Search for a lighter Higgs in Two Higgs Doublet Models

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In collaboration with Giacomo Cacciapaglia[1], Aldo Deandrea[1], Suzanne Gascon-Shotkin[1], Morgan Lethuillier[1], Junquan Tao[2]

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Motivations

- A Higgs boson discovered at LHC;
- Maybe other scalars waiting to be discovered;
- Two Higgs Doublet Model (2HDM): larger scalar sector than SM.

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The Two Higgs Doublet Model

How does it work ?

Reminder

- Two doublets: ϕ_1, ϕ_2, with vev v_1, v_2;
- Angle β: $\tan\beta = \frac{v_2}{v_1}$;
- Mass eigenstates $\Rightarrow$ angle α.

Physical scalars

- Two scalars: h, H;
- A pseudoscalar: A;
- Two charged higgs: $H^{\pm}$.

Parameters in the physical basis

$$m_h,\ m_H = 125\ GeV,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \sin(\beta-\alpha),\ m_{12}^2$$

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The Two Higgs Doublet Model

The different types of 2HDM

Different ways to couple ϕ_1, ϕ_2 to fermions:

	Type			
	I	II	Flipped	Lepton-specific
Up-type quarks	ϕ_2	ϕ_2	ϕ_2	ϕ_2
Down-type quarks	ϕ_2	ϕ_1	ϕ_1	ϕ_2
Leptons	ϕ_2	ϕ_1	ϕ_2	ϕ_1

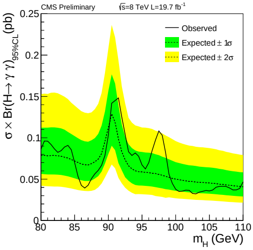
For simplicity: results only for Type I and II.

The Two Higgs Doublet Model

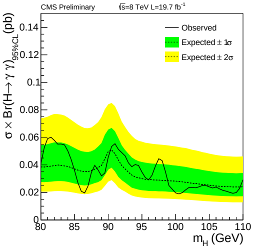
CMS limits on a lighter Higgs

- **Goal:** is LHC Run I at 8 TeV sensitive to a lighter scalar Higgs boson?
- **Channel of interest:** $h \to \gamma\gamma$ for $m_h \in [80; 110]$ GeV.

$\sigma_{gg\to h} \times BR_{h\to\gamma\gamma}$



$\sigma_{VBF/VH\to h} \times BR_{h\to\gamma\gamma}$



cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-14-037/index.html, [CMS-PAS-HIG-14-037]

The Two Higgs Doublet Model

Computation of the $\sigma \times BR_{h \to \gamma\gamma}$

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- **Branching ratios and widths:** computed with **2HDMC**.

  [Eriksson, Rathsmann, Stal; arXiv:0902.0851v2]

$$\kappa_g^2 = \frac{\Gamma_{ggh}^{2HDM}}{\Gamma_{ggh}^{SM}}, \qquad \kappa_V^2 = \frac{\Gamma_{WW}^{2HDM}}{\Gamma_{WW}^{SM}} = \sin(\beta - \alpha)^2$$

- **Cross sections:** computed with the "kappa trick".

  [Cacciapaglia, Deandrea, Drieu La Rochelle, Flament; arXiv:1311.5132v2]

$$\sigma_{ggh}^{2HDM} \simeq \kappa_g^2 \times \sigma_{ggh}^{SM}, \qquad \sigma_{VBF+VH}^{2HDM} \simeq \kappa_V^2 \times \sigma_{VBF+VH}^{SM}$$

SM cross section taken from LHCHXSWG [CERN-2013-004], [arXiv:1307.1347].

Is it coherent with SusHi calculation ?

[Harlander, Liebler, Mantler; sushi.hepforge.org/manual/SusHi150.pdf]

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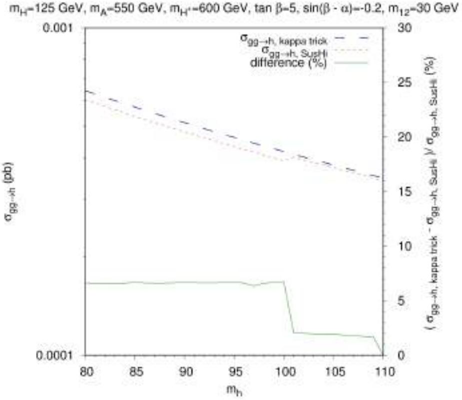
Comparison with SusHi for $gg \to h$ production mode



$\sigma_{gg \to h}$ with "kappa trick" (dashed blue line), SusHi (dotted red line) and deviation between the two (solid green line).

Deviation :

$$\Delta \equiv \frac{\sigma_{gg \to h}^{kappa\ trick} - \sigma_{gg \to h}^{\text{SusHi}}}{\sigma_{gg \to h}^{\text{SusHi}}} \times 100$$

- Good agreement for $gg \to h$ production mode;
- SusHi: only ggh and bbh production;
- We assume "kappa trick" can be used for VBF/VH production mode.

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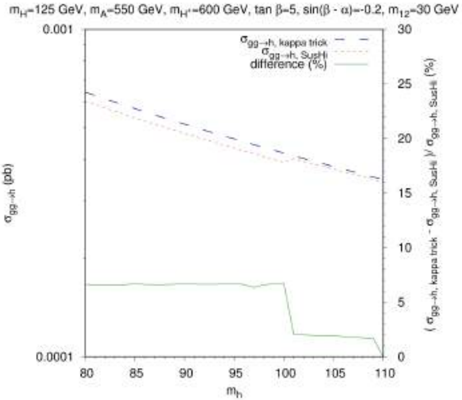

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Constraints on the 2HDM parameter space

Scan generation

- Generation of 1 million random points for each of the four different Types.

Inputs

$$m_h \in [80; 110]\ GeV, \qquad m_H = 125\ GeV, \qquad m_A \in [60; 1000]\ GeV,$$
$$m_{H^\pm} \in [60; 1000]\ GeV, \qquad \tan\beta \in [1/50; 50], \qquad \sin(\beta - \alpha) \in [-1; 1],$$
$$m_{12}^2 \in [-(300\ GeV)^2; +(200\ GeV)^2]$$

Constraints on the 2HDM parameter space

Three types of constraints

- **Indirect constraints:**
  - Electroweak precision tests (S, T, U parameters);
  - Stability, unitarity and perturbativity constraints;
  - Flavor constraints ($B \to X_s\gamma$, $B_s \to \mu\mu$, $\Delta_0(B \to K^*\gamma)$, ΔMd) (SuperIso *[Mahmoudi, arXiv:0808.3144]*)
- **LEP constraints** (HiggsBounds *[Bechtle et al., arXiv:0811.4169]*)
  Including limits on scalar and pseudo-scalar Higgs bosons and light charged Higgs bosons
- **LHC constraints** on the 125 GeV Higgs boson (Run I Legacy combination).
  [ATLAS-HIGG-2015-07; CMS-HIG-15-002], [arXiv:1606.02266]

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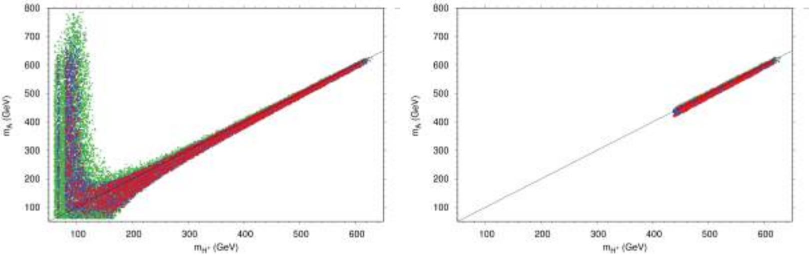
Constraints on the 2HDM parameter space

m_A and $m_{H^\pm}$

m_A vs $m_{H^\pm}$

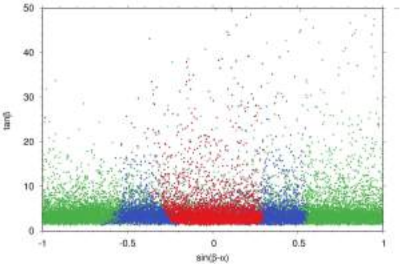


Type I Type II

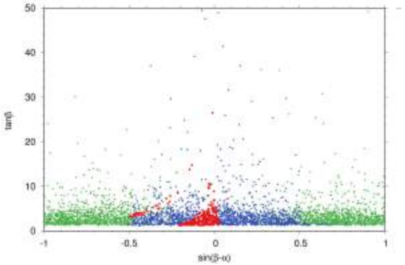
- Strong correlation (due to T parameter)
- Bounds on the masses:
  - Type I: $m_A \in [60; 650]\ GeV$, $m_{H^\pm} \in [60; 630]\ GeV$;
  - Type II: $m_A \in [400; 650]\ GeV$, $m_{H^\pm} \in [430; 630]\ GeV$.

Constraints on the 2HDM parameter space
$\tan\beta$

$\tan\beta$ vs $\sin(\beta-\alpha)$



Type I



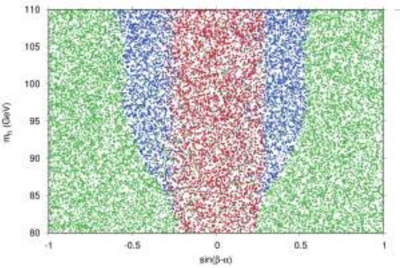
Type II

- Lower bound: $\tan\beta > 1.2$ (Type I and Type II).

Constraints on the 2HDM parameter space

m_h and $\sin(\beta-\alpha)$

m_h vs $\sin(\beta-\alpha)$



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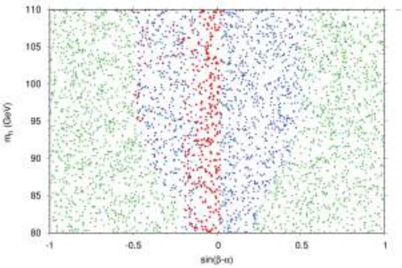
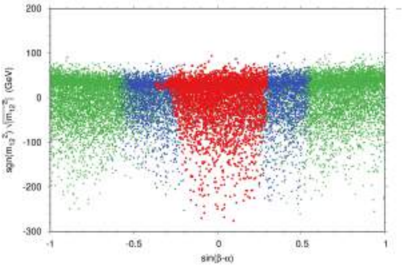


Type II

- No lower bound on m_h
- Constraints on $\sin(\beta-\alpha)$:
  - Type I: $\sin(\beta-\alpha) \in [-0.4; 0.3]$;
  - Type II: $\sin(\beta-\alpha) \in [-0.5; 0.05]$.

Constraints on the 2HDM parameter space
m_{12}^2

m_{12} vs $\sin(\beta - \alpha)$



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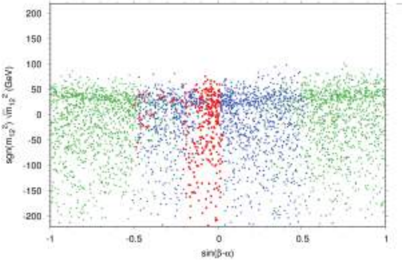


Type II

- Upper bound: $m_{12}^2 < (100\ GeV)^2$ (Type I and Type II).

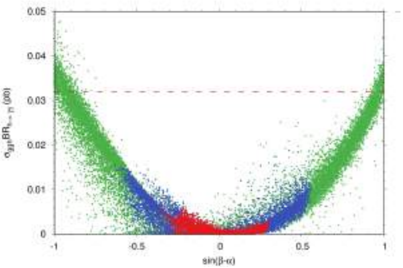
Detection at LHC?

Better restrictions using $\sigma \times BR_{h\to\gamma\gamma}$

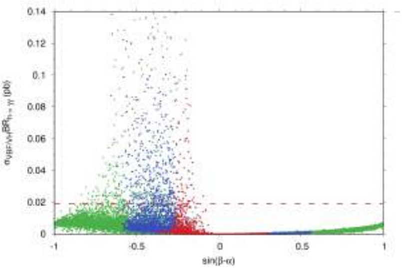
Smallest value of the CMS observed upper limit:

$$\sigma \times BR^{min}_{h\to\gamma\gamma} = 0.032 \text{ pb (ggh), } 0.019 \text{ pb (VBF/VH)}$$

$\sigma \times BR_{h\to\gamma\gamma}$ vs $\sin(\beta-\alpha)$ (Type I)



Gluon fusion channel



VBF/VH channel

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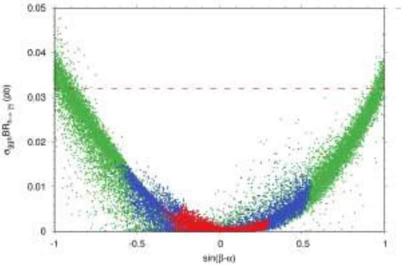
$\sigma \times BR_{h\to\gamma\gamma}$ vs $\sin(\beta-\alpha)$ (Type I)



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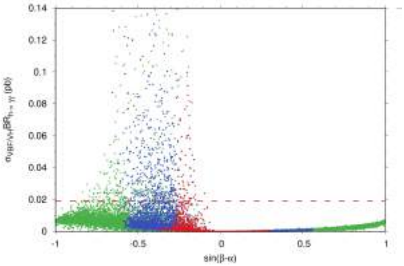


VBF/VH channel

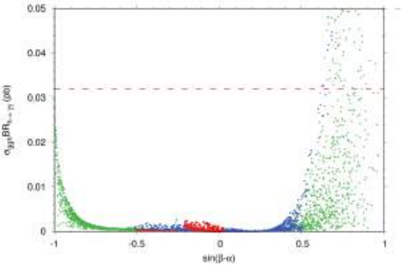
- No sensitivity in gluon fusion production mode;
- Maybe some sensitivity in VBF/VH production mode.

  $\Rightarrow$ Restriction to areas with $\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma} > 0.01$ pb: $\sin(\beta-\alpha) \in [-0.3; -0.05]$.

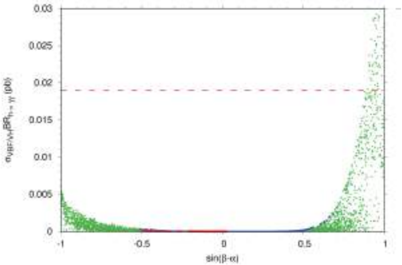
Detection at LHC?

Better restrictions using $\sigma \times BR_{h\to\gamma\gamma}$

$\sigma \times BR_{h\to\gamma\gamma}$ vs $\sin(\beta-\alpha)$ (Type II)



Gluon fusion channel



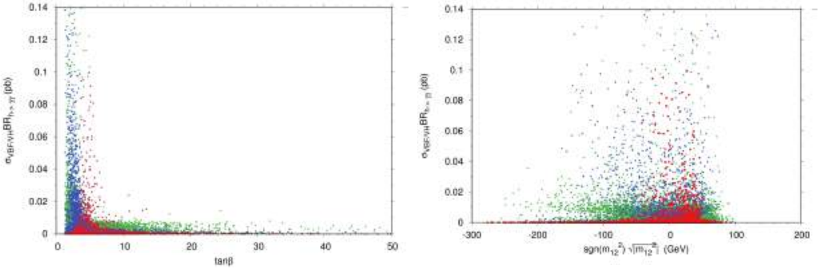
VBF/VH channel

- No sensitivity in both production channel.
  - $\Rightarrow$ Restriction to Type I in the following.

Detection at LHC?

Better restrictions using $\sigma \times BR_{h\to\gamma\gamma}$

$\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma}$ vs $\tan\beta$ (Type I) $\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma}$ vs m_{12} (Type I)



- Restriction to areas with $\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma} > 0.01$ pb:
  - $\tan\beta \in [2; 12]$;
  - $m_{12}^2 \in [-(100\ GeV)^2; +(100\ GeV)^2]$.

Detection at LHC ?

Comparison with the CMS low mass diphoton analysis

- Generation of 1 million random points with the new bounds, only for Type I.

New inputs

$$m_h \in [80; 110]\ GeV, \quad m_H = 125\ GeV, \quad m_A \in [60; 650]\ GeV,$$
$$m_{H^\pm} \in [60; 630]\ GeV, \quad \tan\beta \in [2; 12], \quad \sin(\beta - \alpha) \in [-0.3; -0.05],$$
$$m_{12}^2 \in [-(100\ GeV)^2; +(200\ GeV)^2]$$

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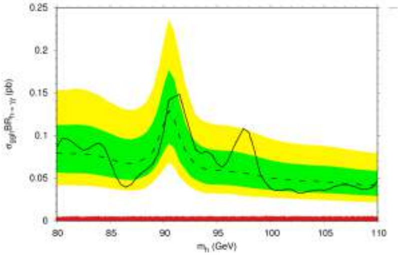
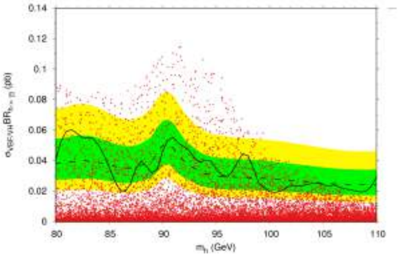
Comparison with the CMS low mass diphoton analysis

$\sigma_{gg\to h} \times BR_{h\to\gamma\gamma}$ vs m_h



$\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma}$ vs m_h

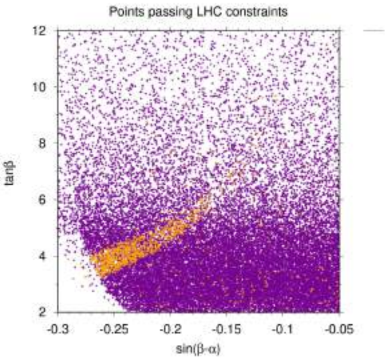


- No sensitivity in gluon fusion production mode;
- Sensitivity in VBF/VH production mode for $m_h < 105$ GeV.

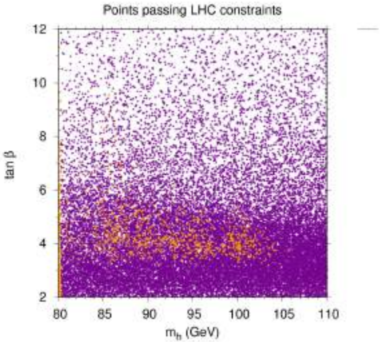
Detection at LHC?

Additional exclusions in the 2HDM parameter space

$\tan\beta$ vs $\sin(\beta-\alpha)$



$\tan\beta$ vs m_h



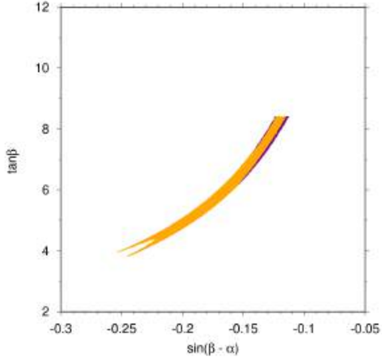
Points passing LHC constraints with $\sigma_{VBF/VH} \times BR_{h\to\gamma\gamma}$ value below the CMS observed upper limit or above it (then excluded).

Be careful with the exclusion !

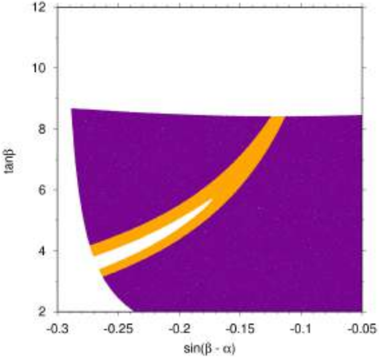
Detection at LHC?

Additional exclusions in the 2HDM parameter space

$m_A = m_{H^\pm} = 80$ GeV



$m_A = m_{H^\pm} = 500$ GeV



Scans with $m_h = 87$ GeV, $m_H = 125$ GeV, $m_{12} = 30$ GeV.

- Different exclusion zone;
- Violet points in the left plot excluded in the right one.

Conclusion

- Study of a lighter scalar for four different types of THDMs with $m_H = 125$ GeV;
- Put constraints on the free parameters;
- Sensitivity at LHC Run 1 only for Type I in VBF/VH production channel;
- CMS 8 TeV low-mass diphoton analysis $\Rightarrow$ additional exclusion in the planes $\tan\beta$ vs $\sin(\beta-\alpha)$ and $\tan\beta$ vs m_h;
- Additional study: search for a lighter **pseudo-scalar**.
  $\Rightarrow$ No sensitivity in diphoton channel for the four different types.
- Ongoing: estimation of the sensitivity at 13 TeV.

Thank you for listening !

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- Sensitivity at LHC Run 1 only for Type I in VBF/VH production channel;
- CMS 8 TeV low-mass diphoton analysis $\Rightarrow$ additional exclusion in the planes $\tan\beta$ vs $\sin(\beta-\alpha)$ and $\tan\beta$ vs m_h;
- Additional study: search for a lighter **pseudo-scalar**.
  $\Rightarrow$ No sensitivity in diphoton channel for the four different types.
- Ongoing: estimation of the sensitivity at 13 TeV.

Thank you for listening !

Conclusion

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Backup

The Two Higgs Doublet Model

How does it work ?

Two doublets: ϕ_1, ϕ_2.

Most general potential:

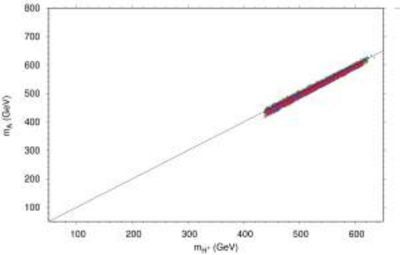
$$\begin{aligned} V =& m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \left(m_{12}^2\phi_1^\dagger\phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 \\ &+ \frac{\lambda_2}{2}\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) \\ &\left\{+\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \left[\cancel{\lambda_6\left(\phi_1^\dagger\phi_1\right)} + \cancel{\lambda_7\left(\phi_2^\dagger\phi_2\right)}\right]\phi_1^\dagger\phi_2 + h.c.\right\} \end{aligned}$$

FCNC $\Rightarrow$ descrete $\mathbb{Z}_2$ symmetry.
$\Rightarrow \lambda_6, \lambda_7 = 0$; $m_{12} \neq 0$ (soft breaking).

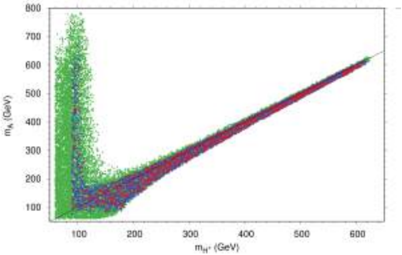
Constraints on the 2HDM parameter space

m_A and $m_{H^\pm}$

m_A vs $m_{H^\pm}$



Flipped model

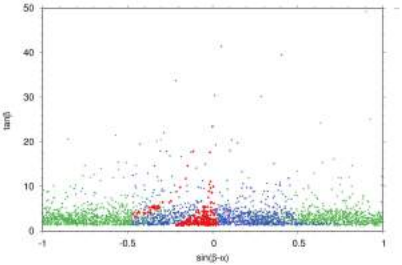


Lepton specific

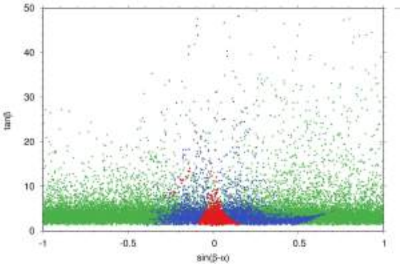
- Strong correlation (due to T parameter)
- Bounds on the masses:
  - Flipped model: $m_A \in [400; 650]\ GeV$, $m_{H^\pm} \in [430; 630]\ GeV$;
  - Lepton specific: $m_A \in [80; 630]\ GeV$, $m_{H^\pm} \in [90; 630]\ GeV$.

Constraints on the 2HDM parameter space
$\tan\beta$

$\tan\beta$ vs $\sin(\beta-\alpha)$



Flipped model



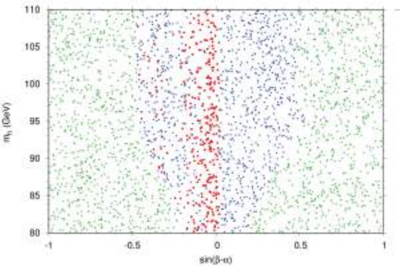
Lepton specific

- Lower bound: $\tan\beta > 1.2$ (Flipped and Lepton specific).

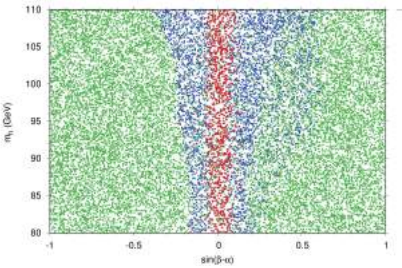
Constraints on the 2HDM parameter space

m_h and $\sin(\beta - \alpha)$

m_h vs $\sin(\beta - \alpha)$



Flipped model



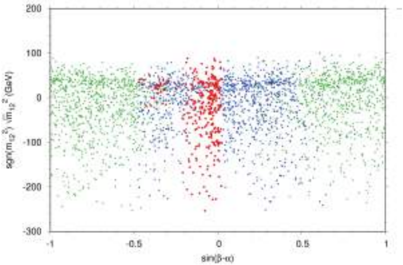
Lepton specific

- No lower bound on m_h
- Constraints on $\sin(\beta - \alpha)$:
  - Flipped model: $\sin(\beta - \alpha) \in [-0.5; 0.05]$;
  - Lepton specific: $\sin(\beta - \alpha) \in [-0.3; 0.2]$.

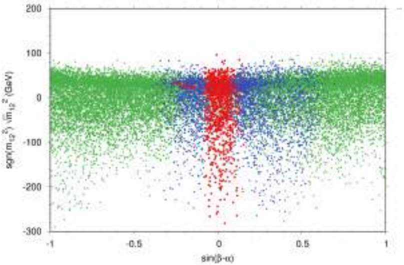
Constraints on the 2HDM parameter space

m_{12}^2

m_{12} vs $\sin(\beta - \alpha)$



Flipped model



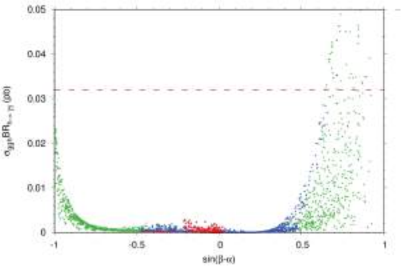
Lepton specific

- Upper bound: $m_{12}^2 < (100\ GeV)^2$ (Flipped and Lepton Specific).

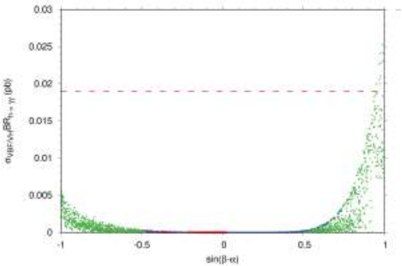
Detection at LHC?

Better restrictions using $\sigma \times BR_{h\to\gamma\gamma}$

$\sigma \times BR_{h\to\gamma\gamma}$ vs $\sin(\beta-\alpha)$ (Flipped model)



Gluon fusion channel



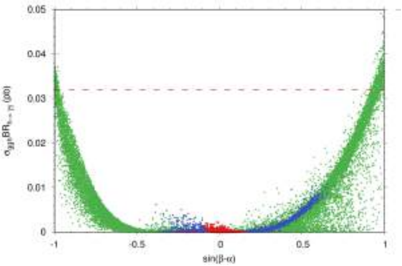
VBF/VH channel

- No sensitivity in both production channel.

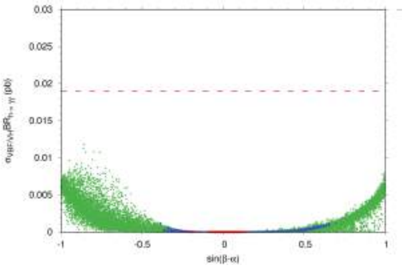
Detection at LHC?

Better restrictions using $\sigma \times BR_{h\rightarrow\gamma\gamma}$

$\sigma \times BR_{h\rightarrow\gamma\gamma}$ vs $\sin(\beta-\alpha)$ (Lepton specific)



Gluon fusion channel



VBF/VH channel

- No sensitivity in both production channel.

Study of a lighter pseudo-scalar Higgs boson

Cross-section computation

- Kappa trick :

$$\sigma_{ggA}^{2HDM} \simeq \kappa_g^2 \times \sigma_{ggA}^{SM}, \qquad \kappa_g^2 = \frac{\Gamma_{A\to gg}^{2HDM}}{\Gamma_{A\to gg}^{SM}}$$

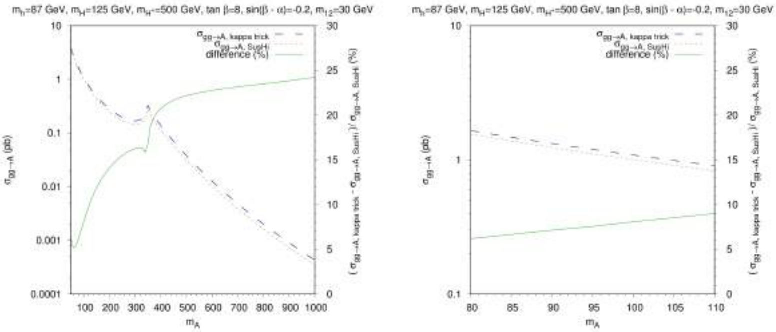
  - σ_{ggA}^{SM} not furnished by the LHCHXSWG but available *via* `SusHi`;
  - $\Gamma_{A\to gg}^{2HDM}$ and $\Gamma_{A\to gg}^{SM}$ calculable analytically.

$\Rightarrow$ Comparison with `SusHi`.

Study of a lighter pseudo-scalar Higgs boson

Cross-section computation

σ_{ggA}^{2HDM} vs m_A (Type I)



- Deviation between the two methods below 10% at low masses;
- Growth of the deviation at high masses as the infinite top mass approximation become false.

Study of a lighter pseudo-scalar Higgs boson

Comparison with CMS low mass diphoton analysis

Inputs

$m_h \in [80; 110]\ GeV$, $m_H = 125\ GeV$, $m_A \in [80; 110]\ GeV$, $m_{H^\pm} \in [60; 630]\ GeV$
$\tan\beta \in [1.5; 50]$, $\sin(\beta - \alpha) \in [-0.4; 0.3]$, $m_{12}^2 \in [-(300\ GeV)^2; +(100\ GeV)^2]$

$\sigma_{gg\to A} \times BR_{A\to\gamma\gamma}$ vs m_A (Type I)