FIND 论坛 Forum for Interdisciplinary Investigations into New Directions at Extreme Scales

系列学术报告

在电弱能标等尺度下寻找CP破缺现象

CP violation at electroweak scale and beyond

Higgs Alignment and CP Violation in 2HDM

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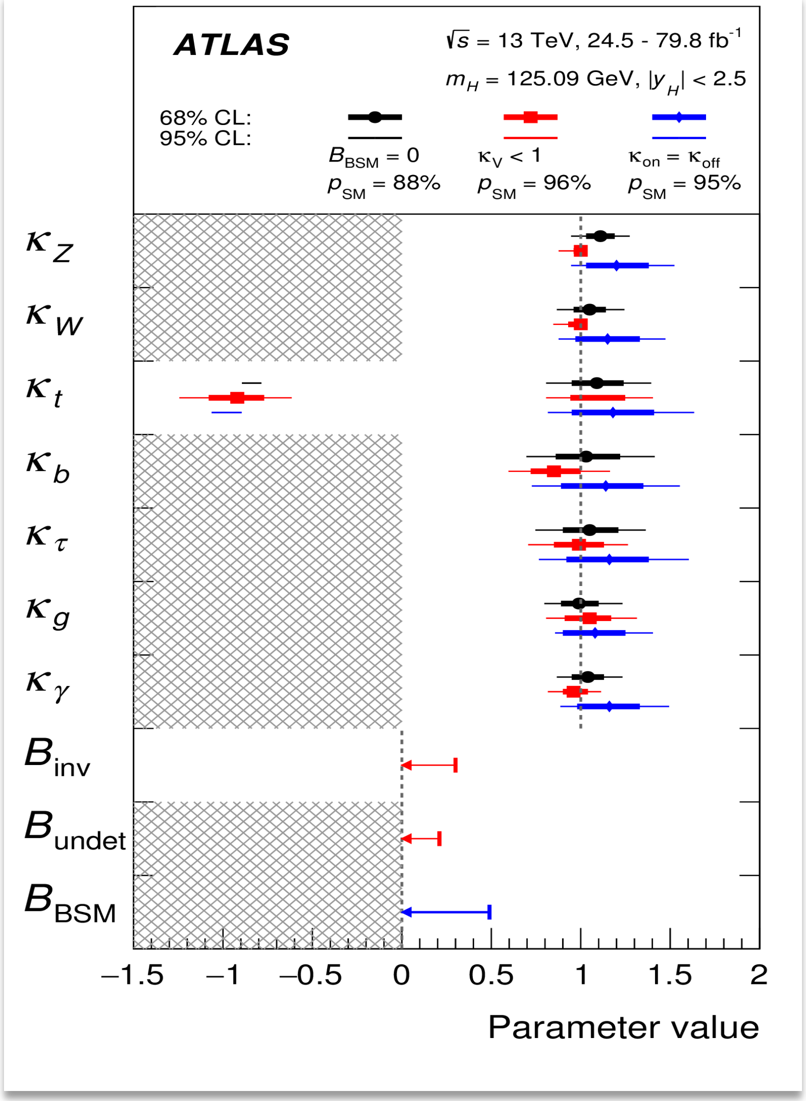
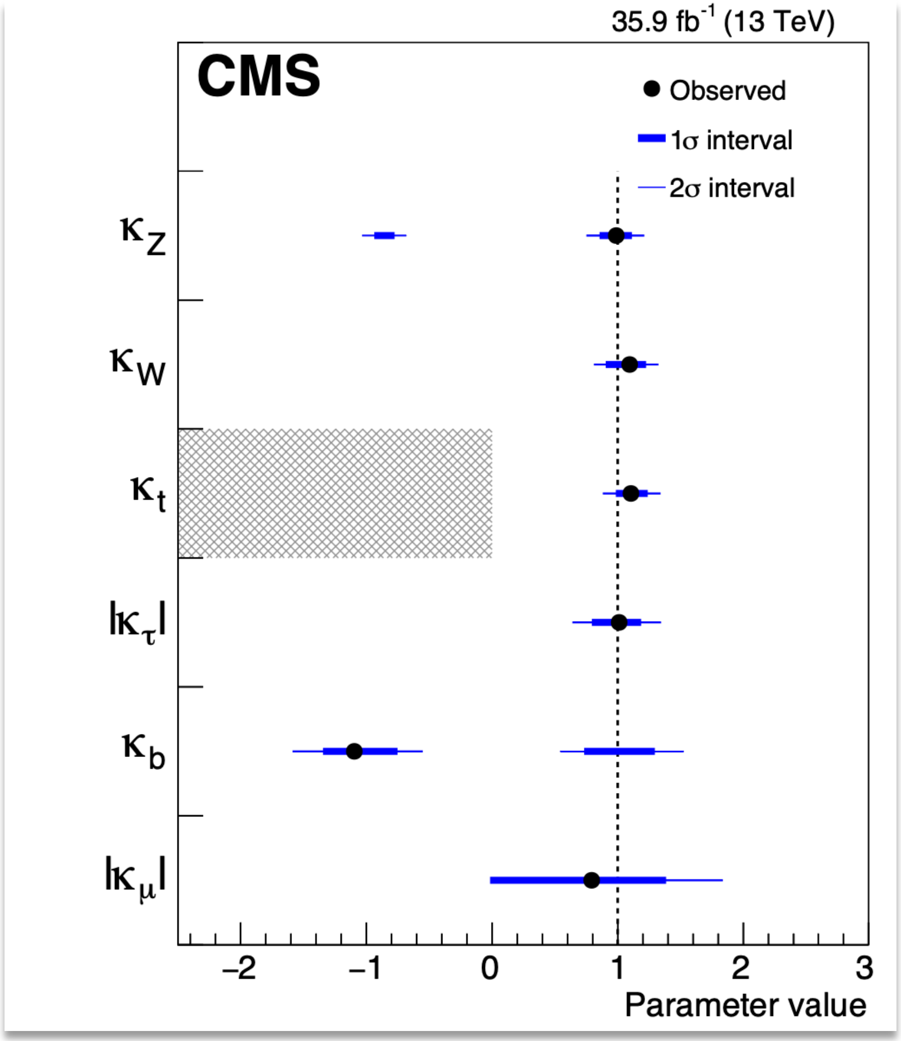
Collaborated with Ian Low, Nausheen R. Shah

A LONG WAY FROM SM HIGGS DISCOVERY



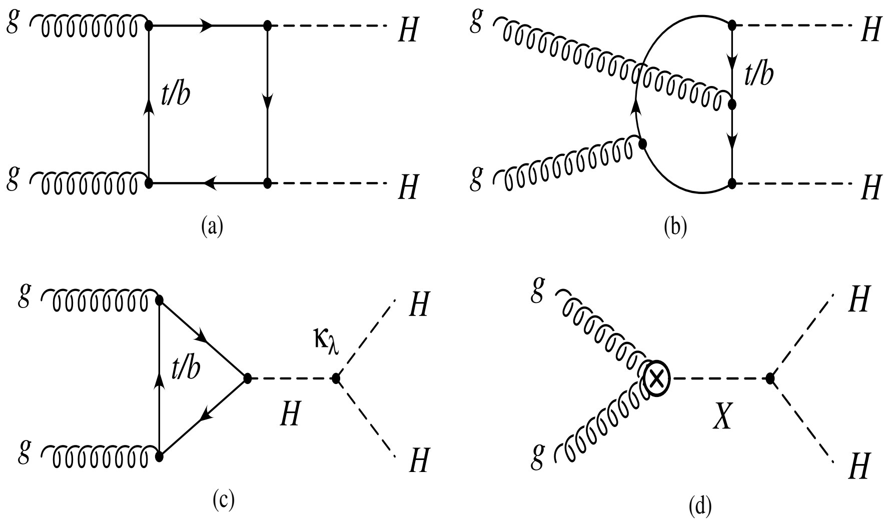
Phys. Rev. D 101 (2020) 012002

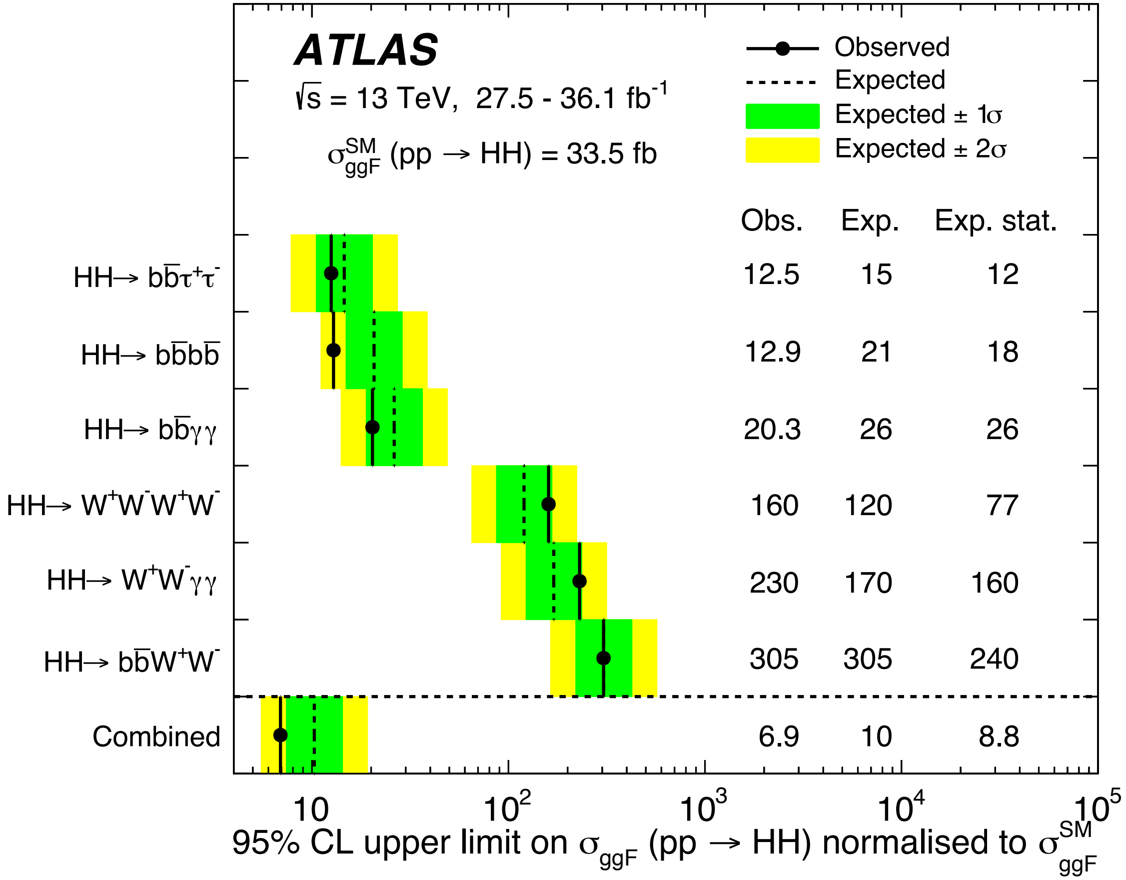


Eur. Phys. J. C 79 (2019) 421

STATUS OF SM HIGGS SEARCH

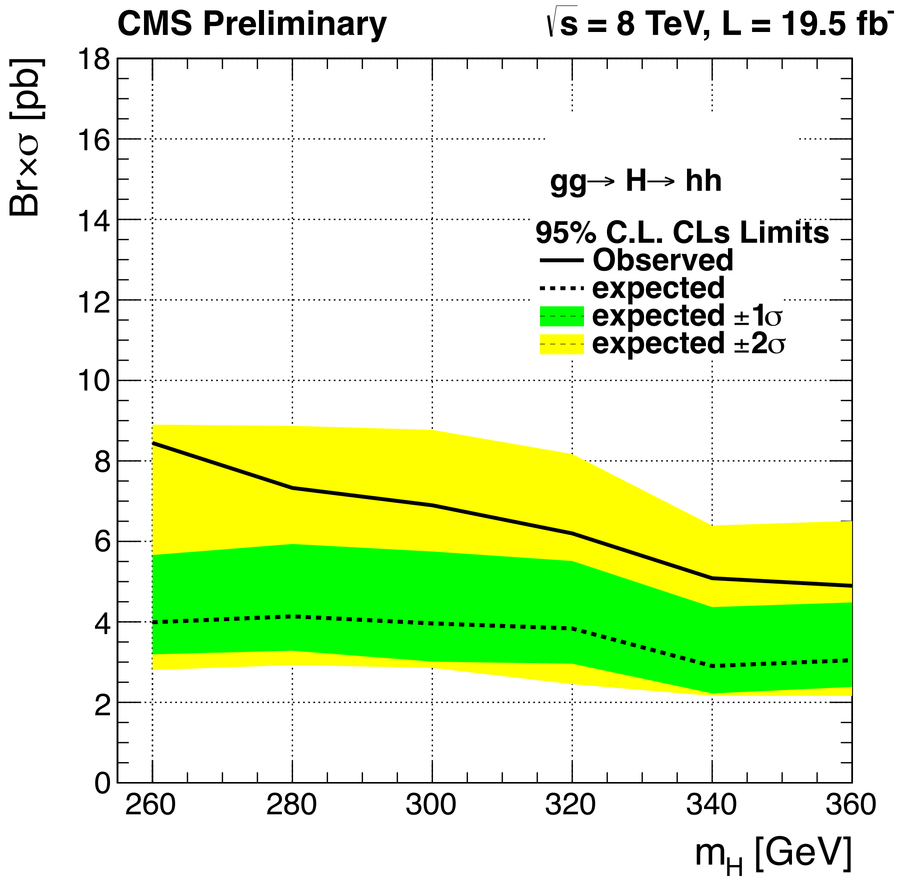
- SM Higgs self-interaction:



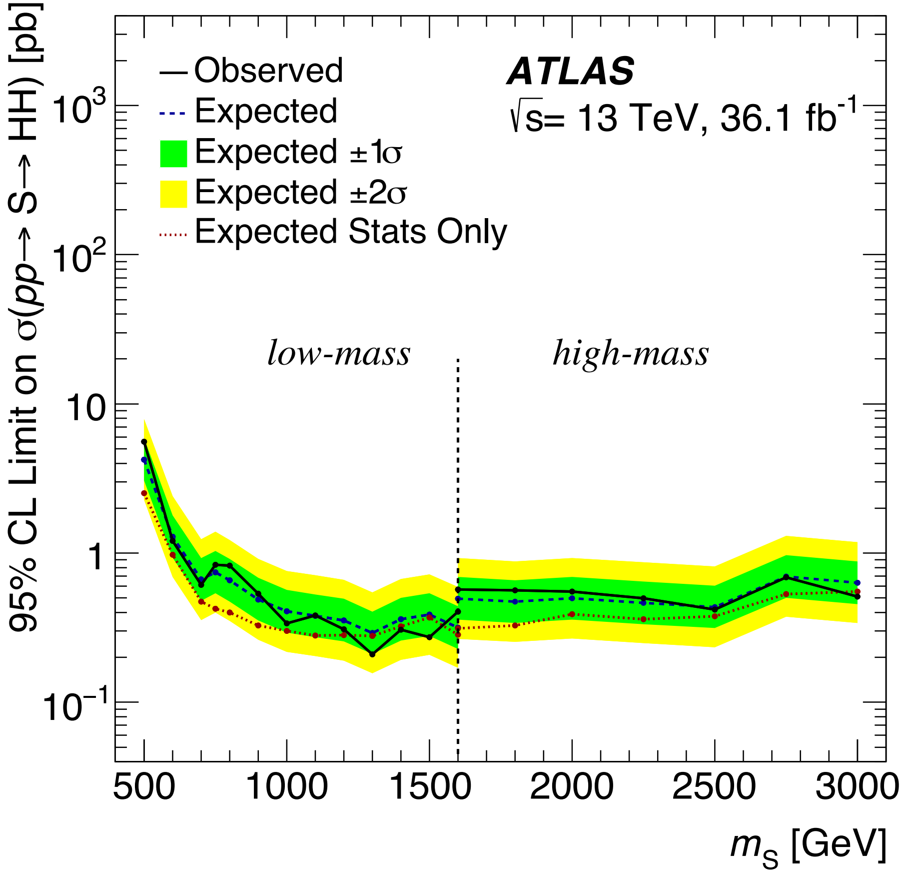


ATLAS, Phys. Lett. B 800 (2020) 135103

EXTRA NEUTRAL HIGGS SEARCH

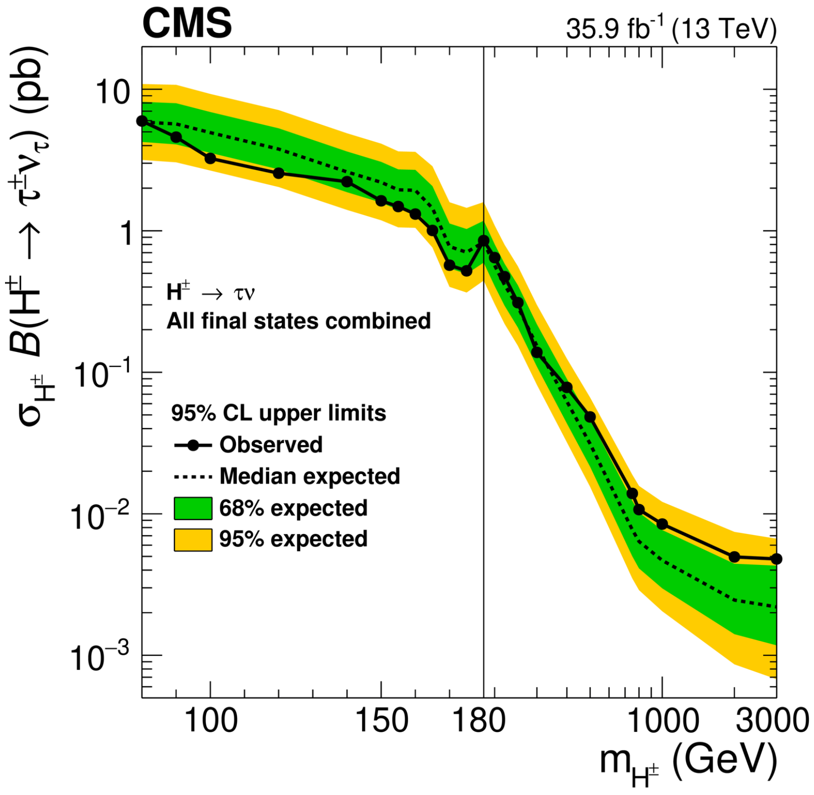


CMS, HIG-13-025-pas

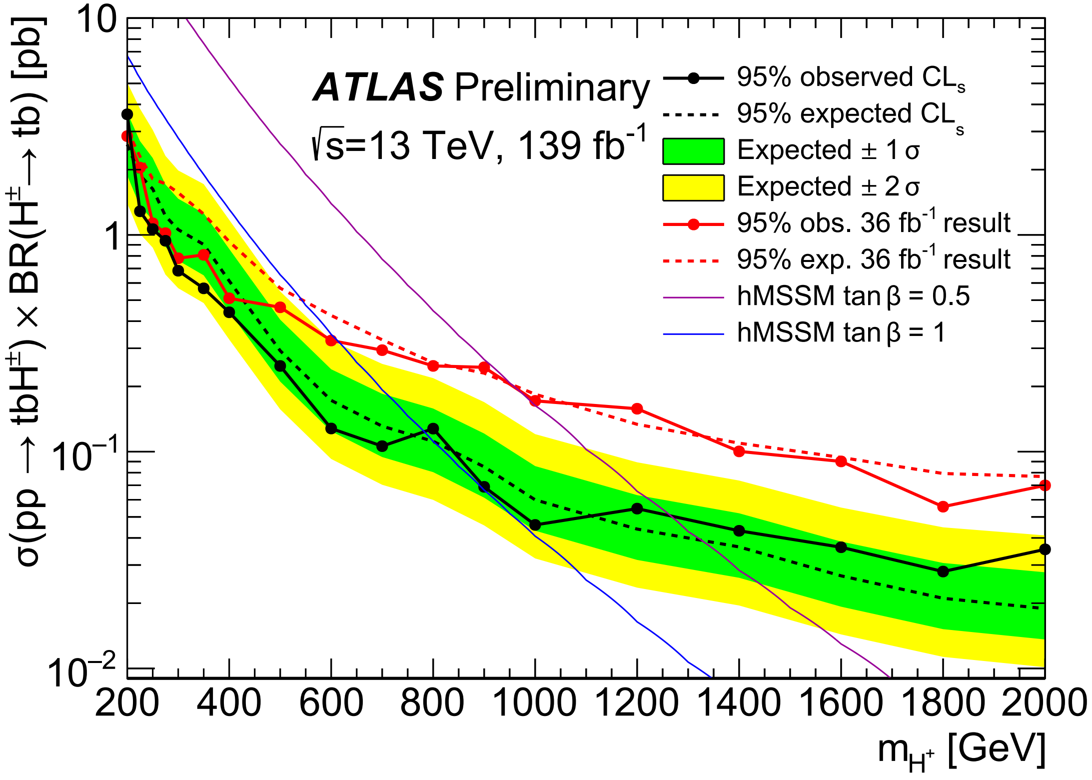


ATLAS, JHEP 1904 (2019) 092

EXTRA CHARGED HIGGS SEARCH



CMS, JHEP07 (2019) 142



ATLAS-CONF-2020-039

QUESTIONS AND POSSIBILITIES

In the SM, generically, **decoupling** effect goes like:

$$\mathcal{O}\left(\frac{v^2}{M_{\text{new}}^2}\right) \sim 5\% \times \left(\frac{1\text{TeV}}{\Lambda}\right)^2$$

For O(15%) accuracy in HVV couplings, M_{new} >~ 600GeV !

Question:

If we continue to pursue the precision in the Higgs coupling measurements, is there any value in direct searches for additional, heavy Higgs bosons?

Yes! It goes by the name of "Alignment without decoupling."

TWO HIGGS DOUBLET MODEL

- To see how "alignment without decoupling" arises by CP even Higgs couplings:

$$g_{h_i VV} = \frac{1}{2} g^2 v_i \ , i = 1,2$$

- It is possible to rotate to Higgs basis

$$\begin{aligned}
\mathcal{V} &= Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 e^{-i\eta} H_1^\dagger H_2 + h.c.\right] \\
&+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\
&+ \left[\frac{Z_5}{2} e^{-2i\eta}(H_1^\dagger H_2)^2 + Z_6 e^{-i\eta}(H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7 e^{-i\eta}(H_2^\dagger H_2)(H_1^\dagger H_2) + h.c.\right]
\end{aligned}$$

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1 \Phi_1 + v_2 \Phi_2}{v} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{v_1 \Phi_2 - v_2 \Phi_1}{v} \qquad \langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \ , \qquad \langle H_2^0 \rangle = 0 \ .$$

TWO HIGGS DOUBLET MODEL

- Mass matrix:

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \mathrm{Re}\left(Z_6 e^{-i\eta}\right) & -\mathrm{Im}\left(Z_6 e^{-i\eta}\right) \\ \mathrm{Re}\left(Z_6 e^{-i\eta}\right) & \frac{1}{2}\left[Z_{34} + \mathrm{Re}\left(Z_5 e^{-2i\eta}\right)\right] + \frac{Y_2}{v^2} & -\frac{1}{2}\mathrm{Im}\left(Z_5 e^{-2i\eta}\right) \\ -\mathrm{Im}\left(Z_6 e^{-i\eta}\right) & -\frac{1}{2}\mathrm{Im}\left(Z_5 e^{-2i\eta}\right) & \frac{1}{2}\left[Z_{34} - \mathrm{Re}\left(Z_5 e^{-2i\eta}\right)\right] + \frac{Y_2}{v^2} \end{pmatrix}$$

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = R \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ a^0 \end{pmatrix} \qquad R = \begin{pmatrix} c_{12}c_{13} & \cdots & \cdots \\ c_{13}s_{12} & \cdots & \cdots \\ s_{13} & \cdots & \cdots \end{pmatrix}$$

- Higgs –V-V couplings:

$$g_{h_i VV} = \frac{1}{2} g^2 v * R_{i1} \ , i = 1,2$$

  - “Alignment without decoupling” occurs when Higgs basis = Mass eigen basis

CP VIOLATION THDM

- Counting the number of d.o.f. in CPX 2HDM

$$
\begin{aligned}
\mathcal{V} &= Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 e^{-i\eta} H_1^\dagger H_2 + h.c.\right] \\
&+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\
&+ \left[\frac{Z_5}{2} e^{-2i\eta}(H_1^\dagger H_2)^2 + Z_6 e^{-i\eta}(H_1^\dagger H_1)(H_1^\dagger H_2) + Z_7 e^{-i\eta}(H_2^\dagger H_2)(H_1^\dagger H_2) + h.c.\right]
\end{aligned}
$$

- Minimization condition in the Higgs basis:

$$Y_1 = -\frac{1}{2} Z_1 v^2 \qquad\qquad Y_3 = -\frac{1}{2} Z_6 v^2$$

- Z_2 Symmetry:

Haber+collaborators: 2001.01430

$$(Z_1 - Z_2)\left[Z_{34} Z_{67}^* - Z_1 Z_7^* - Z_2 Z_6^* + Z_5^* Z_{67})\right] - 2 Z_{67}^*\left(|Z_6|^2 - |Z_7|^2\right) = 0\,.$$

- Free parameters:

$$\{Y_2, Z_1, Z_2, Z_3, Z_4\} \Rightarrow \{Y_2, Z_1, Z_3, Z_4\}$$

$$\{Z_5, Z_6, Z_7\} \Rightarrow \{Z_5, Z_6, \mathrm{Re}[Z_7]\}$$

- 9 real free parameters!

FREE PARAMETERS IN CTHDM

- Diagonalize the mass matrix

$$R = R_{12}R_{13}\overline{R}_{23} = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & -s_{13} \\ 0 & 1 & 0 \\ s_{13} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \bar{c}_{23} & -\bar{s}_{23} \\ 0 & \bar{s}_{23} & \bar{c}_{23} \end{pmatrix}$$

- Redefine the mass matrix

$$\widetilde{\mathcal{M}}^2 \equiv \overline{R}_{23}\,\mathcal{M}^2\,\overline{R}_{23}^T \quad = v^2 \begin{pmatrix} Z_1 & \mathrm{Re}[\tilde{Z}_6] & -\mathrm{Im}[\tilde{Z}_6] \\ \mathrm{Re}[\tilde{Z}_6] & \mathrm{Re}[\tilde{Z}_5] + A^2/v^2 & -\frac{1}{2}\mathrm{Im}[\tilde{Z}_5] \\ -\mathrm{Im}[\tilde{Z}_6] & -\frac{1}{2}\mathrm{Im}[\tilde{Z}_5] & A^2/v^2 \end{pmatrix}$$

- Alignment Limit:

$$\widetilde{R} = R_{12}R_{13} = \begin{pmatrix} c_{12}c_{13} & -s_{12} & -c_{12}s_{13} \\ s_{12}c_{13} & c_{12} & -s_{12}s_{13} \\ s_{13} & 0 & c_{13} \end{pmatrix}$$

$$= \begin{pmatrix} -\epsilon\, c_{12} & -s_{12} & -c_{12}(1-\epsilon^2/2) \\ -\epsilon\, s_{12} & c_{12} & -s_{12}(1-\epsilon^2/2) \\ 1-\epsilon^2/2 & 0 & -\epsilon \end{pmatrix}$$

$$\Rightarrow$$

$$Z_1 = \frac{1}{v^2}\left[m_{h_1}^2 + \epsilon^2\left(m_{h_3}^2 c_{12}^2 + m_{h_2}^2 s_{12}^2 - m_{h_1}^2\right)\right]$$

$$\mathrm{Re}[\tilde{Z}_5] = \frac{1}{v^2}\left[c_{2\theta_{12}}\left(m_{h_2}^2 - m_{h_3}^2\right) + \epsilon^2\left(m_{h_3}^2 c_{12}^2 + m_{h_2}^2 s_{12}^2 - m_{h_2}^2\right)\right]$$

$$\mathrm{Im}[\tilde{Z}_5] = \frac{1}{v^2} s_{2\theta_{12}}\left(1 - \frac{\epsilon^2}{2}\right)\left(m_{h_2}^2 - m_{h_3}^2\right)\ ,$$

$$\mathrm{Re}[\tilde{Z}_6] = \frac{\epsilon}{2v^2} s_{2\theta_{12}}\left(m_{h_3}^2 - m_{h_2}^2\right)\ ,$$

$$\mathrm{Im}[\tilde{Z}_6] = \frac{\epsilon}{v^2}\left(m_{h_2}^2 - m_{h_3}^2 c_{12}^2 - m_{h_1}^2 s_{12}^2\right)\ ,$$

- Free parameters:

$$\{Y_2, Z_3, Z_1, Z_5, Z_6, Re[Z_7], Z_4\} \Rightarrow \{m_{h_1}, m_{h_2}, m_{h_3}, \theta_{12}, \epsilon, Z_3, m_{H^\pm}, \mathrm{Re}[\tilde{Z}_7], v\}$$

CP CONSERVATIVE LIMIT

- Higgs mixing:

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \widetilde{R} \begin{pmatrix} \phi_1^0 \\ \tilde{\phi}_2^0 \\ \tilde{\phi}_3^0 \end{pmatrix} = \begin{pmatrix} -\epsilon\, c_{12} & -s_{12} & -c_{12}(1-\epsilon^2/2) \\ -\epsilon\, s_{12} & c_{12} & -s_{12}(1-\epsilon^2/2) \\ 1-\epsilon^2/2 & 0 & -\epsilon \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ c_{23}\,\phi_2^0 - s_{23}\,a^0 \\ s_{23}\,\phi_2^0 + c_{23}\,a^0 \end{pmatrix}$$

$$\theta_{13} = \frac{\pi}{2} + \epsilon$$

- HHH couplings:

$$g_{h_1 H^+ H^-} = v\left[\left(1 - \frac{\epsilon^2}{2}\right) Z_3 + \epsilon \mathrm{Im}[\tilde{Z}_7]\right]$$

$$g_{h_2 H^+ H^-} = v\left[-\epsilon s_{12} Z_3 + c_{12}\mathrm{Re}[\tilde{Z}_7] + s_{12}\left(1 - \frac{\epsilon^2}{2}\right)\mathrm{Im}[\tilde{Z}_7]\right]$$

$$g_{h_3 H^+ H^-} = v\left[-\epsilon c_{12} Z_3 - s_{12}\mathrm{Re}[\tilde{Z}_7] + c_{12}\left(1 - \frac{\epsilon^2}{2}\right)\mathrm{Im}[\tilde{Z}_7]\right]$$

- Case I: $\theta_{13} = \frac{\pi}{2}, \theta_{23} = 0, \theta_{12} = \left\{0, \frac{\pi}{2}\right\}, \mathrm{Im}\,[Z_7] = 0$
- Case 2: $\theta_{23} = \pi/2\ ,\ \theta_{12} = \{0, \pi/2\}\ ,\ \mathrm{Im}[Z_7] = 0\ .$

CP CONSERVATIVE LIMIT

- Relationships between Z_i and mixing angles:

$$\mathrm{Im}[\tilde{Z}_5] = \frac{1}{v^2} s_{2\theta_{12}} \left(1 - \frac{\epsilon^2}{2}\right) \left(m_{h_2}^2 - m_{h_3}^2\right)$$

$$\mathrm{Re}[\tilde{Z}_6] = \frac{\epsilon}{2v^2} s_{2\theta_{12}} \left(m_{h_3}^2 - m_{h_2}^2\right) \ ,$$

$$\mathrm{Im}[\tilde{Z}_6] = \frac{\epsilon}{v^2} \left(m_{h_2}^2 - m_{h_3}^2 c_{12}^2 - m_{h_1}^2 s_{12}^2\right) \ ,$$

$$\mathrm{CPC1}: \quad \mathrm{Im}[\tilde{Z}_5] = \mathrm{Im}[\tilde{Z}_6] = \mathrm{Im}[\tilde{Z}_7] = 0$$

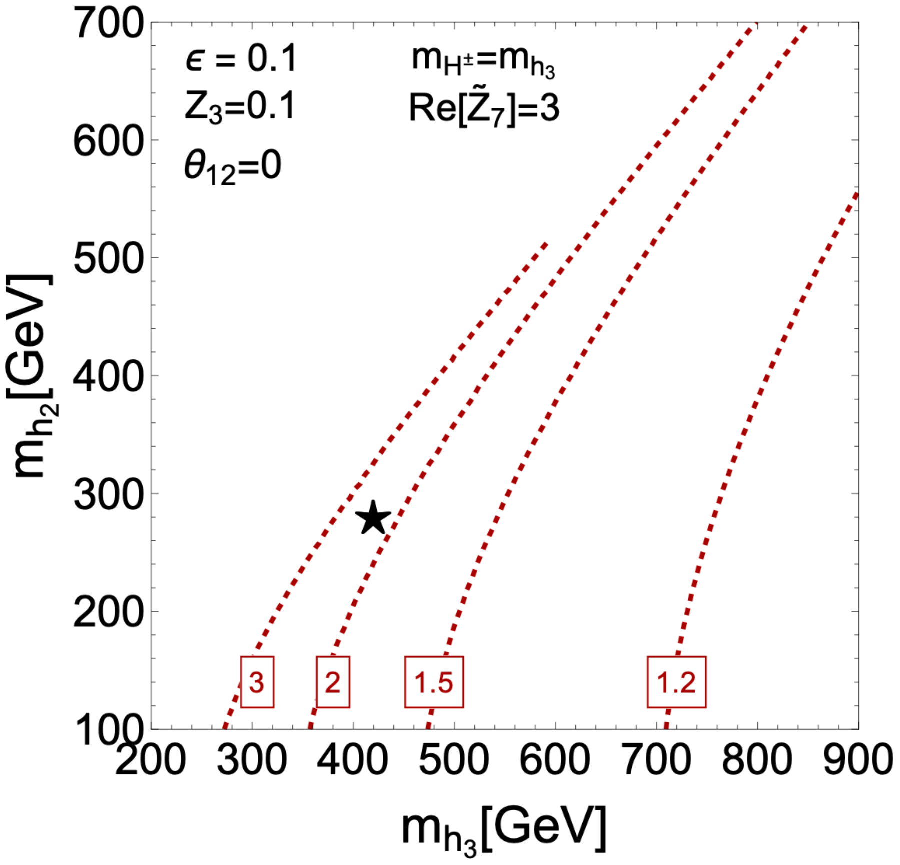
$$\mathrm{CPC2}: \quad \mathrm{Im}[\tilde{Z}_5] = \mathrm{Re}[\tilde{Z}_6] = \mathrm{Re}[\tilde{Z}_7] = 0$$

CP CONSERVATIVE AND ALIGNMENT LIMIT CTHDM

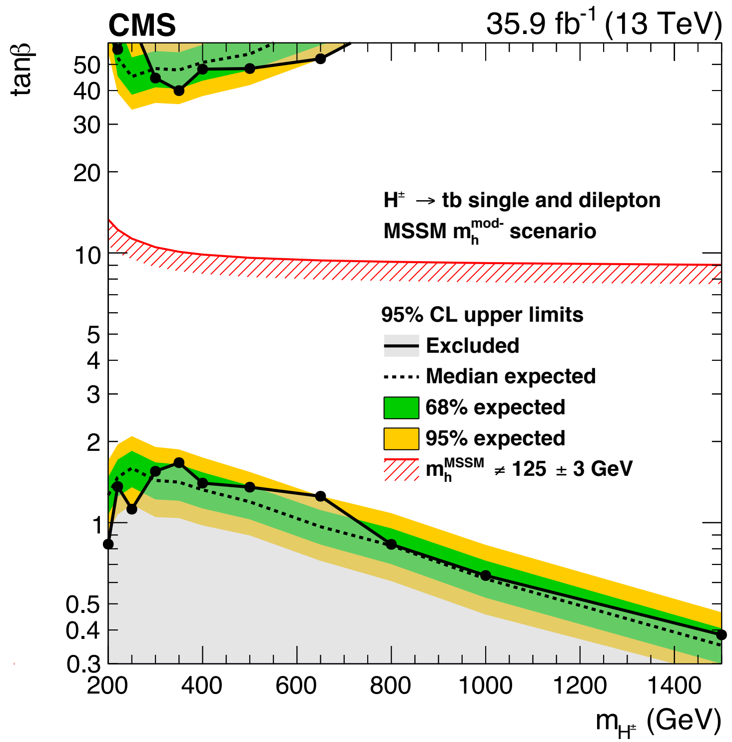
- We are interested in the interplay between the Higgs alignment and CPX in C2HDM. There are two important experimental observations:
  - The 125 GeV Higgs is SM-like. ($m_{h_1} = 125\mathrm{GeV}$)
  - EDM places stringent constraints on CPX.
- These motivates considering the small departures from
  - The exact alignment limit. (Mixing among 3 Higgs)
  - The exact CP-conserving limit. ($\mathrm{Im}[Z_7]\sim 0, \mathrm{Re}[Z_7]\sim 0, \theta_{23} \neq 0, \frac{\pi}{2}$)

CHARGED HIGGS SEARCH

tanβ Contour



CMS, JHEP 2001 (2020) 096



- We choose $\tan\beta > 1$

OBLIQUE PARAMETERS

- The analysis of precision electroweak data get:

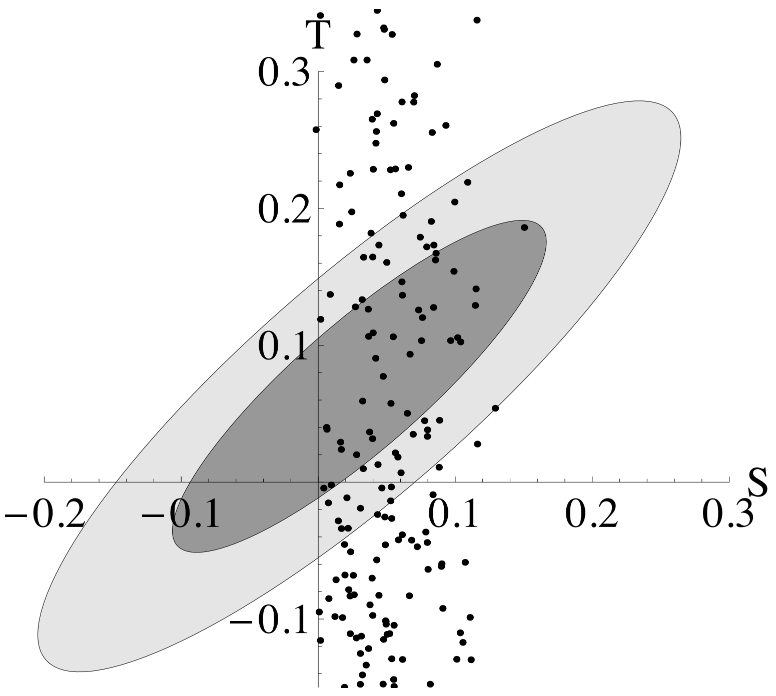
$$S = 0.01 \pm 0.10,$$
$$T = 0.03 \pm 0.11,$$
$$U = 0.06 \pm 0.10,$$

- In the alignment Limit:

$$S \simeq \frac{m_{h_2}^2 + m_{h_3}^2 - 2m_{H^\pm}^2}{24\pi\Lambda^2}$$

$$T \simeq \frac{(m_{H^\pm}^2 - m_{h_2}^2)(m_{H^\pm}^2 - m_{h_3}^2)}{48\pi s_W^2 m_W^2 m_{h_3}^2}$$

- We choose $m_{H^\pm}^2 \sim m_{h_2}^2$



(b)

H.Haber, D.O'Neil Phys.Rev. D83 (2011) 055017

ELECTRON EDM CONSTRAINT

- Fermion contributions:

$$d_f^V(f') \propto \sum_j^3 \int_0^1 dz \left\{ \mathrm{Im}[\kappa_f^j]\mathrm{Re}[\kappa_{f'}^j] \left(\frac{1}{z} - 2(1-z) \right) + \mathrm{Re}[\kappa_f^j]\mathrm{Im}[\kappa_{f'}^j]\frac{1}{z} \right\} C_{f'f'}^{VH_j^0}(z)$$

- Higgs boson-loop contributions:

$$d_f^V(H^\pm) = -\frac{em_f}{(16\pi^2)^2} 4g_{Vff}^v g_{H^+H^-V} \sum_j^3 \mathrm{Im}[\kappa_f^j] \frac{g_{H^+H^-H_j^0}}{v} \int_0^1 dz\,(1-z)\, C_{H^\pm H^\pm}^{VH_j^0}(z)$$

$$d_f^V(H^\pm H^0) = -\frac{eg^2 m_f}{2\,(16\pi^2)^2} \sum_j^3 \mathrm{Im}[\kappa_f^j] \frac{g_{H^+H^-H_j^0}}{v} \int_0^1 dz\,(1-z)\, C_{H^\pm H_j^0}^{WH^\pm}(z).$$

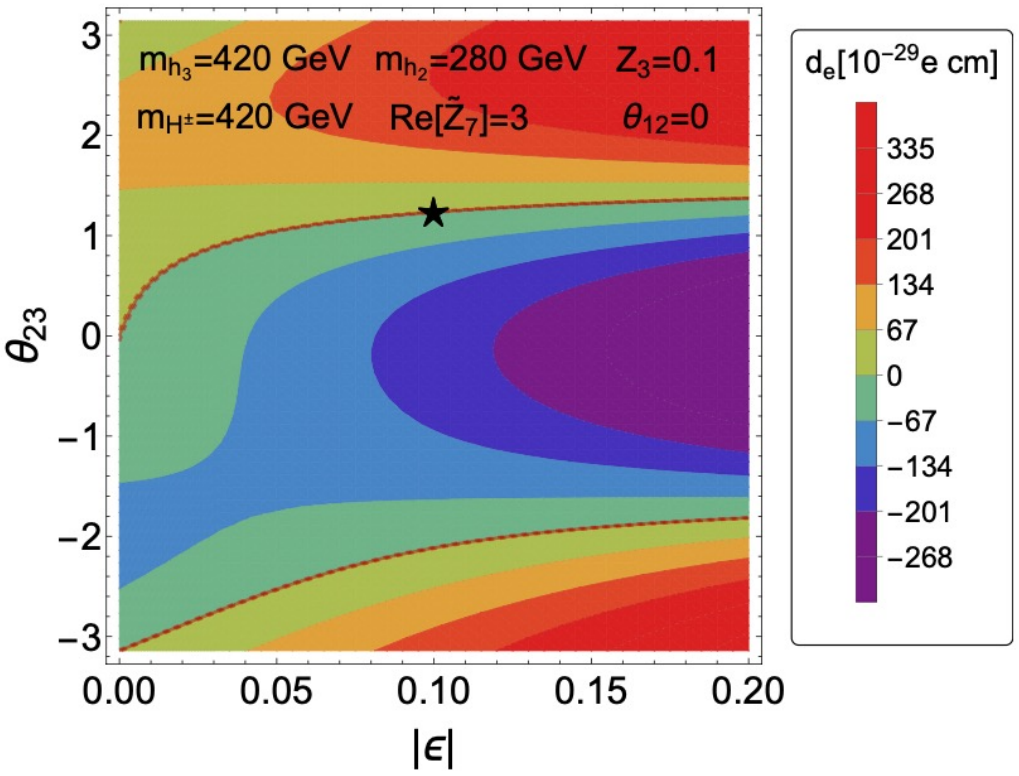
- gauge-loop contributions

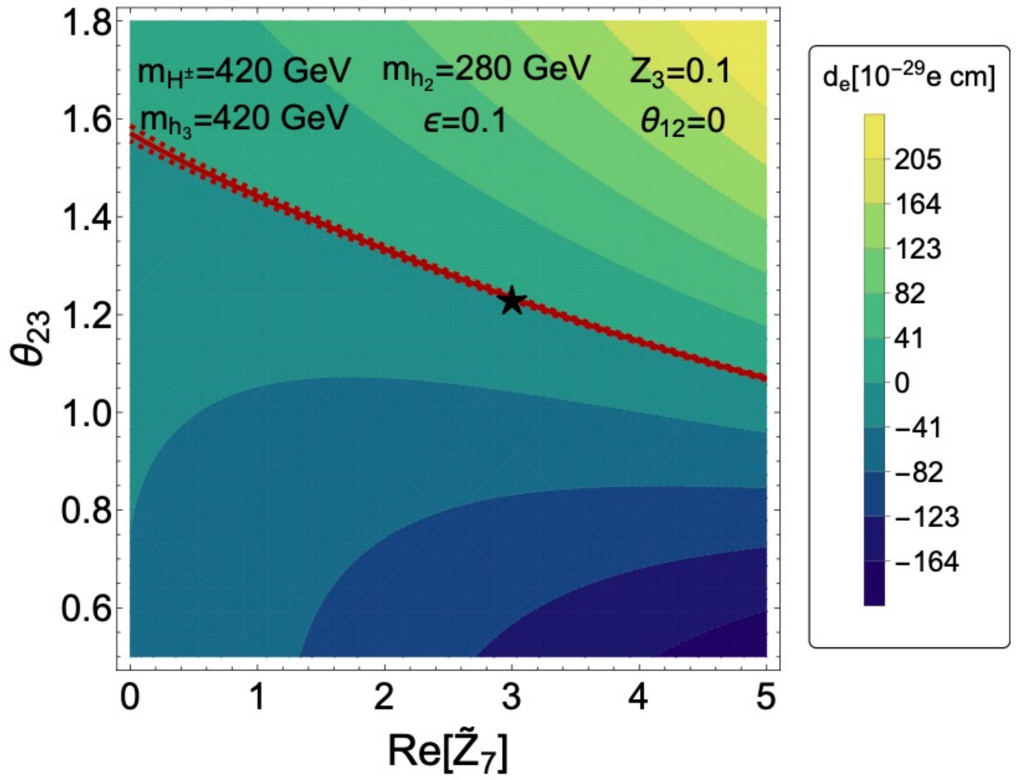
$$d_f^V(W) = \frac{em_f}{(16\pi^2)^2} 8g_{Vff}^v g_{WWV} \frac{m_W^2}{v^2} \sum_j^3 \widetilde{R}_{j1}\mathrm{Im}[\kappa_f^j] \times \int_0^i dz \left[\left\{ \left(6 - \frac{m_V^2}{m_W^2}\right) + \left(1 - \frac{m_V^2}{2m_W^2}\right) \frac{m_{H_j^0}^2}{m_W^2} \right\} \frac{1-z}{2} - \left(4 - \frac{m_V^2}{m_W^2}\right) \frac{1}{z} \right] C_{WW}^{VH_j^0}(z)$$

$$d_f^W(WH^0) = \frac{eg^2 m_f}{2\,(16\pi^2)^2} \frac{m_W^2}{v^2} \sum_j^3 \widetilde{R}_{j1}\mathrm{Im}[\kappa_f^j] \int_0^i dz \left\{ \frac{4-z}{z} - \frac{m_{H^\pm}^2 - m_{H_j^0}^2}{m_W^2} \right\} (1-z)\, C_{WH^\pm}^{WH_j^0}(z)$$

ELECTRON EDM CONSTRAINT

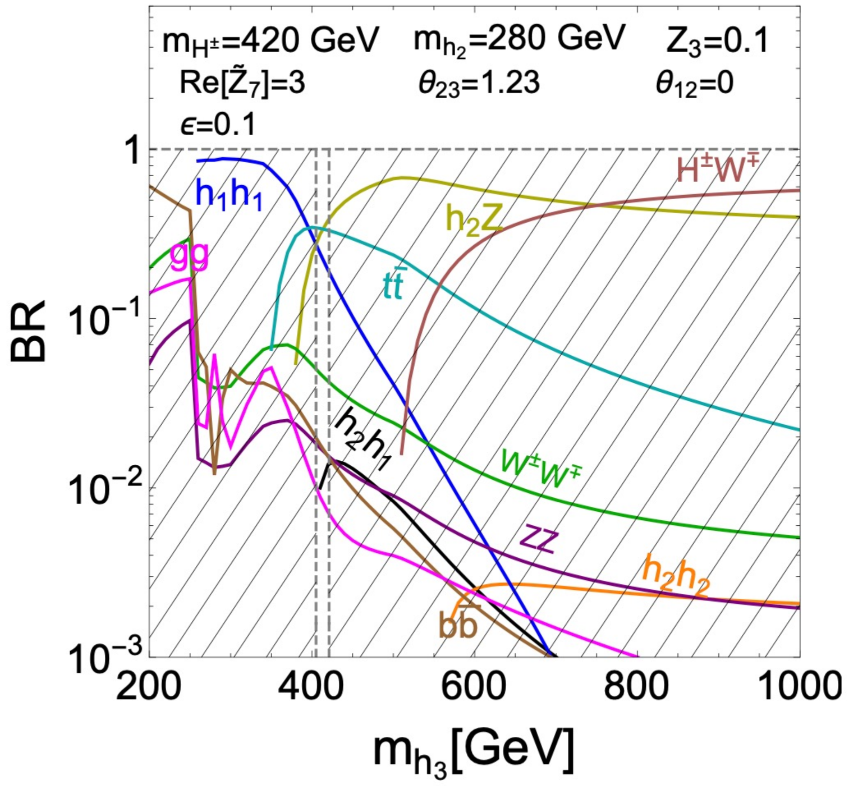
$$\left\{m_{h_3}, \theta_{12} = \frac{\pi}{2}, \epsilon, Z_3, \mathrm{Re}[\tilde{Z}_7], m_{h_2} = m_{H^\pm}\right\} + \theta_{23}$$

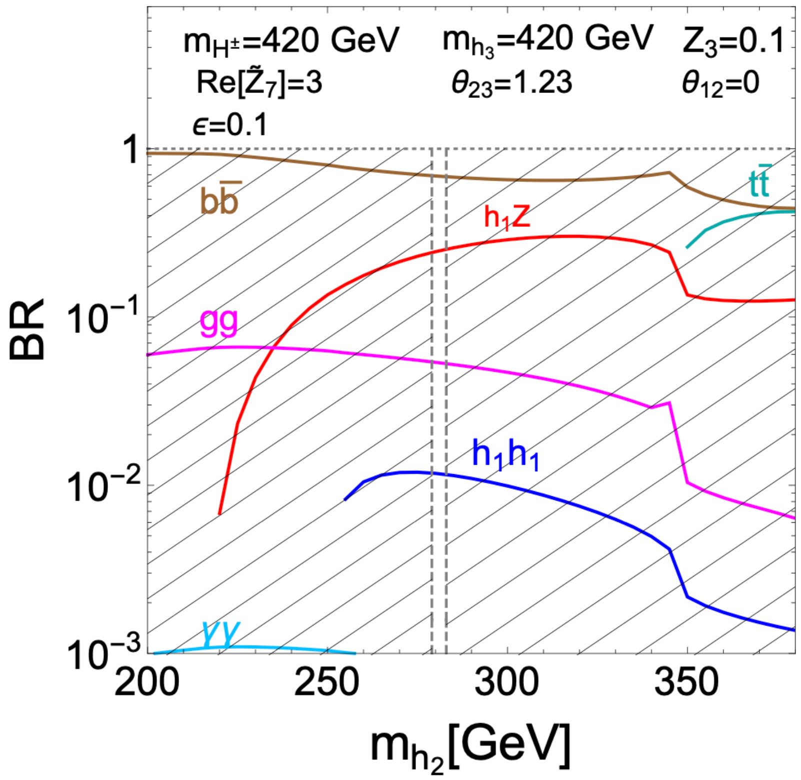




COLLIDER PHENOMENOLOGY

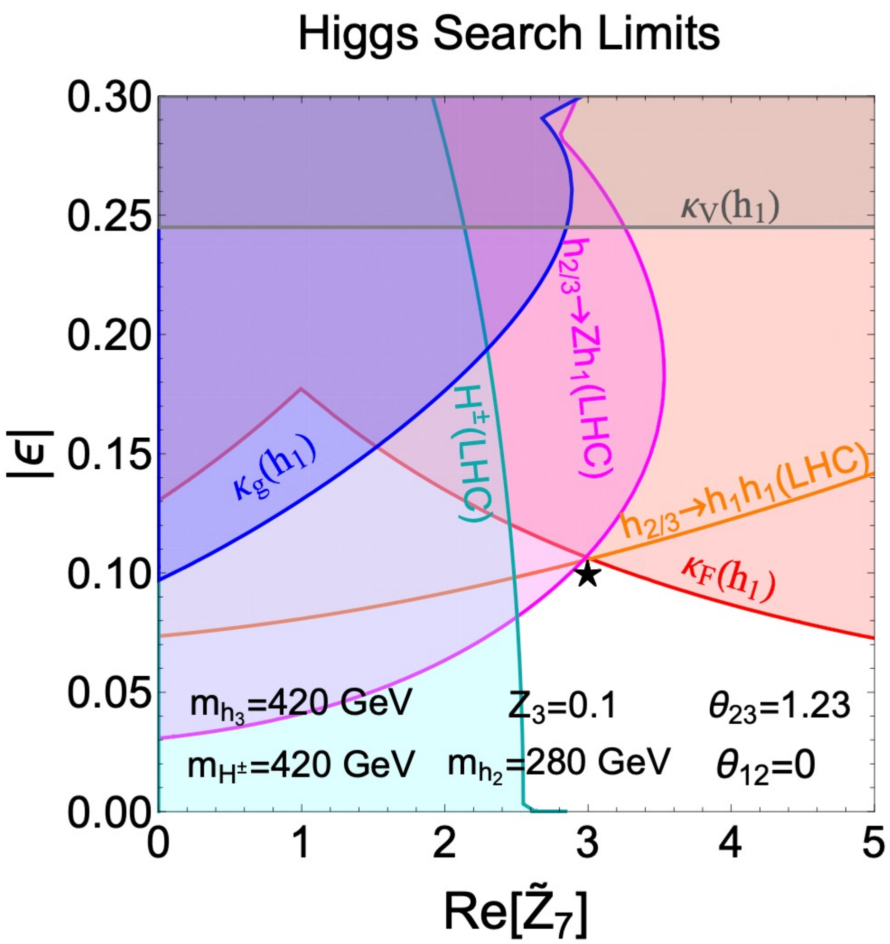
- Branching ratios for benchmark points: $g_{h_1 h_2 h_3} = \epsilon\, v\, \mathrm{Re}[\tilde{Z}_7 e^{-2i\theta_{12}}]$



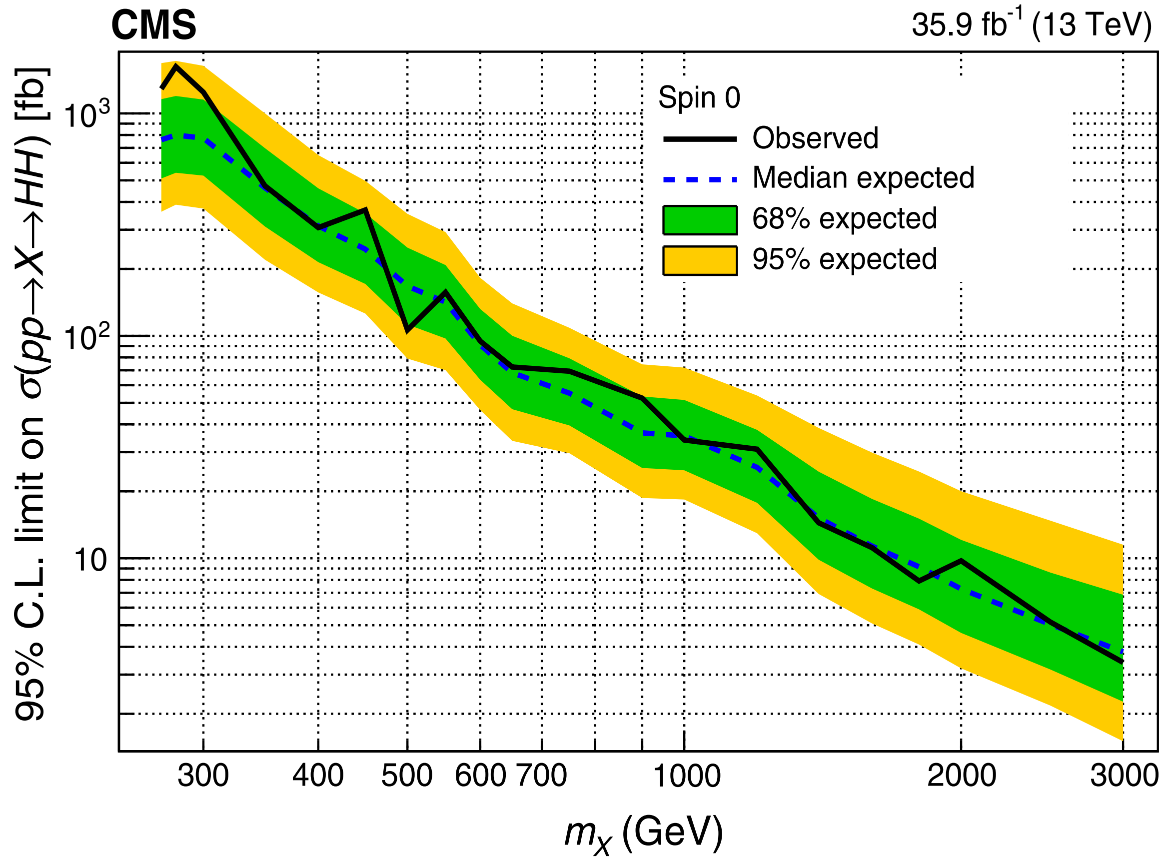


$$\sigma(gg \to h_2) \simeq 5.8\text{pb}, \qquad \sigma(gg \to h_3) \simeq 2.7\text{pb}$$

OTHER CONSTRAINTS



CMS, PhysRevLett.122.121803



SUMMARY

- THERE IS AN INTERESTING INTERPLAY BETWEEN ALIGNMENT LIMIT AND CP CONSERVING LIMIT IN C2HDM. IN ONE CASE, THE ALIGNMENT LIMIT IS IDENTICAL WITH THE CP-LIMIT, WHILE IN THE OTHER CASE THEY ARE INDEPENDENT.
- THERE IS A SMOKING-GUN SIGNAL FOR CP VIOLATION AT THE LHC IN C2HDM, WITHOUT RECOURSE TO ANGULAR DISTRIBUTIONS, BY SEARCHING FOR

$$h_3 \to h_2 h_1 \to h_1 h_1 h_1$$

Thank you