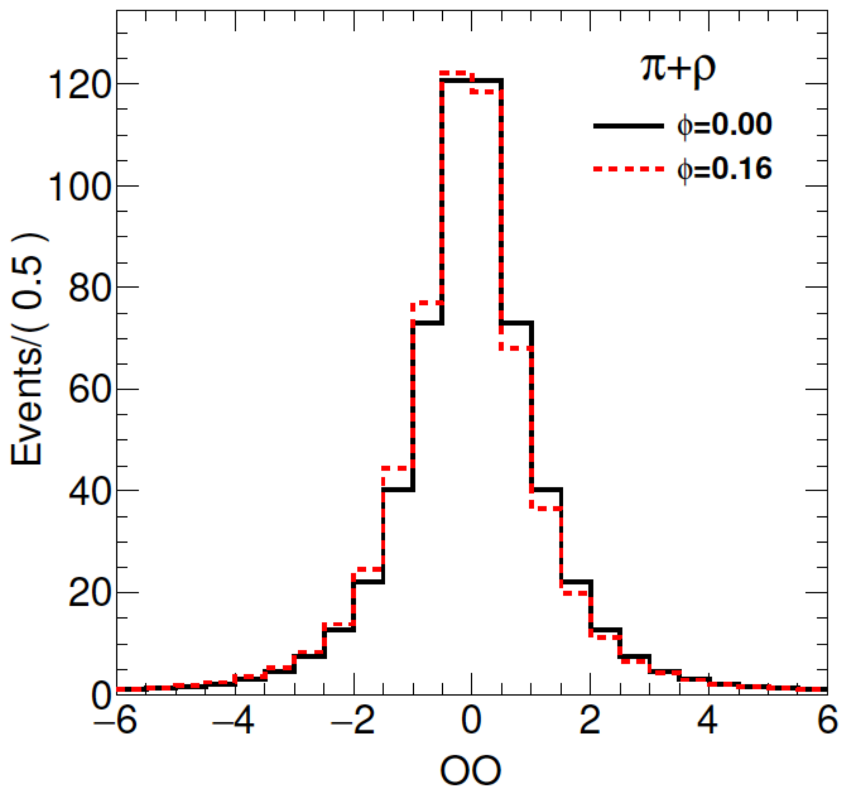
$$|\mathcal{M}|^2 \propto A + \sqrt{B^2+C^2}\cos(\Delta\phi_{ME} - 2\phi)$$

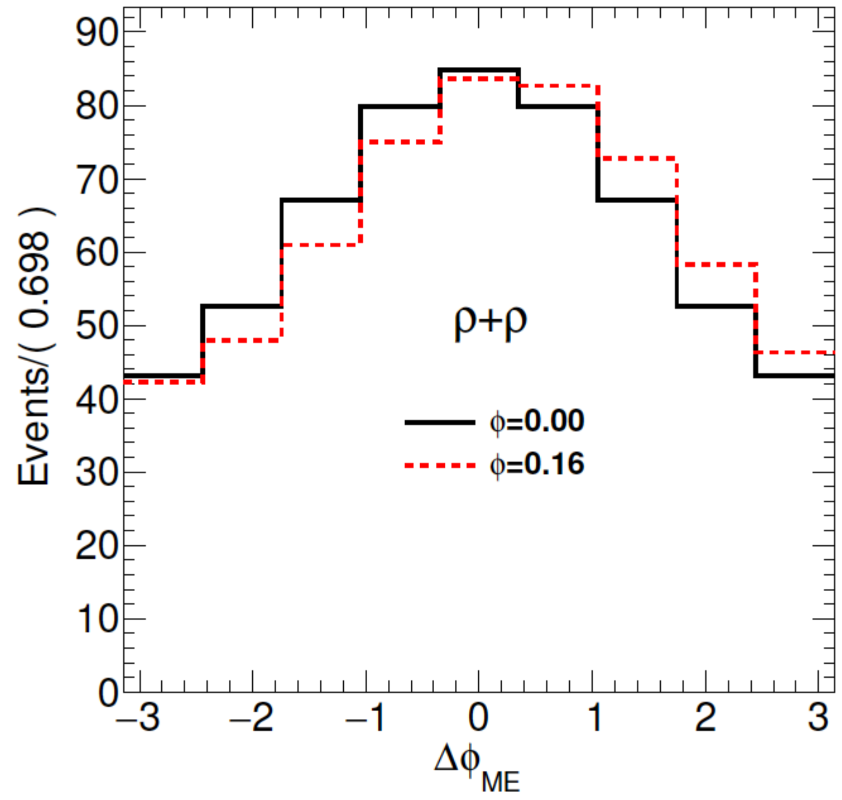
$$\cos(\Delta\phi_{ME}) = \frac{B}{\sqrt{B^2+C^2}}, \quad \sin(\Delta\phi_{ME}) = \frac{C}{\sqrt{B^2+C^2}}$$

At low mixing angle values, the two perform similarly, while in high values of Φ, $\Delta\Phi_{ME}$ is better

Higgs CP

- The OO and $\Delta\Phi_{ME}$ distributions in the π+ρ and ρ+ρ channels for CP even and Φ=0.16





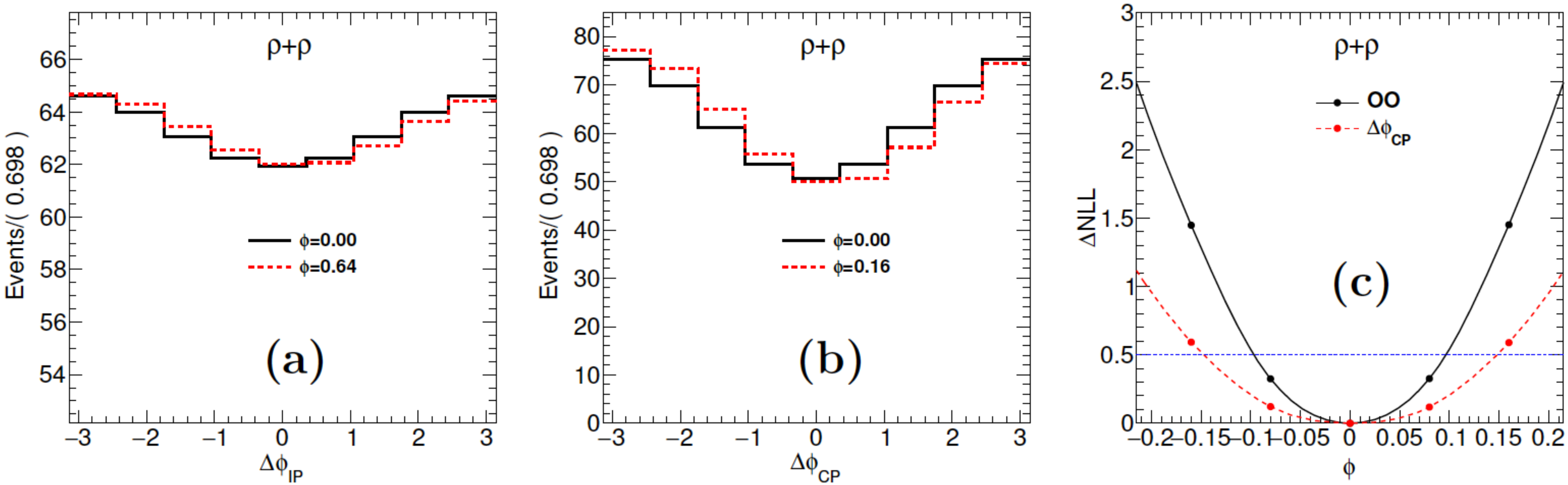
Higgs CP

- The OO or $\Delta\Phi_{ME}$ is better than the other observables such as $\Delta\Phi_{IP}$ and $\Delta\Phi_{CP}$

$$\Phi = \arccos(\hat{p}_{d1}^{\perp} \cdot \hat{p}_{d2}^{\perp}) \times \mathrm{sgn}(\hat{p}_{m1} \cdot (\hat{p}_{d1}^{\perp} \times \hat{p}_{d2}^{\perp}))$$

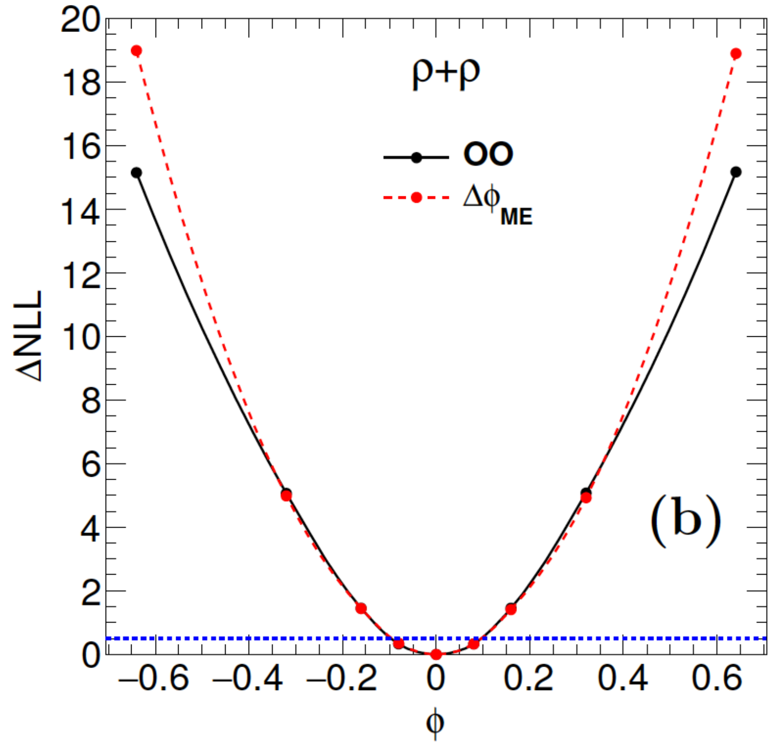
For $\Delta\Phi_{IP}$, $(\hat{p}_{m1},\hat{p}_{d1},\hat{p}_{m2},\hat{p}_{d2}) = (p_{\pi^+} + p_{\pi^0_+}, n^+, p_{\pi^-} + p_{\pi^0_-}, n^-)$

For $\Delta\Phi_{IP}$, $(\hat{p}_{m1},\hat{p}_{d1},\hat{p}_{m2},\hat{p}_{d2}) = (p_{\pi^+}, p_{\pi^0_+}, p_{\pi^-}, p_{\pi^0_-})$



Higgs CP

- Template PDF functions for different CP mixing angle hypotheses are prepared and fit to the pseudo-data. The difference (w.r.t. the minimum) of the Negative Log Likelihood (ΔNLL) is plotted for different Φ, from which the 1σ confidence interval can be found



With 5 (2) ab^{-1} of data, a precision of 2.9^{o} (5.2^{o}) can be reached for the Higgs CP mixing angle measurement

Summary

Testing the CP nature of the Higgs is one of the important tasks after its discovery. This needs a large and pure Higgs signal events with rich decay products, and can be achieved with a high precision at future e^+e^- colliders

The $H \to \tau\tau$ decay is an ideal channel for probing Higgs CP angle for possible effect of CP violation. Our study, based on three tau decay modes, show that with 5 (2) ab^{-1} of data, a precision of 2.9^o (5.2^o) can be reached for the CP angle measurement

Extra Slides