(very) light scalar DM in the Higgs models

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I. 2HDM Snapshot

2HDM Higgs sector

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

The models we studied

1. NO explicit $\mathcal{CP}$ violation: all λ_i and m_{12}^2 are assumed to be real.
2. NO spontaneous $\mathcal{CP}$ breaking: take $\xi = 0$.
3. "soft" Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) breaking: $m_{12}^2 \neq 0$; $\lambda_6 = \lambda_7 = 0$.

our inputs: $m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin\alpha, m_{12}^2$

Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v\cos\beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v\sin\beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

2 CP-even neutral scalars: $h = -\rho_1 \sin\alpha + \rho_2 \cos\alpha$
$H = \rho_1 \cos\alpha + \rho_2 \sin\alpha$

1 CP-odd neutral pseudoscalar: $A = -\eta_1 \sin\beta + \eta_2 \cos\beta$

2 charged scalars: $H^\pm$

2HDM Yukawa sector

$$\mathcal{L} = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry. [1]

Model	u^i_R	d^i_R	e^i_R	Realization
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \to -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$\Phi_1 \to -\Phi_1, d^i_R \to -d^i_R$

$$\mathcal{L}^{\mathbf{2HDM}}_{\mathbf{Yukawa}} = -\sum_{f=u,d,\ell}\frac{m_f}{v}\left(\xi^h_f\bar{f}fh + \xi^H_f\bar{f}fH - i\xi^A_f\bar{f}\gamma_5 fA\right)$$
$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u\xi^A_u\mathrm{P}_L + m_d\xi^A_d\mathrm{P}_R\right)dH^+ + \frac{\sqrt{2}m_\ell\xi^A_\ell}{v}\,\overline{\nu_L}\ell_R H^1 + \mathrm{h.c.}\right\}$$

	ξ^h_u	ξ^h_d	ξ^h_ℓ	ξ^H_u	ξ^H_d	ξ^H_ℓ	ξ^A_u	ξ^A_d	ξ^A_ℓ
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cot\beta$	$\tan\beta$	$\tan\beta$

Higgs-gauge boson couplings: $g_{SM}\sin(\beta-\alpha)$

[1] *Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.*

Theoretical Constraints on the 2HDM Potential

- Theoretically, (denoted jointly as SUP)

1. **Vacuum stability**
   The potential must be bounded from below (positivity).

$$\lambda_1 > 0$$
$$\lambda_2 > 0$$
$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2} \qquad \text{if } \lambda_6 = \lambda_7 = 0$$

2. **Unitarity**
   Requiring the largest eigenvalue for the tree-level for full multi-state scattering matrix in (h, H, A) space to be less than the upper limit 16π.

3. **Perturbativity**
   All self couplings among the mass eigenstates and Yukawa coupling must be finite, $|\Lambda_i| < 4\pi$.

II. 2HDM fitting

w/ J.F. Gunion, S. Kraml, B. Demount arXiv 1307.XXXX (to be appear soon)

We considered …

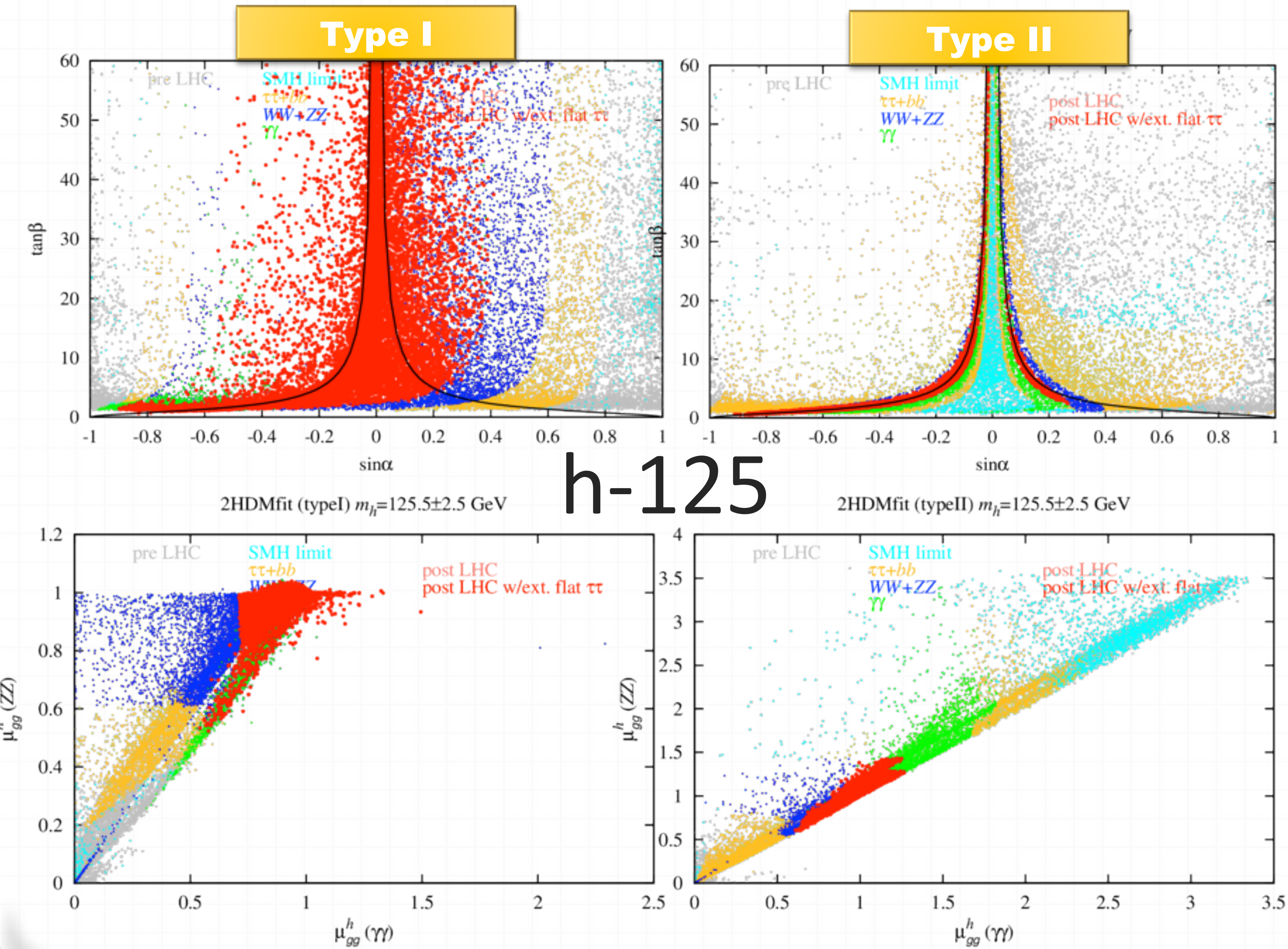
- **preLHC**: SUP, EW precision data (STU), B-Physics, $(g\text{-}2)_\mu$
- **postLHC**: additionally
  - γγ, ZZ, WW, bb, ττ signals for **125 GeV Higgs**

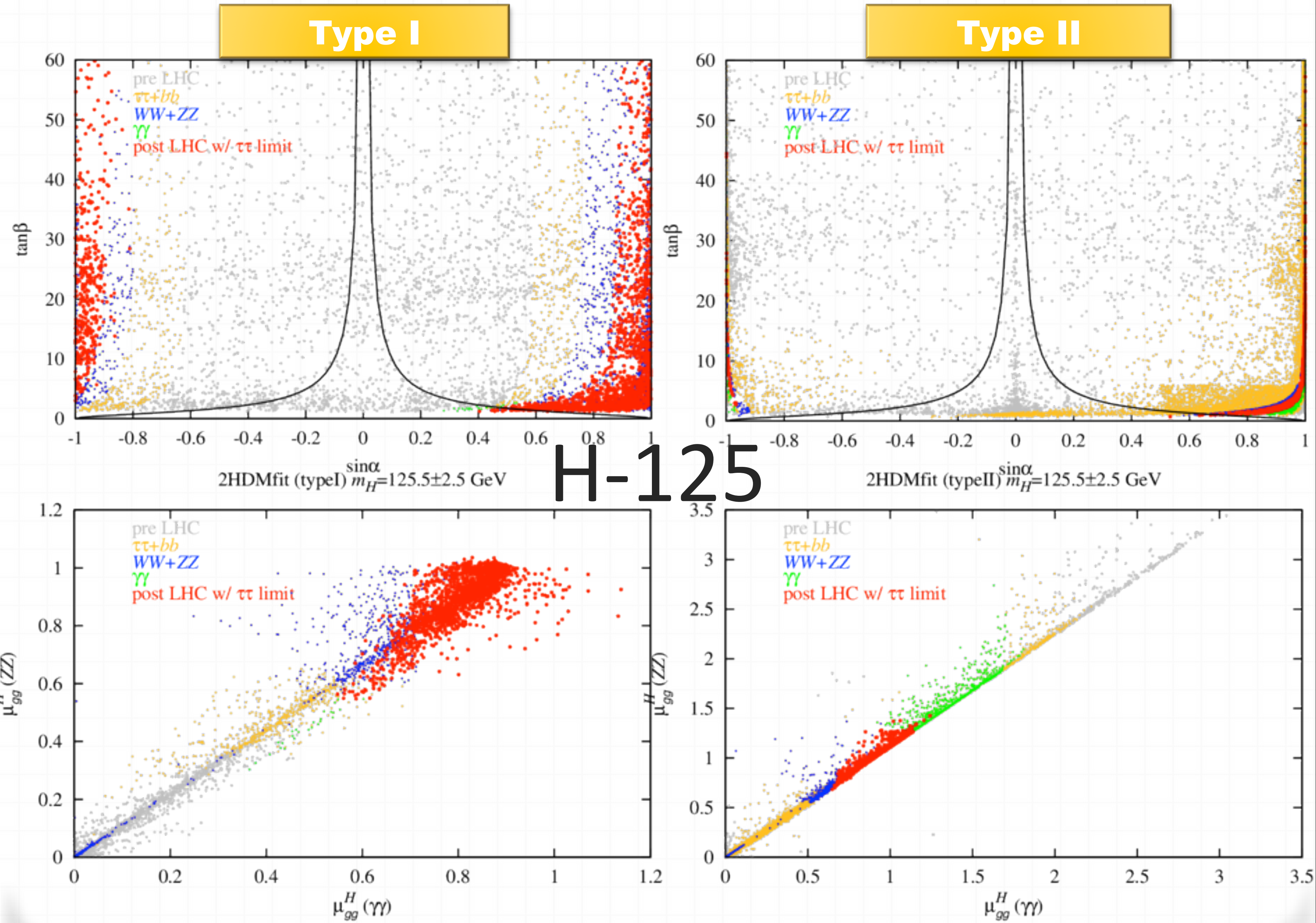
	$\hat{\mu}^{\text{ggF}}$	$\hat{\mu}^{\text{VBF}}$
$\gamma\gamma$	0.98 ± 0.28	1.72 ± 0.59
VV	0.91 ± 0.16	1.01 ± 0.49
$b\bar{b}/\tau\tau$	0.98 ± 0.63	0.97 ± 0.32
$b\bar{b}$	-0.23 ± 2.86	0.97 ± 0.38
$\tau\tau$	1.07 ± 0.71	0.94 ± 0.65

$$\mu_Y^H(X) \equiv \frac{\sigma(Y \to H)BR(H \to X)}{\sigma(Y \to h_{\text{SM}})BR(h_{\text{SM}} \to X)}$$

arXiv:1306.2941

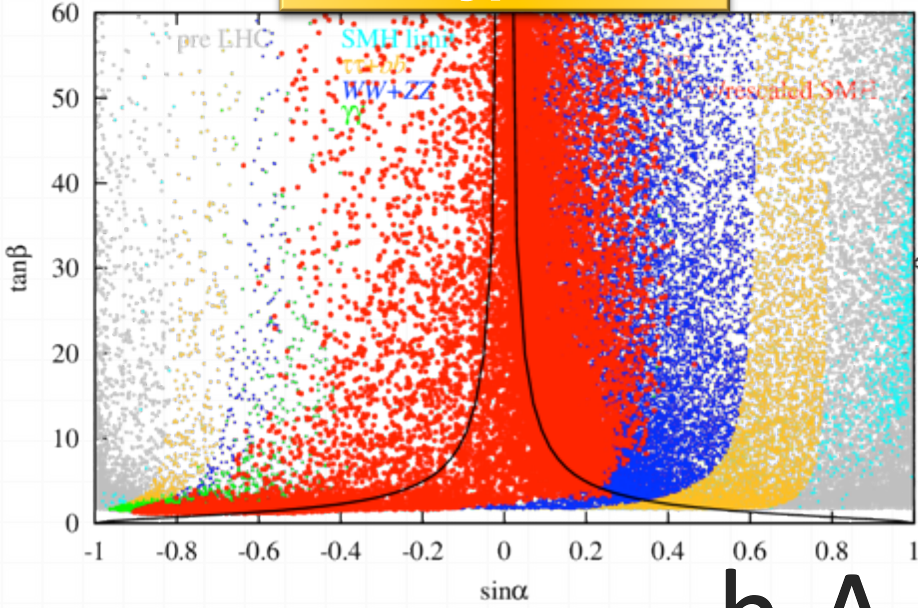
  - H->ZZ*->4l for heavy Higgs up to 1 TeV
  - gg->H->ττ and gg->bbH with H->ττ for heavy Higgs up to 500 GeV

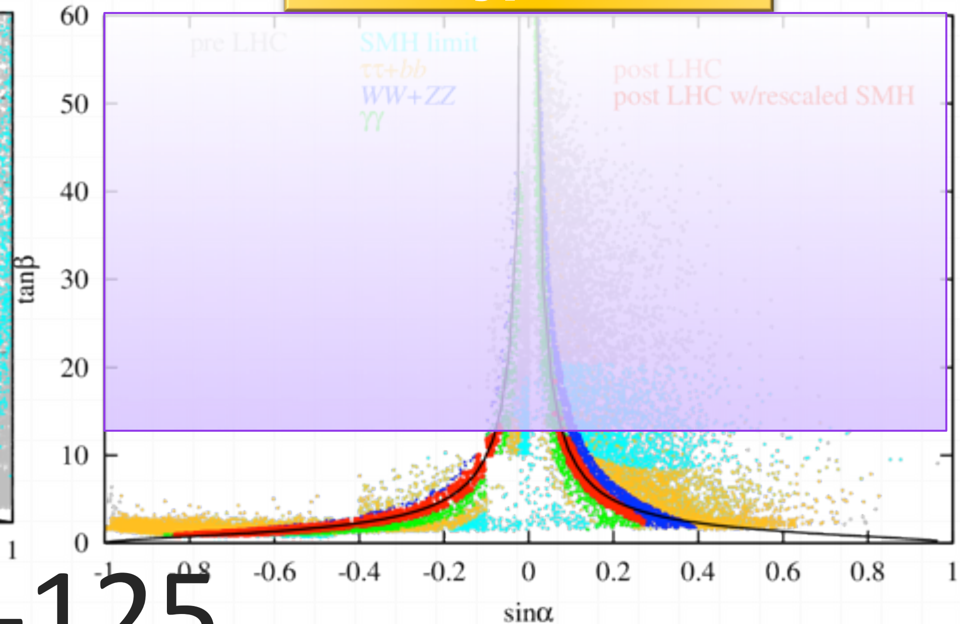

Type I
Type II
h-125
pre LHC
SMH limit
ττ+bb
WW+ZZ
γγ
post LHC
post LHC w/ext. flat ττ
tanβ
sinα
2HDMfit (typeI) m_h=125.5±2.5 GeV
2HDMfit (typeII) m_h=125.5±2.5 GeV
μ^h_{gg} (ZZ)
μ^h_{gg} (γγ)


Type I
Type II
H-125
pre LHC
ττ+bb
WW+ZZ
γγ
post LHC w/ ττ limit
tanβ
sinα
2HDMfit (typeI) m_H=125.5±2.5 GeV
2HDMfit (typeII) m_H=125.5±2.5 GeV
μ^H_{gg} (ZZ)
μ^H_{gg} (γγ)

Type I

Type II

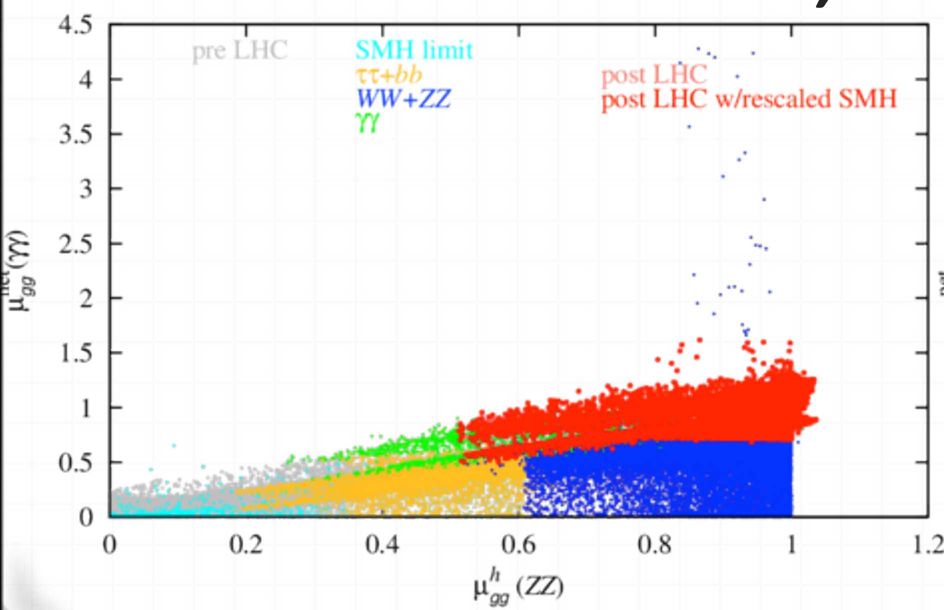


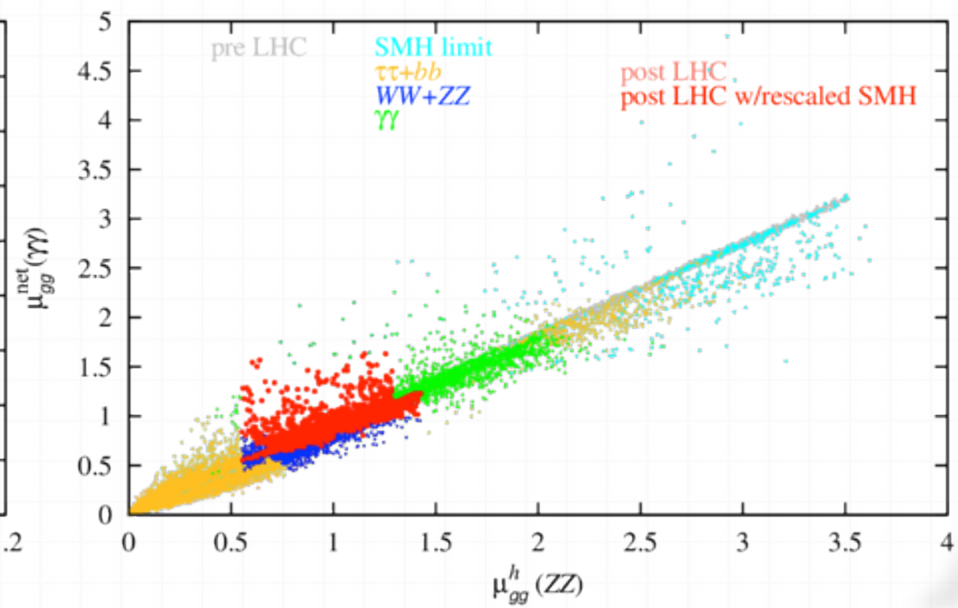


h,A-125

2HDMfit (typeI) m_h, m_A=125.5±2.5 GeV

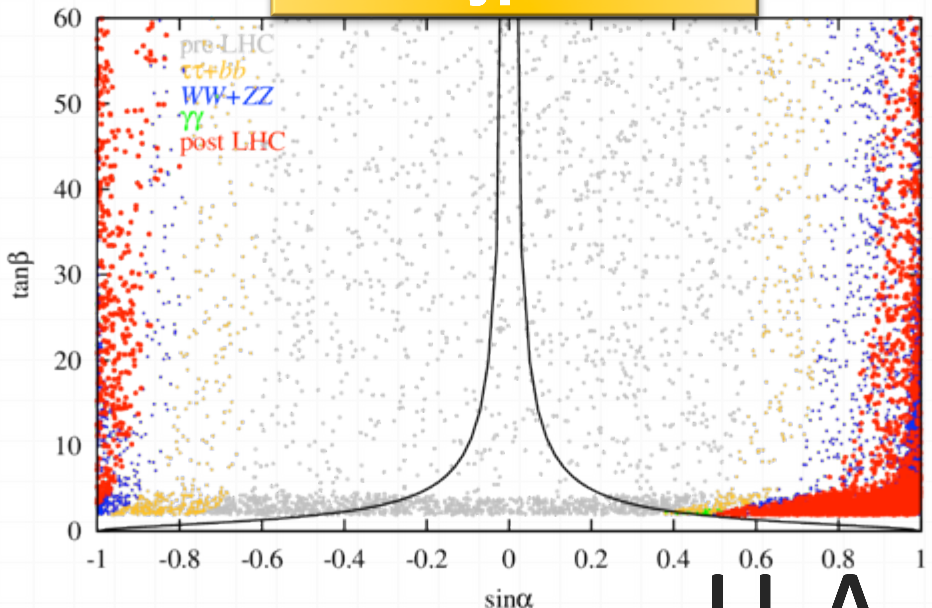
2HDMfit (typeII) m_h, m_A=125.5±2.5 GeV



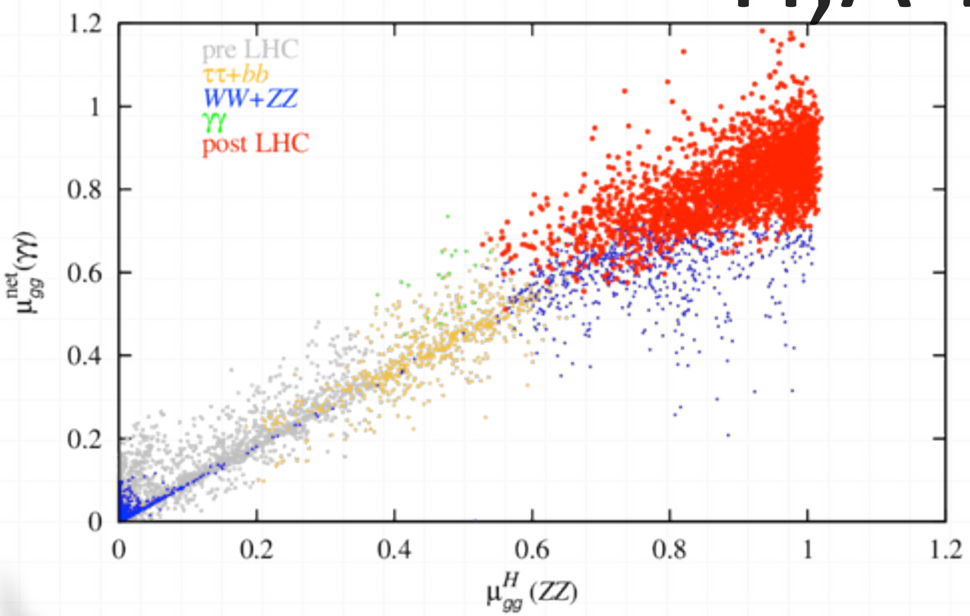


Type I

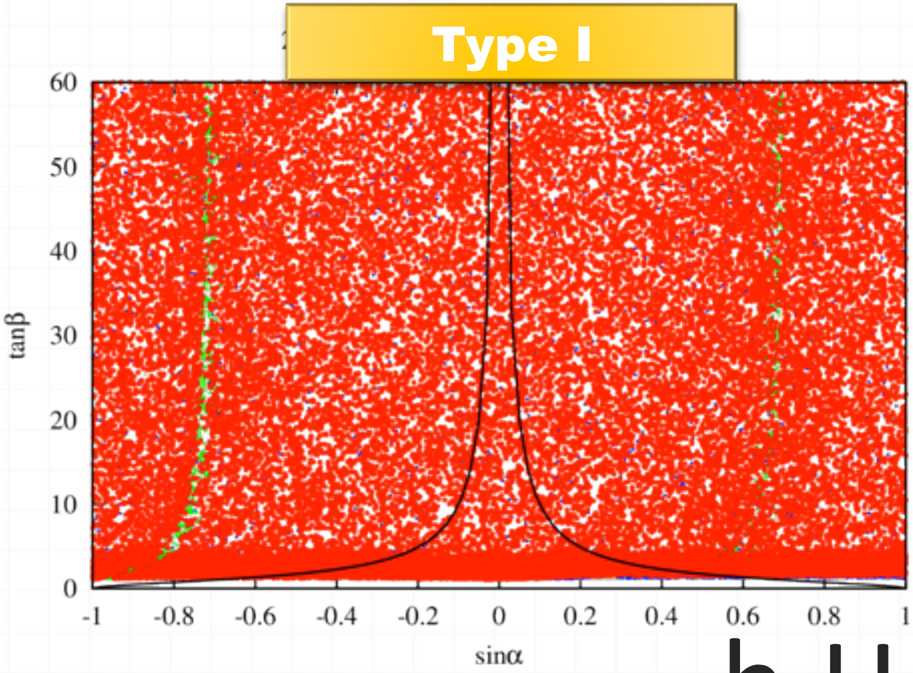
Type II

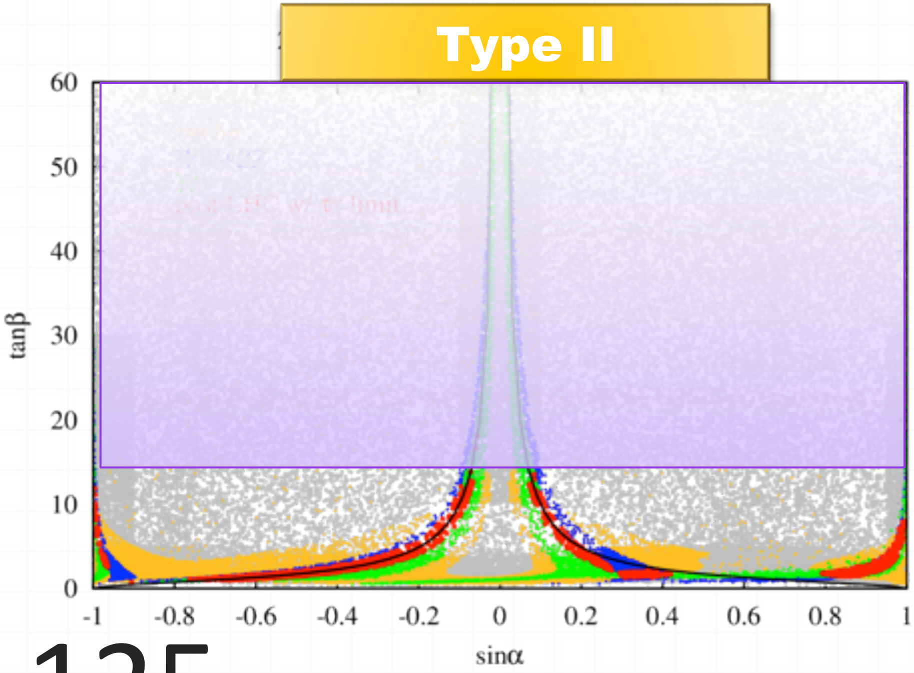


2HDMfit (typeI) m_H,m_A=125.5±2.5 GeV



H,A-125


Type I
tanβ
sinα
60
50
40
30
20
10
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

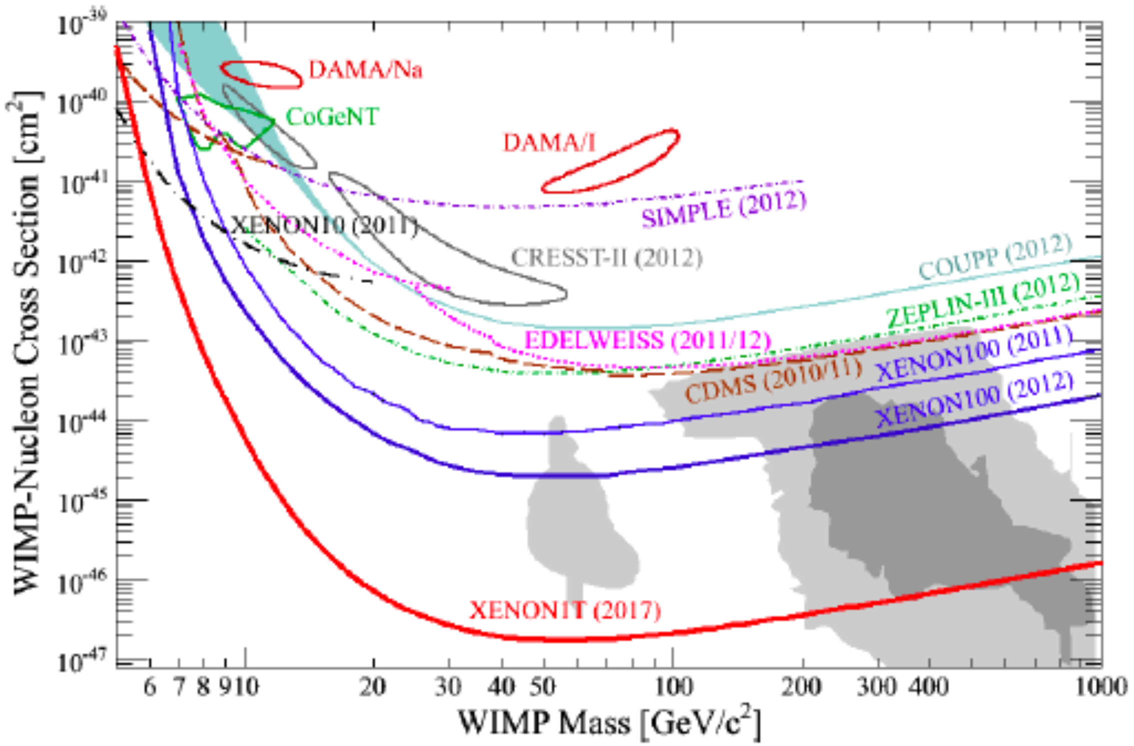

Type II
tanβ
sinα
60
50
40
30
20
10
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

h,H-125

Where is DM?

DM mass is not known at present.

few GeV ~ few TeV



CDM relic abundance

	Planck		Planck+lensing		Planck+WP		Planck+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68 % limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.0002	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027	0.11889	0.1187 ± 0.0017

arXiv: 1303.5062, 1303.5076

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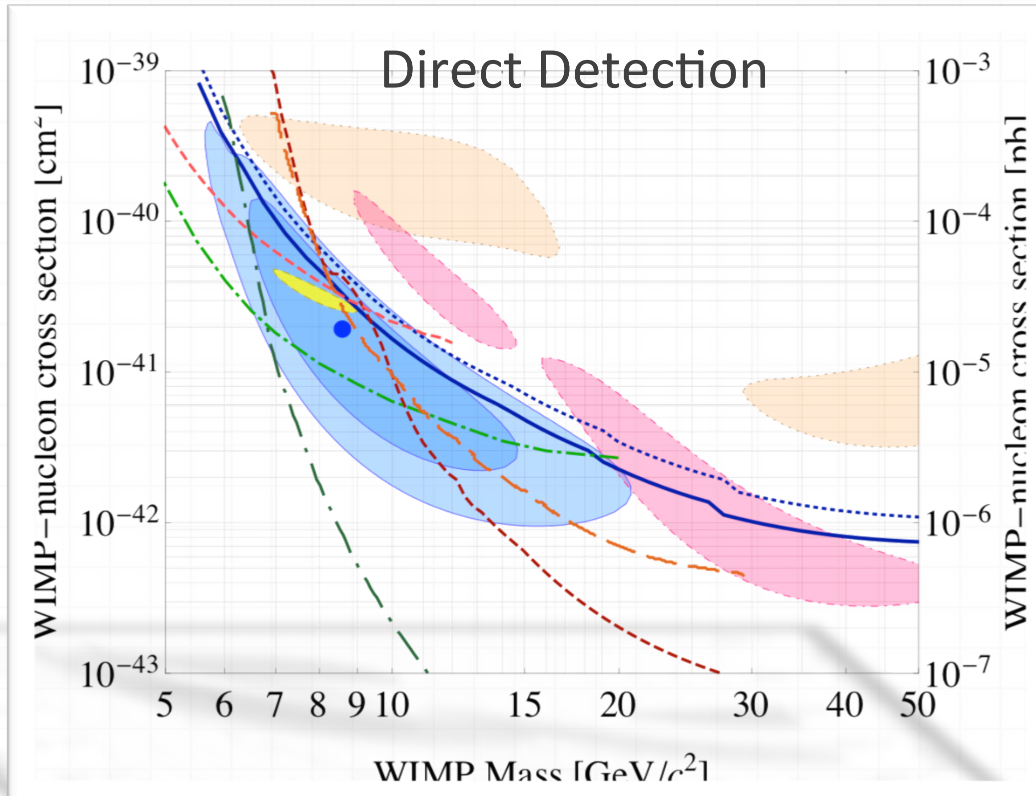


1304.4279 CDMS-II, PRL109(2012)181301 XENON

III. SM+Singlet

SM + Darkon (D)

- Add an extra gauge singlet D
- Introduce a Z_2 symmetry under which D→-D

$$\mathcal{L}_D = -\frac{\lambda_D}{4} D^4 - \frac{m_0^2}{2} D^2 - \lambda D^2 H^\dagger H$$

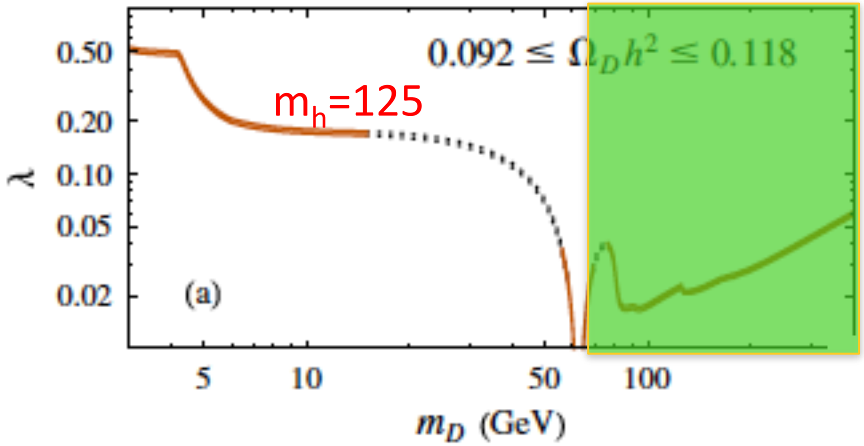
D is stable, being a DM candidate

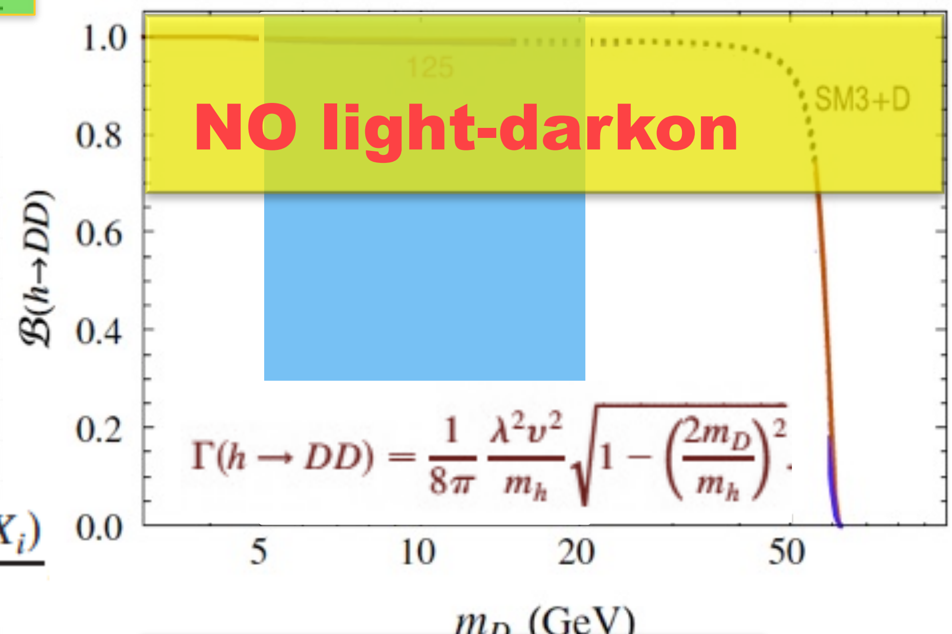
After EWSB: $$\mathcal{L}_D = -\frac{\lambda_D}{4} D^4 - \frac{(m_0^2 + \lambda v^2)}{2} D^2 - \frac{\lambda}{2} D^2 h^2 - \lambda v D^2 h$$

Free parameter set: $(\lambda_D, m_D, \lambda)$

SM + Darkon

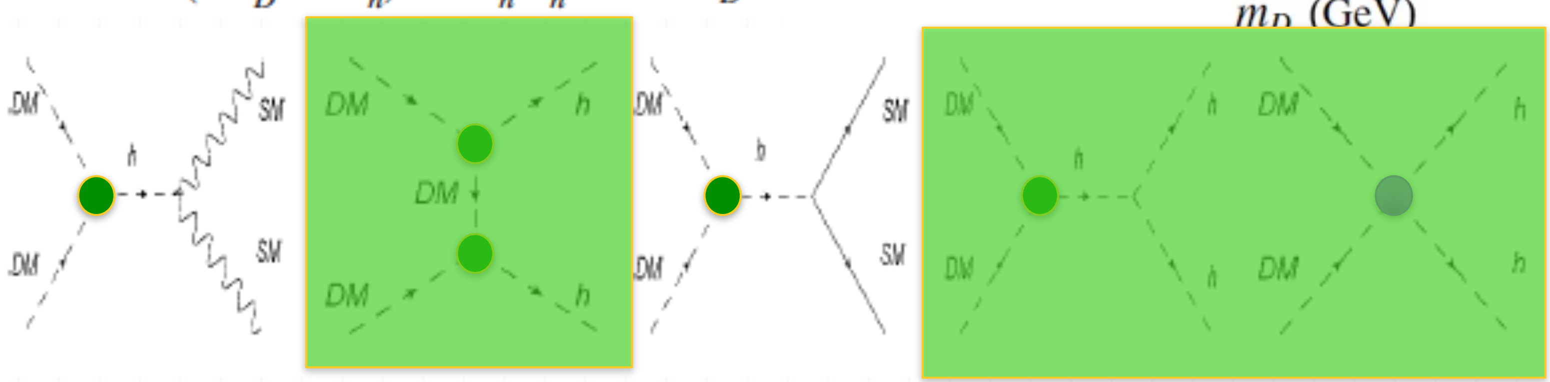
Xiao-gang He et. al. PRD85(2012)093019





$$\Omega_D h_0^2 \sim 30[\mathrm{fb}]\,\frac{g_*^{1/2}}{g_S}\,\frac{x_f}{\langle \sigma_{\mathrm{ann}} v\rangle_{DD\to XX}}$$

$$\sigma_{\mathrm{ann}} v_{\mathrm{rel}} = \frac{8\lambda^2 v^2}{(4m_D^2 - m_h^2)^2 + \Gamma_h^2 m_h^2}\,\frac{\sum_i \Gamma(\tilde{h} \to X_i)}{2m_D}$$



IV. 2HDM+Singlet (S)

working in progress w/ JFG,BG,AD

2HDMS DM sector

- Add an extra gauge singlet S
- S is Z'_2-odd under ($H_1 \rightarrow H_1$, $H_2 \rightarrow H_2$, $S \rightarrow -S$)

$$\mathcal{L}_S \supset -\frac{1}{2} m_0^2 S^2 - \kappa_1 S^2 (H_1^\dagger H_1) - \kappa_2 S^2 (H_2^\dagger H_2) - \frac{1}{4!} \lambda_S S^4$$

After EWSB:

$$\mathcal{L}_S \supset -\frac{1}{2} \underbrace{[m_0^2 + (\kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta) v^2]}_{m_S^2} S^2$$

$$- \underbrace{(\kappa_1 \cos\alpha \cos\beta + \kappa_2 \sin\alpha \sin\beta)}_{\lambda_h} v h S^2$$

$$- \underbrace{(-\kappa_1 \sin\alpha \cos\beta + \kappa_2 \cos\alpha \sin\beta)}_{\lambda_H} v H S^2$$

$$+ (HH, hH, hh, AA, H^+H^-) S^2 \text{ terms}$$

an additional physical state

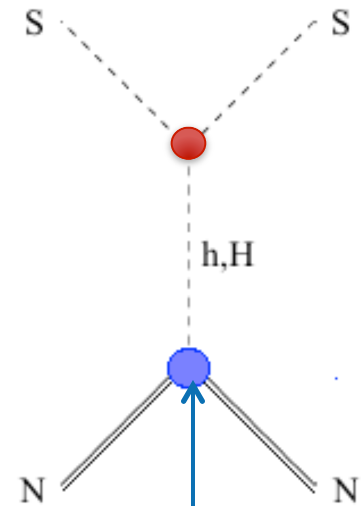
NO AS^2 term !

2HDMS

Xiao-gang He et. al. PRD83(2011)083524

- Direct detection

$$\sigma_{\rm el} \simeq \frac{m_N^2 v^2}{\pi(m_D+m_N)^2}\left(\frac{\lambda_h g_{NNh}^{\rm THDM}}{m_h^2}+\frac{\lambda_H g_{NNH}^{\rm THDM}}{m_H^2}\right)^2$$



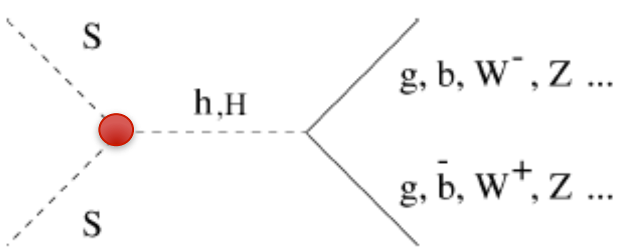
Higgs-Nucleons effective coupling

$$g_{NN\mathcal{H}}^{\rm THDM} = (k_u^{\mathcal{H}} - k_d^{\mathcal{H}})\frac{\sigma_{\pi N}}{2v} + k_d^{\mathcal{H}}\frac{m_N}{v} + \frac{4k_u^{\mathcal{H}} - 25k_d^{\mathcal{H}}}{27}\frac{m_B}{v}$$

- Relic abundance

$$\Omega_D h_0^2 \sim 30[\mathrm{fb}]\frac{g_*^{1/2}}{g_S}\frac{x_f}{\langle\sigma_{\rm ann}v\rangle_{SS\to XX}}$$

$$\sigma_{\rm ann} v_{\rm rel} = \frac{8\lambda_h^2 v^2}{(4m_D^2 - m_h^2)^2 + \Gamma_h^2 m_h^2}\frac{\sum_i \Gamma(\tilde{h}\to X_i)}{2m_D} + \frac{8\lambda_H^2 v^2}{(4m_D^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\frac{\sum_i \Gamma(\tilde{H}\to X_i)}{2m_D}$$

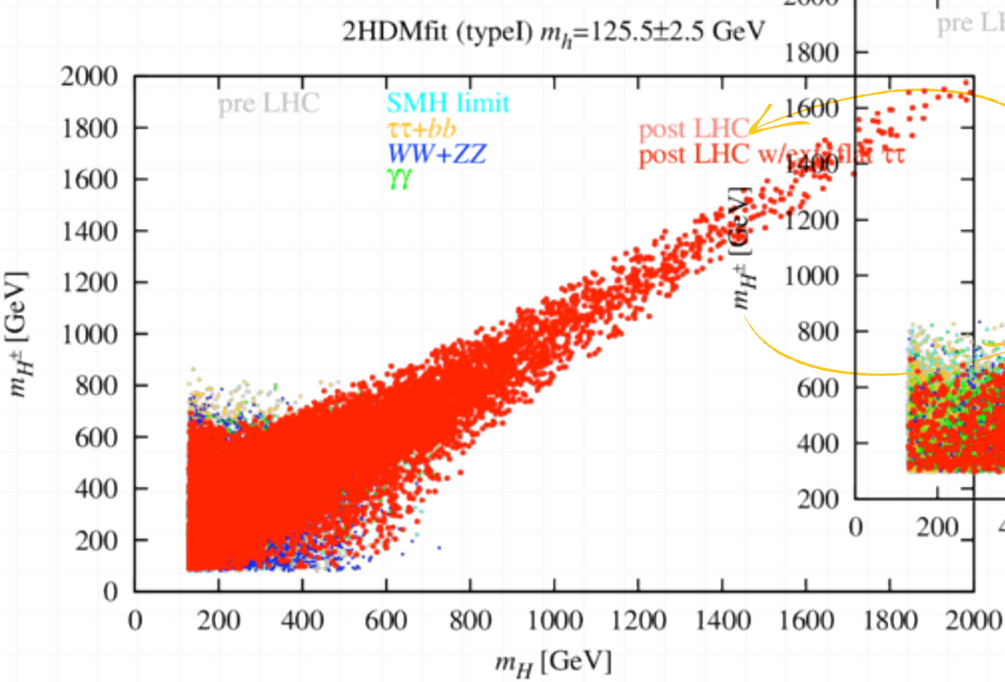


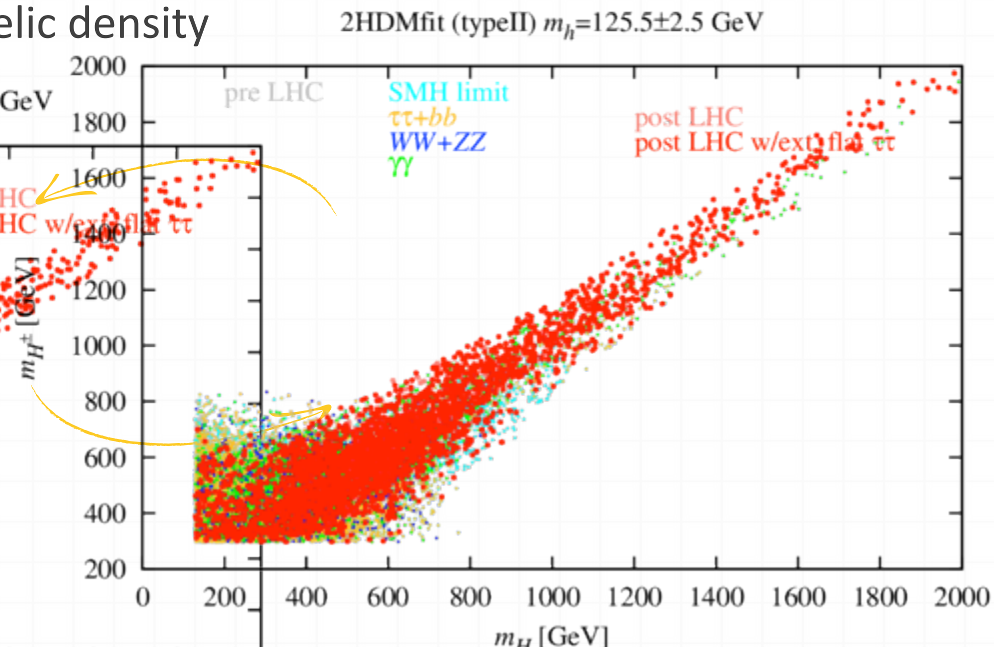
The cases we are studying …

Assume $m_S \sim 5 - 20\ \mathrm{GeV}$, a very light DM to interpret the CDMS-II data

h-125

- small λ_h to avoid large Higgs invisible decay
- H-mediator responsible to DM relic density





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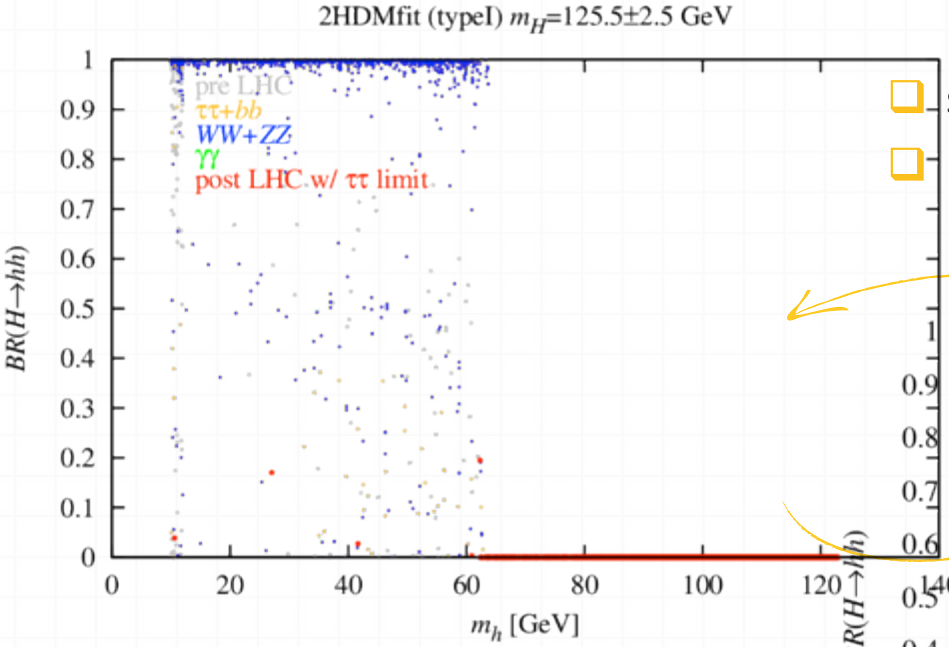

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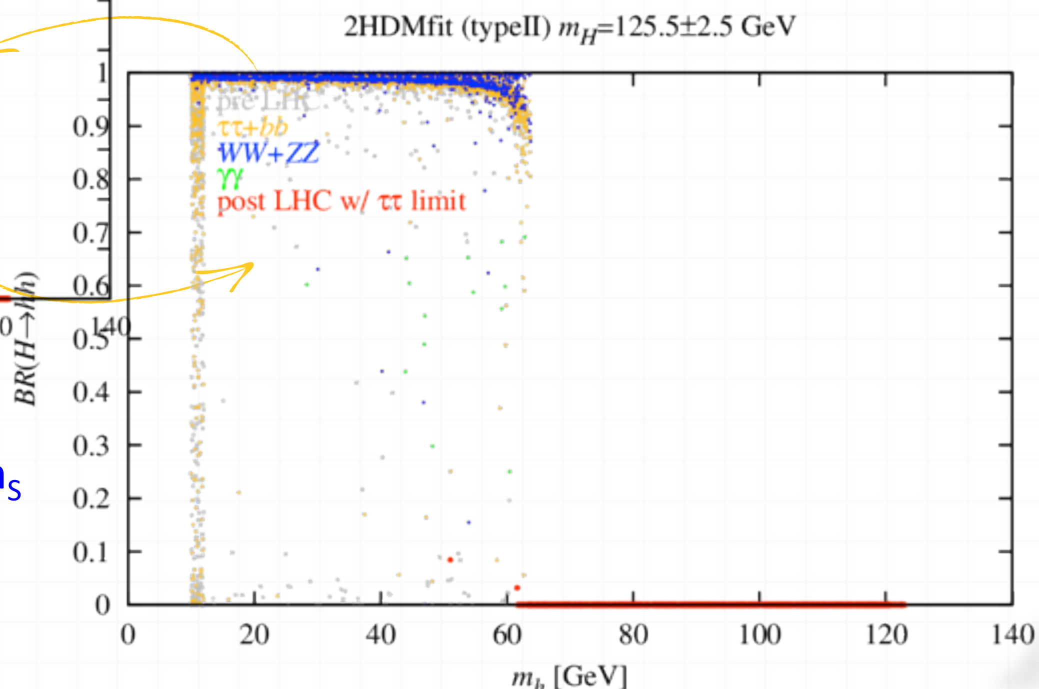

We have points at which $m_h \cong 2m_S$

The cases we are studying …

Assume $m_S \sim 5 - 20\ \mathrm{GeV}$, a very light DM to interpret the CDMS-II data

with degeneracy

(h,A), (H,A) (h,H) -125

maybe also interesting

Procedure

- Generate the Feynman rules (FeynRules)
- Starting with a few our BMPs from 2HDM fitting with LHC Higgs signal, at which seven 2HDM parameters are already given
- Random/grid scan over the parameter space (κ_1,κ_2,m_S,λ_S) in the extra DM sector
- Interface with micrOmegas 3.0 to calculate ……
- ……

One h-125 sample

$m_h = 125, m_A = 200, \tan\beta = 4.0, m_H = 225, m_{H+} = 90, m_{12} = 100, \sin\alpha = -0.1$

Range for the scalar singlet part: $m_S = 1 - 61$ GeV, $|\kappa_{1,2}| = 0 - 1$

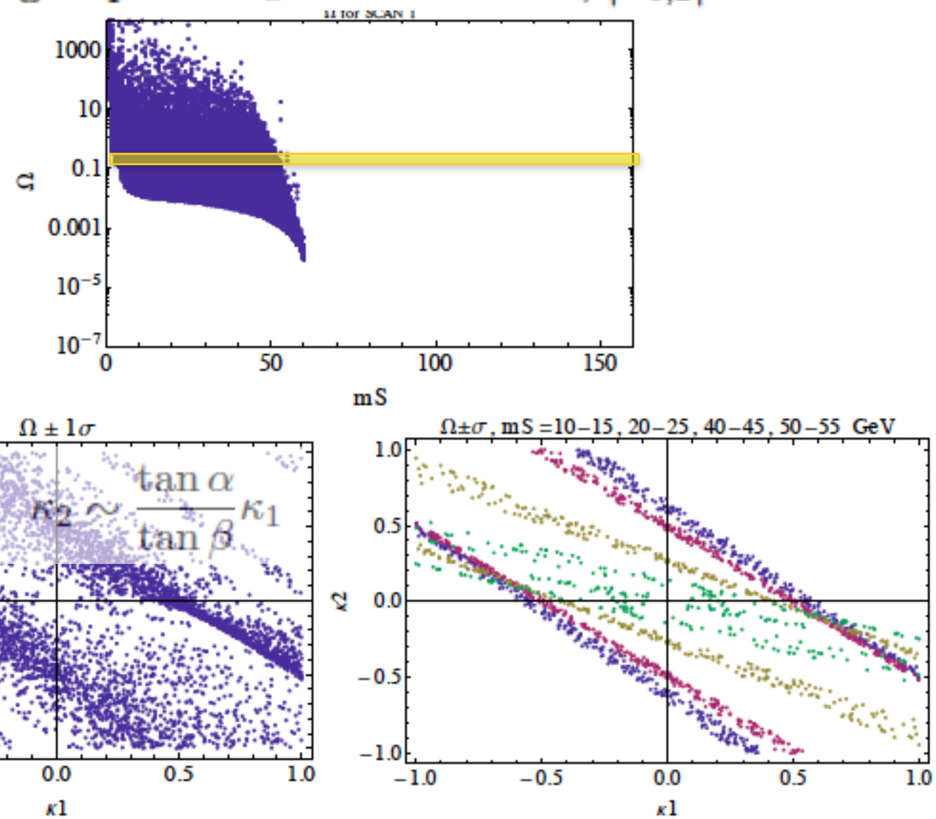

Fig. 2: SCAN 1: BLUE: m_S = 10-15 GeV, PURPLE: m_S = 20-25 GeV, m_S = YELLOW: 40-45 GeV, m_S = GREEN: 50-55 GeV

One h-125 sample

$m_h = 125, m_A = 200, \tan\beta = 4.0, m_H = 225, m_{H+} = 90, m_{12} = 100, \sin\alpha = -0.1$

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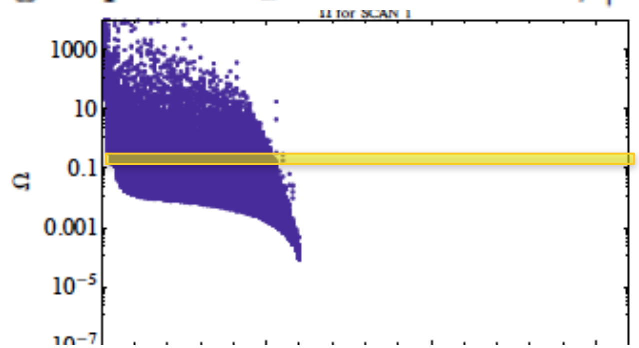


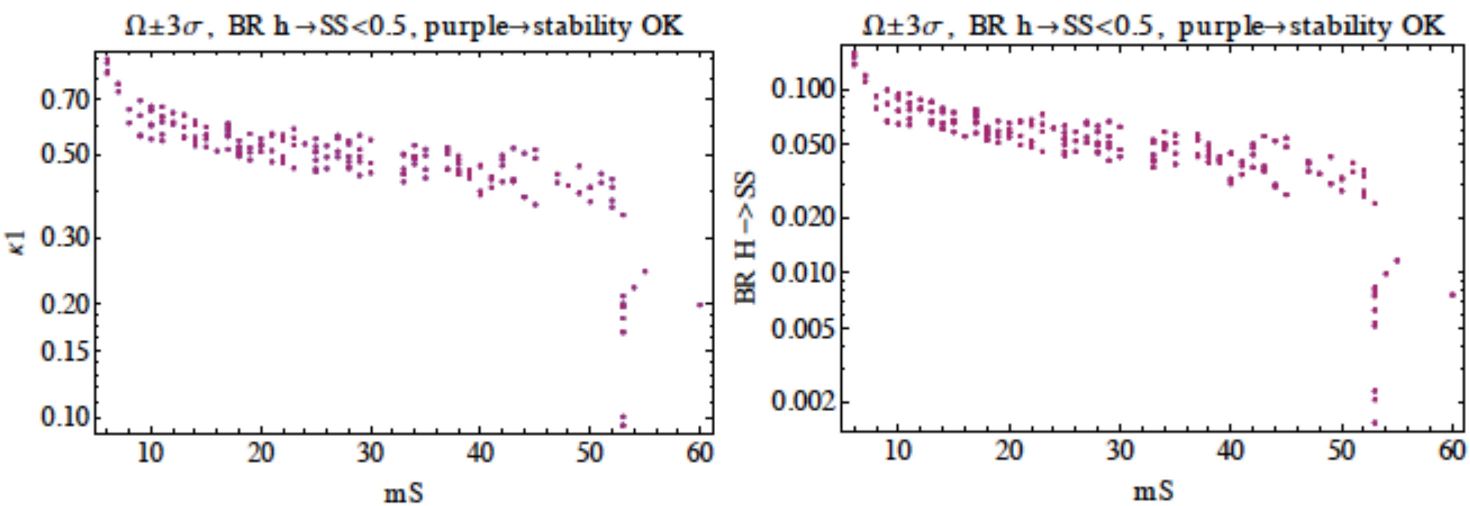
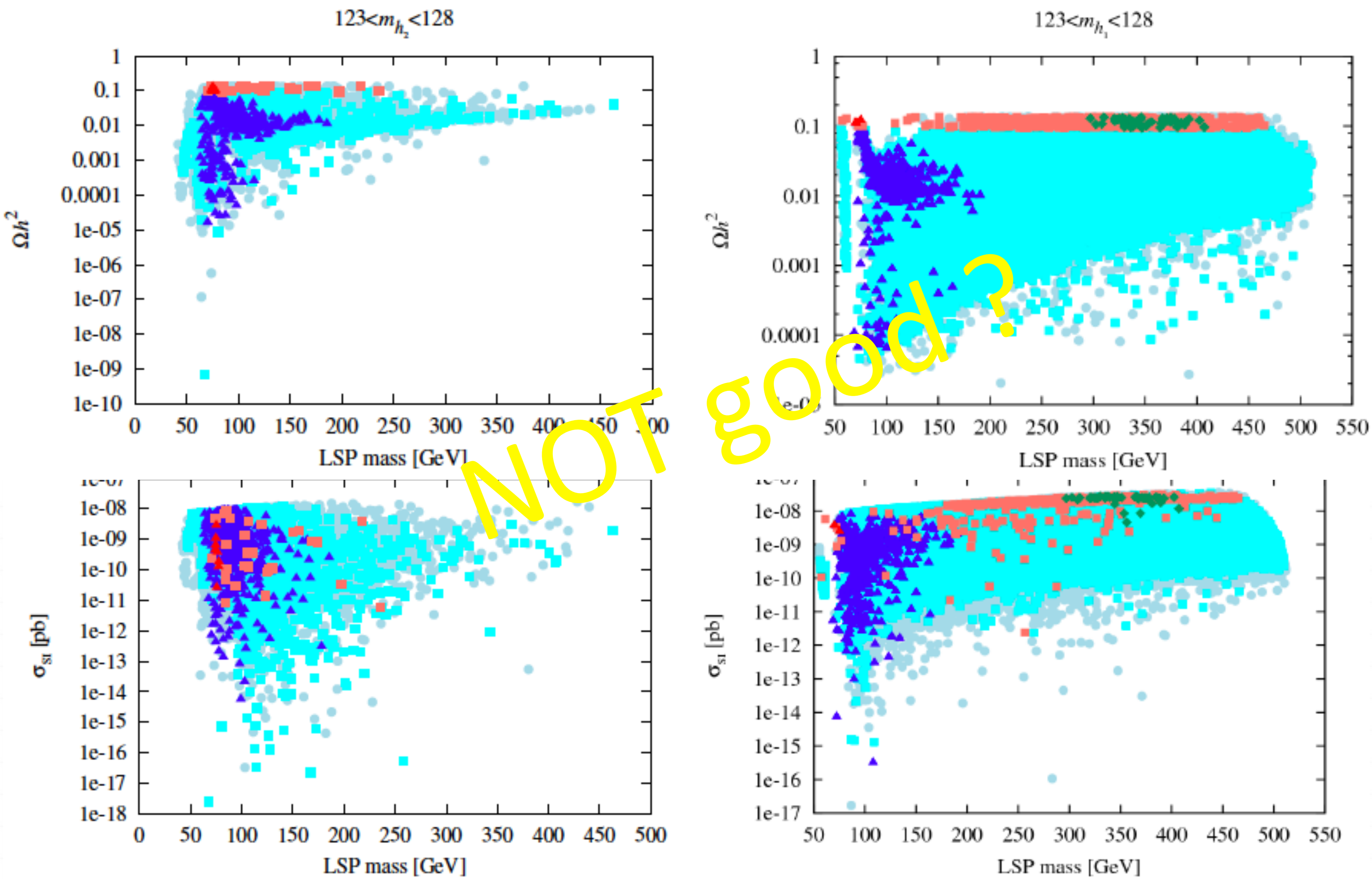


Fig. 4: SCAN 1, BLUE: $\Omega \pm 3\sigma$, $BR_{h\to SS} < 0.5$, PURPLE:$\Omega \pm 3\sigma$, $BR_{h\to SS} < 0.5$, STABILITY OK

Very light DM in the scNMSSM?



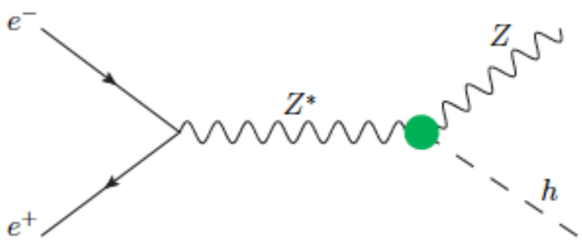
General comments

- ✓ There is consistent descriptions with the LHC Higgs signal in the both Type I and Type II 2HDMs.
- ✓ 2HDM+singlets with a dark matter candidate is an natural extension that worths studying.
- ✓ More interesting conclusions, please stay tuned.

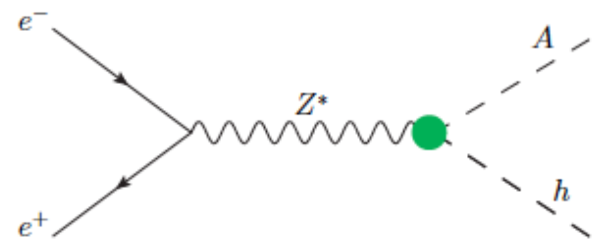
Back up

Basic Constraints – LEP

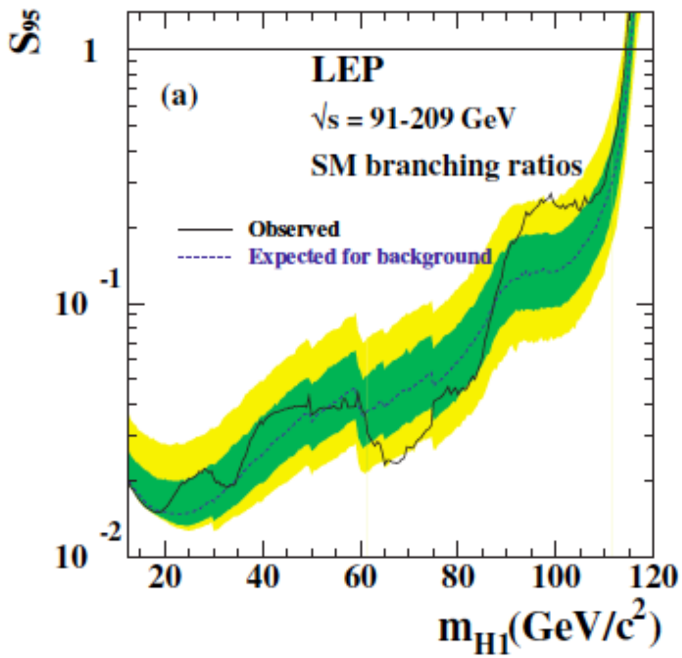
LEP constraints on Higgs mass limits

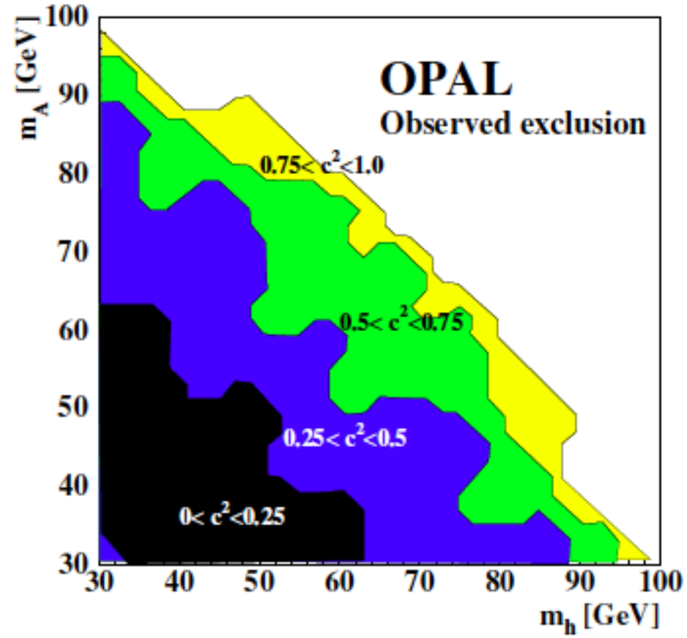


$$\frac{\sigma(e^+e^- \to Z\,h)}{\sigma(e^+e^- \to Z\,h_{SM})} \sim \sin^2(\alpha - \beta)$$



$$\frac{\sigma(e^+e^- \to A\,h)}{\sigma(e^+e^- \to Z\,h_{SM})} \sim \cos^2(\alpha - \beta)$$

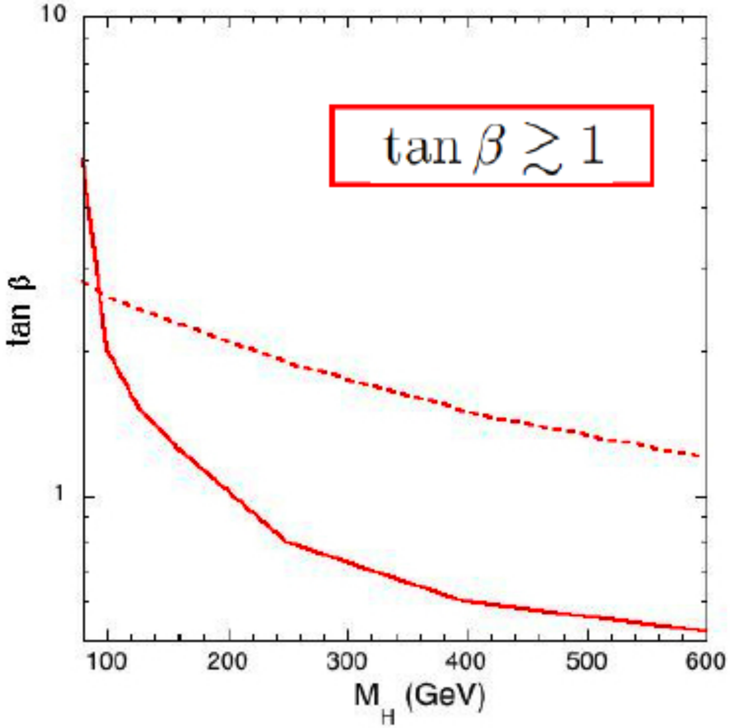




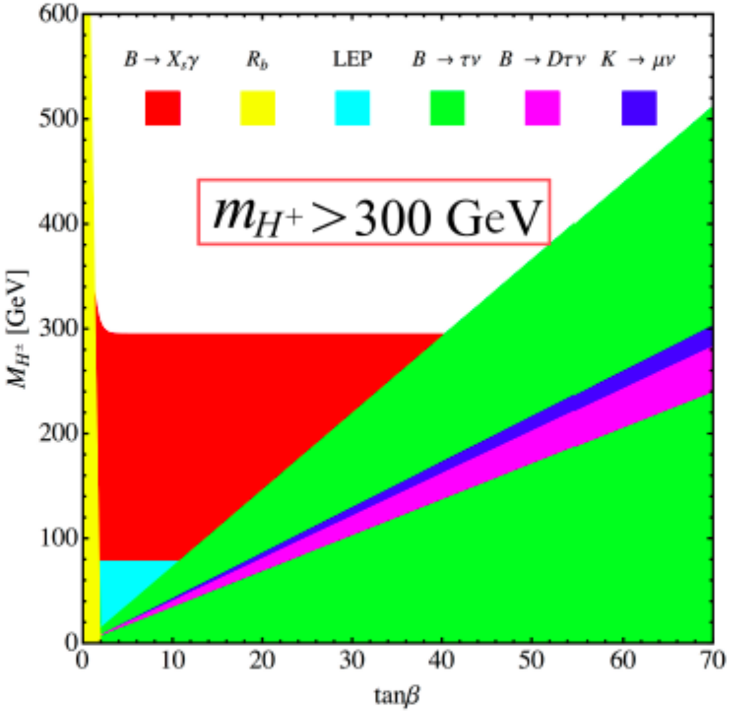
Basic Constraints – B-physics

B-physics constraints ($\mathrm{BR}(B_s \to X_s\gamma)$, R_b, ΔM_{B_s}, ϵ_K, $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$ and $\mathrm{BR}(B^+ \to D\tau^+\nu_\tau)$): set up lower bound on $m_{H^\pm}$.

Type I



Type II



Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}

Dash: $\bar{B} \to X_s\gamma$ in models with FCNC