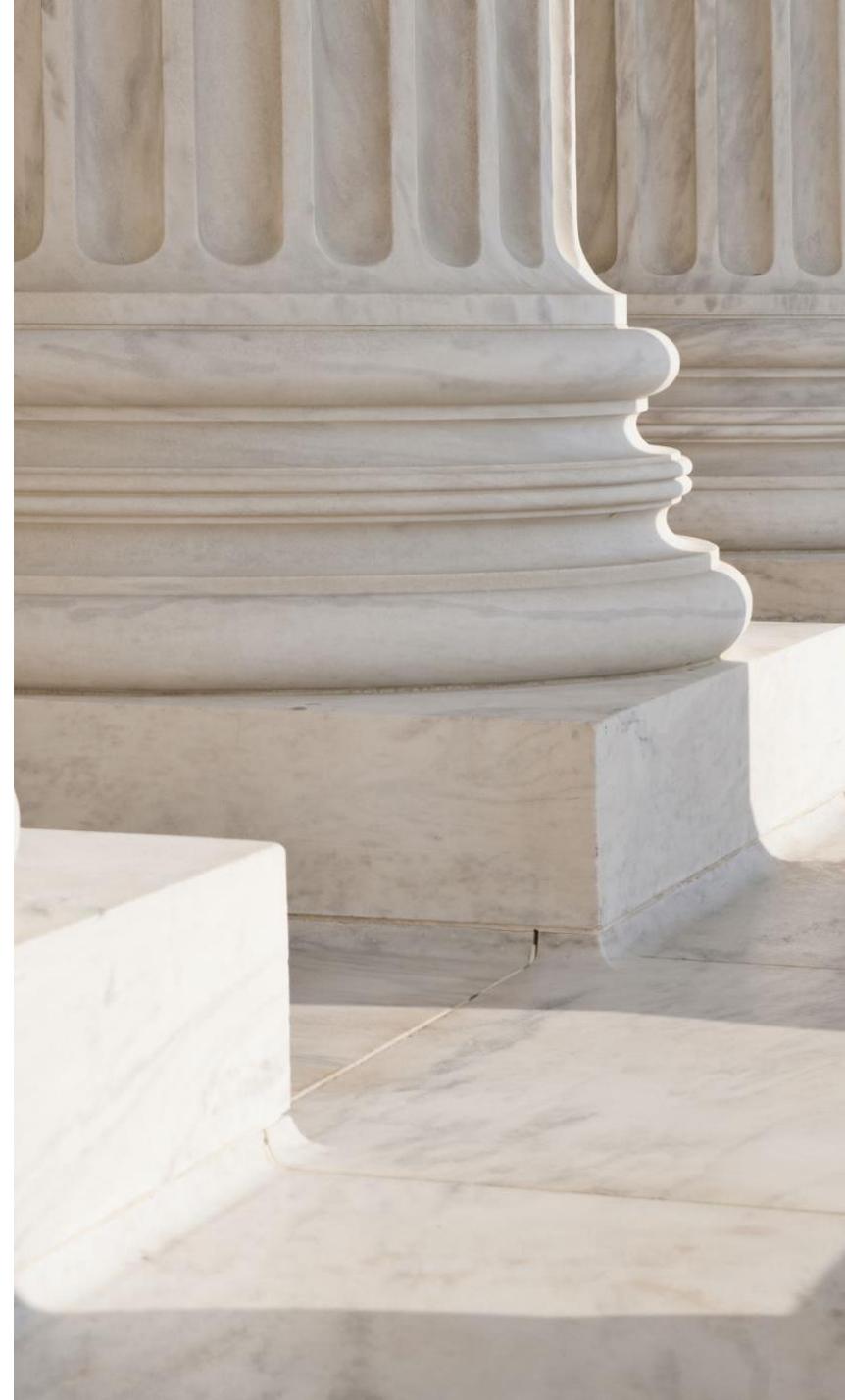


Phenomenology of the 2HDM+a

University of Messina

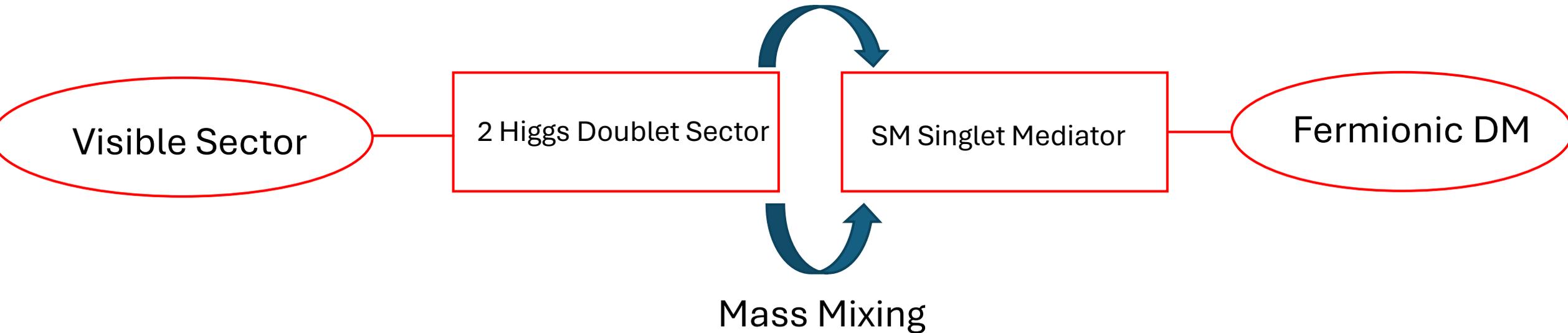
Giorgio Arcadi



2HDM+a belongs to the so called Next generation simplified models

LHC Dark Matter Working Group: Phys. Dark. Univ. 27 (2020) 100351

(see also e.g. M. Bauer et al. *JHEP* 05 (2017) 138, T. Robens *Symmetry* 13 (2021) 12, 2341)



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).

Conventional (Z_2 symmetric) 2HDM Potential

$$V_{2HDM} = m_1^2 \phi_1^\dagger \phi_1 + m_2^2 m_1^2 \phi_2^\dagger \phi_2 - m_3^2 (\phi_1^\dagger \phi_2 + h.c.) + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \frac{1}{2} \lambda_5 \left((\phi_1^\dagger \phi_2)^2 + h.c. \right) \\ + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1)$$

$$V(\Phi_1, \Phi_2, a_0) = V_{2HDM}(\phi_1, \phi_2) + V_{self}(a_0) + V_{a_0, 2HDM}(\phi_1, \phi_2, a_0)$$

Self Interaction Lagrangian

$$V_{self}(a_0) = \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{1}{4} \lambda_a a_0^4$$

Singlet Doublet Interaction Lagrangian

$$V_{a_0, 2HDM}(\phi_1, \phi_2, a_0) = \kappa (i a_0 \phi_1^\dagger \phi_2 + h.c.) + \lambda_{1P} a_0^2 \phi_1^\dagger \phi_1 + \lambda_{2P} a_0^2 \phi_2^\dagger \phi_2$$

EW Symmetry Breaking

$$\langle \phi_1 \rangle = v_1$$

$$\langle \phi_2 \rangle = v_2$$

$$\frac{v_2}{v_1} = \tan \beta$$

$$(\phi_1, \phi_2, a_0) \longrightarrow (h, a, H, A, H^\pm)$$

Mixing between pseudoscalar states

$$\begin{pmatrix} A^0 \\ a^0 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix} \quad L_{Yuk} = \sum_f \frac{m_f}{v} [g_{hff} h \bar{f} f + g_{Hff} H \bar{f} f - i g_{aff} a \bar{f} \gamma_5 f - i g_{Aff} A \bar{f} \gamma_5 f]$$

$$g_{hff} = 1 \quad g_{Aff} = \cos \theta g_{A^0 ff}$$

$$g_{aff} = \sin \theta g_{A^0 ff}$$

	Type I	Type II	Type X	Type Y
g_{htt}	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$			
g_{hbb}	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$	$-\frac{\sin \alpha}{\cos \beta} \rightarrow 1$	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$	$-\frac{\sin \alpha}{\cos \beta} \rightarrow 1$
$g_{h\tau\tau}$	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$	$-\frac{\sin \alpha}{\cos \beta} \rightarrow 1$	$-\frac{\sin \alpha}{\cos \beta} \rightarrow 1$	$\frac{\cos \alpha}{\sin \beta} \rightarrow 1$
g_{Htt}	$\frac{\sin \alpha}{\sin \beta} \rightarrow -\frac{1}{\tan \beta}$			
g_{Hbb}	$\frac{\sin \alpha}{\sin \beta} \rightarrow -\frac{1}{\tan \beta}$	$\frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta$	$\frac{\sin \alpha}{\sin \beta} \rightarrow -\frac{1}{\tan \beta}$	$\frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta$
$g_{H\tau\tau}$	$\frac{\sin \alpha}{\sin \beta} \rightarrow -\frac{1}{\tan \beta}$	$\frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta$	$\frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta$	$\frac{\sin \alpha}{\sin \beta} \rightarrow -\frac{1}{\tan \beta}$
$g_{A^0 tt}$	$\frac{1}{\tan \beta}$	$\frac{1}{\tan \beta}$	$\frac{1}{\tan \beta}$	$\frac{1}{\tan \beta}$
$g_{A^0 bb}$	$-\frac{1}{\tan \beta}$	$\tan \beta$	$-\frac{1}{\tan \beta}$	$\tan \beta$
$g_{A^0 \tau\tau}$	$-\frac{1}{\tan \beta}$	$\tan \beta$	$\tan \beta$	$-\frac{1}{\tan \beta}$

95 GeV Excess

CMS Collaboration JHEP 07 (2023) 073

CMS Collaboration Phys. Lett. B793 (2019)

ATLAS Collaboration ATLAS-CONF-2023-035

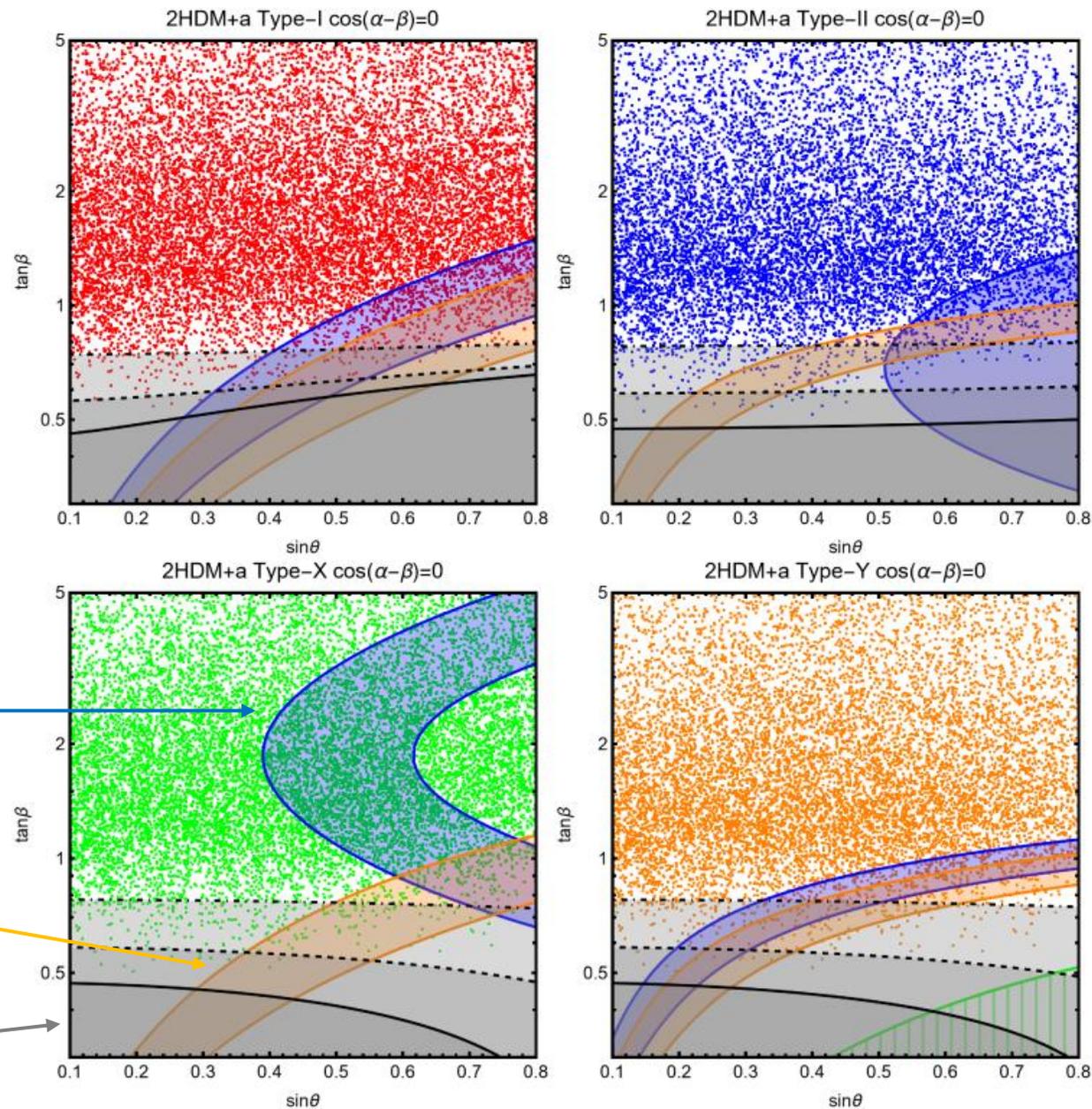
$$\mu_{\tau\tau} = \frac{\sigma_{\phi} Br(\phi \rightarrow \tau\tau)}{\sigma_{\phi,SM} Br(\phi \rightarrow \tau\tau)_{SM}} = R_{gg} R_{\tau\tau} = \frac{\Gamma(\phi \rightarrow gg)}{\Gamma(\phi \rightarrow gg)_{SM}} \frac{\Gamma(\phi \rightarrow \tau\tau)}{\Gamma(\phi \rightarrow \tau\tau)_{SM}}$$

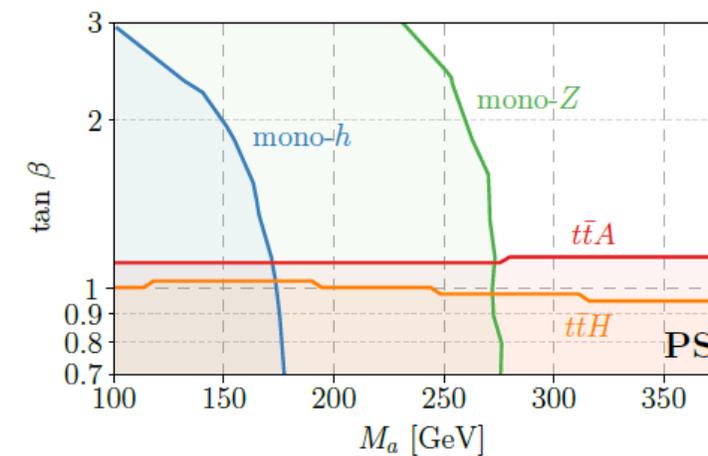
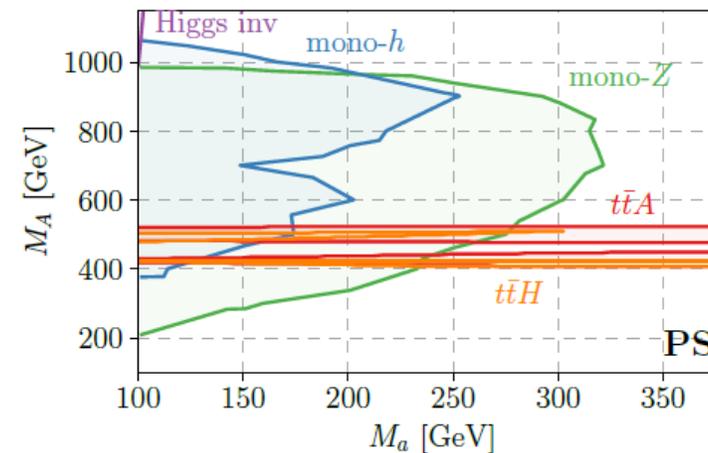
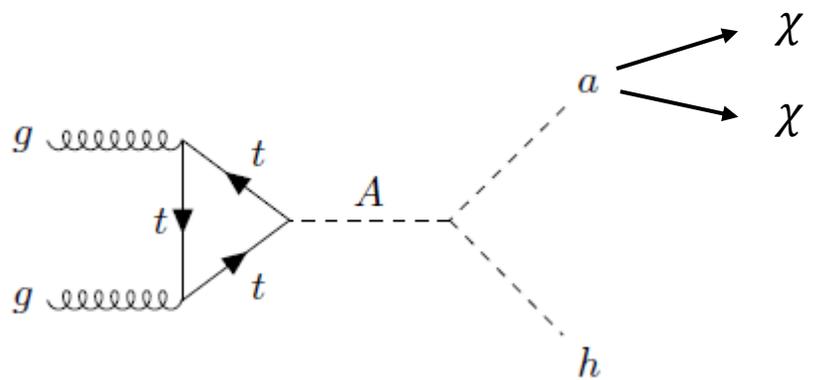
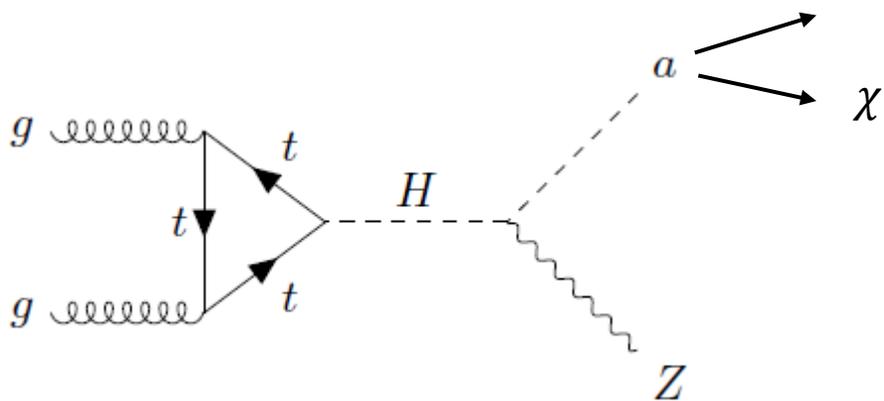
$$\mu_{\gamma\gamma} = \frac{\sigma_{\phi} Br(\phi \rightarrow \gamma\gamma)}{\sigma_{\phi,SM} Br(\phi \rightarrow \gamma\gamma)_{SM}} = R_{gg} R_{\gamma\gamma} \frac{\sigma_{gg\phi,SM}}{\sigma_{\phi,SM}}$$

For our study we have used:

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

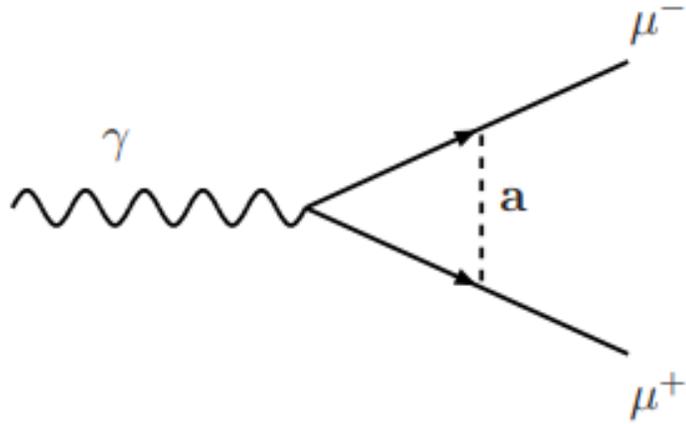
G.A., G. Busoni, D. Cabo-Almeida, N. Krishnan
arXiv:2311.14486



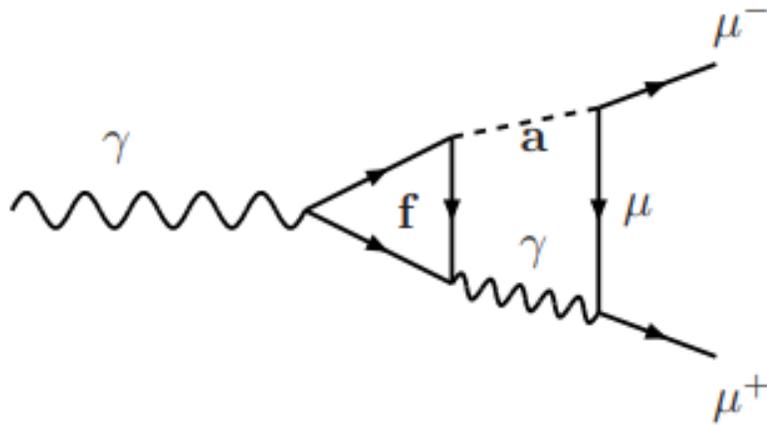


G. A., G. Busoni, T. Hugle and V. Tenorth; JHEP 06 (2020) 098

Connection with g-2



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

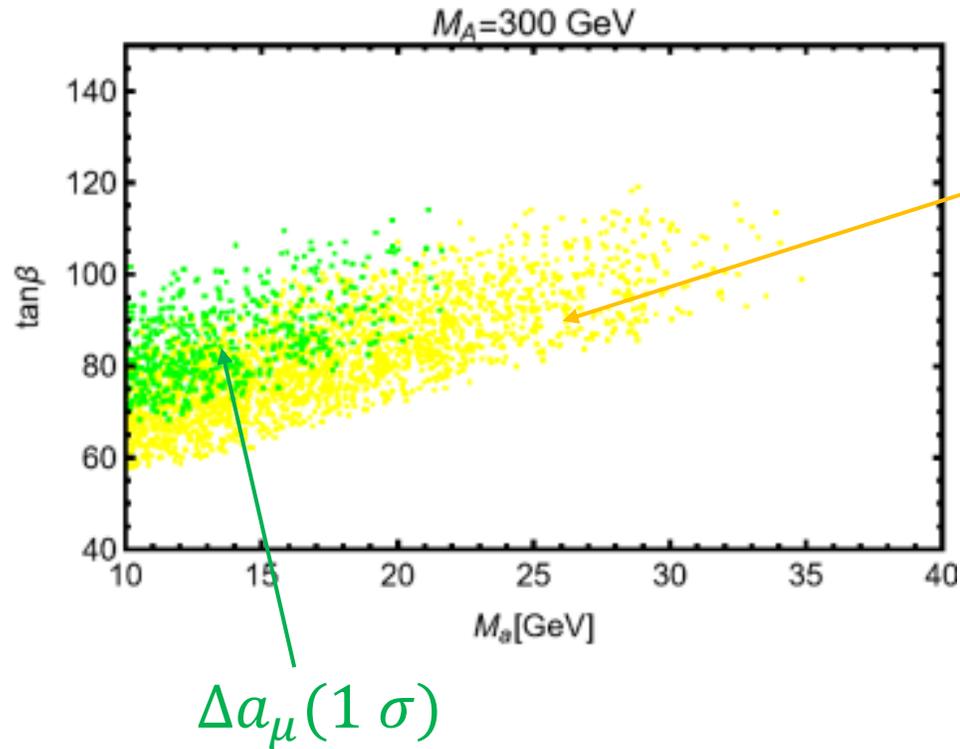


$$\Delta a_\mu^{2-loop} = \frac{\alpha^2}{8\pi^2 \sin^2 \theta_W} \frac{m_\mu^2}{M_W^2} g_{a\mu\mu} \sum_f g_{aff} N_c^f Q_f \frac{m_f^2}{M_a^2} F\left(\frac{m_f^2}{M_a^2}\right)$$

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

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.

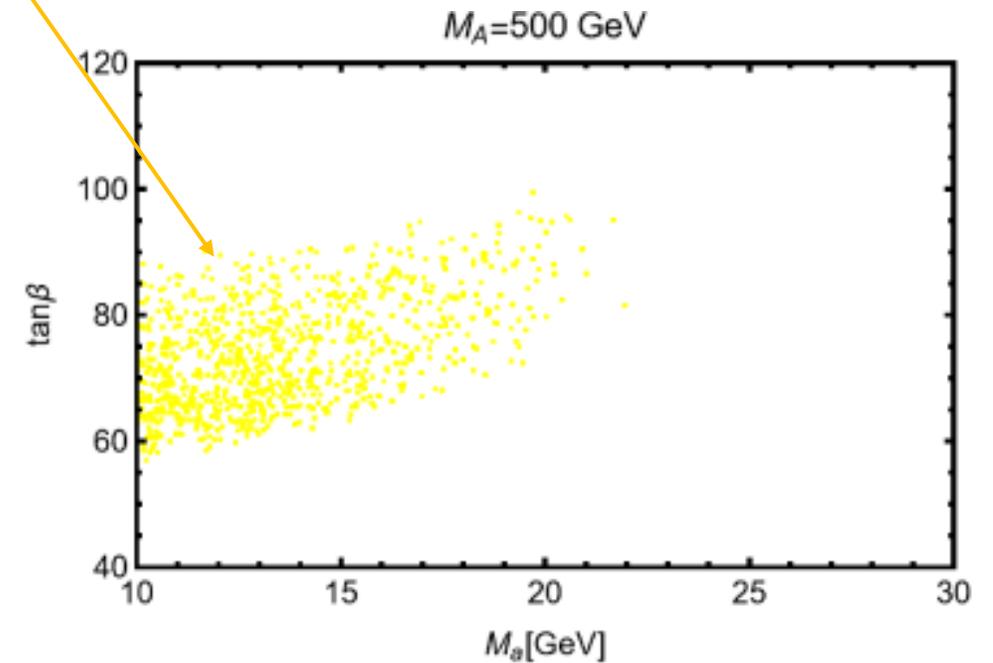
g-2 in the Type-X 2HDM+a



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

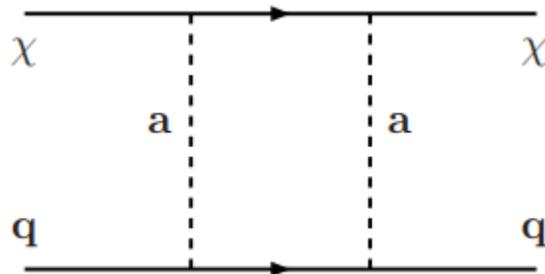
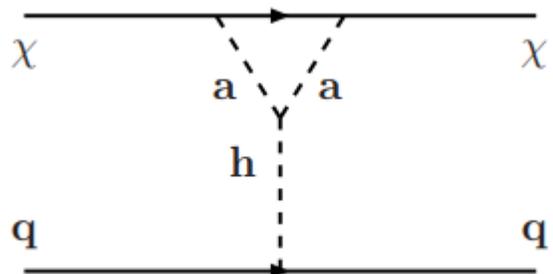
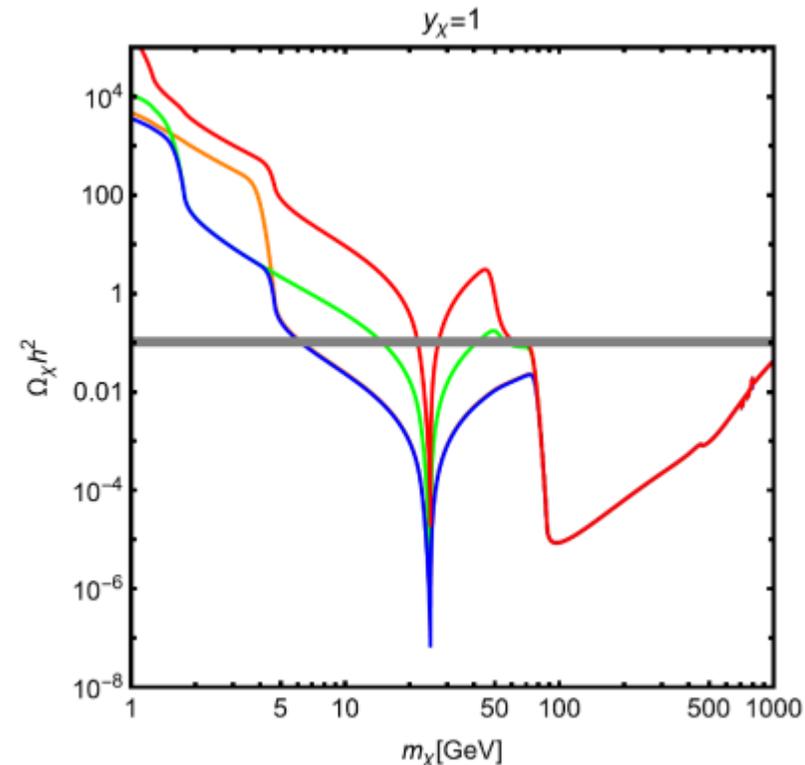
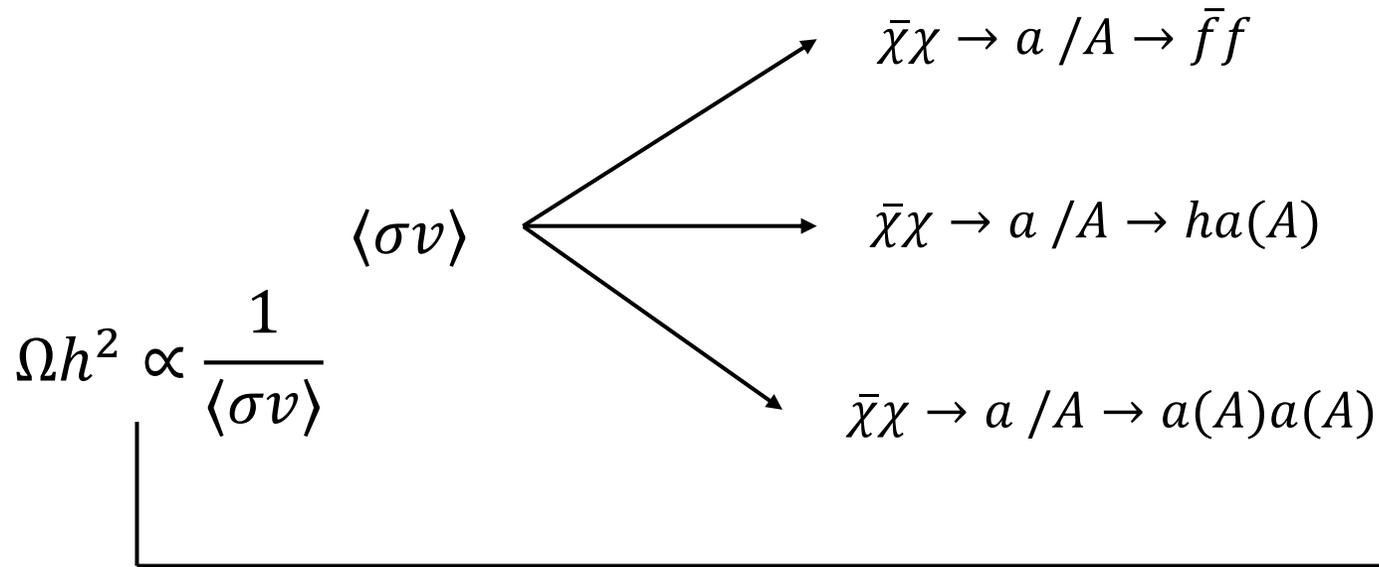
E. Jin Chun et al JHEP 07 (2016) 110



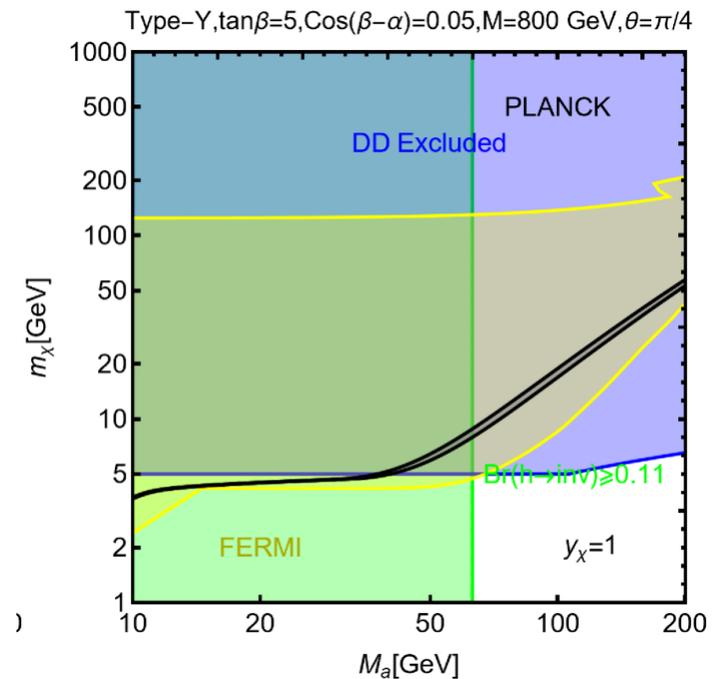
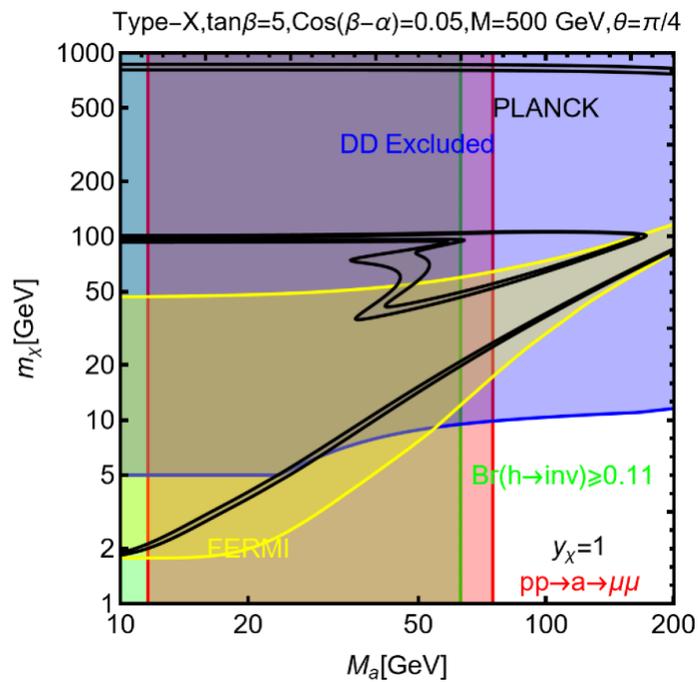
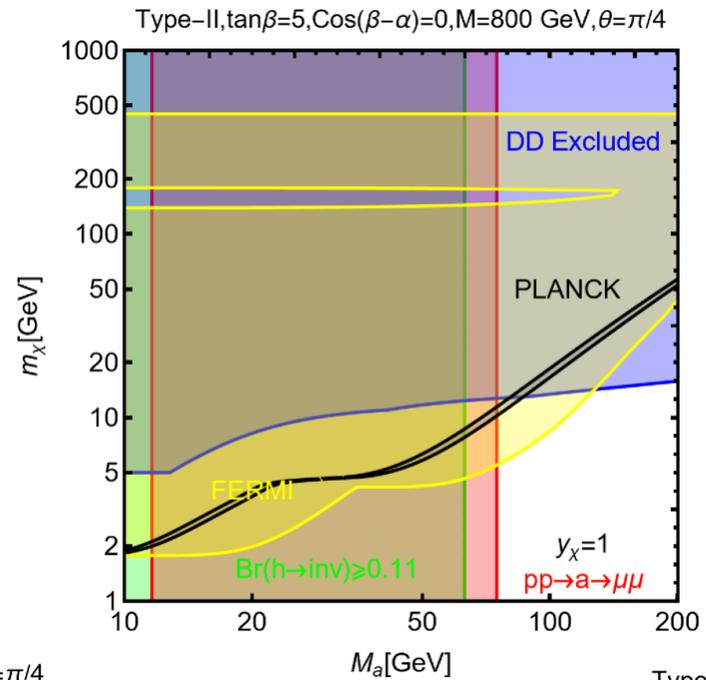
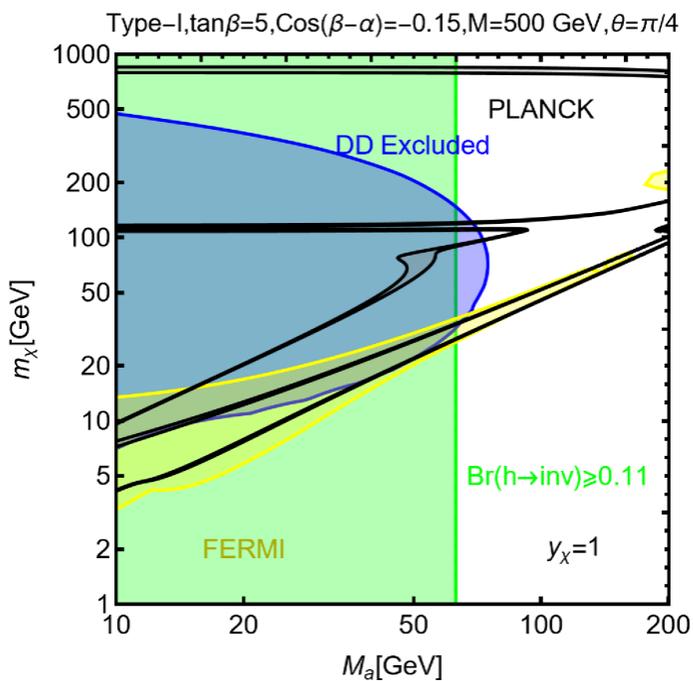
G.A. and A. Djouadi, *Phys.Rev.D* 106 (2022) 9, 095008

DM Phenomenology

$$L_{DM} = iy_\chi \bar{\chi} \gamma_5 \chi a_0 \longrightarrow iy_\chi (a \cos \theta + A \sin \theta) \bar{\chi} \gamma_5 \chi$$



← Induced at one-loop



Benchmark for g-2

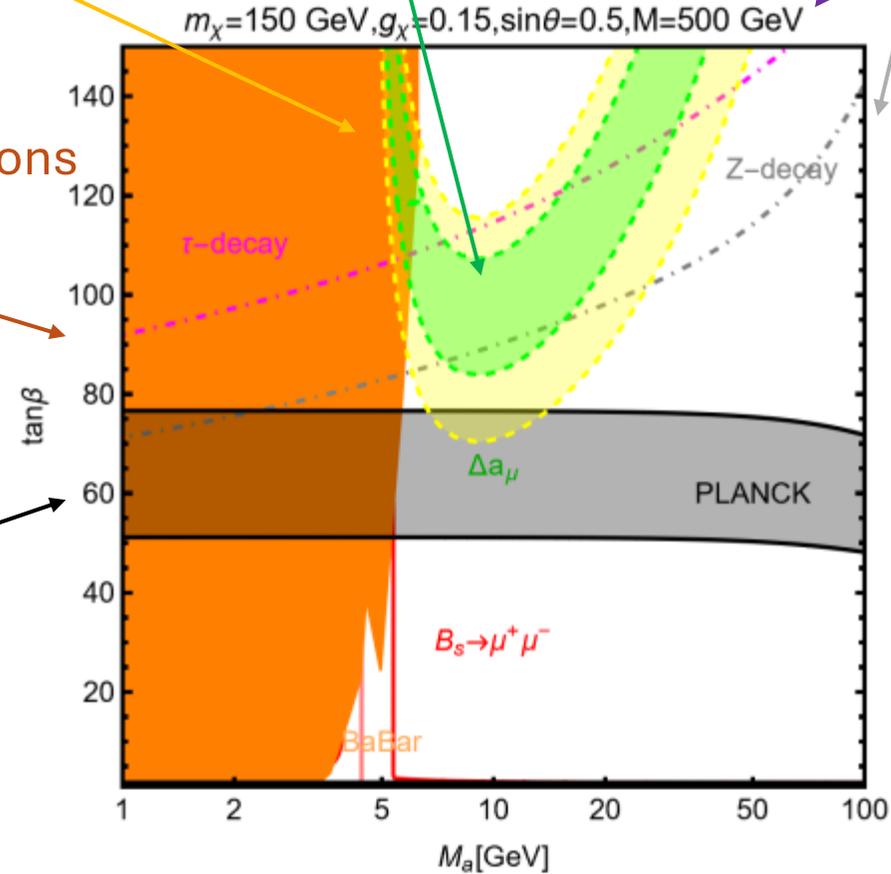
Bounds from lepton universality in Z and τ decays (exclusion above the lines)

Δa_μ 2 σ

Δa_μ 1 σ

Exclusion from searches of light leptophilic bosons

Correct relic density



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

Phys.Lett.B 834 (20
22) 137436

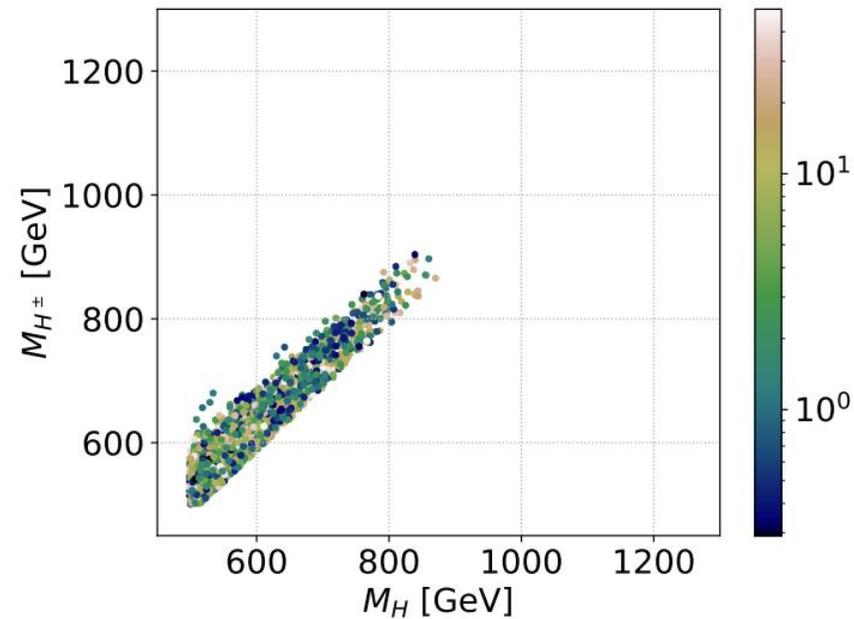
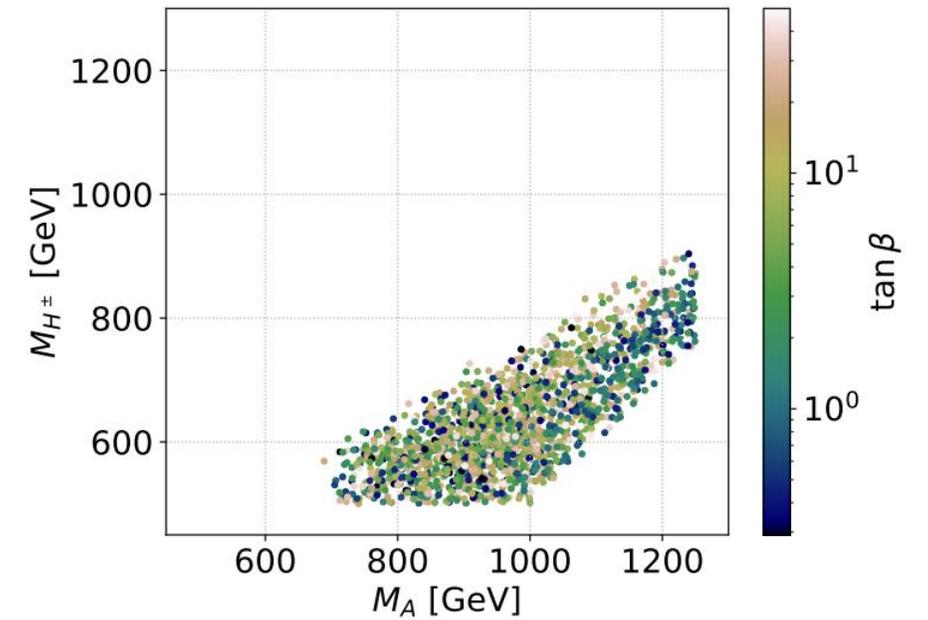
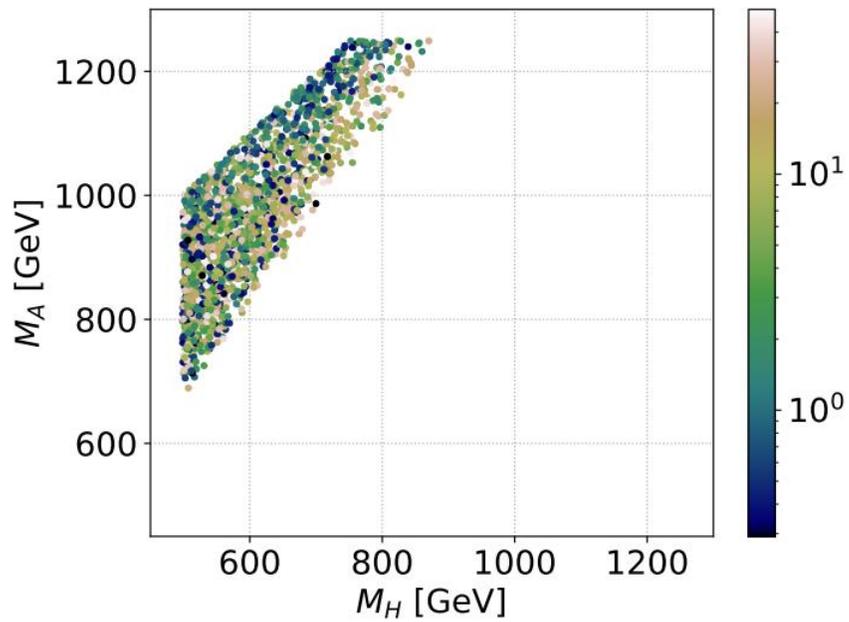
Parameter of the scalar potential fine-tuned to set $Br(h \rightarrow aa) \simeq 0$

One-loop thermal effective potential

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

The diagram illustrates the decomposition of the one-loop thermal effective potential into four terms, each with a color-coded arrow pointing to its description:

- Tree-level potential** (red arrow pointing to V_0)
- One loop quantum corrections** (blue arrow pointing to V_{CW})
- Counterterms (to compensate the shift from V_{CW} to the vevs)** (green arrow pointing to V_{CT})
- Thermal corrections** (yellow arrow pointing to V_T)



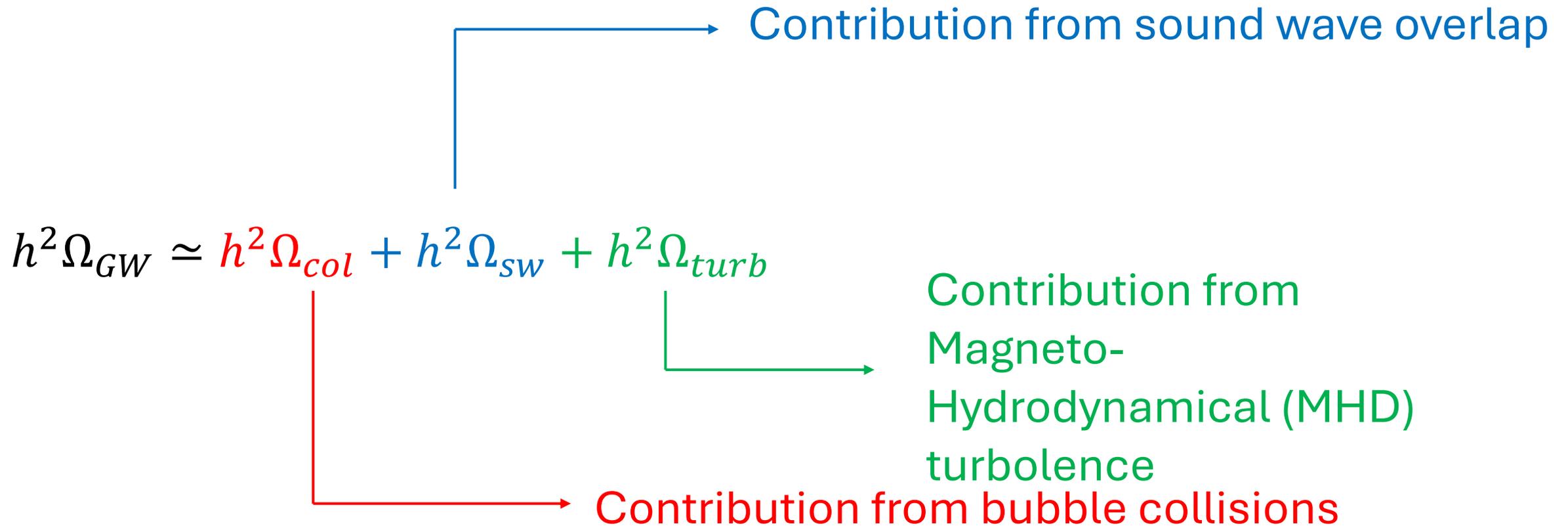
Parameter space
leading to FOPT

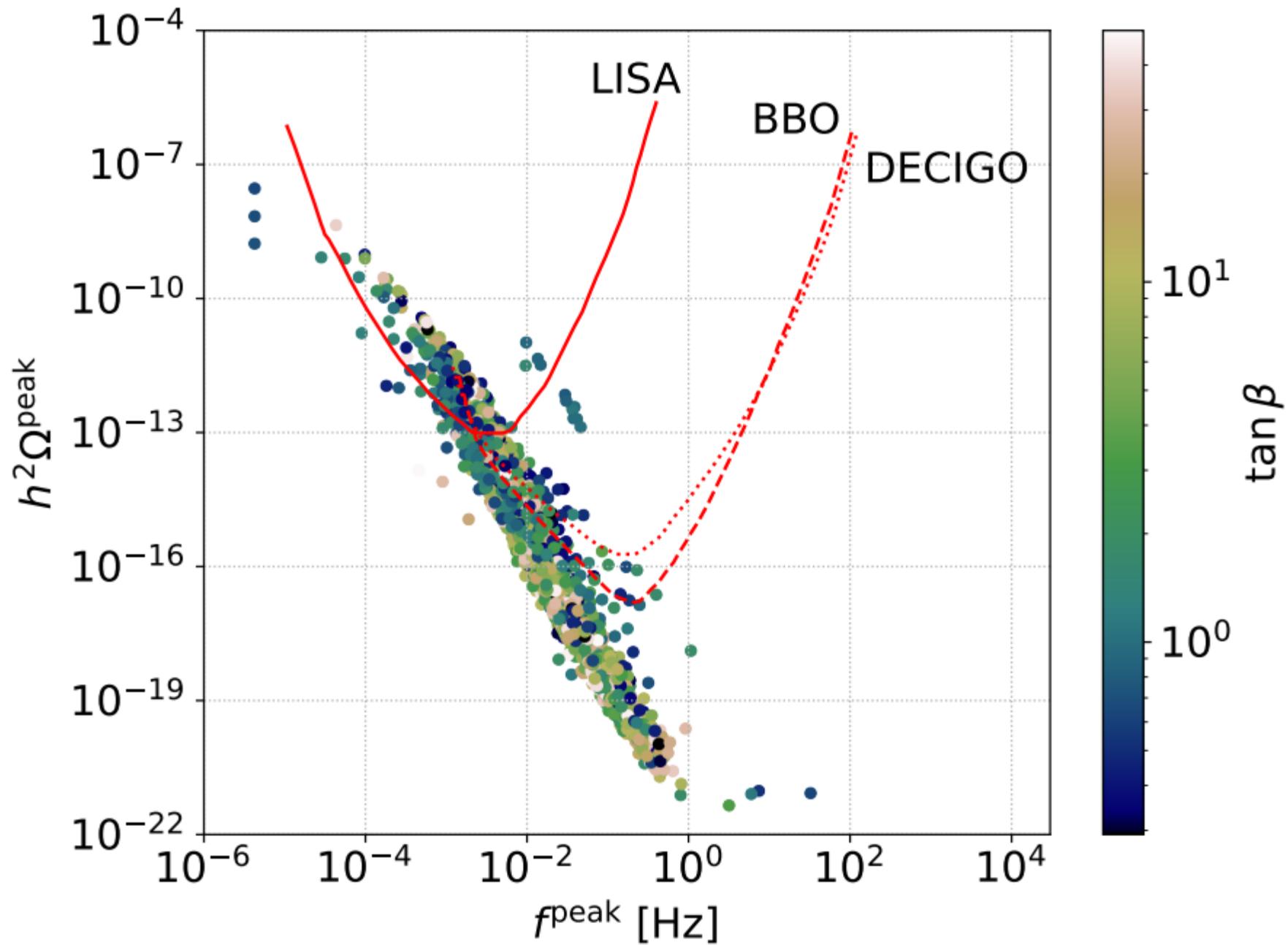
For reference the plot refers to Type-I.
No substantial differences for the other
Yukawa configurations though.

GW Signal

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

C. Caprini et al JCAP 04 (2016) 001





Conclusions

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

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

We have shown the possibility of reproducing the $g-2$ signal.

We have explored the possibility of GW signals from FOPTs in the Early Universe.

Connections with DM have been considered.