Identifying CP-odd component in Higgs boson

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In collabration with Q.-H. Cao, K. Cheng, Y. Liu, X.-K. Wen and H. Zhang, in preparation.

Why focus on CP-odd components?

1.CP symmetry (C-charge conjugation & P-parity) is important and widely discussed in HEP:

Matter-antimatter imbalance: Sakharov conditions

1. B violation
2. C & CP violation
3. Out of thermal equilibrium

→ CP phase in CKM: not enough

→ Additional CPV source is needed: CP-odd component is important

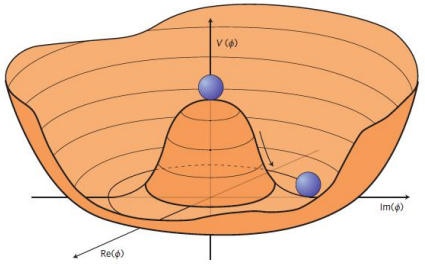
2.Higgs boson in the Standard Model (SM) is CP-even:

In the SM:

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

After EWSB: $\phi^0 = \frac{1}{\sqrt{2}}(v + h + ia)$ Goldstone

CP-even



3.Many new physics (NP) models predict CP-odd scalar by extending the scalar sector:

MSSM, 2HDM, Peccei–Quinn axion model, Georgi Machacek model ……

A sophisticated mechanism of EWSB exists if a CP-odd scalar or component is discovered.

Searching for a CP-odd scalar

To find CP-odd scalars (components)

Energy Frontier

Heavy CP-odd resonance

Null result

m > 377 GeV
MSSM
(PDG, 2022)

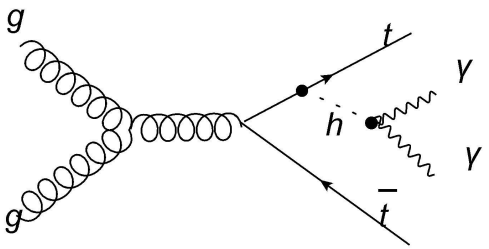
Precision Frontier

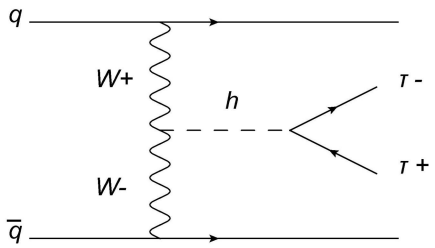
CP property of the 125 GeV Higgs boson

A purely CP-odd scalar excluded
(ATLAS, 2004.04545, 2002.05315)

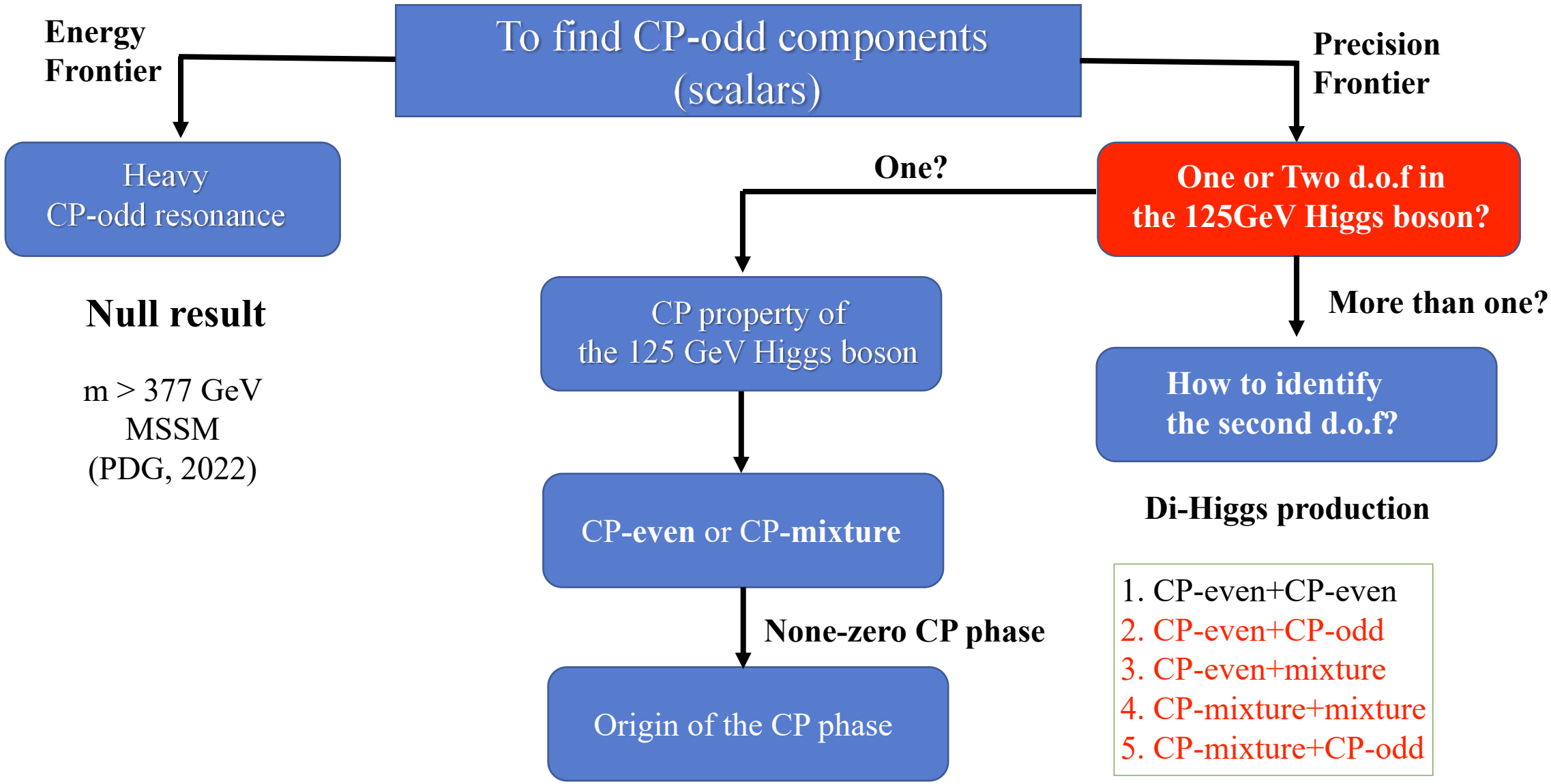
CP-**even** or CP-**mixture**

$$h_{\text{eff}} = h\cos\delta + A\sin\delta$$

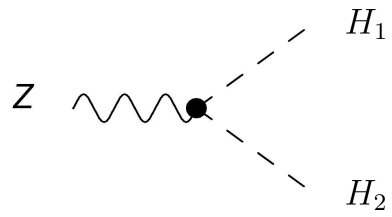




Searching for a CP-odd scalar



ZHH as a probe for CP-odd component



$$\mathcal{L} \supset i g_{ZH_1H_2} \left(H_1 \partial^\mu H_2 - H_2 \partial^\mu H_1\right) Z_\mu$$

$$m_{H_1} = m_{H_2} = 125\text{GeV}$$

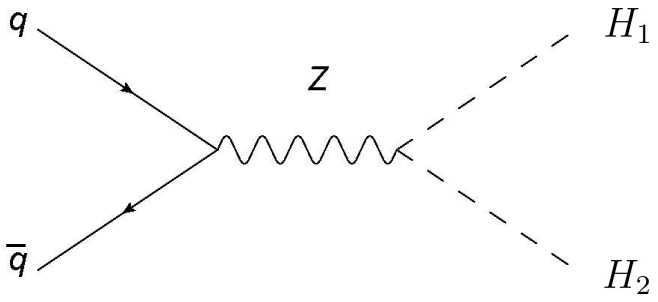
$$\begin{cases} \neq 0 & \mathrm{H_1} \neq \mathrm{H_2}, \mathrm{CP_{H_1}} \neq \mathrm{CP_{H_2}} \\ = 0 & \mathrm{H_1} = \mathrm{H_2} \text{ or } \mathrm{CP_{H_1}} = \mathrm{CP_{H_2}} \end{cases}$$

Di-Higgs production can be used to identify CP-odd component in Higgs boson

Upper limit from LHC
$\sim 6\sigma_{SM}$ (CMS, 2207.00043)

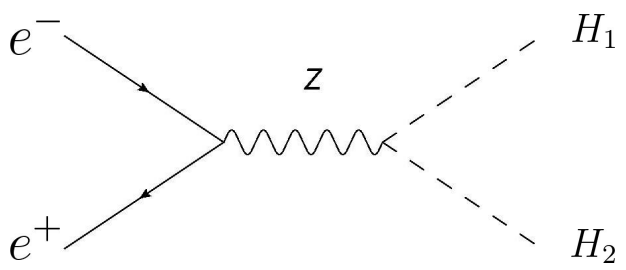
$$\sigma_{H_1H_2} < 5 \times \sigma_{SM}(gg \to HH) = 183 \text{ fb}$$
$$g_{ZH_1H_2} < 0.43$$

Hadron collider



$$\sqrt{s} = 13\text{TeV}$$
$$\sigma_{H_1H_2} = 956 g^2_{ZH_1H_2} \text{fb}$$

e^+e^- collider

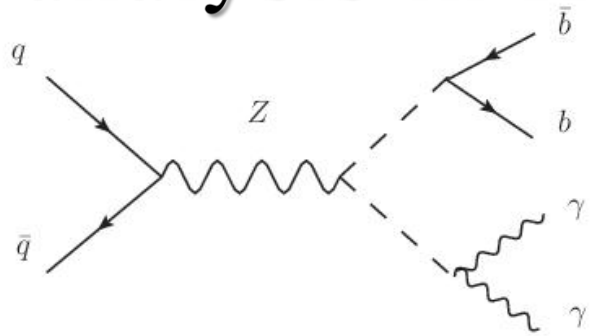


$$\sqrt{s} = 350\text{GeV}$$
$$\sigma_{H_1H_2} = 282.82 g^2_{ZH_1H_2} \text{fb}$$

General analysis in HL-LHC

HL-LHC

$b\bar{b}\gamma\gamma$ final state
14TeV
3000 fb^{-1}



Process	# of Events (L= 3000 fb^{-1})
$q\bar{q} \to Z^* \to hA$	$167 g^2_{ZH_1H_2} \frac{Br^b_{H_1} Br^\gamma_{H_2} + Br^b_{H_2} Br^\gamma_{H_1}}{2 Br^b_{SM} Br^\gamma_{SM}}$
$gg \to hh$	8.4
QCD background	47

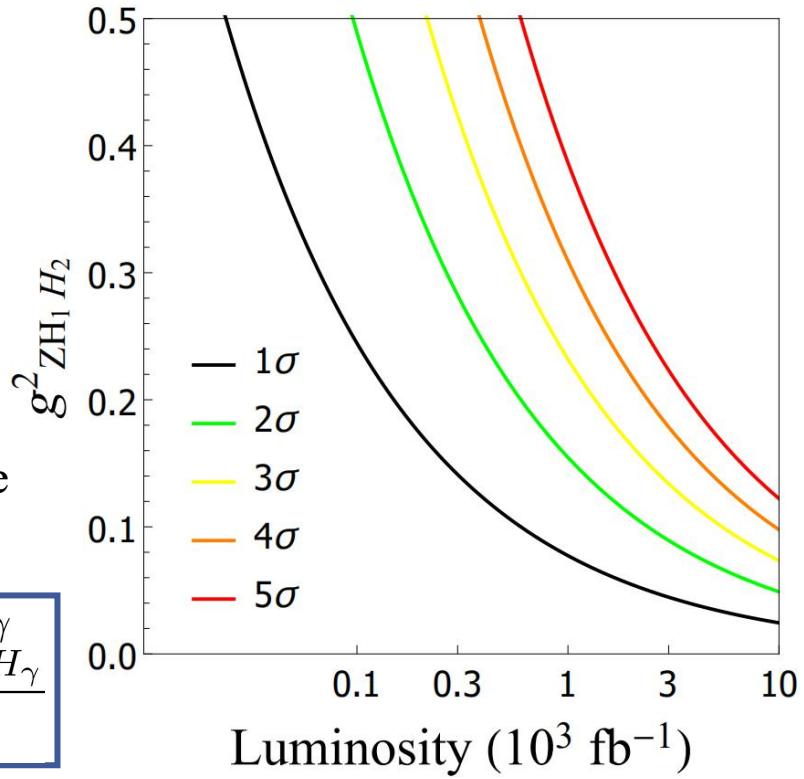
Event Selection Criteria
≥ 2 isolated photons, with p_T > 30 GeV, $\|\eta\|$ < 1.37 or 1.52 < $\|\eta\|$ < 2.37
≥ 2 jets identified as *b*-jets with leading/subleading p_T > 40/25 GeV, $\|\eta\|$ < 2.5
No isolated leptons with p_T > 25 GeV, $\|\eta\|$ < 2.5
< 6 jets with p_T > 25 GeV, $\|\eta\|$ < 2.5
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}}$ > 110 GeV

(ATLAS, ATL-PHYS-PUB-2014-019)

After imposing the selection cut used in TDR, we show the significance

Significance

$$Z \simeq 2.24 \times \left(\frac{L \cdot \text{fb}}{3000}\right)^{1/2} \left(\frac{g^2_{ZH_1H_2}}{0.1}\right) \frac{Br^b_{H_1} Br^\gamma_{H_2} + Br^b_{H_2} Br^\gamma_{H_\gamma}}{2 Br^b_{SM} Br^\gamma_{SM}}$$



Mass Degenerate hA in 2HDM

We focus on the CP-concerving scalar potential, with a soft broken Z_2 symmtry to prevent FCNC.

$$V\left(\Phi_1,\Phi_2\right)=m_{11}^2\Phi_1^\dagger\Phi_1+m_{22}^2\Phi_2^\dagger\Phi_2-m_{12}^2\left(\Phi_1^\dagger\Phi_2+\Phi_2^\dagger\Phi_1\right)+\frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2+\frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2+\lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1+\frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2+\left(\Phi_2^\dagger\Phi_1\right)^2\right].$$

Three neutral mass eigenstate are

$$h=-h_1\sin\alpha+h_2\cos\alpha\quad H=h_1\cos\alpha+h_2\sin\alpha\quad A=-a_1\sin\beta+a_2\cos\beta$$

$m_A=m_h=125\text{GeV}$ and $m_{H,H^\pm}>>m_{h,A}$

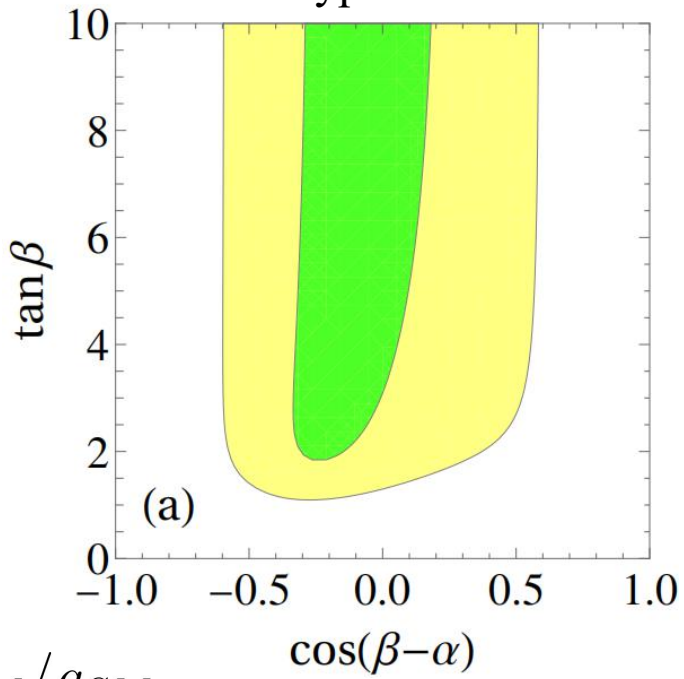
(h, H degnerate has been discussed by Ning Chen, 1712.01299)

ZhA couplings:

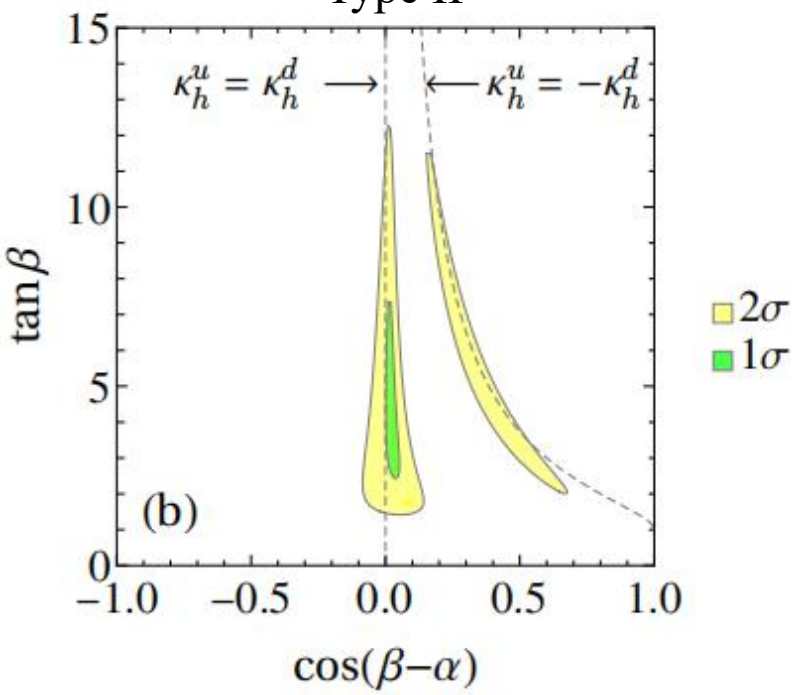
$$\mathcal{L}\supset i\left(h\partial_\mu A-A\partial_\mu h\right)Z^\mu\frac{g}{2\cos\theta_w}\cos(\beta-\alpha)$$ ($\cos(\beta-\alpha)\simeq 0$ is the alignment limit)

Current LHC Single Higgs Measurement

Type I



Type II



$\kappa = g_{BSM}/g_{SM}$

Type-I: $\kappa_h^f = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = -\frac{1}{\tan\beta}$

Type-II: $\kappa_h^u = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

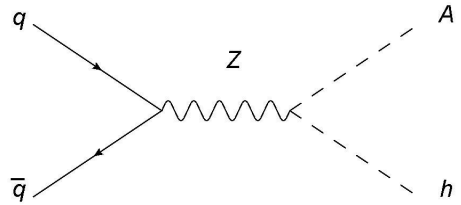
$\kappa_h^{d,\ell} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta$

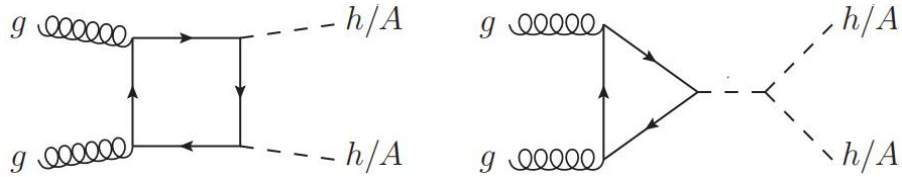
$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = \tan\beta$

Di-Higgs in HL-LHC

14 TeV HL-LHC: 3000 fb^{-1}

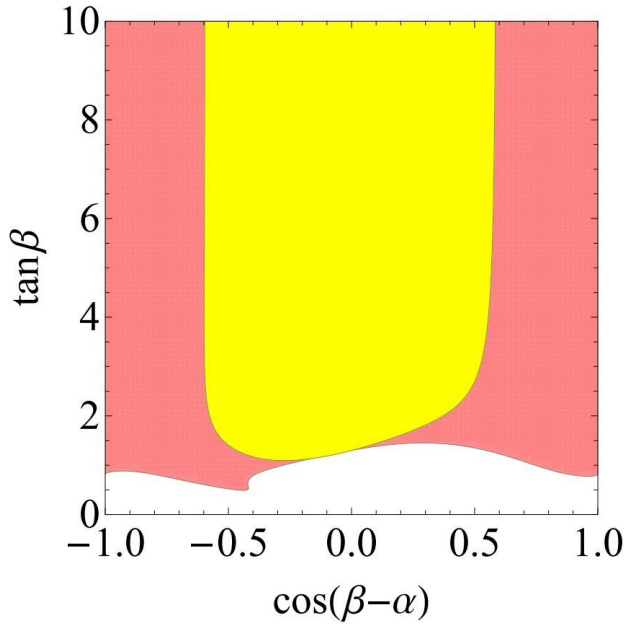
$b\bar{b}\gamma\gamma$ final state
$\kappa_{hhh} = 1$
$\kappa_{hAA} = 1.5$

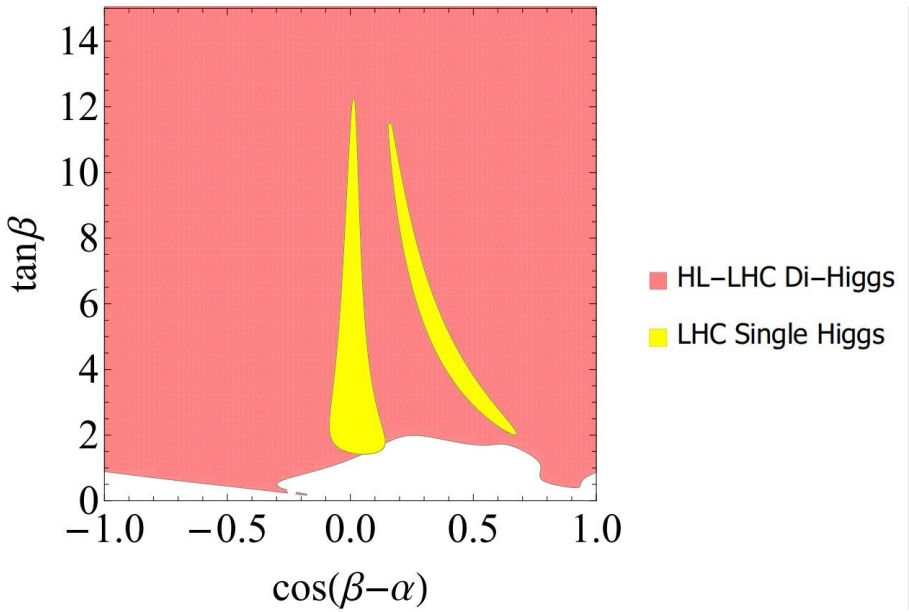




Type I

Type II





Type-I: $\kappa_h^f = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = -\frac{1}{\tan\beta}$

Type-II: $\kappa_h^u = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

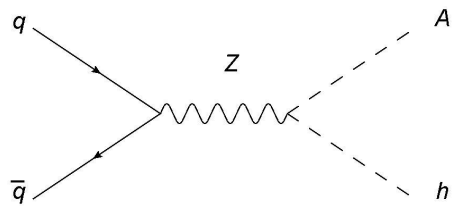
$\kappa_h^{d,\ell} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta$

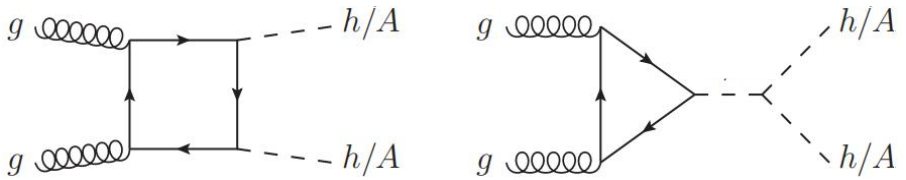
$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = \tan\beta$

Di-Higgs in Fcc-hh

100 TeV Fcc-hh: 30 ab^{-1}

$b\bar{b}\gamma\gamma$ final state
$\kappa_{hhh} = 1$
$\kappa_{hAA} = 1.5$





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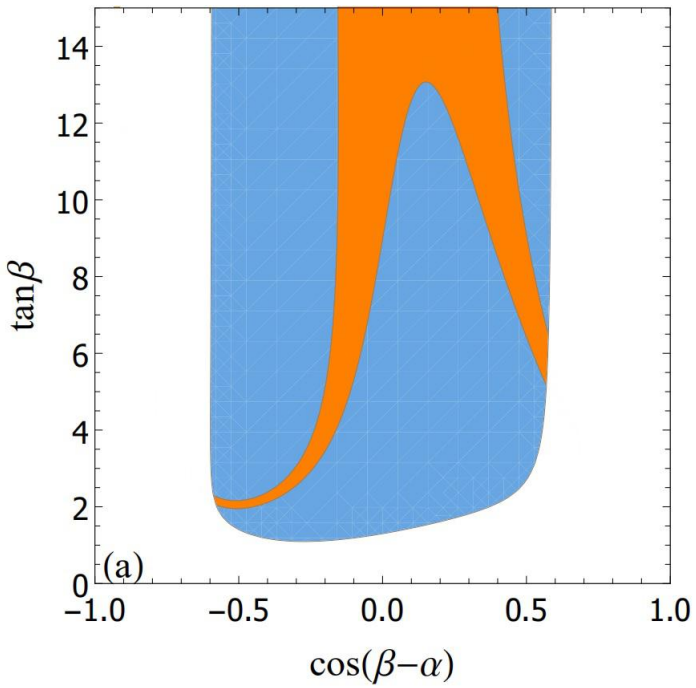
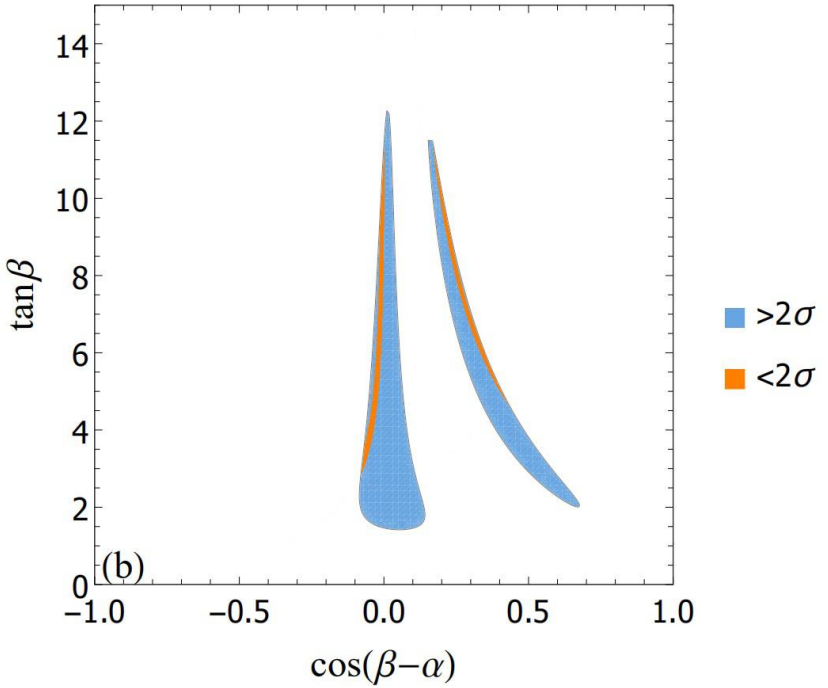


Type II



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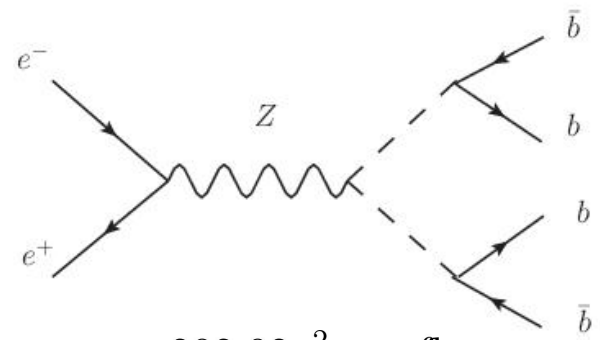
Type-II: $\kappa_h^u = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$
$\kappa_h^{d,\ell} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta$
$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = \tan\beta$

General analysis in CEPC/ILC/FCC-ee

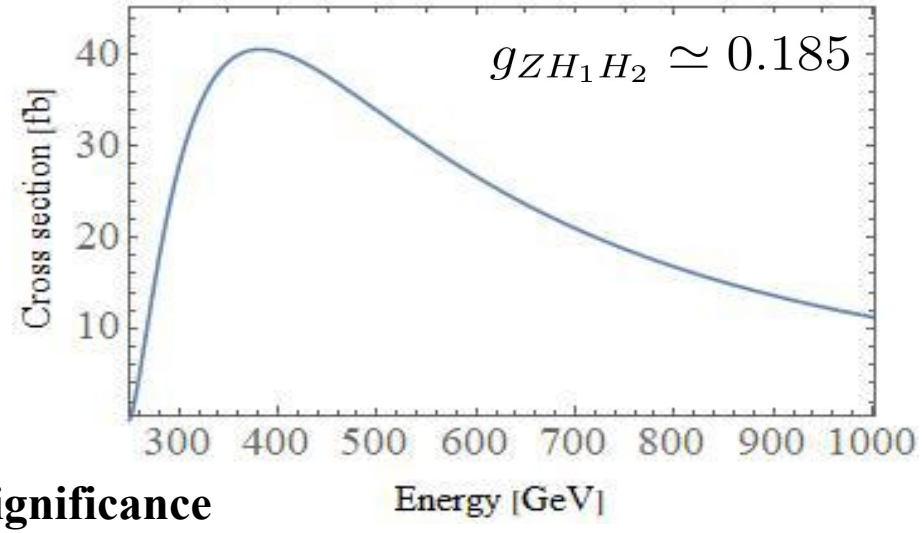


$b\bar{b}b\bar{b}$ final state
350 GeV
1000 fb^{-1}

$n^b = 4, \quad p_T^b > 25\text{GeV},$
$|\eta^b| < 2.4, \quad \Delta R^{bb} > 0.5,$
$110\text{GeV} < m_{bb} < 140\text{GeV}$

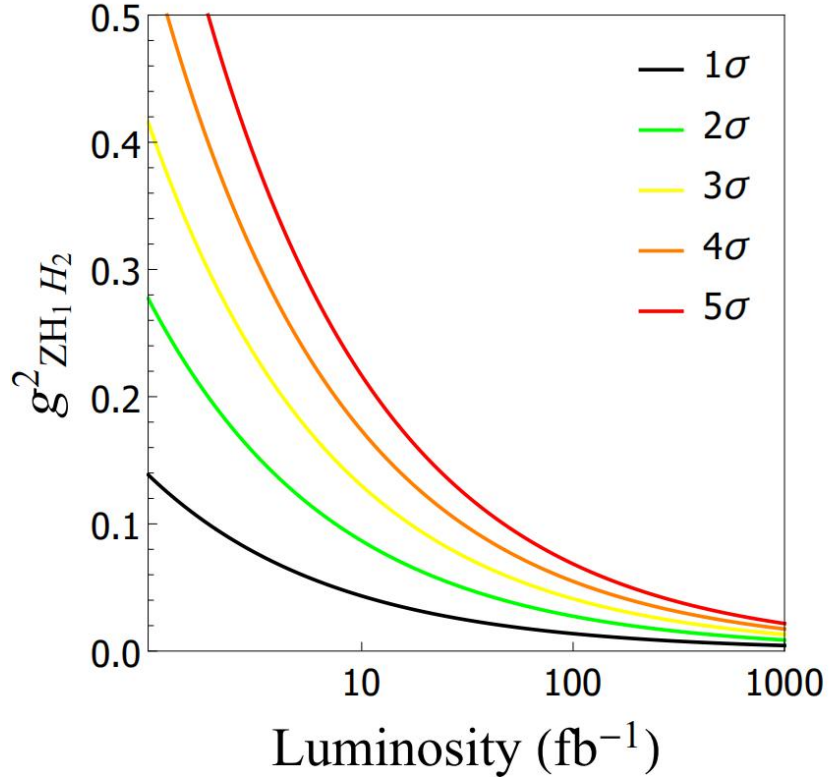
Process	Cross section [fb]	After selection [fb]
$e^+e^- \to hA \to b\bar{b}b\bar{b}$	$282.82 g^2_{ZH_1H_2}\text{Br}_\text{h}\text{Br}_\text{A}$	$14.02 g^2_{ZH_1H_2}\text{Br}_\text{h}\text{Br}_\text{A}$
$e^+e^- \to b\bar{b}b\bar{b}$	7.014	0.1368
$e^+e^- \to zh \to b\bar{b}b\bar{b}$	9.731	0.2742

$\sigma_{ZH_1H_2} = 282.82 g^2_{ZH_1H_2}\text{fb}$
$\sigma_{SM} \sim 1.2 \times 10^{-2}$ fb



Significance

$$Z \simeq 7.3 \times \left(\frac{\mathcal{L} \cdot \text{fb}}{100}\right)^{1/2} \left(\frac{g^2_{ZH_1H_2}}{0.1}\right) \frac{\text{Br}_\text{h}\text{Br}_\text{A}}{\text{Br}_\text{SM}}$$

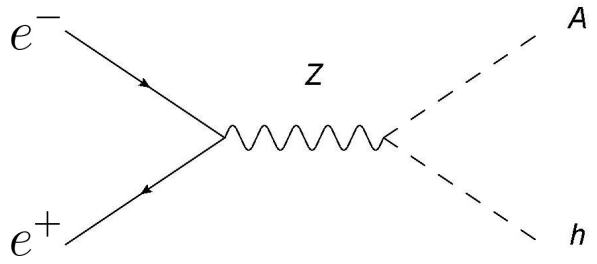


Di-Higgs in CEPC/ILC/FCC-ee

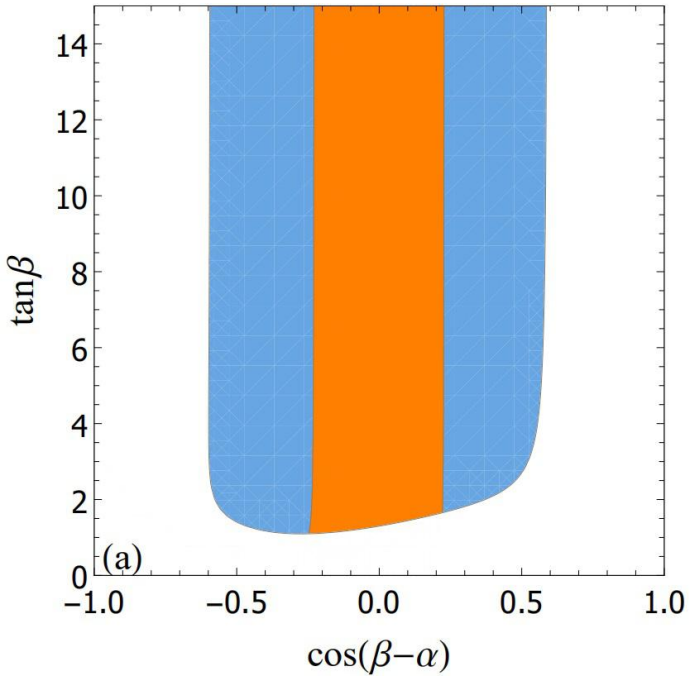
350 GeV e^+e^- collider: $1\ \mathrm{ab}^{-1}$

$b\bar{b}b\bar{b}$ final state

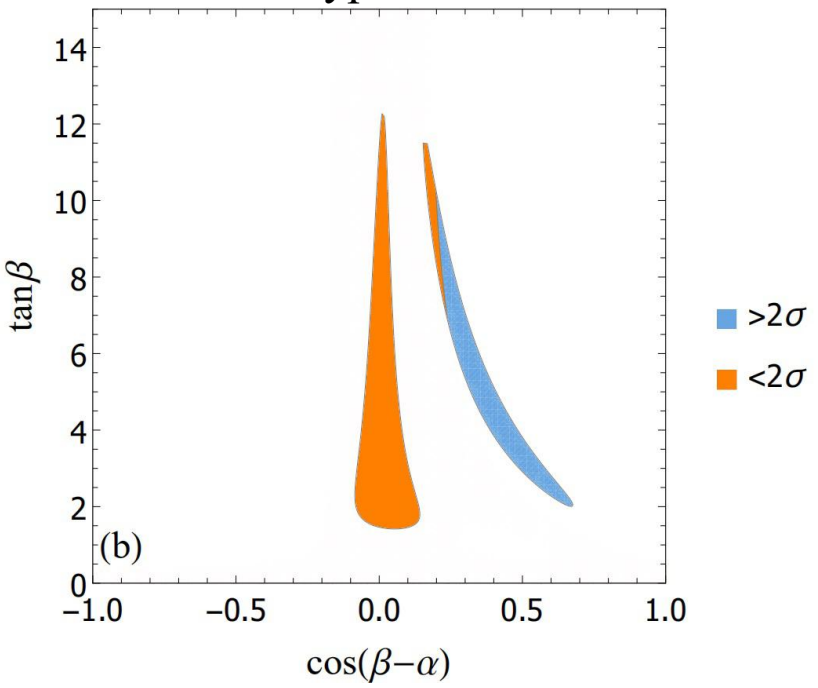
$$\mathcal{L}_{ZhA} \sim i\,(h\partial_\mu A - A\partial_\mu h)\,Z^\mu \frac{g}{2\cos\theta_w}\cos(\beta-\alpha)$$



Type I



Type II



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$\kappa_A^u = \frac{1}{\tan\beta} \quad \kappa_A^{d,\ell} = \tan\beta$

Conclusion

1.CP-odd components in scalar sector is important in the discussion of the CP symmetry and CP violation. As no new resonance has been found, high precision measurement of 125GeV Higgs boson in the future collider may help to search CP-odd components.

2.The number of d.o.f in 125GeV Higgs boson is a problem ignored for a long time. We suggest to use Di-Higgs production to measure the **ZHH** vertex, which is a model independent way to identify the CP-odd component around 125GeV.

3.Future electron-positron colliders are more powerful for exploring the **ZHH** Di-Higgs production.

Thanks for listening!