Status of Models with extended Higgs Sectors

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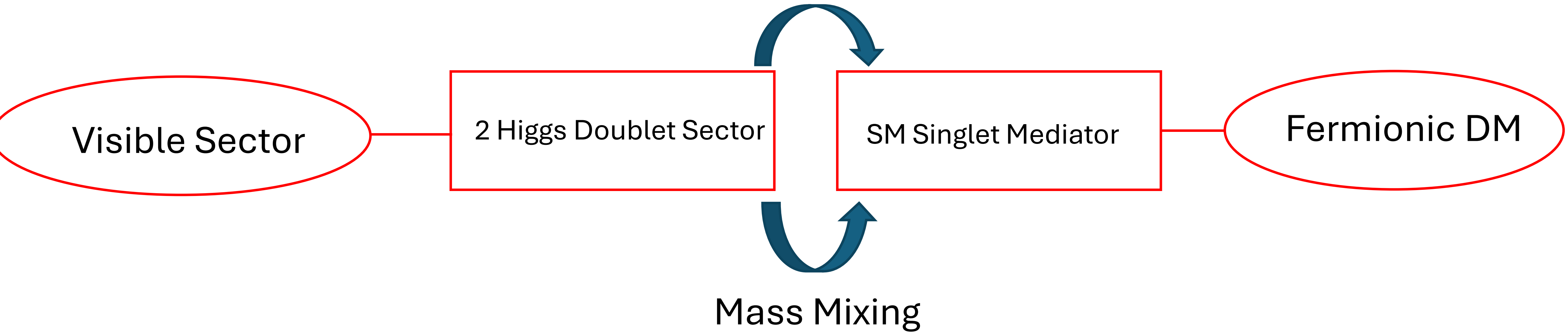
General Setup



Good compromise between theoretical consistency and predictivity (still limited number of free parameters);
Benchmark for a large variety of collider studies;
Interesting Dark Matter phenomenology.
Possibility of triggering First Order Phase Transition (FOPT).

$$V_S(S) = \frac{1}{2}M_{SS}^2 S^2 + \frac{1}{3}\mu_S S^3 + \frac{1}{4}\lambda_S S^4$$

$$V_{S,2HDM}(\Phi_1, \Phi_2, S)$$
$$= \mu_{11S}(\Phi_1\Phi_1^\dagger)S + \mu_{22S}(\Phi_2\Phi_2^\dagger)S + (\mu_{12S}\Phi_1\Phi_2^\dagger S + h.c.)$$
$$+ \frac{\lambda_{11S}}{2}(\Phi_1\Phi_1^\dagger)S^2 + \frac{\lambda_{22S}}{2}(\Phi_2\Phi_2^\dagger)S^2 + \frac{1}{2}(\lambda_{12S}\Phi_1\Phi_2^\dagger S^2 + h.c.)$$

Conventional 2HDM Potential

$$V(\Phi_1, \Phi_2, S/P) = V_{2HDM}(\Phi_1, \Phi_2) + V_{self}(S/P) + V_{S/P,2HDM}(\Phi_1, \Phi_2, S/P)$$

Self Interaction lagrangian

$$V_P(P) = \frac{1}{2}M_{PP}^2 P^2 + \frac{1}{4}\lambda_P P^4$$

Singlet Doublet Interaction Lagrangian

$$V_{P,2HDM}(P) = \frac{\lambda_{11P}}{2}(\Phi_1\Phi_1^\dagger)P^2 + \frac{\lambda_{22P}}{2}(\Phi_2\Phi_2^\dagger)P^2 + \mu_{12P}P(i\Phi_1^\dagger\Phi_2 + h.c.)$$

$$L_{Yukawa} = -\sum_{n=h,H} \left(Y_n^u Q_L u_R \widetilde{\Phi}_n + Y_n^d Q_L d_R \Phi_n + Y_n^l L_L e_R \Phi_n \right)$$

2HDM+s $\longrightarrow$ (Φ_1, Φ_2, S) $\longrightarrow$ $(h, S_1, S_2, A, H^{\pm})$

2HDM+a $\longrightarrow$ (Φ_1, Φ_2, P) $\longrightarrow$ $(h, a, H, A, H^{\pm})$

	Type I	Type II	Type-X/Lepton-specific	Type-Y/Flipped
g_{huu}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{hdd}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$
g_{hll}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{Huu}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Hdd}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$
g_{Hll}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Auu}	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$
g_{Add}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$-\frac{1}{\tan\beta}$	$\tan\beta$
g_{All}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$\tan\beta$	$-\frac{1}{\tan\beta}$

2HDM+S

$$Y_h^i = g_{hii} Y_{h,SM}^i$$

$$Y_{S_1}^i = g_{Hii} \cos\theta \, Y_{h,SM}^i$$

$$Y_{S_2}^i = -g_{Hii} \sin\theta \, Y_{h,SM}^i$$

$$Y_A^i = g_{Aii} Y_{h,SM}^i$$

2HDM+PS

$$Y_h^i = g_{hii} Y_{h,SM}^i$$

$$Y_H^i = g_{Hii} \cos\theta \, Y_{h,SM}^i$$

$$Y_A^i = g_{Aii} \cos\theta \, Y_{h,SM}^i$$

$$Y_a^i = -g_{Aii} \sin\theta \, Y_{h,SM}^i$$

95 GeV Excess

CMS Collaboration JHEP 07 (2023) 073
CMS Collaboration Phys. Lett. B793 (2019)
ATLAS Collaboration ATLAS-CONF-2023-035

$$\mu_{\tau\tau} = \frac{\sigma_\phi Br(\phi \to \tau\tau)}{\sigma_{\phi,SM} Br(\phi \to \tau\tau)_{SM}} = R_{gg} R_{\tau\tau} = \frac{\Gamma(\phi \to gg)}{\Gamma(\phi \to gg)_{SM}} \frac{\Gamma(\phi \to \tau\tau)}{\Gamma(\phi \to \tau\tau)_{SM}}$$

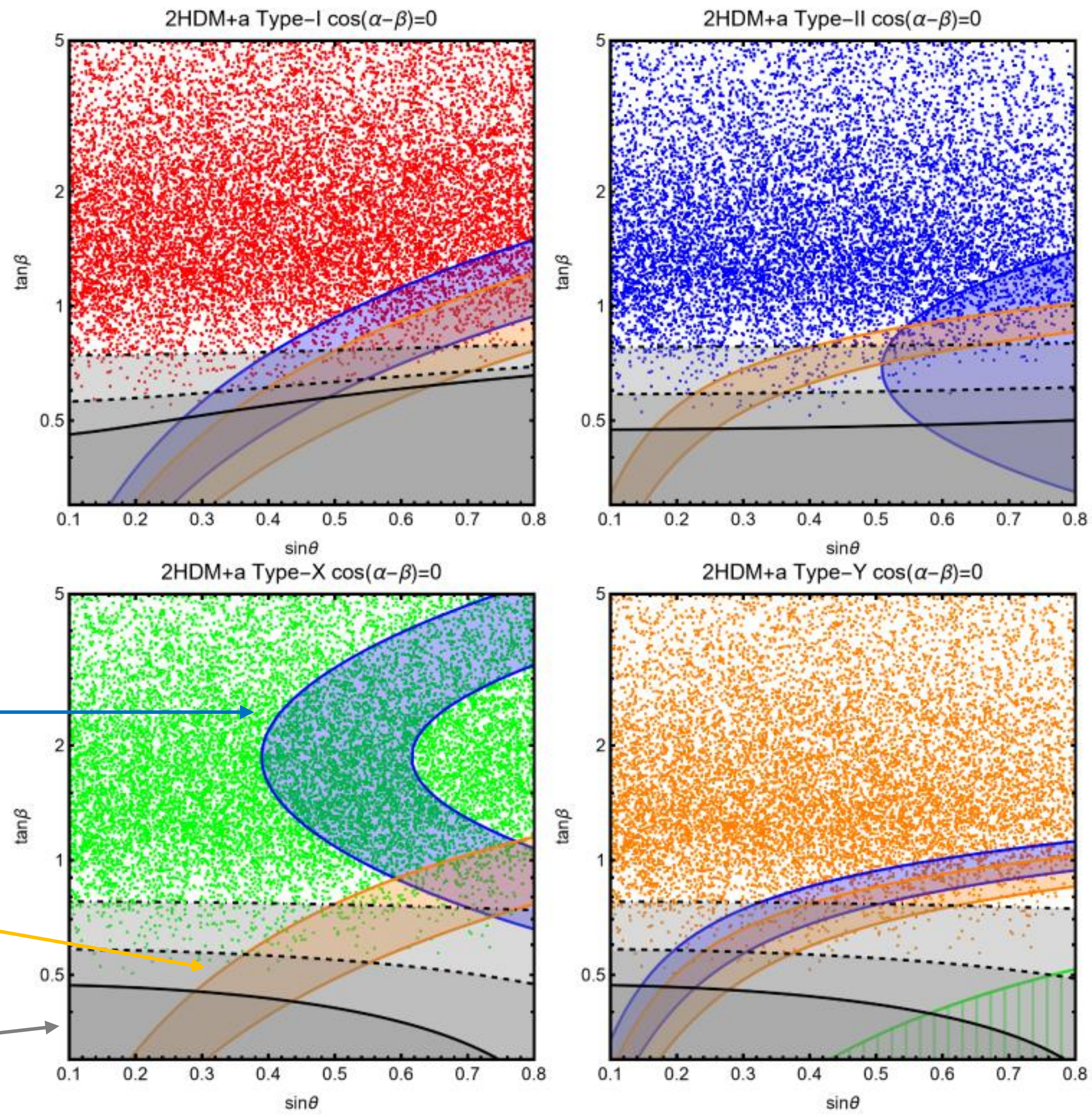
$$\mu_{\gamma\gamma} = \frac{\sigma_\phi Br(\phi \to \gamma\gamma)}{\sigma_{\phi,SM} Br(\phi \to \gamma\gamma)_{SM}} = \begin{cases} R_{gg} R_{\gamma\gamma} \dfrac{\sigma_{gg\phi,SM}}{\sigma_{\phi,SM}} \; (PS) \\ \dfrac{R_{gg}\sigma_{gg\phi,SM} + R_V \sigma_{V,BF} + R_{tt}\sigma_{tt\phi,SM}}{\sigma_{\phi,SM}} R_{\gamma\gamma} \; (S) \end{cases}$$

For our study we have used:

$$0.73 < \mu_{\tau\tau} < 1.83$$
$$0.17 < \mu_{\gamma\gamma} < 0.37$$

Interpretation within the 2HDM+a.

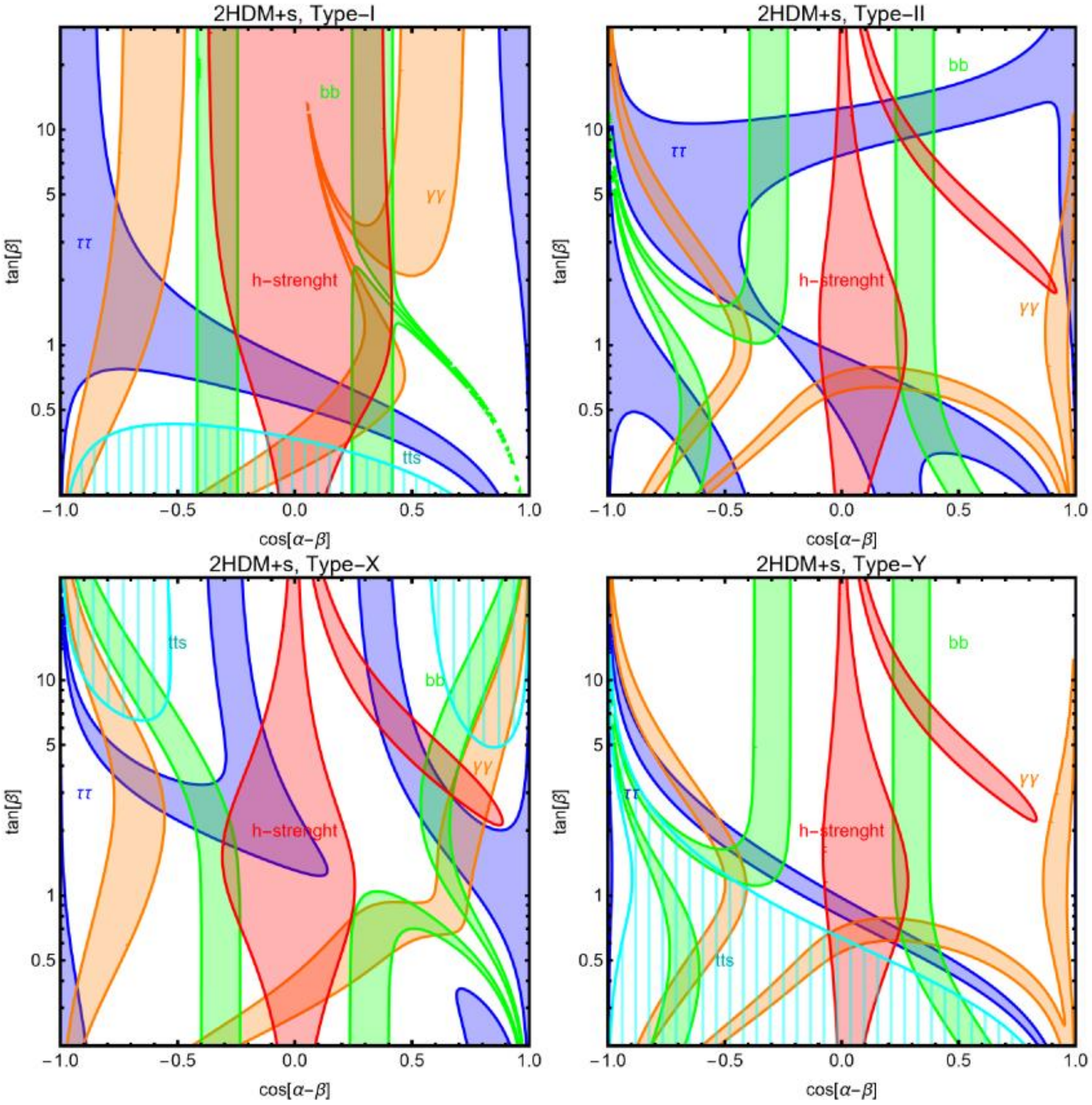
G.A., G. Busoni, D. Cabo-Almeida, N. Krishnan
arXiv:2311.14486

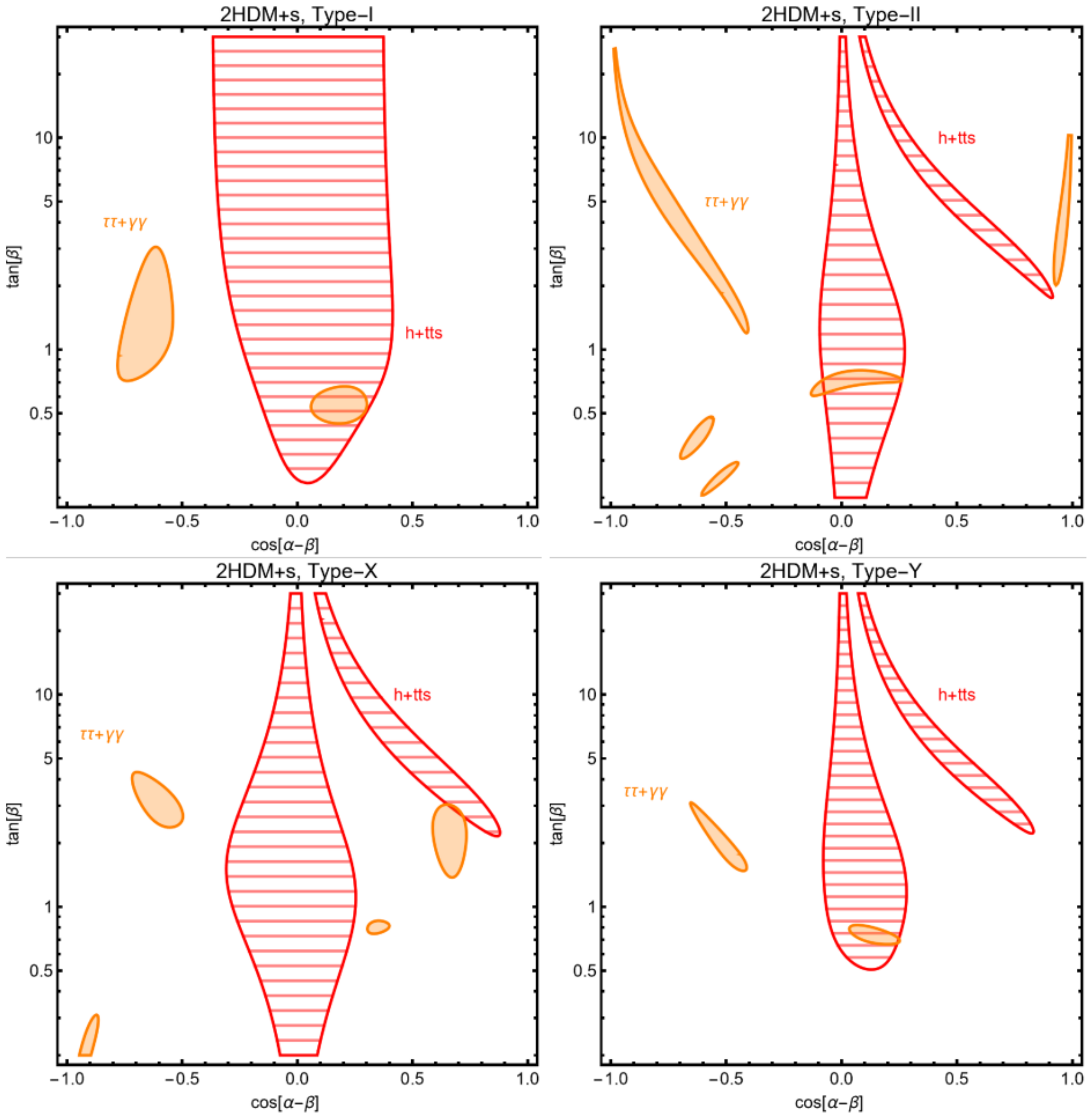


$pp \to a \to \tau\tau$

$pp \to a \to \gamma\gamma$

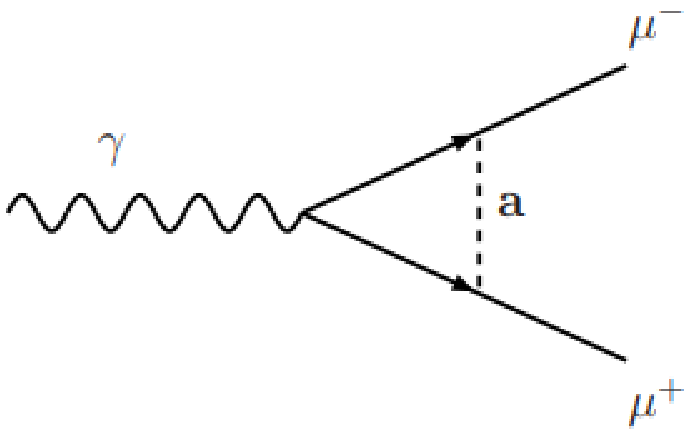
Excluded by Flavour


2HDM+s, Type-I
2HDM+s, Type-II
2HDM+s, Type-X
2HDM+s, Type-Y
tan[β]
cos[α−β]
ττ
bb
γγ
h-strenght
tts
10
5
1
0.5
−1.0
−0.5
0.0
0.5
1.0

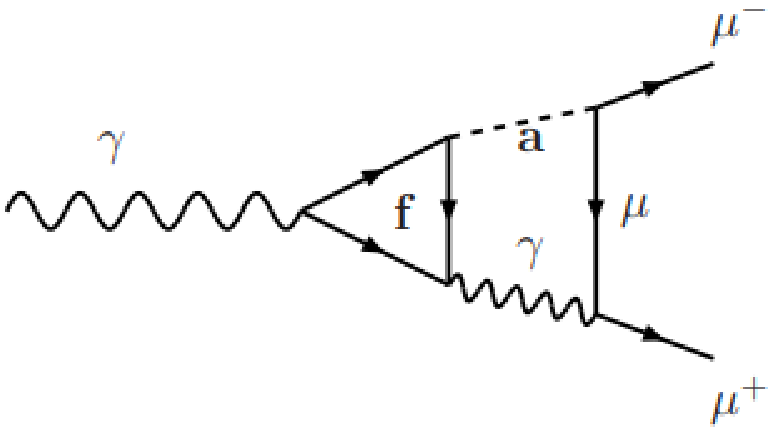


The best fit regions are not compatibile with the hint by LEP for $\bar{b}b$ signal.

Interpretation of g-2 in the 2HDM+PS



$$\Delta a_\mu^{1-loop} \approx -\frac{\alpha}{8\pi \sin^2\theta_W}\frac{m_\mu^4}{M_W^2 M_a^2} g_{a\mu\mu}^2 \left[\log\left(\frac{M_a^2}{m_\mu^2}\right) - \frac{11}{6}\right]$$

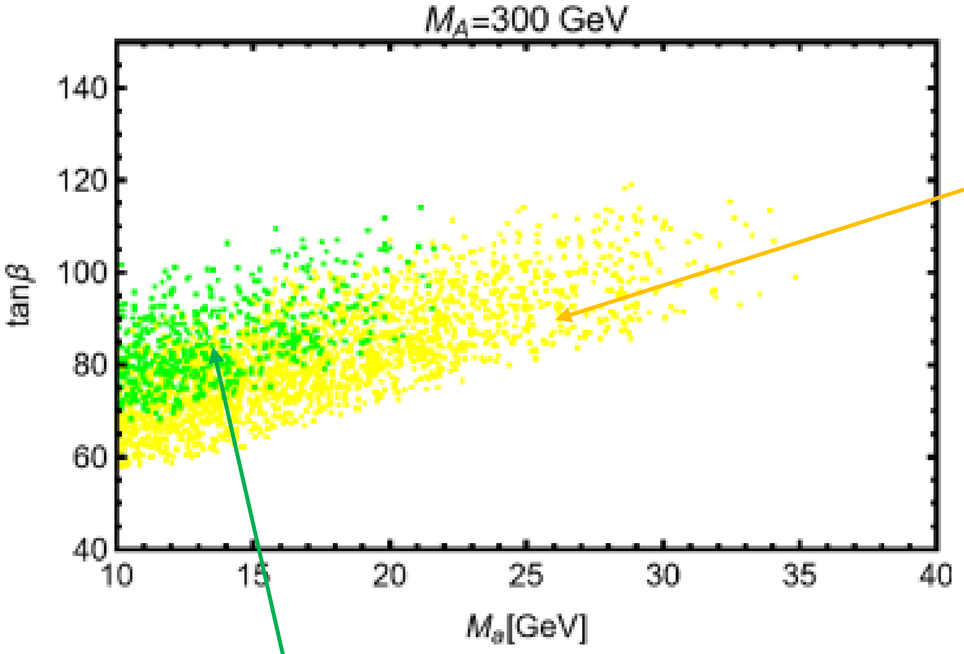


$$\Delta a_\mu^{2-loop} = \frac{\alpha^2}{8\pi^2 \sin^2\theta_W}\frac{m_\mu^2}{M_W^2} g_{a\mu\mu} \sum_f g_{aff} N_c^f Q_f \frac{m_f^2}{M_a^2} F\left(\frac{m_f^2}{M_a^2}\right)$$

$$F(r) = \int_0^1 dx \frac{\log(r) - \log[x(1-x)]}{r - x(1-r)}$$

To have a sizable Δa_μ we need $g_{a\mu\mu} \propto tan\beta$. We need to go for Type-II or Type-X configurations.

g-2 in the Type-X 2HDM+a

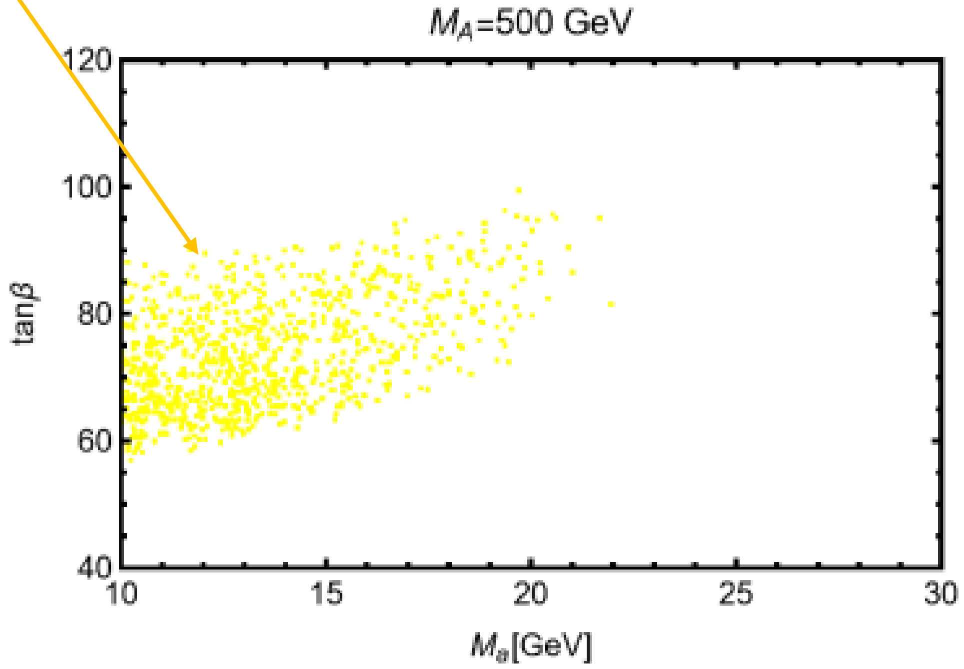


$\Delta a_\mu(2\,\sigma)$

$\Delta a_\mu(1\,\sigma)$

Viable parameter space limited by lepton universality in decays of Z-boson and τ lepton. (see next slides).

Abe et al. JHEP 07 (2015) 064
E. Jin Chun et al JHEP 07 (2016) 110



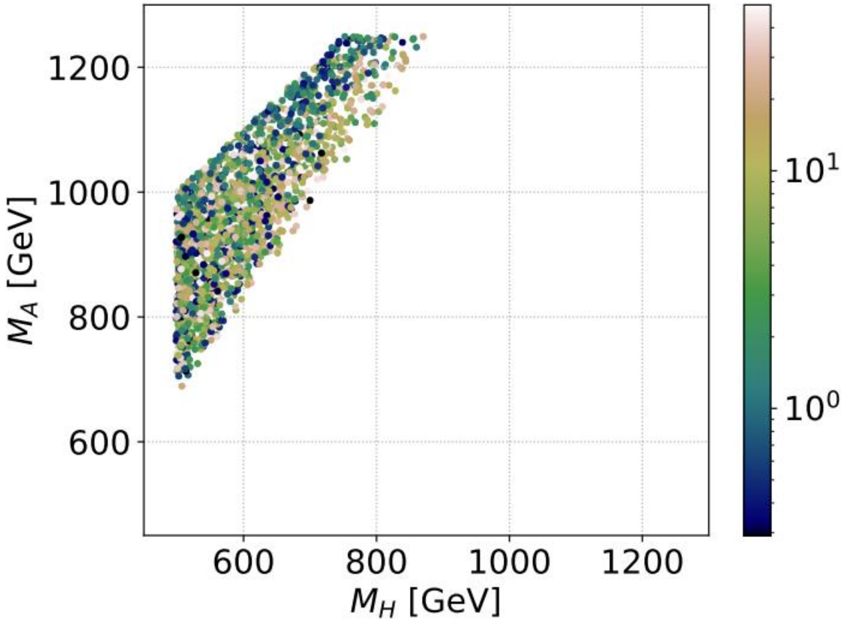
G.A. and A. Djouadi, *Phys.Rev.D* 106 (2022) 9, 095008

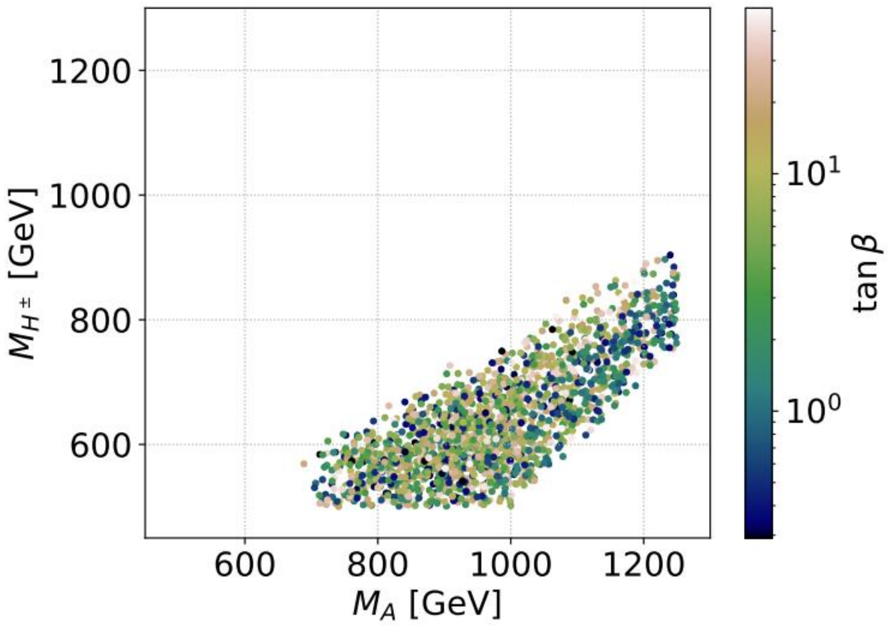
FOPT and GW in the 2HDM+a

One-loop thermal effective potential

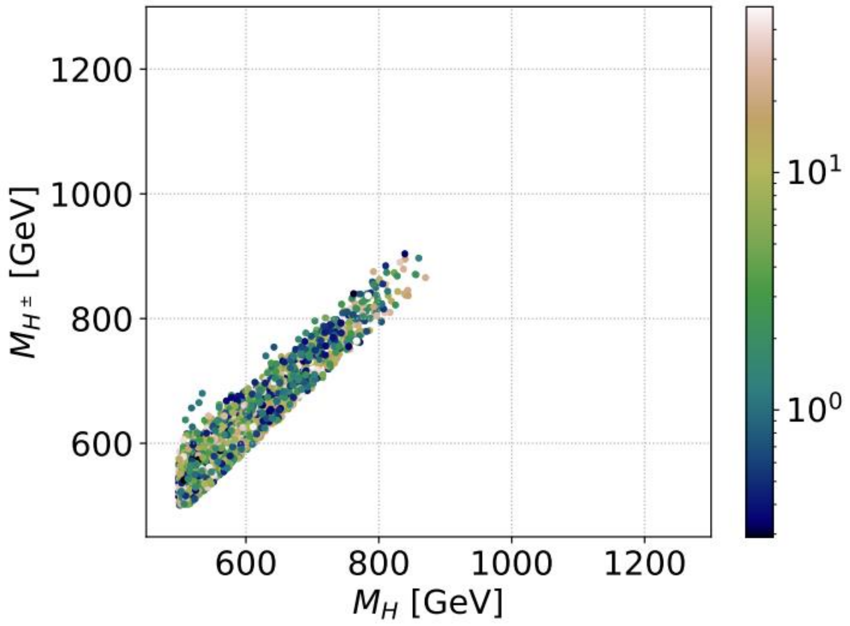
$$V_{eff}(h^0, H^0, T) = V_0 + V_{CW} + V_{CT} + V_T$$

- V_0 → Tree-level potential
- V_{CW} → One loop quantum corrections
- V_{CT} → Counterterms (to compensate the shift from V_{CW} to the vevs)
- V_T → Thermal corrections





Parameter space leading to FOPT



GW Signal

GW background is typically the (linear) combination of three kinds of contributions

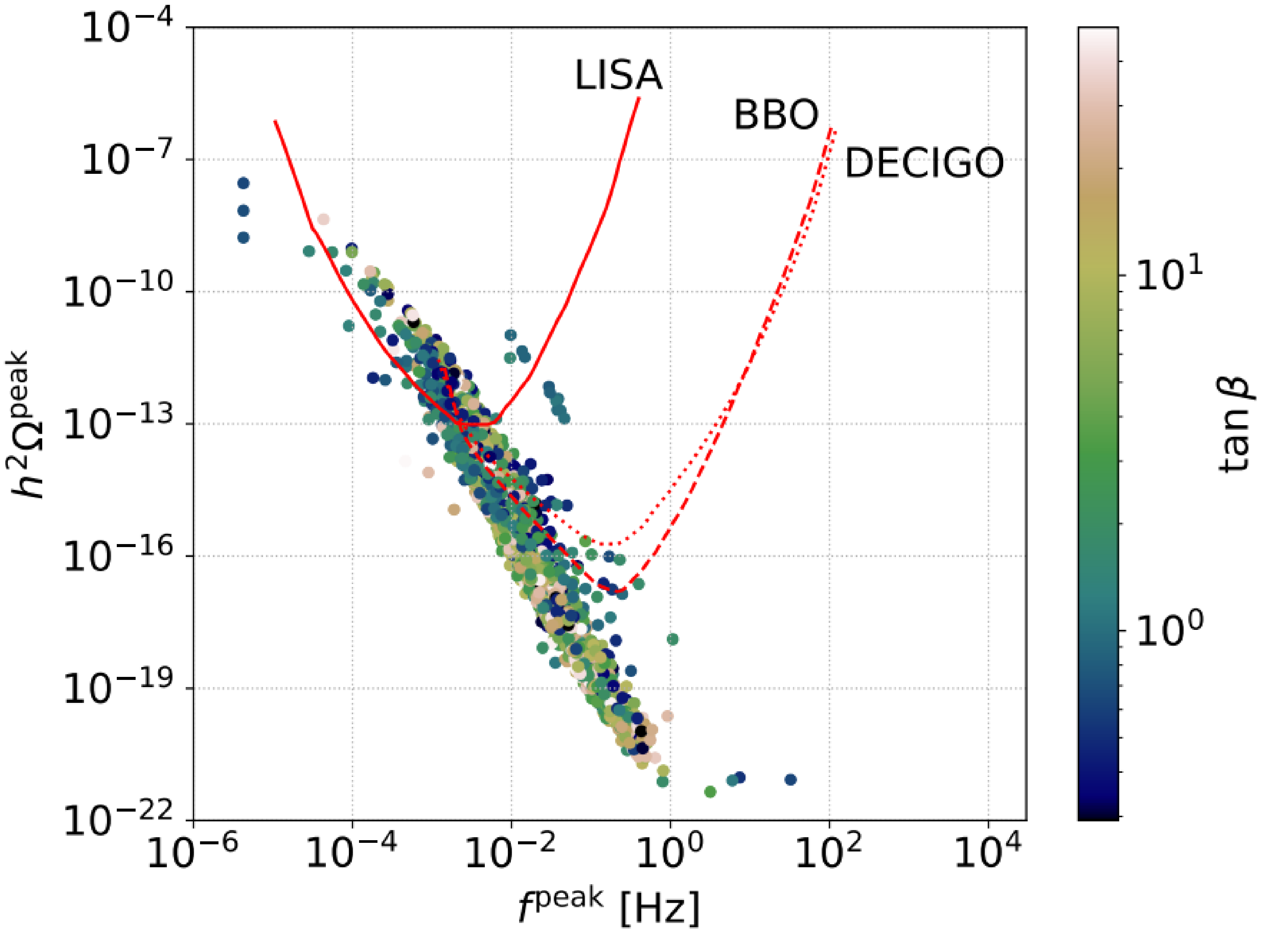
C. Caprini et al JCAP 04 (2016) 001

Contribution from sound wave overlap

$$h^2\Omega_{GW} \simeq h^2\Omega_{col} + h^2\Omega_{sw} + h^2\Omega_{turb}$$

Contribution from Magneto-Hydrodynamical (MHD) turbolence

Contribution from bubble collisions



G.A, N. Benincasa, A. Djouadi, K. Kannike, *Phys.Rev.D* 108 (2023) 5, 055010

Conclusions

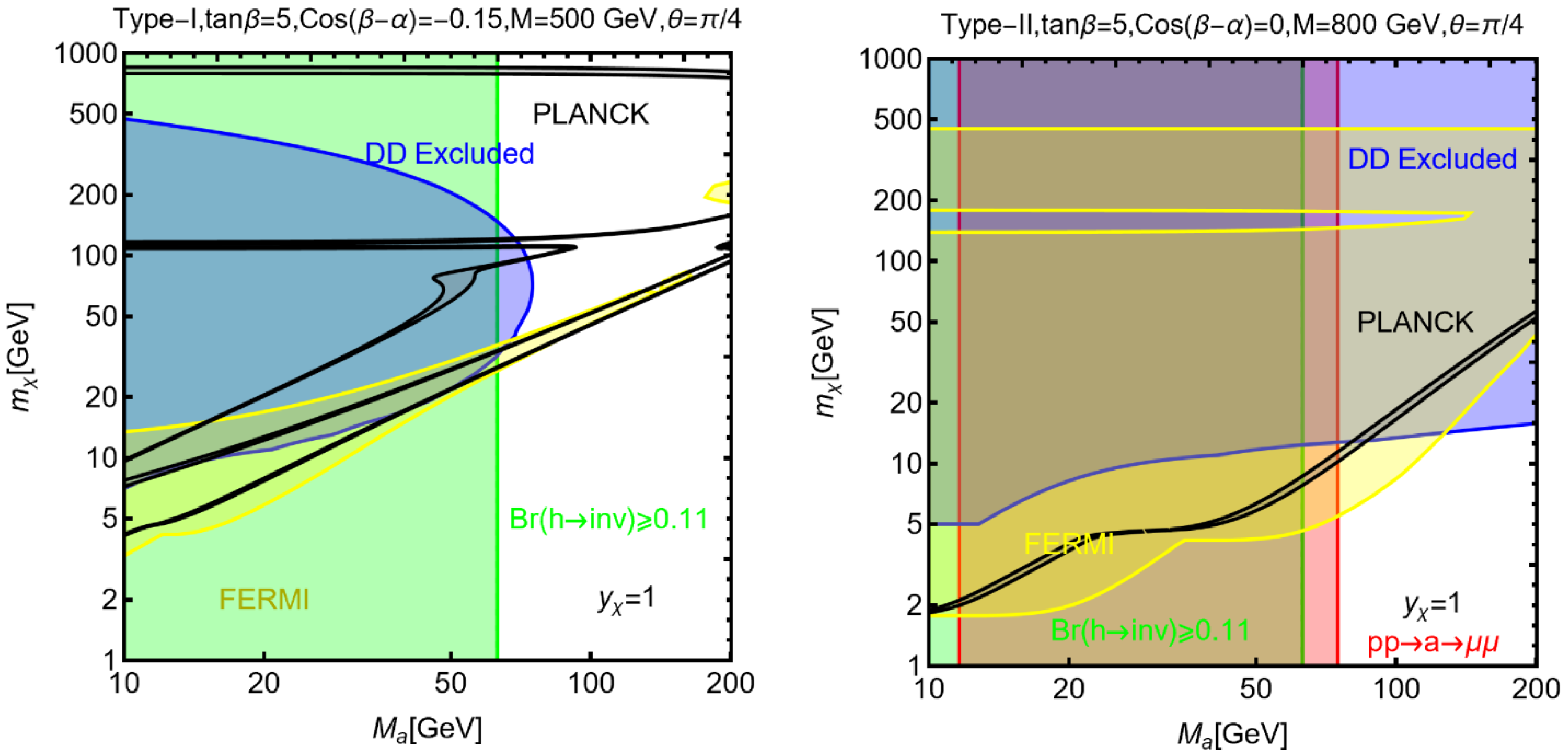
The 2HDM+s and 2HDM+a are very interesting BSM benchmarks which can be used to interpret very different experimental signals.

We have considered the capability of such models of interpreting the 95 GeV excess at LHC.

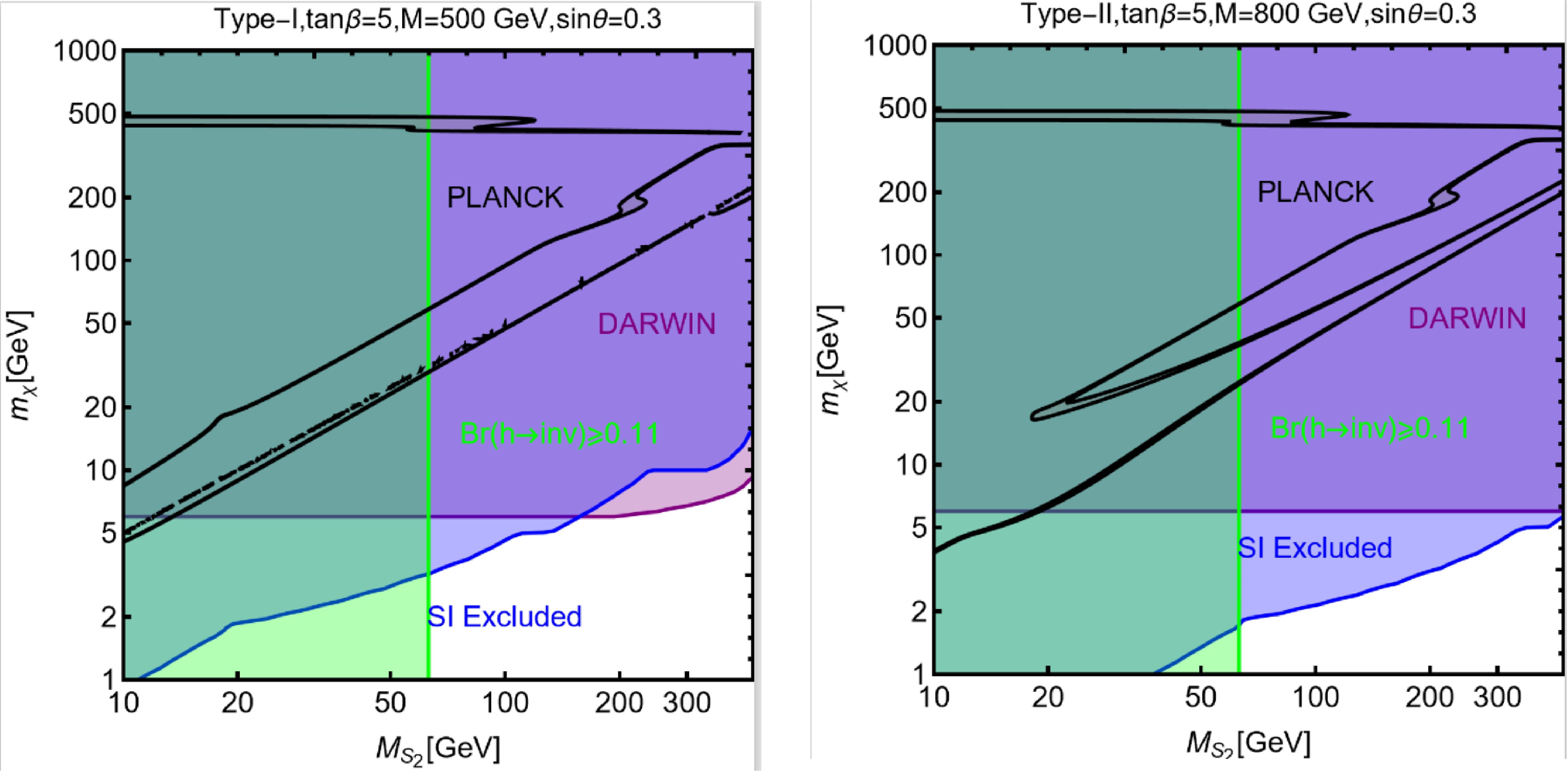
In the 2HDM+a we have shown the possibility of reproducing the g-2 signal as well as providing GW signals from FOPTs in the Early Universe.

Back up

DM in the 2HDM+a



DM in the 2HDM+s



Benchmark for g-2

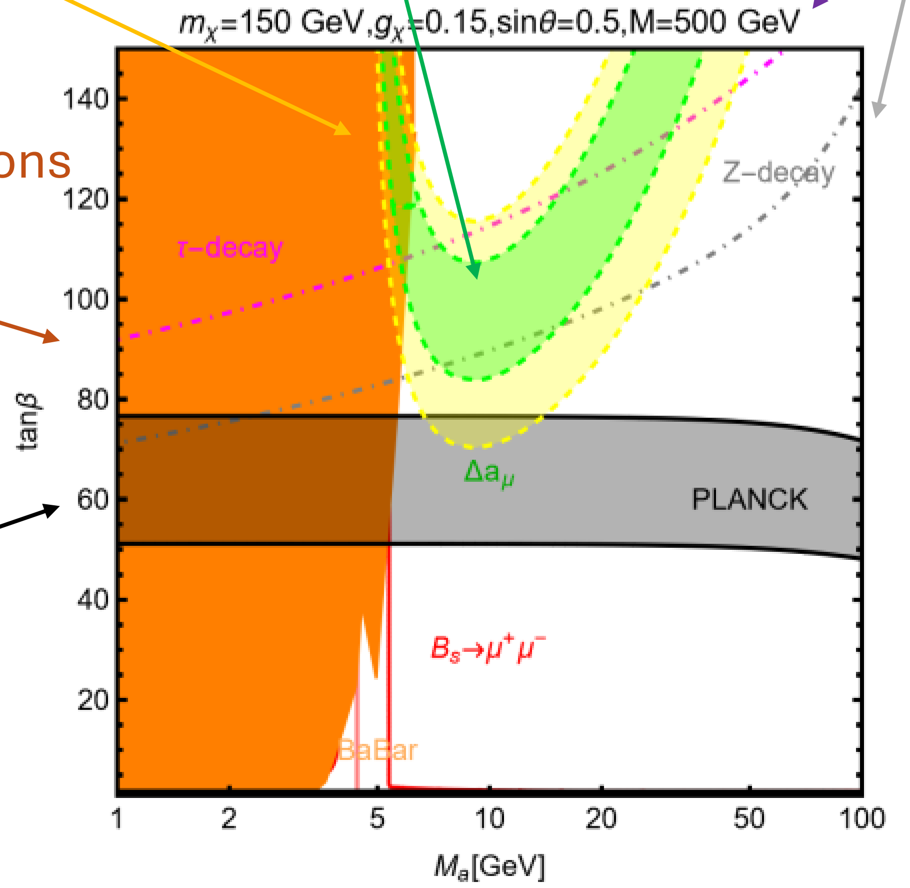
Δa_μ 2 σ

Δa_μ 1 σ

Bounds from lepton universality in Z and τ decays (exclusion above the lines)

Exclusion from searches of light leptophilic bosons

Correct relic density



G.A., A. Djouadi, F. S. Queiros

Phys.Lett.B 834 (2022) 137436

Parameter of the scalar potential fine-tuned to set $Br(h \to aa) \simeq 0$