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HIGGS ALIGNMENT AND CP VIOLATION IN 2HDM

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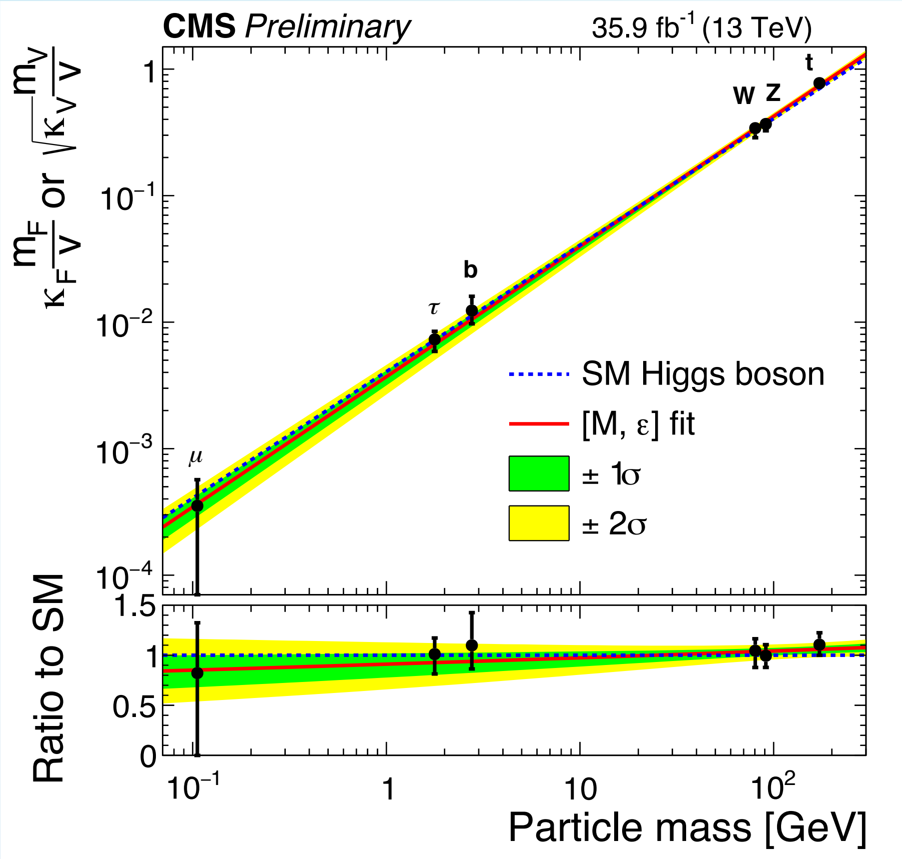
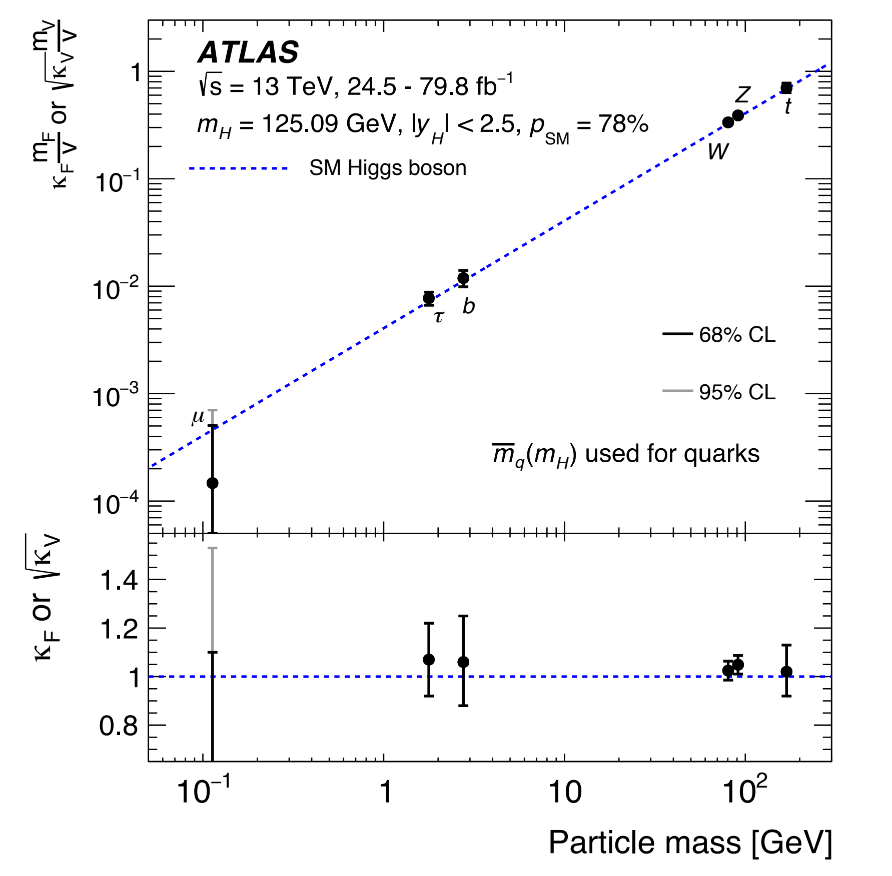
BASED ON ARXIV:2012.00773, COLLABORATED WITH IAN LOW, NAUSHEEN R. SHAH

SM MASS ORIGIN

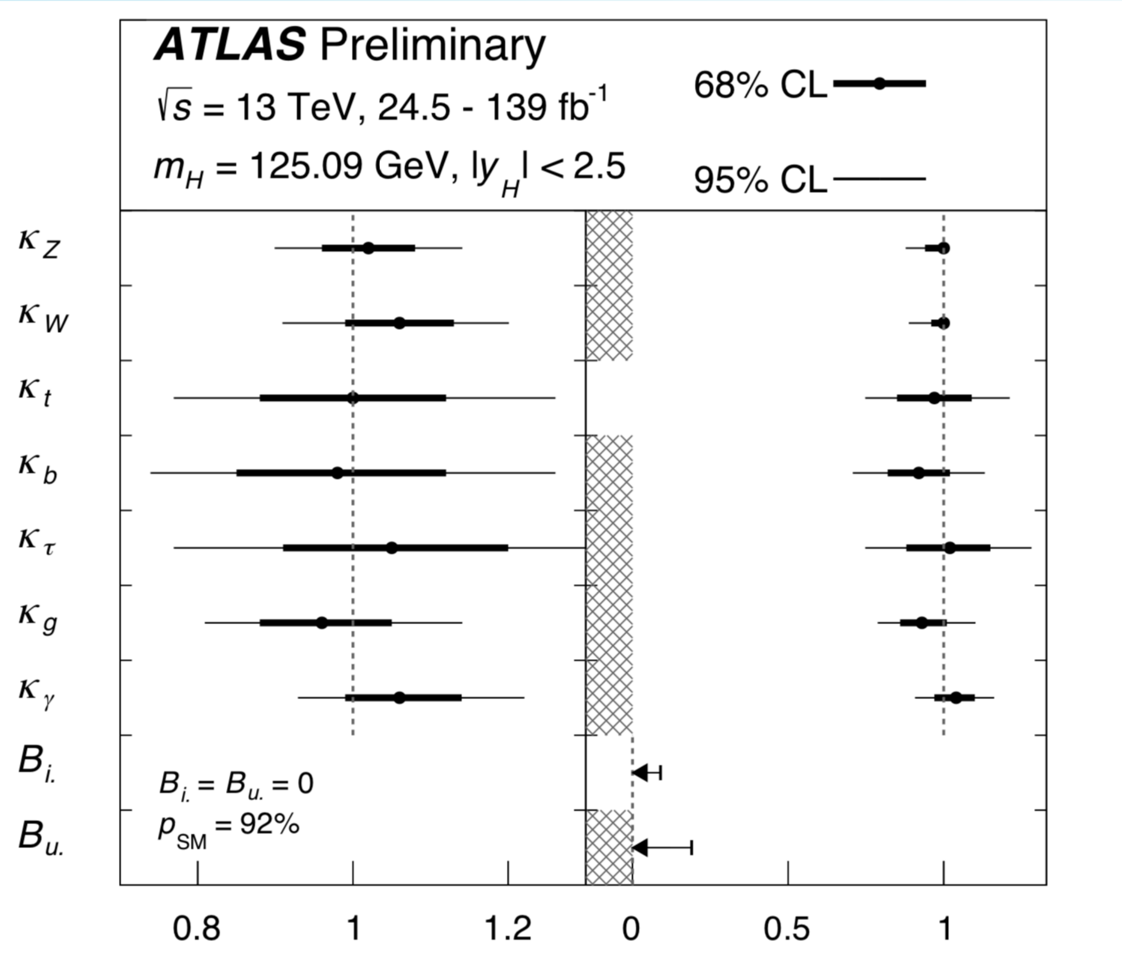


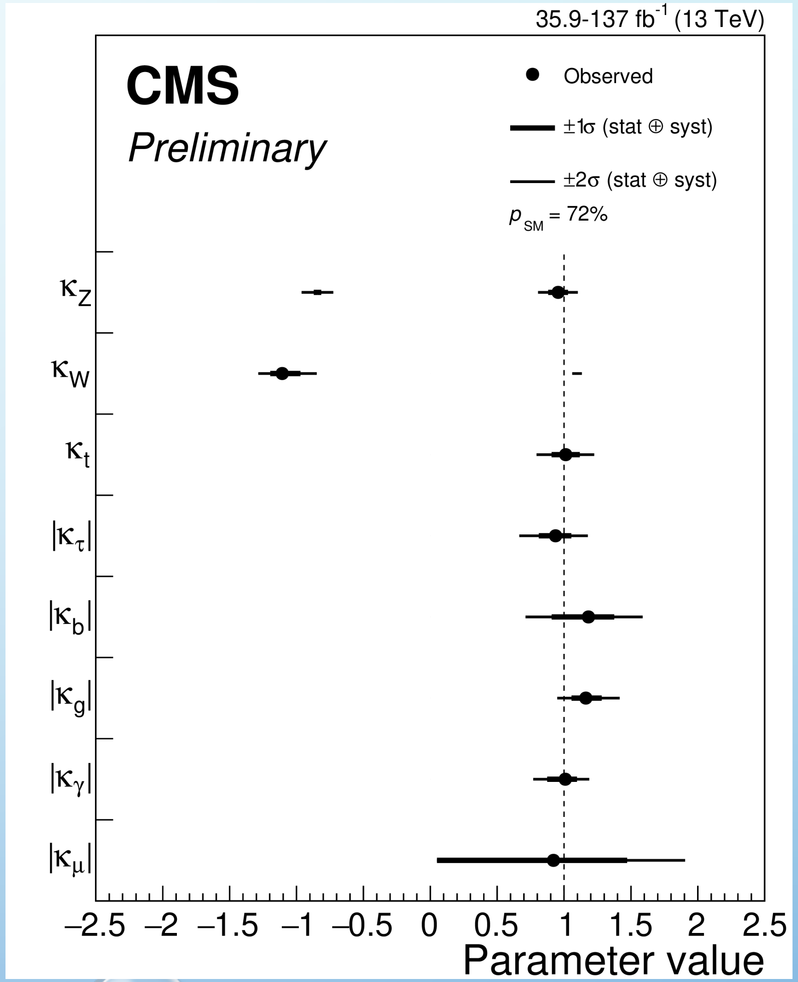


CMS, CMS-PAS-HIG-17-031

ATLAS, Phys.Rev. D101 (2020) no.1, 012002

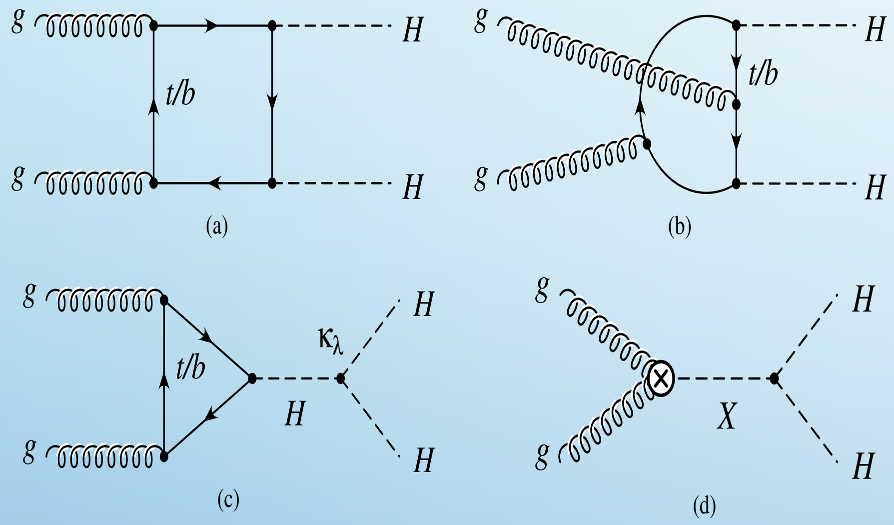
SM HIGGS SEARCH

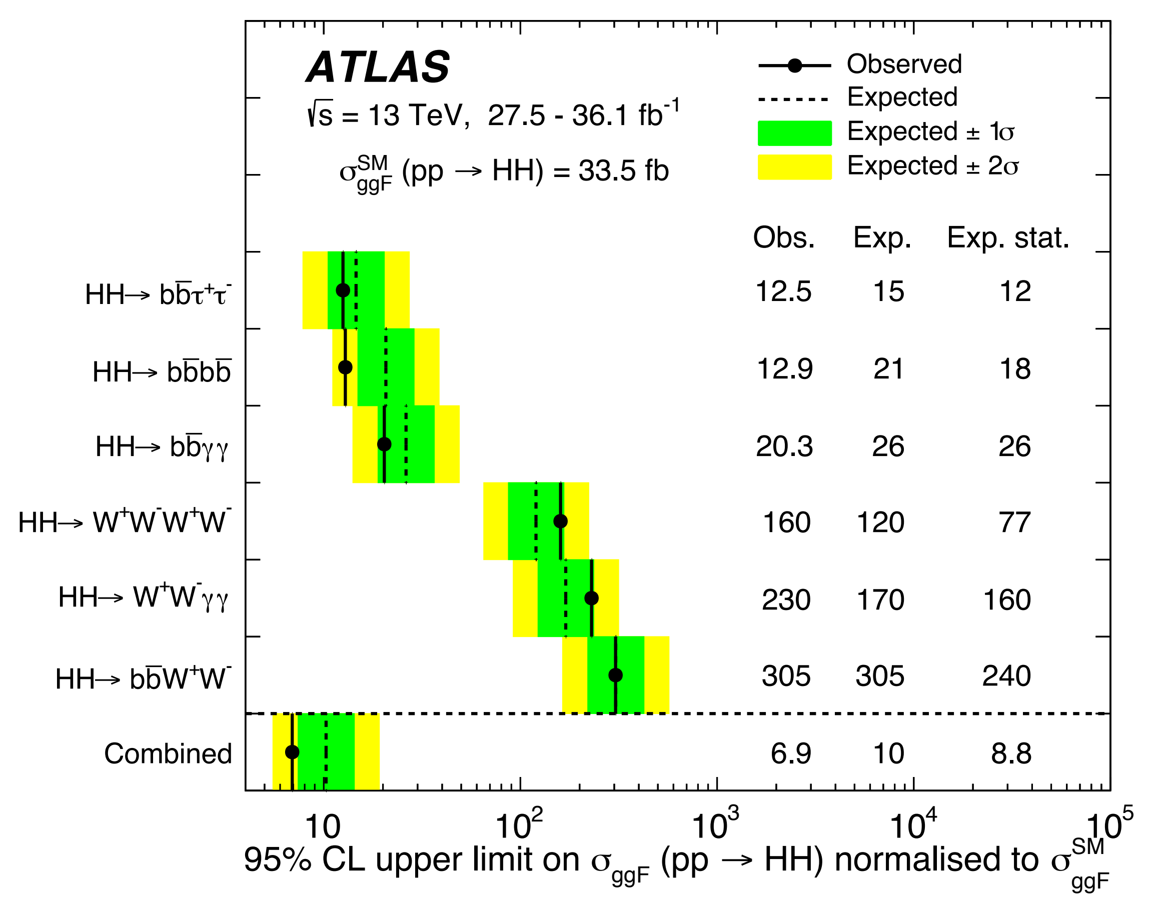




SM HIGGS SEARCH

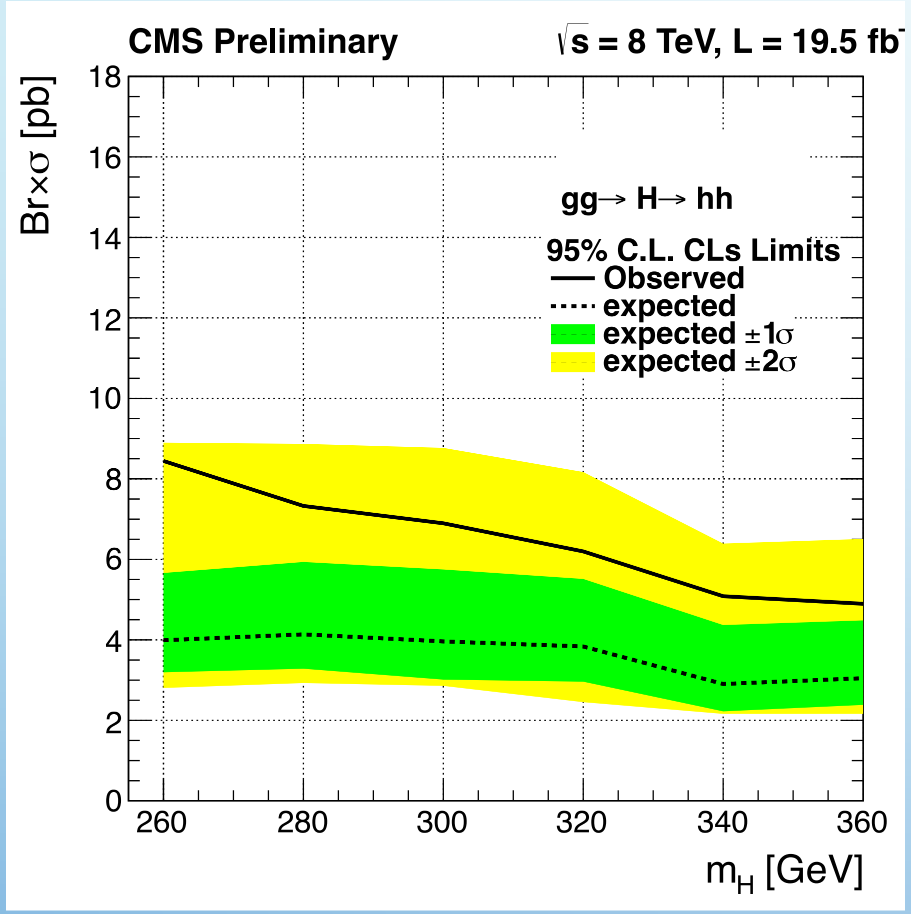
- SM Higgs self-interaction:



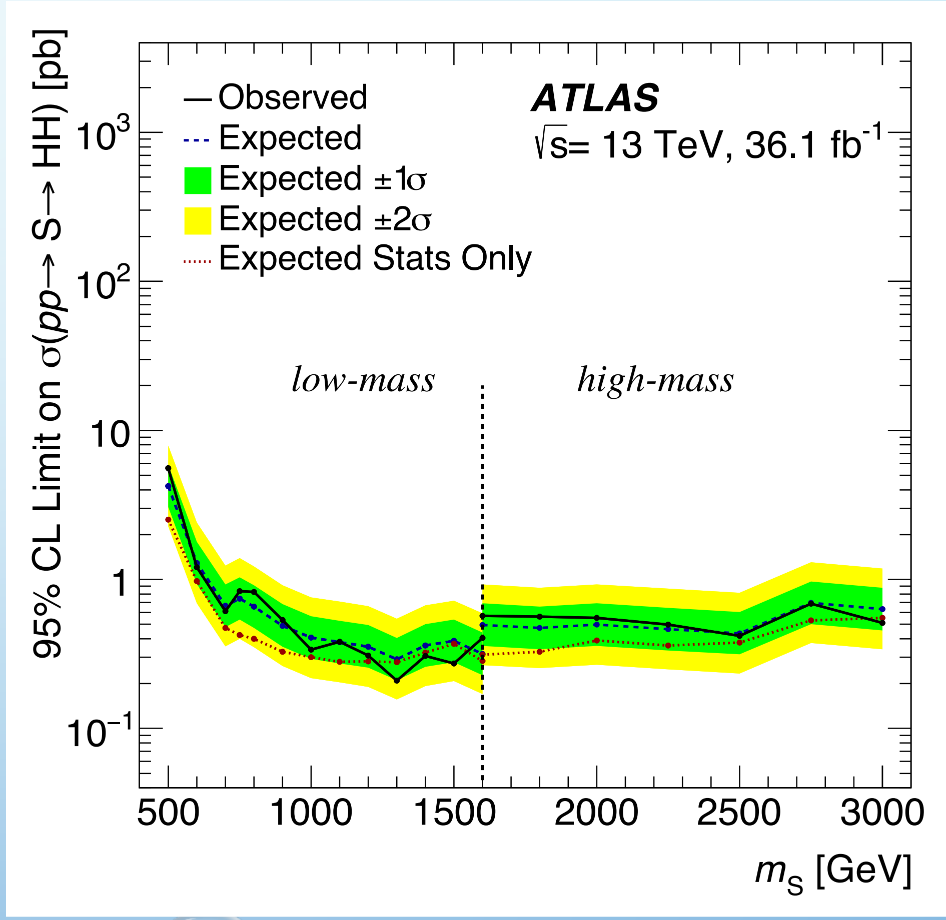


ATLAS, Phys. Lett. B 800 (2020) 135103

EXTRA NEUTRAL HIGGS SEARCH

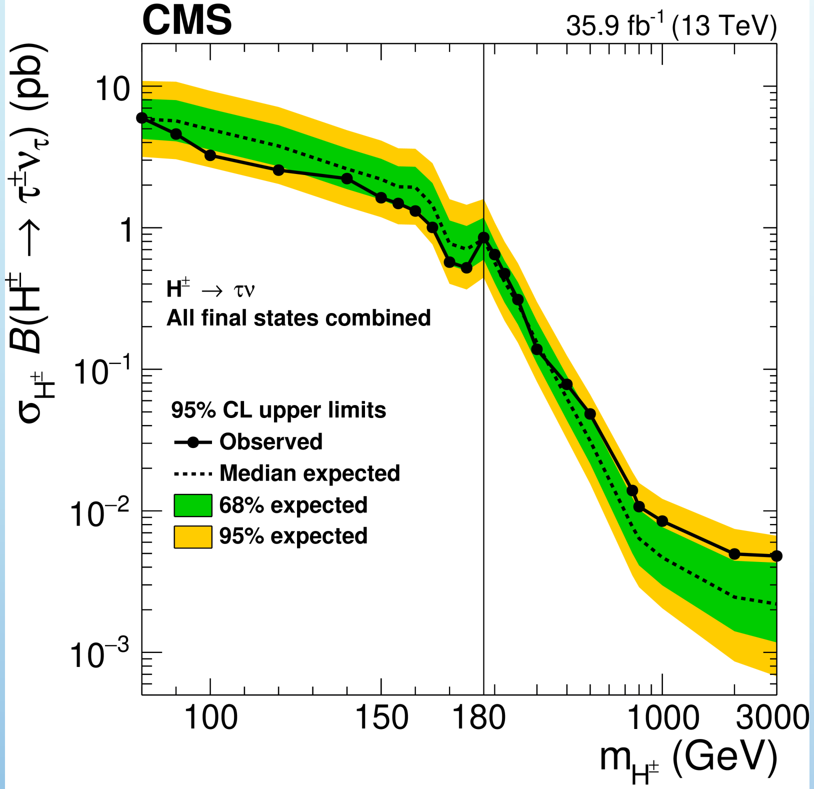


CMS, HIG-13-025-pas

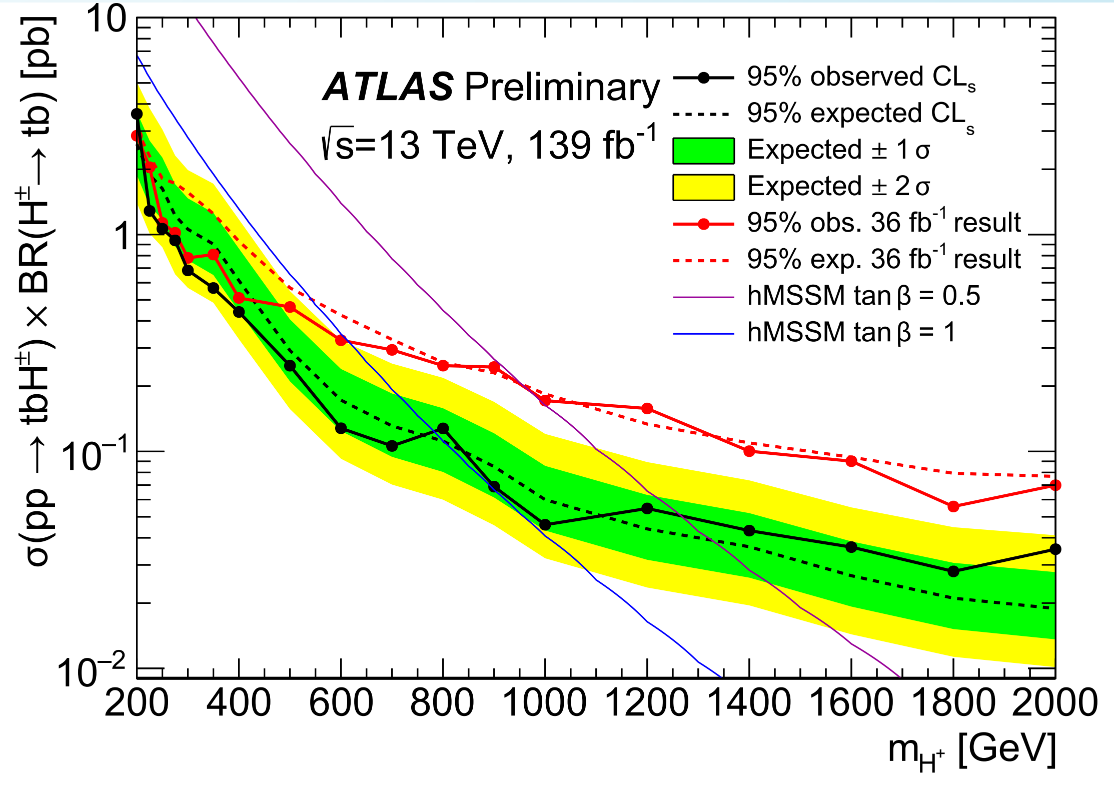


ATLAS, JHEP 1904 (2019) 092

EXTRA CHARGED HIGGS SEARCH



CMS, JHEP07 (2019) 142



ATLAS-CONF-2020-039

TWO HIGGS DOUBLET MODEL

- CP conserving 2HDM:

$$\mathcal{V} = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right]$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) - \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right] ,$$

- In the basis, all the parameters are real. The VEVs are:

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix} \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2} = 246\ \text{GeV} \qquad \tan\beta = \frac{v_2}{v_1}$$

- There are 8 real degrees of freedom:

3 eaten Goldstones and 5 physical scalars -- 2 charged Higgs, 1 CP-odd neutral Higgs and 2 CP-even neutral Higgs.

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:

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

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

- Higgs –V-V couplings:

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

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

CP VIOLATION THDM

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

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

- Minimization condition in the Higgs basis:

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

- Z_2 Symmetry:

Haber+collaborators: 2001.01430

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

- 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:

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

CP CONSERVATIVE LIMIT

- Higgs mixing:

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

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

- Relationships between Z_i and mixing angles:

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

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

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

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

$\Rightarrow$

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

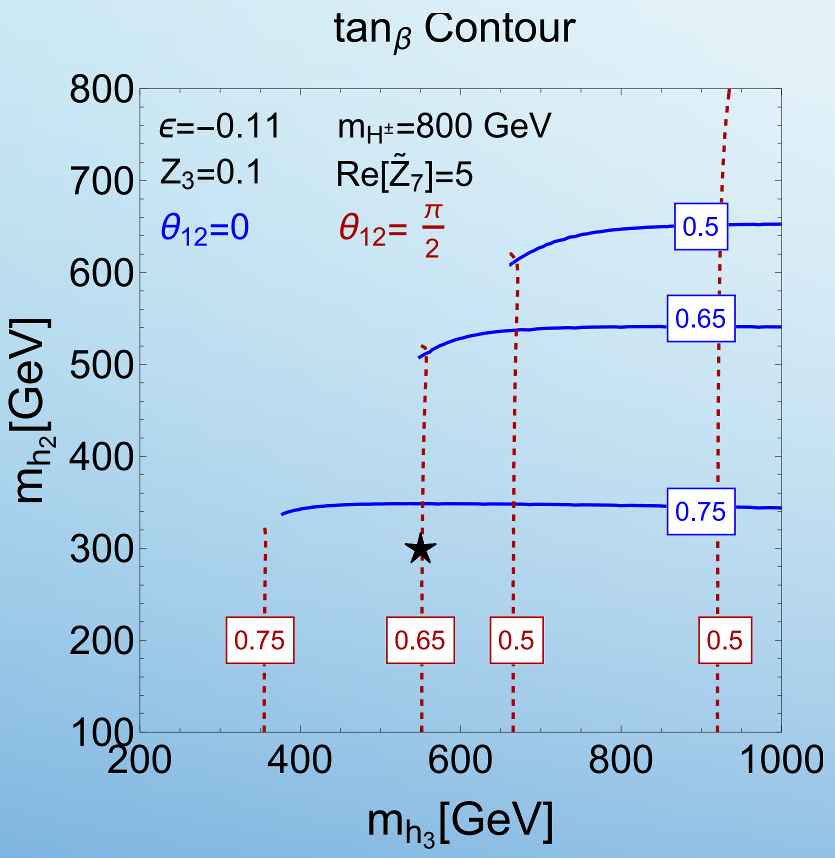
$$\mathrm{CPC2}:\ \mathrm{Im}[\tilde{Z}_5] = \mathrm{Re}[\tilde{Z}_6] = \mathrm{Re}[\tilde{Z}_7] = 0$$

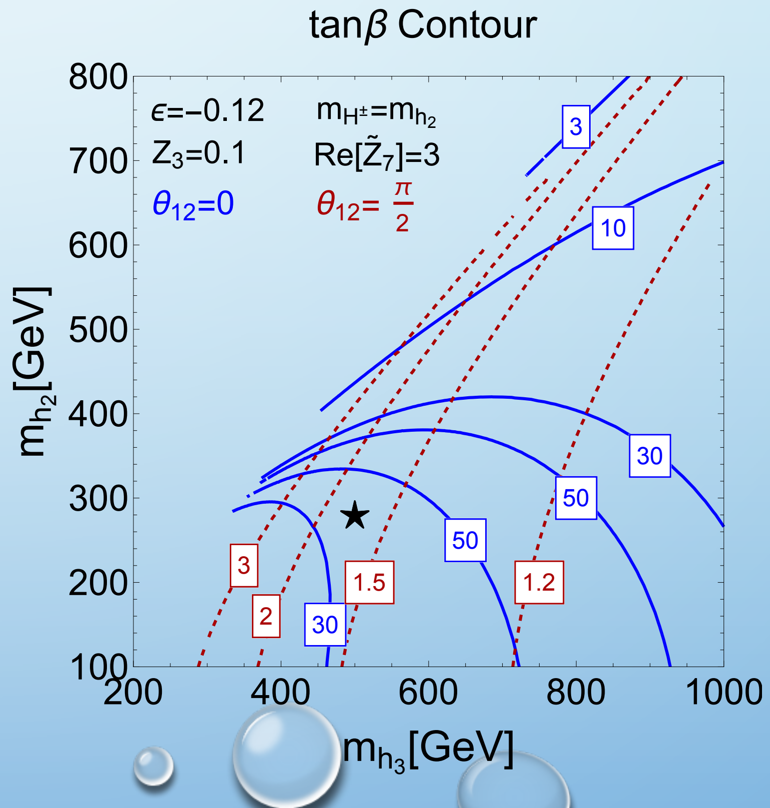
CP CONSERVATIVE AND ALIGNMENT LIMIT CTHDM

- 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. ($m_{h_1} = 125\text{GeV}$)
  - 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. ($\text{Im}[Z_7]\sim 0, \text{Re}[Z_7]\sim 0, \theta_{23} \neq 0, \frac{\pi}{2}$)

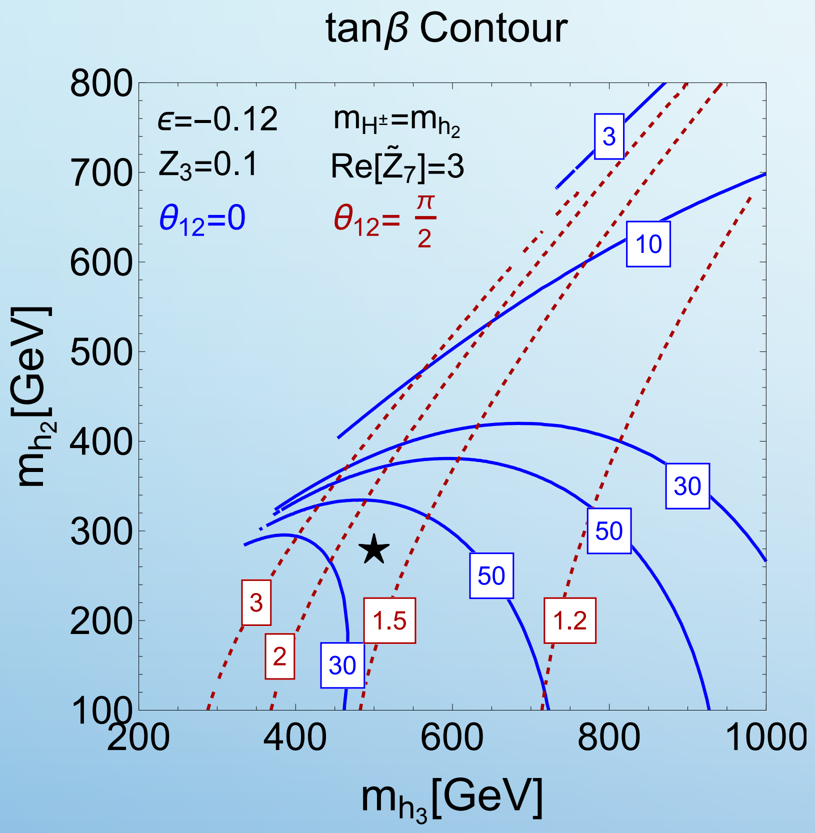
OTHER PARAMETERS DEPENDENCE

$$Z_2 \simeq Z_1 + \frac{(\mathrm{Re}[\tilde{Z}_7])^2}{Z_{3451}} \qquad \mathrm{Im}[\tilde{Z}_7] \simeq -\left(1 + \frac{\mathrm{Re}[\tilde{Z}_7]}{\mathrm{Re}[\tilde{Z}_5]Z_{3451}}\right)\mathrm{Im}[\tilde{Z}_6] \qquad \tan 2\beta = \pm\frac{2|Z_{67}|}{Z_2 - Z_1}$$

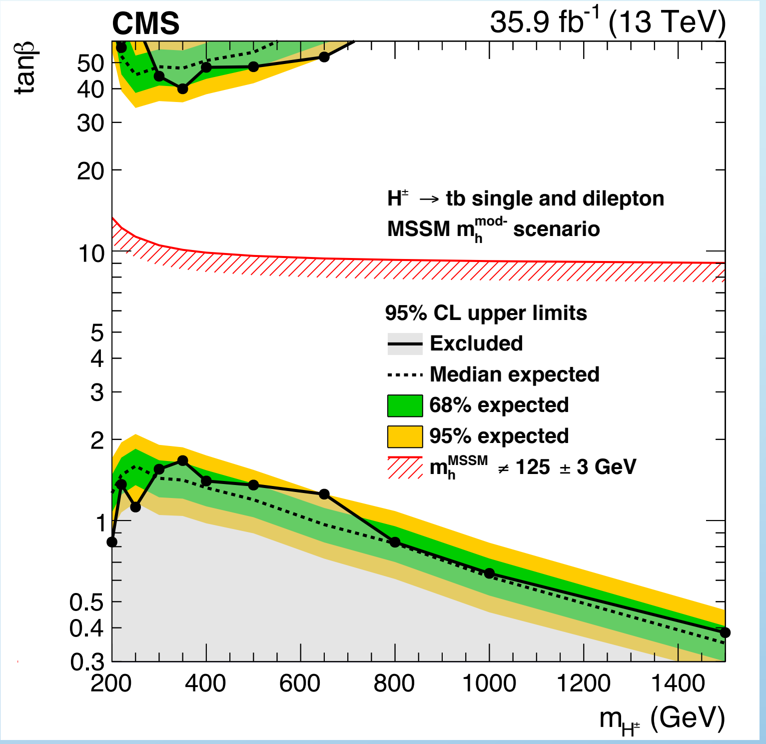




CHARGED HIGGS SEARCH



CMS, JHEP 2001 (2020) 096



- We choose $\tan\beta > 1$

OBLIQUE PARAMETERS

- The analysis of precision electroweak data get:

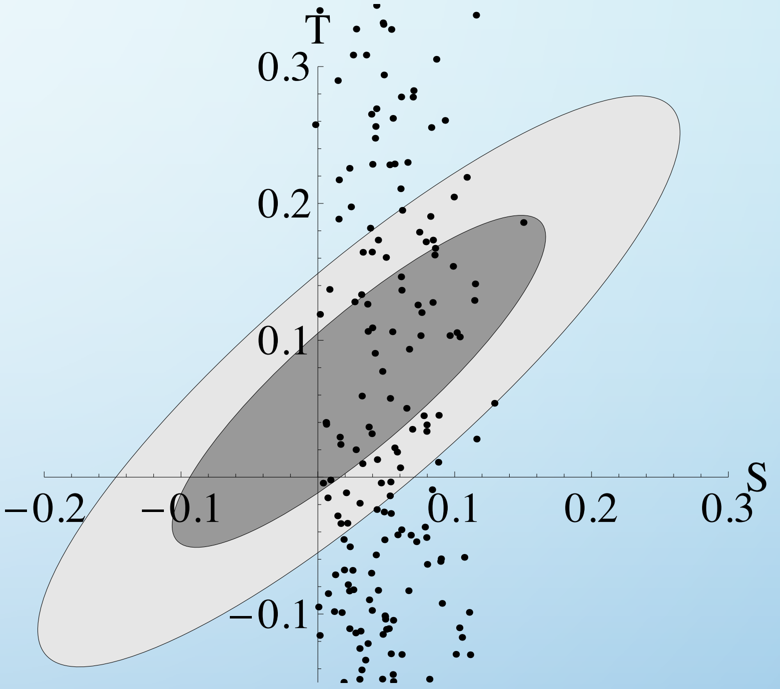
$$S = 0.01 \pm 0.10,$$
$$T = 0.03 \pm 0.11,$$
$$U = 0.06 \pm 0.10,$$

- 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:

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

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

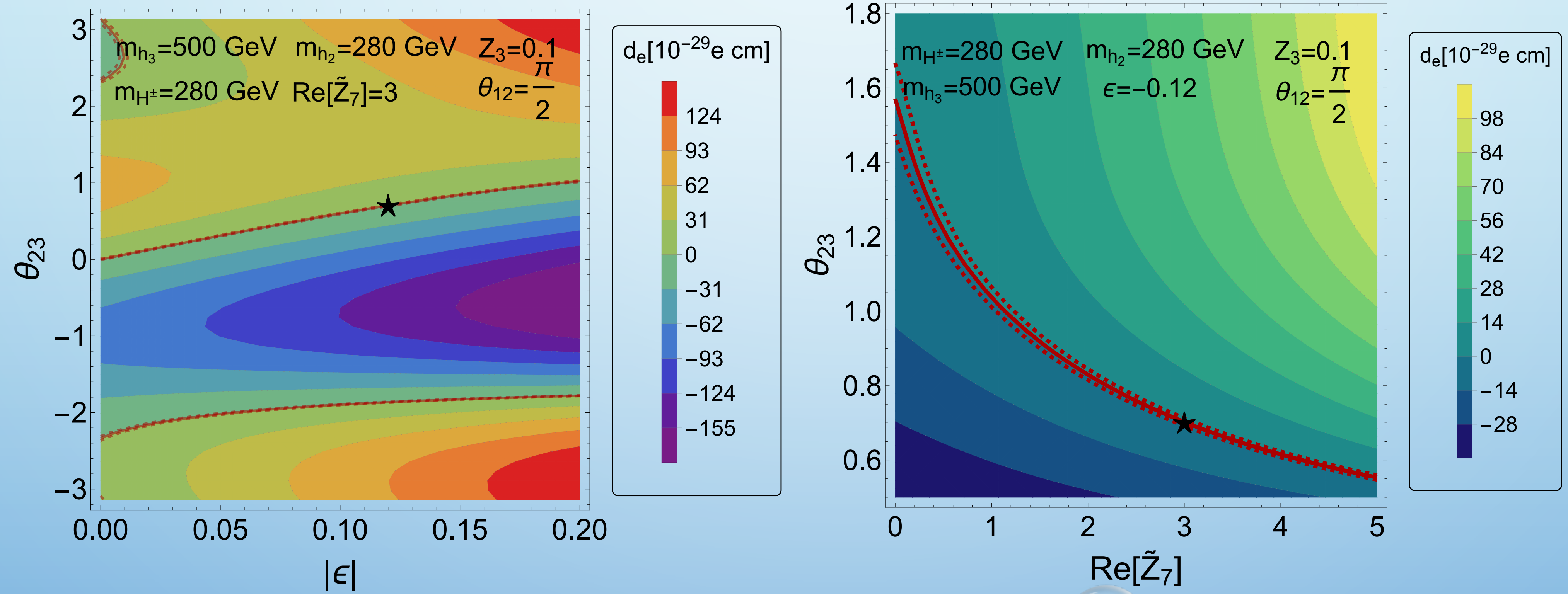
- gauge-loop contributions

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

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

ELECTRON EDM CONSTRAINT

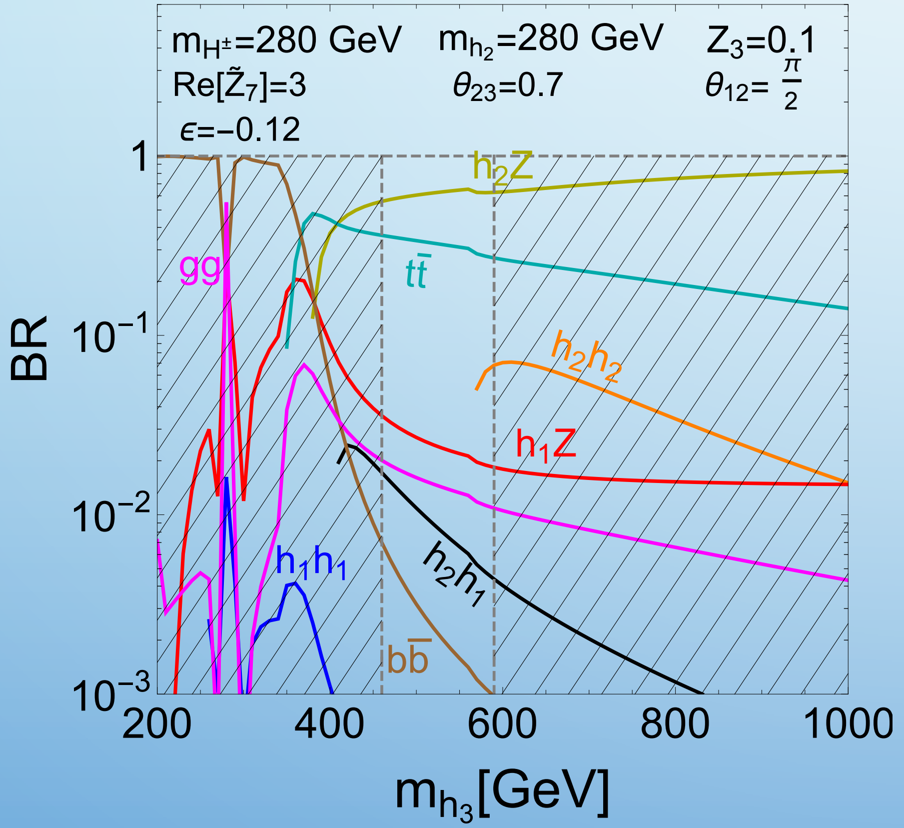
$$\left\{m_{h_3}, \theta_{12} = \frac{\pi}{2}, \epsilon, Z_3, \mathrm{Re}[\tilde{Z}_7], m_{h_2} = m_{H^\pm}\right\} + \theta_{23}$$

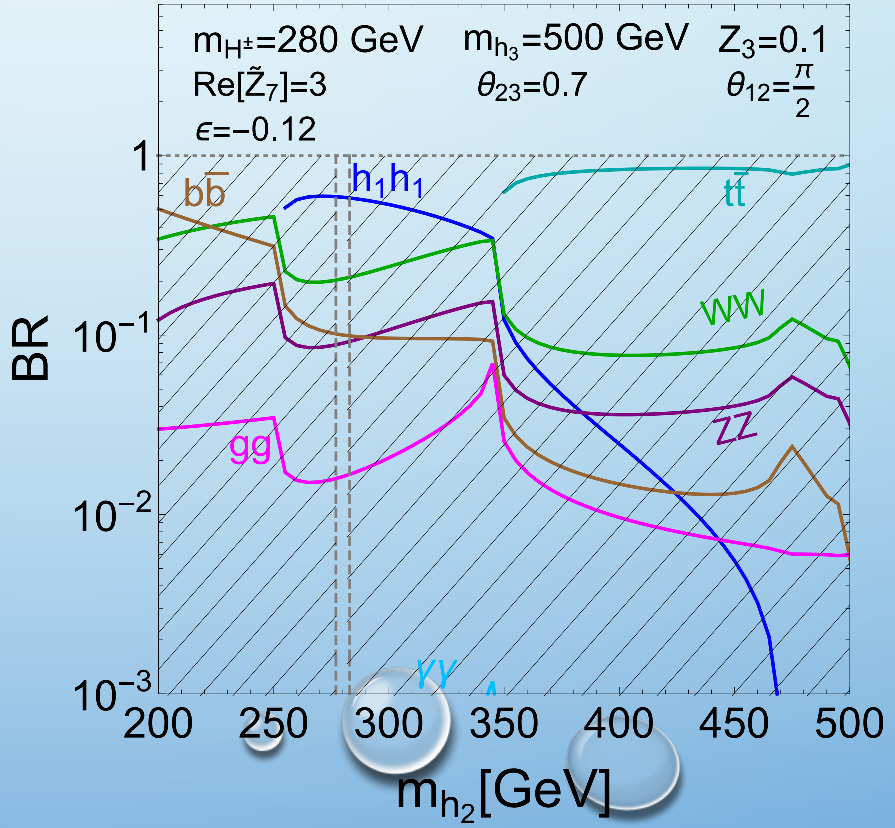


COLLIDER PHENOMENOLOGY

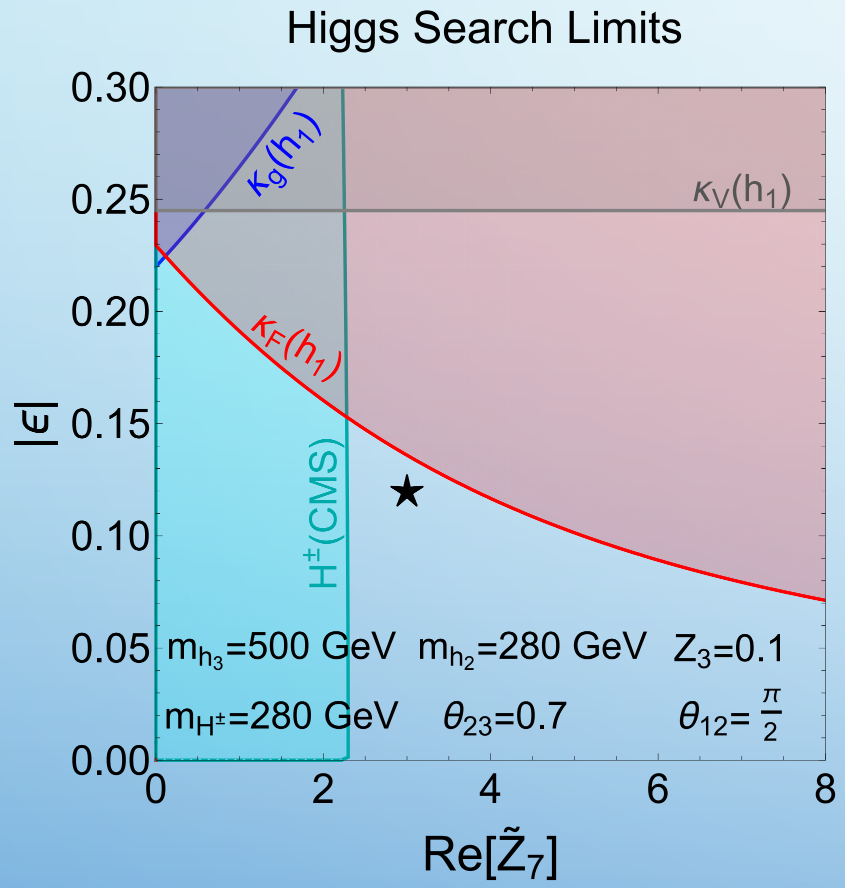
$$\sigma(gg \to h_2) \simeq 1.7 \text{ pb} , \qquad \sigma(gg \to h_3) \simeq 0.36 \text{ pb}$$

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

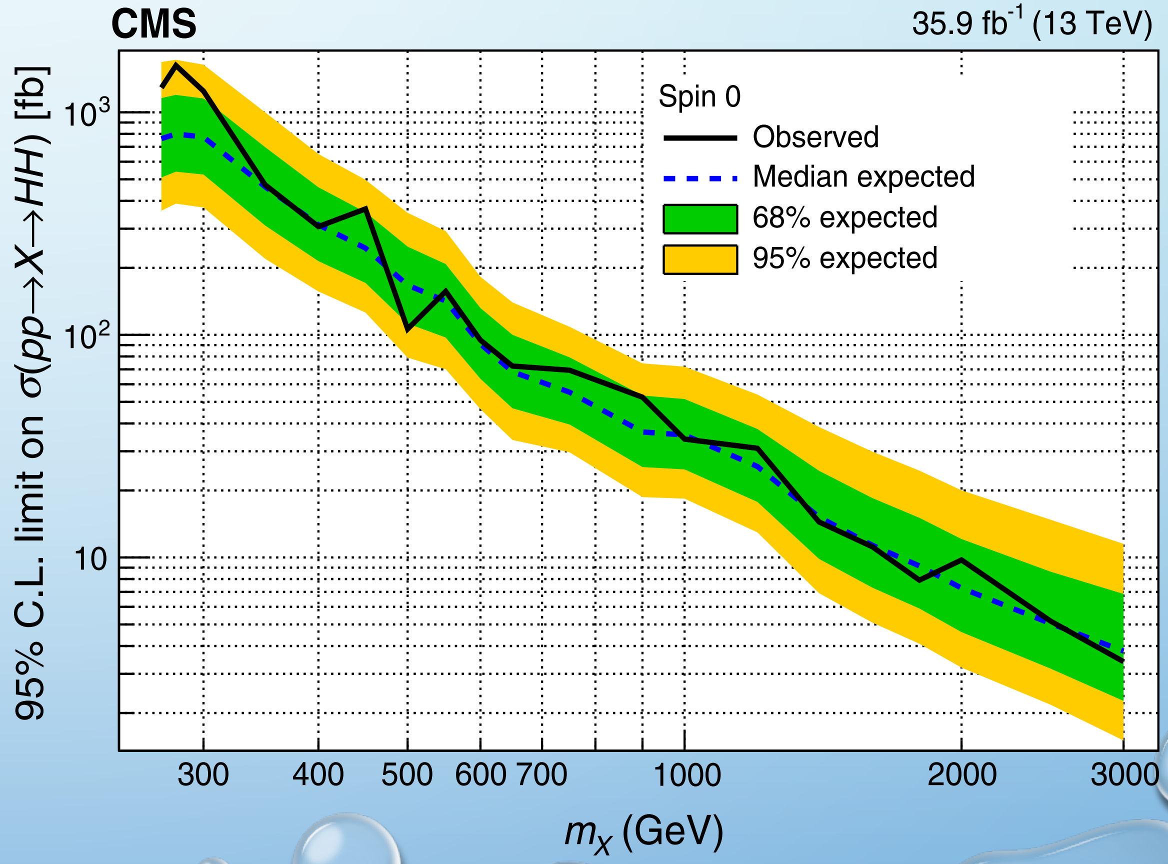




OTHER CONSTRAINTS



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