NMSSM and Type II 2HDM Higgs in Light of the LHC Higgs Searches

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In collaboration with
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Barath Coleppa, Felix Kling, 1301.xxxx (2HDM)

Outline

- Introduction: Higgs searches @ LHC (skip)
- A little bit on MSSM...
- NMSSM Higgs sector
  - general discussion
  - H1 126 GeV
  - H2 126 GeV
  - H3 126 GeV (?)
- Type II 2HDM Higgs sector
  - general discussion
  - h^0 126 GeV
  - H^0 126 GeV
- Conclusion

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Strategy

- Focus on the Higgs sector (and stop sector)
- Only consider Higgs search results

  flavor? g-2? DM? ...

Study the consequence of

(I) current Higgs search limit of 95% CL limit on σXBr

(II) H_i in the mass range of 124 - 128 GeV

(III) $\sigma XBr(gg \rightarrow H_i \rightarrow \gamma\gamma)_{NMSSM,\ 2HDM} > 80\% (\sigma XBr)_{SM}$

$\sigma XBr(gg \rightarrow H_i \rightarrow WW/ZZ)_{NMSSM,\ 2HDM} > 40\% (\sigma XBr)_{SM}$

MSSM Higgs Sector

- **Type II Two Higgs Doublet Model**

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \rightarrow v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \rightarrow v_d/\sqrt{2}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2 \qquad \tan\beta = v_u/v_d$$

after EWSB
5 physical Higgses
CP-even Higgses: h^0, H^0
CP-odd Higgs: A^0
Charged Higgses: $H^\pm$

- **tree level masses determined by m_A, tanβ**

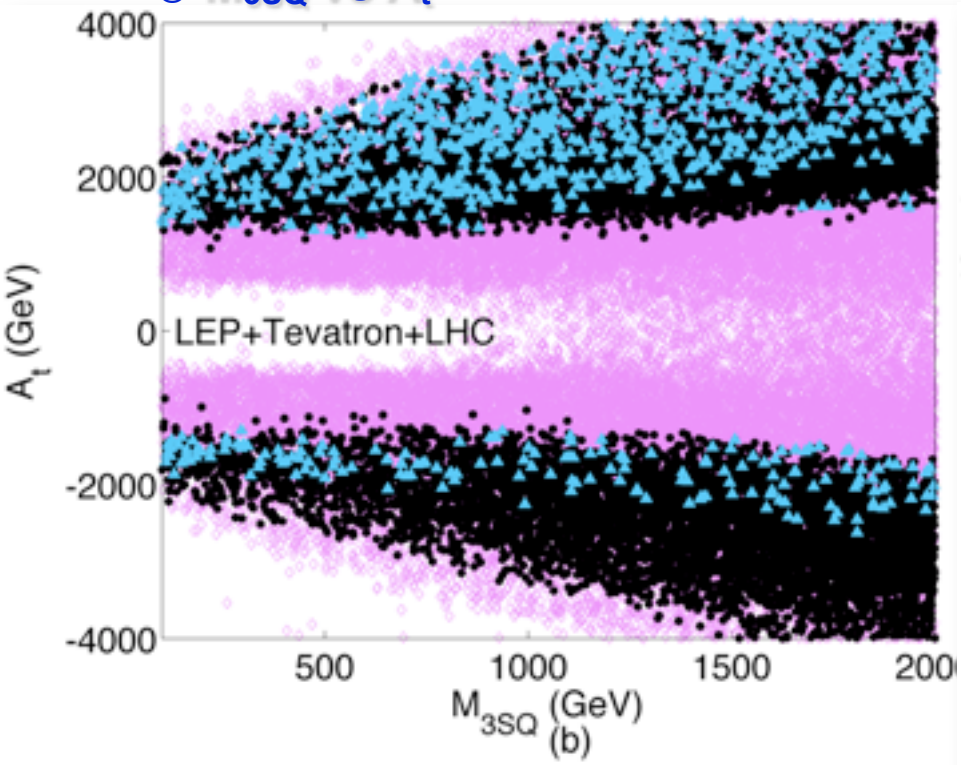
$$m^2_{h^0,H^0} = \frac{1}{2}\left((m_A^2 + m_Z^2) \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right)$$

$$m^2_{H^\pm} = m_A^2 + m_W^2, \quad \cos^2(\beta - \alpha) = \frac{m^2_{h^0}(m_Z^2 - m^2_{h^0})}{m_A^2(m^2_{H^0} - m^2_{h^0})}.$$

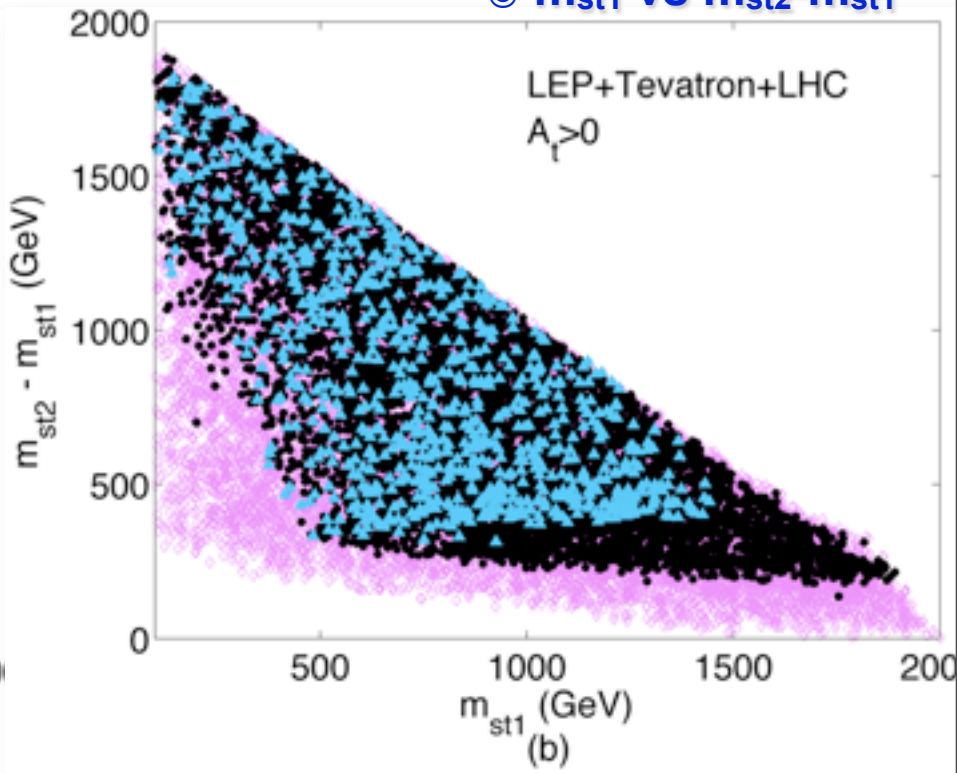
Stop Masses

Heavy stops and/or large LR mixing.

◉ M_{3SQ} vs A_t



◉ m_{st1} vs m_{st2}-m_{st1}



purple: pass exp

black dots: 123 < m_{h0} or m_{H0} < 127 GeV

blue dots: $\sigma XBr(gg \rightarrow h^0, H^0 \rightarrow \gamma\gamma)_{MSSM} > 80\% (\sigma XBr)_{SM}$

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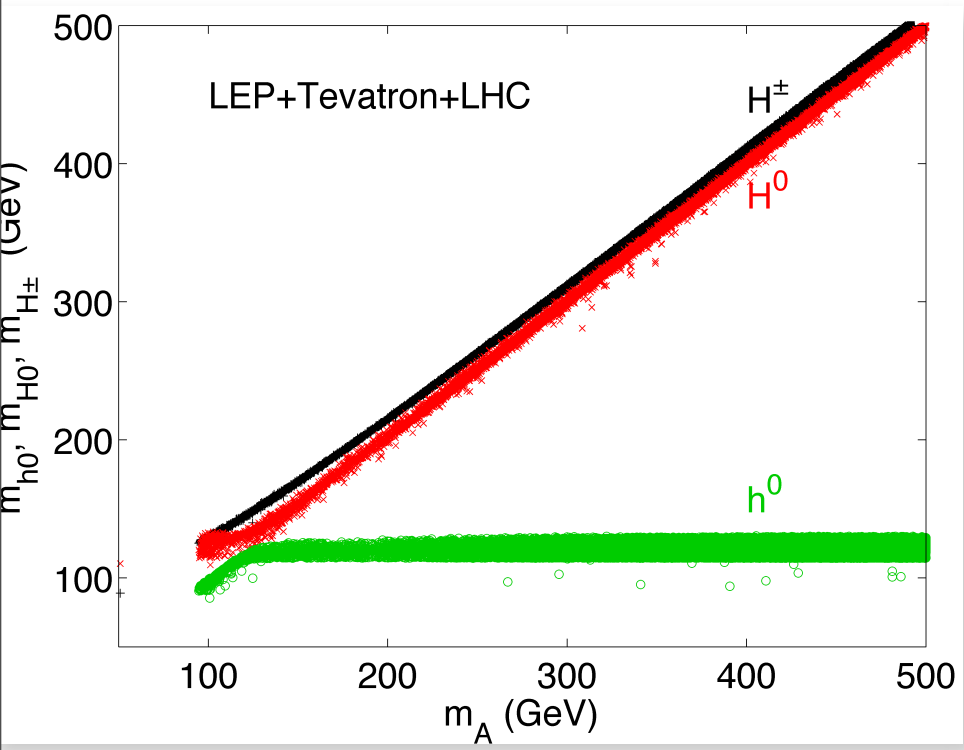
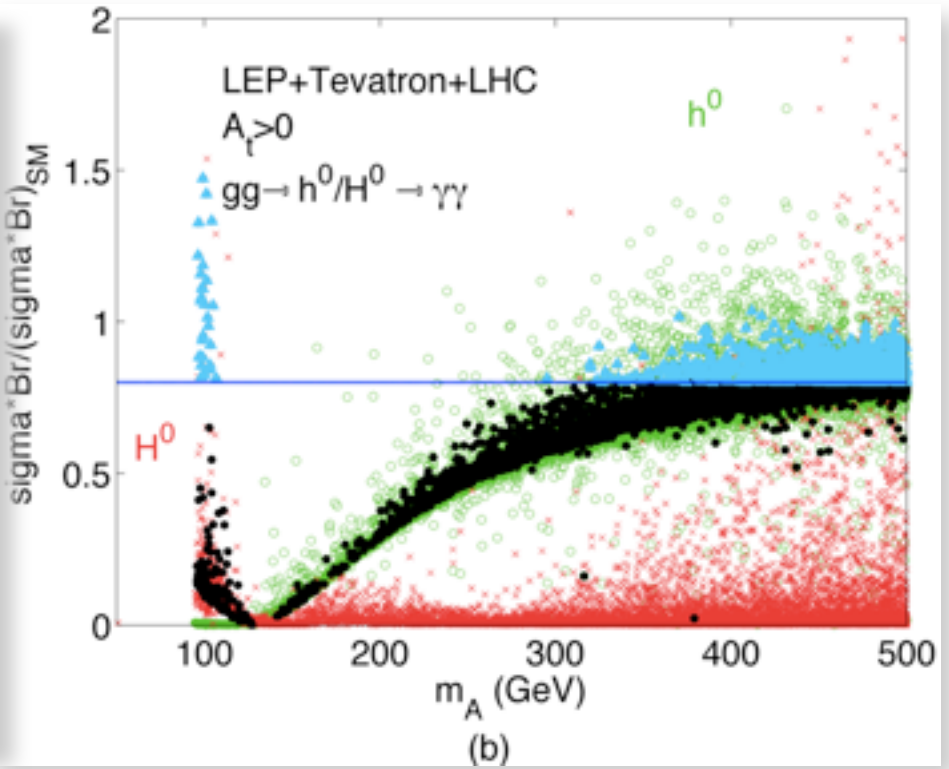
non-decoupling vs. decoupling region





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non-decoupling vs. decoupling region

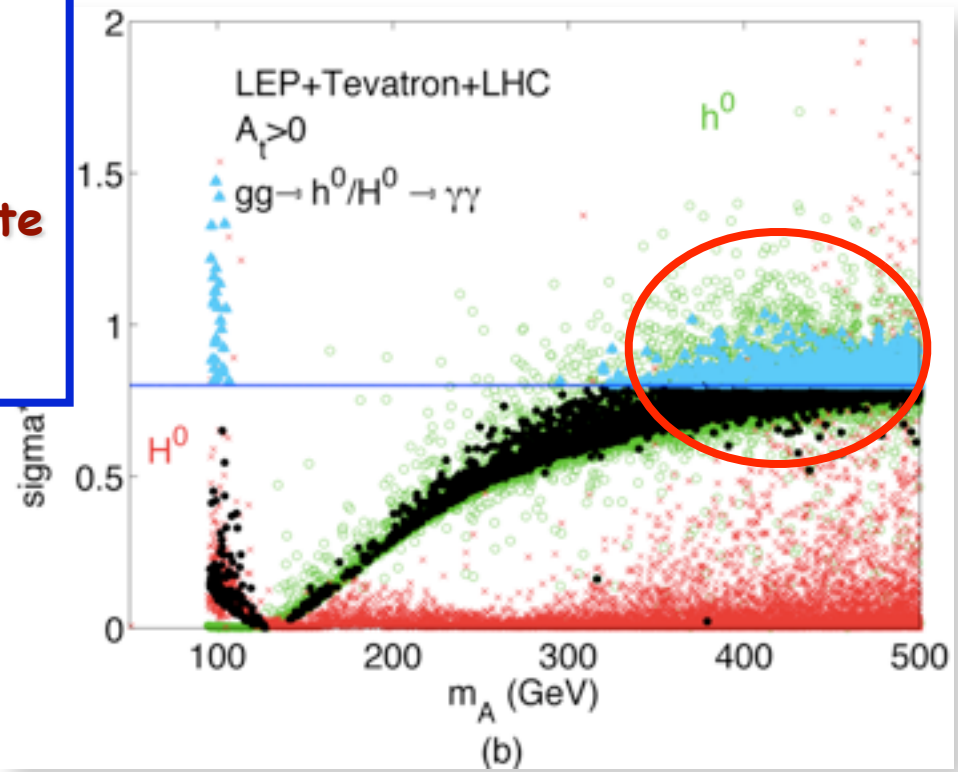
- **decoupling limit**

$$m_A \gg m_Z$$

$$\sin(\beta-\alpha) \sim 1,\ \cos(\beta-\alpha) \sim 0$$

  - **h^0 light, SM like,**
  - **H^0, A^0, $H^\pm$ heavy, nearly degenerate**
  - **H^0WW, H^0ZZ coupling suppressed**
    - **~ cos(β-α)**

decoupling region



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- **non-decoupling limit**

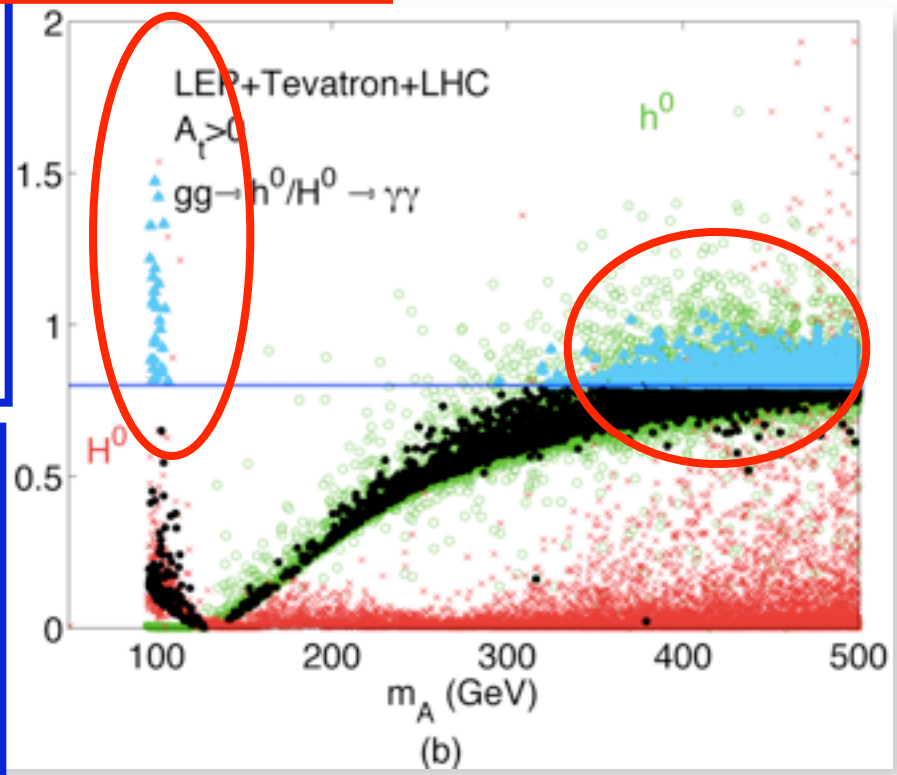
  $m_A \sim m_Z$

  $\sin(\beta-\alpha) \sim 0,\ \cos(\beta-\alpha) \sim 1$

  - all Higgses light
  - H^0 SM like
  - h^0WW, h^0ZZ coupling suppressed

non-decoupling region

decoupling region



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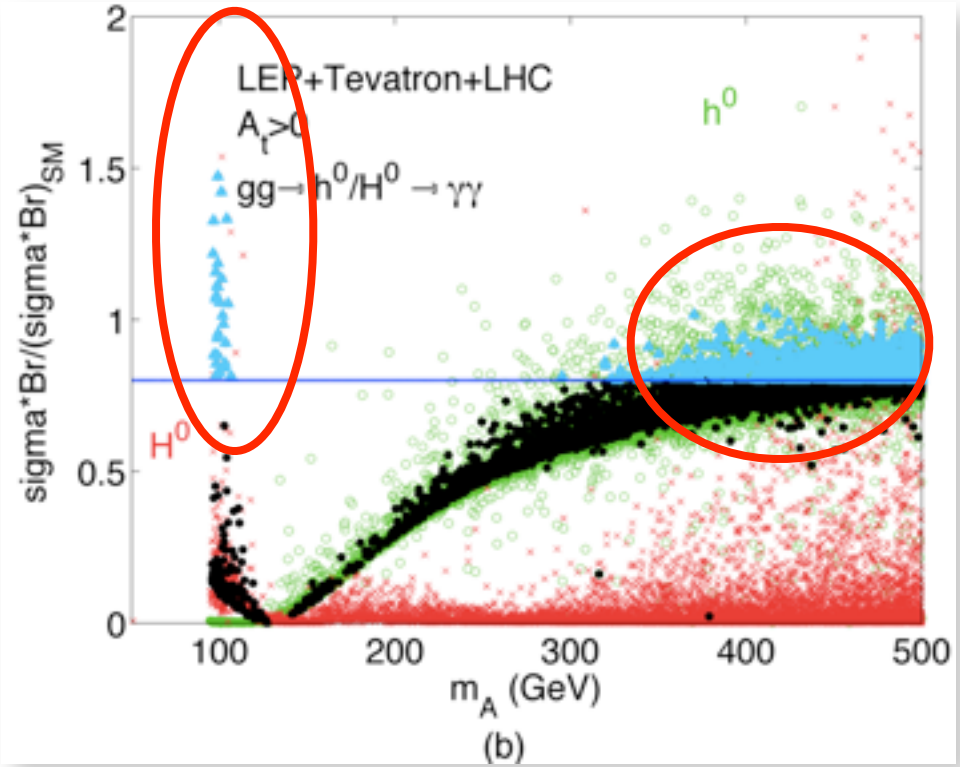
non-decoupling vs. decoupling region

non-decoupling region

decoupling region

- h^0 SM-like: large mA ≥ 300 GeV
- small $m_A \sim m_Z$: H^0 SM-like

Not always true in NMSSM!



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NMSSM Higgs Sector

- **Type II Two Higgs Doublet Model plus singlet S**

$$W_{\rm NMSSM} = Y_u \bar{u} H_u Q + Y_d \bar{d} H_d Q + Y_e \bar{e} H_d L + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

$$V_{H,Soft} = m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + M_S^2 |S|^2 + (\lambda A_\lambda (H_t^T \epsilon H_d) S + \frac{1}{3}\kappa A_\kappa S^3 + c.c.)$$

- **SSB**

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \to v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \to v_d/\sqrt{2} \qquad S \to v_s/\sqrt{2}$$

$$(\mu = \lambda v_s/\sqrt{2})$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

after EWSB, 7 physical Higgses

CP-even Higgses: H_1, H_2, H_3

CP-odd Higgs: A_1, A_2

Charged Higgses: $H^\pm$

NMSSM: Masses for Higgses

- **Charged Higgs**

$$\begin{aligned} H_d^- &= H^- \sin\beta - G^- \cos\beta, \\ H_u^+ &= H^+ \cos\beta + G^+ \sin\beta, \end{aligned}$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

- **CP-odd Higgses**

$$\begin{pmatrix} A_{\rm MSSM} \\ G^0 \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \sqrt{2}\,{\rm Im}H_d^0 \\ \sqrt{2}\,{\rm Im}H_u^0 \end{pmatrix}, \quad A_{\rm S} = \sqrt{2}\,{\rm Im}S$$

$$\frac{1}{2}(A_{\rm MSSM}, A_{\rm S}) \begin{pmatrix} m_A^2 & \\ & \end{pmatrix} \begin{pmatrix} A_{\rm MSSM} \\ A_{\rm S} \end{pmatrix}$$

$$m_A^2 = \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right)$$

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$$\frac{1}{2}(A_{\rm MSSM}, A_{\rm S}) \begin{pmatrix} m_A^2 & \frac{1}{2}(m_A^2 \sin 2\beta - 3\lambda\kappa v_s^2)\frac{v}{v_s} \\ * & \frac{1}{4}(m_A^2 \sin 2\beta + 3\lambda\kappa v_s^2)\frac{v^2}{v_s^2}\sin 2\beta - \frac{3}{\sqrt{2}}\kappa v_s A_\kappa \end{pmatrix} \begin{pmatrix} A_{\rm MSSM} \\ A_{\rm S} \end{pmatrix}$$

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NMSSM: Masses for Higgses

- **CP-even Higgses**

$$\begin{pmatrix} h_{\rm SM} \\ H \end{pmatrix} = \begin{pmatrix} -\sin\beta & \cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \sqrt{2}\,({\rm Re}H_d^0 - v_d) \\ \sqrt{2}\,({\rm Re}H_u^0 - v_u) \end{pmatrix}, \quad S = \sqrt{2}\,({\rm Re}S - v_s)$$

$$\frac{1}{2}(H, h_{\rm SM}, S) \begin{pmatrix} m_A^2 + m_Z^2 \sin^2 2\beta & * & * \\ * & m_Z^2 \cos^2 2\beta & * \\ * & * & \end{pmatrix} \begin{pmatrix} H \\ h_{\rm SM} \\ S \end{pmatrix}$$

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NMSSM: Masses for Higgses

- **Effects of singlet**
  - **lift $(m_{hsm})_{tree}$, small tanβ, large λ** $(m^2_{h_{\rm SM}})_{\rm tree} = m_Z^2 \cos^2 2\beta + \frac{1}{2}(\lambda v)^2 \sin^2 2\beta$
  - **mixing with singlet: change H_iWW/ZZ, $H_i$bb, $H_i$gg, H_iγγ**
- **Lots of work on (125 GeV) Higgs in NMSSM framework ...**

Gunion et. al, 1201.0982
Ellwanger 1112.3548
King et. al., 1201.2671
Cao et. al., 1202.5821
EllWanger et. al., 1203.5048
Benbrik et. al., 1207.1096
Gunion et. al., 1207.1545
Gunion et. al., 1208.1817
Cheng et. al., 1207.6392
Belanger et. al., 1208.4952
Agashe et. al., 1209.2115
Belanger et. al., 1210.1976

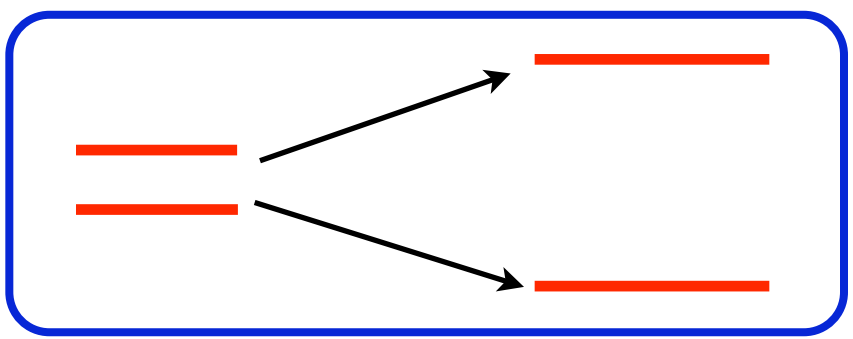
Heng, 1210.3751
Choi et. al., 1211.0875
King et. al., 1211.5074
Dreiner et. al., 1211.6987
... many other Jack's paper ...
(incomplete list)

- **H3 heavy, m_A large**
- **H1 126 or H2 126**
- **h_{SM}/S mixing**

NMSSM: Masses for Higgses

- **CP-even Higgses**

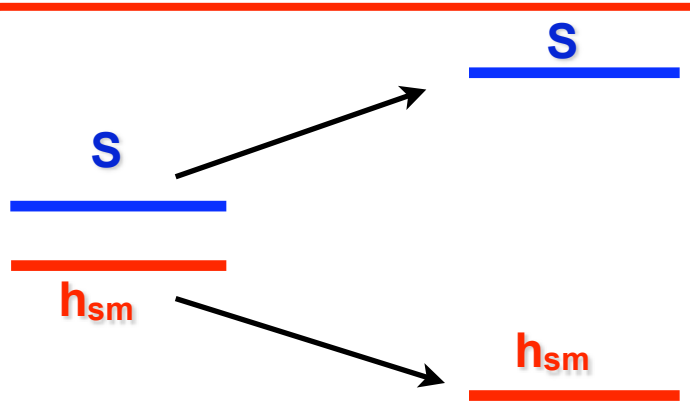
$$\frac{1}{2}(H, h_{\rm SM}, S)\begin{pmatrix} m_A^2 + m_Z^2 \sin^2 2\beta & * & * \\ -\frac{1}{2}(\lambda v)^2 \sin^2 2\beta & & \\ * & m_Z^2 \cos^2 2\beta & * \\ & +\frac{1}{2}(\lambda v)^2 \sin^2 2\beta & \\ * & * & \frac{1}{4} m_A^2 \sin^2 2\beta \frac{v^2}{v_s^2} + 2\kappa^2 v_s^2 \\ & & +\frac{1}{\sqrt{2}} \kappa v_s A_\kappa - \frac{1}{4}\lambda\kappa v^2 \sin 2\beta \end{pmatrix}\begin{pmatrix} H \\ h_{\rm SM} \\ S \end{pmatrix}$$



- **mass splitting: off-diag comparing to average of diag**
- **state mixing: off-diag comparing to difference of diag**

NMSSM: m_A decouple case

- push down: $m_{hsm} < m_S$

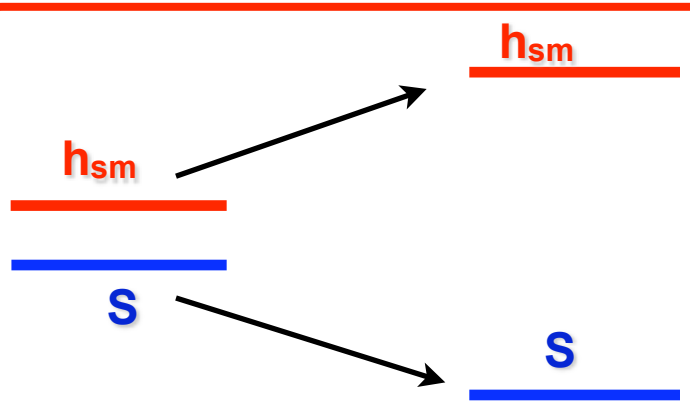


- H_1 (SM-like) still heavy enough ≥ 124 GeV

⇒ not too large mass mixing

(to push down m_{H1} too low)

- push up: $m_{hsm} > m_S$



- H_1 (singlet-like) not ruled out by LEP

⇒ not too large state mixing

(to have too much H_1ZZ coupling)

Agashe et. al., 1209.2115

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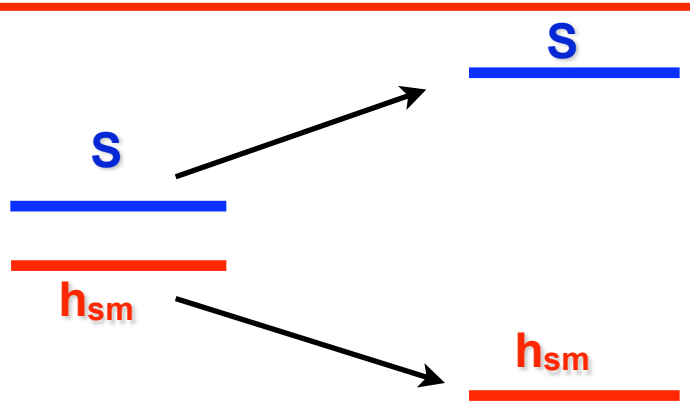

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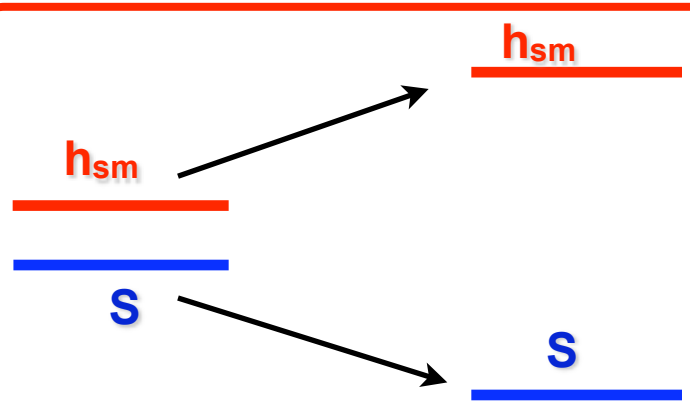

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(to have too much H_1ZZ coupling)

Need some tuning to make it work (without too much help from stops)

Agashe et. al., 1209.2115

NMSSM: Masses for Higgses

Our work: Focus on the NMSSM "non-decoupling" region: small m_A

All Higgses light
- **could have large mixing effects**
- **can be probed experimentally**

$$(m^2_{h_{\rm SM}})_{\rm tree} = m_Z^2 \cos^2 2\beta + \frac{1}{2}(\lambda v)^2 \sin^2 2\beta$$

$$(m^2_H)_{\rm tree} = m_A^2 + (m_Z^2 - \frac{1}{2}(\lambda v)^2) \sin^2 2\beta$$

- **ignore singlet for now...**

MSSM
- $m_A^2 \geq m_Z^2$ (cos 4 β): H_1 SM-like
- $m_A^2 \leq m_Z^2$ (cos 4 β): H_2 SM-like

NMSSM (small m_A)
- H_1 or H_2 SM-like, depending on m_A, λ, tanβ
- large m_A, large λ, small tan β, H_2 SM-like

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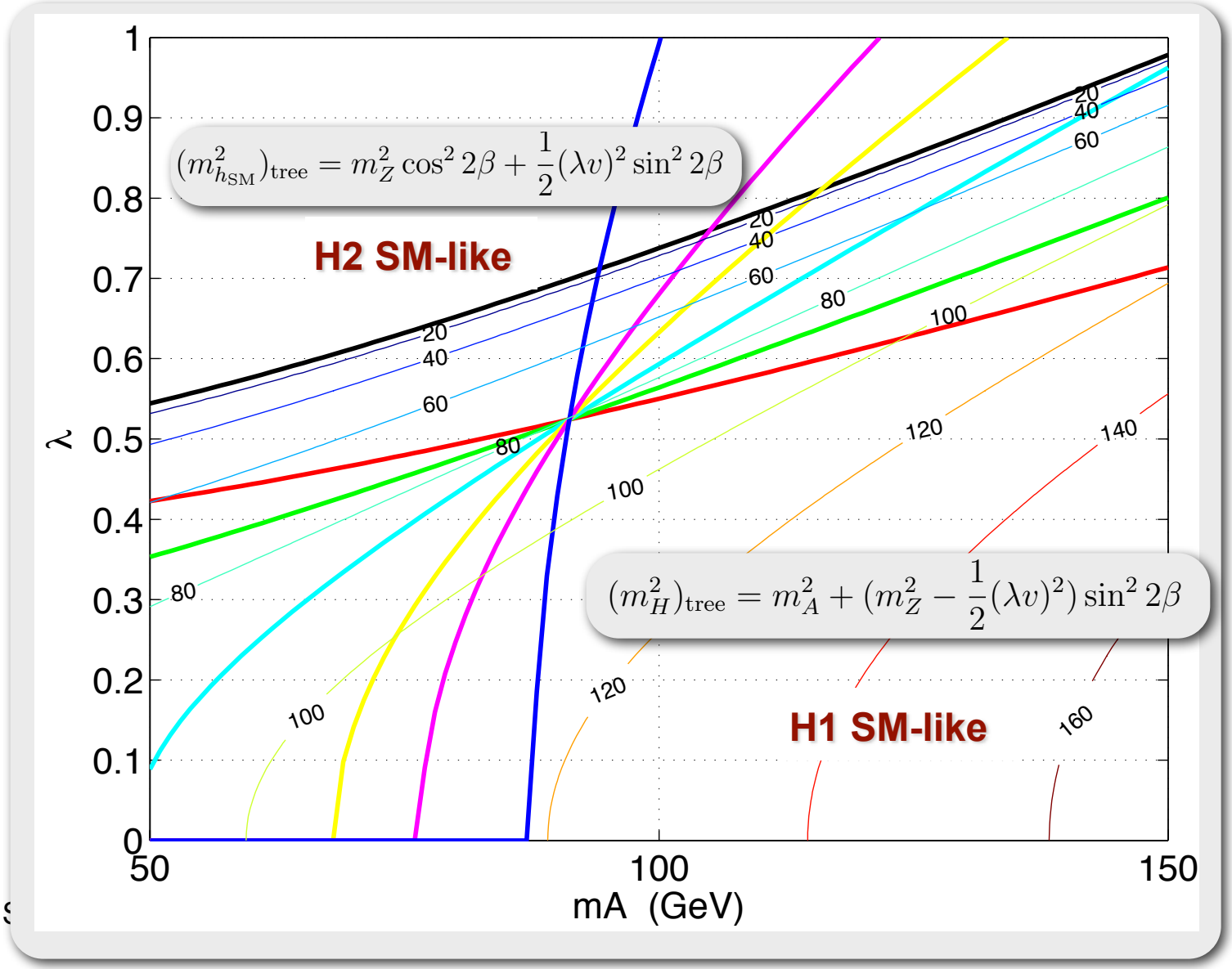
NMSSM: Masses for Higgses



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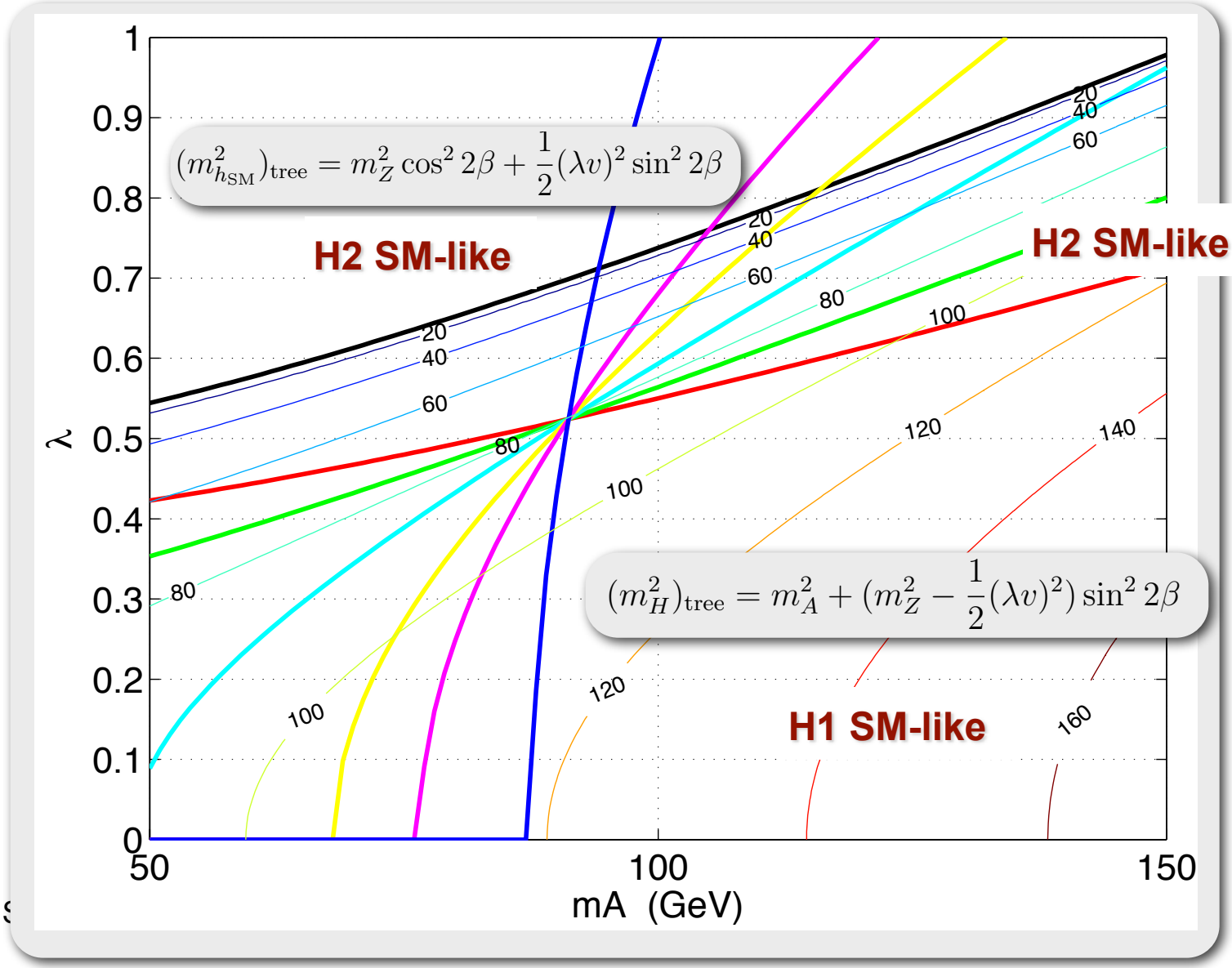

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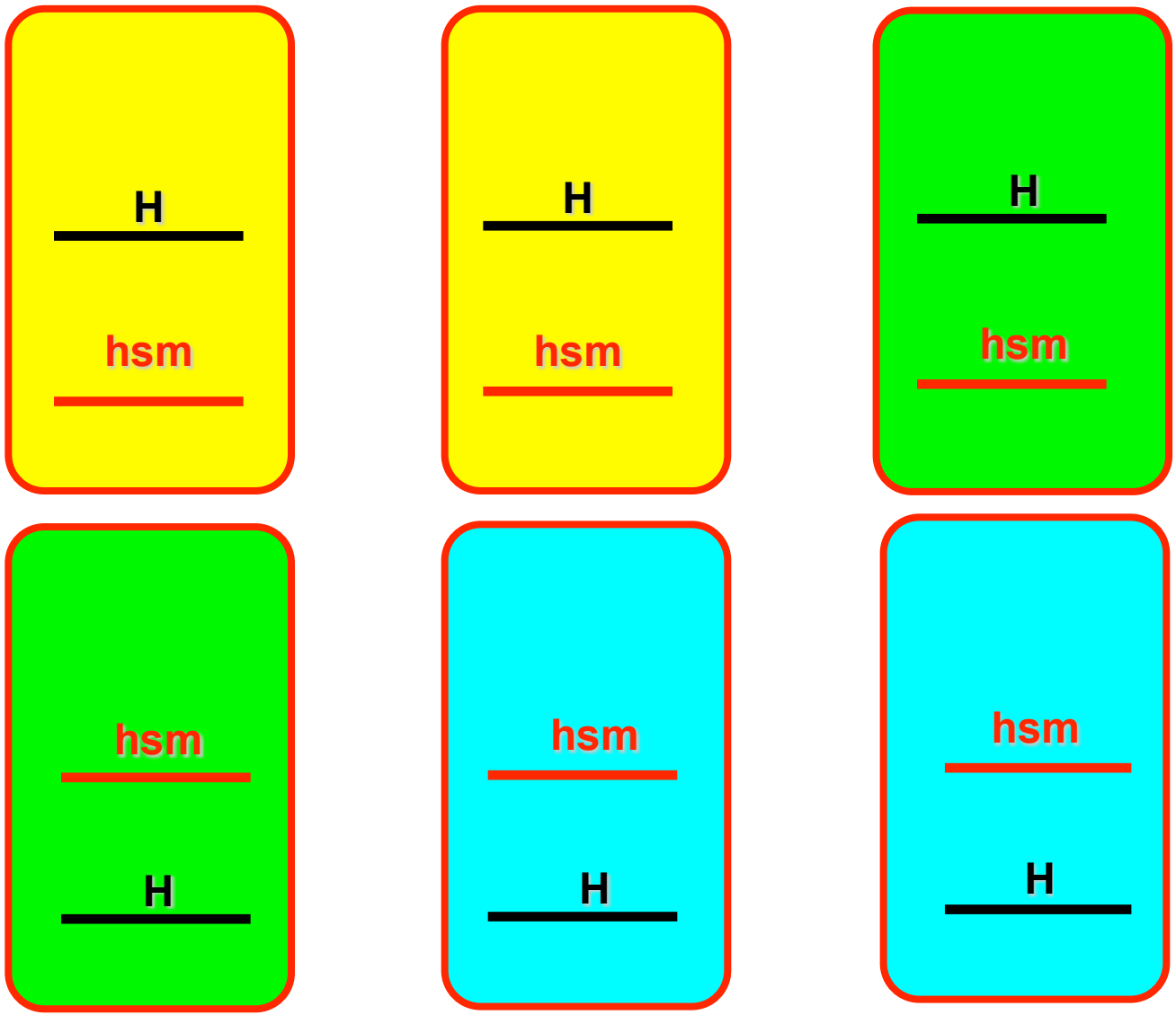
NMSSM non-decoupling cases



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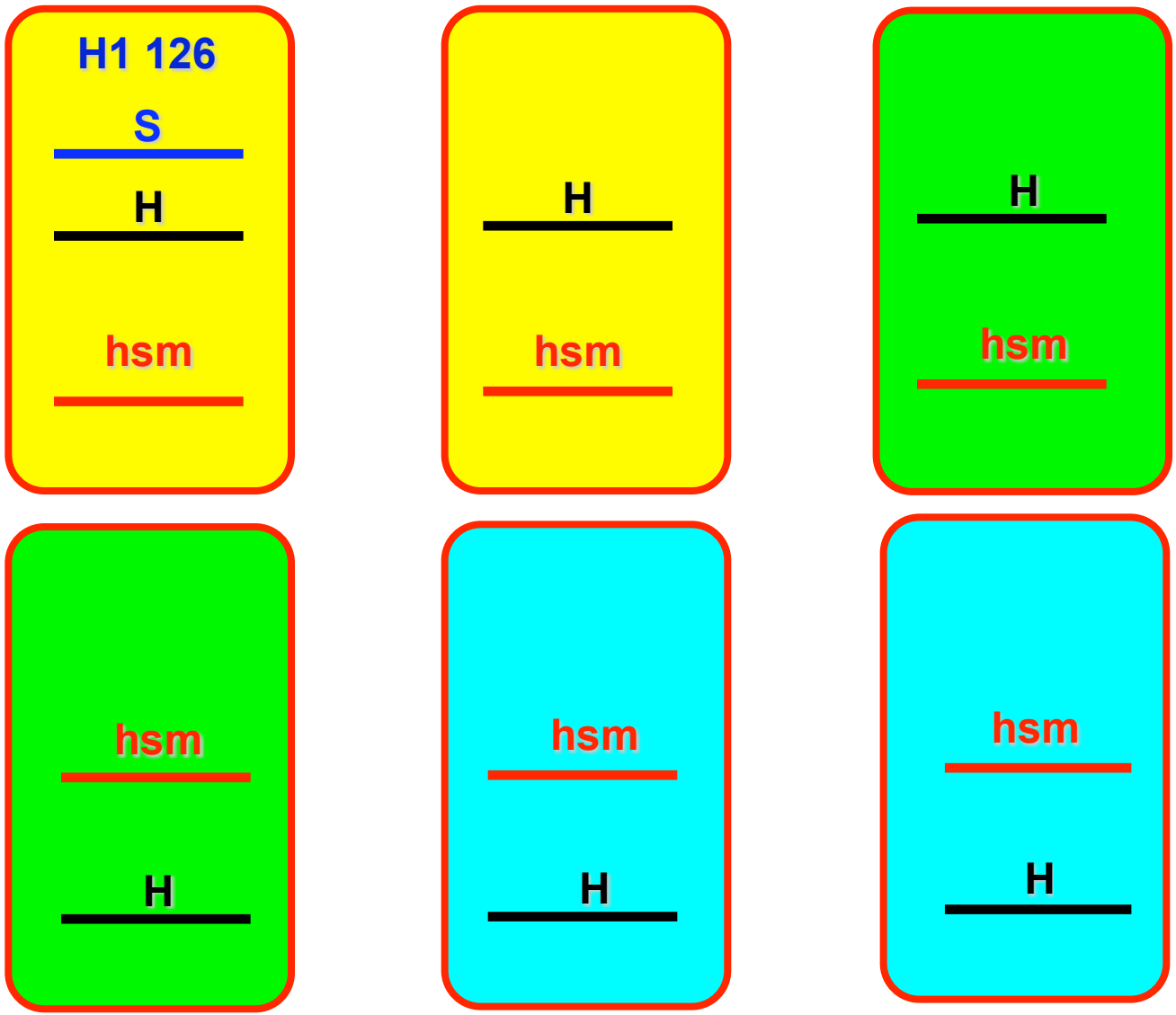

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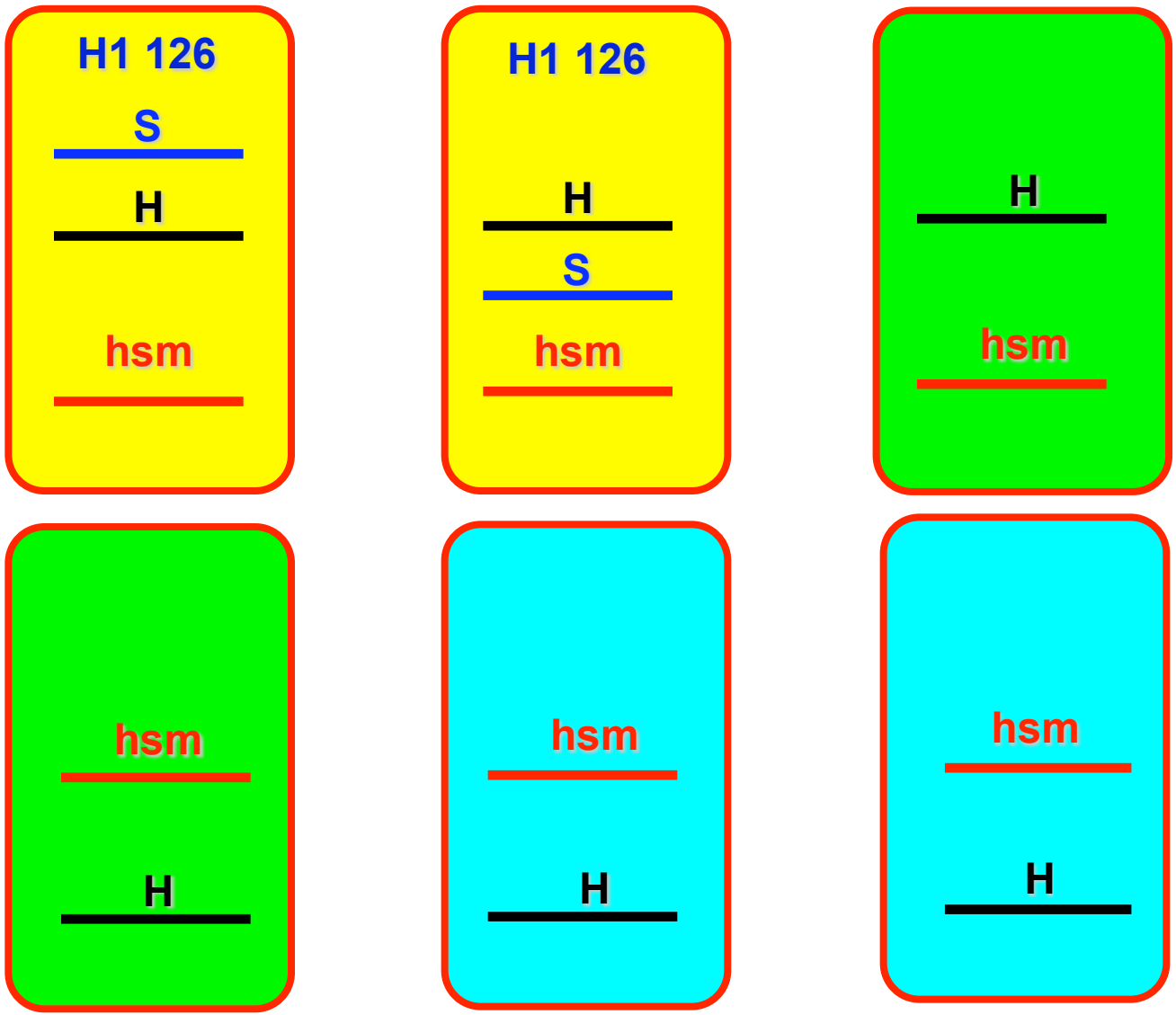

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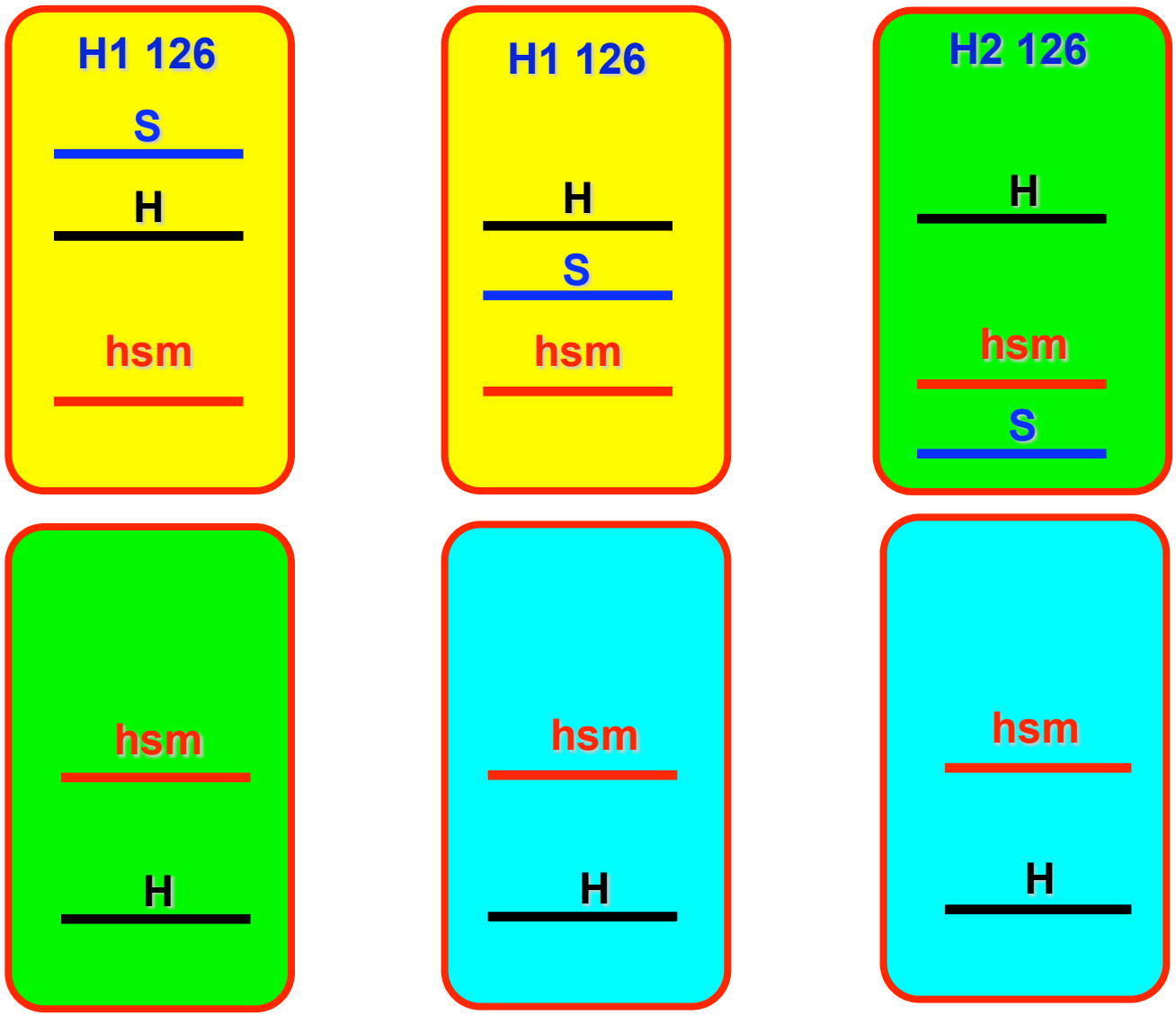

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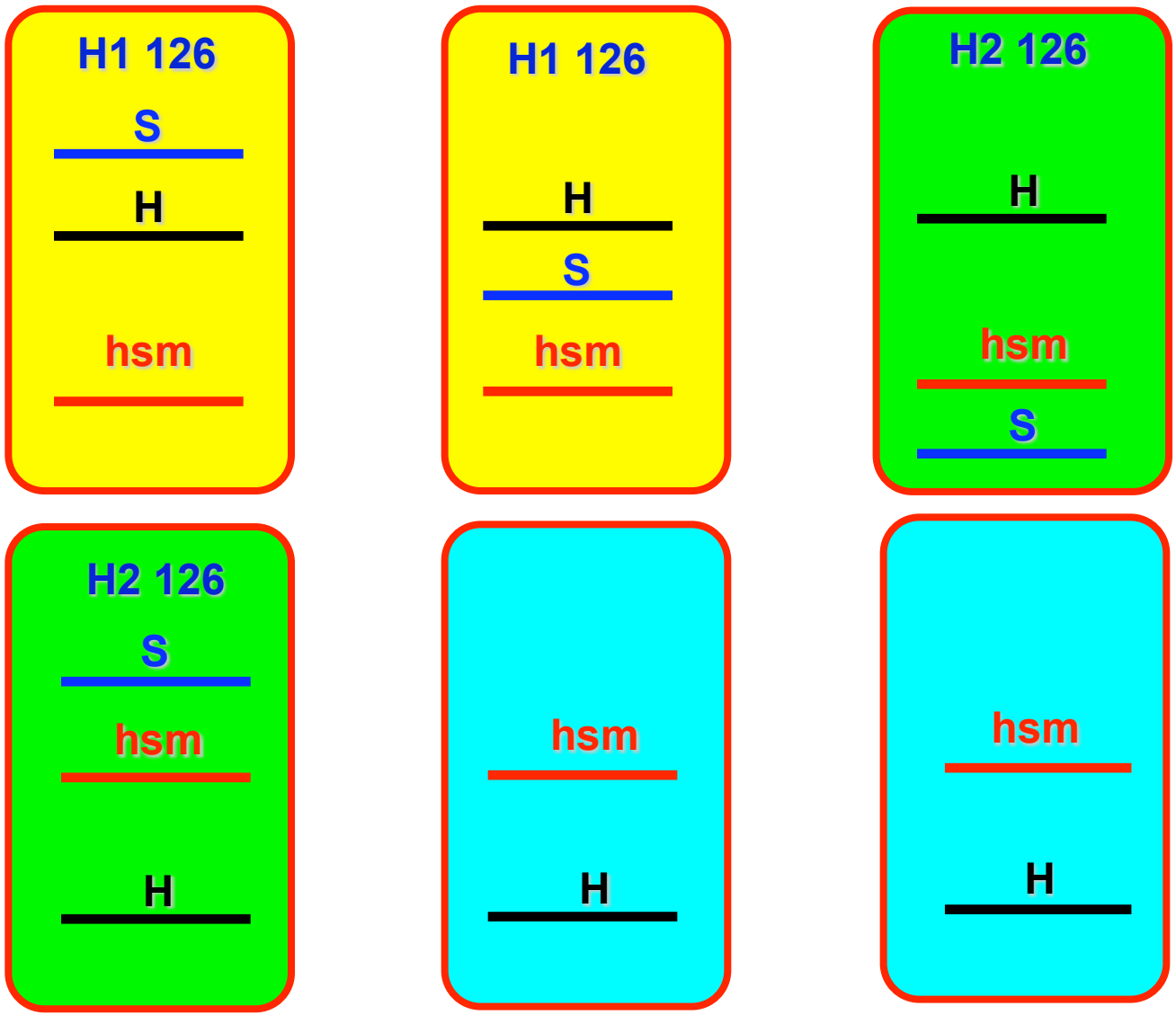

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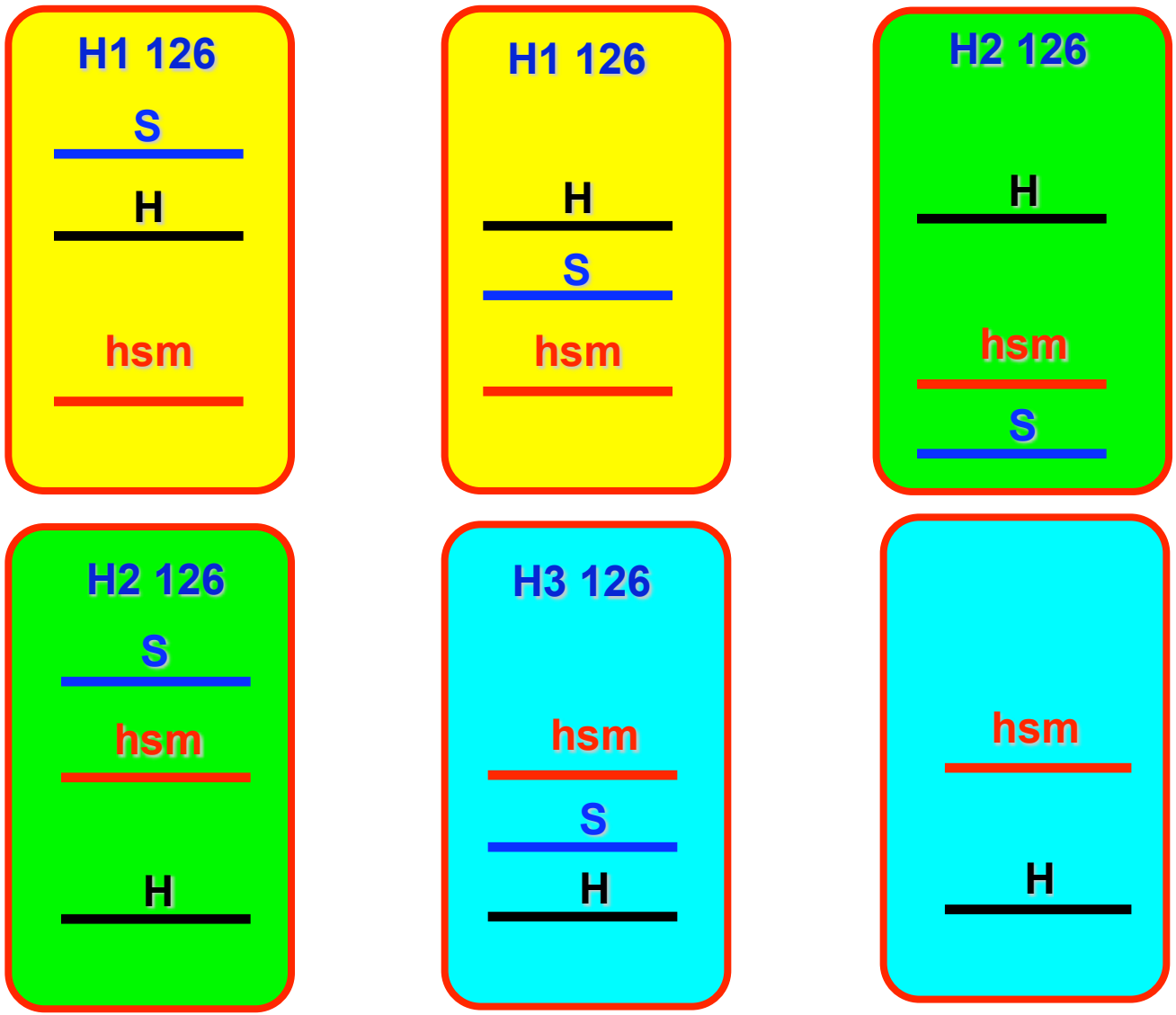
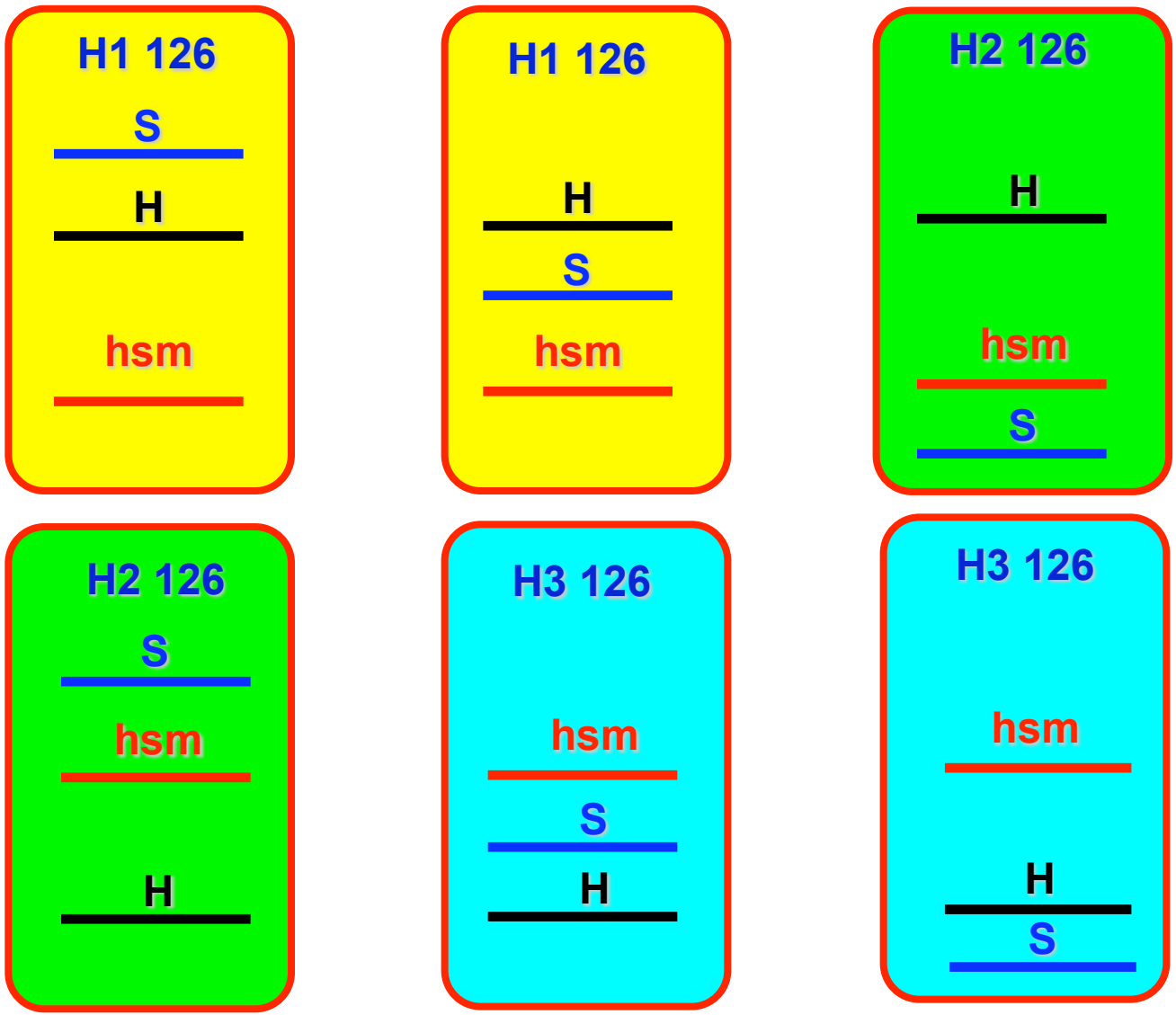


S. Su

NMSSM non-decoupling cases



S. Su

NMSSM parameters

parameters

- NMSSM

  m_A, tan β, μ, (v)

  M3SQ, M3SU, A_t

- NMSSM

  λ, κ, A_λ, A_κ, tan β, v_s, (v)

  M3SQ, M3SU, At

- NMSSM

  λ, κ, m_A, A_κ, tan β, μ, (v)

  M3SQ, M3SU, A_t

Parameter Scan

$1 < \tan\beta < 10$

$0\ \text{GeV} < m_A < 200\ \text{GeV}$

$100\ \text{GeV} < \mu < 1000\ \text{GeV}$

$0 < \lambda < 1$

$0 < \kappa < 1$

$-1500\ \text{GeV} < A_\kappa < 500\ \text{GeV}$

$100\ \text{GeV} < M_{3SU}, M_{3SQ} < 2000\ \text{GeV}$

$-4000\ \text{GeV} < A_t < 4000\ \text{GeV}$

decoupling other parameters (3 TeV)

NMSSMTools

Parameter Scan

$1 < \tan\beta < 10$

$0\ \text{GeV} < m_A < 200\ \text{GeV}$ — non-decoupling region

$100\ \text{GeV} < \mu < 1000\ \text{GeV}$

$0 < \lambda < 1$

$0 < \kappa < 1$

$-1500\ \text{GeV} < A\kappa < 500\ \text{GeV}$

$100\ \text{GeV} < M_{3SU}, M_{3SQ} < 2000\ \text{GeV}$

$-4000\ \text{GeV} < A_t < 4000\ \text{GeV}$

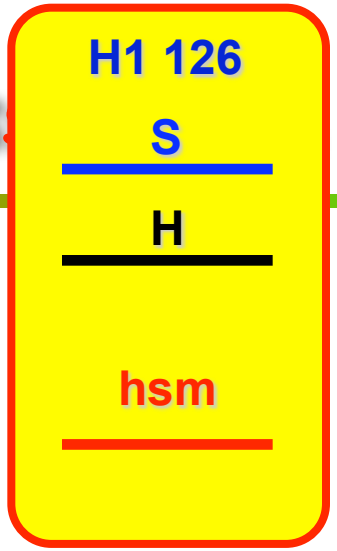
decoupling other parameters (3 TeV)

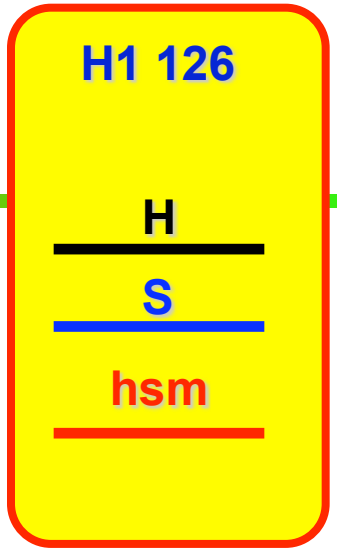
NMSSMTools

H_1 126 GeV, SM-like

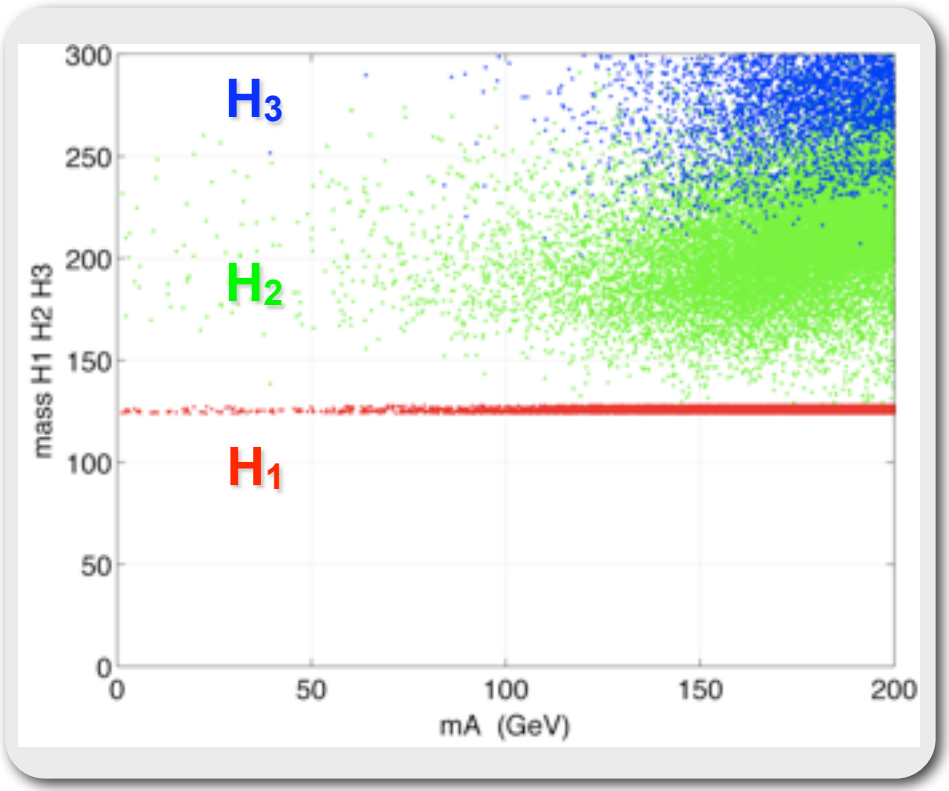
H_1 as 126 GeV SM-like Higgs

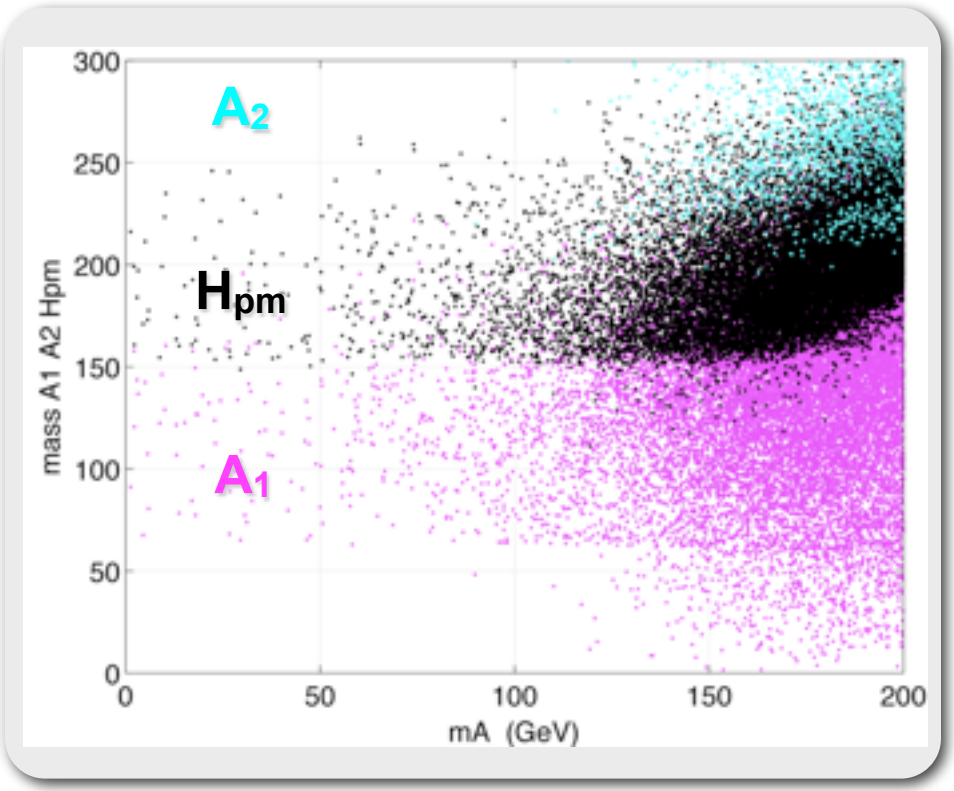
H_1 126 GeV: mass



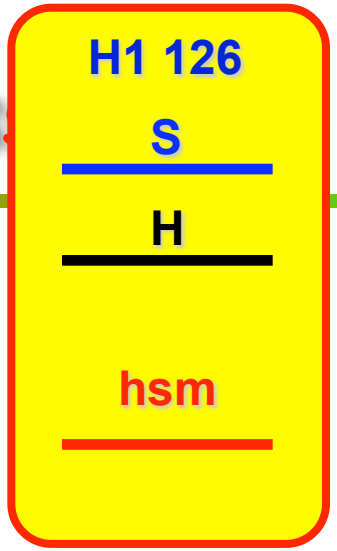


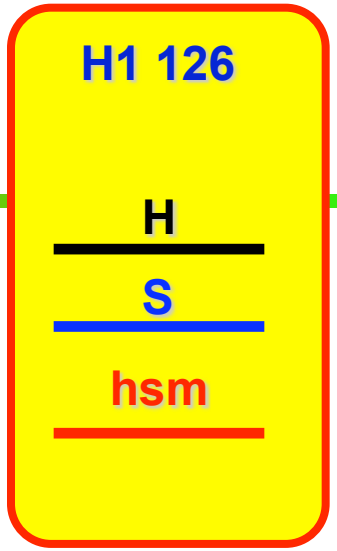
- M_{Hi} vs m_A



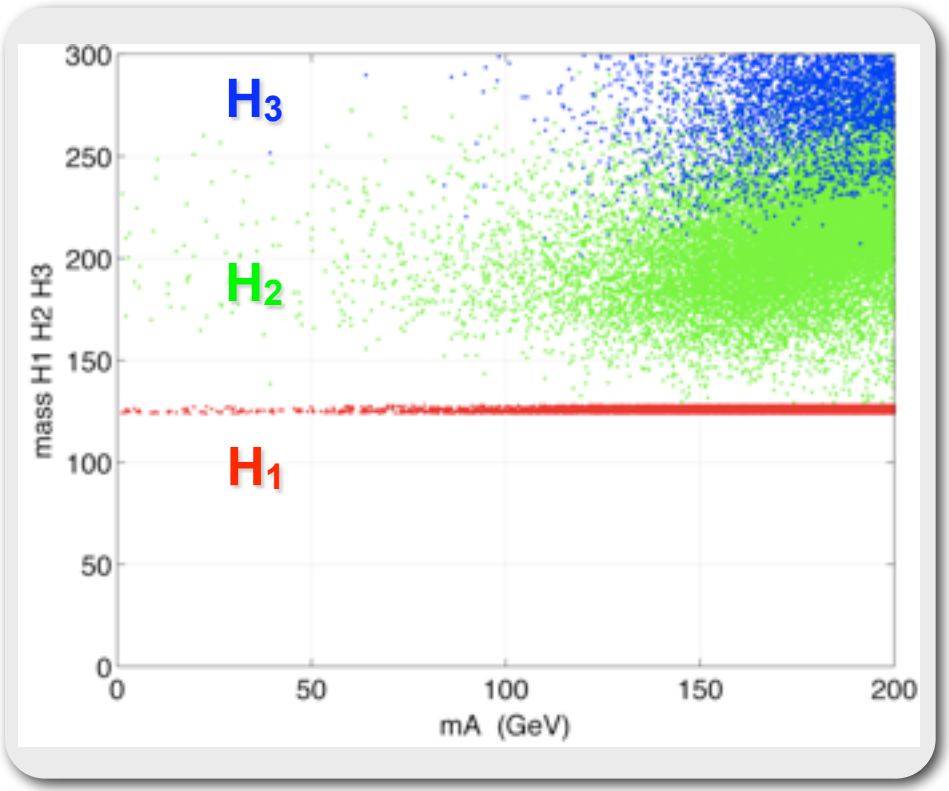


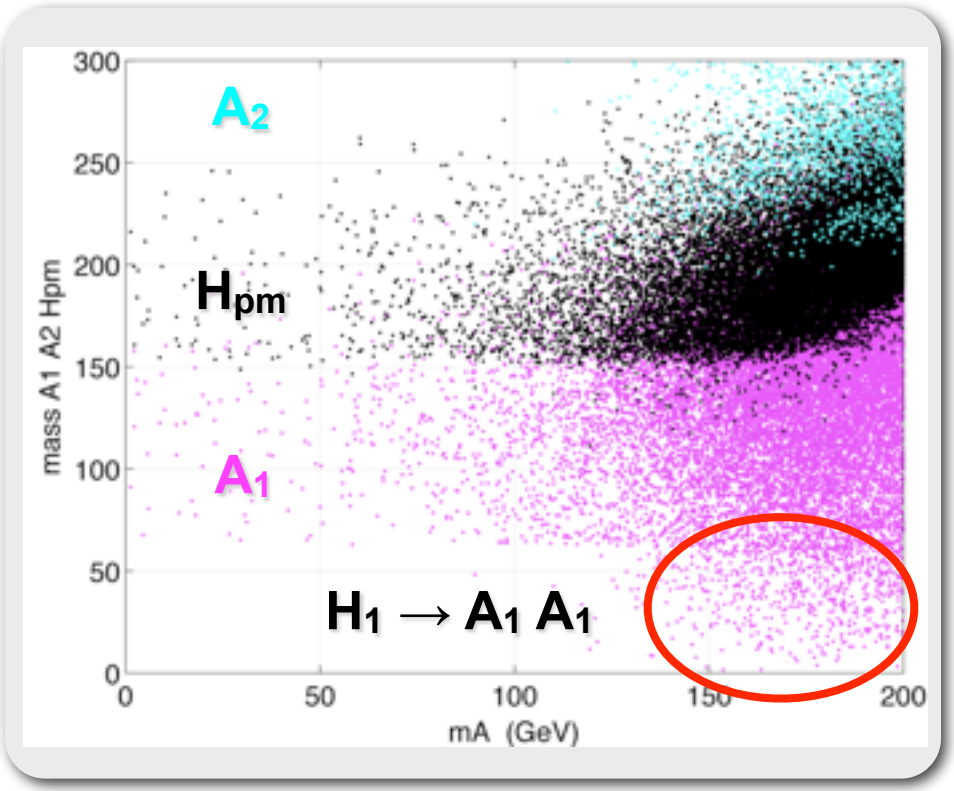
H_1 126 GeV: mass





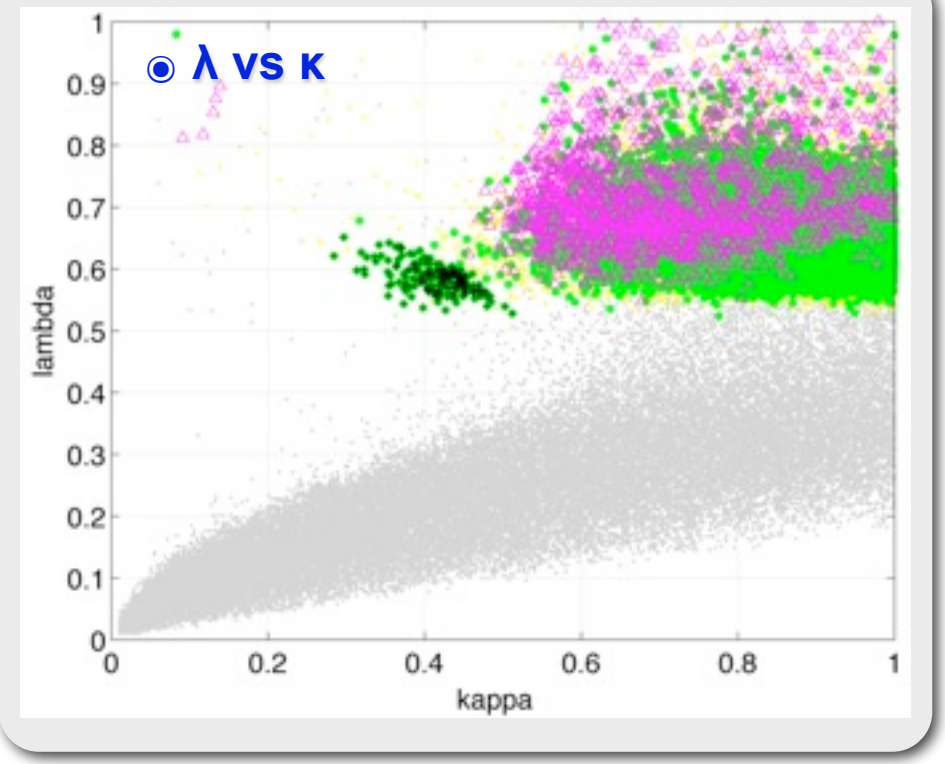
- M_{Hi} vs m_A

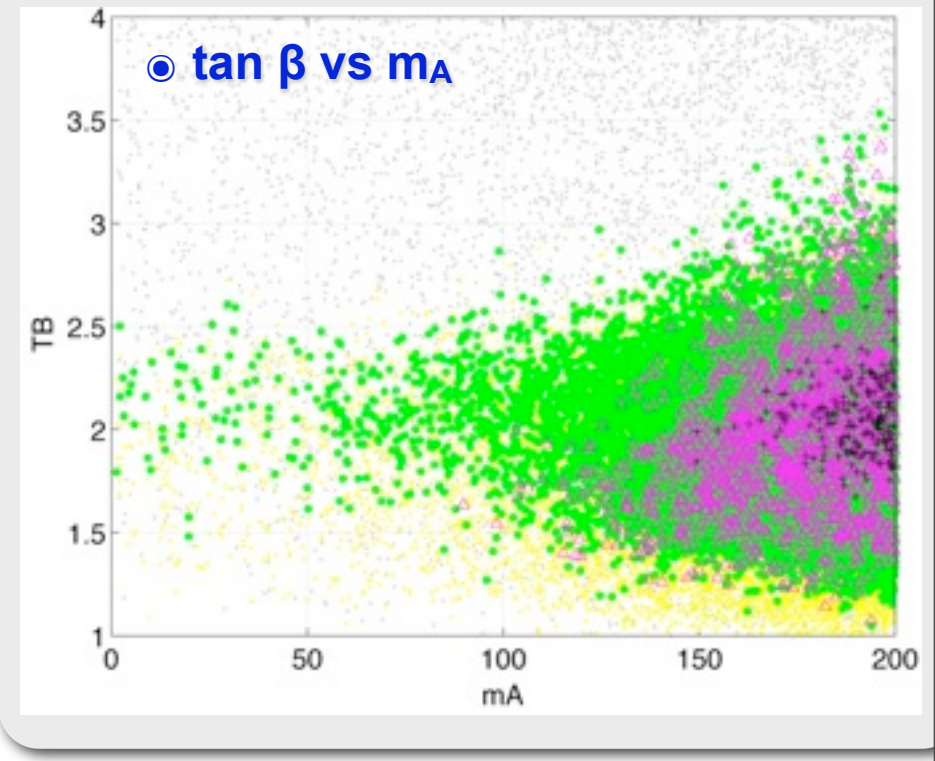




H_1 126 GeV: parameter regions

- pass exp
- yellow dots: $124 < m_{H1} < 128$ GeV
- green, purple, black: satisfy σXBr(γγ, WW)
- purple: $H_1 \rightarrow A_1 A_1$
- black: perturbativity till m_{pl}





tanβ	1 to 3.5	~ 2	1 to 3.5
m_A	0 to 200 GeV	150 to 200 GeV	100 to 200 GeV
λ	≥ 0.55	0.55 to 0.6	≥ 0.55
κ	≥ 0.3	0.3 to 0.5	≥ 0.5

H_1 126 GeV: parameter regions

- pass exp
- yellow dots: $124 < m_{H1} < 128$ GeV
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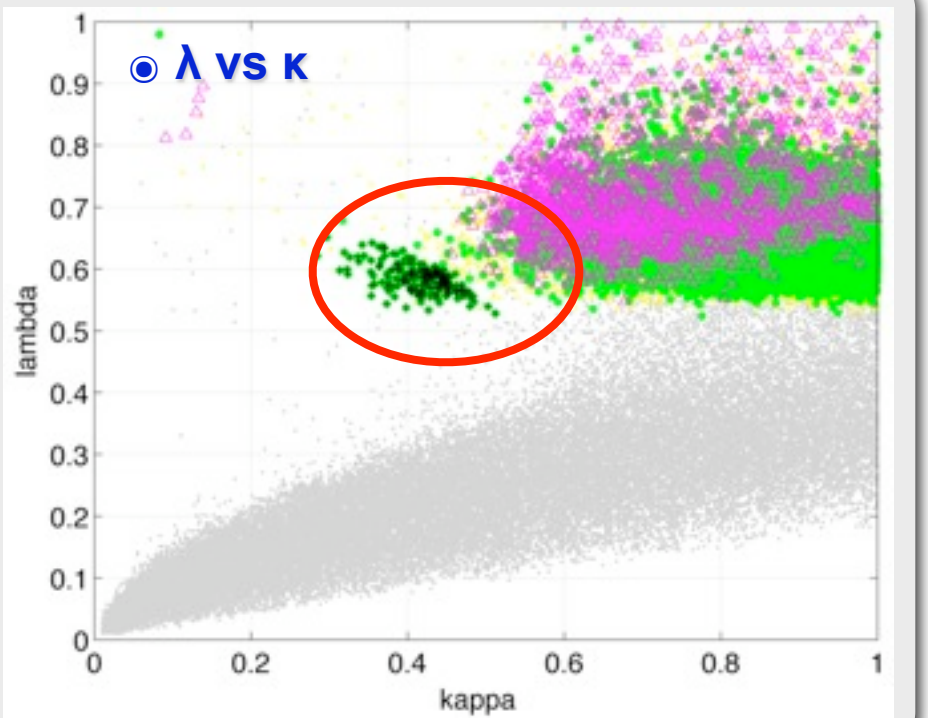

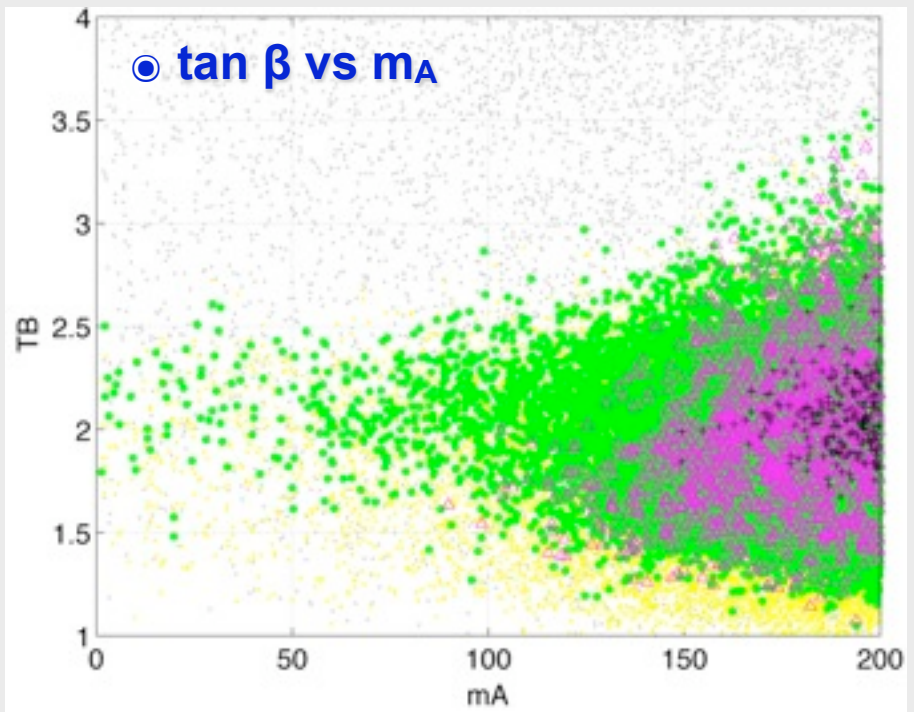

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m_A	0 to 200 GeV	150 to 200 GeV	100 to 200 GeV
λ	≥ 0.55	0.55 to 0.6	≥ 0.55
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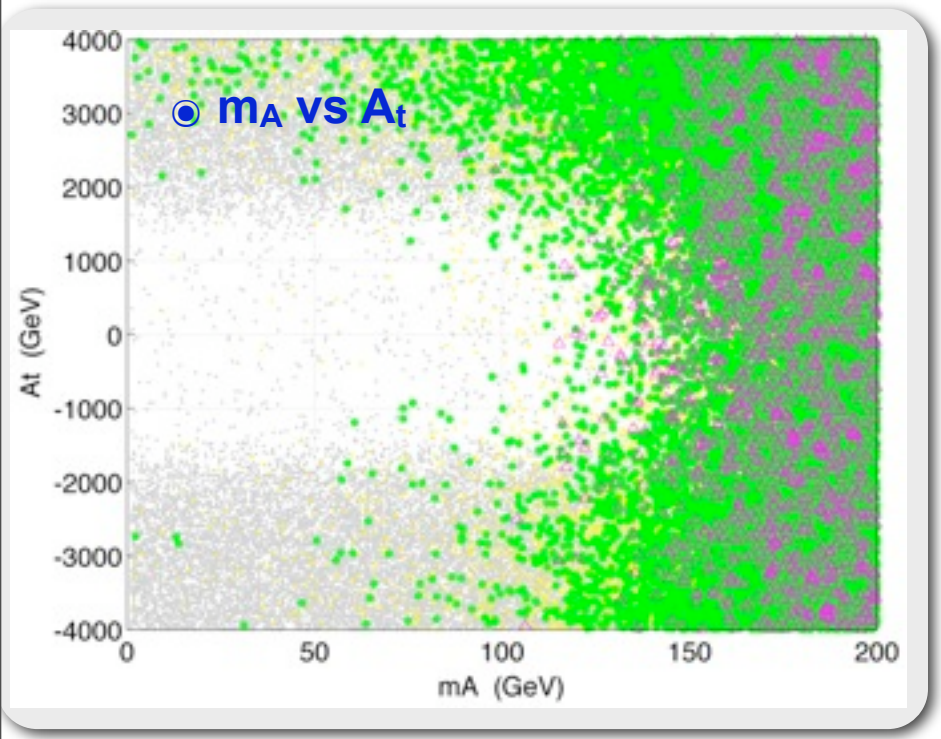
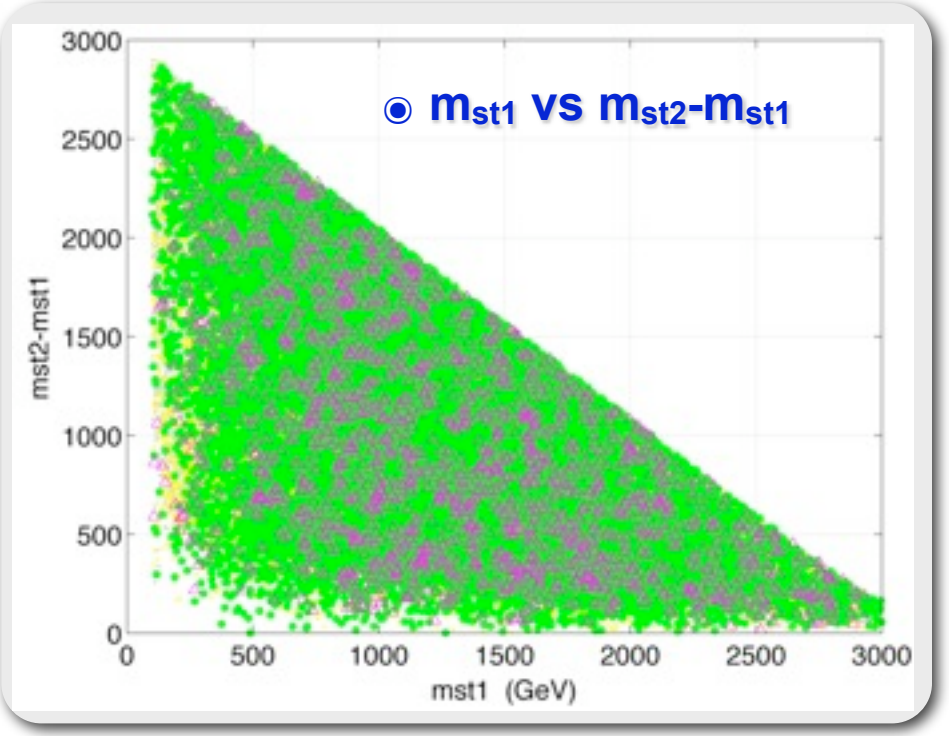
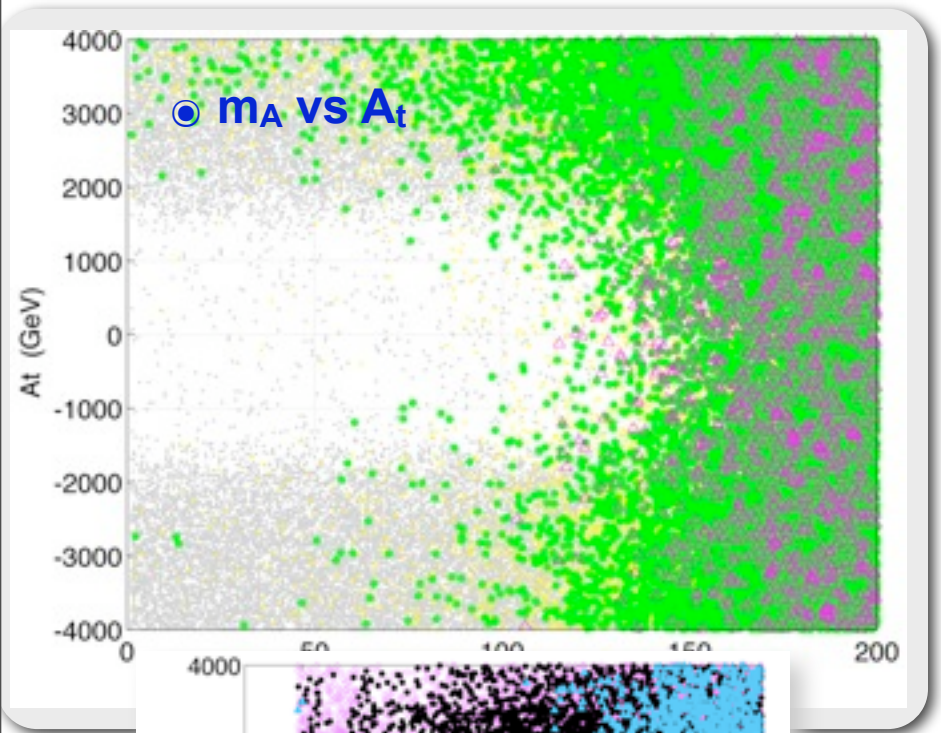
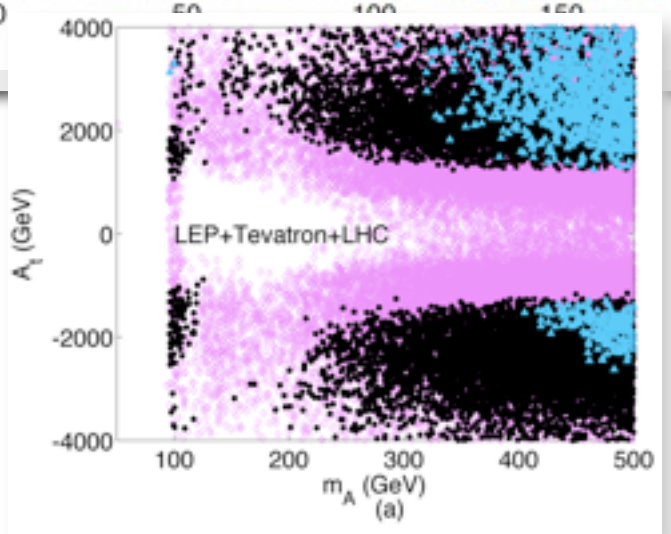
H_1 126 GeV: stops

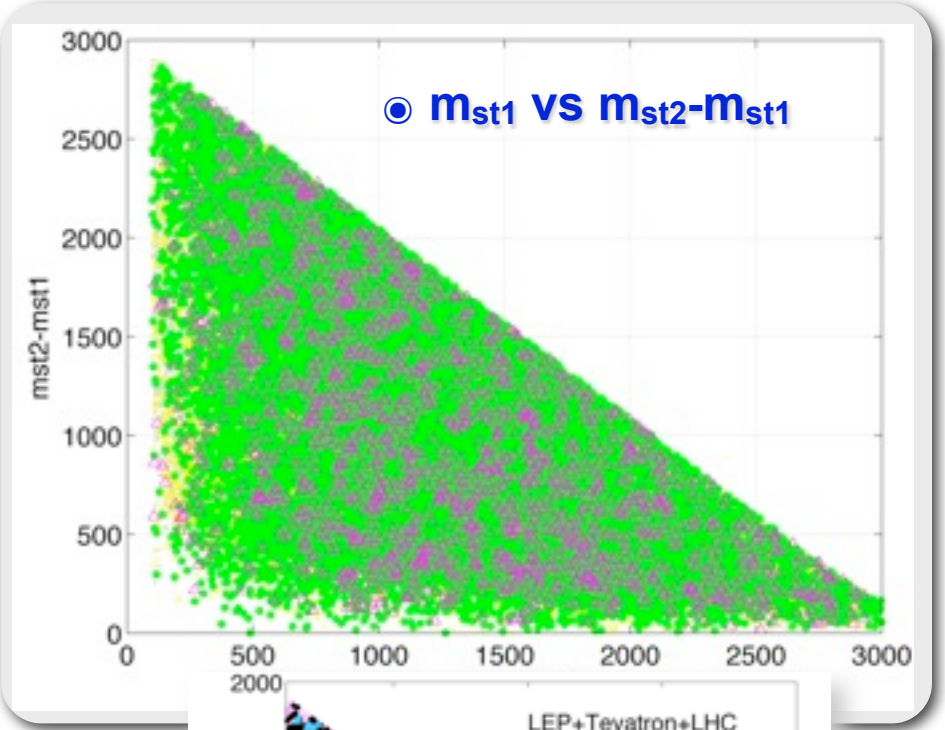


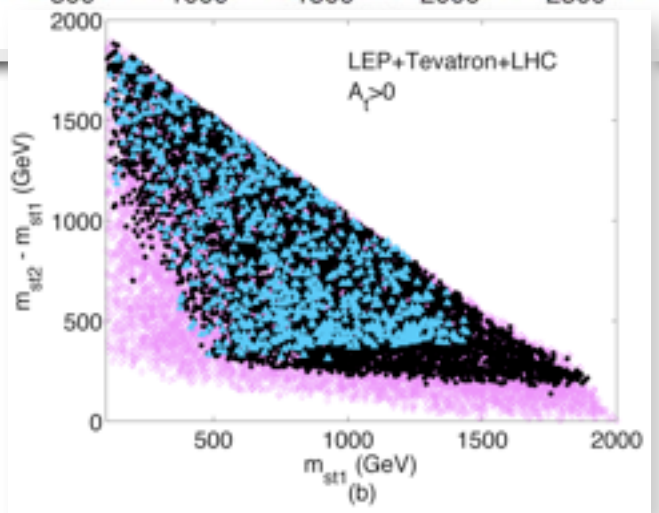


H_1 126 GeV: stops







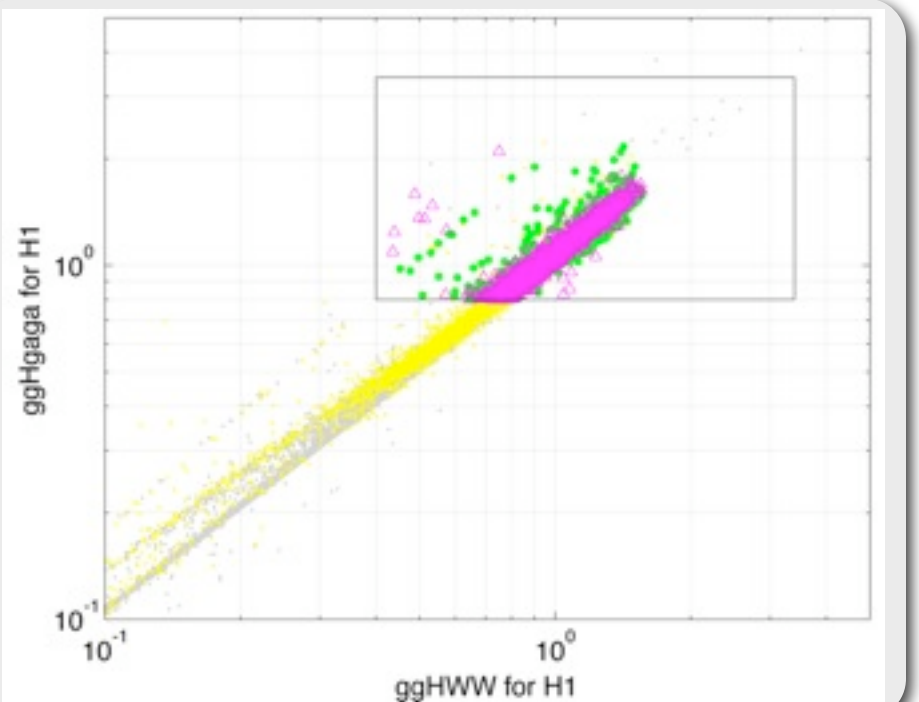


Parameter regions

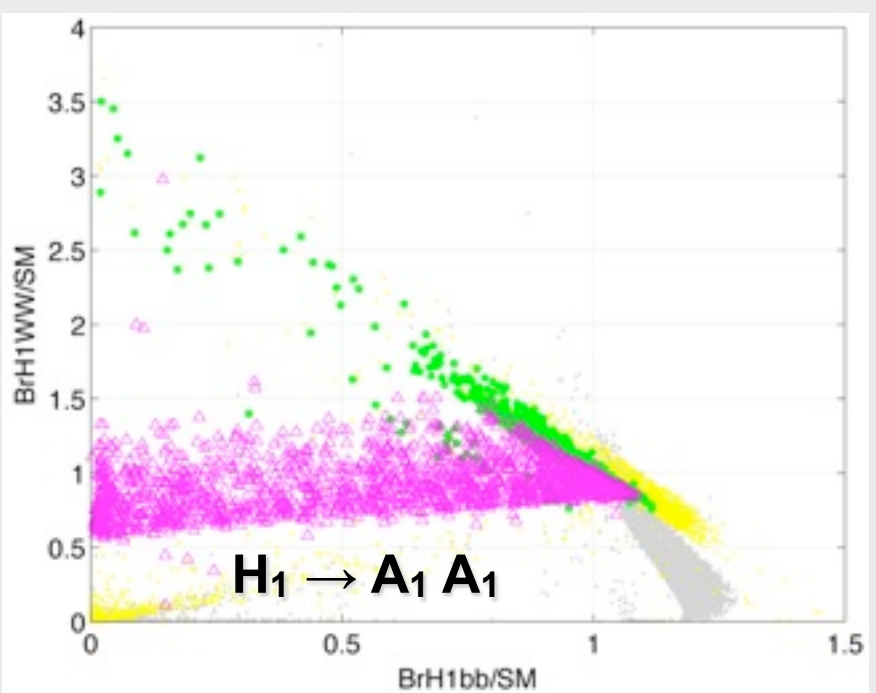
	H_1 126	perturbativity	$m_{A1}<m_{H1}/2$
tanβ	1 to 3.5	~ 2	1 to 3.5
m_A	0 to 200 GeV	150 to 200 GeV	100 to 200 GeV
μ	μ ≤ 500 GeV	100 to 150 GeV	100 to 200 GeV
λ	≥ 0.55	0.55 to 0.6	≥ 0.55
κ	≥ 0.3	0.3 to 0.5	≥ 0.5
A_κ	-1200 to 200 GeV	-150 to 100 GeV	-50 to 30 GeV
A_λ	-650 to 300 GeV	-30 to 230 GeV	-150 to 150 GeV
$\|A_t\|$		≥ 1200 GeV	

H_1 126 GeV: cross sections

◉ $\sigma_{\gamma\gamma}$ vs σ_{WW}



◉ Br_{WW} vs Br_{bb}



- pass exp
- yellow dots: $124 < m_{H1} < 128$ GeV
- green, purple, black: satisfy σXBr(γγ, WW)
- purple: $H_1 \rightarrow A_1 A_1$
- black: perturbativity till m_{pl}

H_1 126 GeV: h_{SM}-, H-, S- fraction

- pass exp
- yellow dots: $124 < m_{H1} < 128$ GeV
- green, purple, black: satisfy σXBr(γγ, WW)
- purple: $H_1 \rightarrow A_1 A_1$
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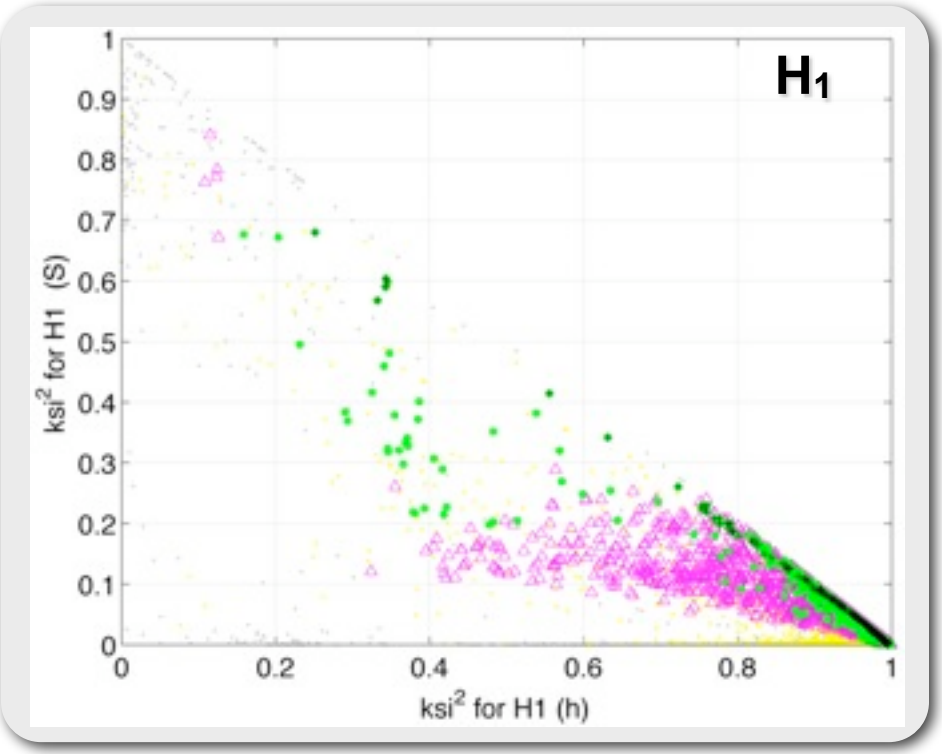

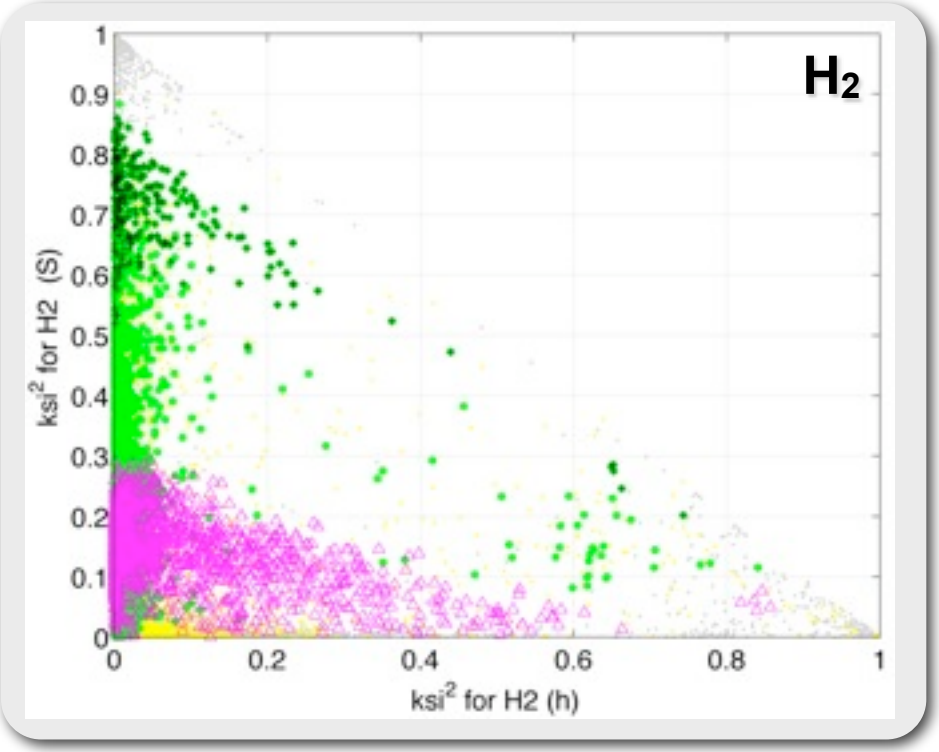

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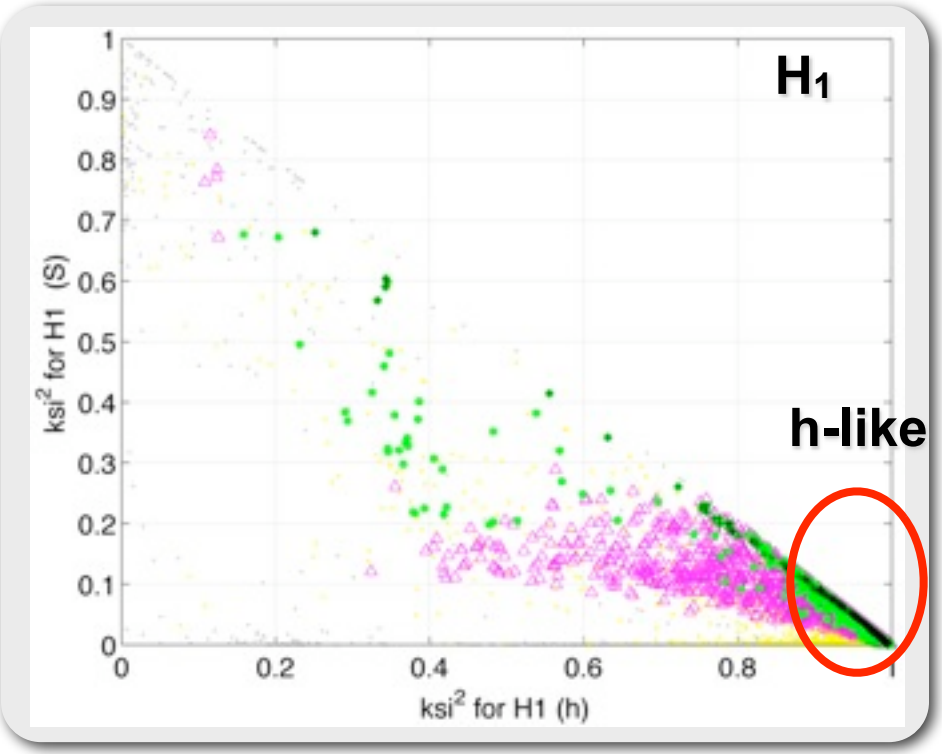

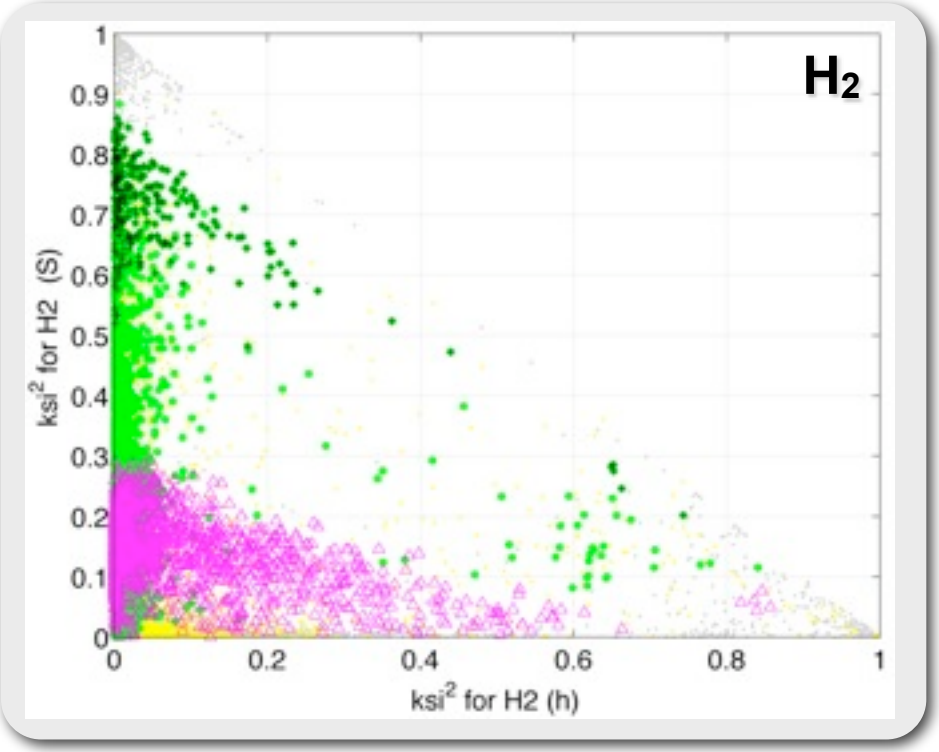

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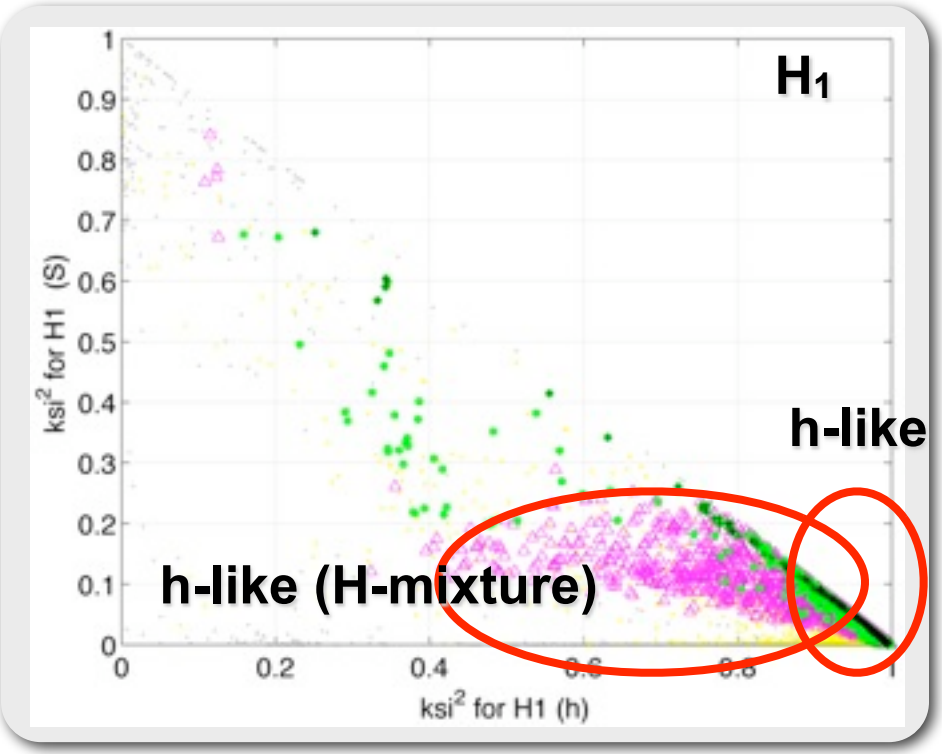

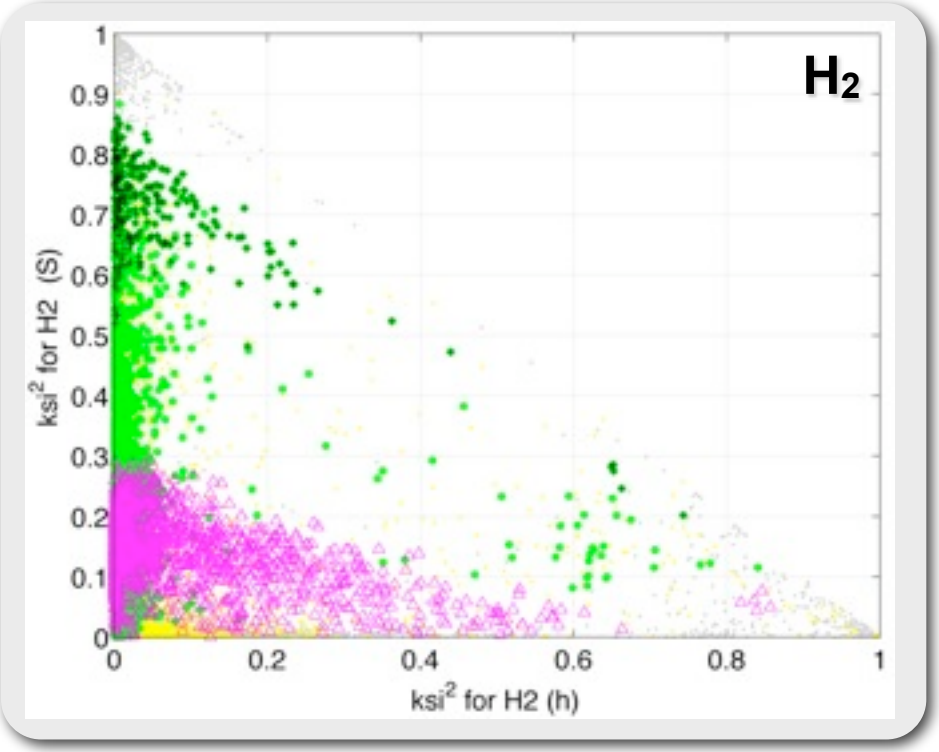

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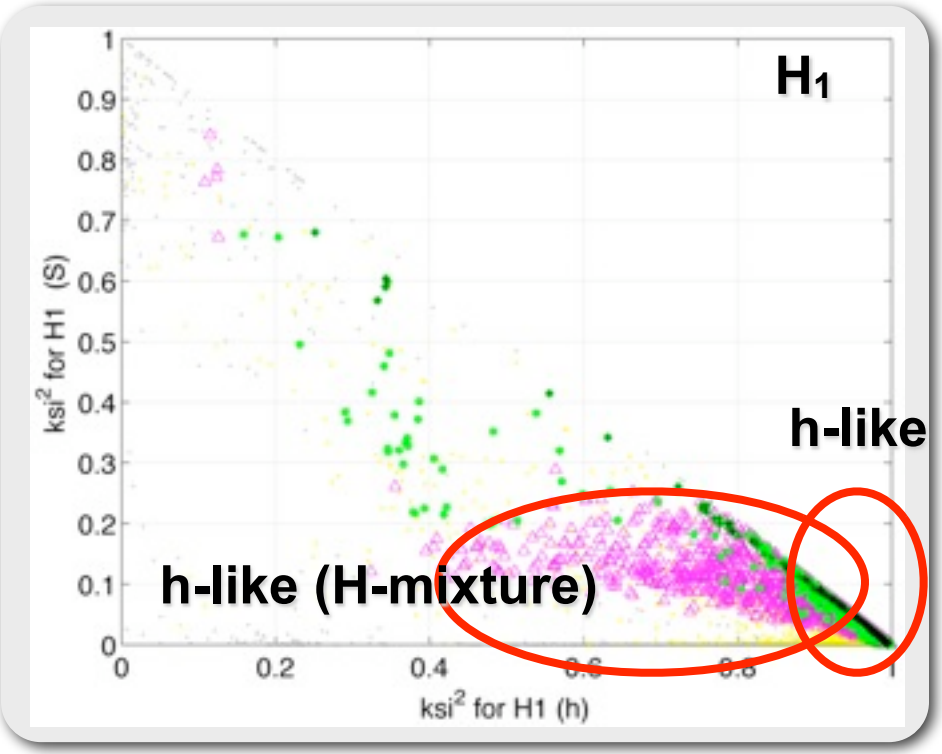

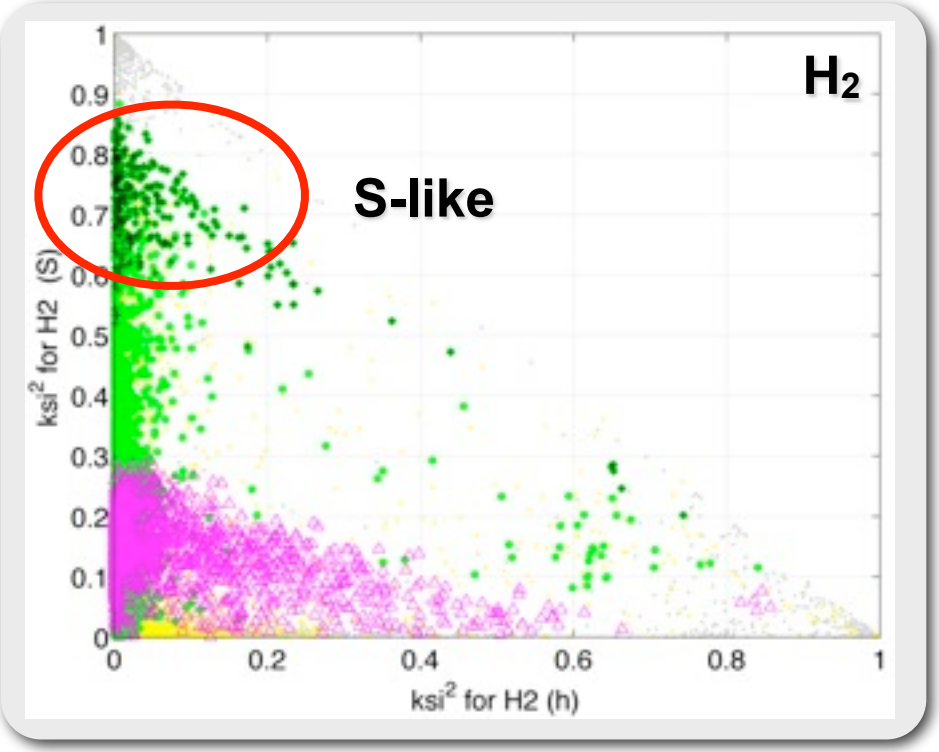

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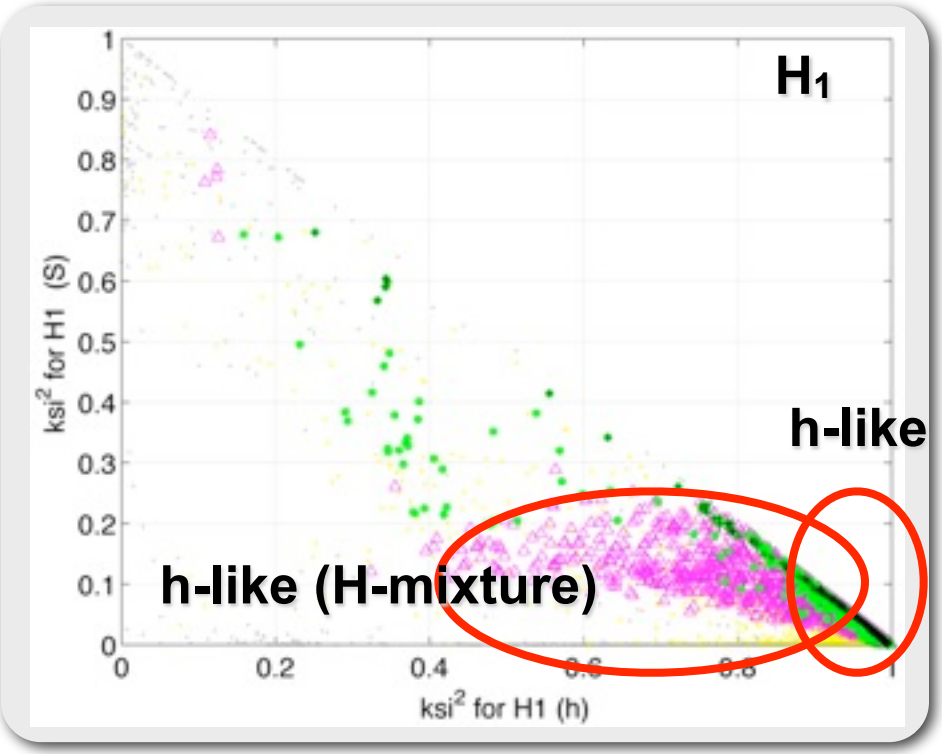

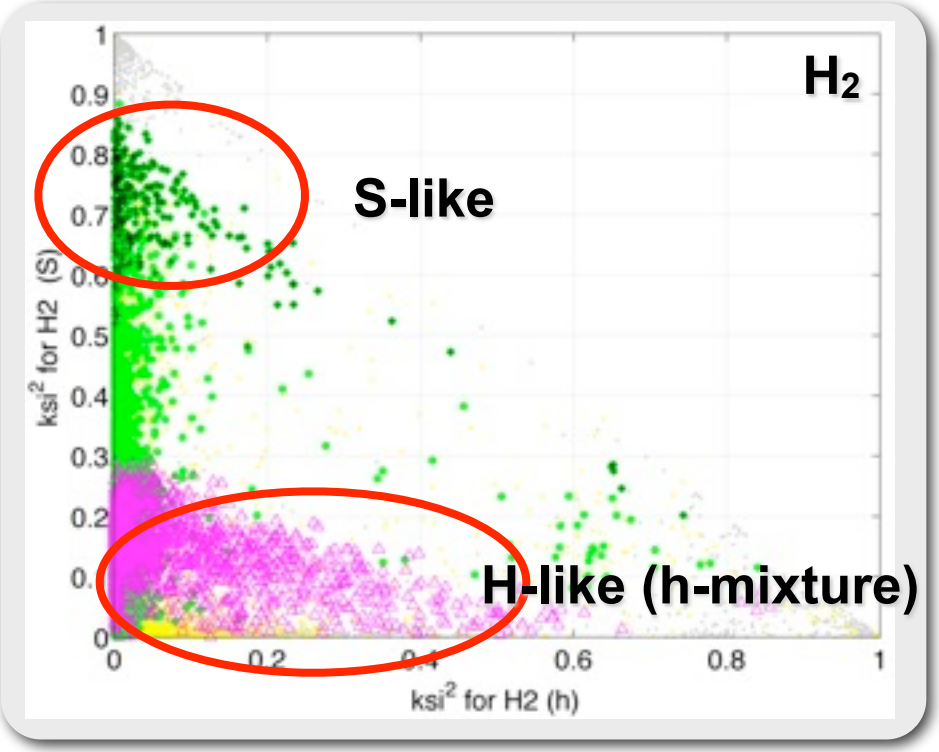

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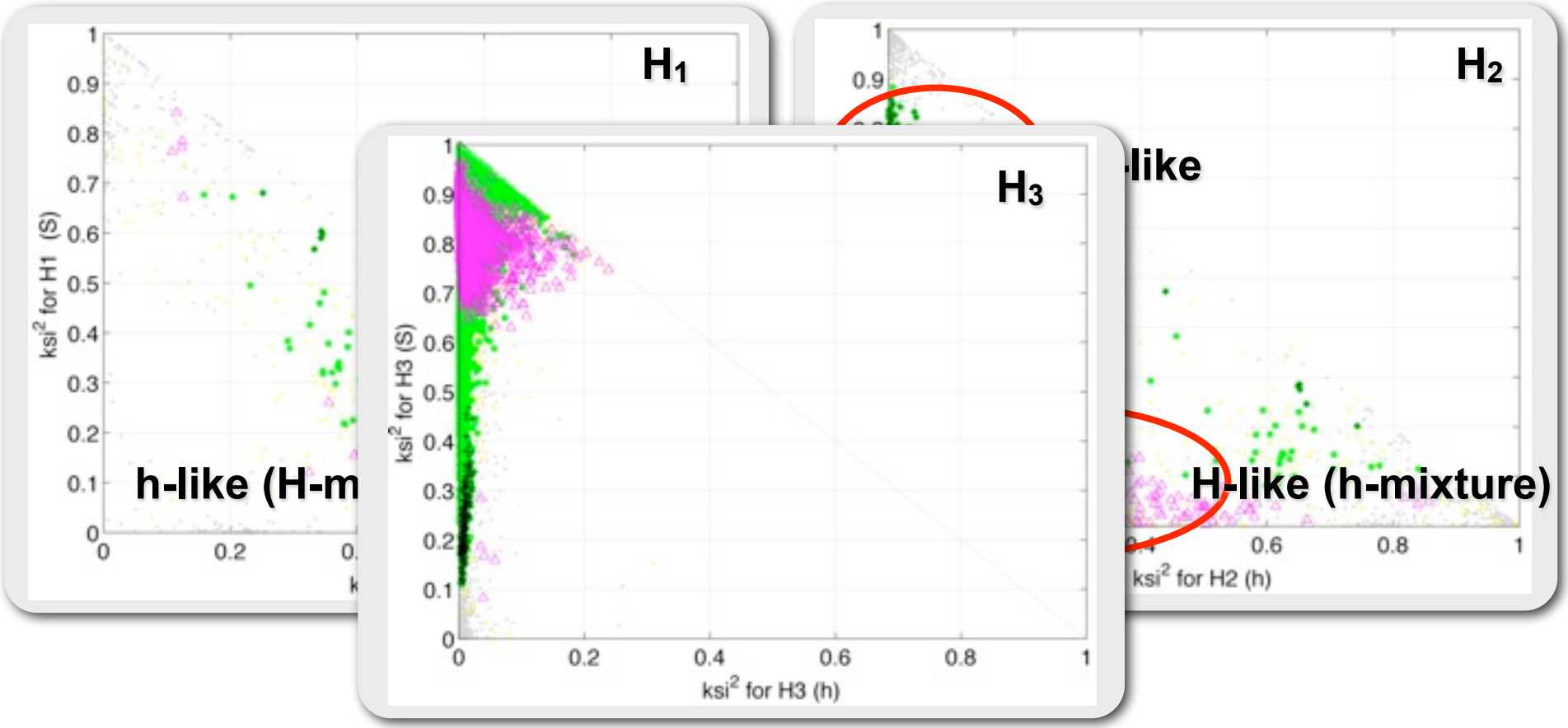

H_1 126 GeV: h_{SM}-, H-, S- fraction

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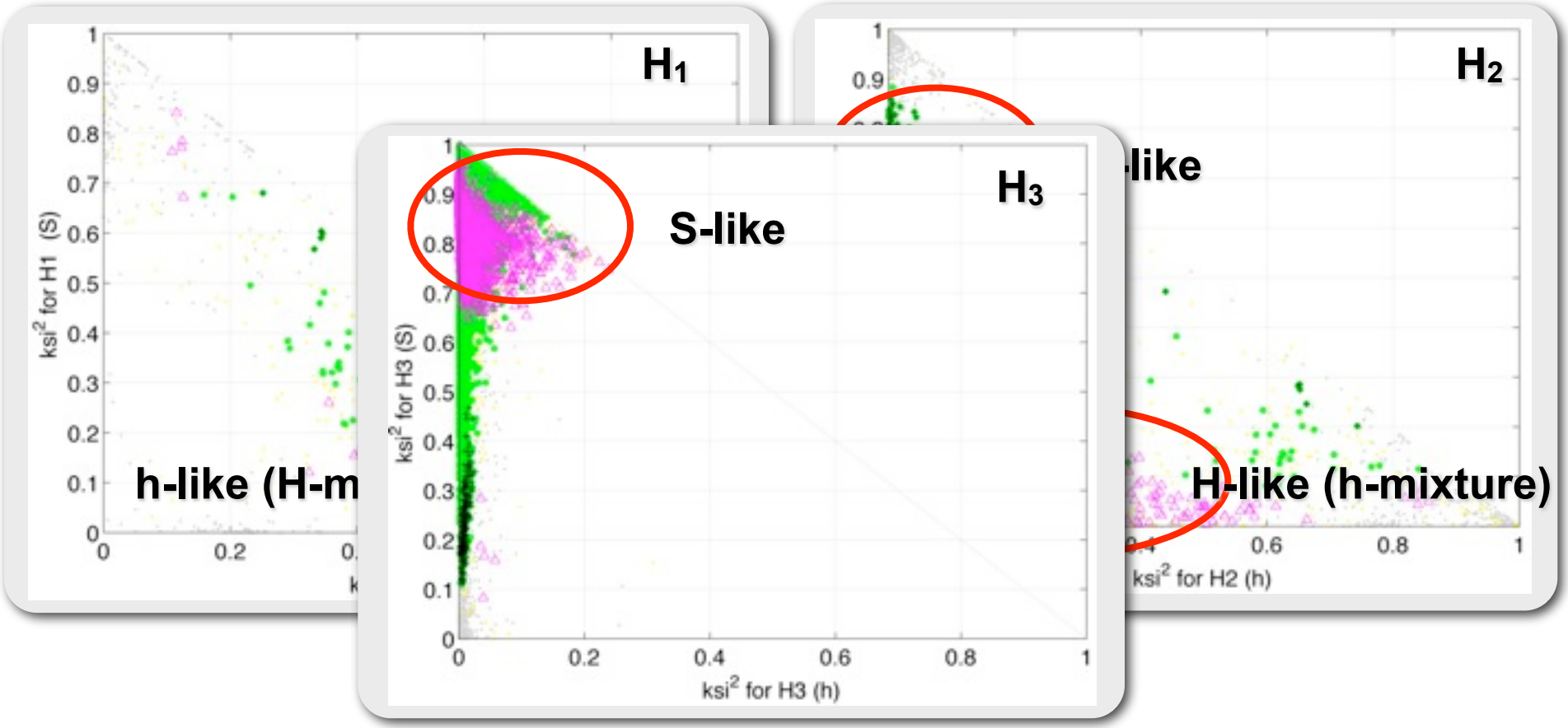

H_1 126 GeV: h_{SM}-, H-, S- fraction

- pass exp
- yellow dots: $124 < m_{H1} < 128$ GeV
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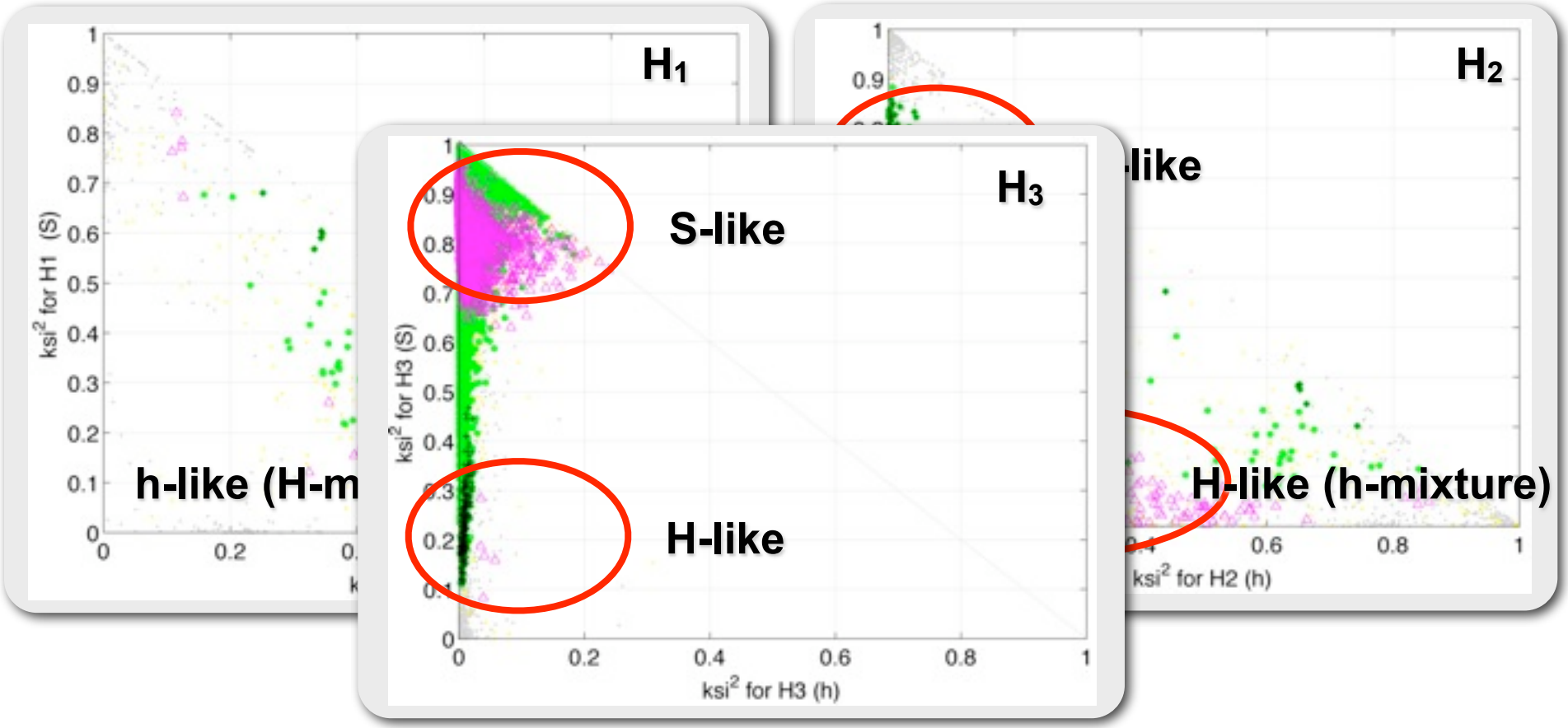
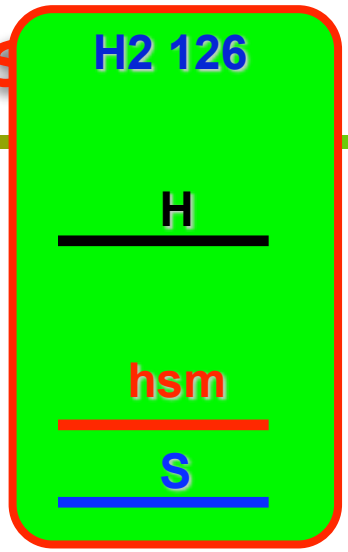
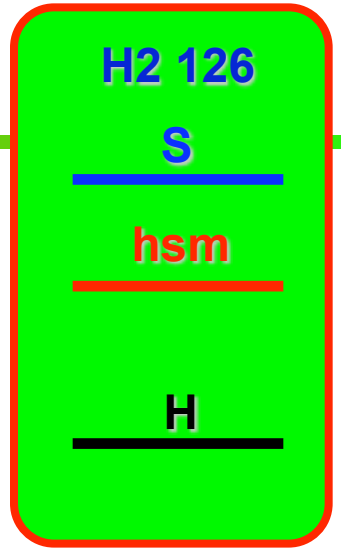


H_2 126 GeV, SM-like

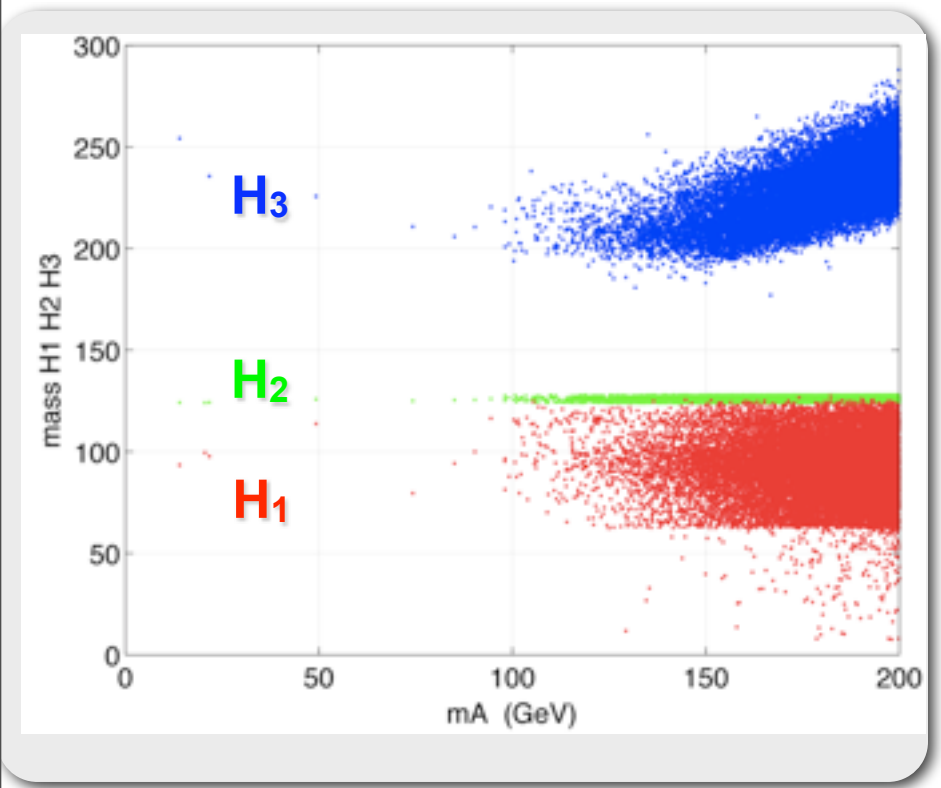
H_2 as 126 GeV SM-like Higgs

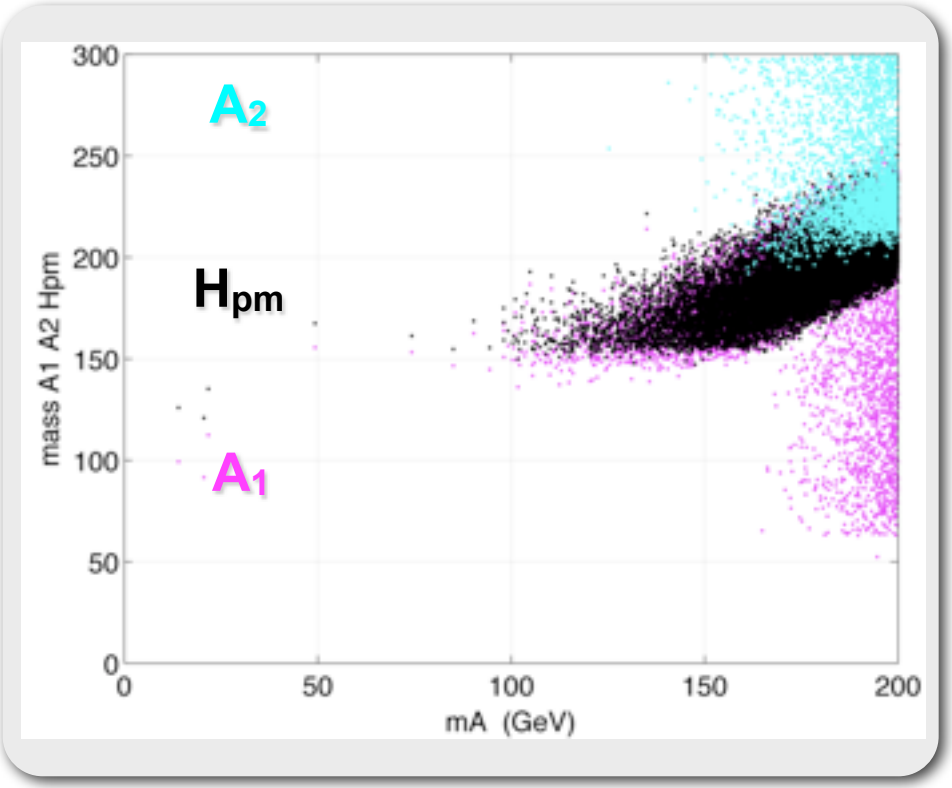
H_2 126 GeV: mass



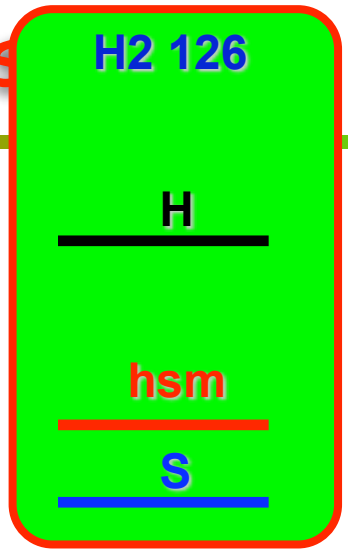


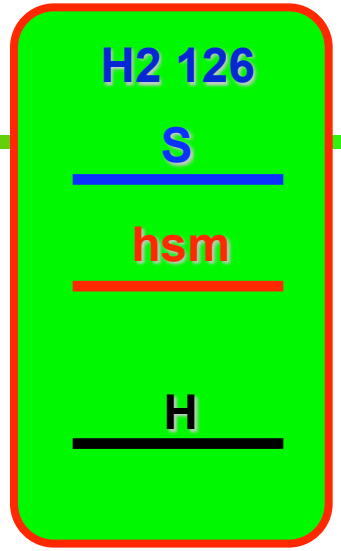
- M_{Hi} vs m_A



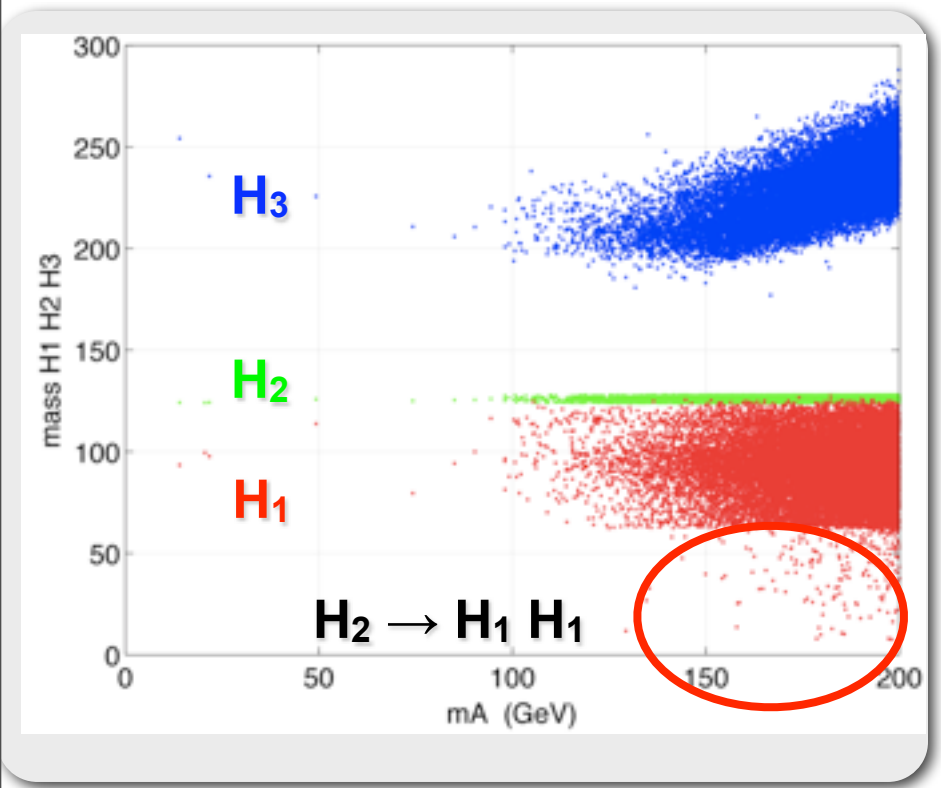


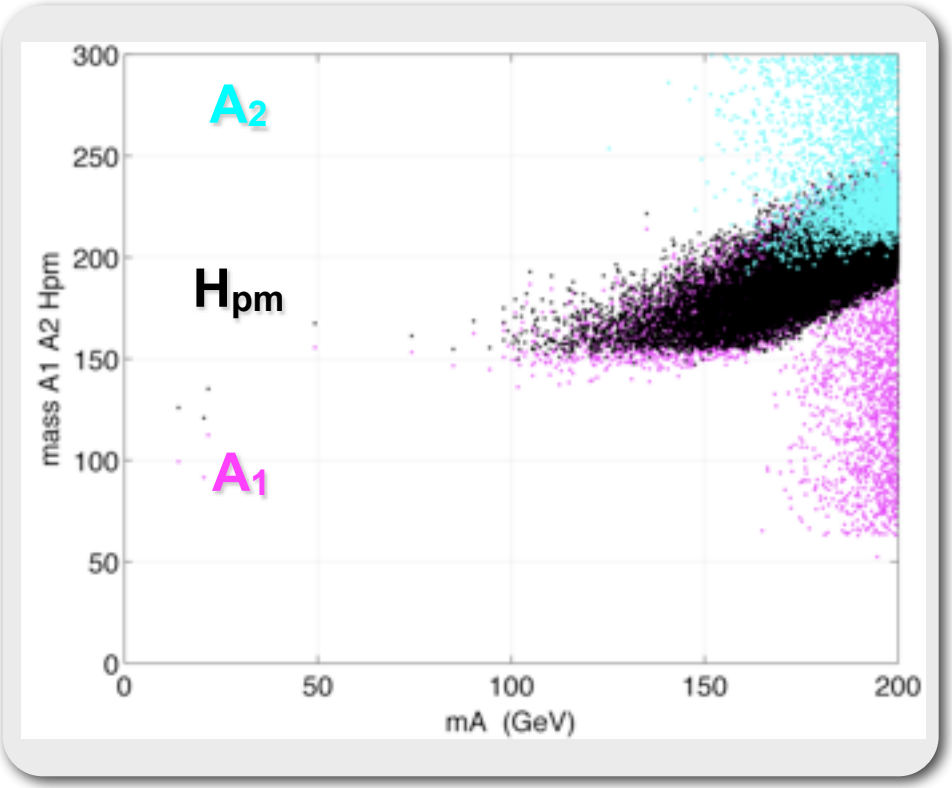
H_2 126 GeV: mass



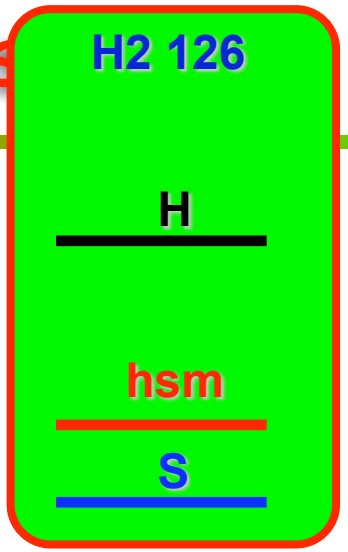


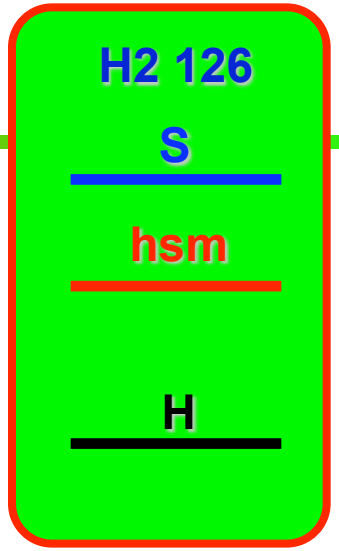
- M_{Hi} vs m_A



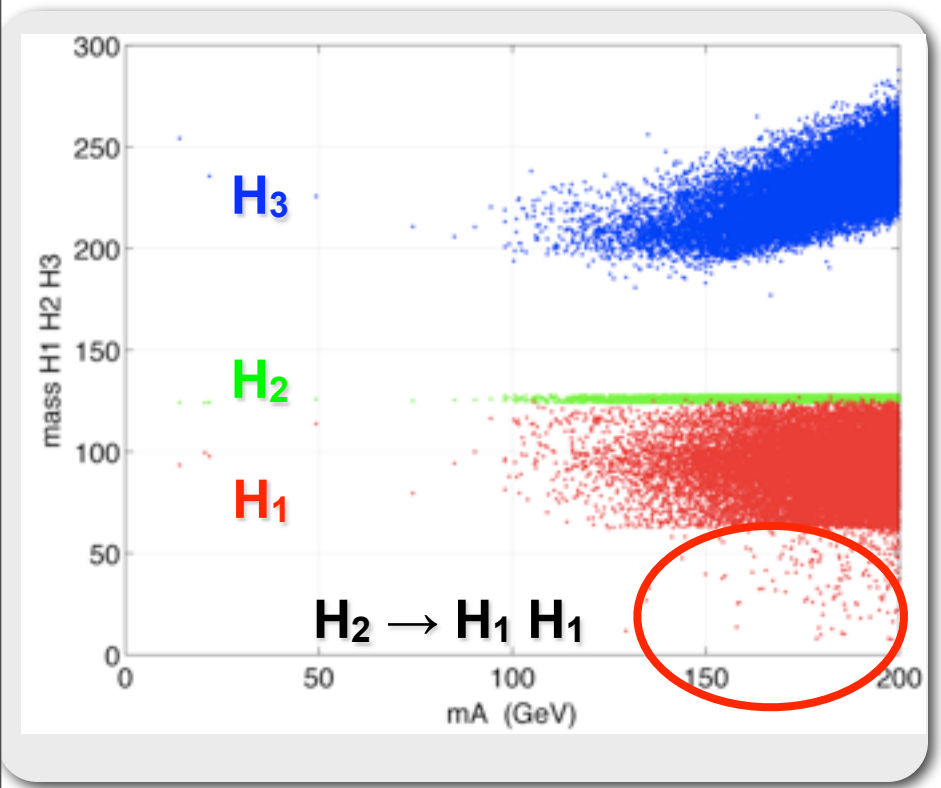


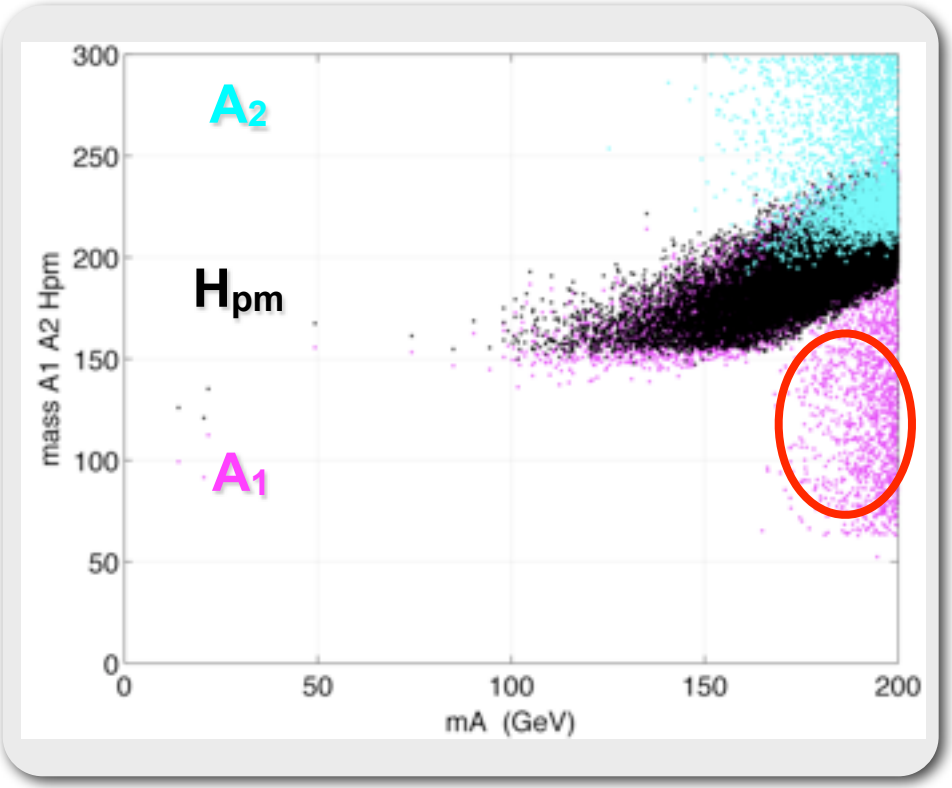
H_2 126 GeV: mass





- M_{Hi} vs m_A



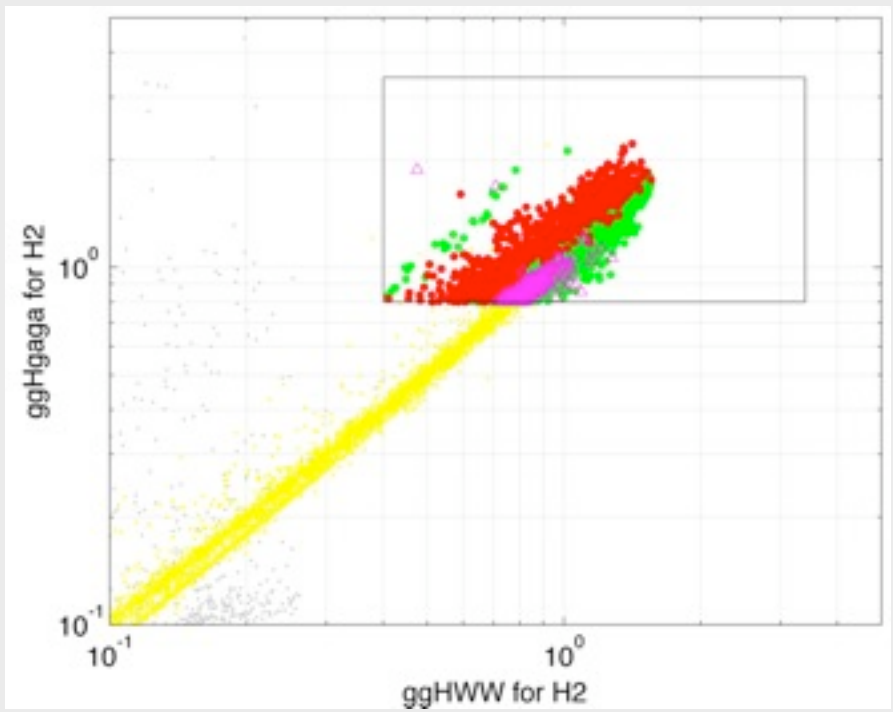


Parameter regions

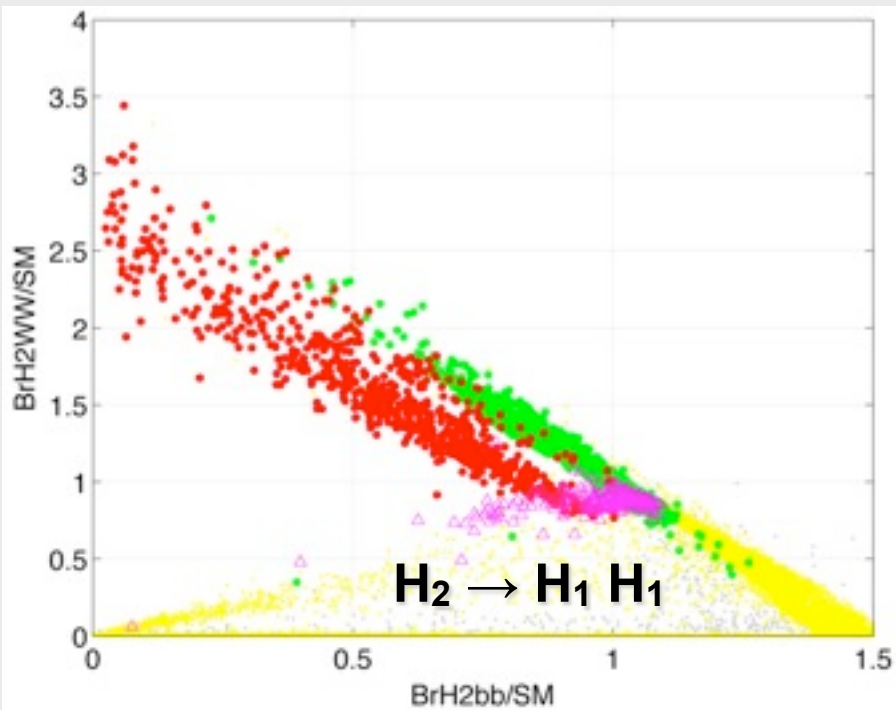
	H_2 126	perturbativity	$m_{H1}<m_{H2}/2$
tanβ	1 to 3.25	1.5 to 2.5	1.25 to 2.5
m_A	100 to 200 GeV	170 to 200 GeV	125 to 200 GeV
μ	100 to 200 GeV	100 to 130 GeV	100 to 150 GeV
λ	0.4 to 0.75	0.5 to 0.7	0.5 to 0.75
κ	≥ 0.05	0.05 to 0.6	≥ 0.3
A_κ	-1200 to 50 GeV	-300 to 50 GeV	-500 to -250 GeV
A_λ	-300 to 300 GeV	0 to 300 GeV	0 to 200 GeV

H_2 126 GeV: cross sections

◉ $\sigma_{\gamma\gamma}$ vs σ_{WW}



◉ Br_{WW} vs Br_{bb}



- pass exp
- yellow dots: $124 < m_{H2} < 128$ GeV
- green, purple, red, black: satisfy σXBr(γγ, WW)
- purple: $H_2 \rightarrow H_1 H_1$
- black: perturbativity till m_{pl}

H_2 126 GeV: h_{SM}-, H-, S- fraction

- pass exp
- yellow dots: $124 < m_{H2} < 128$ GeV
- green, purple, red, black: satisfy σXBr(γγ, WW
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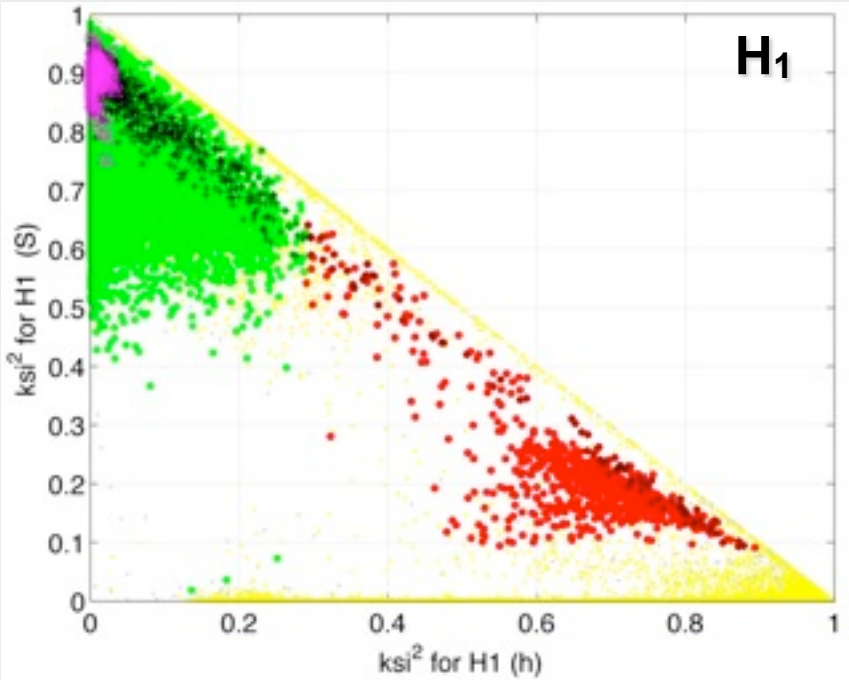

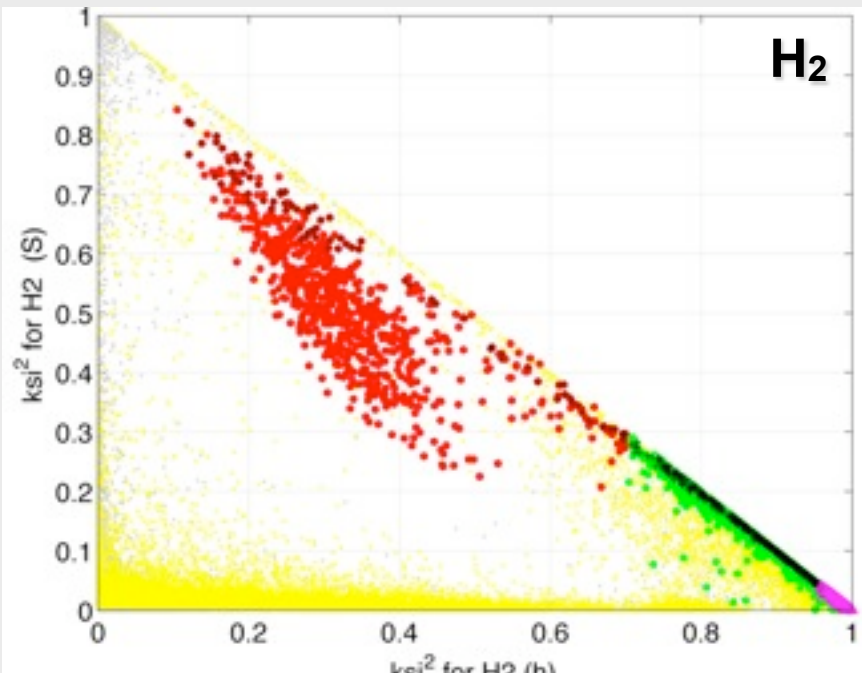

H_2 126 GeV: h_{SM}-, H-, S- fraction

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- yellow dots: $124 < m_{H2} < 128$ GeV
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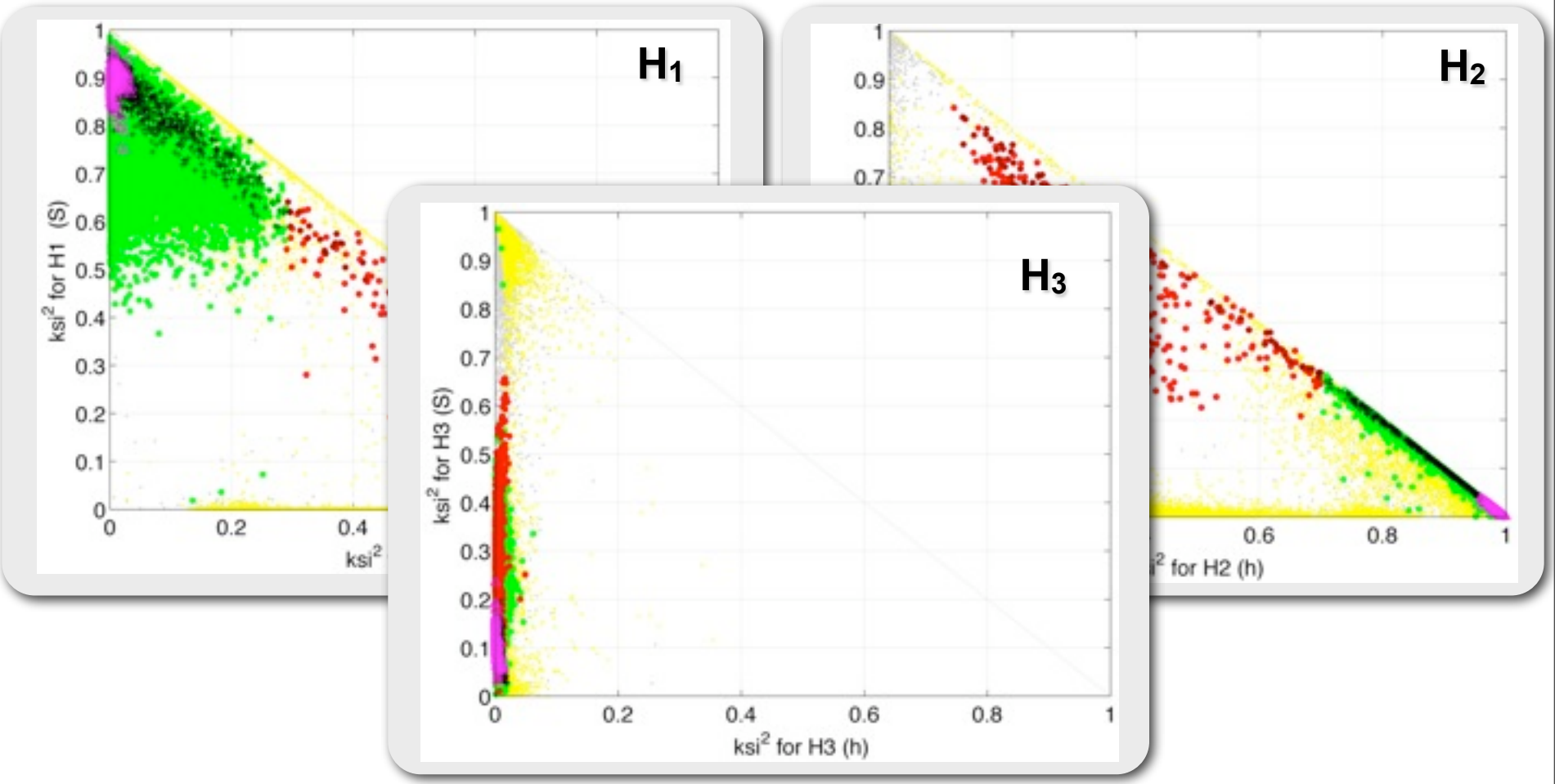


H_3 126 GeV, SM-like

H_3 as 126 GeV SM-like Higgs

H_3 126 GeV, SM-like

H_3 as 126 GeV SM-like Higgs

Fine tuned region,
Still working on it...

Conclusion (part I)

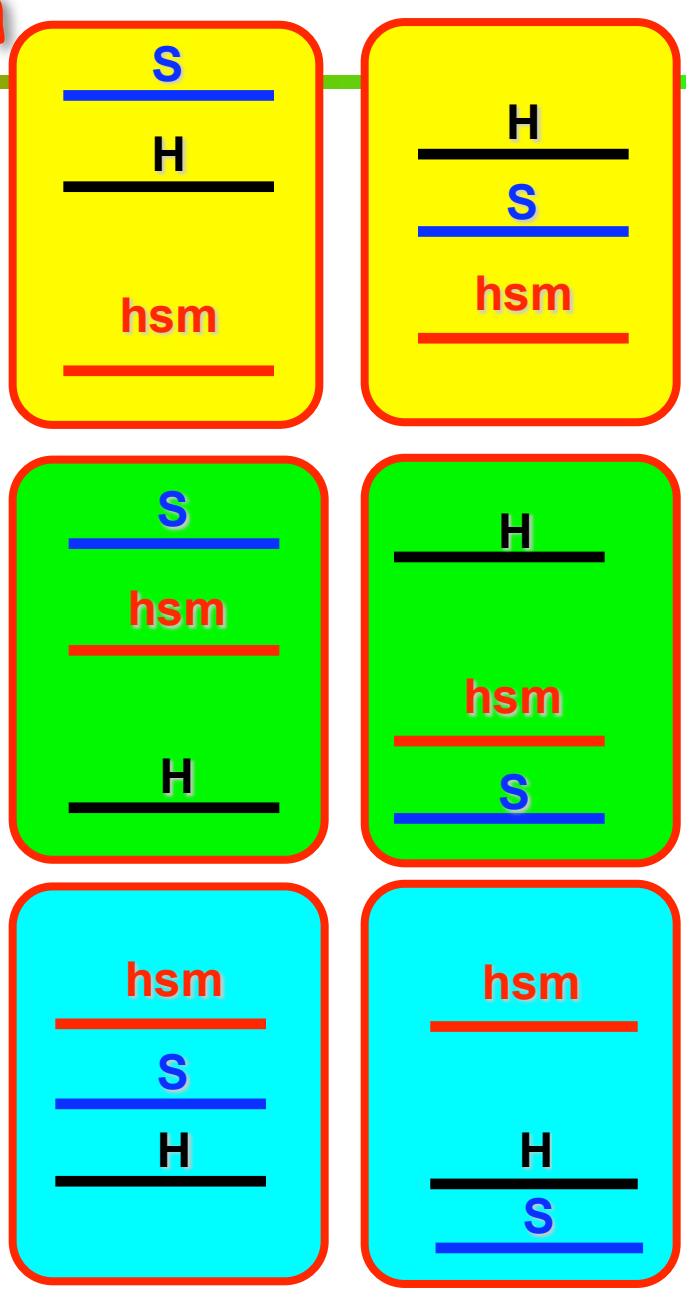
- 126 ± 2 GeV (~SM strength) in NMSSM: non-decoupling region
  - small m_A (≤ 200 GeV), all Higgses light, possible large mixing effects
  - singlet helps to lift mass: large λ, small tan β
  - mixing with singlet, change Γ_{bb}, $\Gamma_{WW/ZZ}$, ...

- MSSM
  - $m_A \sim m_Z$, non-decoupling, H_1 SM-like
  - $m_A \geq 300$ GeV, decoupling, H_2 SM-like
  - stops either heavy or large LR-mixing

- NMSSM
  - m_A : 0 - 200 GeV
  - either H_1 or H_2 (or H_3) SM-like
  - interesting features in each region
  - stop sector less constrained

Conclusion

- H_1 126 GeV
  - $\lambda \geq 0.55$, $\kappa \geq 0.3$, $1 \leq \tan\beta \leq 3.5$
  - H_1 SM h-like, H2, H3 S-H mixture
  - $H_1 \rightarrow A_1 A_1$: H_1, H_2 h-H mixture, H3 S-like
- H_2 126 GeV
  - $0.4 \leq \lambda \leq 0.75$, $\kappa \geq 0.05$, $1 \leq \tan\beta \leq 3.25$
  - $100 \leq m_A \leq 200$ GeV, small μ
  - case with $H_2 \rightarrow H_1 H_1$
  - H_2 h-S mixture, H_3 S-H mixture
  - H_1, H_2, h-H-S mixture; H_3: S-H mixture
- H_3 126 GeV: tuned region



S. Su

2HDM Higgs Sector

- **Type II Two Higgs Doublet Model**

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\} + \left\{\lambda_6\left[(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + \text{h.c.}\right\}$$

- **Z2 symmetry**
- **EWSB**

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \rightarrow v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \rightarrow v_d/\sqrt{2}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

after EWSB, 5 physical Higgses
CP-even Higgses: h, H
CP-odd Higgs: A
Charged Higgses: H±

2HDM Higgs Sector

- **Type II Two Higgs Doublet Model**

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
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2HDM Higgs Sector

- **Type II Two Higgs Doublet Model**

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after EWSB, 5 physical Higgses
CP-even Higgses: h, H
CP-odd Higgs: A
Charged Higgses: $H^\pm$

2HDM Higgs Sector

- **couplings**

ξ_h^{VV}	$\sin(\beta-\alpha)$	ξ_H^{VV}	$\cos(\beta-\alpha)$	ξ_A^{VV}	0
ξ_h^{u}	$\cos\alpha/\sin\beta$	ξ_H^{u}	$\sin\alpha/\sin\beta$	ξ_A^{u}	$\cot\beta$
ξ_h^{d}	$-\sin\alpha/\cos\beta$	ξ_H^{d}	$\cos\alpha/\cos\beta$	ξ_A^{d}	$\tan\beta$
ξ_h^{l}	$-\sin\alpha/\cos\beta$	ξ_H^{l}	$\cos\alpha/\cos\beta$	ξ_A^{l}	$\tan\beta$

- **parameters**

$$m_{11}^2,\ m_{22}^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5 \longrightarrow v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

- **Theoretical constrains**
  - vacuum stability
  - perturbativity
  - unitarity
  - Δρ

- **Experimental constraints**
  - LEP Higgs searches (neutral Higgs, charged Higgs)
  - Tevatron Higgs searches
  - LHC Higgs searches (SM-like Higgs searches, MSSM Higgs searches)

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2HDM Higgs Sector

- **previous work in 2HDM ...**

Ferreira et. al., 1112.3772, 2HDM, H1 125, tan β vs. sin α
Basso et. al., 1205.6569, CP violating 2HDM, H1 125,
Cheon et. al., 1207.1083, Type II 2HDM, H1 or H2 125
Chang et. al., 1210.3439, 2HDM, H1 or H2 or degenerate H1/A, χ2 fit
Drozd et. al., 1211.3580, Type I and II 2HDM, H1 or H2 125 or degenerate, $m_{12}^2 \neq 0$,
Craig and Thomas, 1207.4835, 2HDM, H1 125, various search channels
Ferreira et. al., 1211.3131, degenerate Higgses
...

Our work:

- **Type II 2HDM with $m_{12}^2=0$, 5 parameter scan**
- **impose theoretical and experimental constraints**
- **h^0 or H^0 125 GeV**
- **study parameter space and correlations**

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h^0 125 GeV

Light CP-even Higgs as 125 GeV SM-like Higgs

Type II 2HDM: h^0 125 GeV

$$\frac{\sigma(gg \to h \to \gamma\gamma, WW/ZZ)}{\sigma(gg \to h_{\rm SM} \to \gamma\gamma, WW/ZZ)} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \times \frac{\rm BR(h \to \gamma\gamma, WW/ZZ)}{\rm BR(h_{SM} \to \gamma\gamma, WW/ZZ)}$$

Type II 2HDM: h^0 125 GeV

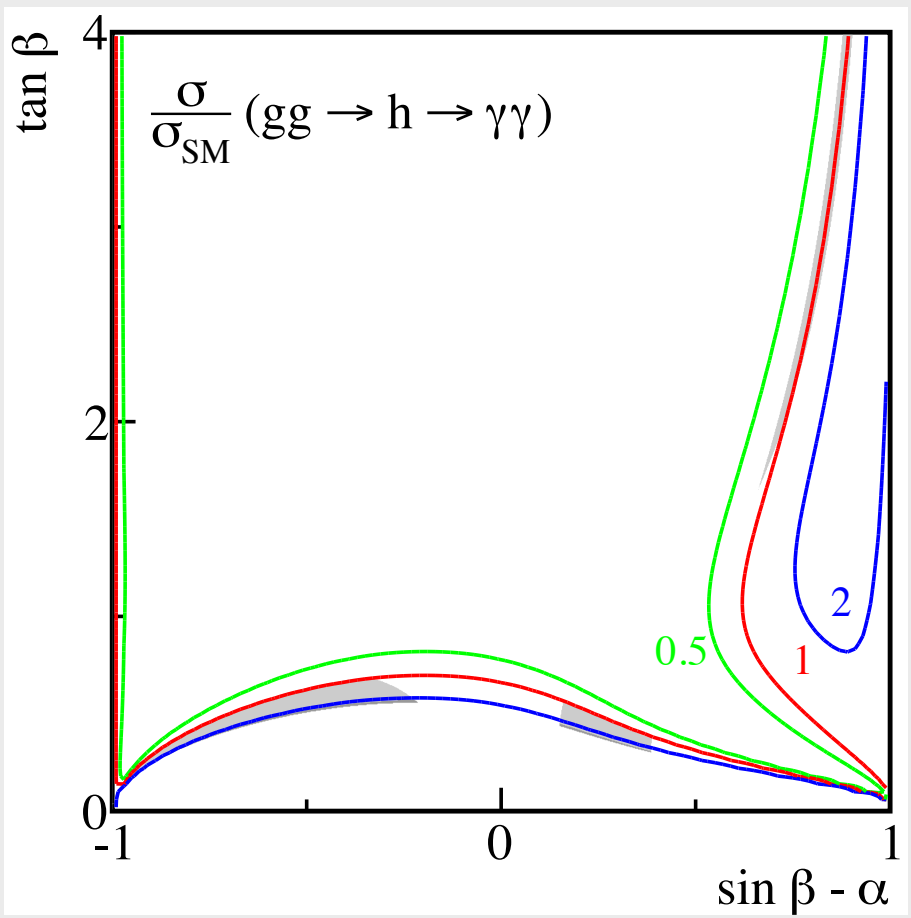
$$\frac{\sigma(gg \to h \to \gamma\gamma, WW/ZZ)}{\sigma(gg \to h_{\rm SM} \to \gamma\gamma, WW/ZZ)} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \times \frac{\mathrm{BR}(h \to \gamma\gamma, WW/ZZ)}{\mathrm{BR}(h_{SM} \to \gamma\gamma, WW/ZZ)}$$

$$\frac{\cos^2\alpha}{\sin^2\beta} + \frac{\sin^2\alpha}{\cos^2\beta}\frac{|A(\tau_b)|^2}{|A(\tau_t)|^2}$$

Type II 2HDM: h^0 125 GeV

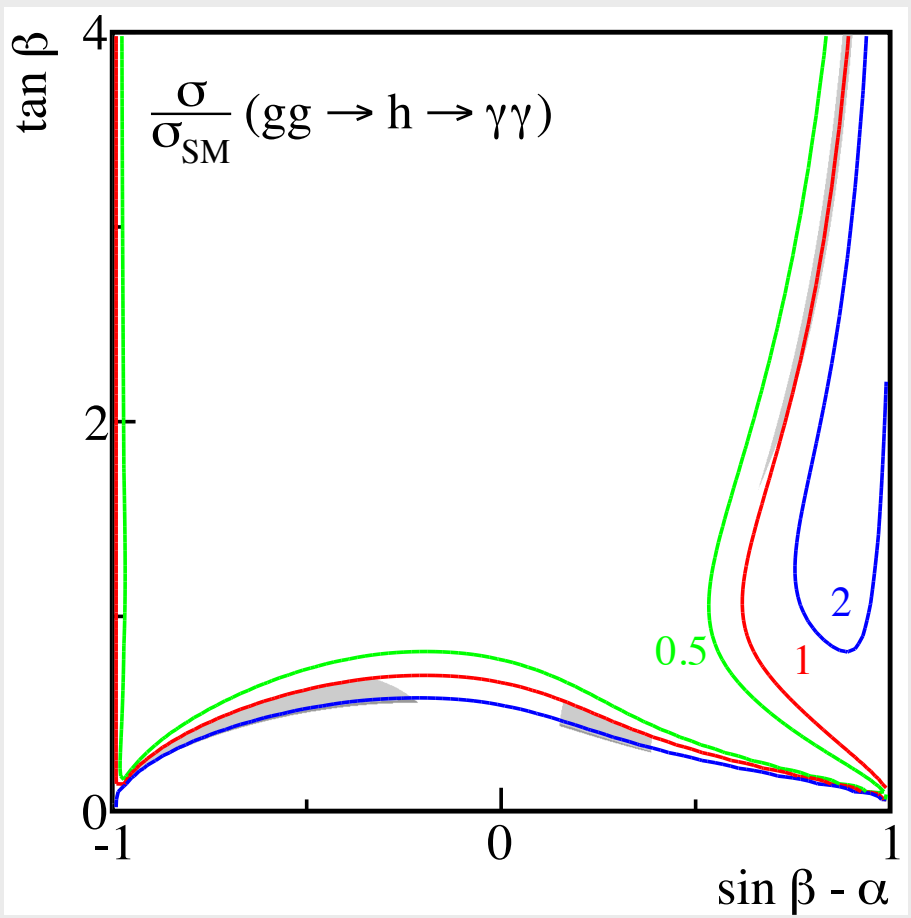
$$\frac{\sigma(gg \to h \to \gamma\gamma, WW/ZZ)}{\sigma(gg \to h_{\rm SM} \to \gamma\gamma, WW/ZZ)} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \times \frac{\mathrm{BR}(h \to \gamma\gamma, WW/ZZ)}{\mathrm{BR}(h_{SM} \to \gamma\gamma, WW/ZZ)}$$

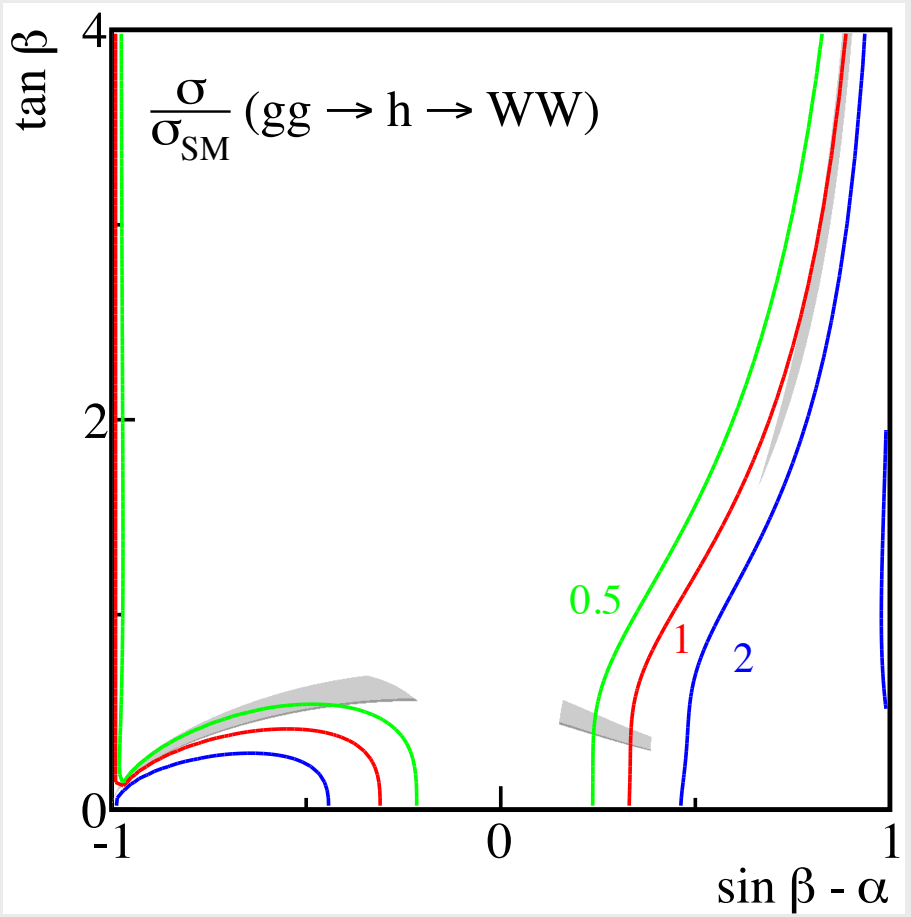
$$\frac{\sin^2\alpha}{\cos^2\beta}\frac{|A(\tau_b)|^2}{|A(\tau_t)|^2}$$



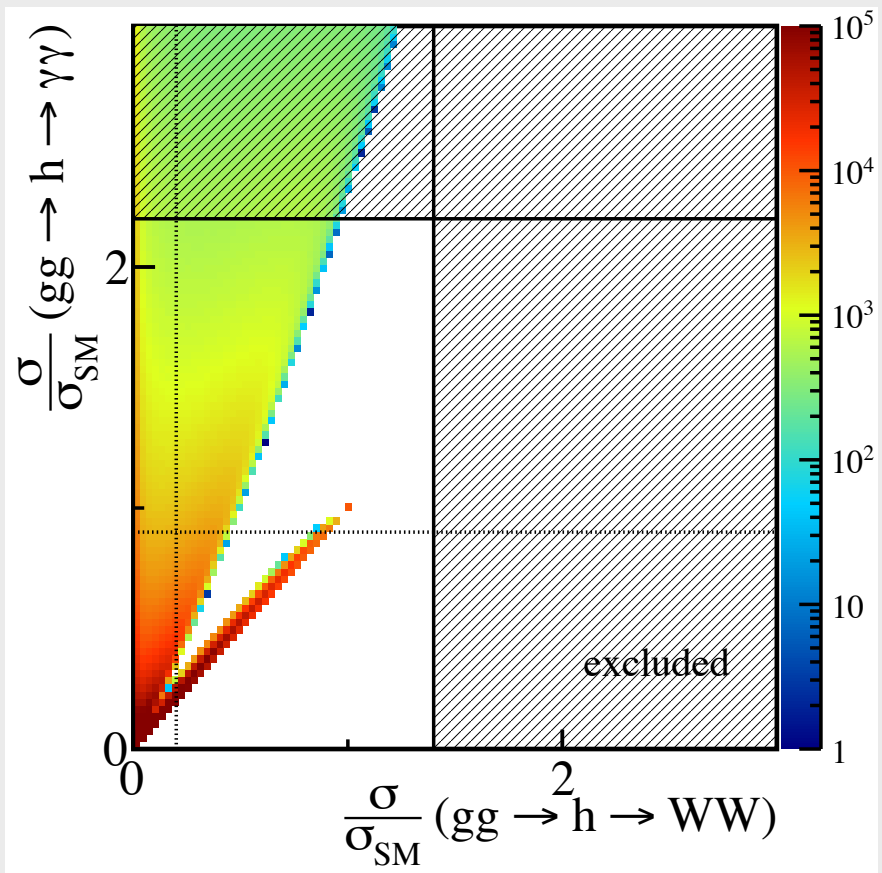
Type II 2HDM: h^0 125 GeV

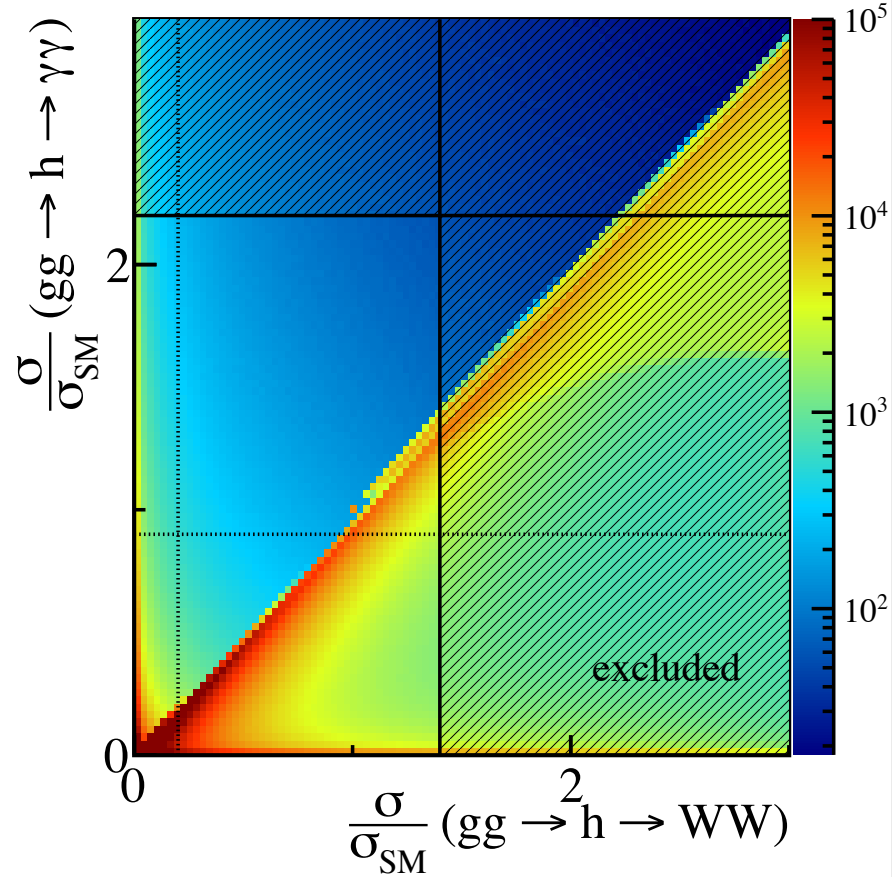
$$\frac{\sigma(gg \to h \to \gamma\gamma, WW/ZZ)}{\sigma(gg \to h_{\rm SM} \to \gamma\gamma, WW/ZZ)} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \times \frac{\mathrm{BR}(h \to \gamma\gamma, WW/ZZ)}{\mathrm{BR}(h_{SM} \to \gamma\gamma, WW/ZZ)}$$



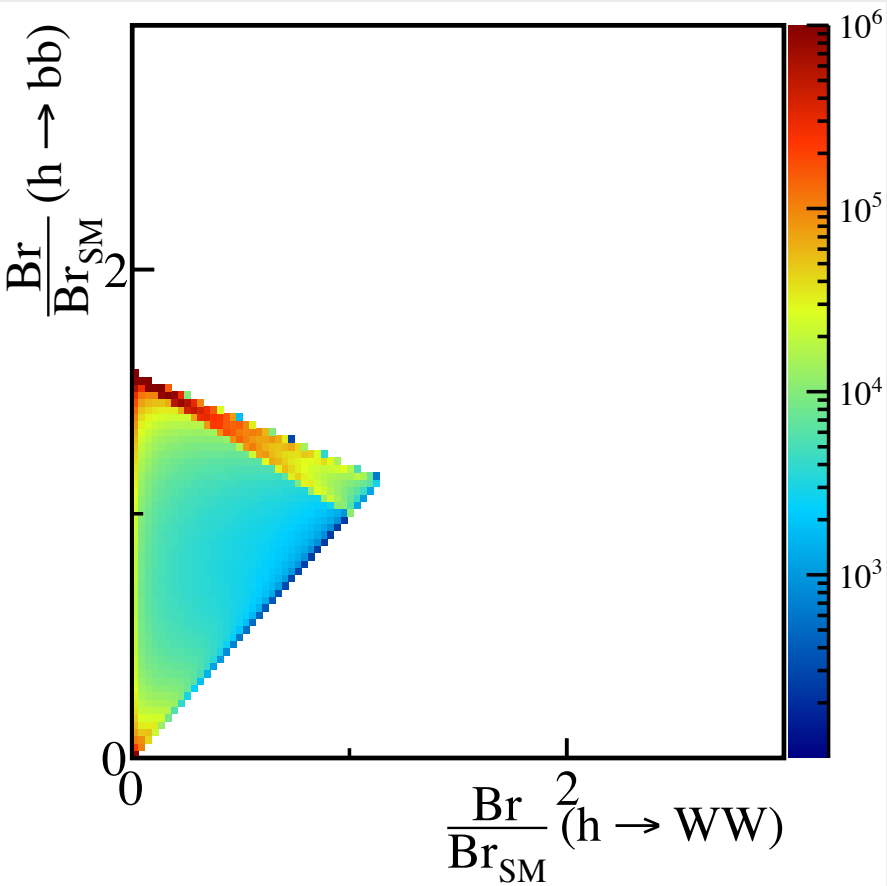


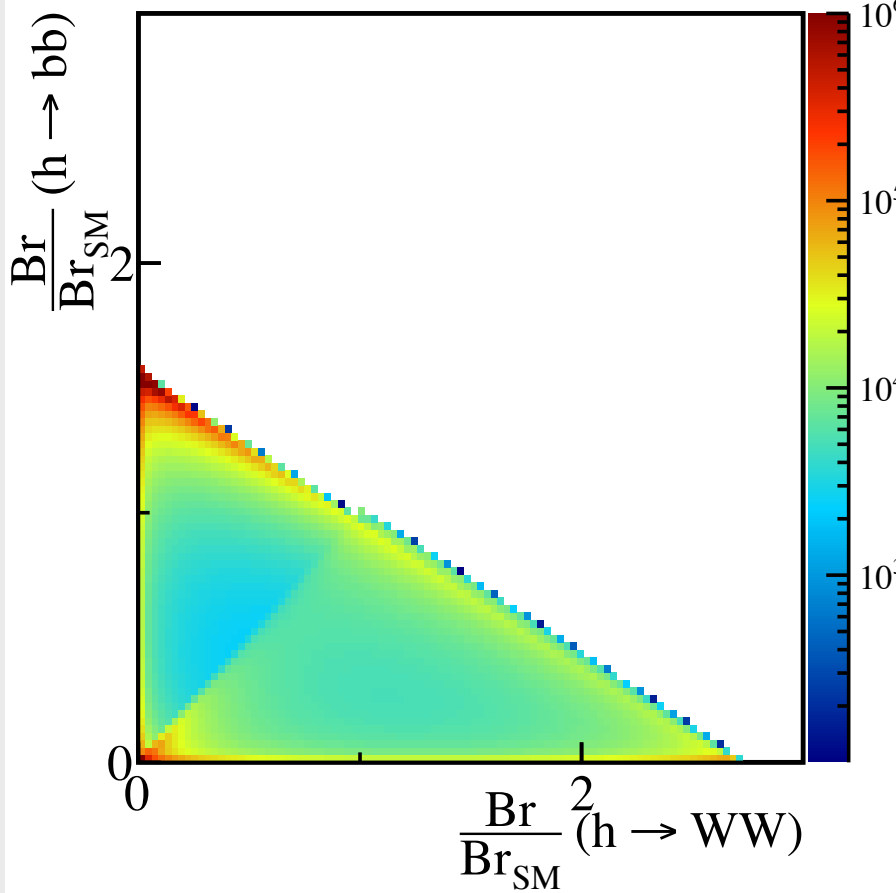
h^0 125 GeV: γγ vs. WW correlation





h^0 125 GeV: bb vs. WW correlation





Parameter Scan: h^0 125

$0.25 \leq \tan\beta \leq 5$

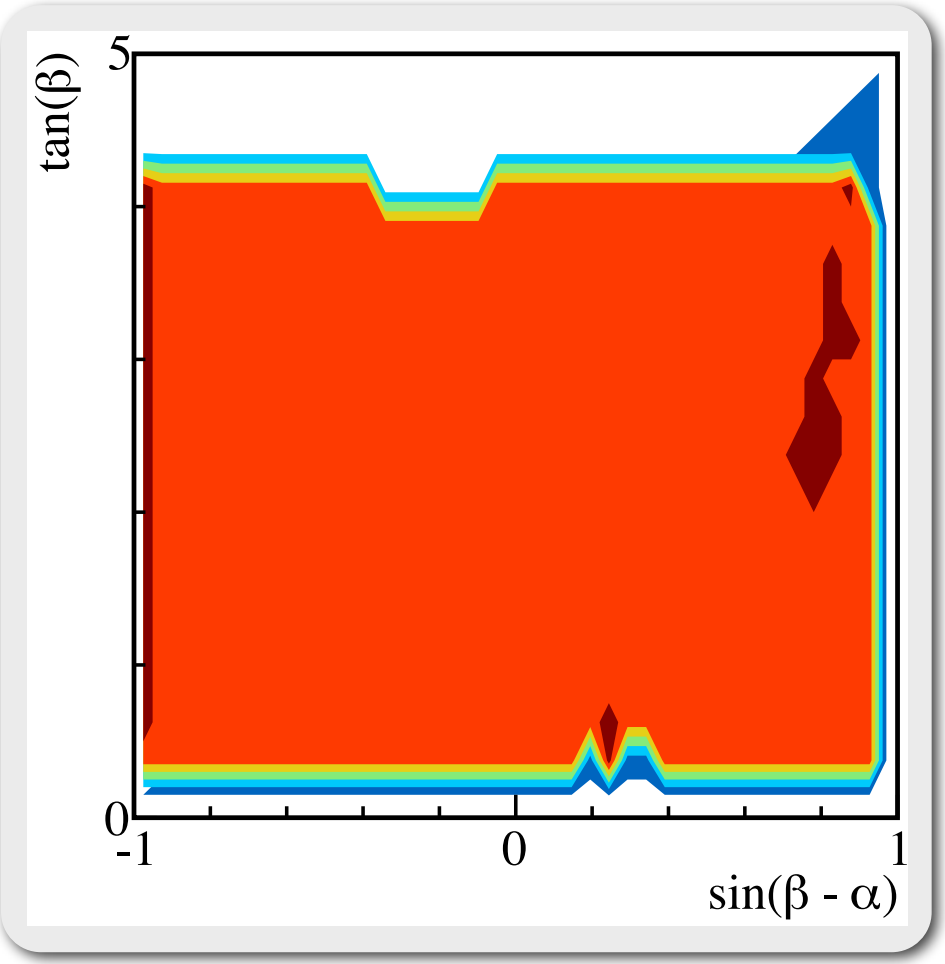
$-1 \leq \sin(\beta-\alpha) \leq 1$

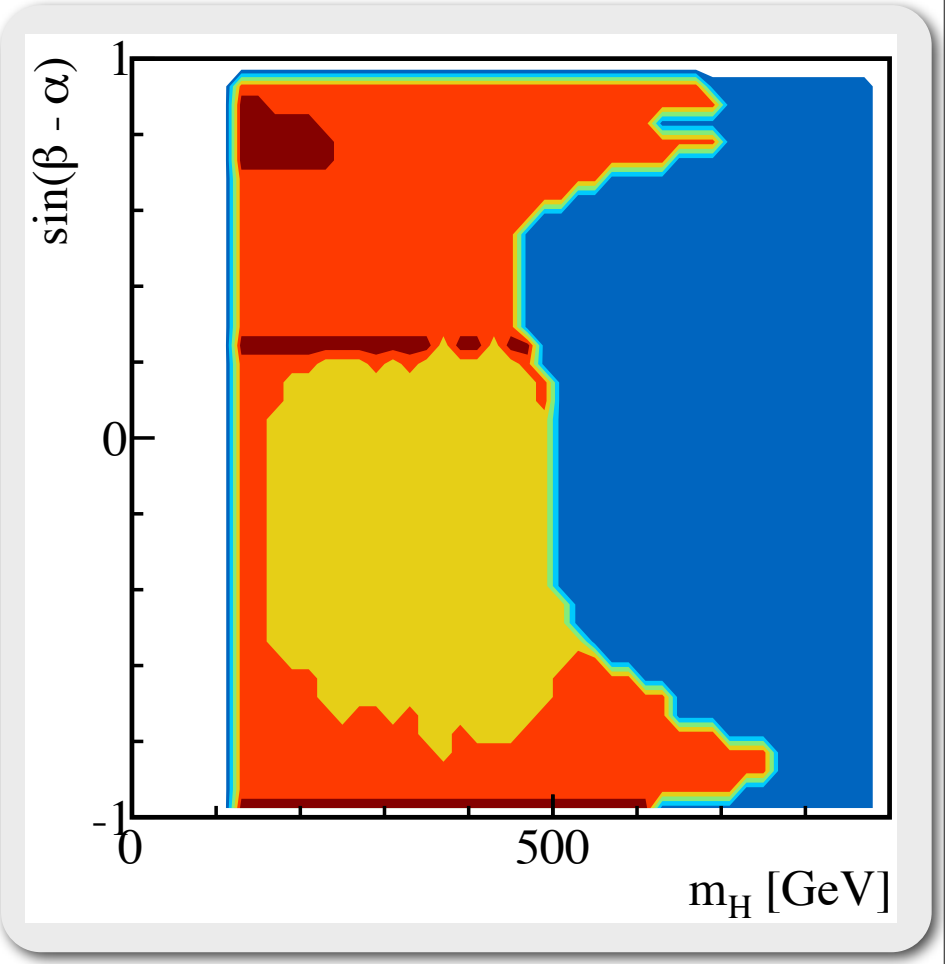
$125\ \text{GeV} < m_H \leq 1000\ \text{GeV}$

$20\ \text{GeV} \leq m_A, m_C \leq 1000\ \text{GeV}$

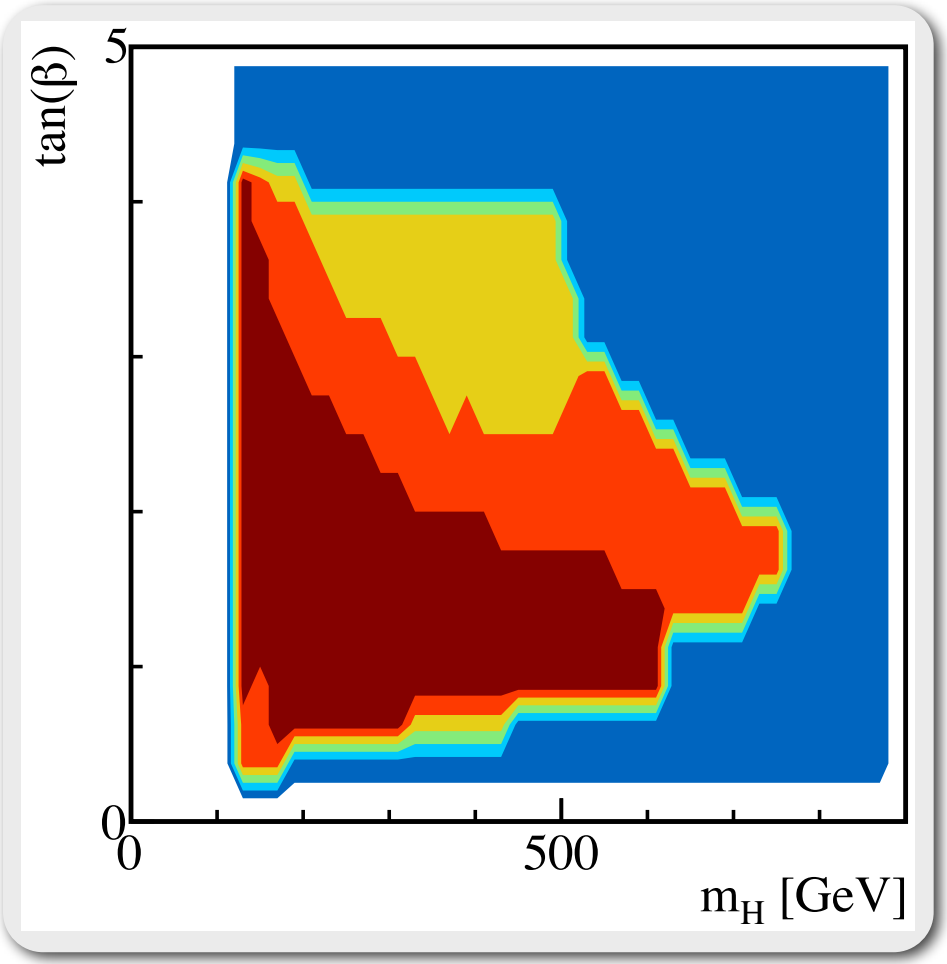
2HDM Calculator (2HDMC) + HIGGSBOUNDS + latest LHC bounds

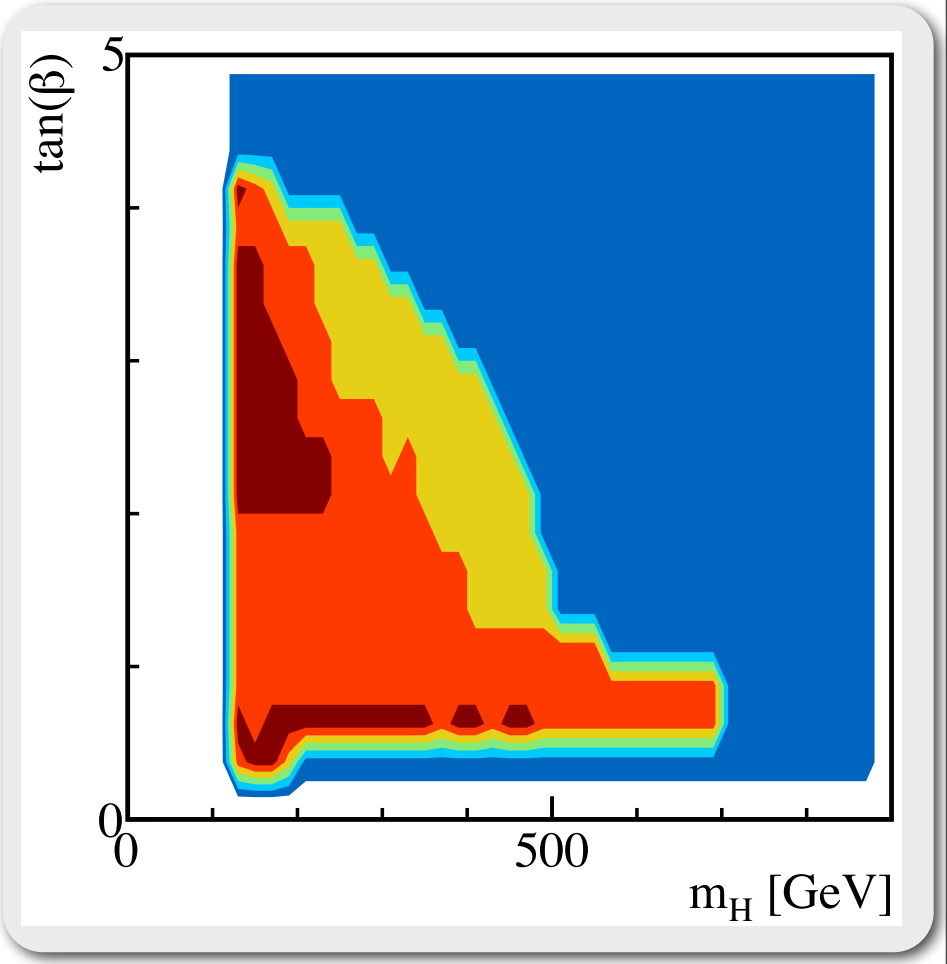
h^0 125 GeV: sin(β-α)



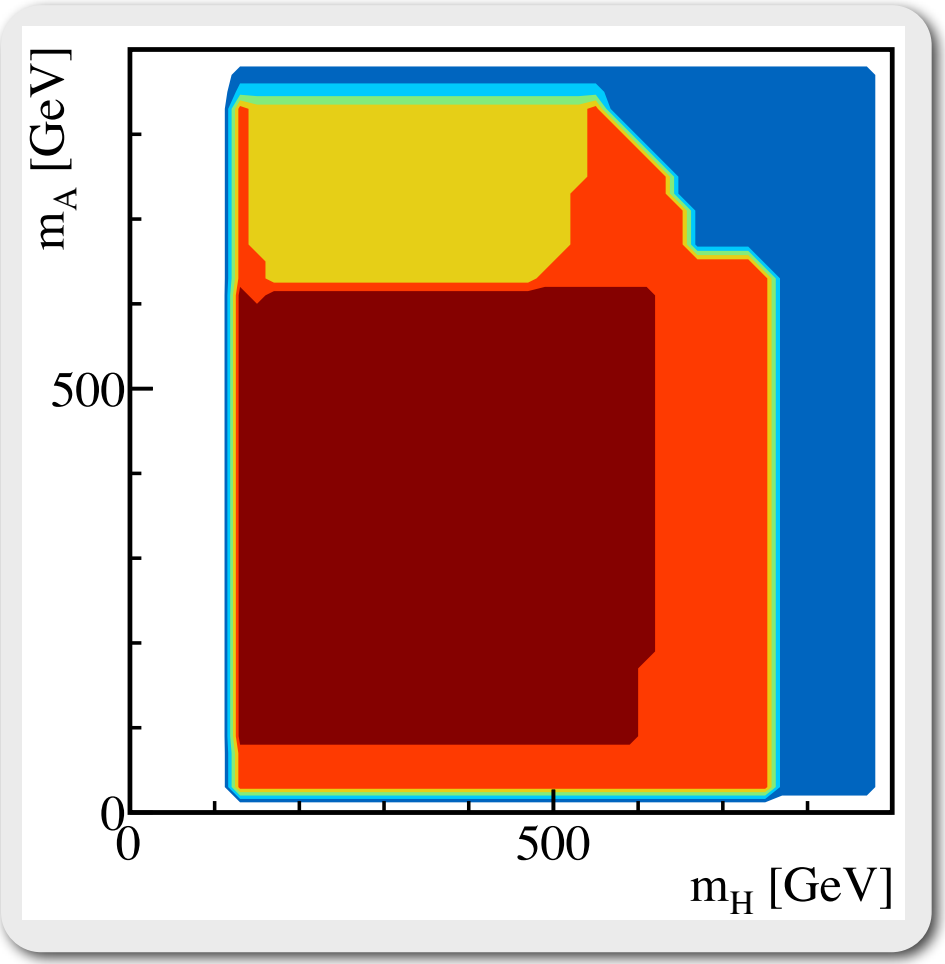


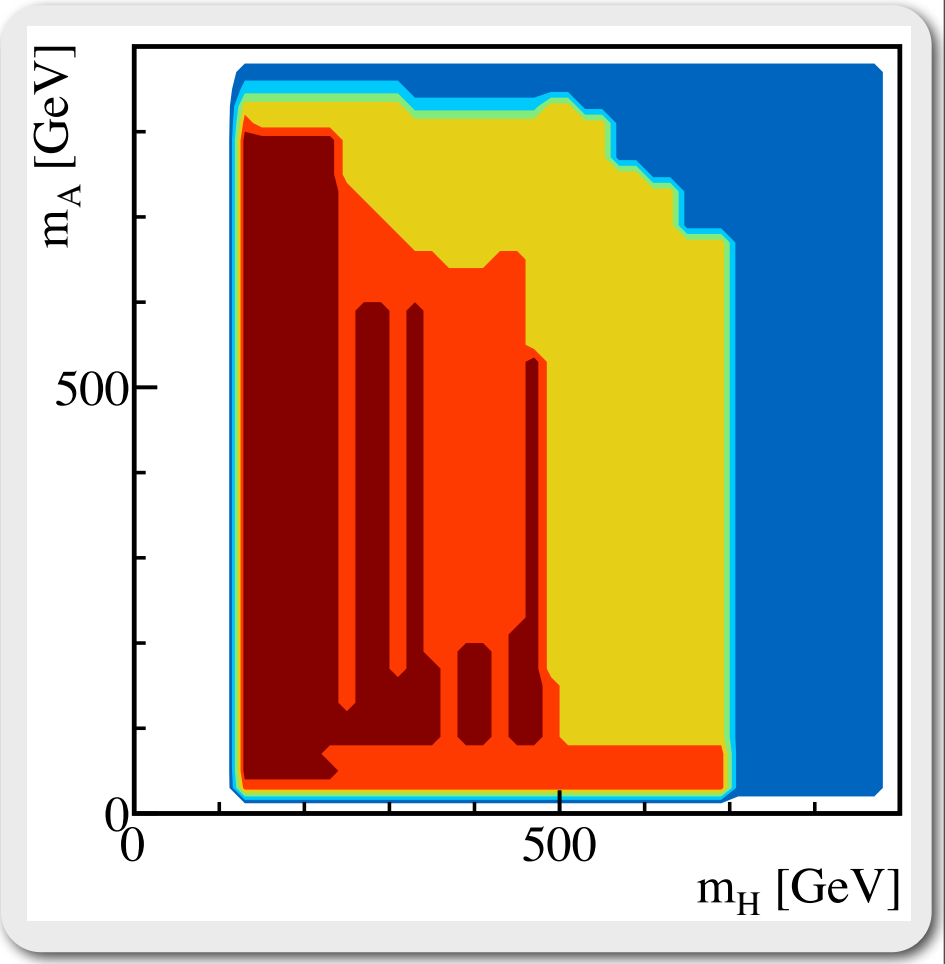
h^0 125 GeV: m_H vs. tanβ



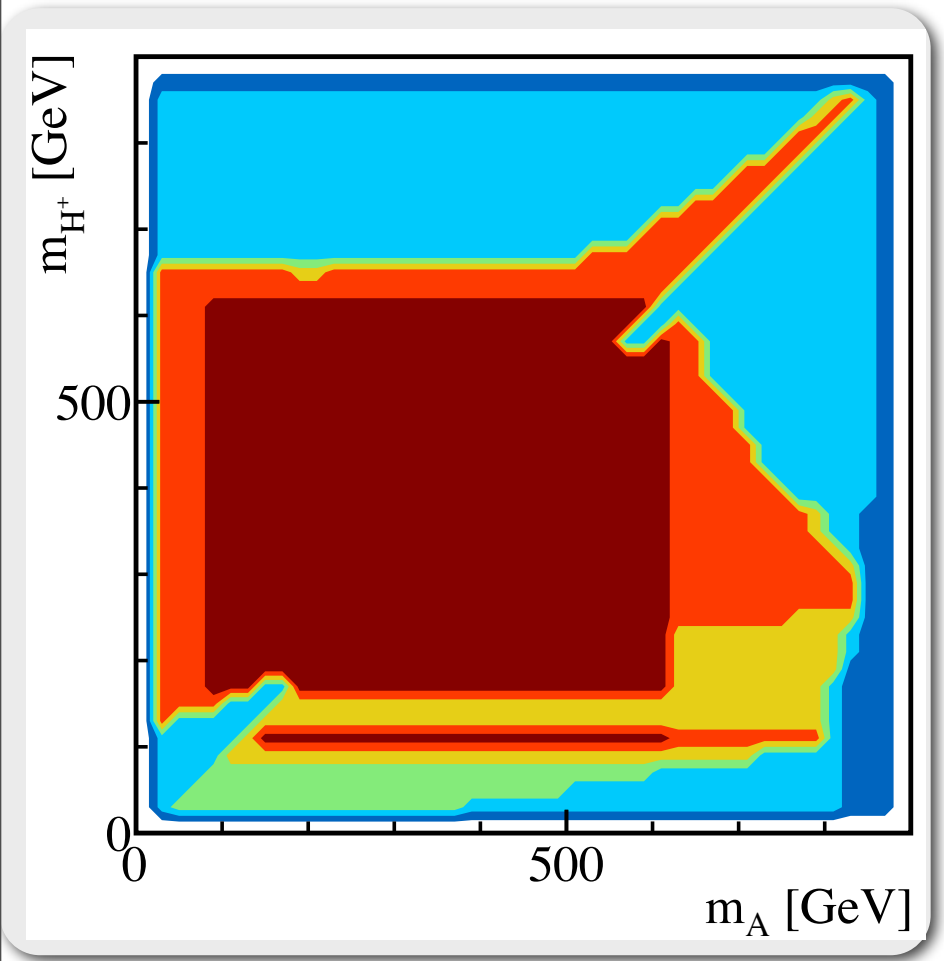


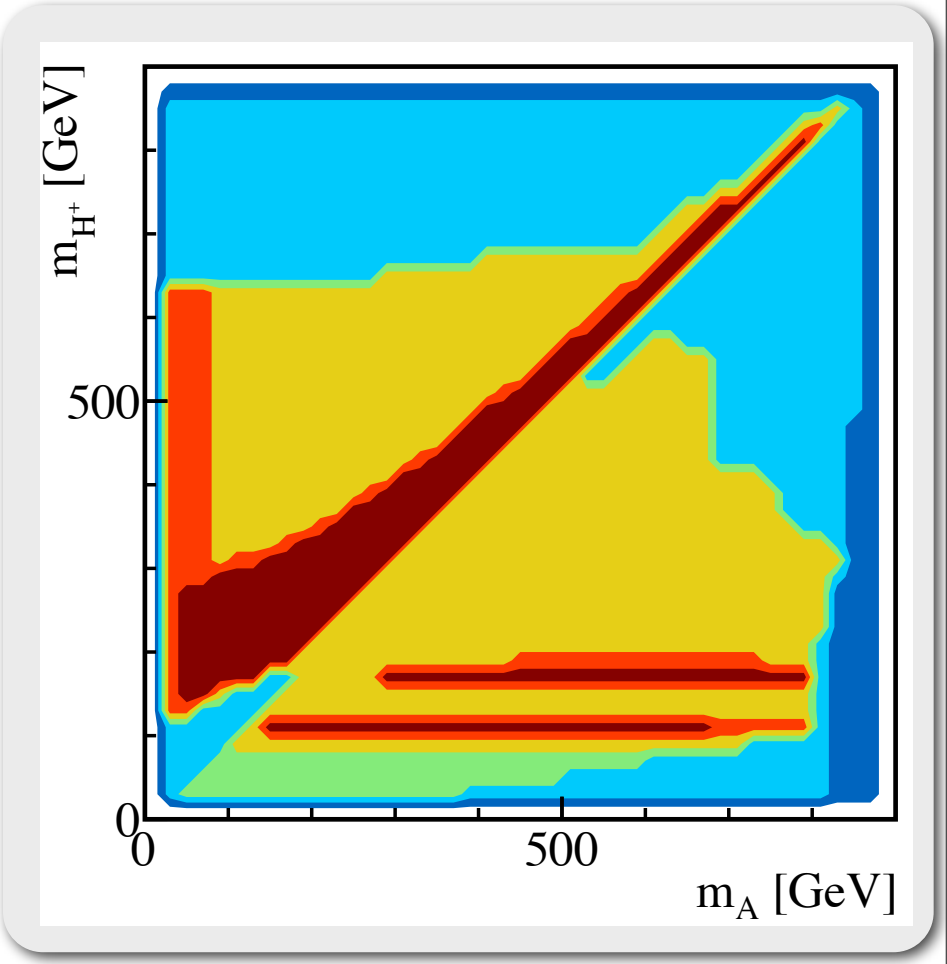
h^0 125 GeV: m_A vs. m_H



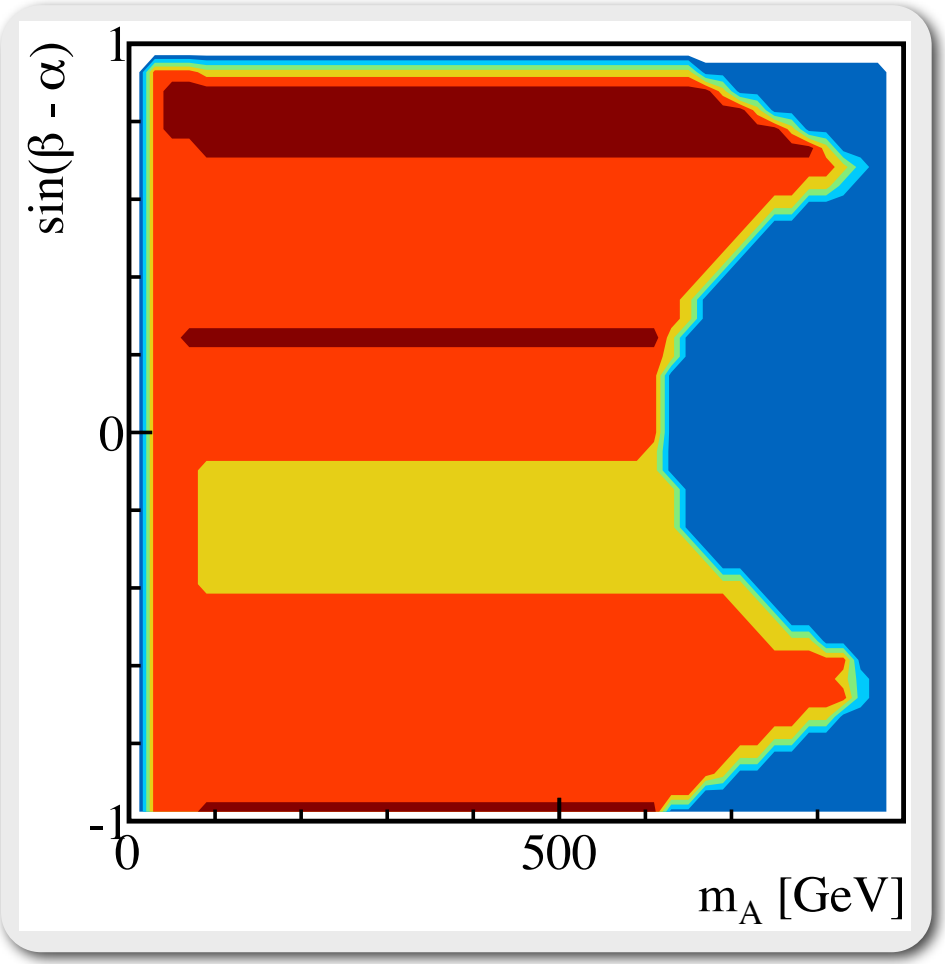


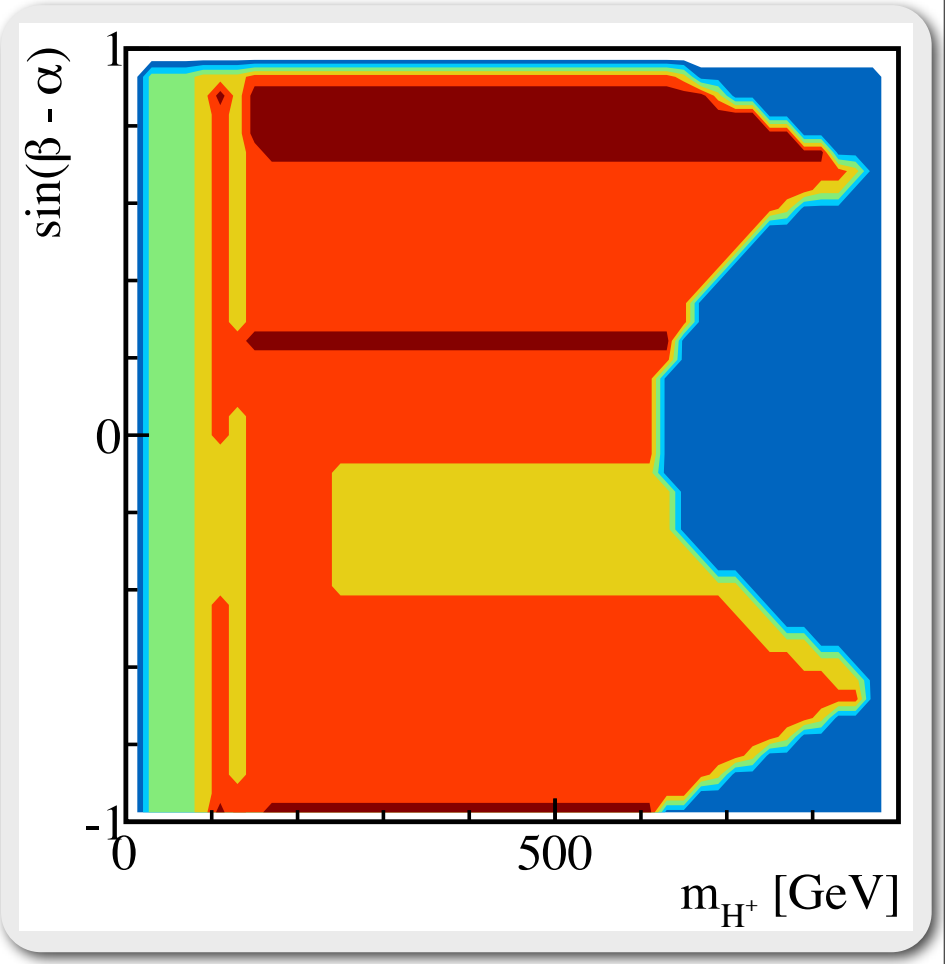
h^0 125 GeV: m_A vs. m_{Hpm}



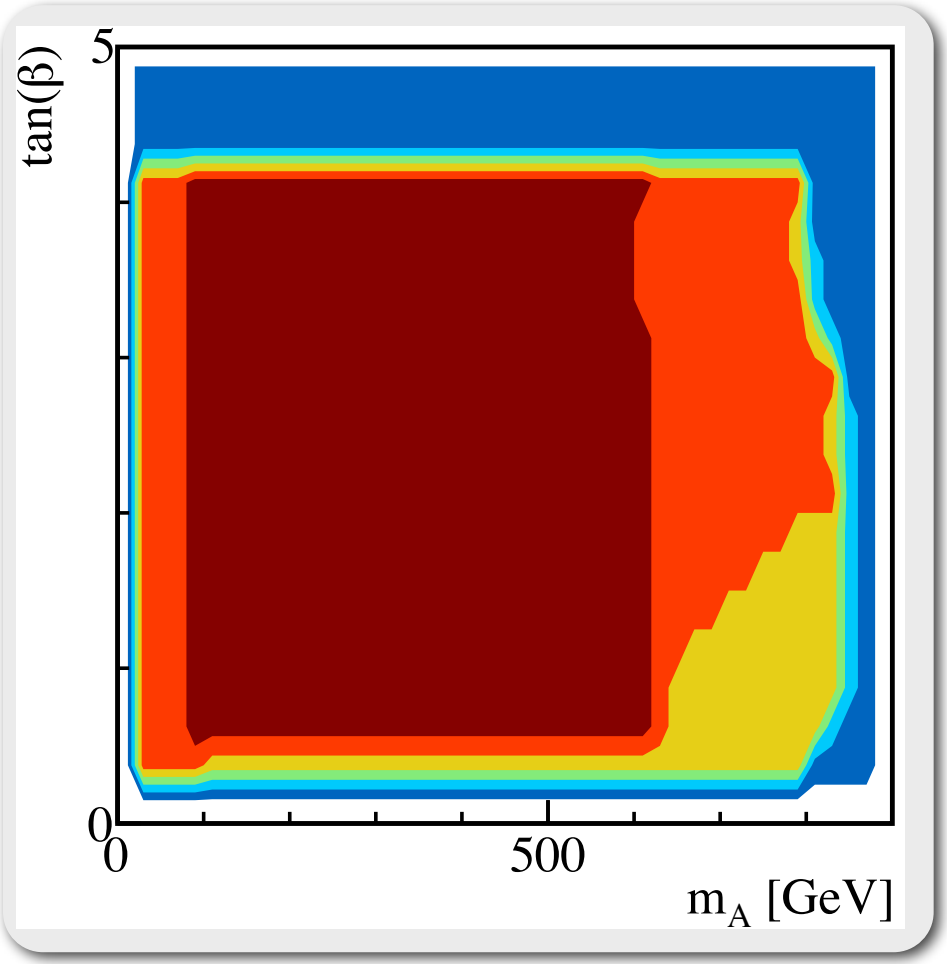


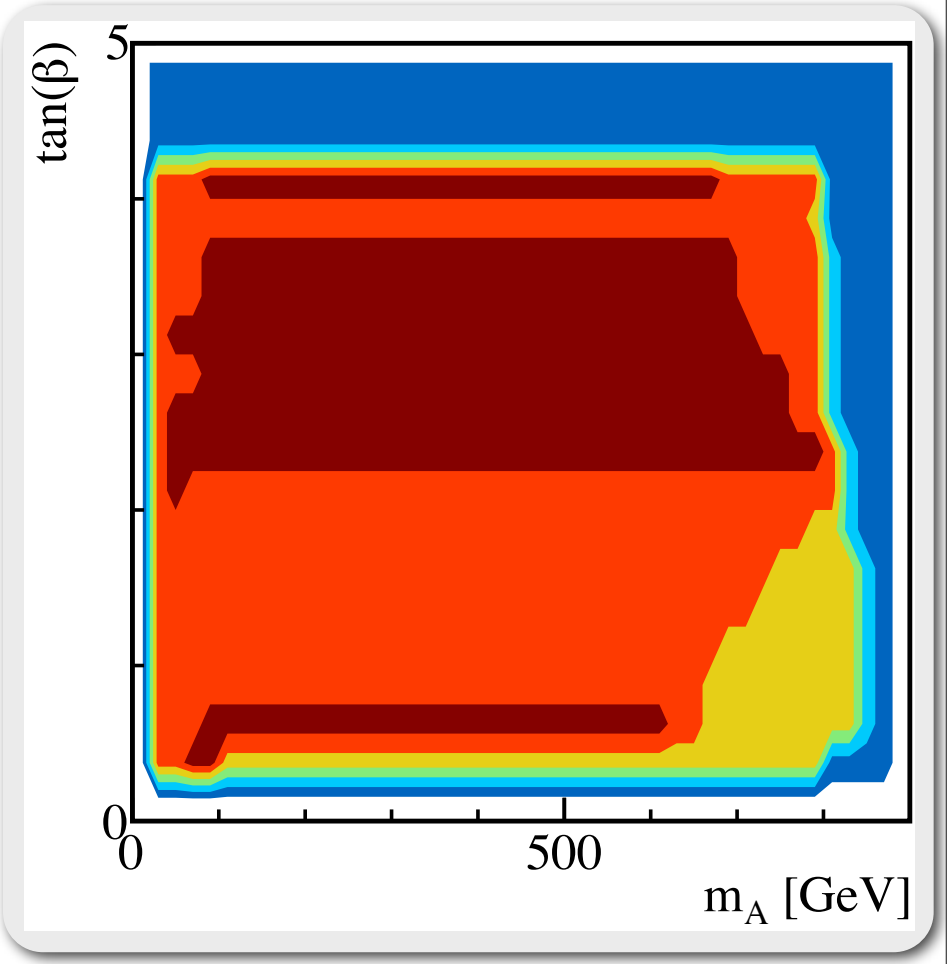
h^0 125 GeV: $\sin(\beta-\alpha)$ vs. m_A (m_{Hpm})



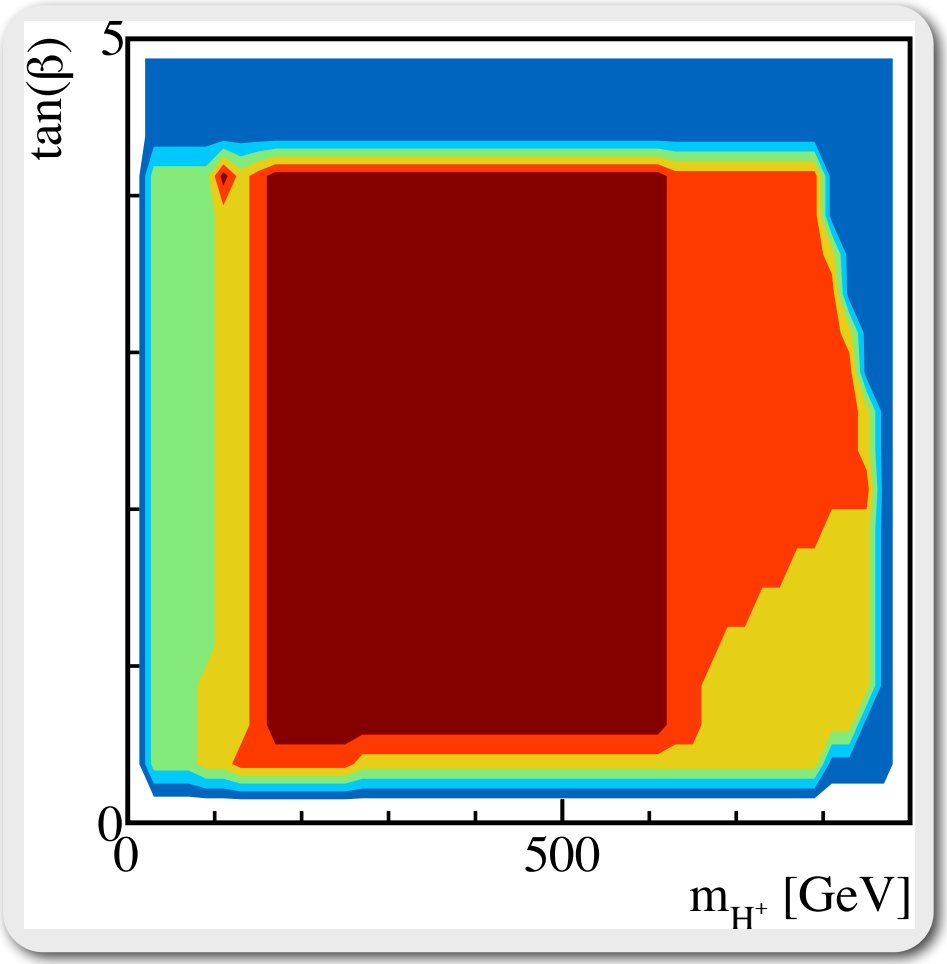


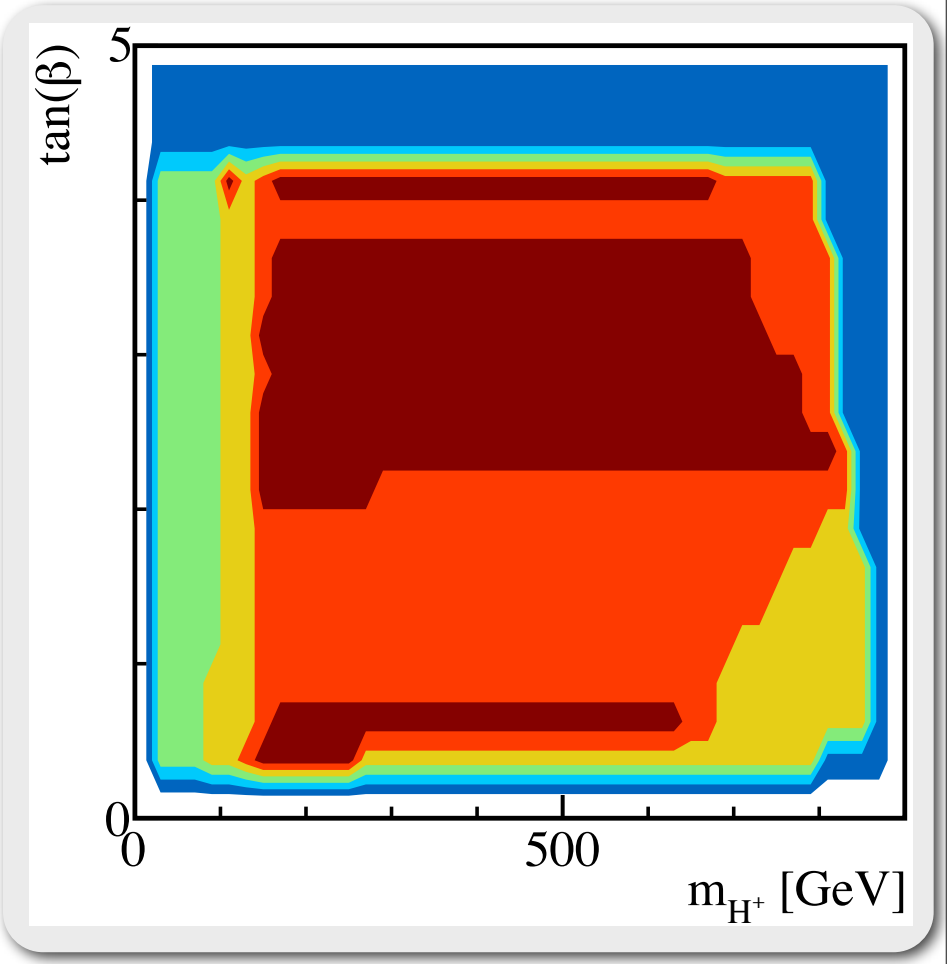
h^0 125 GeV: m_A vs. tanβ



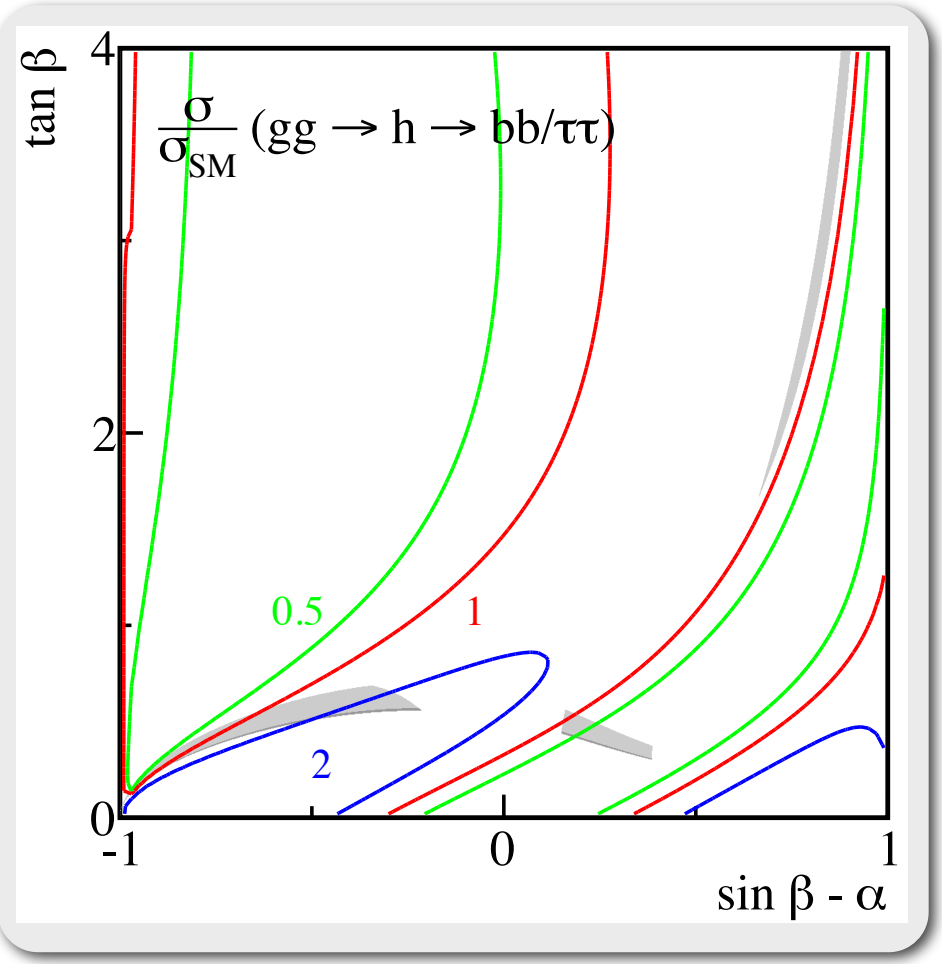


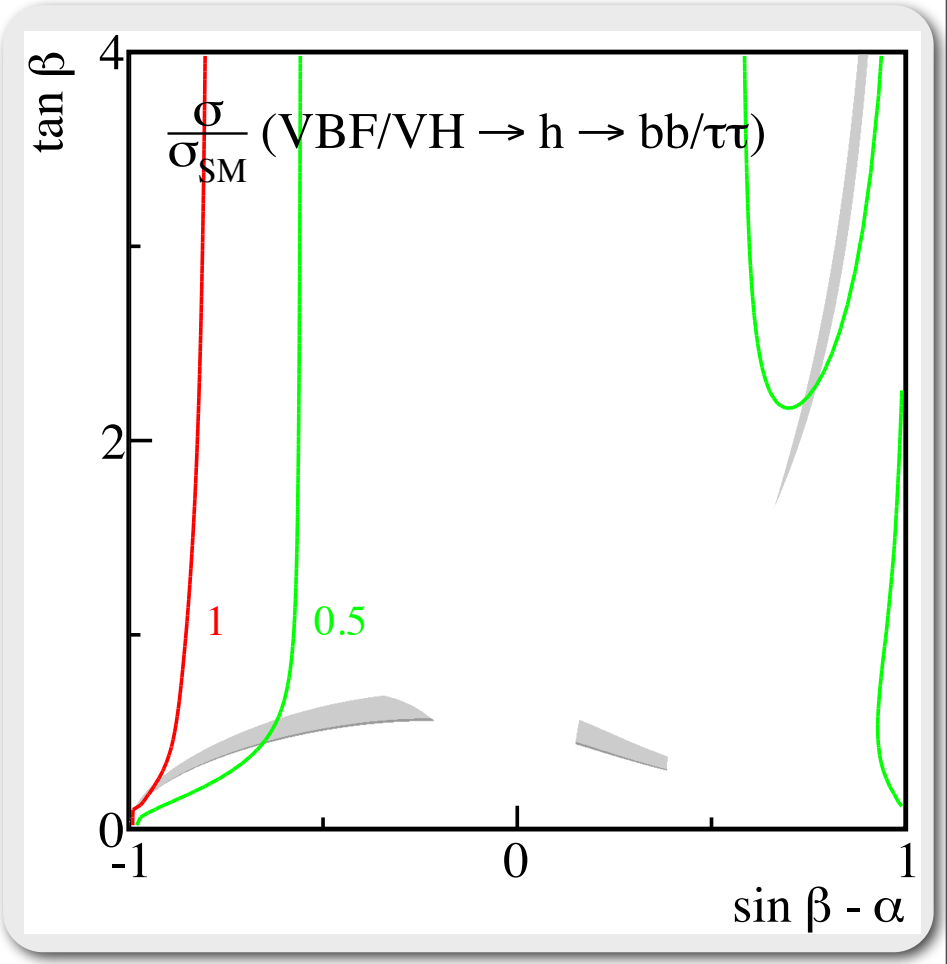
h^0 125 GeV: m_{Hpm} vs. tanβ



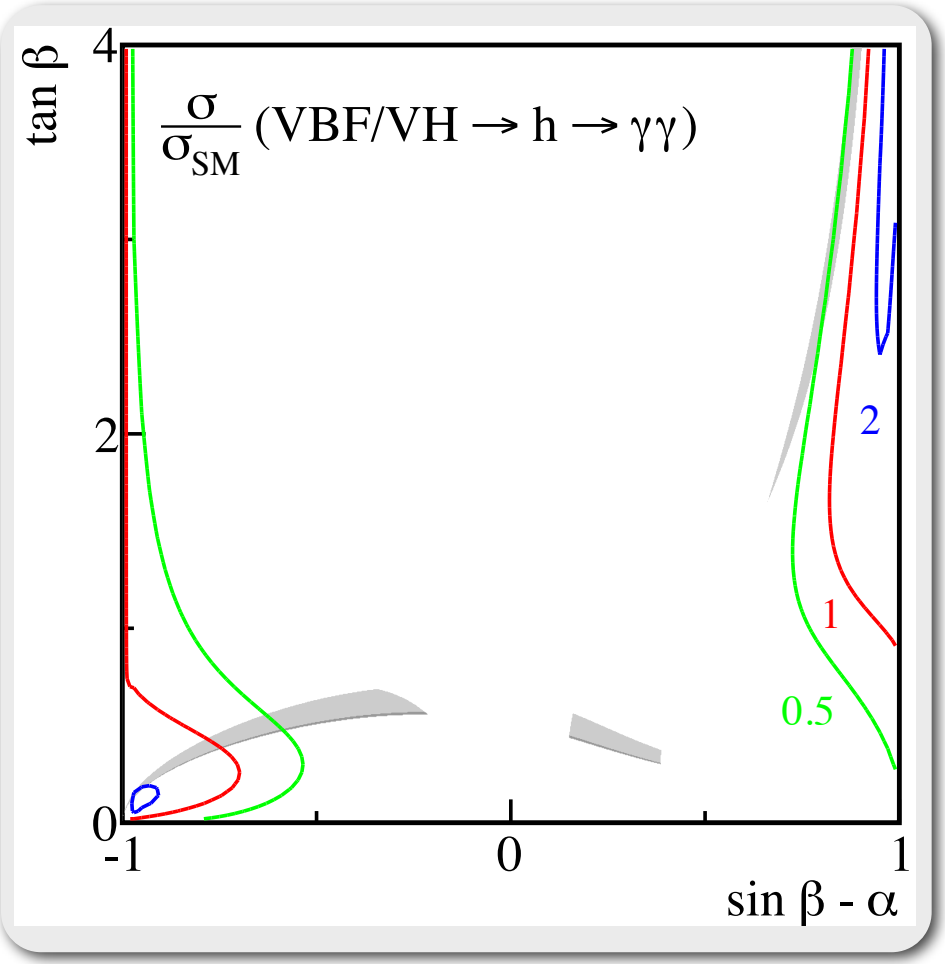


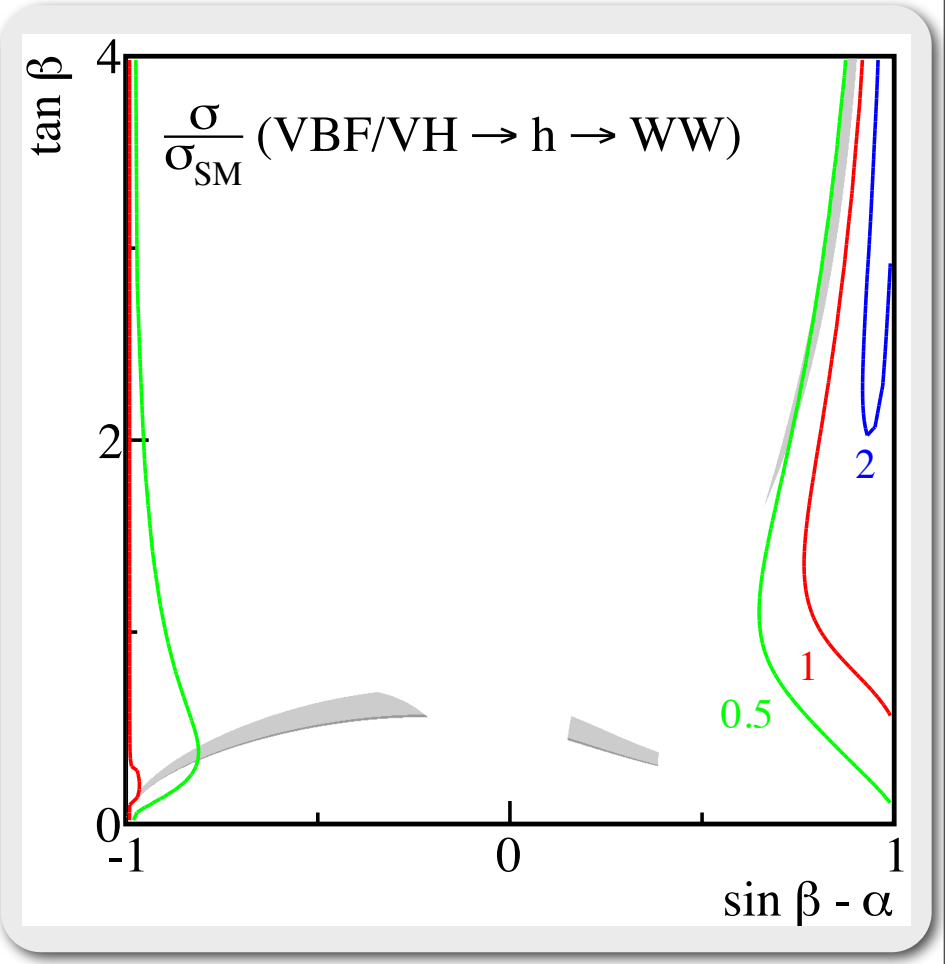
h^0 125 GeV: bb and ττ





h^0 125 GeV: $\gamma\gamma$ and WW/ZZ





H^0 125 GeV

Heavy CP-even Higgs as 125 GeV SM-like Higgs

Parameter Scan: H^0 125 GeV

$1 \leq \tan\beta \leq 30$

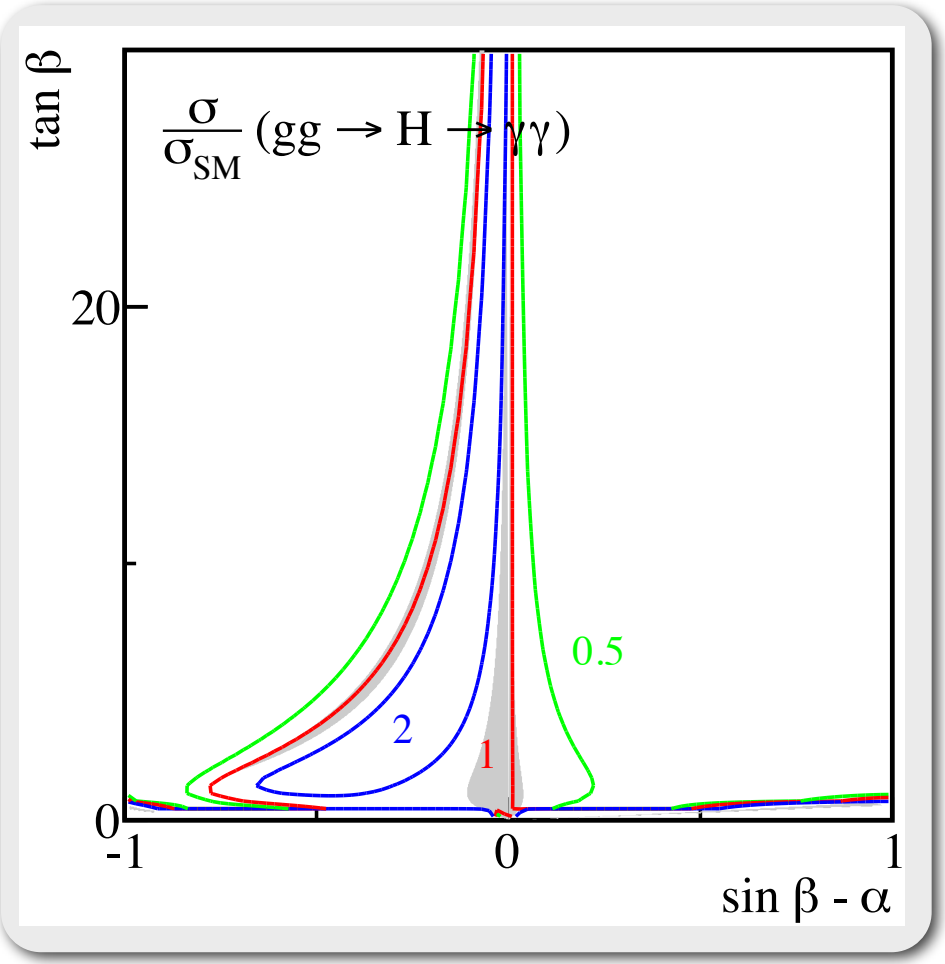
$-1 \leq \sin(\beta-\alpha) \leq 1$

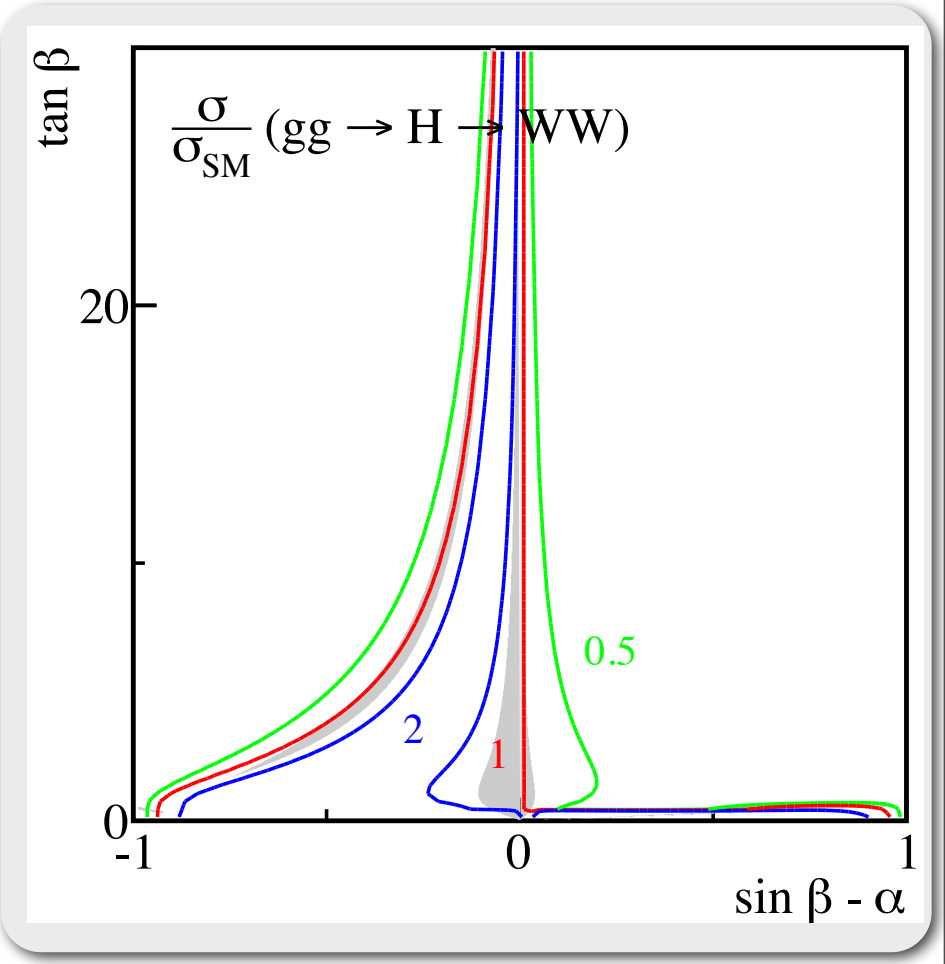
$5\ \text{GeV} < m_H < 125\ \text{GeV}$

$20\ \text{GeV} \leq m_A, m_C \leq 1000\ \text{GeV}$

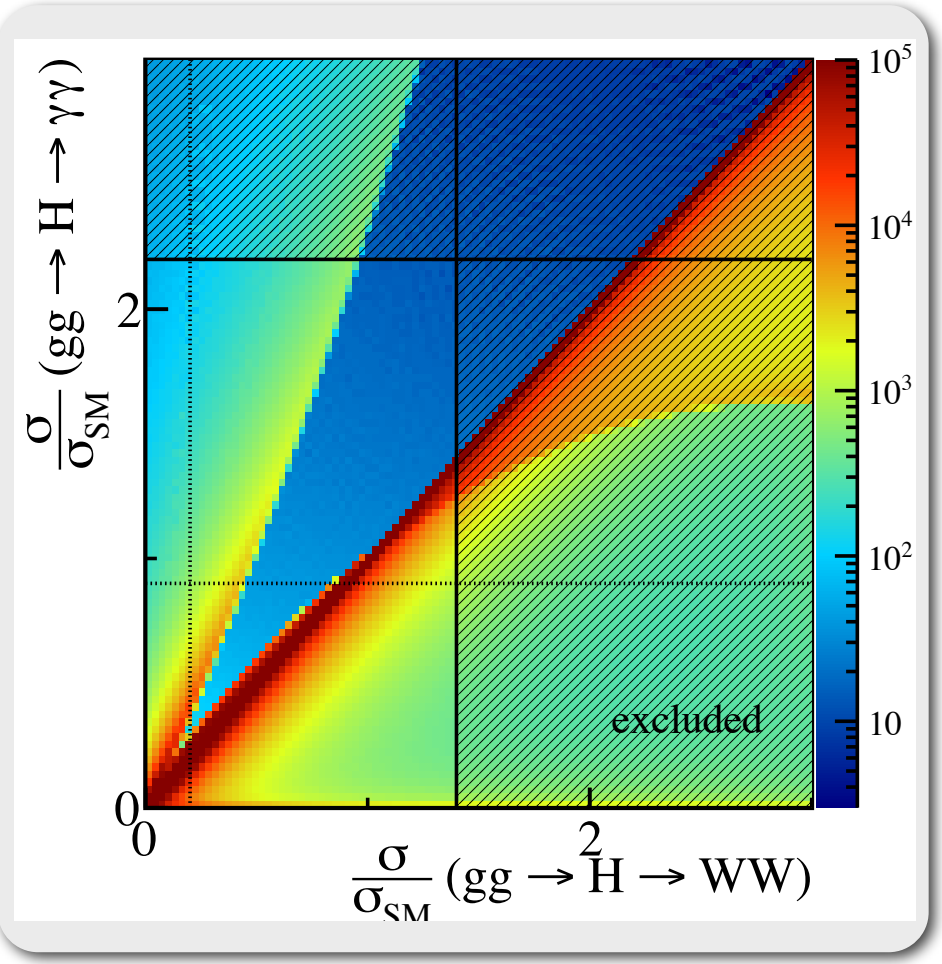
2HDM Calculator (2HDMC) + HIGGSBOUNDS + latest LHC bounds

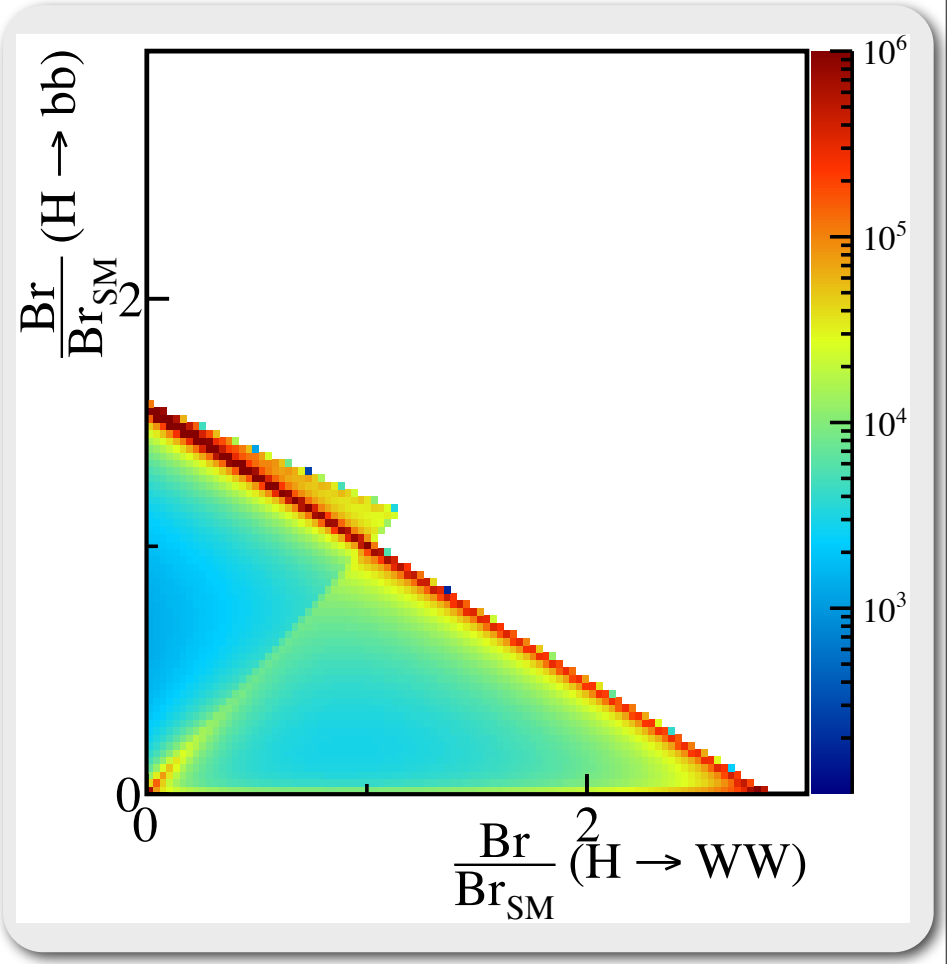
H^0 125 GeV: γγ and WW



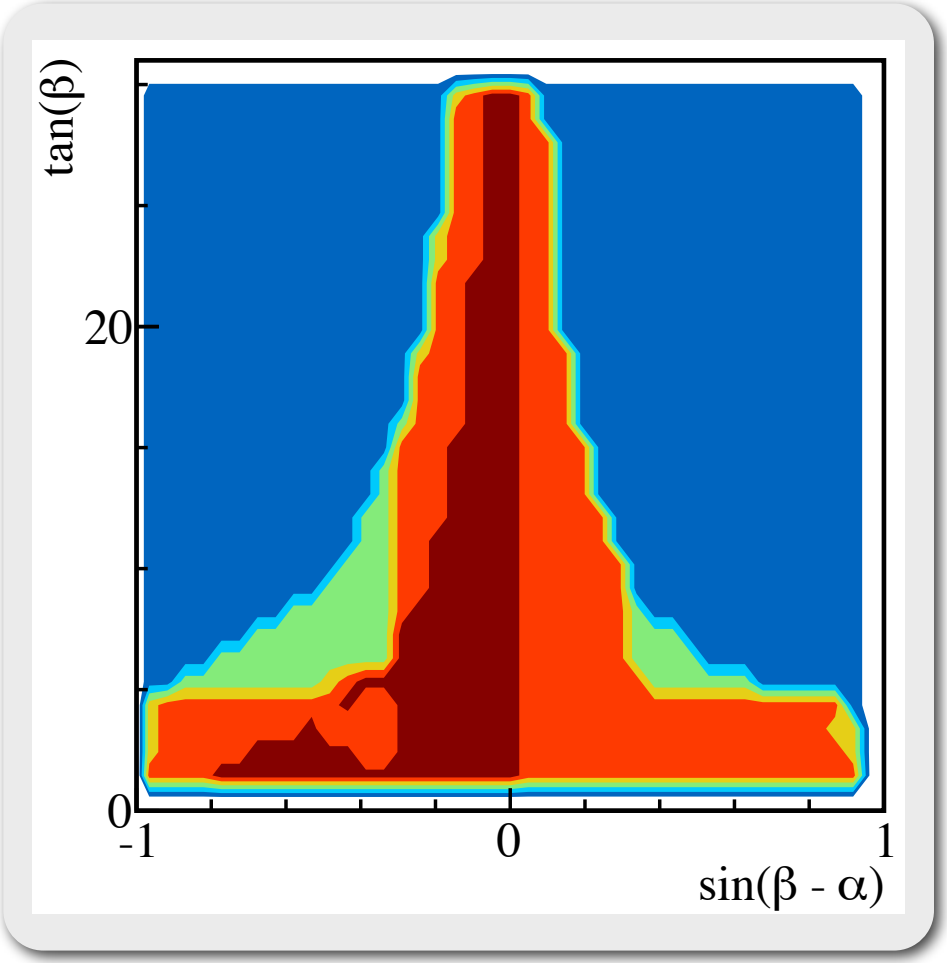


H^0 125 GeV: γγ vs. WW correlation

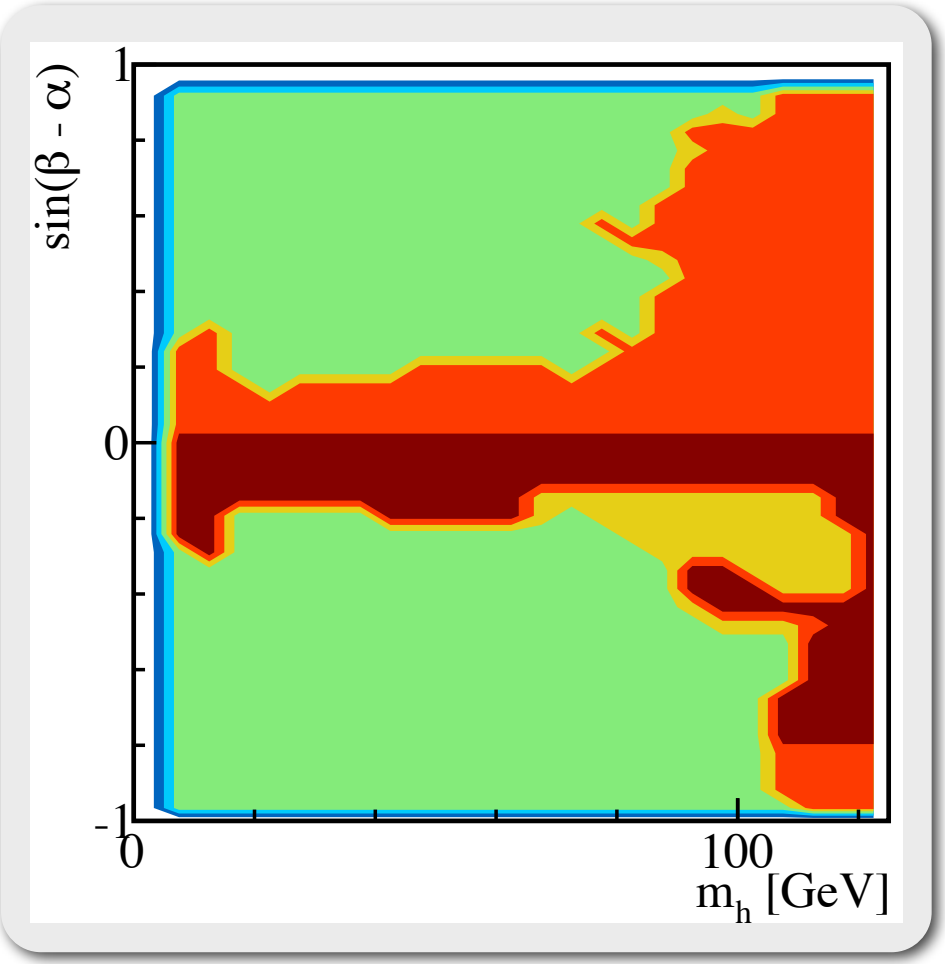


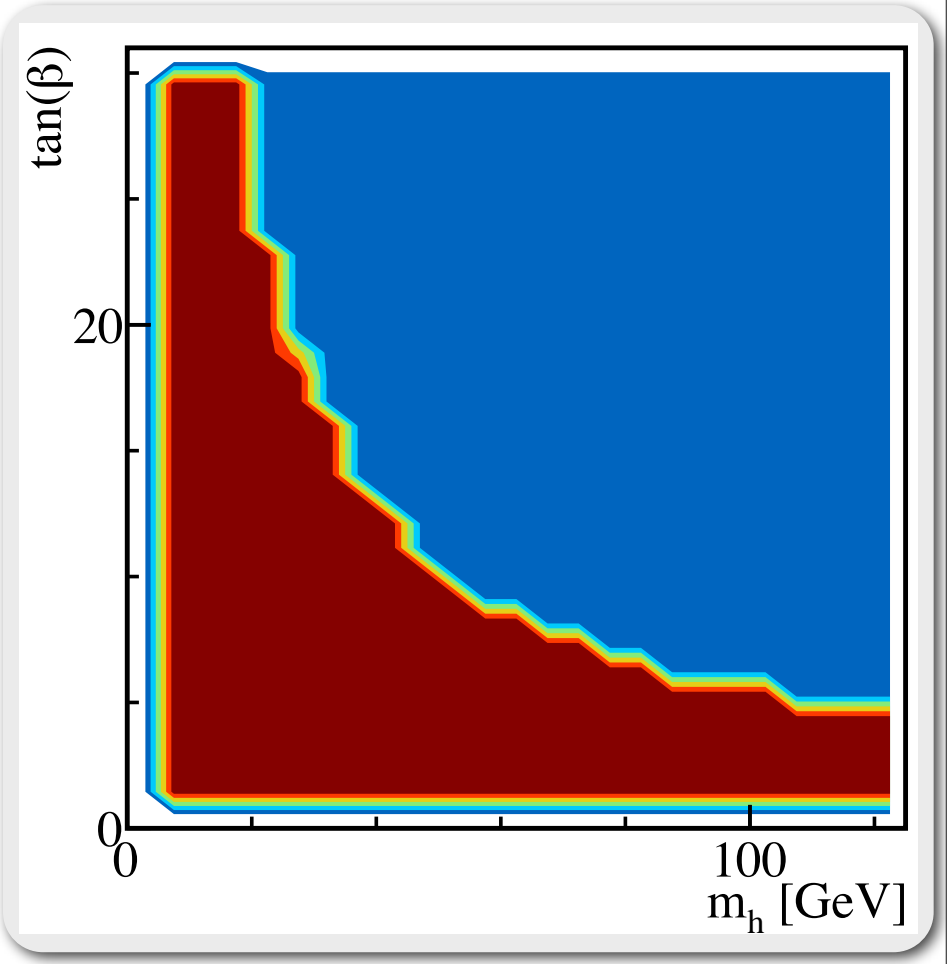


H^0 125 GeV: sin(β-α) vs. tan β

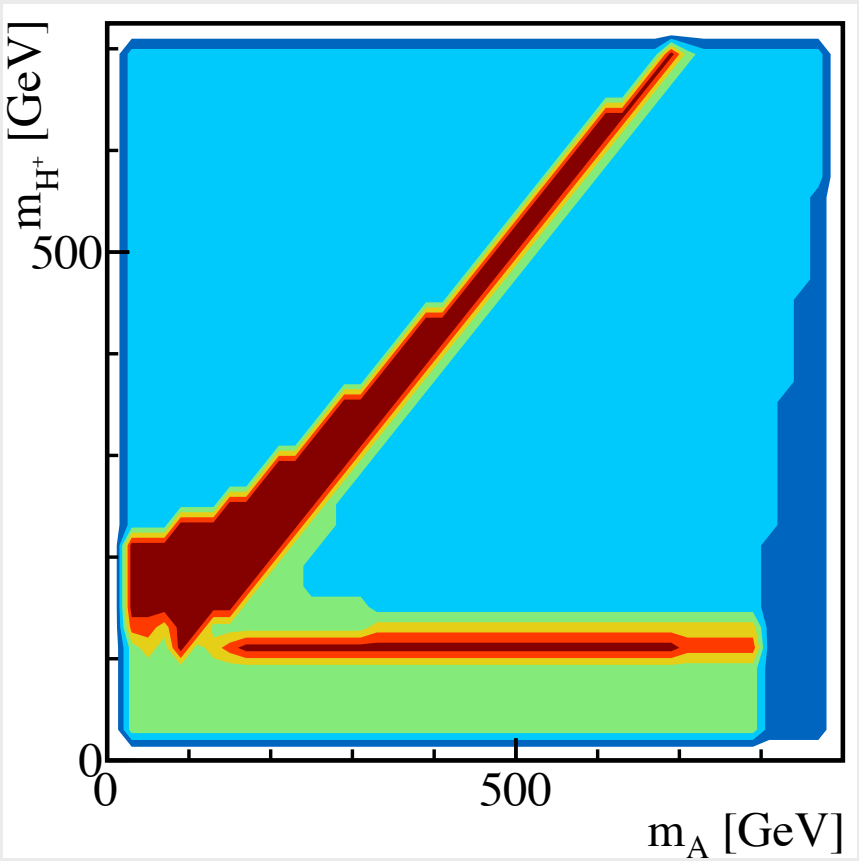


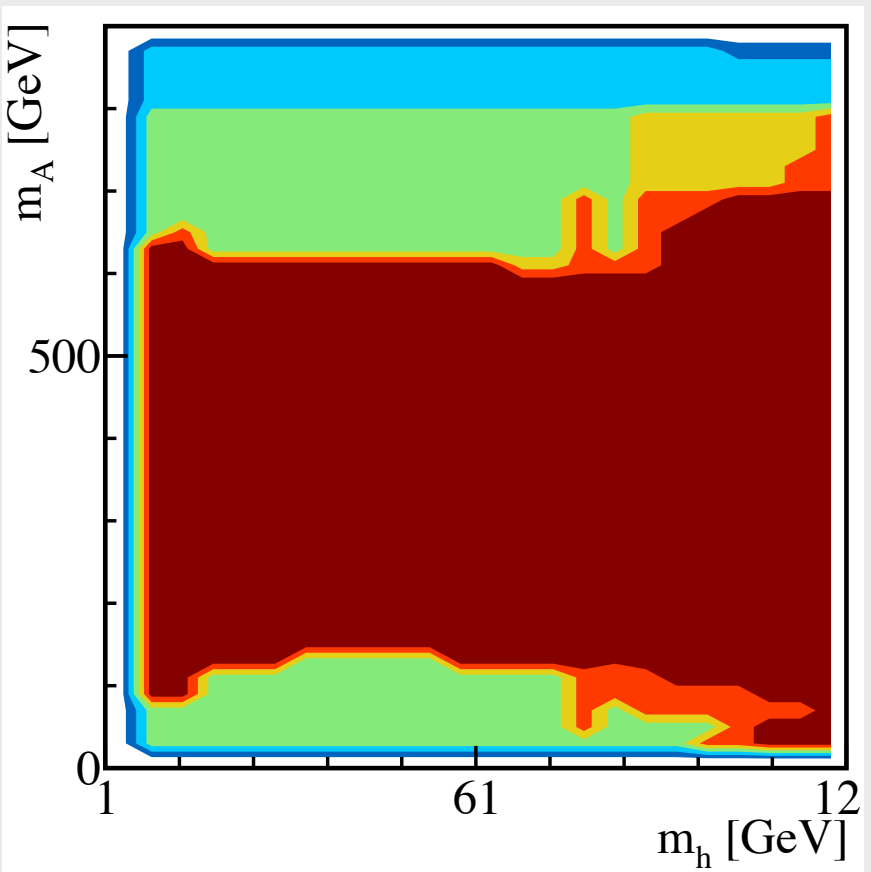
H^0 125 GeV: h^0



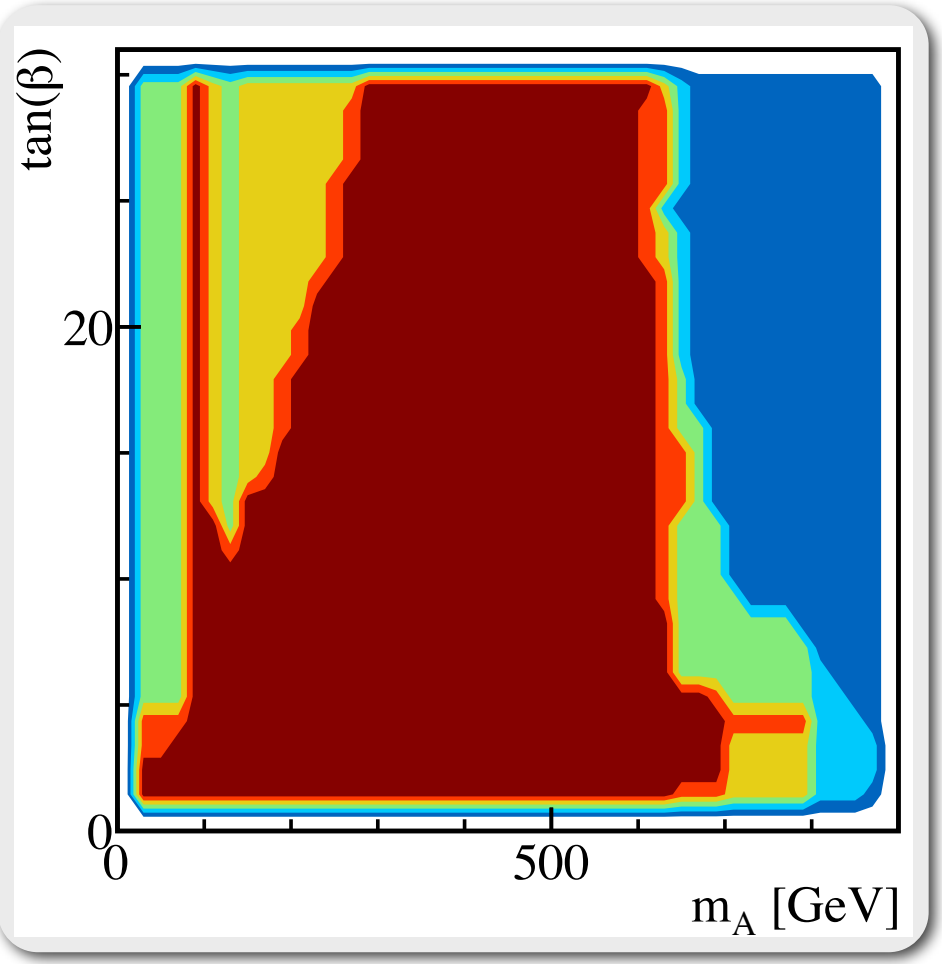


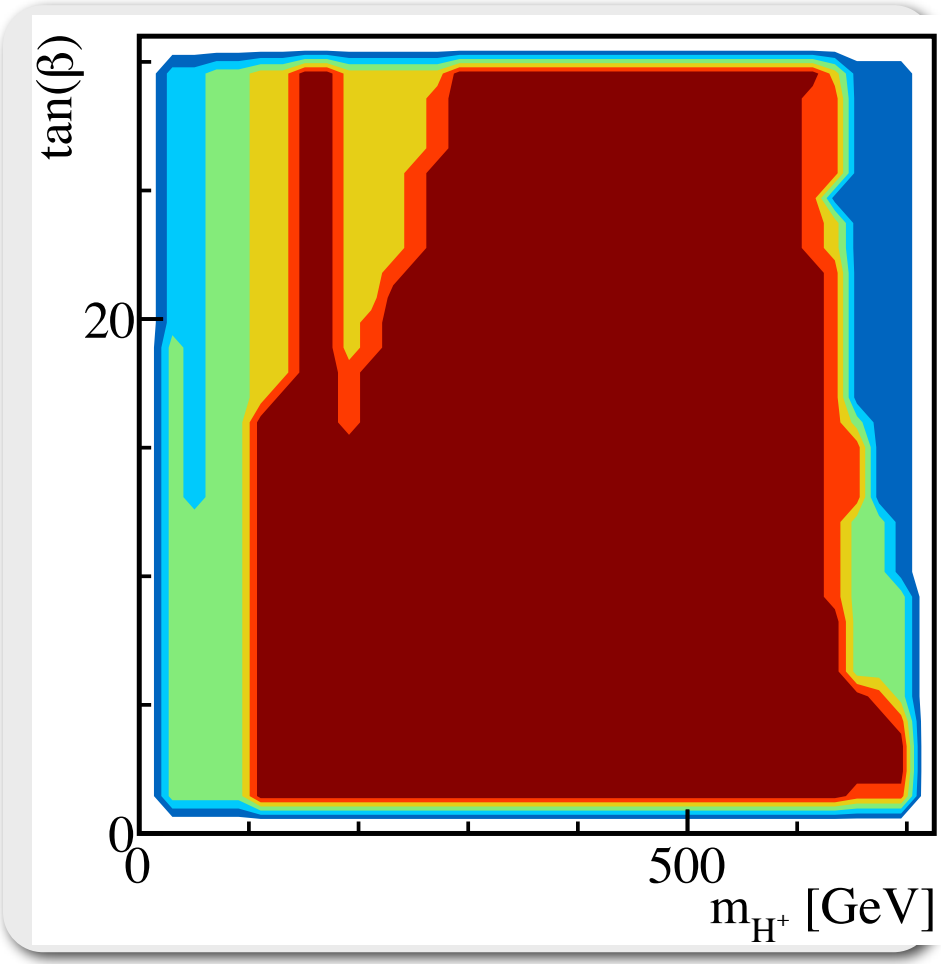
H^0 125 GeV: mh^0 vs. $m_{A/Hpm}$



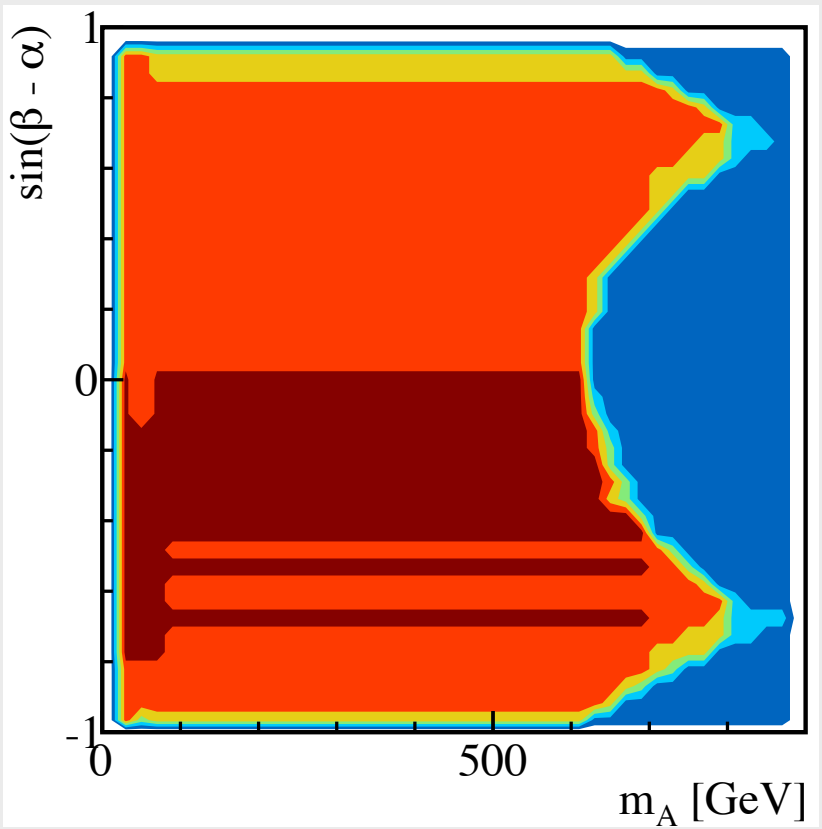


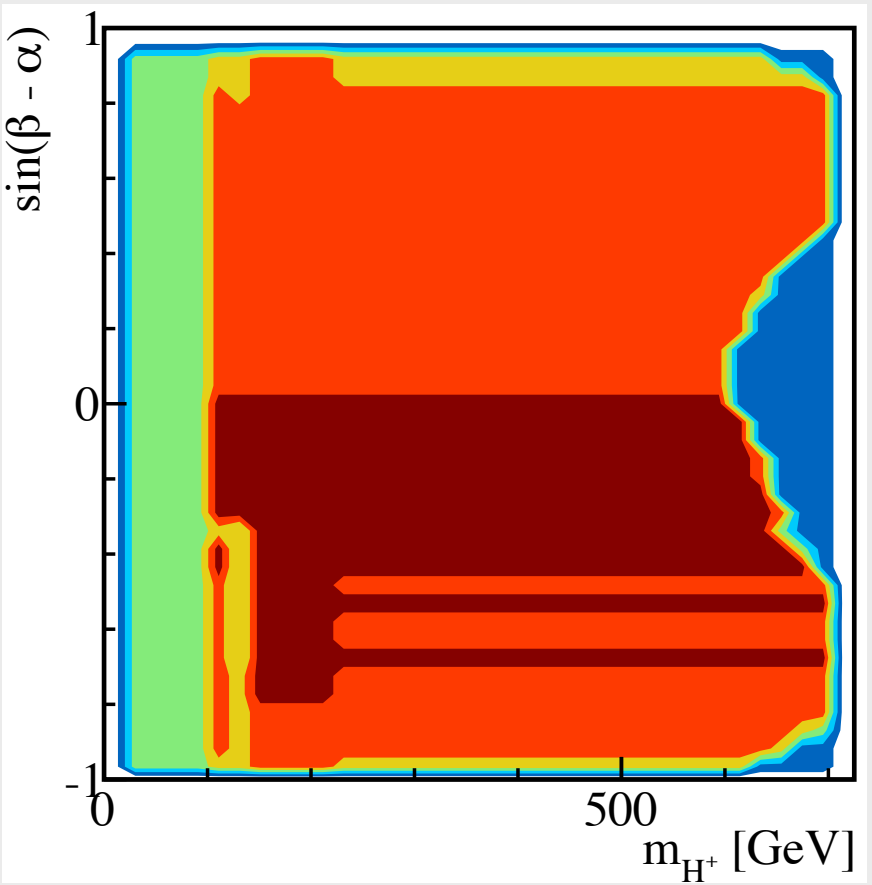
H^0 125 GeV: tan β



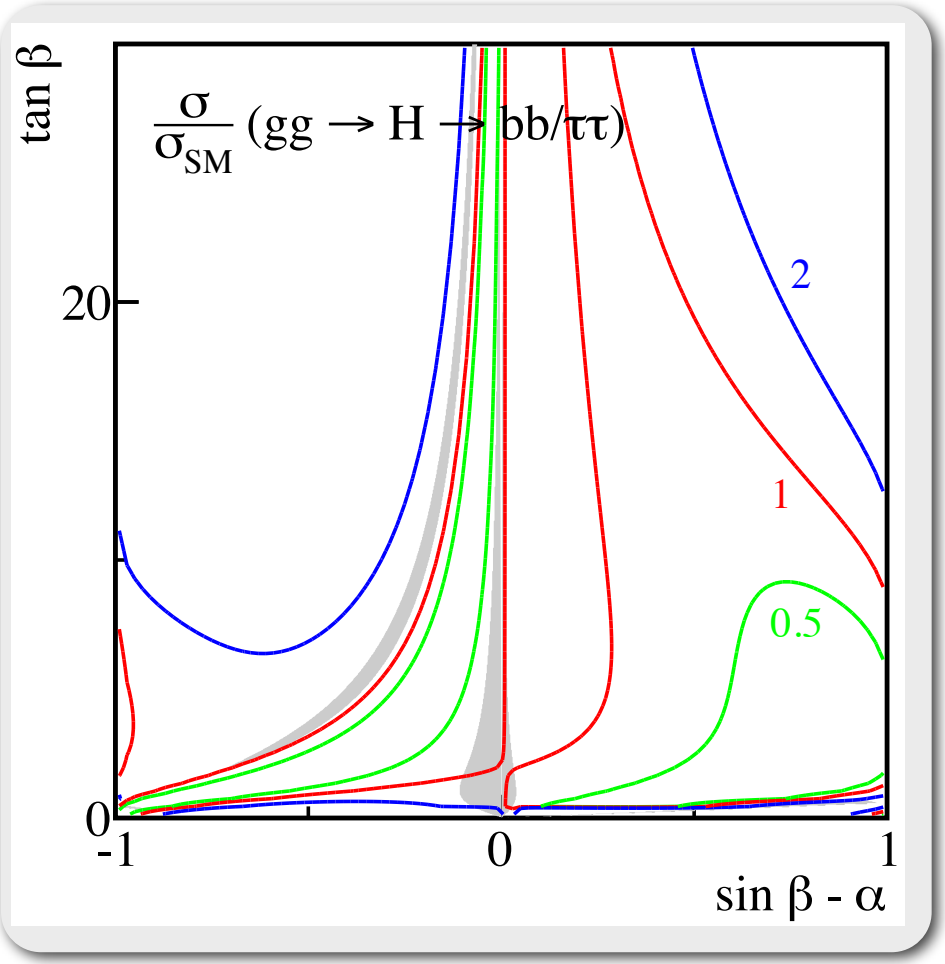


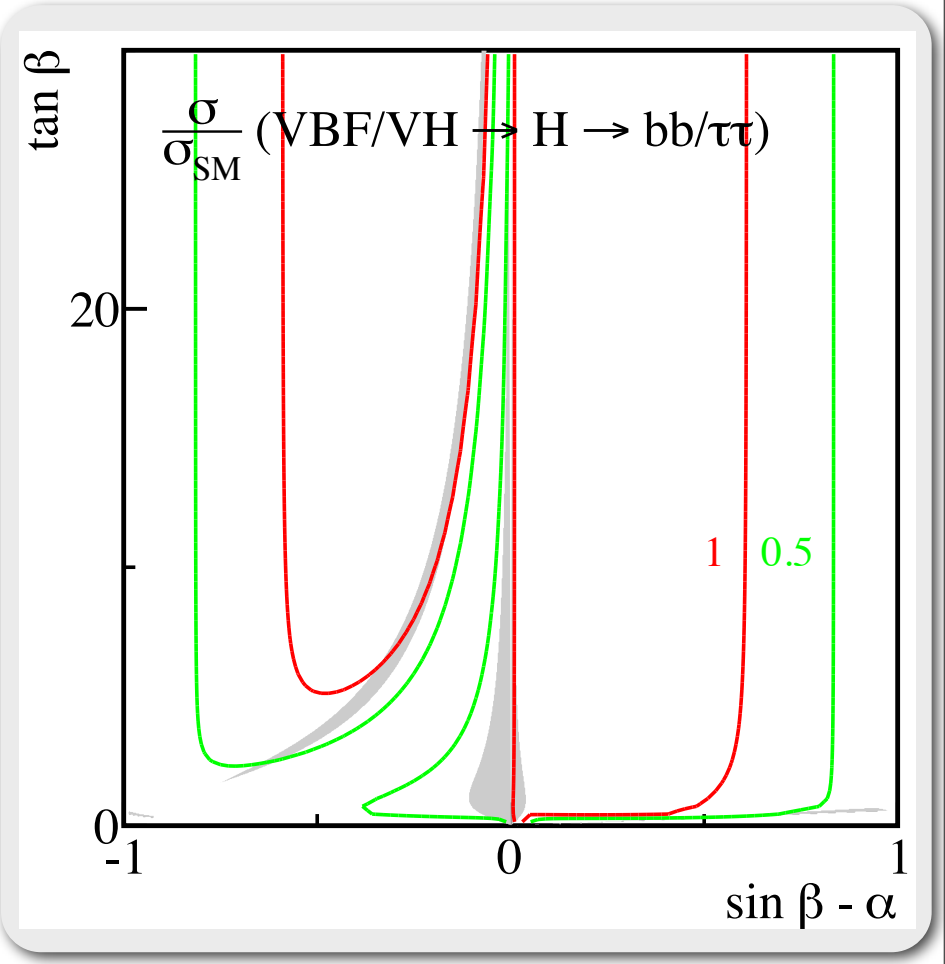
H^0 125 GeV: sin(β-α)



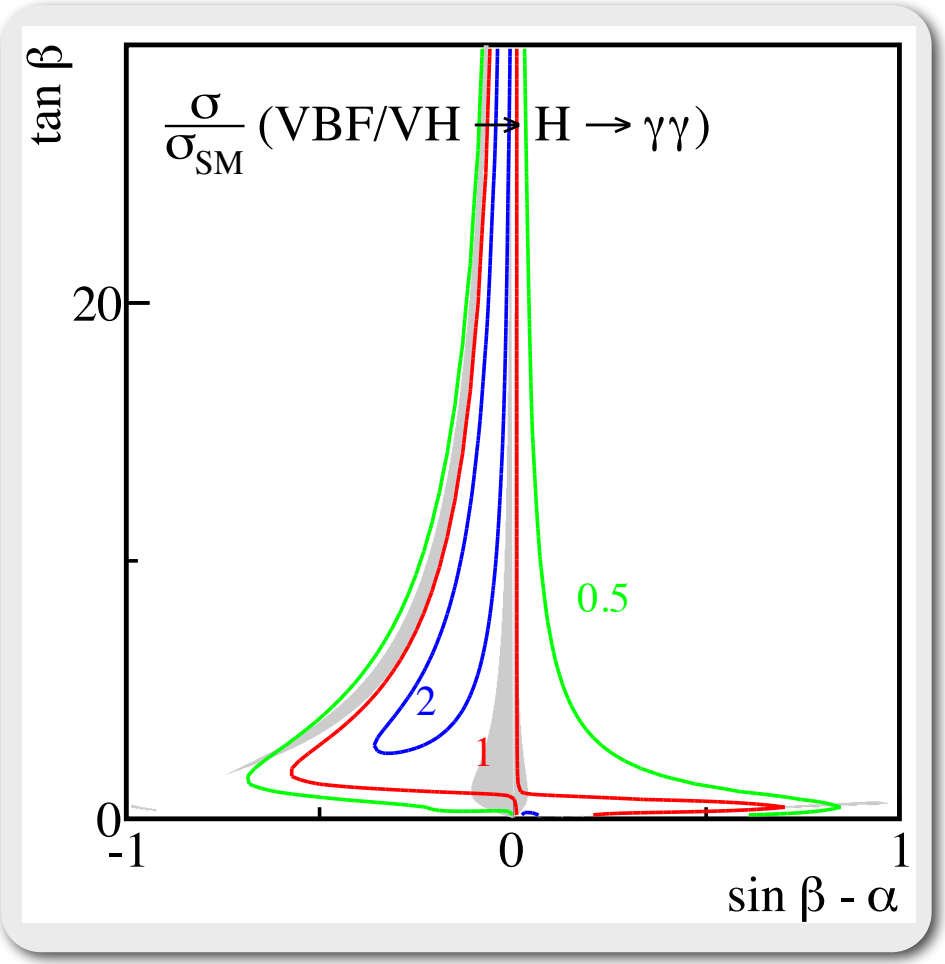


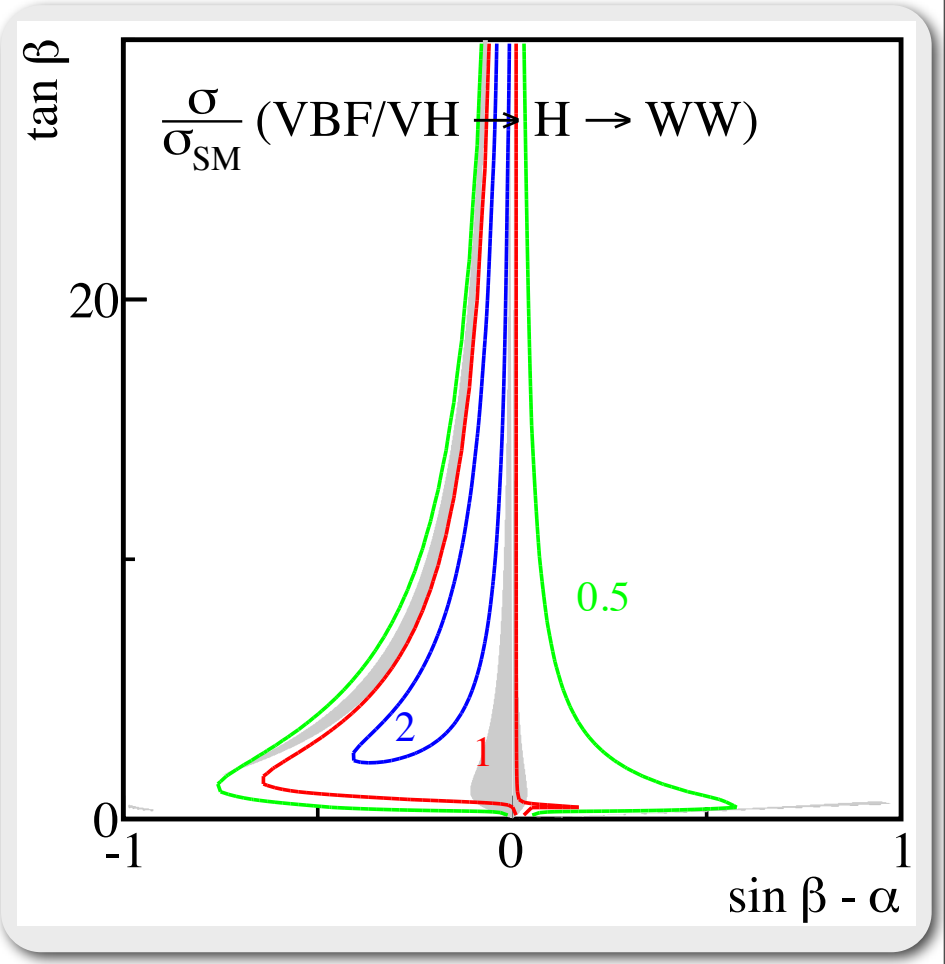
H^0 125 GeV: bb and ττ





H^0 125 GeV: γγ and WW





Conclusion (part II)

- 125 GeV (~SM strength) in Type II 2HDM
  - parameters and σXBr study
- h^0 125 GeV
  - small tan β ≤4
  - sin(β-α) branches: >0 and <0
  - correlations between m_H and tan β
  - correlation between m_A and m_{Hpm} for sin(β-α)
  - correlation between γγ, WW/ZZ and bb modes
- H^0 125 GeV
  - accommodate large tan β
  - sin(β-α) ≤ 0 branch
  - correlation between m_A and m_{Hpm}
  - correlation between γγ, WW/ZZ and bb modes