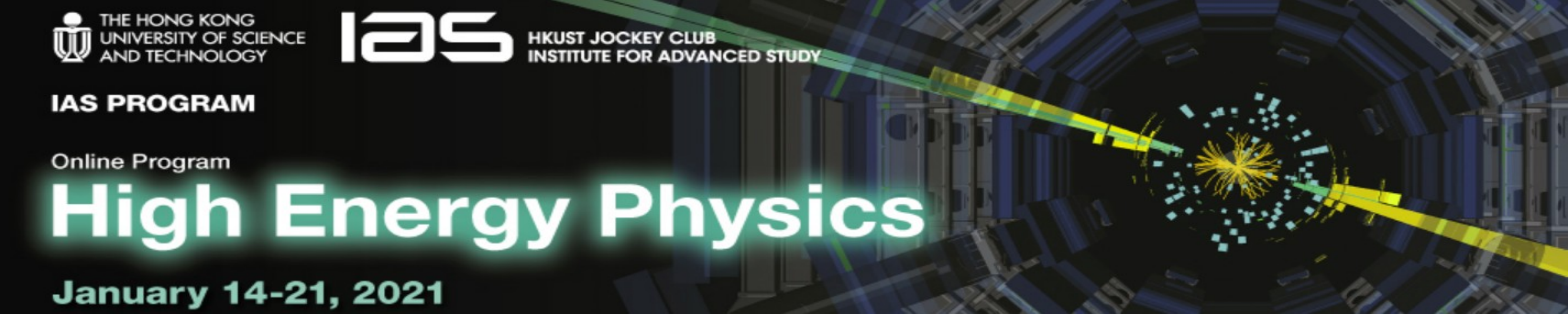

Higgs-ττ CP Violation Phase @ Future Lepton Colliders

Shao-Feng Ge

gesf@sjtu.edu.cn

IAS Program on High Energy Physics (HEP 2021)

SFG, Gang Li, Michael Ramsey-Musolf, Pedro Pasquini [arXiv:2012.13922]

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

李政道研究所
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Higgs Decay Modes

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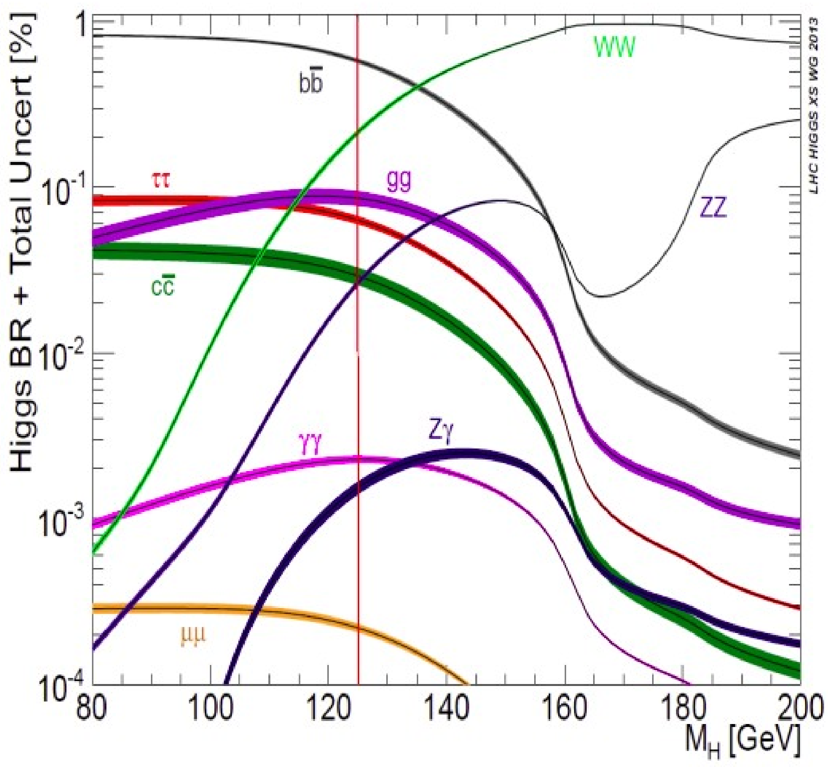
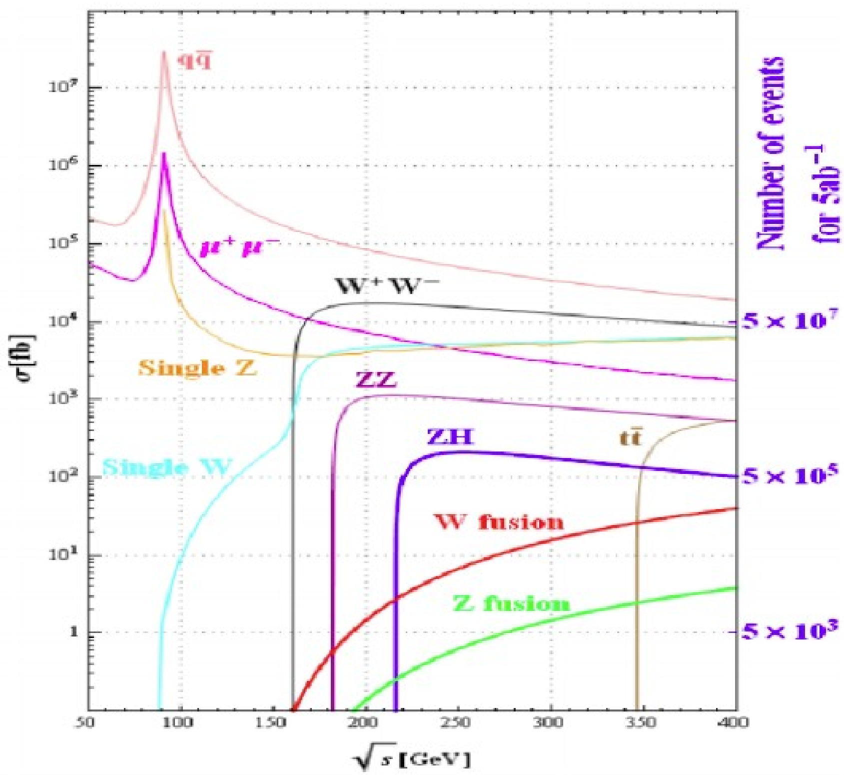
- **LHC** tells us: $h(125)$ is **SM-like** → **Dream Case for Experiments!**
- **ILC250 & CEPC** produces $h(125)$ via $e^+e^- \to \mathbf{Zh}, \nu\bar{\nu}\mathbf{h}, \mathbf{e^+e^-h}$
- **Indirect Probe** to **New Physics**. **5/ab** with 2 detectors in 10y → $\mathbf{10^6}$ Higgs → **Relative Error** $\sim \mathbf{10^{-3}}$.





Mo, Li, Ruan & Lou, Chin.Phys.C 2015

Higgs @ Future Lepton Colliders

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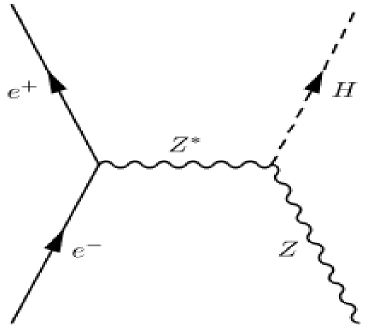

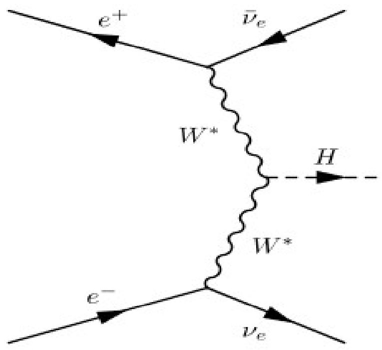

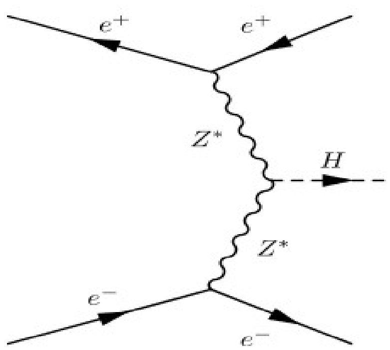

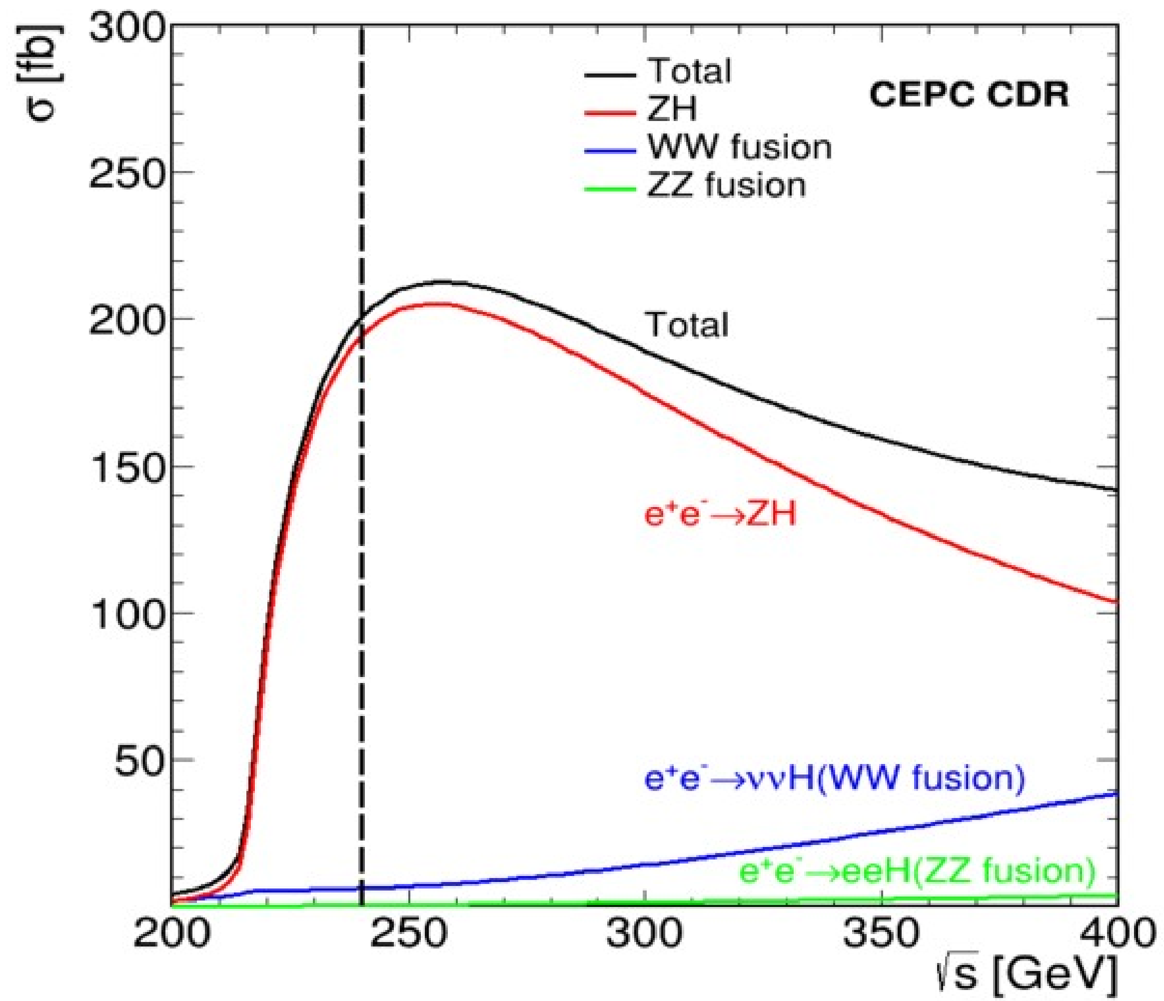

CEPC CDR vol 2 – Physics & Detector, Chapter 11

Higgs Precision Observables

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$\mathrm{Br}(b\bar{b})$	$\mathrm{Br}(c\bar{c})$	$\mathrm{Br}(gg)$	$\mathrm{Br}(\tau\bar{\tau})$	$\mathrm{Br}(WW)$	$\mathrm{Br}(ZZ)$	$\mathrm{Br}(\gamma\gamma)$	$\mathrm{Br}(\mu\bar{\mu})$	$\mathrm{Br}(\mathrm{inv})$
58.1%	2.10%	7.40%	6.64%	22.5%	2.77%	0.243%	0.023%	0

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.27%	0.56%
$H \to c\bar{c}$	3.3%	3.3%
$H \to gg$	1.3%	1.4%
$H \to WW^*$	1.0%	1.1%
$H \to ZZ^*$	5.1%	5.1%
$H \to \gamma\gamma$	6.8%	6.9%
$H \to Z\gamma$	15%	15%
$H \to \tau^+\tau^-$	0.8%	1.0%
$H \to \mu^+\mu^-$	17%	17%
$H \to \mathrm{inv}$	–	$< 0.30\%$

CEPC CDR vol 2 – Physics & Detector, Table 11.3

Why CEPC?

Qing-Hong Cao,
CLHCP18

Precision = Discovery

m_W m_Z $\sin\theta_W$	EW symmetry breaking Global symmetry of scalar potential
A_{FB}	Parity violation; weak isospin
Γ_Z	3 active neutrinos
m_t	Fermion mass origin (the only natural quark)
Γ_t	Equivalence theorem
m_H	Vacuum stability
Γ_H	fundamental or composite, or ……

We, bump hunters, are also excellent painters of Nature's details.

… excluded (ruled out) …

… consistent with the SM …

→

We discover … is not supported at 95% CL

We discover a tight constraint on NP …

More than Precision Machines

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CP-violating Higgs Di-tau Decays: Baryogenesis and Higgs Factories

arXiv:2012.13922

Shao-Feng Ge, Gang Li, Pedro Pasquini, Michael J. Ramsey-Musolf

We demonstrate how probes of CP-violating observables in Higgs di-tau decays at prospective future lepton colliders could provide a test of weak scale baryogenesis with significant discovery potential. Measurements at the Circular Electron Positron Collider, for example, could exclude a CP phase larger than 2.9° (5.6°) at 68% (95%) C.L. assuming the Standard Model value for magnitude of the tau lepton Yukawa coupling. Conversely, this sensitivity would allow for a $5\,\sigma$ discovery for 82% of the CP phase range $[0, 2\pi)$. The reaches of the Future Circular Collider - ee and International Linear Collider are comparable. As a consequence, future lepton colliders could establish the presence of CP violation required by lepton flavored electroweak baryogenesis with at least $3\,\sigma$ sensitivity. Our results illustrate that Higgs factories are not just precision machines but can also make $\mathcal{O}(1)$ measurement of the new physics beyond the Standard Model.

h-ττ Yukawa Coupling

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SM:

$$\mathcal{L} = -\frac{m_\tau}{v\sqrt{2}} h\bar{\tau}\tau$$

BSM:

$$\mathcal{L} = -\frac{m_\tau}{v\sqrt{2}} h\bar{\tau}\left(\cos\Delta + i\gamma_5 \sin\Delta\right)\tau$$

Δ is the CP phase in the h-ττ Yukawa coupling!

The CP phase can introduce O(1) effect on Yukawa coupling

New Physics behind CP Phase

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Type-III THDM

$$\mathcal{L}_Y = -\overline{L} Y_1 \ell_R \Phi_1 - \overline{L} Y_2 \ell_R \Phi_2 + \text{h.c.}$$

which contributes 3 neutral scalars (h, H, A)

$$-\frac{m_\tau}{v} \overline{\tau}_L \tau_R \left[\left(s_{\beta-\alpha} + \frac{N_{\tau\tau}}{m_\tau} c_{\beta-\alpha} \right) h + \left(c_{\beta-\alpha} - \frac{N_{\tau\tau}}{m_\tau} s_{\beta-\alpha} \right) H + i A N_{\tau\tau} \right]$$

The SM-like Higgs h has the τ Yukawa coupling as

$$\kappa_\tau (\cos\Delta + i \sin\Delta) = s_{\beta-\alpha} + \frac{N_{\tau\tau}}{m_\tau} c_{\beta-\alpha}$$

H. K. Guo, Y. Y. Li, T. Liu, M. Ramsey-Musolf and J. Shu [arXiv:1609.09849 [hep-ph]]

Baryogenesis for matter-antimatter asymmetry!

More background in Xiao-Ping Wang & Wei Su's talks

h –> ττ Decay

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	Integrated luminosity	$\sqrt{s}$	Number of Higgs bosons
CEPC [7]	5.6 ab^{-1}	240 GeV	1.1×10^6
FCC-ee [8]	5 ab^{-1}	240 GeV	1.0×10^6
ILC [9]	2 ab^{-1}	250 GeV	0.64×10^6

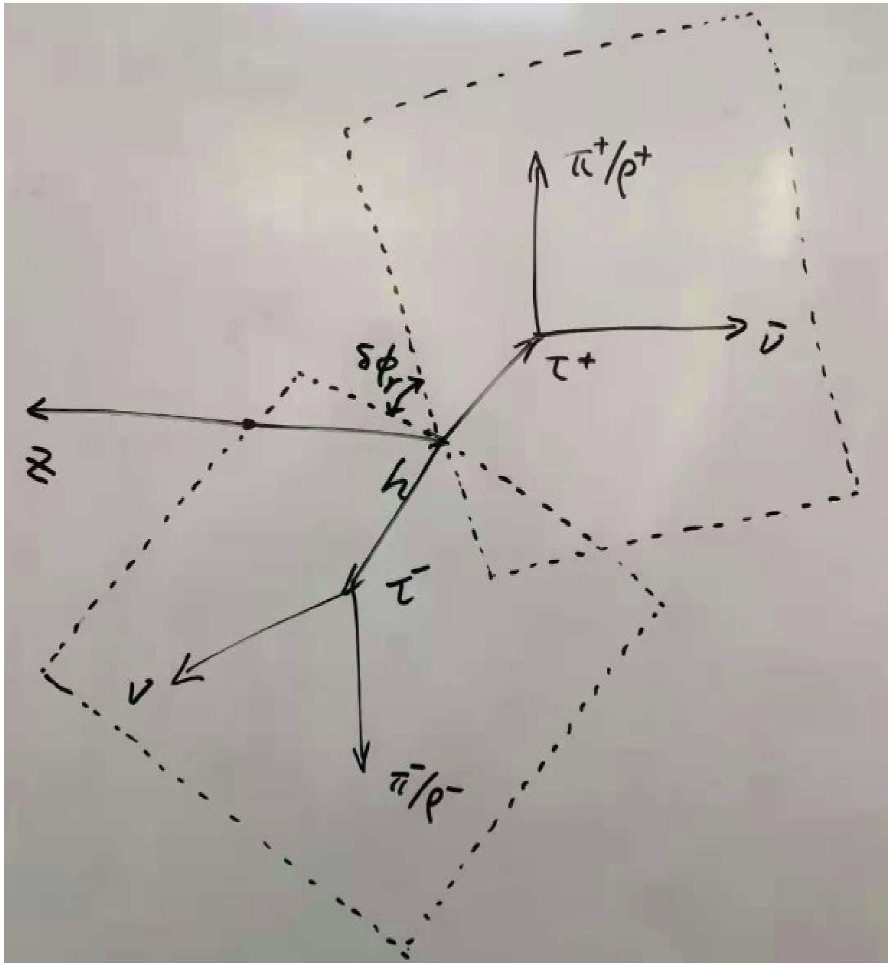
Decay modes	Branching ratio
$Z \to$ vis.	80%
$h \to \tau^+\tau^-$	6.64%
$\tau \to \pi\nu_\tau$	10.82%
$\tau \to \rho\nu_\tau$	25.49%

$$\tau^\pm \to \pi^\pm \nu$$

$$\tau^\pm \to \rho^\pm \nu \to \pi^\pm \pi^0 \nu$$

τ decay products	Number of Higgs decay events					
	CEPC		FCC-ee		ILC	
	before	after	before	after	before	after
(π, π)	684	99	622	90	398	58
(π, ρ)	3223	465	2930	423	1875	271
(ρ, ρ)	3797	541	3451	491	2209	314

Event Topology



The angular distribution can be generally parametrized as:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

1. The 1st term fixed by normalization

2. The 2nd term parameters (A, δϕ) have various choices!

Angular Differential Distributions

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$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

1. Natural Azimuthal Angle

$$\delta\phi = \delta\phi_\nu \qquad A = \frac{\pi^2}{16}\begin{cases} 1 & \tau \to \pi\nu \\ \left(\frac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2}\right)^2 & \tau \to \rho\nu \end{cases}$$

J. H. Kuhn and F. Wagner, NPB '84

A factor of 0.2 suppression

2. Polarimeter

$$\tau \to \pi\nu : \mathbf{r}_\pm \equiv -\hat{\mathbf{p}}_{\nu_{\tau^\pm}}$$

$$\tau \to \rho\nu : \mathbf{r}_\pm \equiv -\frac{1}{N_\pm}\left[\hat{\mathbf{p}}_{\nu_{\tau^\pm}} + \frac{2m_\tau}{m_\rho^2 - 4m_\pi^2}\frac{E_{\pi^\pm} - E_{\pi^0_\pm}}{E_{\pi^\pm} + E_{\pi^0_\pm}}\left(\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0_\pm}\right)\right]$$

$$\delta\phi = \delta\phi_r \qquad A = \frac{\pi^2}{16}$$

Uniformly large for both channels

B. Grzadkowski & J. F. Gunion, PLB '95

Angular Differential Distributions

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$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

1. **Natural Azimuthal Angle**

2. **Polarimeter**

3. **Acoplanarity**

$$\tan\phi^* \equiv \frac{\hat{\mathbf{p}}_{\rho^-} \cdot \left[(\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^0_+}) \times (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^0_-})\right]}{(\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^0_+}) \cdot (\mathbf{p}_{\pi^-} \times \mathbf{p}_{\pi^0_-})}$$

G. R. Bower, T. Pierzchala, Z. Was & M. Worek [hep-ph/0204292]
M. Worek [hep-ph/0305082]

4. **The θ Variable**

$$\tan\Theta \equiv \frac{\hat{\mathbf{p}}_{\tau^+} \cdot (\mathbf{E}_+ \times \mathbf{E}_-)}{\mathbf{E}_- \cdot \mathbf{E}_+ - (\mathbf{E}_+ \cdot \hat{\mathbf{p}}_{\tau^+})(\mathbf{E}_- \cdot \hat{\mathbf{p}}_{\tau^+})}$$

$$\mathbf{E}_\pm \equiv \frac{m_\rho^2 - 4m_\pi^2}{2m_\tau}\left[\frac{m_\tau^2 - m_\rho^2}{m_\tau^2 + m_\rho^2}\hat{\mathbf{p}}_{\nu_{\tau^\pm}} + \frac{2m_\tau}{m_\rho^2 - 4m_\pi^2}\frac{(E_{\pi^\pm} - E_{\pi^0})}{(E_{\pi^\pm} + E_{\pi^0})}\left(\mathbf{p}_{\pi^\pm} - \mathbf{p}_{\pi^0_\pm}\right)\right]$$

R. Harnik, A. Martin, T. Okui, R. Primulando and F. Yu, PRD 2013

Angular Differential Distributions

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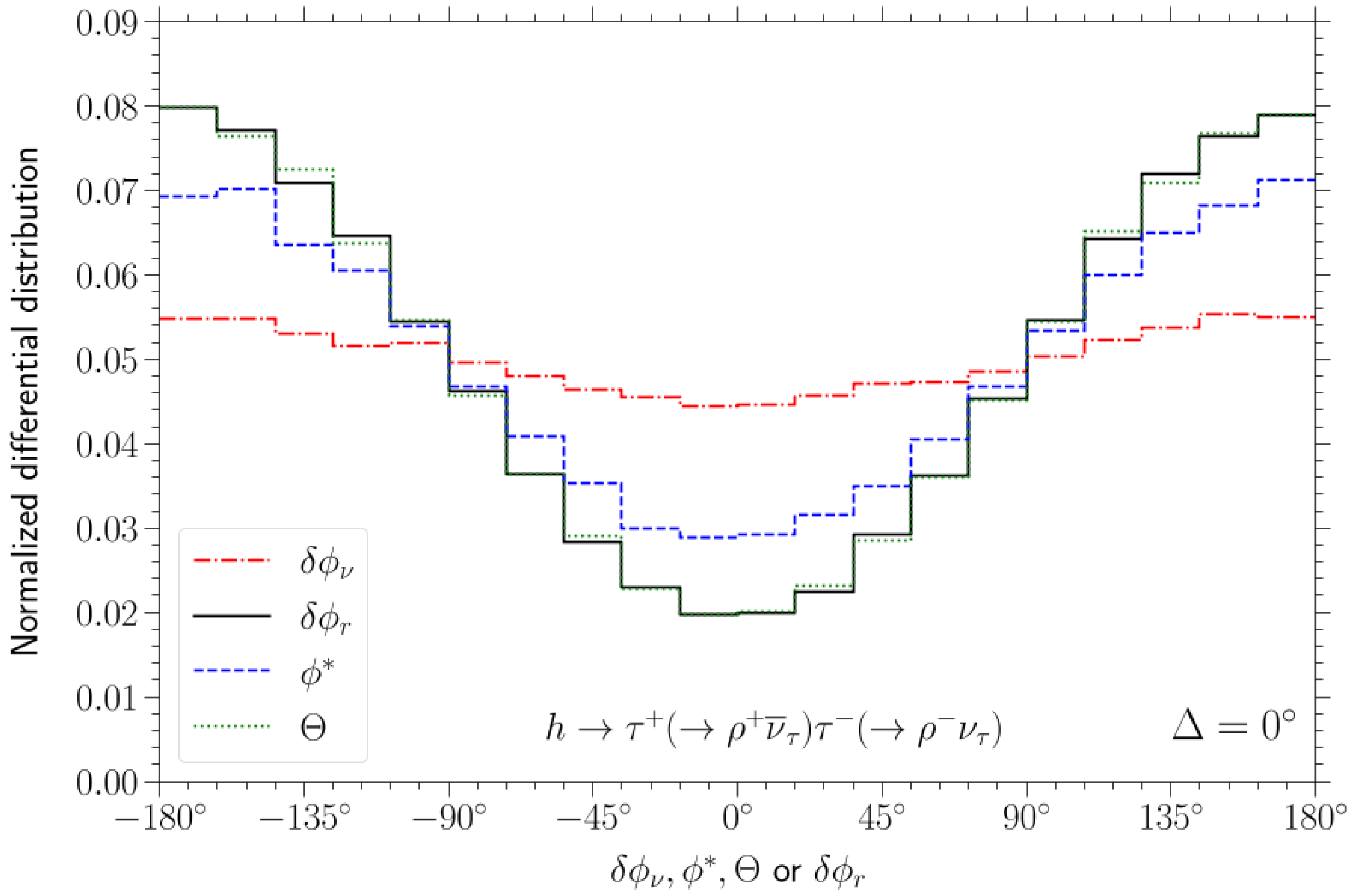

The dependence on the CP phase is O(1) effect!

Momentum Reconstruction

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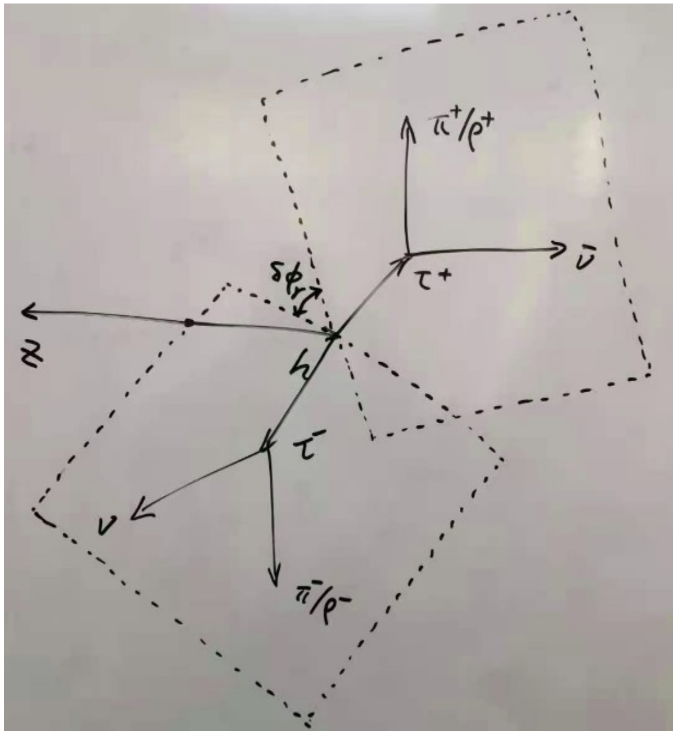

The Higgs momentum is reconstructed in terms of the Z momentum

$$p_h = (\sqrt{s}, 0, 0, 0) - p_Z$$

Higgs Smearing

Observables	Uncertainty
$P_{x,y}$	1.82 GeV
$P_z \ (Z \to jj)$	2.3 GeV
$P_z \ (Z \to l\bar{l})$	0.57 GeV

X. Chen and Y. Wu, EPJC 2017 [arXiv:1703.04855]

The measurable momenta are those of Z, π, ρ

$$80 \text{ GeV} < \sqrt{p_Z^2} < 100 \text{ GeV}$$

The π / ρ momentum reconstructed from final-state particles

$\lvert \mathbf{p}_T \rvert$	$0.036 \lvert \mathbf{p}_T \rvert$

Degeneracy in Neutrino Momentum

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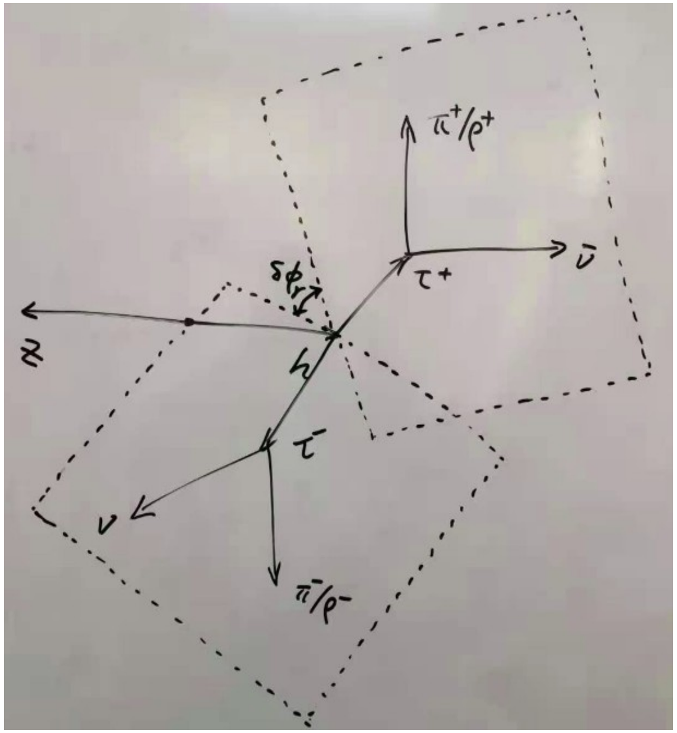

Two-fold degeneracy

Neutrino Momentum

decay planes & azimuth angle difference

1、 Neutrino (p_ν) & Anti-Neutrino Momentum ($p_{\bar{\nu}}$)

8 d.o.f

2、 Energy-momentum conservation $p_\nu = P - p_{\bar{\nu}}$

4 d.o.f

3、 Neutrino on-shell conditions $p_\nu^2 = p_{\bar{\nu}}^2 = 0$

2 d.o.f

4、 τ on-shell conditions $p_{\tau^\pm}^2 = m_{\pi^\pm}^2$

0 d.o.f

Impact Parameter

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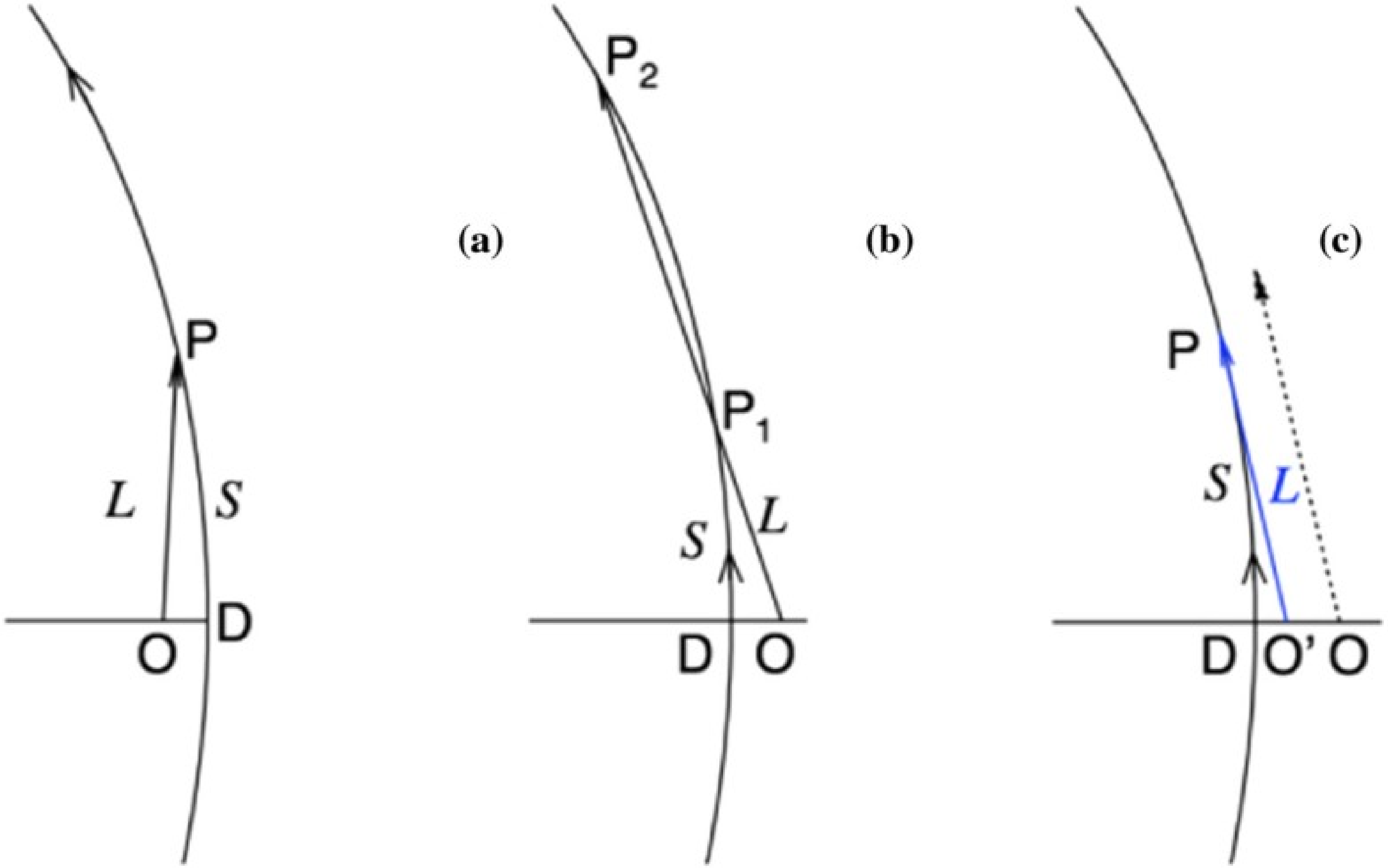

D. Jeans and G. W. Wilson, PRD 2018 [arXiv:1804.01241]
X. Chen and Y. Wu, EPJC 2017 [arXiv:1703.04855]

Essentially remove the degeneracy!

CP Discovery Potential

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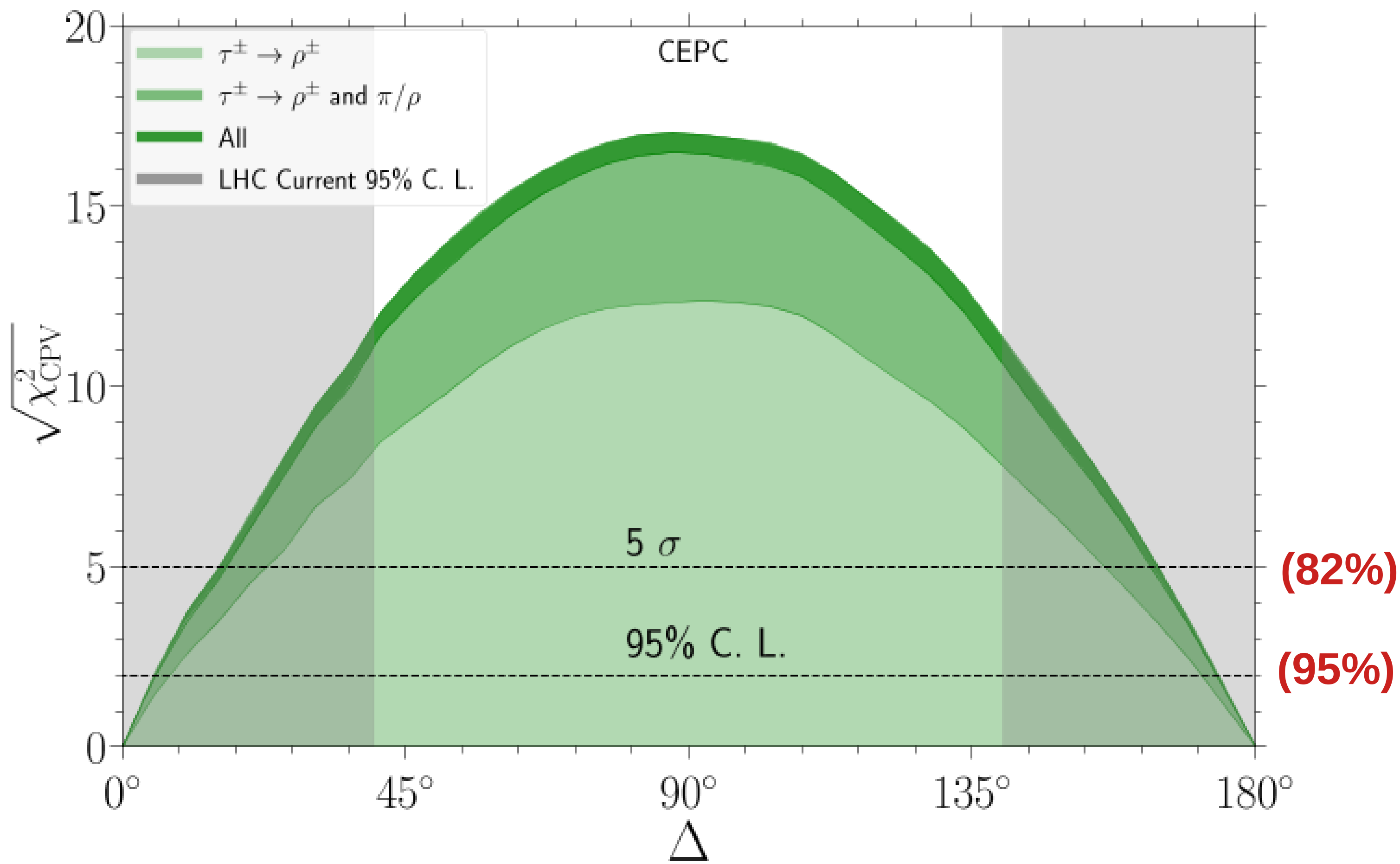
$$\chi^2_{\mathrm{CPV}}(\Delta^{\mathrm{true}}) \equiv \min[\chi^2(\Delta^{\mathrm{true}}, \Delta^{\mathrm{test}} = 0^\circ), \chi^2(\Delta^{\mathrm{true}}, \Delta^{\mathrm{test}} = 180^\circ)]$$



CEPC, FCC-ee, ILC

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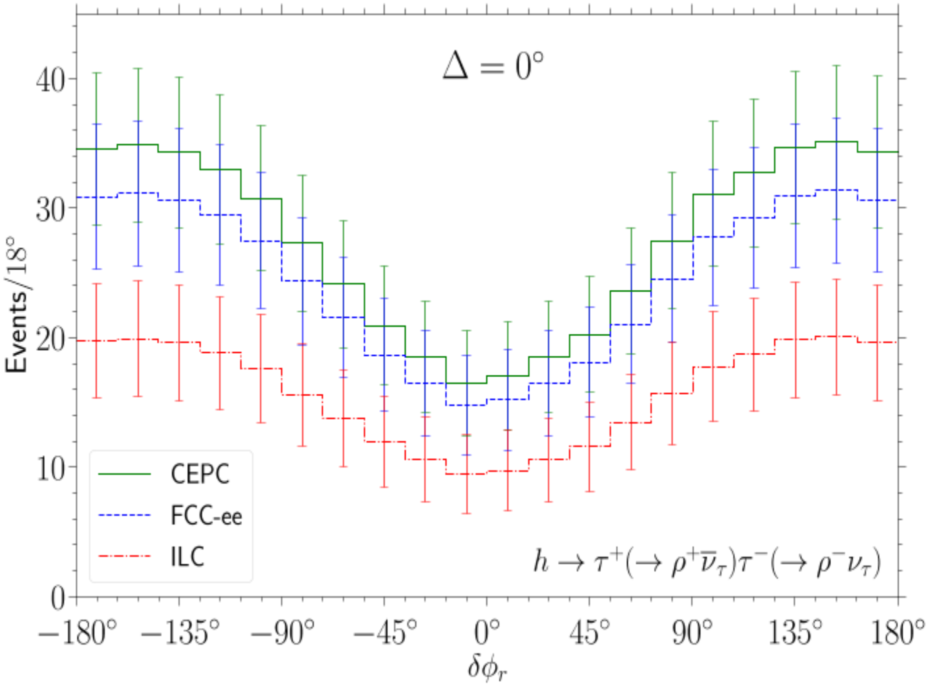
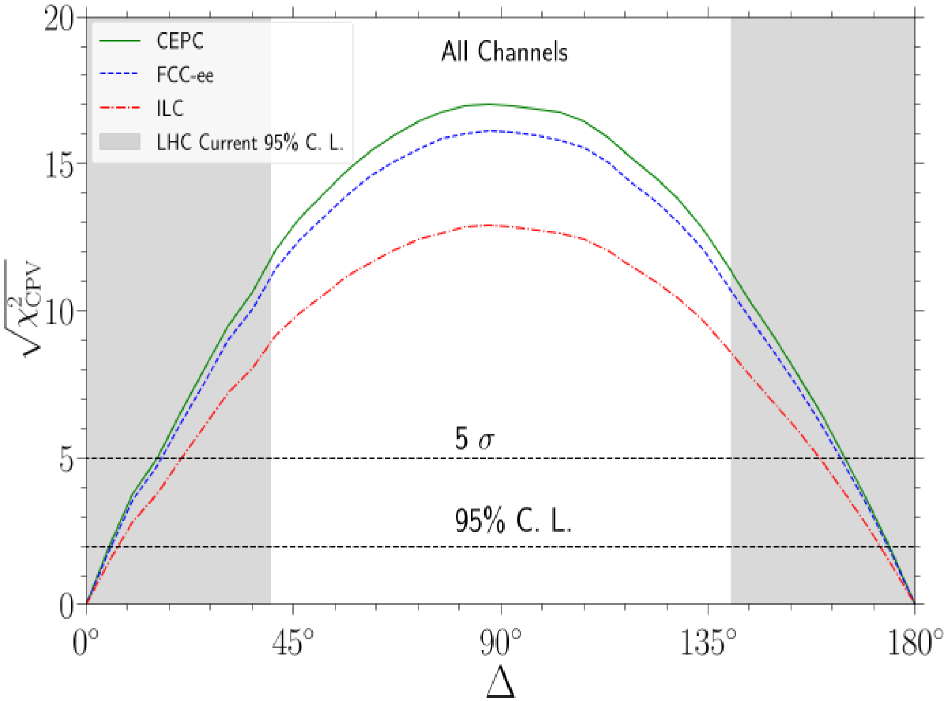
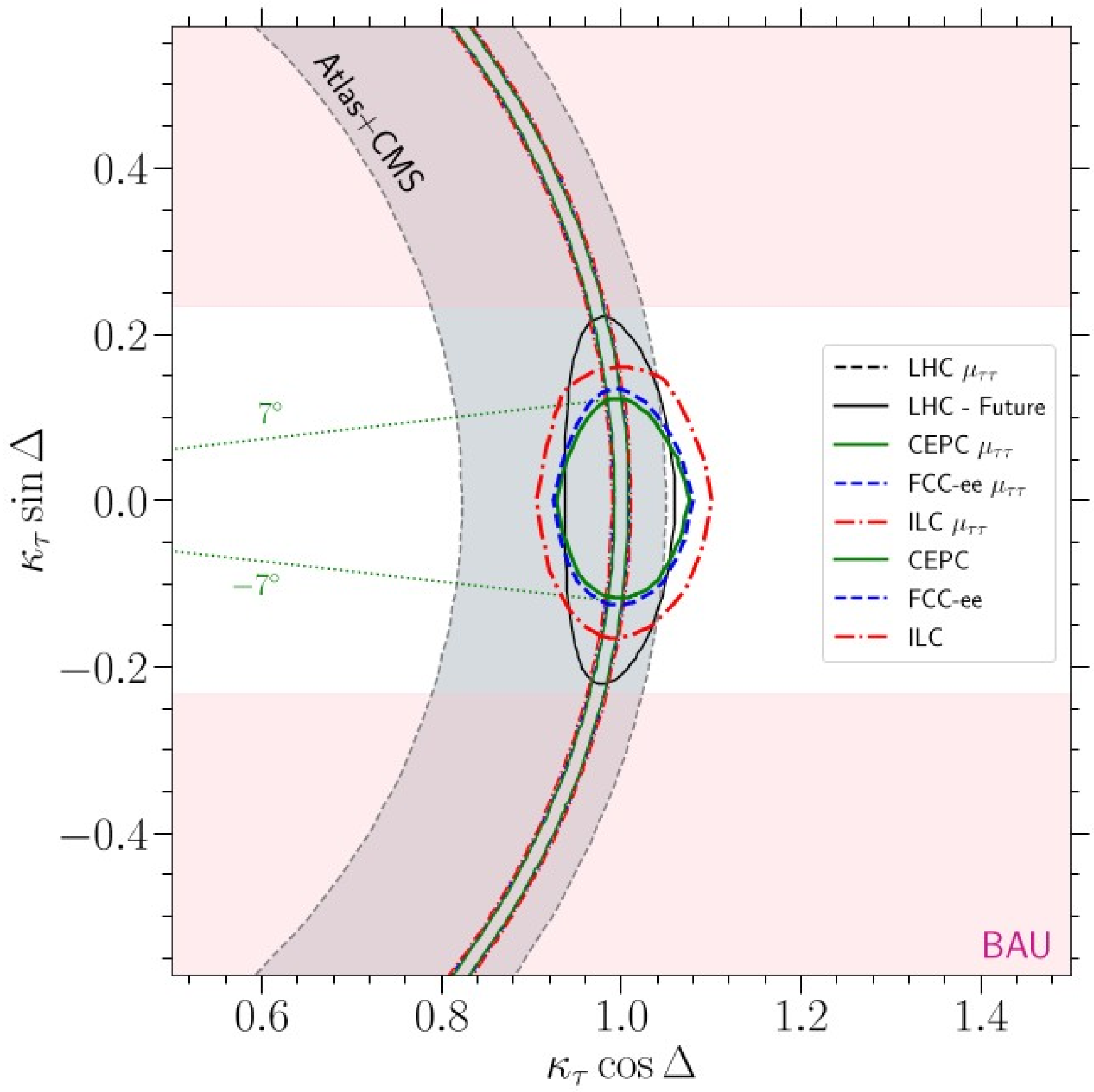




	68% C.L. for $m = 1$	95% C.L. for $m = 1$	95% C.L. for $m = 2$	Number of Higgs bosons
CEPC	2.9°	5.6°	7.0°	1.1×10^6
FCC-ee	3.2°	6.3°	7.8°	1.0×10^6
ILC	3.8°	7.4°	9.3°	0.64×10^6

CP Sensitivity



3σ Discovery of Baryogenesis Region

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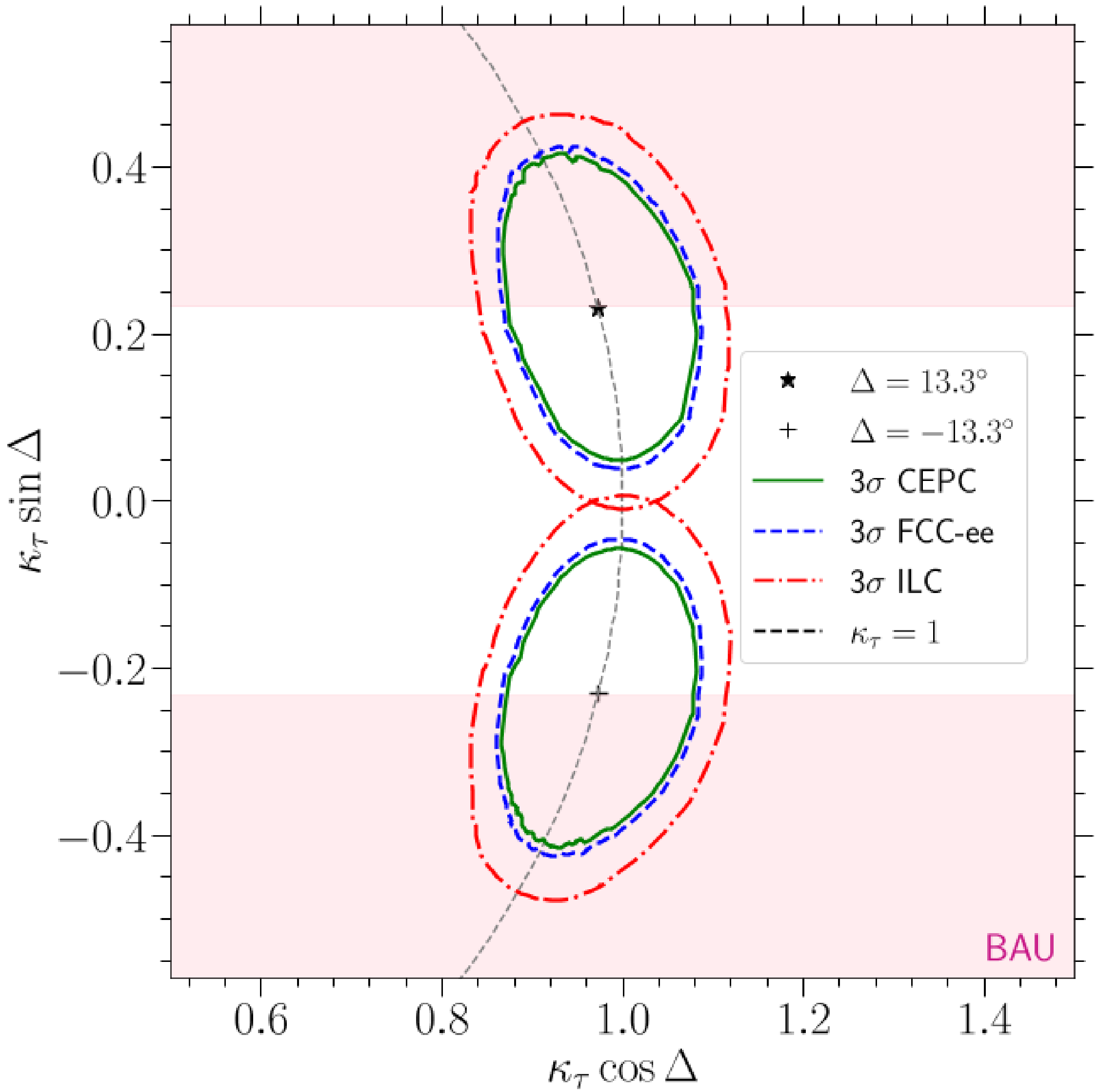

If the baryogenesis scenario with Type-III THDM is correct, it can be verified @ **future lepton colliders** with **~3σ sensitivities**!

Baryogenesis @ CEPC

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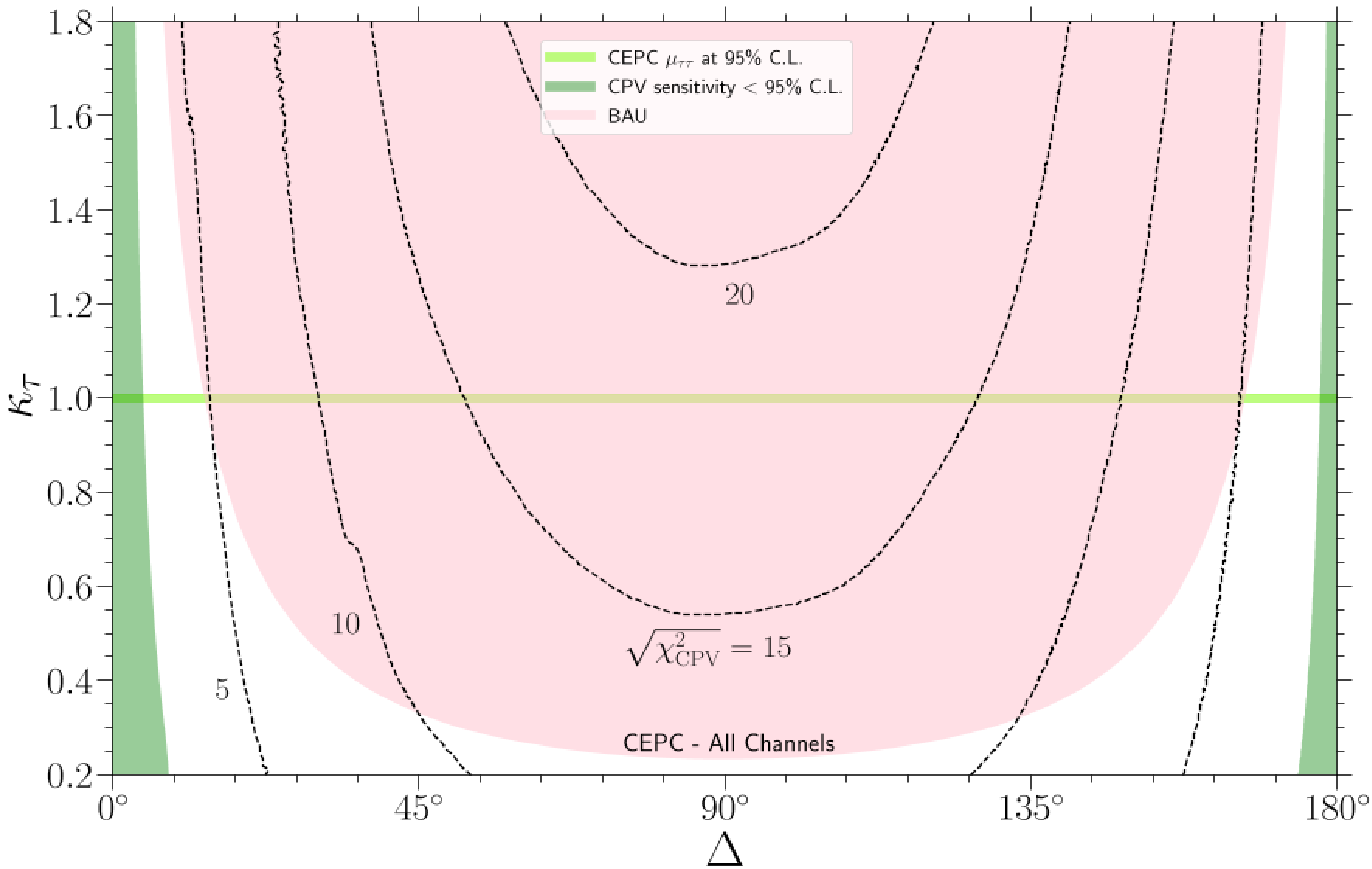

Even with free strength, most of the baryogenesis region can be verified $\gtrsim 5\sigma$

Summary

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1、 Future lepton colliders: **golden machines** for measuring Higgs properties

2、 **Not just precision machines**, but can make **O(1) measurement of NP**

3、 CP discovery potential

(a) **95%** of parameter space above **95% C.L.**

(b) **82%** of parameter space above **5σ C.L.**

4、 **1σ sensitivity** can reach (**2.9º**, **3.2º**, **3.8º**) @ (**CEPC**, **FCC-ee**, **ILC**)

5、 **3σ capability** of distinguishing EWBG from CP conserving case

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Thank You

Backup

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