Higgs CP Measurement through $h \to \tau\tau$ at CEPC

Yongcheng Wu
Nanjing Normal University

CEPC Workshop @ Fudan University

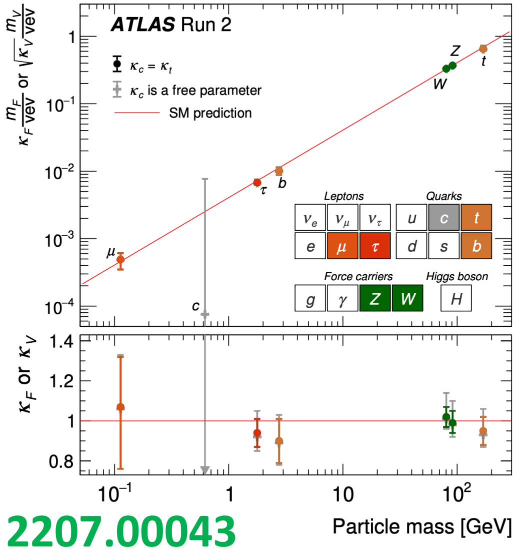
2023.08.15

Based On: X. Chen, YW; EPJC 77 (2017) 10, 697
X. Chen, YW; PLB 790 (2019) 332
X. Chen, YW; JHEP 10 (2019) 089

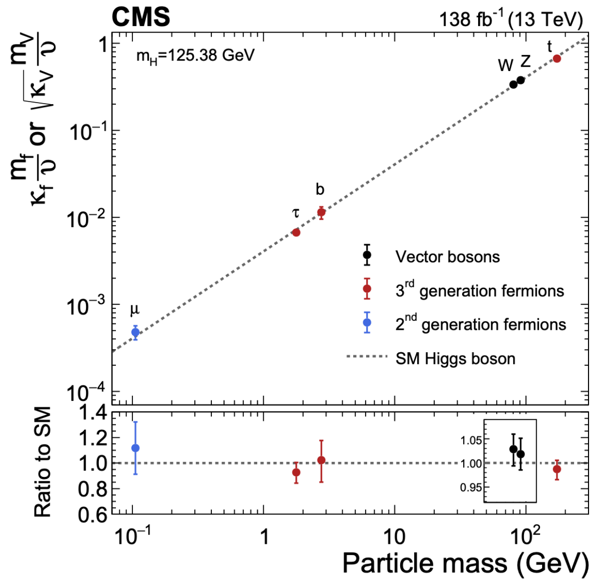
Introduction

- 10+ years since discovery of the Higgs
- Window to New Physics
  - Precision measurement of the properties
    - Mass, Width, Couplings

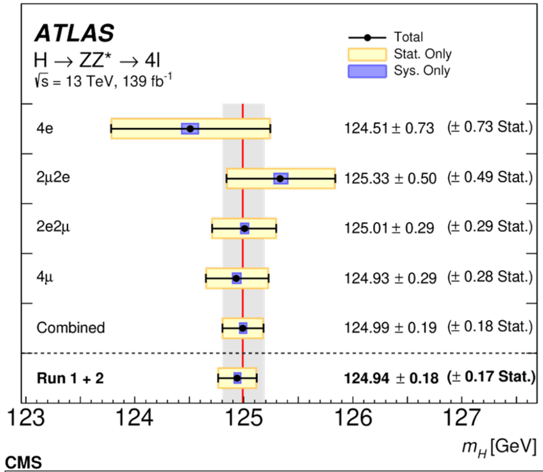
ATLAS: 2207.00092



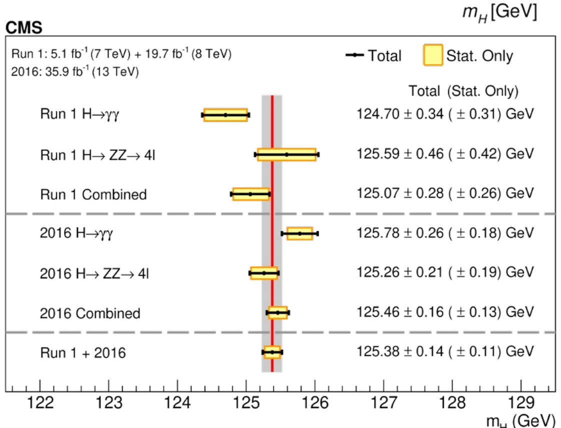
CMS: 2207.00043

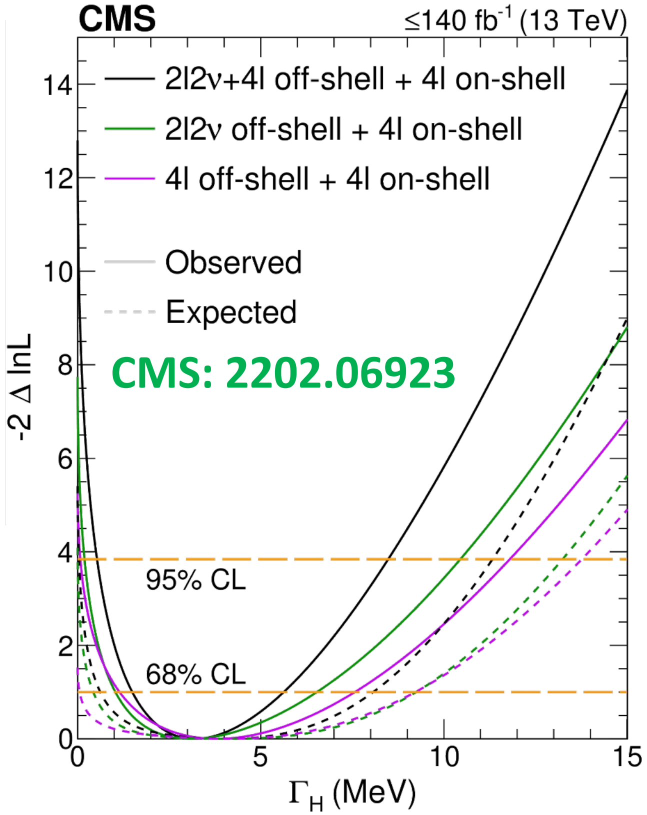


ATLAS: 2207.00320



CMS: 2002.06398





CMS: 2202.06923

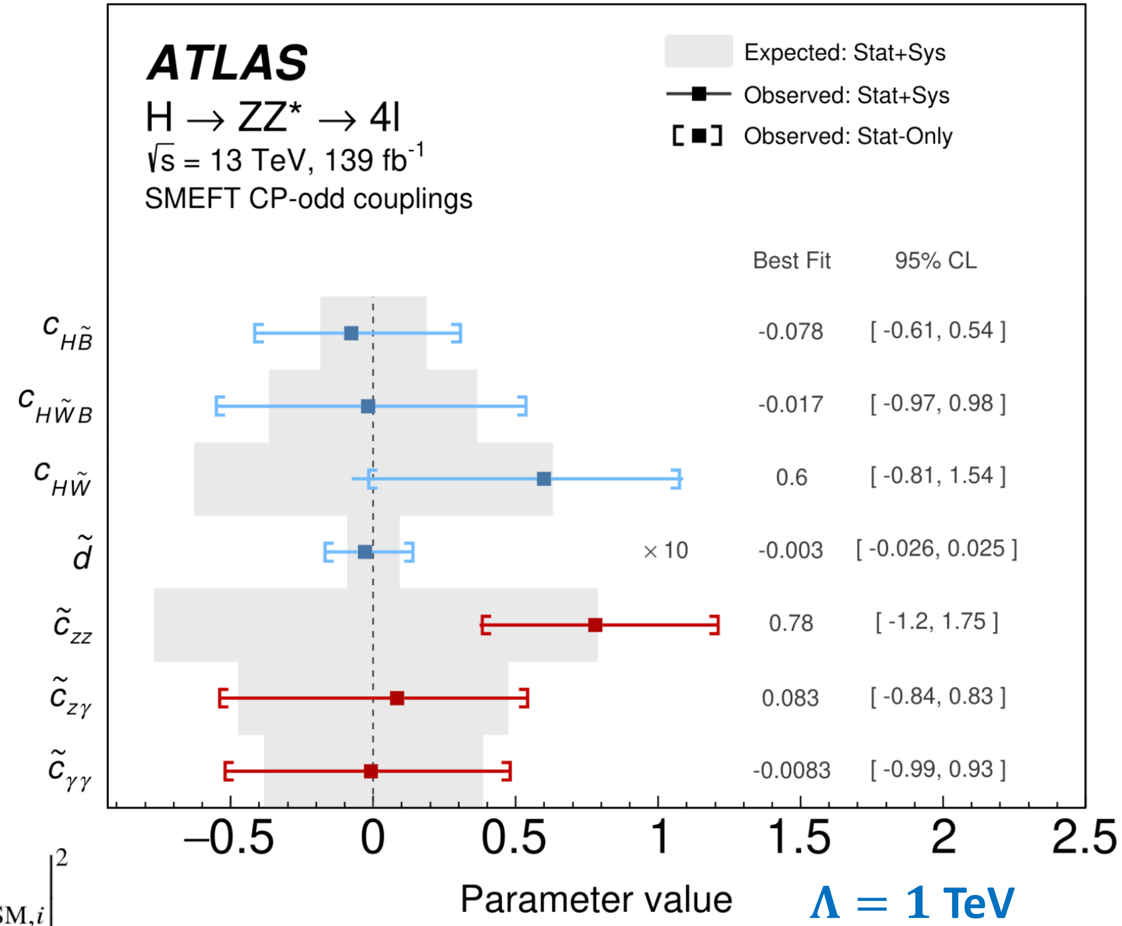
Higgs CP Measurements

- With Vector Bosons
  - High dimensional operators (suppressed)

Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

  - VBF production, $H \to ZZ^*$ decays
  - Optimal Observable

ATLAS: 2304.09612



$\Lambda = 1$ TeV

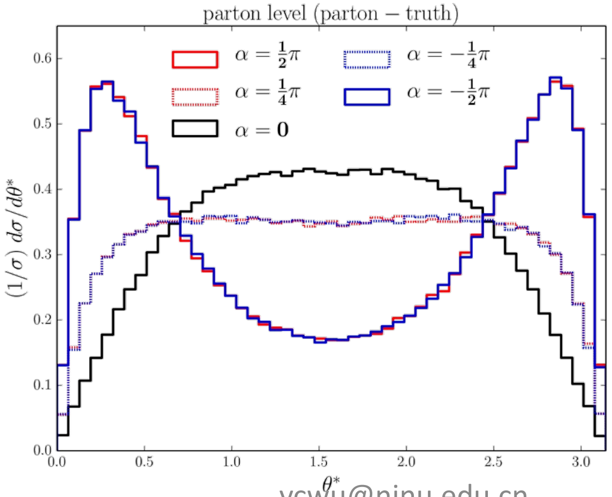
$$OO = \frac{2\Re\left(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm BSM}\right)}{|\mathcal{M}_{\rm SM}|^2}.$$

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_{{\rm BSM},i}\right|^2$$
$$= |\mathcal{M}_{\rm SM}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\Re\left(\mathcal{M}^*_{\rm SM}\mathcal{M}_{{\rm BSM},i}\right) + \sum_i\sum_j \frac{c_i c_j}{\Lambda^4}\Re\left(\mathcal{M}^*_{{\rm BSM},i}\mathcal{M}_{{\rm BSM},j}\right)$$

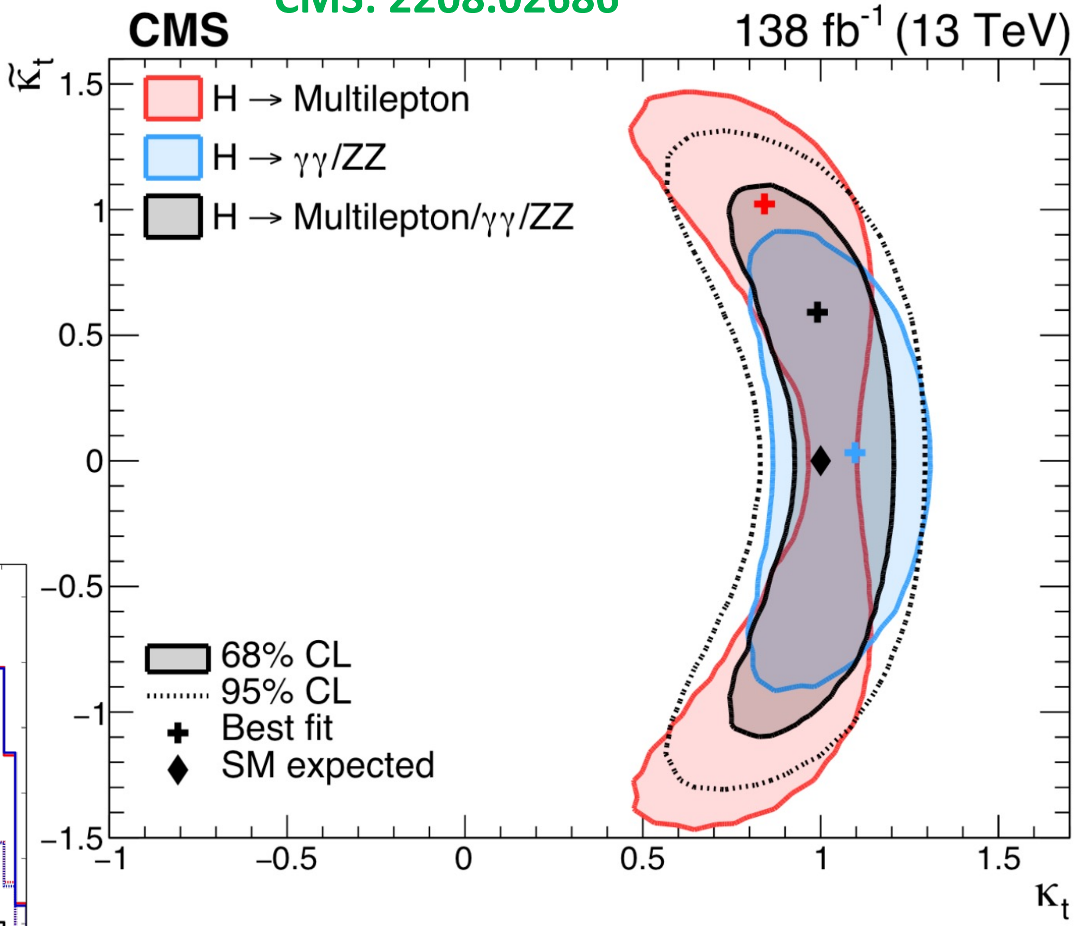
Higgs CP Measurements

- With Fermions
  - CPV appears at d-4 operator
    - $\mathcal{L} = \frac{m_f}{v} \kappa_f \bar{f} (\cos\phi + i \sin\phi \, \gamma^5) f H$
- Top quark
  - Through production:
    - $t\bar{t}H$ or tH
  - Machine learning based
    - $m_{t\bar{t}H}$, $\Delta\eta_{BB}$, etc.
  - Angular Observable

In top pair rest frame
Angle between top and beam axis

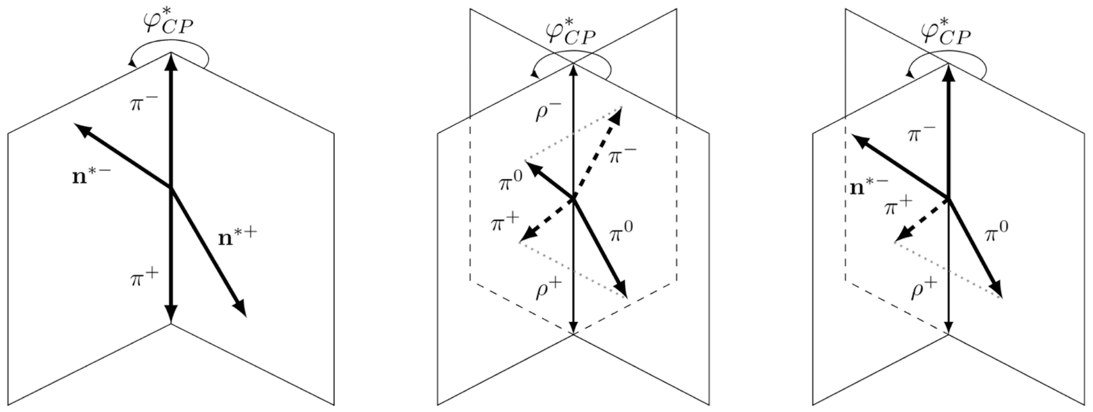


CMS: 2208.02686



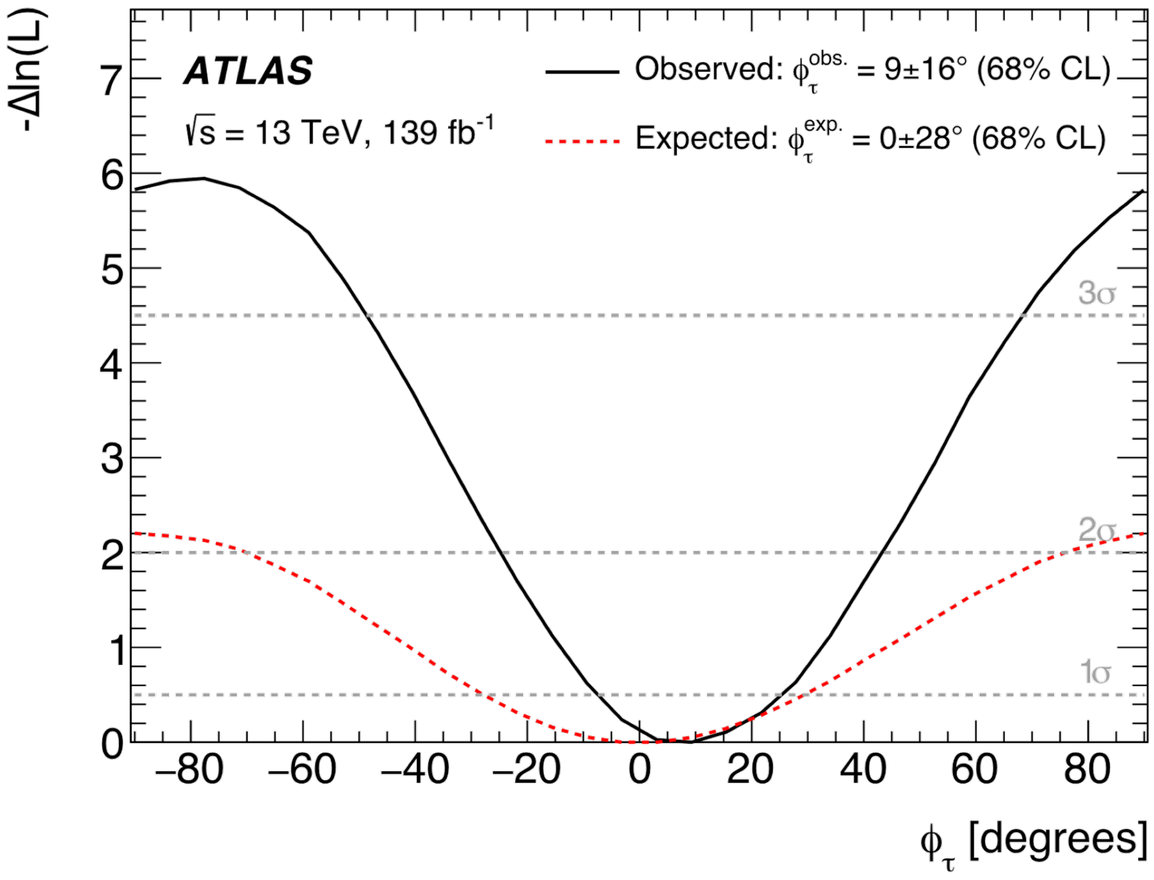
Higgs CP Measurements

- With Fermions
  - CPV appears at d-4 operator
    - $\mathcal{L} = \frac{m_f}{v}\kappa_f \bar{f}(\cos\phi + i\sin\phi\,\gamma^5)fH$
- Tau Lepton
  - Through decay: $H \to \tau\tau$
  - Decay plane
    - By visible products of τ decay
    - Or together with impact parameter



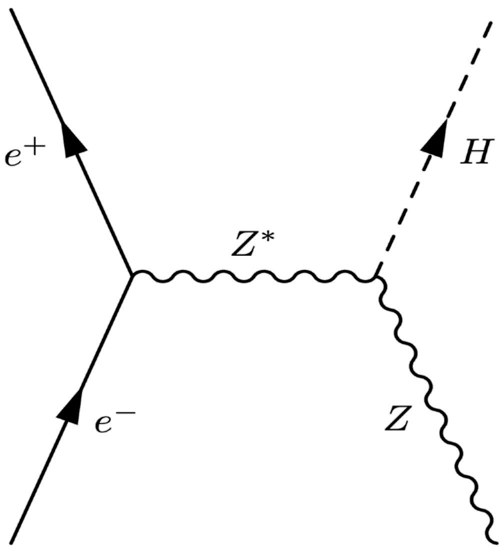
(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$ (b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$ (c) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

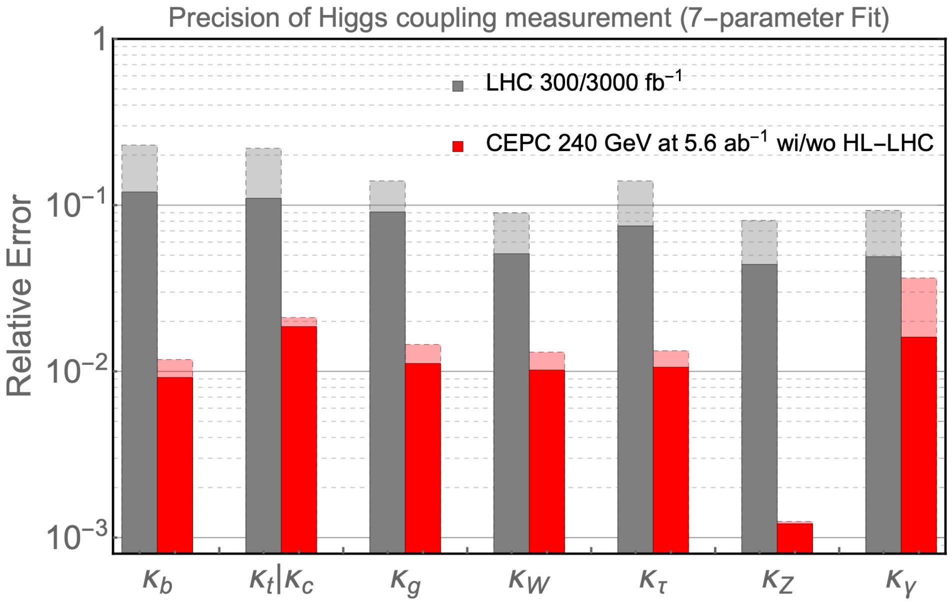
ATLAS: 2212.05833



Higgs Measurement at Lepton Collider

- CEPC as Higgs Factory
  - $\sqrt{s} = 240$ GeV
  - ~1 million Higgs
- For Higgs CP Measurement
  - Clean Background
  - Longitudinal Information





- **With Z Boson:**
  - Inclusive
  - The relation between:
    - Z decay products
    - Beams
- **With τ Lepton:**
  - Higgs Decay
  - The spin correlation among decay products

Higgs CP with $h \to \tau\tau$

- Signal

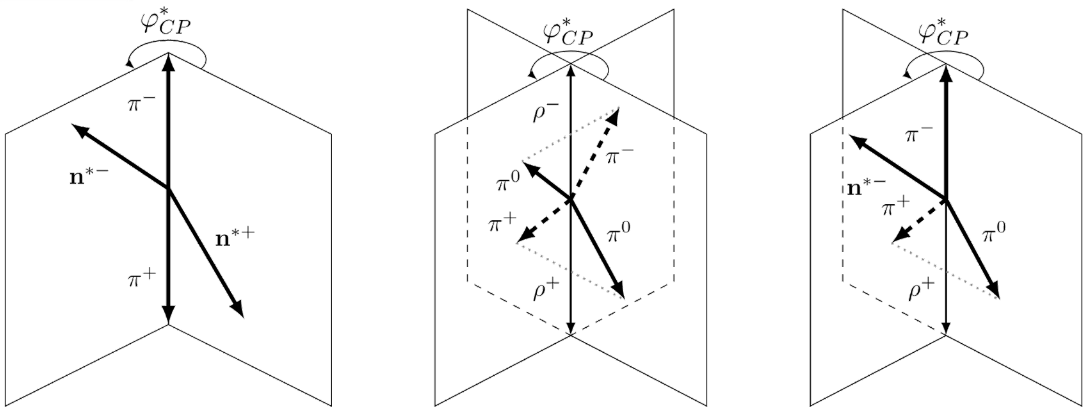
$$e^+e^- \to Zh, \qquad h \to \tau\tau$$

- τ Decays

Mode	$e^\pm\nu\nu$	$\mu^\pm\nu\nu$	$h^\pm\nu$	$h^\pm\pi^0\nu$	$h^\pm\pi^0\pi^0\nu$	$h^\pm h^\mp h^\pm\nu$
Type	τ_e	τ_μ	τ_h	τ_h	τ_h	τ_h
$\mathcal{B}(\%)$	17.8	17.4	11.5	25.9	9.5	9.8
Resonance	—	—	—	$\rho(770)$	$a_1(1260)$	$a_1(1260)$
Symbol	e	μ	π	ρ	a_1^{1pr}	a_1^{3pr}

- Background
  - $e^+e^- \to ZZ, Z \to \tau\tau, Z \to \ell\ell(jj)$
  - $e^+e^- \to Zh, Z \to \tau\tau, h \to bb$
  - $e^+e^- \to Zh, Z \to \tau\tau, h \to \ell\nu\ell\nu$

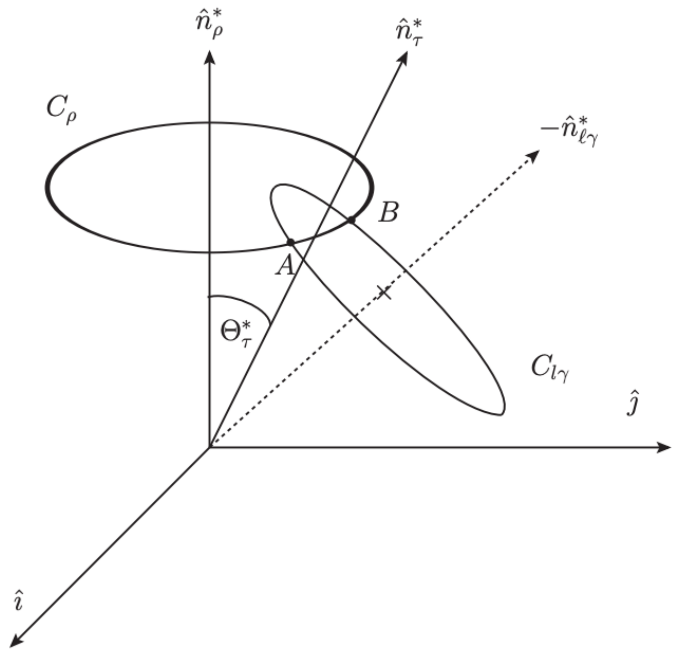
Neutrino!

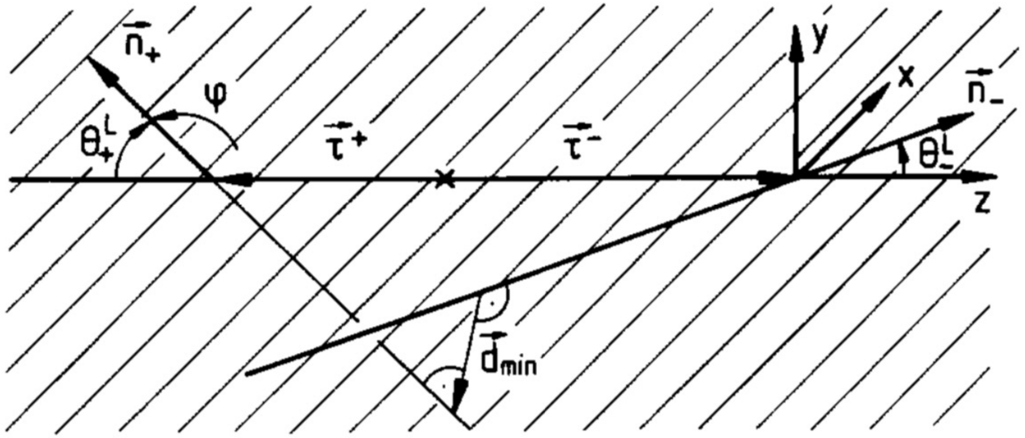


(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$ (b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$ (c) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$

Neutrino Reconstruction

- Using the momentum/energy information of the system
  - Two-fold ambiguity

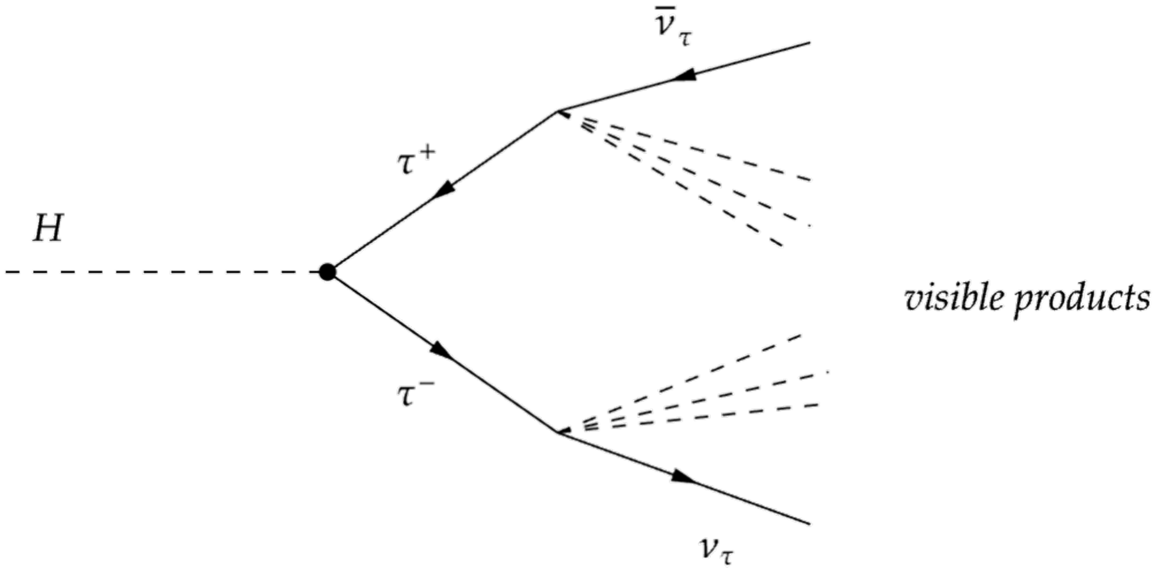




Phys. Lett. B 313 (1993) 458

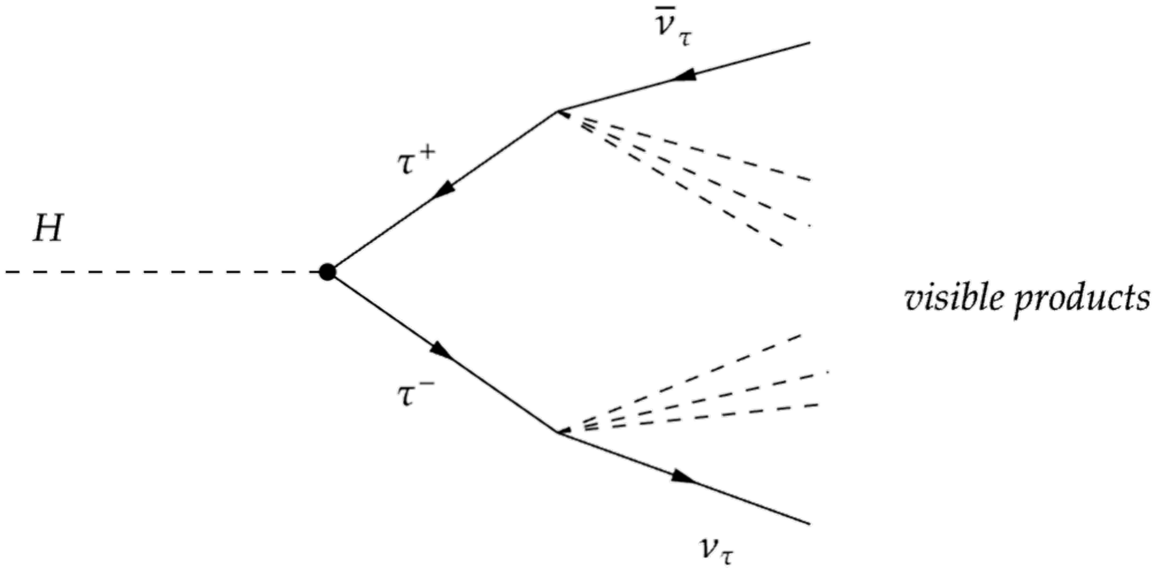
Neutrino Reconstruction

- Global Fitting:
  - Higgs four momentum (recoil) (4 constraints)
  - Two tau masses (2 constraints)
  - Impact parameter (2 constraint)
  - Other intermediate state, each provide one constraint
- Hadronic tau:
  - Reconstruct the neutrino
- Leptonic tau:
  - Reconstruct the sum of two neutrinos



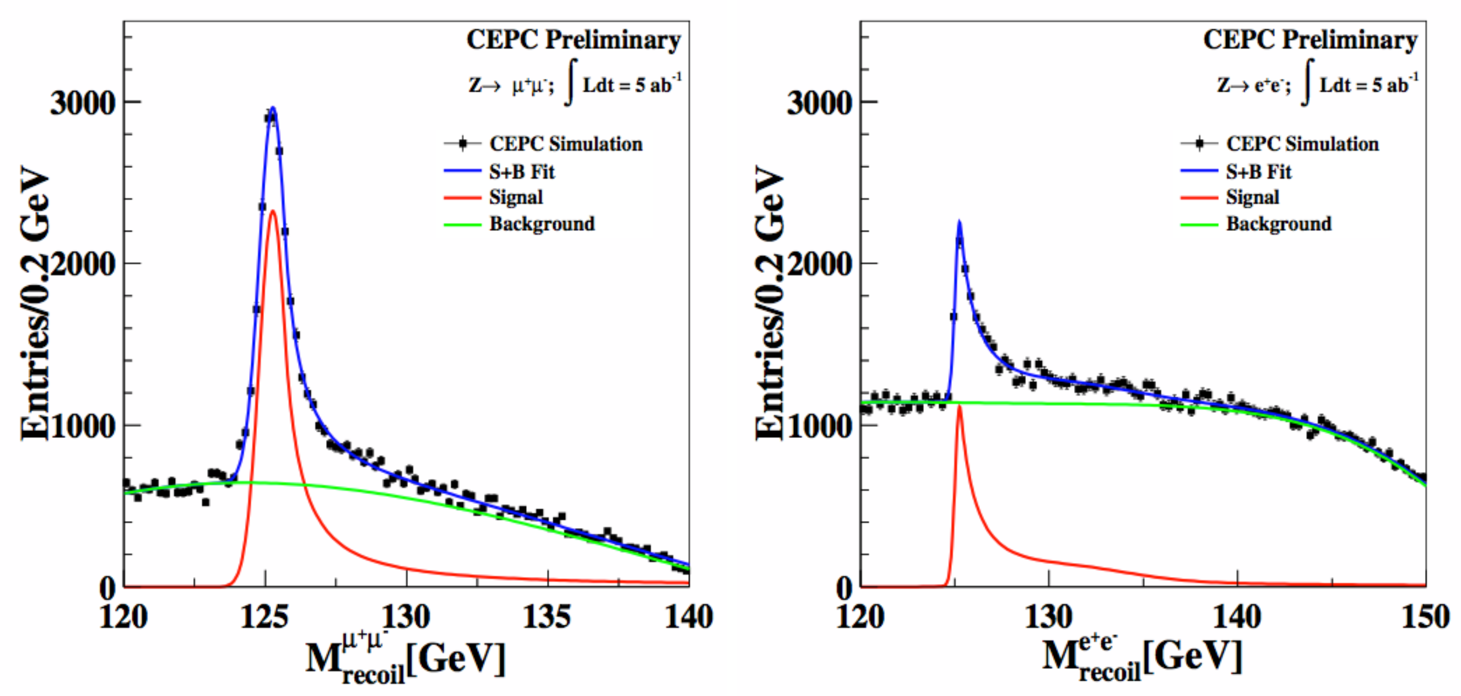
Neutrino Reconstruction

- Global Fitting:
  - Higgs four momentum (recoil) (4 constraints)
  - Two tau masses (2 constraints)
  - Impact parameter (2 constraint)
  - Other intermediate state, each provide one constraint
- Hadronic tau:
  - Reconstruct the neutrino
- Leptonic tau:
  - Reconstruct the sum of two neutrinos



Neutrino Reconstruction

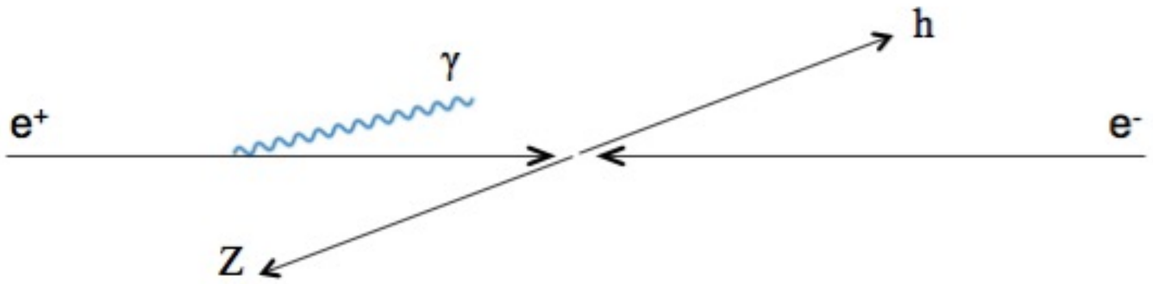
- Refine Higgs Momentum



  - Dealing with ISR
- Dealing with Impact Parameter
  - Additional Constraints for Neutrino

Neutrino Reconstruction

- Dealing with ISR



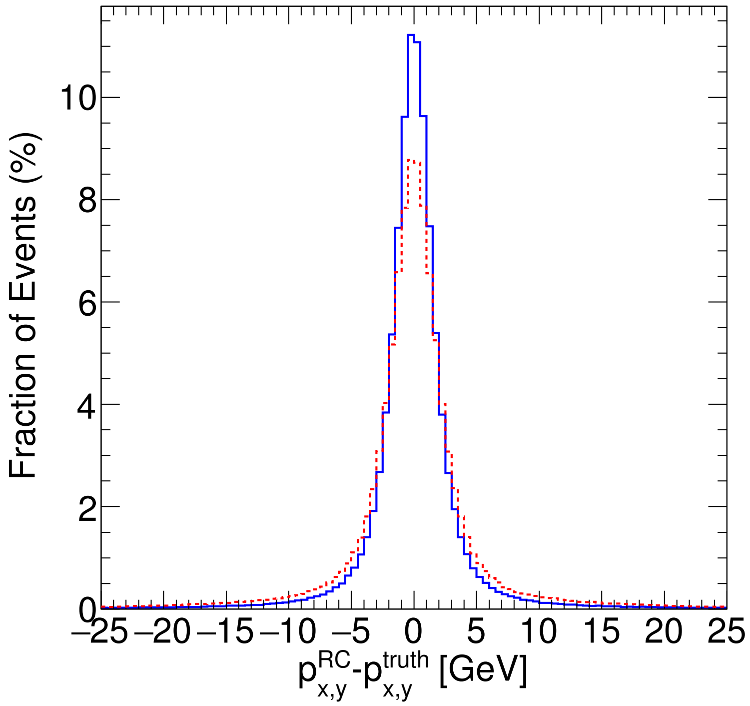
- Assumption 1: ISR collinear with initial states
  - $p_\gamma = \left(\frac{|x|E_{CM}}{2}, 0, 0, \frac{xE_{CM}}{2}\right)$
- Assumption 2: It is Z-Higgs system (Bad for background)

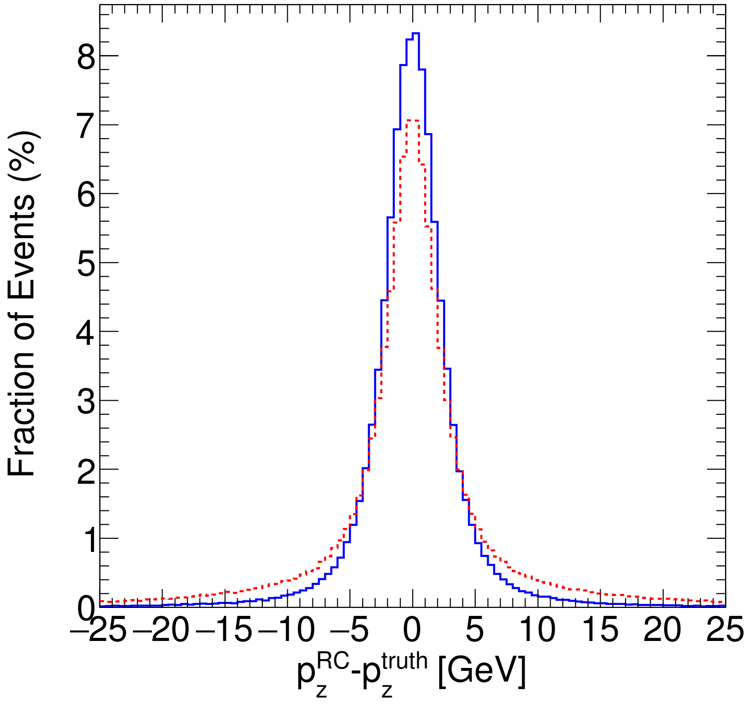
$$x = \frac{E_{\mathrm{CM}}^2 - 2E_{\mathrm{CM}}E + m^2 - m_h^2}{\pm E_{\mathrm{CM}}^2 \mp E_{\mathrm{CM}}E + E_{\mathrm{CM}}p_z},$$

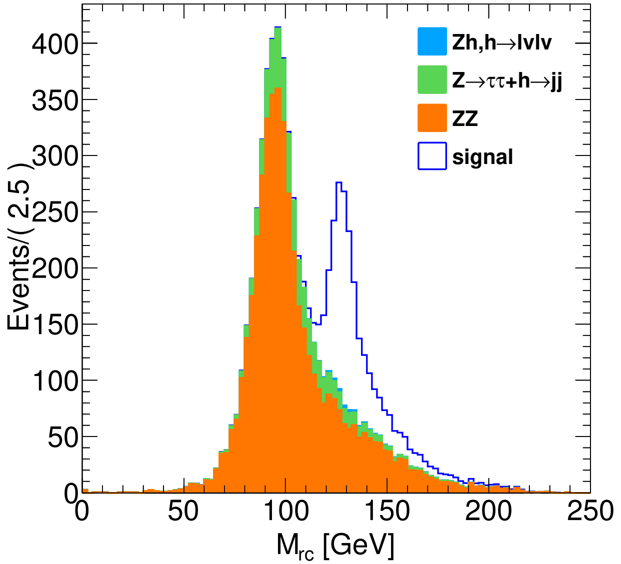
$$\chi^2(x_1, x_2, f_{j1}, f_{j2}) = \sum_{i=0}^{3}\left(\frac{p_{h,i}^c - p_{h,i}^{rc}}{\sigma_h}\right)^2 + \left(\frac{\sqrt{p_Z^2} - m_Z}{\sigma_Z}\right)^2 + \left(\frac{f_{j1} - 1}{\sigma_j}\right)^2 + \left(\frac{f_{j2} - 1}{\sigma_j}\right)^2$$

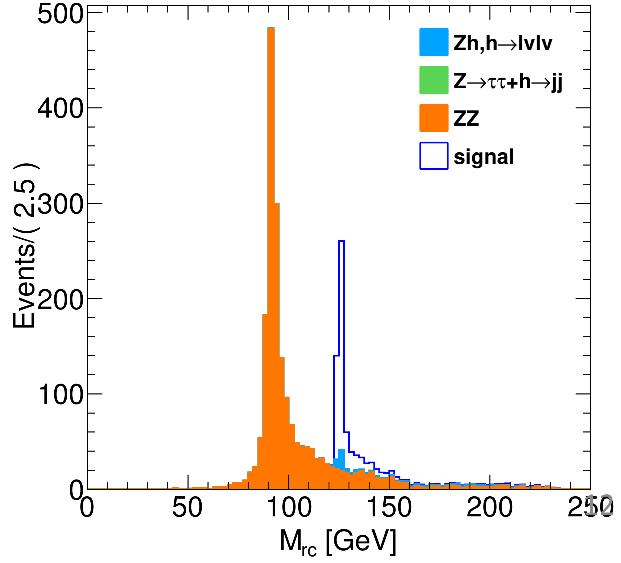
Neutrino Reconstruction

- Dealing with ISR
  - ⇒ Better Higgs momentum reconstruction





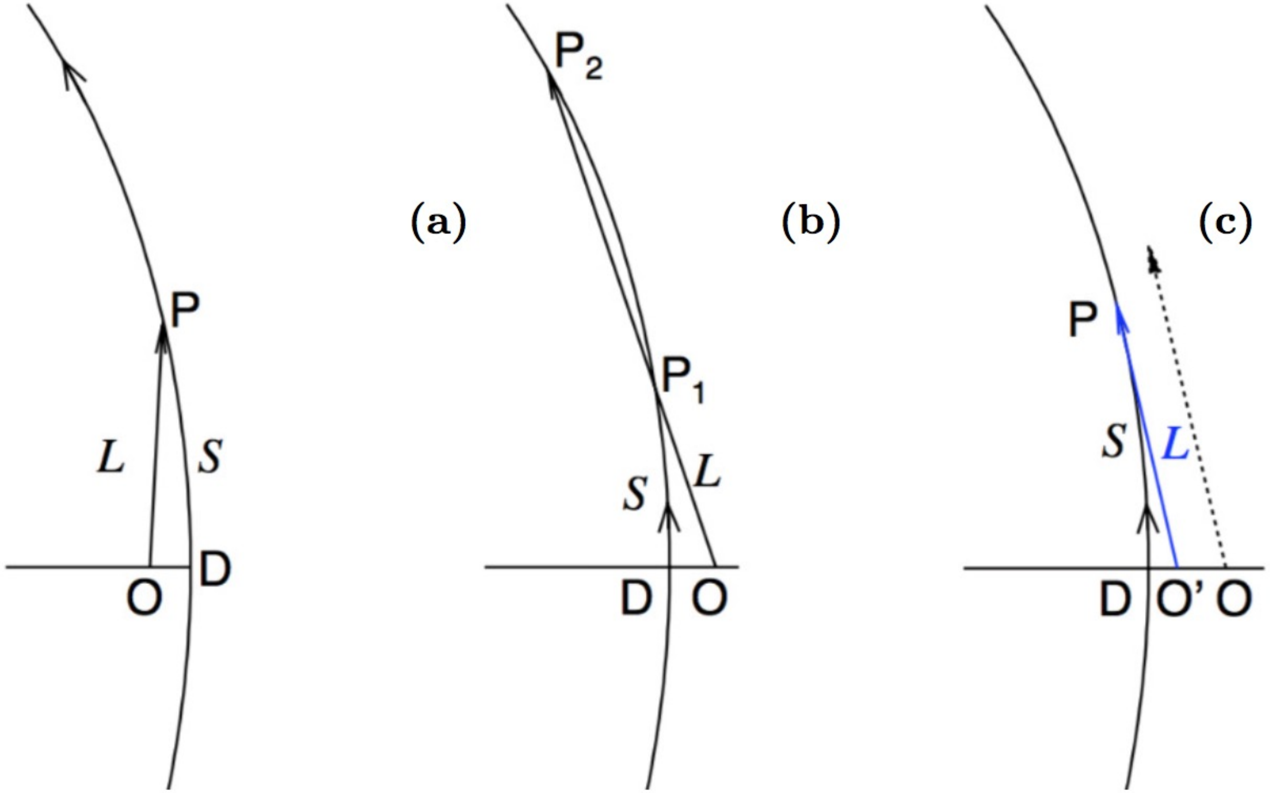




Red: uncorrected jet energy, Blue: improved jet energy

Neutrino Reconstruction

- Dealing with the Impact Parameter:
  - For τ lepton: $c\tau \approx 87\ \mu m$

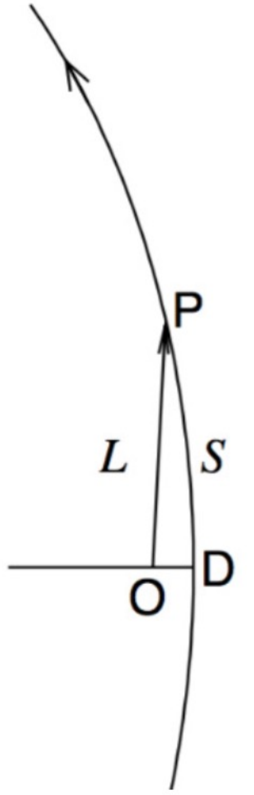


- O: τ Production point
- P: τ Decay point
- $\vec{L}$: The direction of τ
- $\hat{S}$: The trajectory of the charged decay product
- OD: The impact parameter
  - Z-axis: z_0
  - XY-plane: d_0

Neutrino Reconstruction

- Procedure to utilize the impact parameter
  - Given neutrino momenta: $p_{\nu 1}, p_{\nu 2}$ and track momenta (visible products)
    - $\Rightarrow \tau$ Lepton direction: $\vec{L}$
  - Given the transverse impact parameter d_0^f
    - $\Rightarrow$ Intersect point P, the distance L and the arc length S
  - The Longitudinal impact parameter can be calculated as
    - $z_0^f = L \sinh \eta_\tau - S \sinh \eta_{track}$
- Contribution to overall χ^2
  - $\chi^2_{imp} = \left(\frac{d_0^f - d_0}{\sigma_d}\right)^2 + \left(\frac{z_0^f - z_0}{\sigma_z}\right)^2$
  - Function of $p_{\nu 1}, p_{\nu 2}$ and d_0^f

Measurement Precision:
- $\sigma_d = 5\ \mu m$
- $\sigma_z = 10\ \mu m$



Neutrino Reconstruction

- Global Fitting:
  - Given the neutrino momenta $p_{\nu 1}, p_{\nu 2}$
    - $p_{\tau 1} = p_{\nu 1} + p_{vis1}$, $p_{\tau 2} = p_{\nu 2} + p_{vis2}$
    - $p_h = p_{\tau 1} + p_{\tau 2}$

$$\chi^2 = \sum_{i=0}^{3} \left(\frac{p_{h,i} - p_{h,i}^c}{\sigma_{rc}} \right)^2 + \left(\frac{\sqrt{p_{\tau 1}^2} - m_\tau}{\sigma_\tau} \right)^2 + \left(\frac{\sqrt{p_{\tau 2}^2} - m_\tau}{\sigma_\tau} \right)^2 + \chi_{imp}^2$$

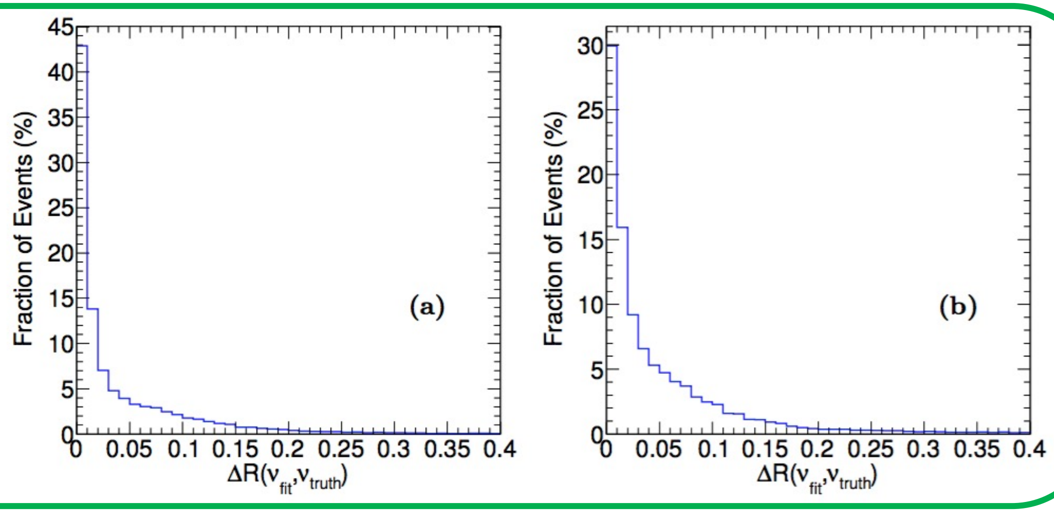
    - Additional terms will be added for any intermediate state
  - Minimized for $p_{\nu 1}, p_{\nu 2}$ and d_0^f

Neutrino Reconstruction

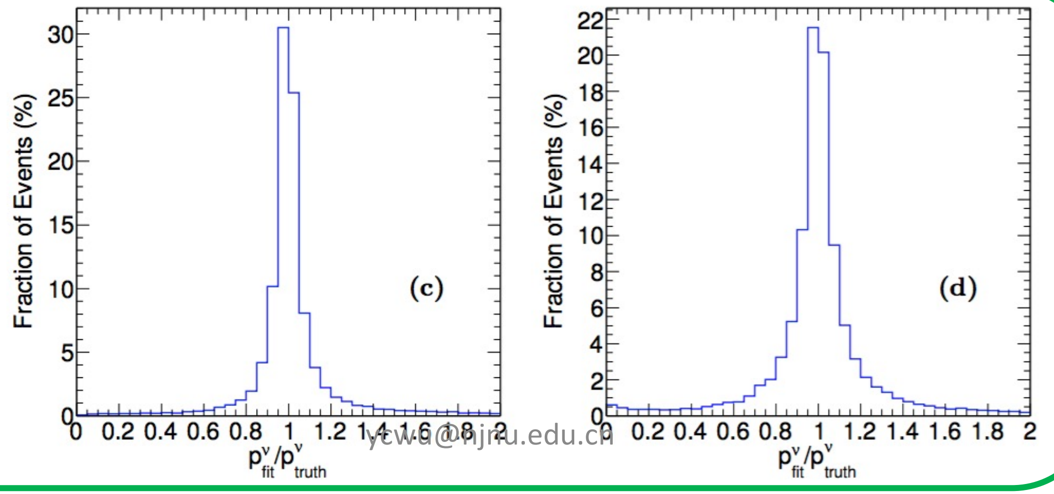
- Compare with truth information:

$\tau \to \pi\nu$ $\tau \to \rho\nu \to \pi\pi\nu$

Direction:

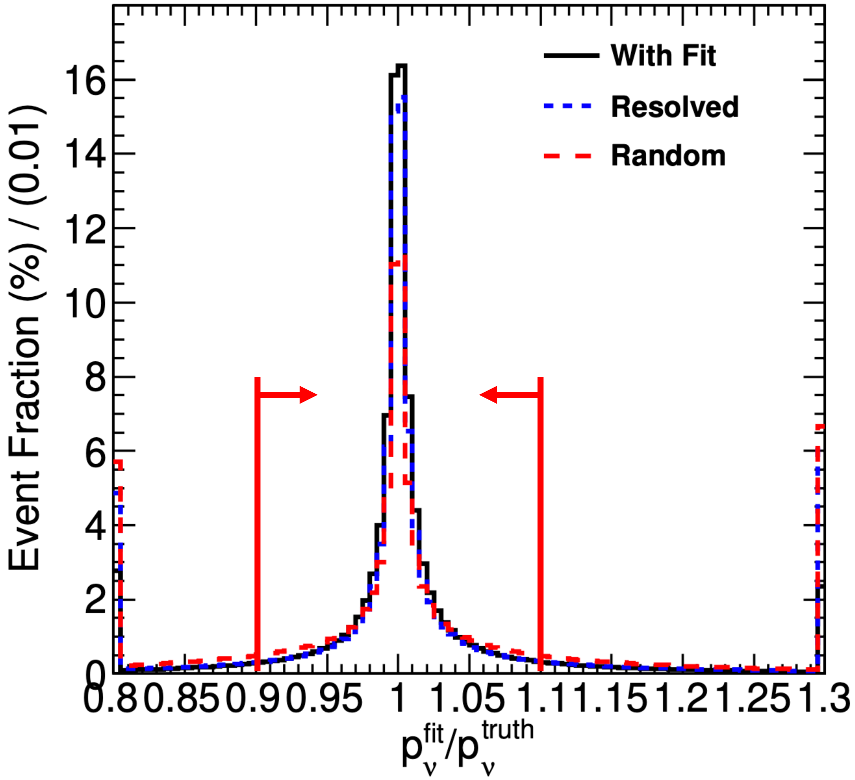


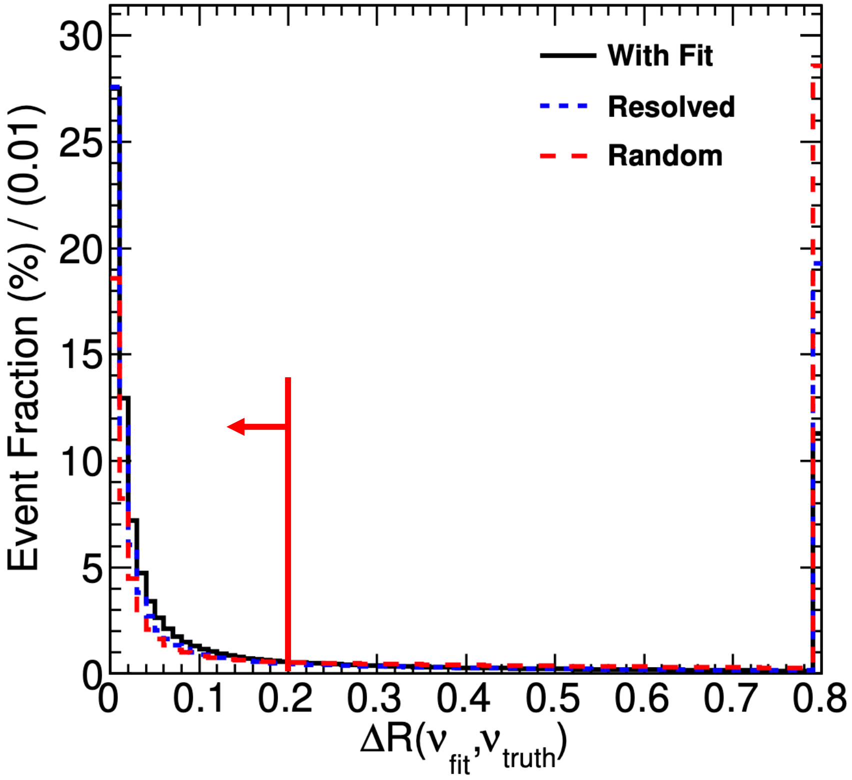
Momentum:



Neutrino Reconstruction

- Compare with other methods





Fraction within red region: 42% ⇒ 59% ⇒ 65%

Higgs CP Measurement with $h \to \tau\tau$

- All decay products from Higgs are reconstructed
- Matrix Element of Higgs decay can be calculated event by event

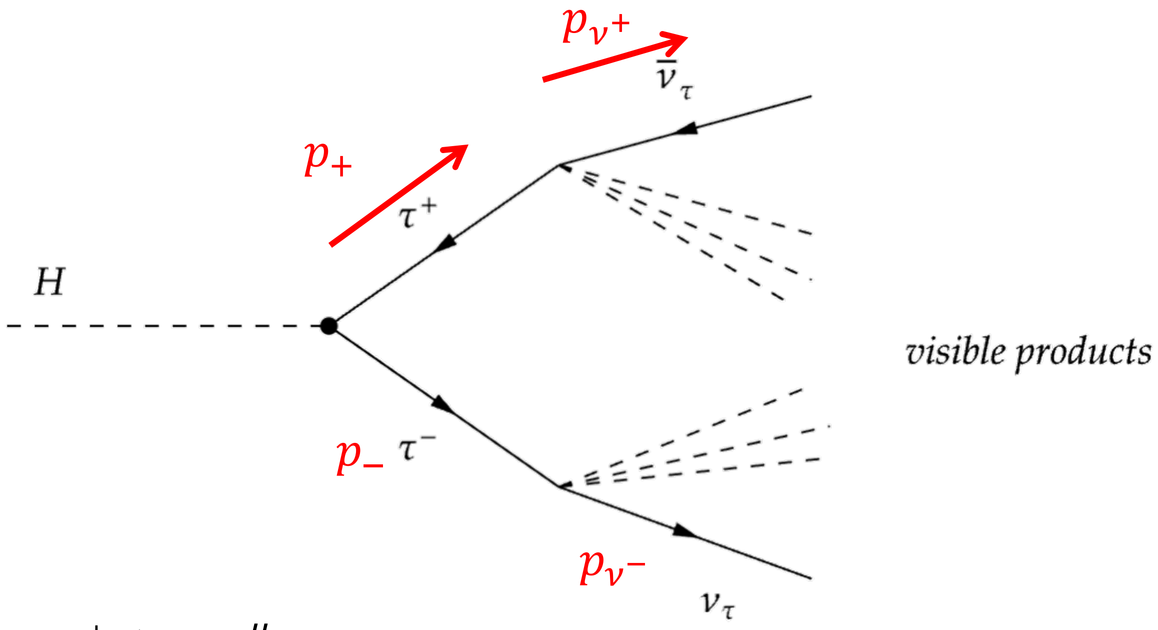
$$\mathcal{L} = -\frac{y_\tau}{\sqrt{2}}(\cos\phi\,\bar{\tau}\tau + i\sin\phi\ \bar{\tau}\gamma^5\tau)h$$

$$|\mathcal{M}|^2 \propto A + B\cos 2\phi + C\sin 2\phi$$

$$A = 2(k_-\cdot p_-)(k_+\cdot p_-) - p_-^2(k_-\cdot k_+) + (p_- \leftrightarrow p_+)$$

$$B = 2(g^{\mu\rho}g^{\nu\sigma} + g^{\mu\sigma}g^{\nu\rho} - g^{\mu\nu}g^{\rho\sigma})k_-^\mu k_+^\nu p_-^\rho p_+^\sigma$$

$$C = 2\epsilon_{\mu\nu\rho\sigma}k_-^\mu k_+^\nu p_-^\rho p_+^\sigma$$



- Spin analyzer (Polarimetric vector)
  - $k_\pm^\mu \equiv 2(J_\pm\cdot p_{\nu^\pm})J_\pm^\mu - J_\pm^2 p_{\nu^\pm}^\mu$

$\tau^\pm(s_\pm) \to \nu\, h\cdots$

$|\mathcal{T}|^2 \propto 1 + k_\pm^\mu s_{\pm\mu}$

- $J_\pm^\mu(\tau^\pm \to \pi^\pm\nu) = p_{\pi^\pm}^\mu$
- $J_\pm^\mu(\tau^\pm \to \pi^\pm\pi^0\nu) = p_{\pi^\pm}^\mu - p_{\pi^0}^\mu$
- $J_\pm^\mu(\tau^\pm \to \pi_1^\pm\pi_2^\pm\pi_3^\mp\nu) = F^{13}(q_1^\mu - q_3^\mu - G^{13}Q^\mu) + (1\leftrightarrow 2)$

ycwu@njnu.edu.cn

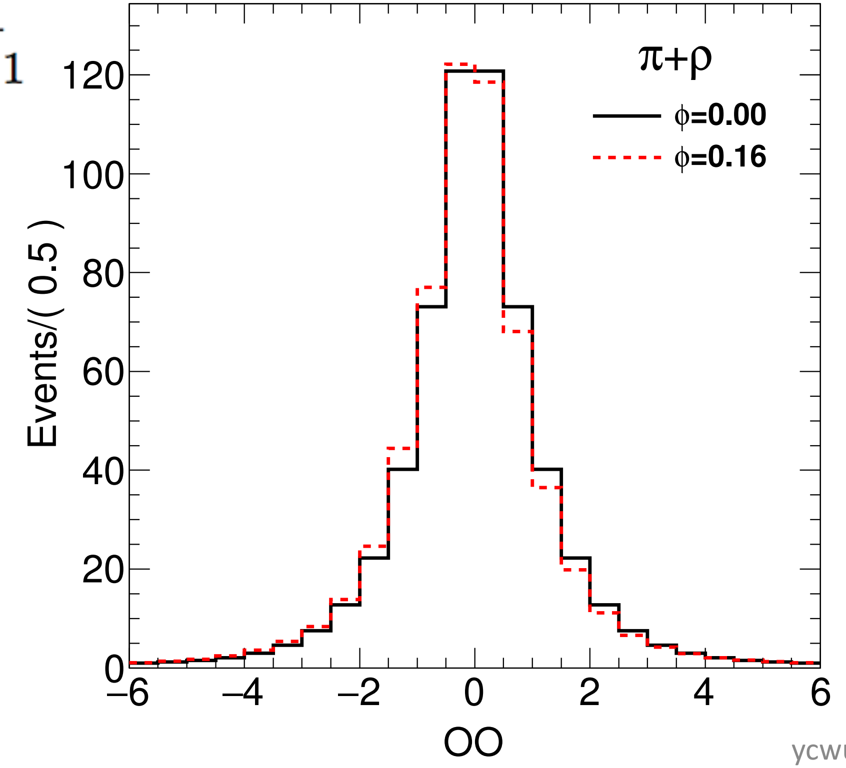
Observables

- Two observables based on matrix element can be build:

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

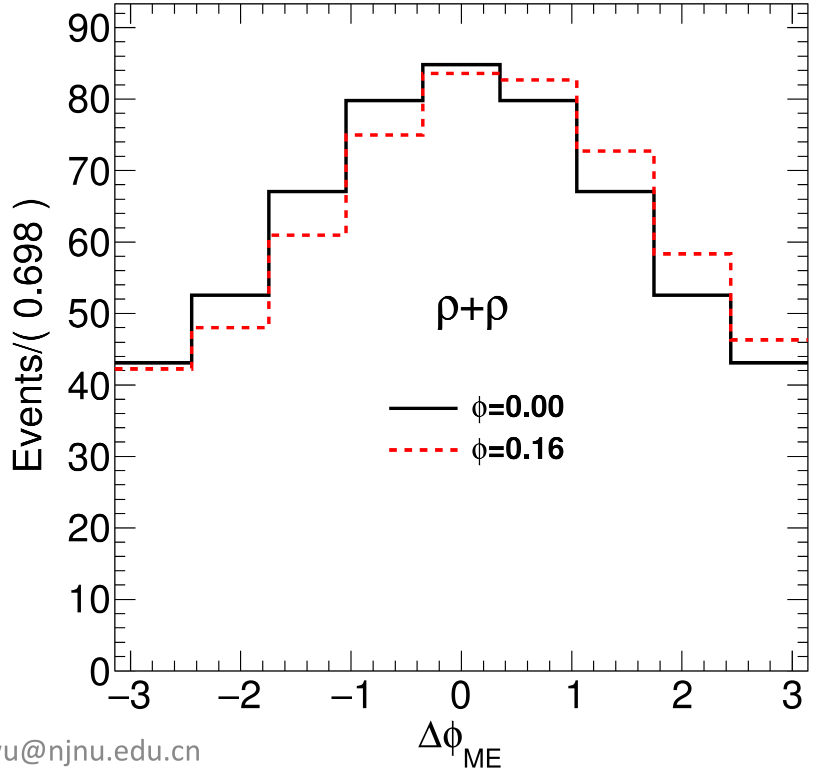
Optimal Observable

$$OO = I_2/I_1$$



ME Angle

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

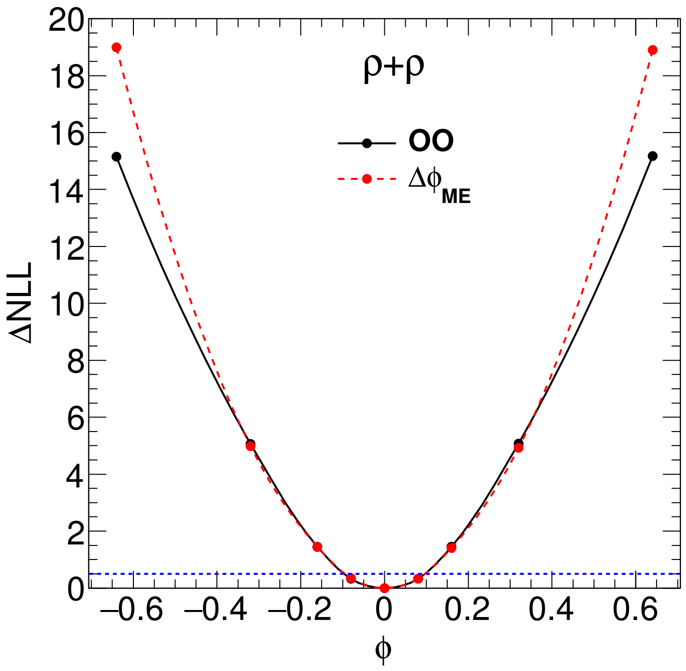


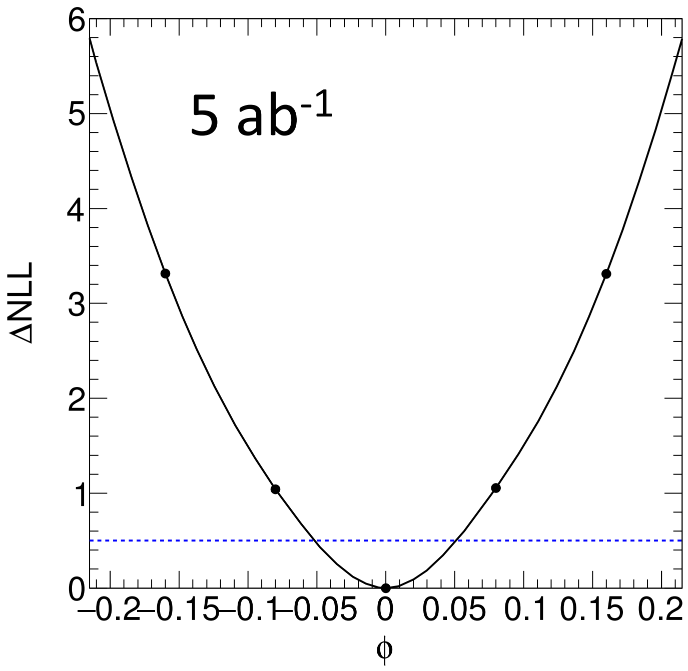
$$\cos(\Delta\phi_{ME}) = \frac{B}{\sqrt{B^2+C^2}},$$
$$\sin(\Delta\phi_{ME}) = \frac{C}{\sqrt{B^2+C^2}}.$$

CP Sensitivity

- Template PDFs are extracted from MC simulation

ME Angle uses more information than OO at large ϕ



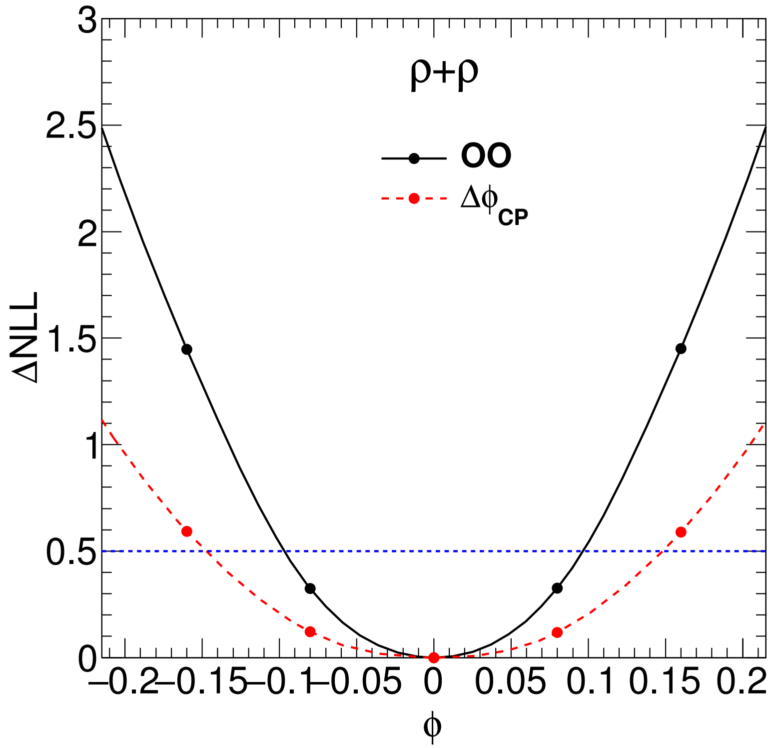


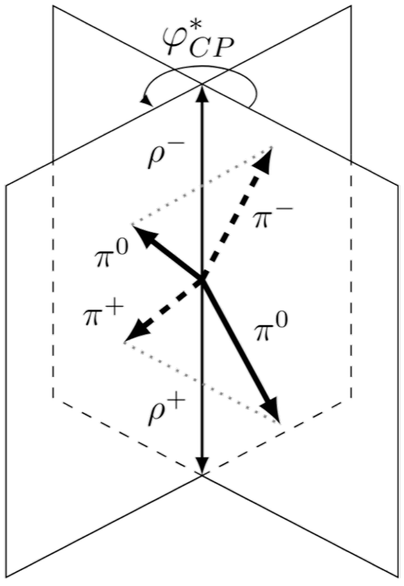
- With 5 (2) ab^{-1}, 2.9°(5.2°) can be reached
  - Without 3-prong

CP Sensitivity: Comparison

- Compare with the "Decay plane":
  - $k_{\pm}^{\mu} \equiv 2(J_{\pm} \cdot p_{\nu^{\pm}})J_{\pm}^{\mu} - J_{\pm}^{2} p_{\nu^{\pm}}^{\mu}$
- The OO vs. 4-π plane (Decay through ρ)

- $J_{\pm}^{\mu}(\tau^{\pm} \to \pi^{\pm}\nu) = p_{\pi^{\pm}}^{\mu}$
- $J_{\pm}^{\mu}(\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu) = p_{\pi^{\pm}}^{\mu} - p_{\pi^{0}}^{\mu}$
- $J_{\pm}^{\mu}(\tau^{\pm} \to \pi_1^{\pm}\pi_2^{\pm}\pi_3^{\mp}\nu) = F^{13}(q_1^{\mu} - q_3^{\mu} - G^{13}Q^{\mu}) + (1 \leftrightarrow 2)$





(b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$

Summary and Prospects

- Method to reconstruct the neutrino from tau-decay
  - Also applicable to the LHC ($\pm$15.5(5.2)° for 300 (3000) fb^{-1}) **X. Chen, YW; PLB 790 (2019) 332**
- The precision of CPV effects in $h \to \tau\tau$
  - Based on realistic MC simulation with full detector effects
  - Higgs factory, 250 GeV, 5 ab^{-1}, CP Mixing angle: $\pm$2.9°
- Applicable to other measurement with τ lepton:
  - The EDM/g-2 at tau-charm factory
  - etc.

$\mathcal{L}$	1 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$\vert d_\tau^{NP}\vert$ (e·cm)	1.44×10^{-18}	4.56×10^{-19}	2.04×10^{-19}
$\vert a_\tau^{NP}\vert$	1.24×10^{-4}	3.92×10^{-5}	1.75×10^{-5}

$a_\tau^{SM} = 0.00117721(5)$ **X. Chen, YW; JHEP 10 (2019) 089**

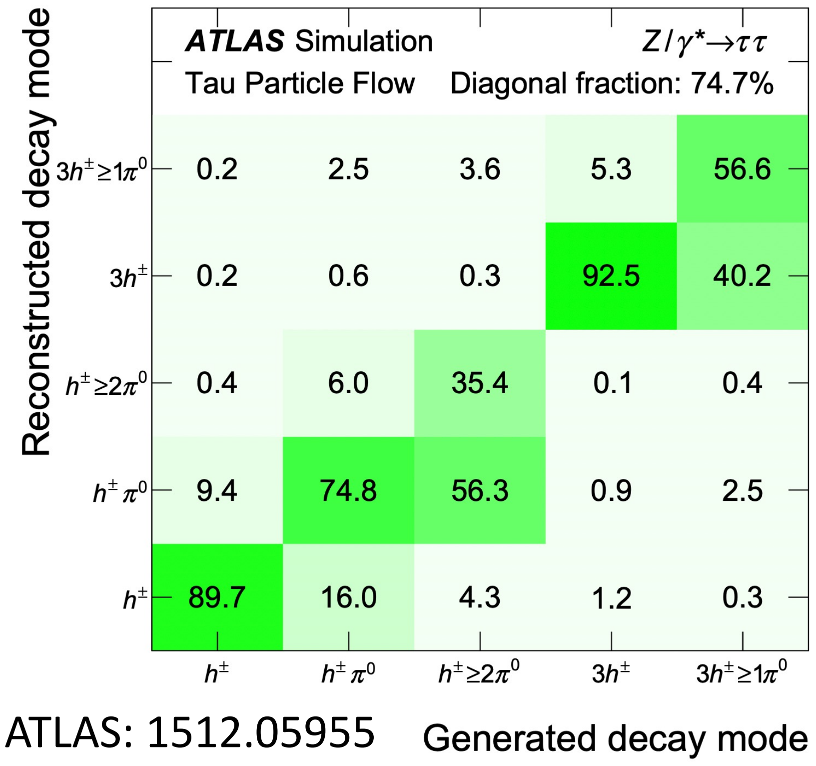
Thanks for your attention!

Event Reconstruction

- Detector Simulation
  - Tracking efficiency: 99%
  - Tracking pseudorapidity: $|\eta| < 2.4$
  - Track momentum smearing: $\sqrt{0.01^2 + (10^{-4}p_T)^2}$
  - Track direction resolution: 0.001
  - Muon/electron identification: 95%
  - Calorimeter coverage: $|\eta| < 3.0$
  - Calorimeter energy smearing: $\sqrt{A^2E^2 + B^2E}$
    - Ecal: A = 1.0%, B = 15%
    - Hcal: A = 1.5%, B = 50%
  - Neutral Pion Energy Resolution: 10% assumed

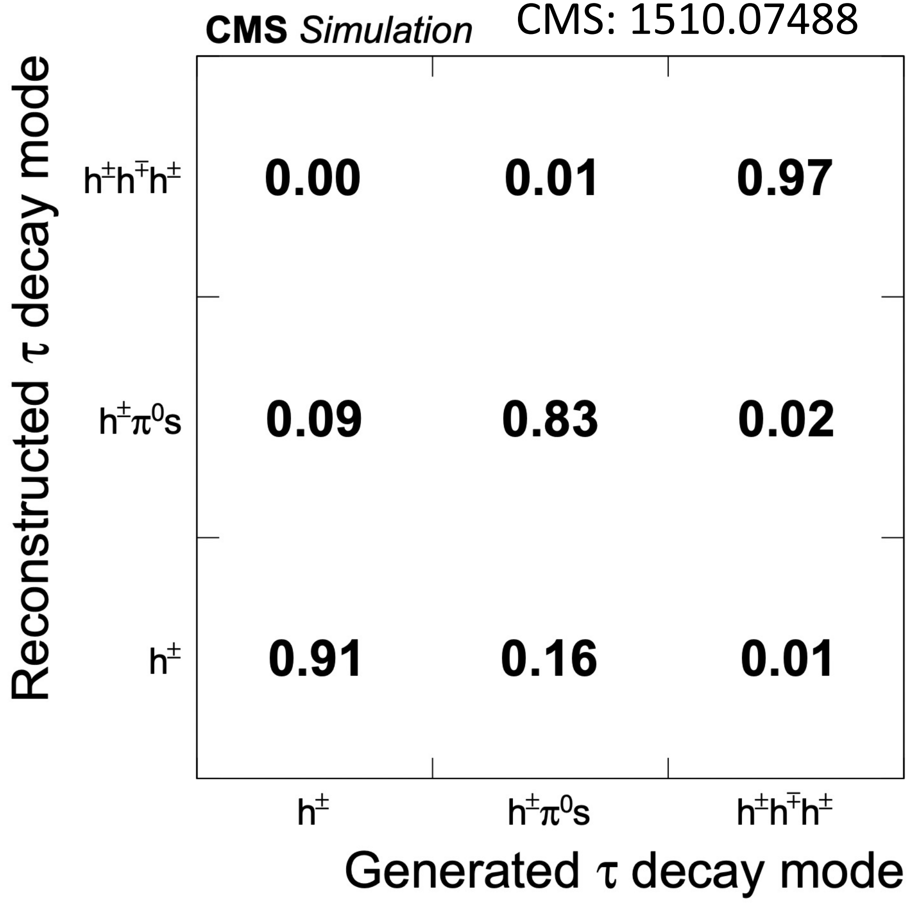
Event Reconstruction

- τ Decay Identification



ATLAS: 1512.05955

CMS: 1510.07488



ycwu@njnu.edu.cn

Event Reconstruction

- Lepton and charged pion:
  - $p_T > 5$ GeV
- Anti-kT for hadronic tau
  - Tagging effeiciency: 60%
  - Fake rate: 0.5%
- Coneless exclusive (kT) for hadronic Z

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

Table 1. The combined efficiencies of selecting the leptons, taus and jets for the different Z and ditau decay modes (neutrinos are omitted in the notation).

Event Selection

- Cuts

$Z \to \ell\ell$	$Z \to jj$
$m_Z > 70$ 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)	

Table 2. Further kinematic cuts applied to enhance the signal significance.

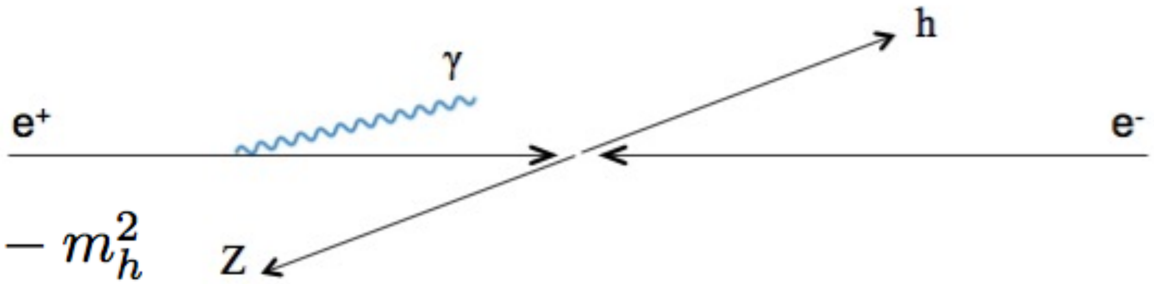
- Events

	$\ell+\pi$	$\ell+\rho$	$\pi+\pi$	$\pi+\rho$	$\rho+\rho$
signal	112.4	194.8	147.2	541.6	523.2
background	9.5	12.6	15.5	46.7	48.6

Table 3. The expected numbers of signal and background events with 5 ab^{-1} of data in each channel after the cuts in Tab. 2 with $Z \to \ell\ell, jj$ combined. Note that the $\ell+\pi/\rho$ and $Z \to jj$ channels are excluded.

Detail in χ^2 for ISR Part

- With ISR included



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

  - $p_h^{rc} = p_{CM} - p_{ISR} - p_Z$
- Assumption: Neutrinos are collinear with corresponding visible part
  - Not good, but enough to improve the Higgs momentum reconstruction
  - $p_h^c = \frac{p_{vis1}}{x_1} + \frac{p_{vis2}}{x_2}$
- For hadronic Z, adding corrections for the jet energy scale factor:
  - f_{j1}, f_{j2}
  - $p_Z = f_{j1}p_{j1} + f_{j2}p_{j2}$ or $p_Z = p_{\ell 1} + p_{\ell 2}$

Detail in χ^2 for ISR Part

- Construction of χ^2:

$$\chi^2(x_1, x_2, f_{j1}, f_{j2}) = \sum_{i=0}^{3}\left(\frac{p_{h,i}^{c} - p_{h,i}^{rc}}{\sigma_h}\right)^2 + \left(\frac{\sqrt{p_Z^2} - m_Z}{\sigma_Z}\right)^2 + \left(\frac{f_{j1} - 1}{\sigma_j}\right)^2 + \left(\frac{f_{j2} - 1}{\sigma_j}\right)^2$$

  - $\sigma_h = 0.5$ GeV, tuned according to simulation to obtain the “best” Higgs reconstruction
  - $\sigma_Z = \Gamma_Z \approx 2.5$ GeV
  - $\sigma_j \approx 6\%$, may be improved to 4% (only for hadronic Z)
- The χ^2 is minimized w.r.t $(x_1, x_2, f_{j1}, f_{j2})$ for each event

Global Fitting

$$\chi^2 = \sum_{i=0}^{3} \left(\frac{p_{h,i} - p_{h,i}^c}{\sigma_{rc}} \right)^2 + \left(\frac{\sqrt{p_{\tau 1}^2} - m_\tau}{\sigma_\tau} \right)^2 + \left(\frac{\sqrt{p_{\tau 2}^2} - m_\tau}{\sigma_\tau} \right)^2 + \chi_{imp}^2$$

	Hadronic Z	**Leptonic Z**
σ_{RC}	4 GeV	0.5 GeV
σ_τ	0.2 GeV	0.1 GeV
σ_ρ	0.3 GeV	0.15 GeV
σ_{f_ρ}	10%	10%