# Exposing new scalars hiding behind the Higgs boson

Qing-Hong Cao

School of Physics, Peking University

In collaboration with :

Kun Cheng, Yandong Liu, Xin-Kai Wen, and Changlong Xu, Hao Zhang, 2212.05390,
Phys. Rev. D **107** (2023) 055040.

# CP-odd scalar component: new physics beyond the SM

**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 a must.

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

In the SM:

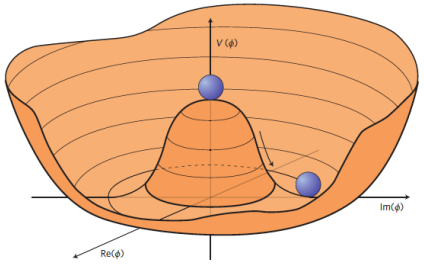
$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

After EWSB:

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

Goldstone

CP-even



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

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

**A sophisticated mechanism of electroweak symmetry breaking exists if a CP-odd scalar or CP-odd component is discovered.**

# Searching for a CP-odd scalar

To find CP-odd scalars (components)

**Energy Frontier** → Heavy CP-odd resonance

**Null result**

$M_A > 377$ GeV
MSSM
(PDG, 2022)

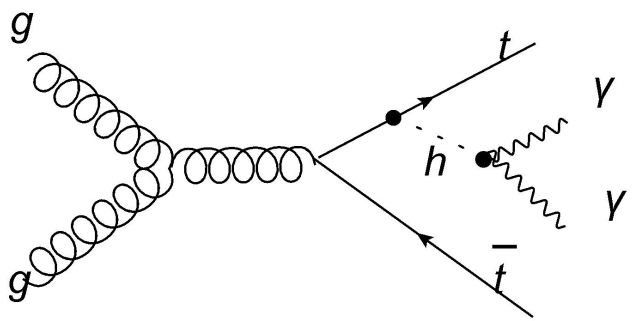
**Heavy or feeble interaction**

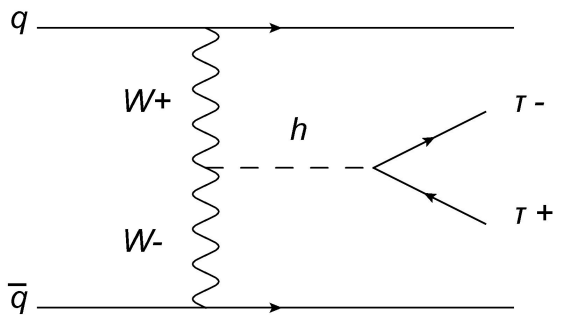
**Precision Frontier** → CP property of the 125 GeV Higgs boson

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

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

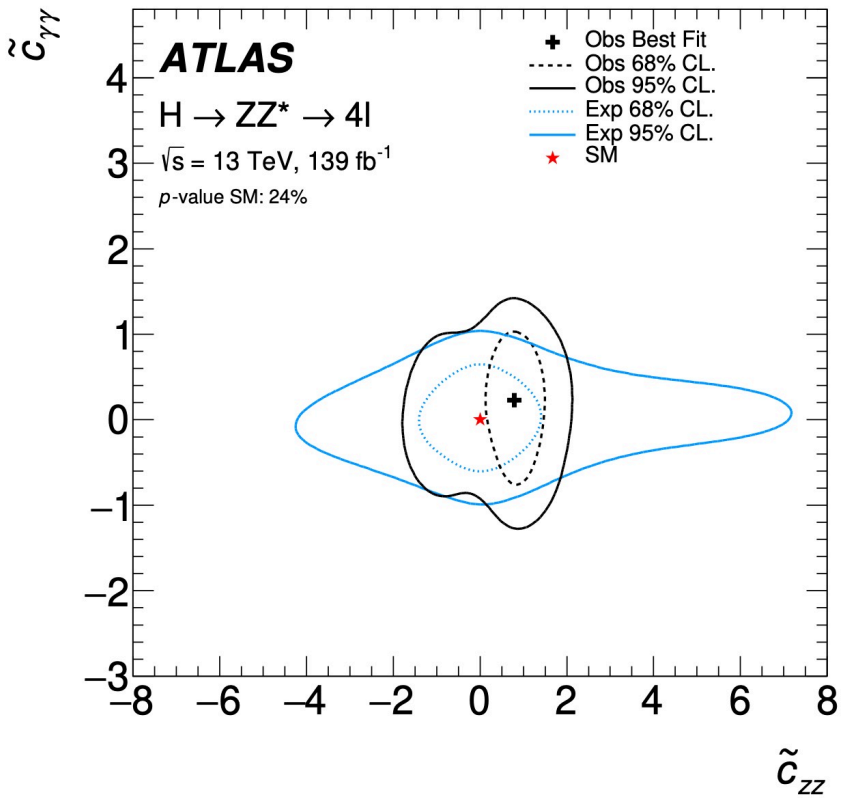
$$h_{125} = h\cos\delta + A\sin\delta$$

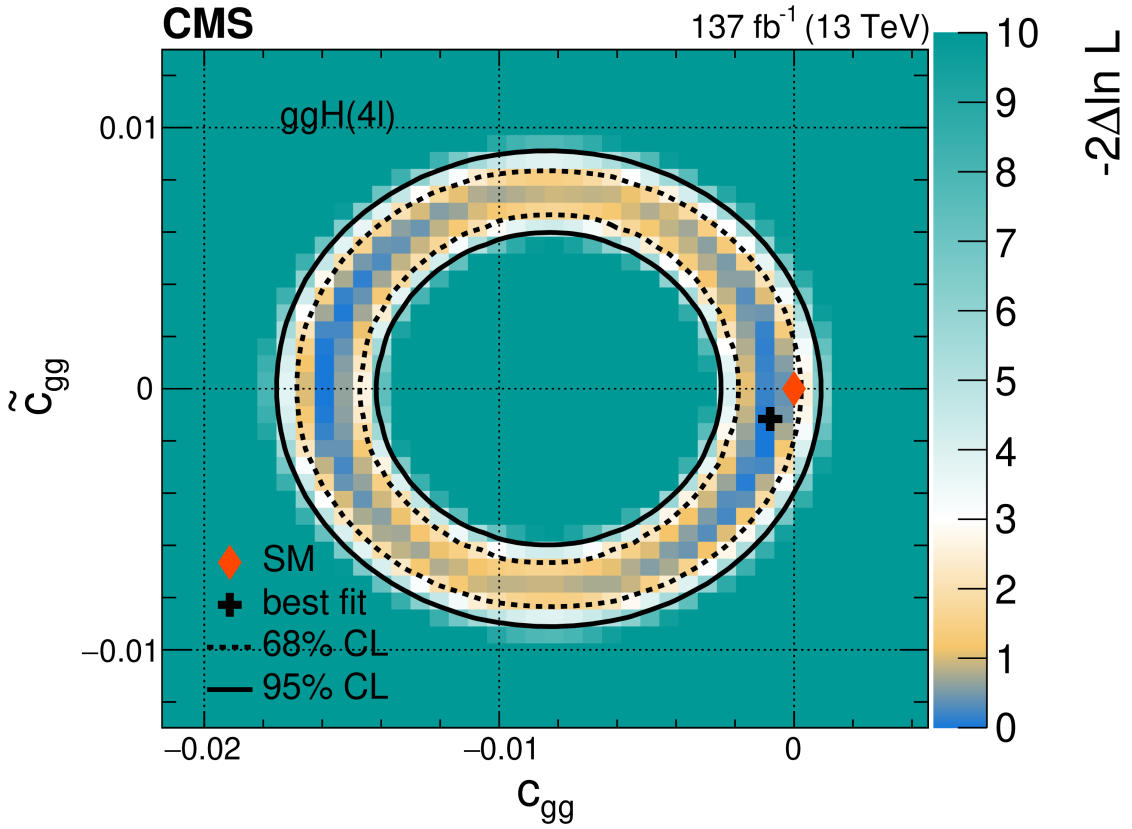


# New scalars — Where are they?

- CP property of the 125GeV Higgs boson
- HVV




ATLAS collaboration, arXiv:2304.09612[hep-ex];
CMS collaboration, Phys. Rev. D **104** (2021) 052004.

# New scalars — Where are they?

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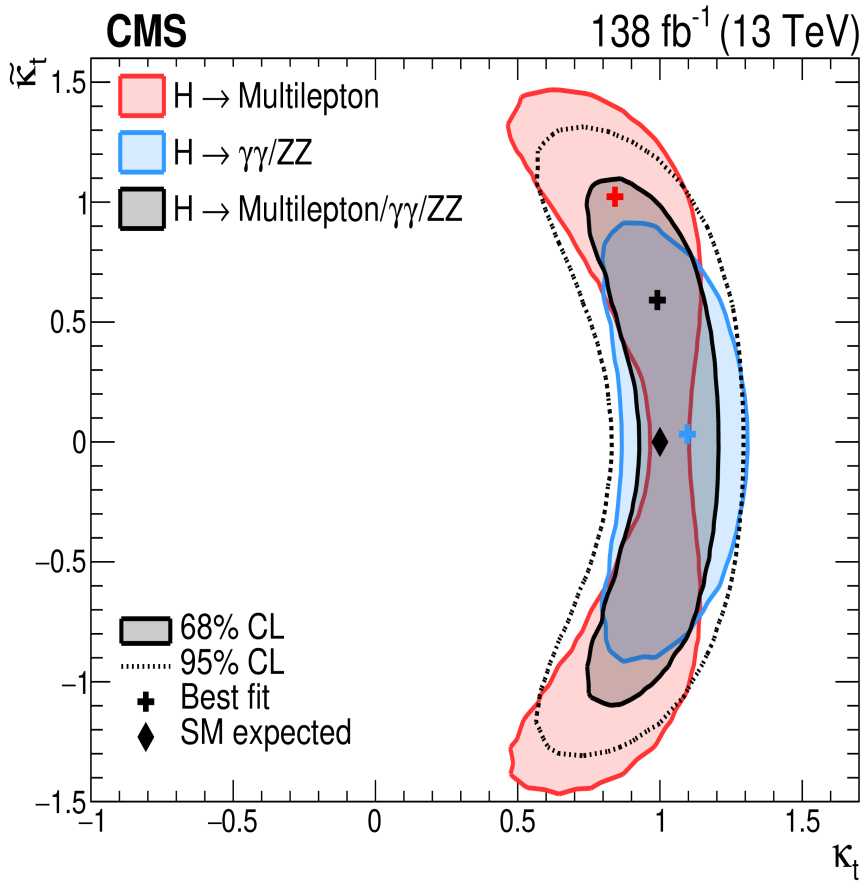


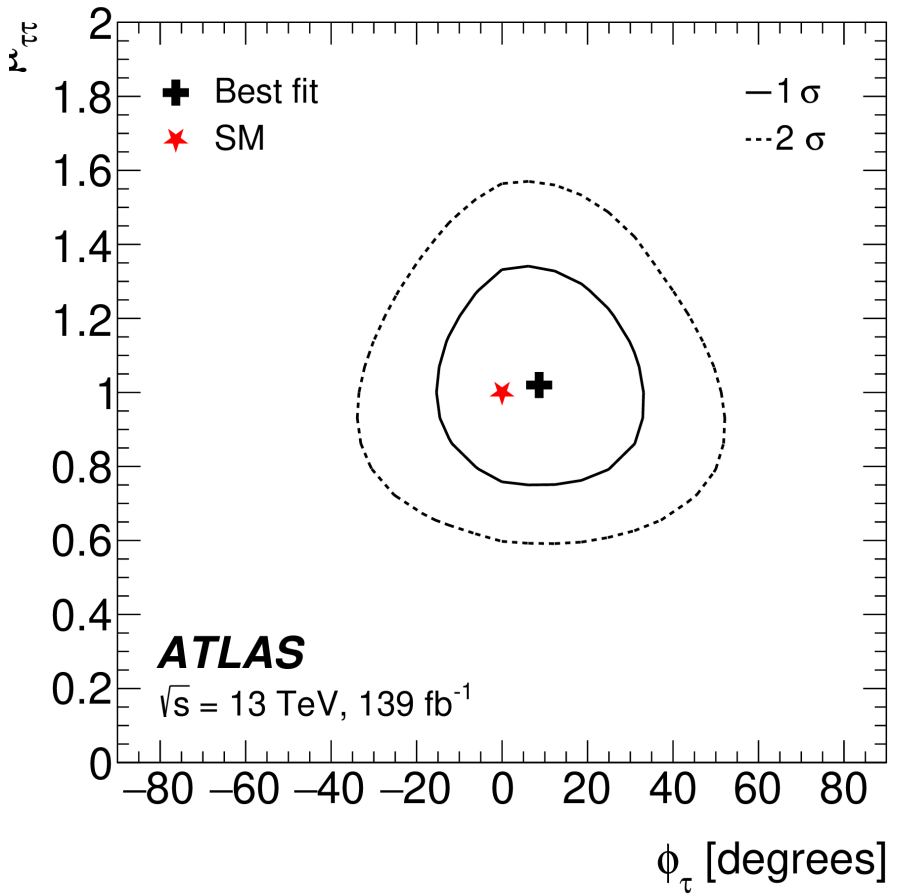


CMS collaboration, arXiv:2208.02686[hep-ex];
ATLAS collaboration, arXiv:2212.05833[hep-ex].

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**Energy Frontier**

To find CP-odd scalars (components)

**Precision Frontier**

Heavy CP-odd resonance

CP property of the 125 GeV Higgs boson

**Null result**

$M_A > 377$ GeV
MSSM
(PDG, 2022)

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

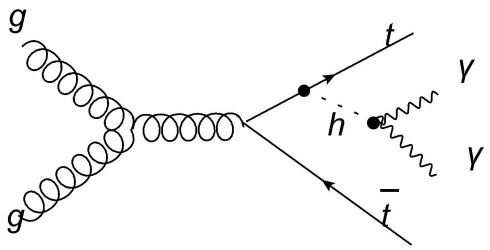
CP-**even** or CP-**mixture**

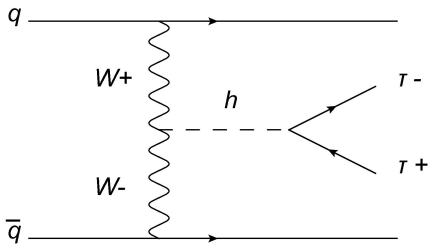
**None-zero CP phase**

**Origin of the CP phases**

**Heavy or feeble interaction**

$$h_{125} = h\cos\delta + A\cos\delta$$

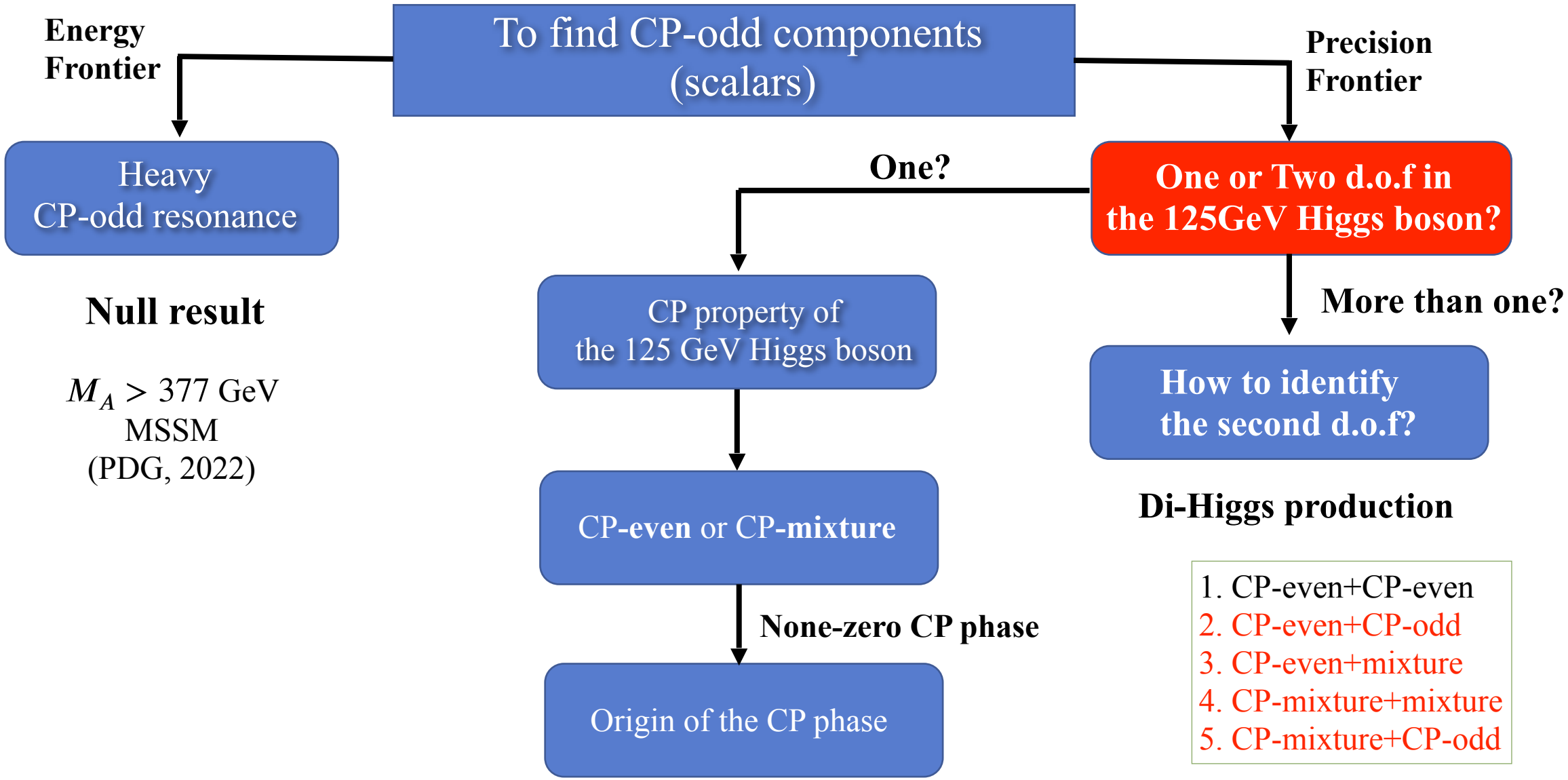



**Explicit CPV**: Yukawa, CKM, Scalar potential
**Spontaneously CPV**

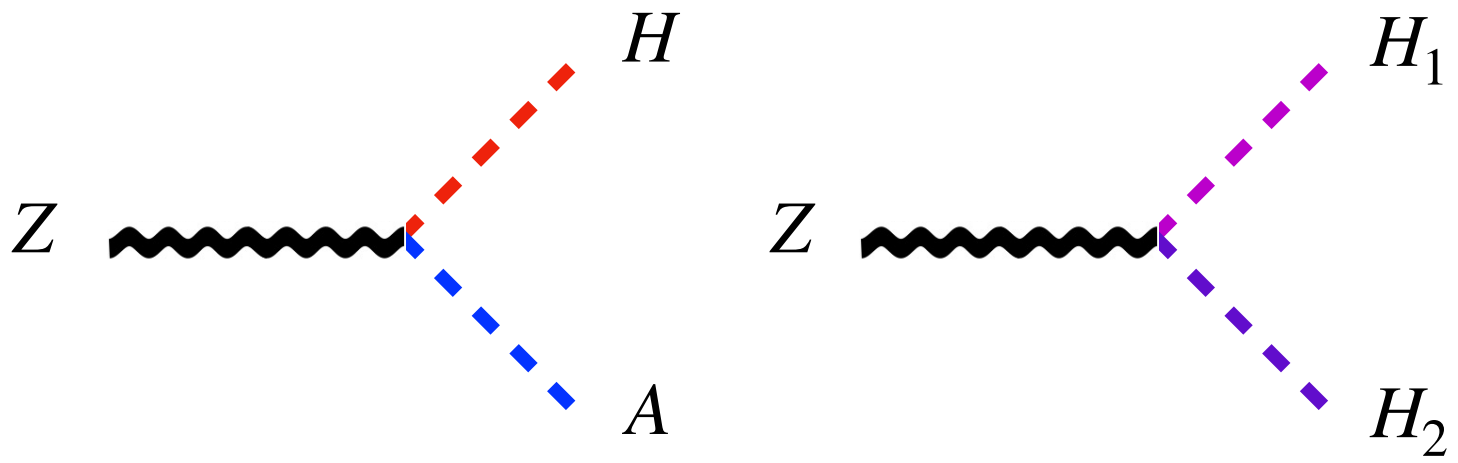
**Example: 2HDM**

# Searching for a CP-odd scalar



# Searching for the hidden scalar

- The smoking gun of the shadow Higgs boson



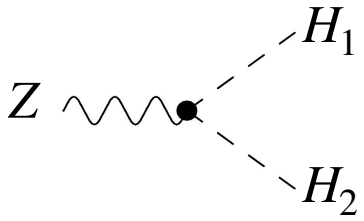

$$\mathscr{L} \supset i g_{ZH_1H_2} \left( H_1 \partial^\mu H_2 - H_2 \partial^\mu H_1 \right) Z_\mu$$

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

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

# ZHH as a probe for CP-odd component

QHC, Cheng, Liu, Wen, Xu and Zhang, 2212.05390

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

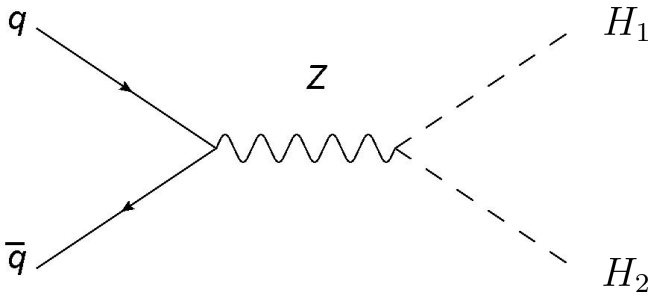
Upper limit from LHC
$\sim 3.4\sigma_{SM}$ (CMS, 2207.00043)

$$\sigma_{H_1H_2} < 2.4 \times \sigma_{SM}(gg \to HH) = 87.84\text{fb}$$

$$g_{H_1H_2} < 0.30$$

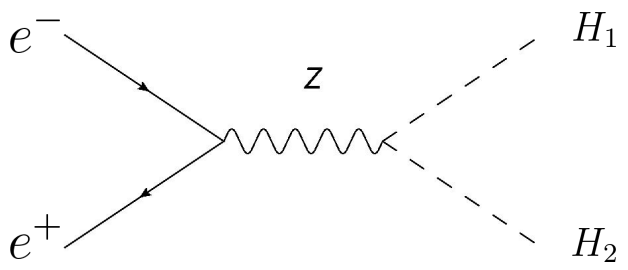
Hadron collider

$\sqrt{s} = 13\text{TeV}$




$$\sigma_{H_1H_2} = 956\ g^2_{ZH_1H_2}\ \text{fb}$$

$e^+e^-$ collider



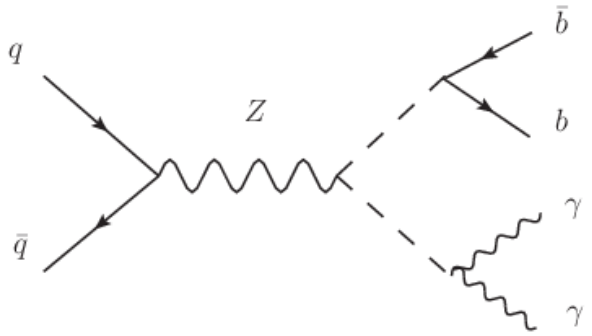

$\sqrt{s} = 350\text{GeV}$

$$\sigma_{H_1H_2} = 282.82\ g^2_{ZH_1H_2}\ \text{fb}$$

# Collider simulation at the HL-LHC

14 TeV

3000 fb$^{-1}$




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

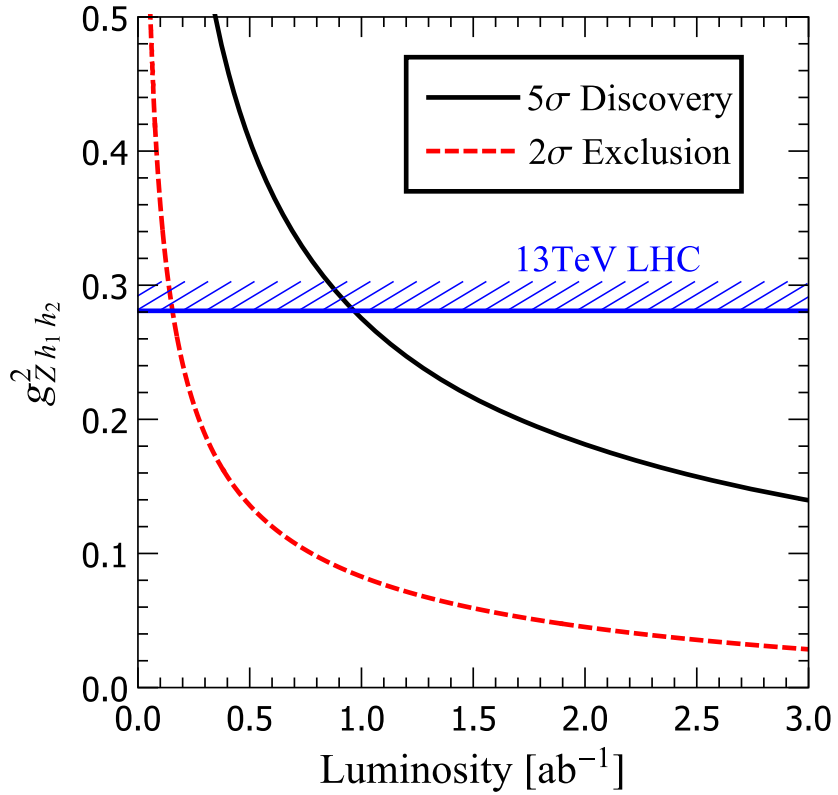
| Process | # of Events (L= 3000 fb$^{-1}$) |
|---|---|
| $q\bar{q} \to Z^* \to hA$ | $167 g^2_{ZH_1H_2} \frac{Br^b_{H_1} Br^\gamma_{H_2} + Br^b_{H_2} Br^\gamma_{H_1}}{2 Br^b_{SM} Br^\gamma_{SM}}$ |
| $gg \to hh$ | 8.4 |
| QCD background | 47 |

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

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

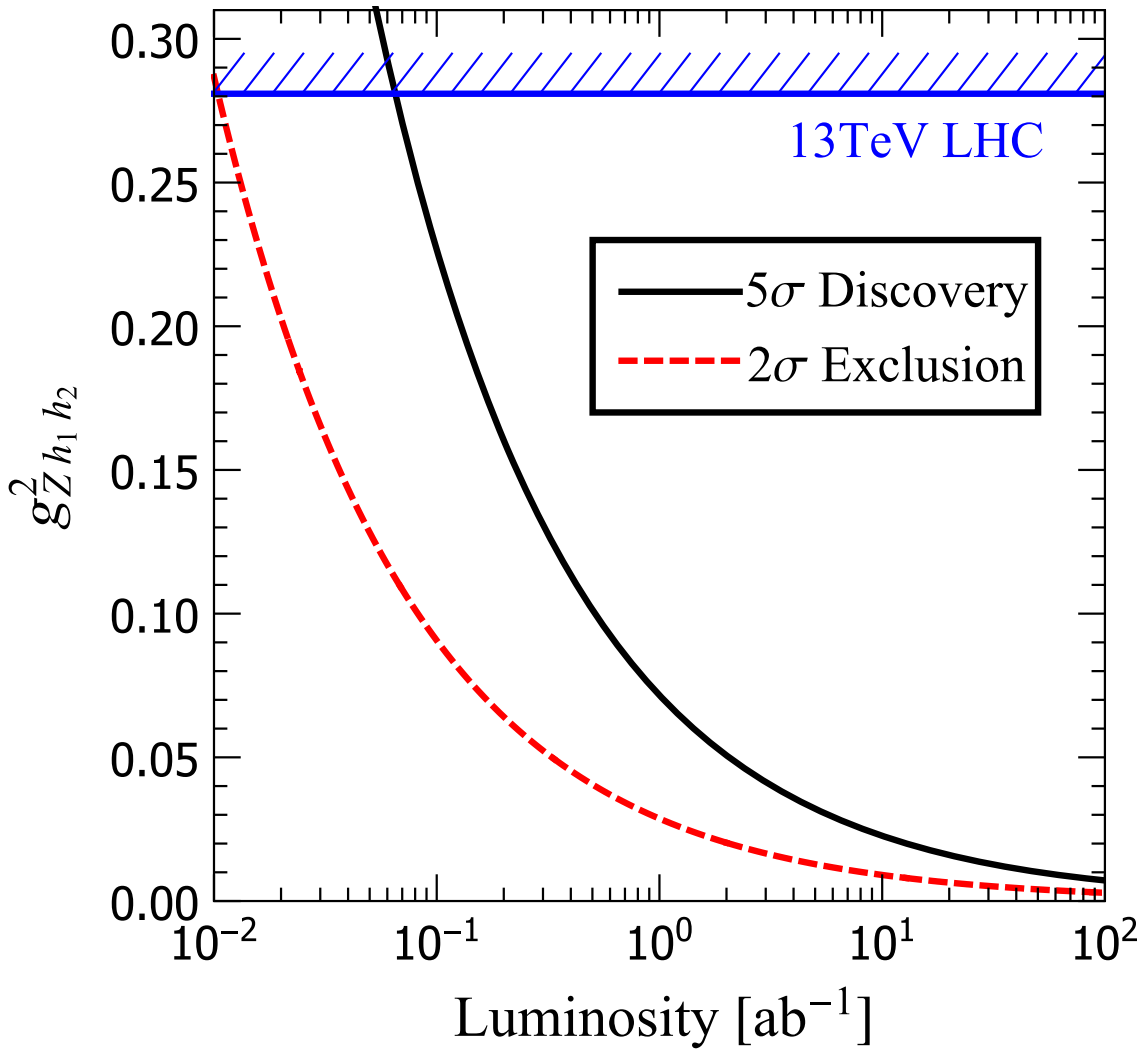
**Significance**

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

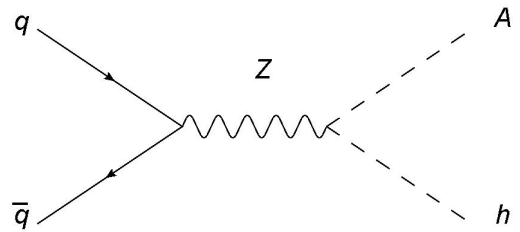


# Search for the hidden Higgs at FCC-hh

**100 TeV, 30 ab$^{-1}$**




$$\sigma_{Zh_1h_2} = 12010 \times g^2_{Zh_1h_2} \quad \text{fb}$$




$b\bar{b}\gamma\gamma$ mode

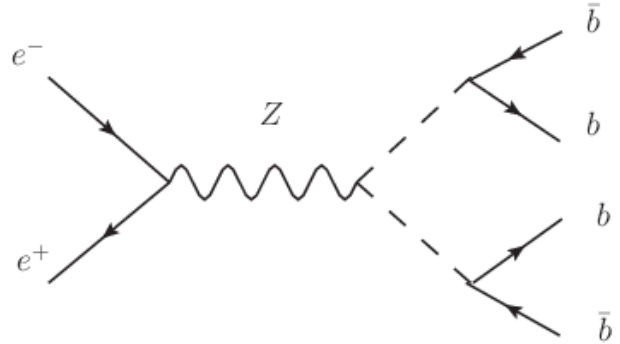
$$p_{\mathrm{T}}^{b_1,\gamma_1} > 60\,\mathrm{GeV}, \quad p_{\mathrm{T}}^{b_2,\gamma_2} > 35\,\mathrm{GeV}, \quad |\eta_{\gamma,b}| < 4.5,$$

$$100\,\mathrm{GeV} < m_{b_1b_2} < 150\,\mathrm{GeV},$$
$$123\,\mathrm{GeV} < m_{\gamma_1\gamma_2} < 127\,\mathrm{GeV},$$

$$\Delta R^{b_1b_2},\ \Delta R^{\gamma_1\gamma_2} < 3.5,$$

$$p_{\mathrm{T}}^{b_1b_2},\ p_{\mathrm{T}}^{\gamma_1\gamma_2} > 100\,\mathrm{GeV}$$

# Phenomenology at the CEPC/ILC/FCC-ee

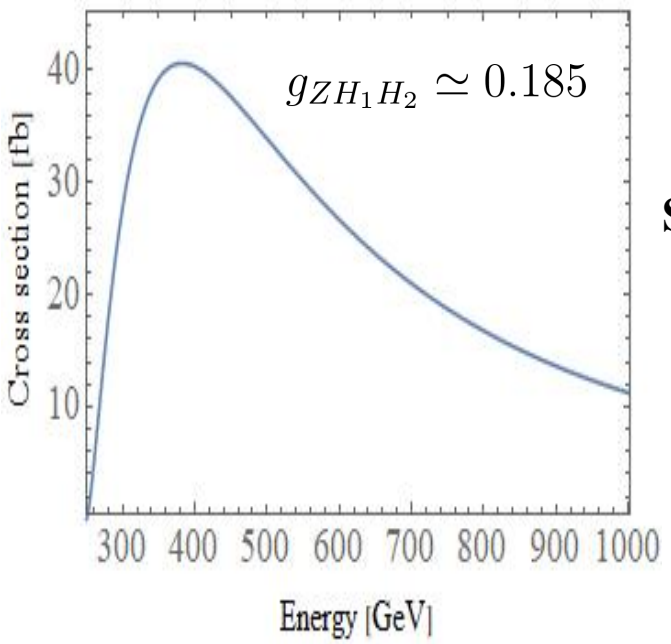



$\sigma_{ZH_1H_2} = 282.82 g^2_{ZH_1H_2}\,\mathrm{fb}$

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

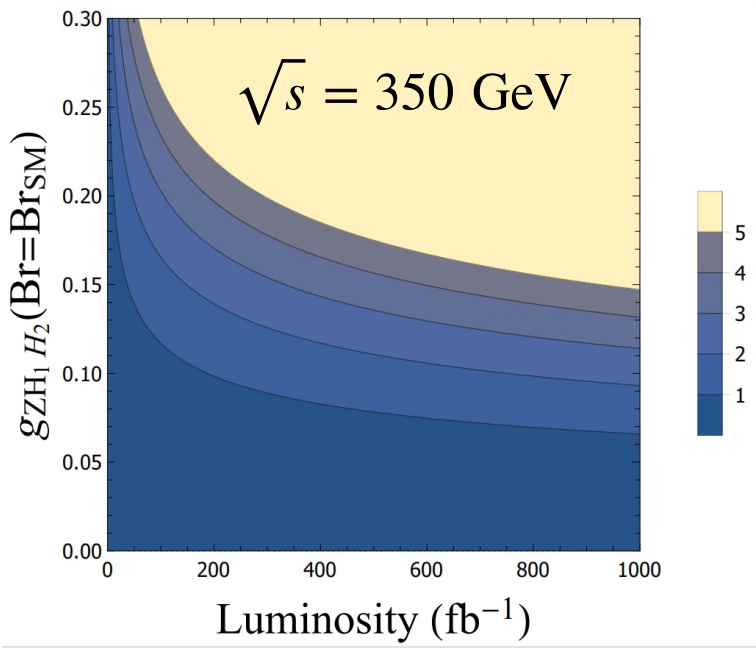
$n^b = 4, \quad p_T^b > 25\mathrm{GeV},$
$|\eta^b| < 2.4, \quad \Delta R^{bb} > 0.5,$
$110\mathrm{GeV} < m_{bb} < 140\mathrm{GeV}$

| Process | Cross section [fb] | After selection [fb] |
|---|---|---|
| $e^+e^- \to hA \to bb\bar{b}\bar{b}$ | $282.82 g^2_{ZH_1H_2}\mathrm{Br_h Br_A}$ | $14.02 g^2_{ZH_1H_2}\mathrm{Br_h Br_A}$ |
| $e^+e^- \to bb\bar{b}\bar{b}$ | 7.014 | 0.1368 |
| $e^+e^- \to zh \to bb\bar{b}\bar{b}$ | 9.731 | 0.2742 |

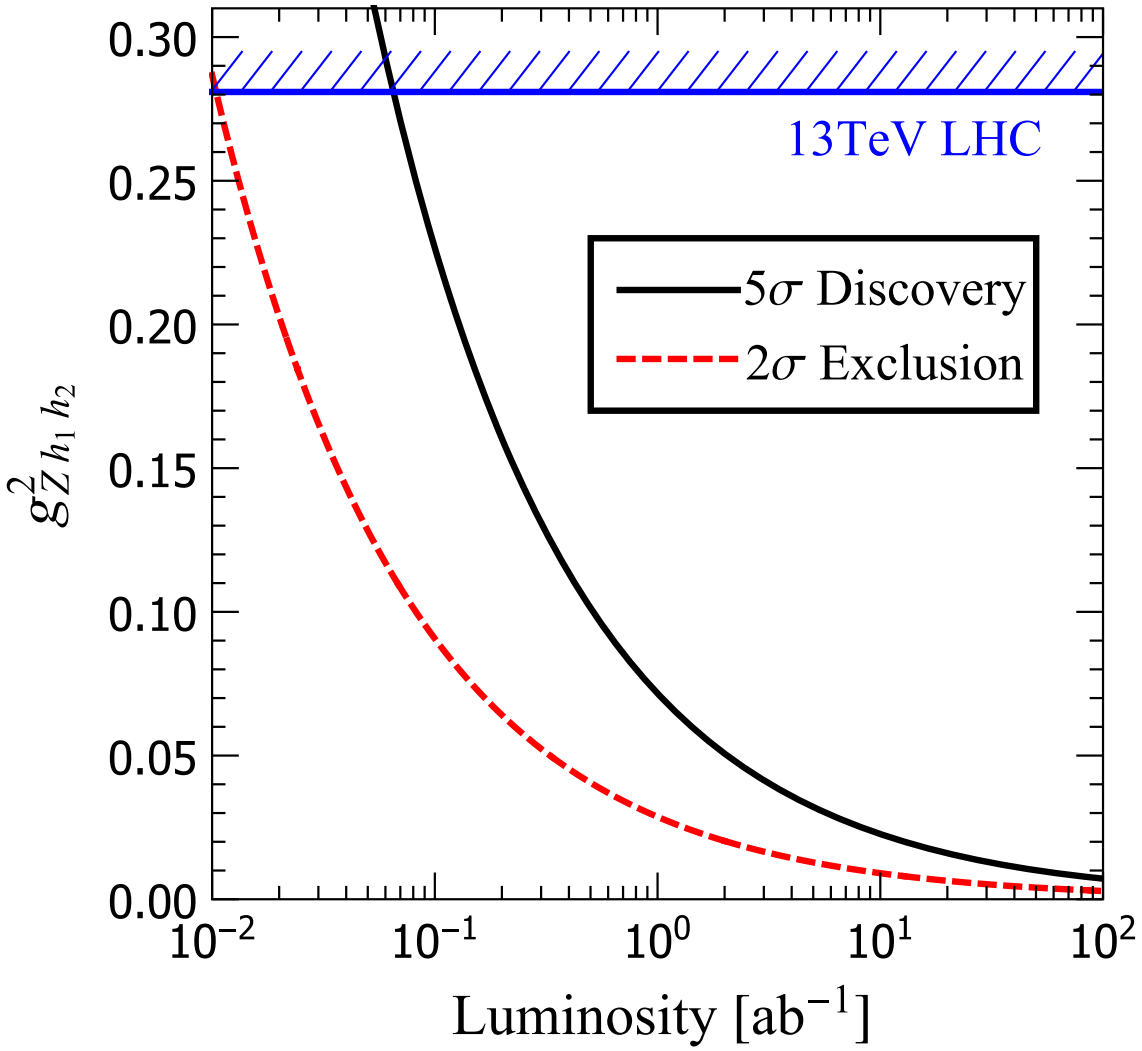



**Significance**

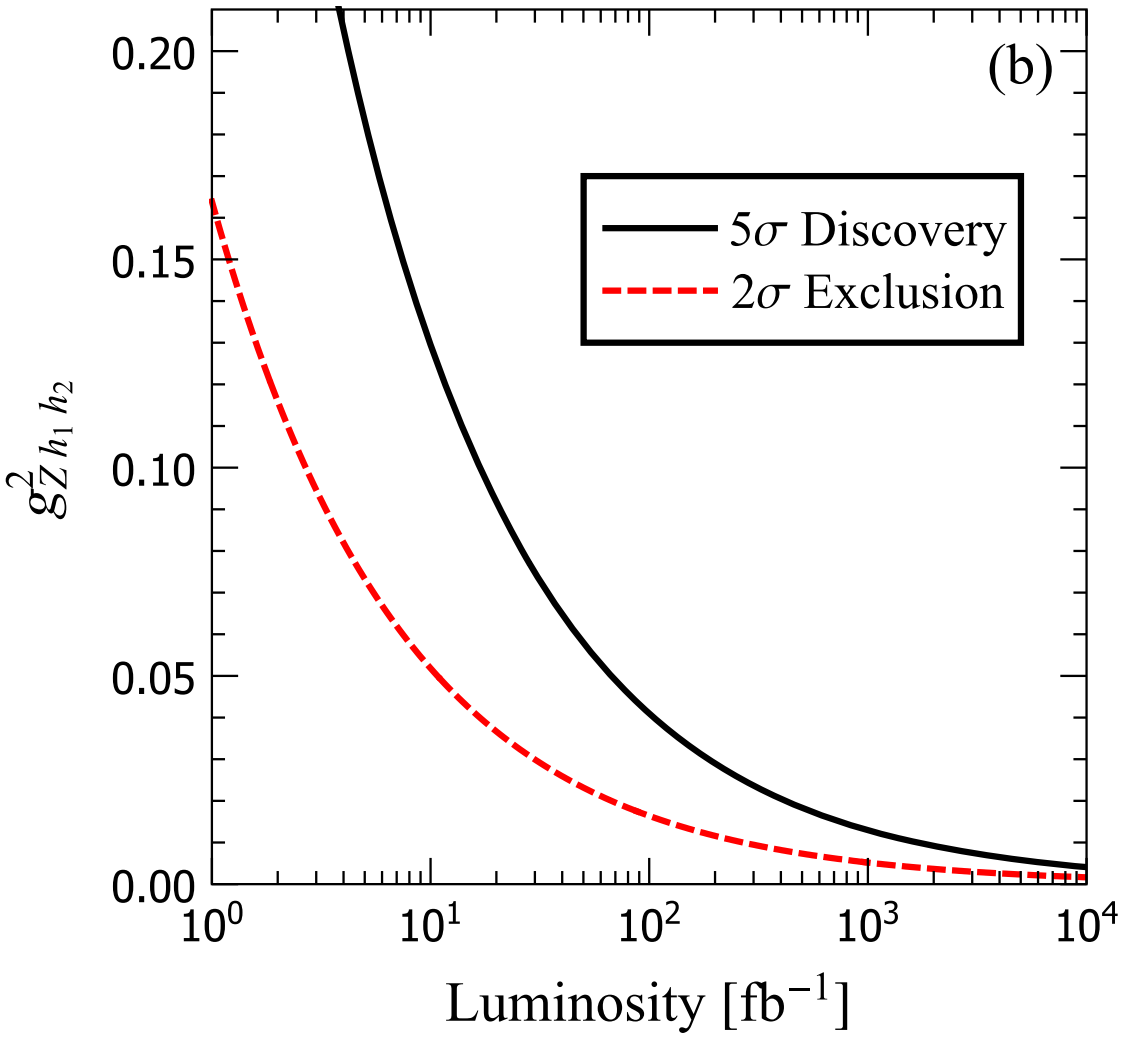
$$Z \simeq 7.3 \times \left(\frac{\mathcal{L}\cdot \mathrm{fb}}{100}\right)^{1/2} \left(\frac{g^2_{ZH_1H_2}}{0.1}\right) \frac{\mathrm{Br_h Br_A}}{\mathrm{Br_{SM}}}$$



# Search for the "shadow" Higgs at future colliders




FCC-HH (100 TeV)




CEPC/ILC/FCC-ee (350 GeV)

# Degenerate $h$ and $A$ in 2HDM

We focus on the CP-conserving scalar potential with a soft broken $Z_2$ symmetry 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

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

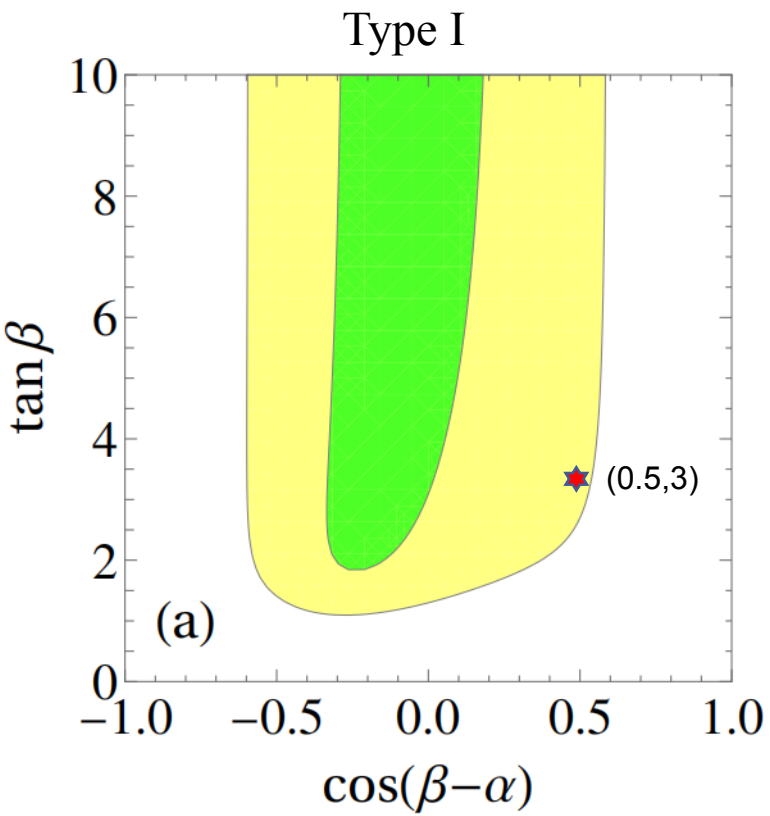
$m_A=m_h=125\text{GeV}$ and $m_{H,H^\pm}>>m_{h,A}$

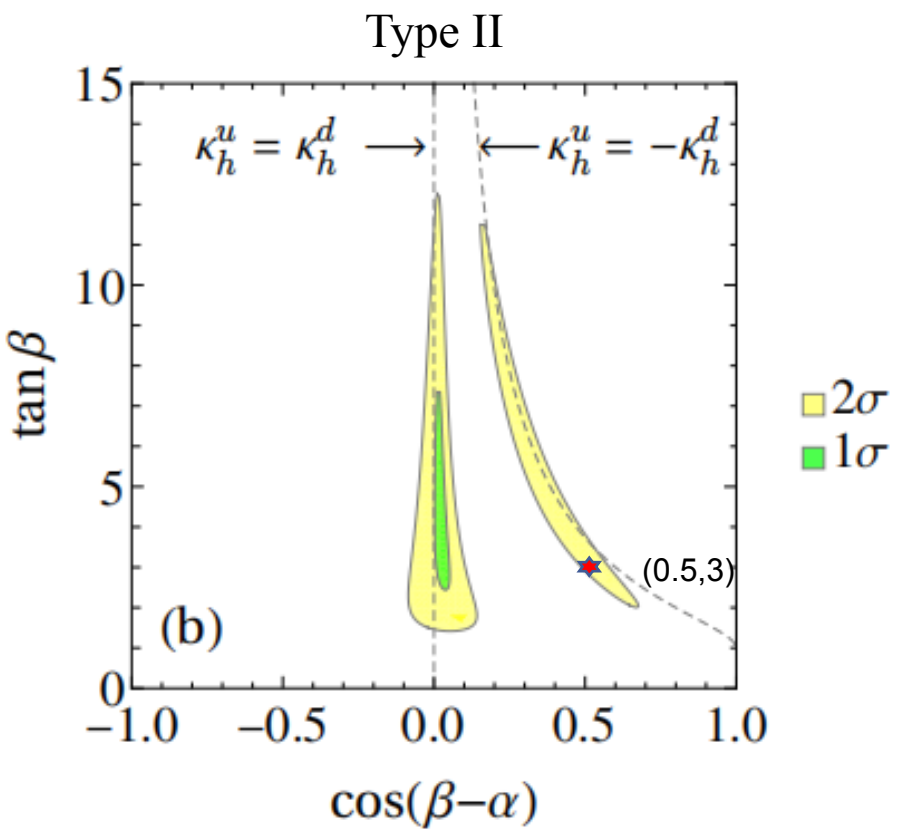
$ZhA$ couplings:

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

The case of $h$ and $H$ degeneracy discussed by Chen, 1712.01299.

# Allowed parameter space by single Higgs Measurement at the LHC




$$\kappa \equiv \frac{g_{\rm BSM}}{g_{\rm SM}}$$

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

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

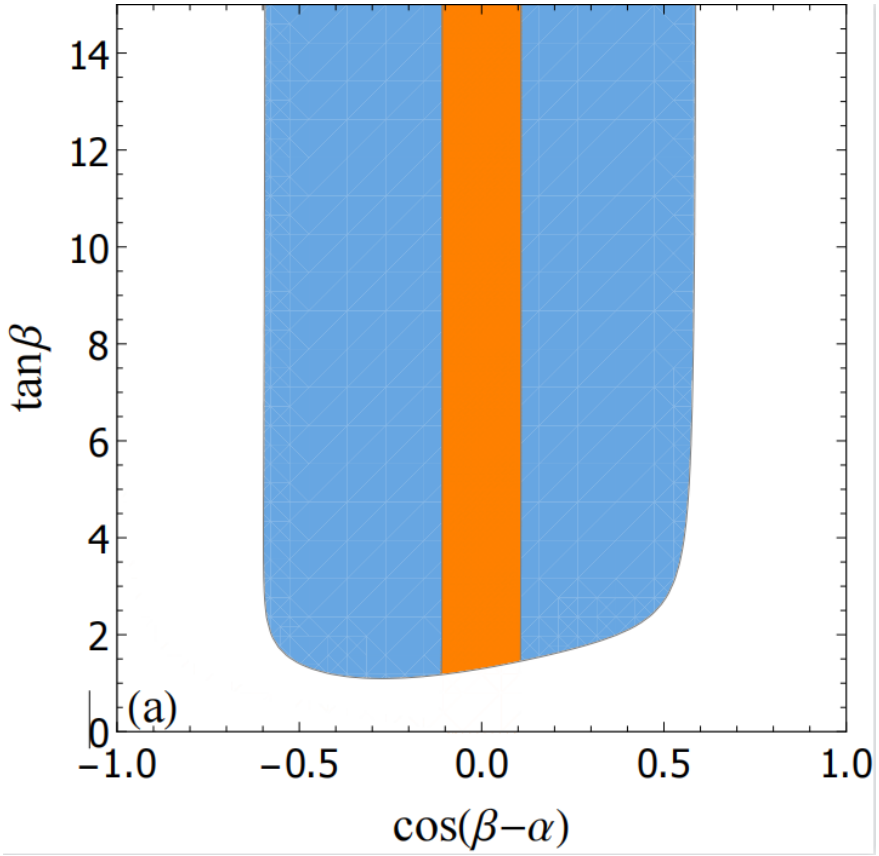
Type-II: $\kappa_h^u = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

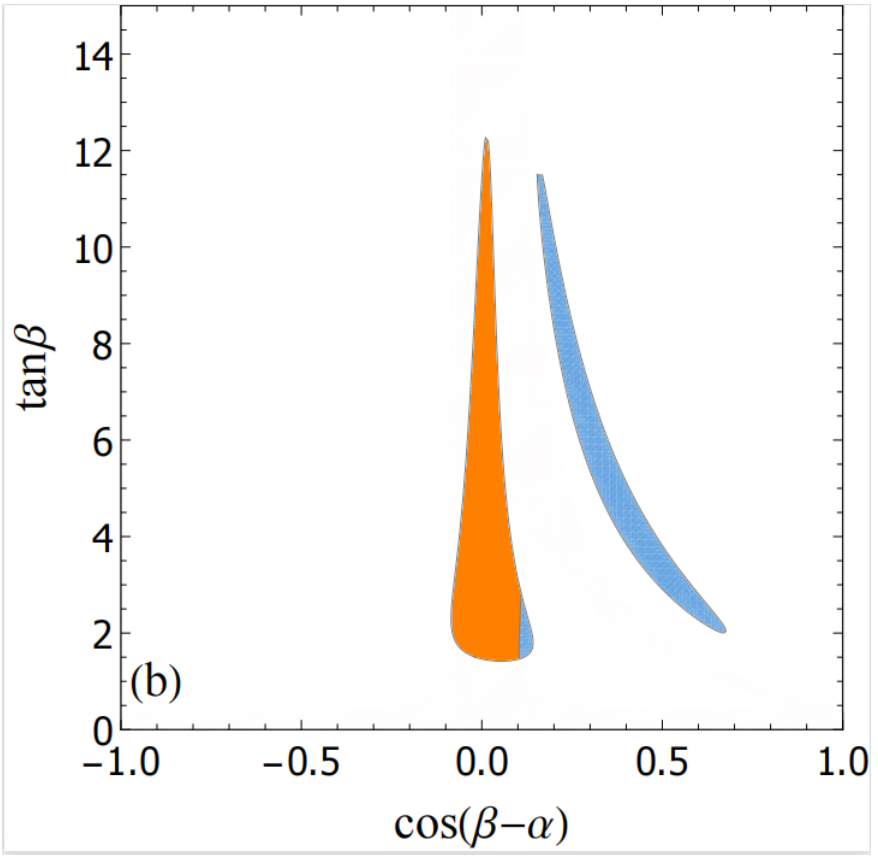
$\kappa_h^{d,\ell} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta$

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

# Di-Higgs production at CEPC/ILC/FCC-ee

**350 GeV, 1000fb$^{-1}$**

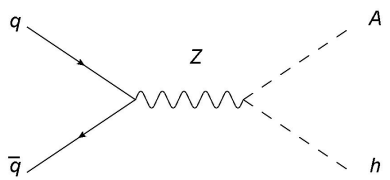


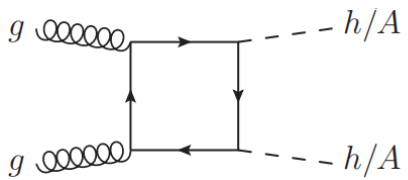



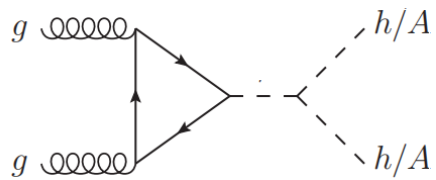

The blue regions can be probed at the CEPC.

# Di-Higgs production at the Fcc-hh

**100 TeV**
**30 ab$^{-1}$**

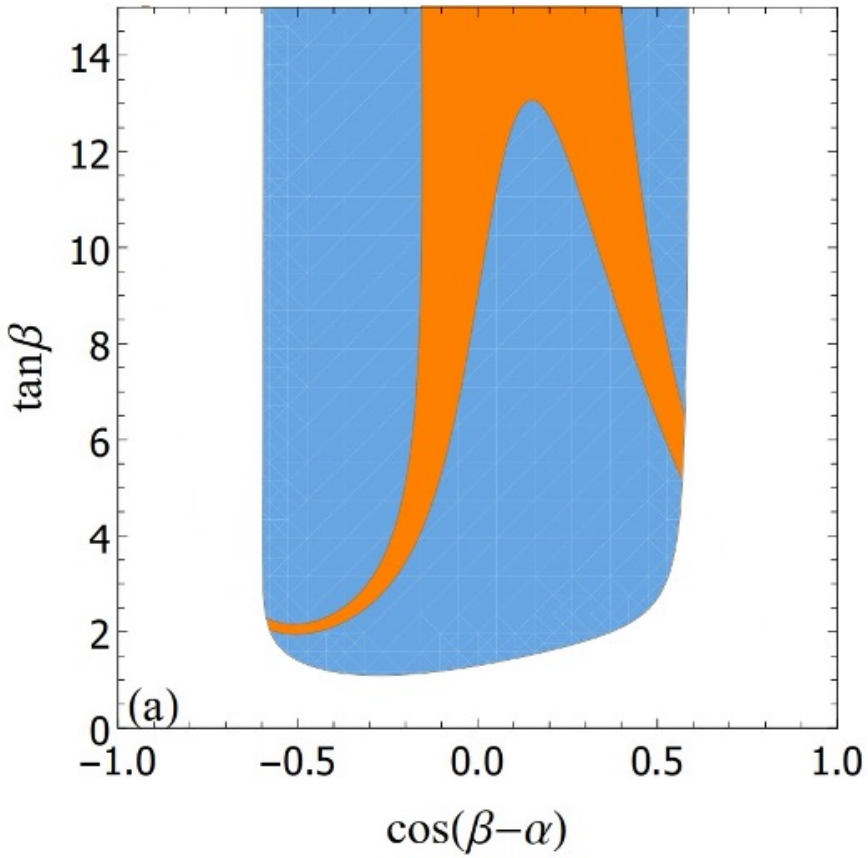


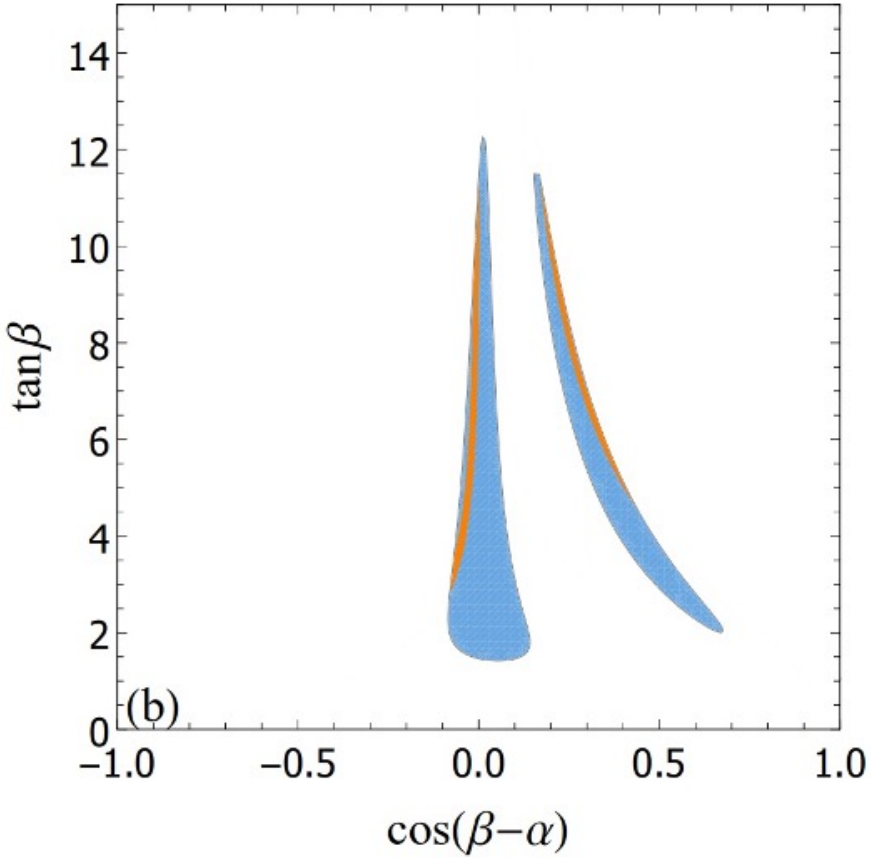




$b\bar{b}\gamma\gamma$ final state

Type I




Type II



# Conclusion

To find CP-odd components (scalars)

**Energy Frontier**

Heavy CP-odd resonance

**Null result**

$M_A > 377$ GeV
MSSM
(PDG, 2022)

**Precision Frontier**

**One or Two d.o.f in the 125GeV Higgs boson?**

**One?**

CP property of the 125 GeV Higgs boson

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

**None-zero CP phase**

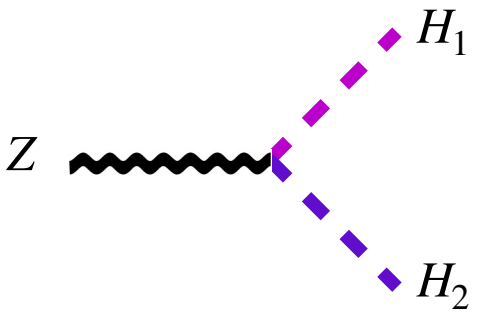
Origin of the CP phase

**More than one?**

**How to identify the second d.o.f?**

**Di-Higgs production**

1. CP-even+CP-even
2. CP-even+CP-odd
3. CP-even+mixture
4. CP-mixture+mixture
5. CP-mixture+CP-odd




***It is very promising to discover the hidden scalar at CEPC.***

***Thank You!***