W-mass and g-2 anomaly in the 2HDM+a

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Based on

G.A., A. Djoaudi, F.S. Queiros *Phys.Lett.B* 834 (2022) 137436

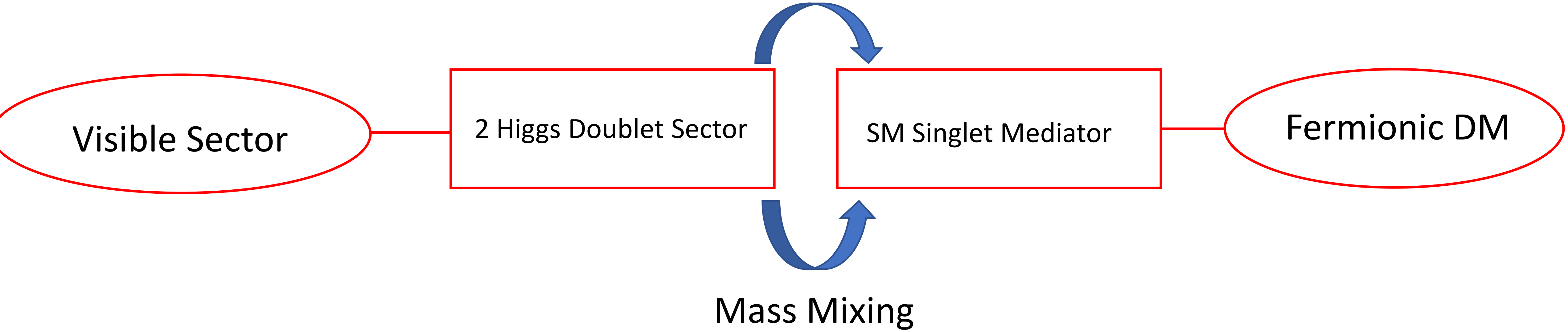
G.A., A. Djouadi *Phys.Rev.D* 106 (2022) 9, 095008

G.A., N. Benicasa, A. Djouadi, K. Kannike arXiv: 2212.14788

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;
Intersting Dark Matter phenomenology.

Purpose of the study

- Investigate the impact of the extended scalar sector on the EWPO, possibly accounting for the anomalous measure of the W-mass;

- Investigate the possibility of explaining the deviation of the anomalous magnetic moment of the muon (assuming it is due to New Physics) with respect to the SM;

- Retain interesting connection with Dark Matter;

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

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

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

$$\begin{pmatrix} A^0 \\ a^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}$$

$$\tan 2\theta = \frac{2\kappa v}{M_A^2 - M_a^2}$$

$$L_{Yuk} = \sum_f \frac{m_f}{v}\left[g_{hff} h\bar{f}f + g_{Hff} H\bar{f}f - i g_{aff} a\bar{f}\gamma_5 f - i g_{Aff} A\bar{f}\gamma_5 f\right]$$

$$g_{hff} = 1$$

$$g_{aff} = sin\theta\, g_{A^0 ff} \qquad g_{Aff} = cos\theta\, g_{A^0 ff}$$

	Type-I	Type-II	Type-X	Type-Y
g_{Huu}	$-1/tan\beta$	$-1/tan\beta$	$-1/tan\beta$	$-1/tan\beta$
g_{Hdd}	$-1/tan\beta$	$tan\beta$	$-1/tan\beta$	$\tan\beta$
g_{Hll}	$-1/tan\beta$	$tan\beta$	$tan\beta$	$-1/tan\beta$
g_{A^0uu}	$1/tan\beta$	$1/tan\beta$	$1/tan\beta$	$1/tan\beta$
g^0_{Add}	$1/tan\beta$	$-tan\beta$	$1/tan\beta$	$-tan\beta$
g^0_{All}	$1/tan\beta$	$-tan\beta$	$-tan\beta$	$1/tan\beta$

Theoretical Constraints

Perturbative unitarity

$$|\lambda_{1,2P}| \leq 4\pi \qquad |\lambda_3 \pm \lambda_4| \leq 4\pi \qquad \left|\frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_k^2}\right)\right| < 8\pi \;\; k = 4,5$$

$$|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| < 8\pi \qquad |\lambda_3 \pm \lambda_5| < 8\pi$$

Potential bounded from below

$$\lambda_{1,2,a} > 0 \qquad \bar{\lambda}_{12} \equiv \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \min(0, \lambda_4 - |\lambda_5|) > 0 \qquad \bar{\lambda}_{1,2P} \equiv \sqrt{\frac{\lambda_a \lambda_{1,2}}{2}} + \lambda_{1,2P} > 0$$

$$\sqrt{\frac{\lambda_1 \lambda_2 \lambda_a}{2}} + \lambda_{1P}\sqrt{\lambda_2} + \sqrt{\lambda_1}\lambda_{2P} + [\lambda_3 + \min(0, \lambda_4 - |\lambda_5|)]\sqrt{\frac{\lambda_a}{2}} + \sqrt{2\bar{\lambda}_{1P}\bar{\lambda}_{2P}\bar{\lambda}_{12}} > 0$$

$$\lambda_1 v^2 = -M^2 \tan^2\beta + \frac{\sin^2\alpha}{\cos^2\beta} M_h^2 + \frac{\cos^2\alpha}{\cos^2\beta} M_H^2$$

$$M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$$

$$\lambda_2 v^2 = -\frac{M^2}{\tan^2\beta} + \frac{\cos^2\alpha}{\sin^2\beta} M_h^2 + \frac{\sin^2\alpha}{\sin^2\beta} M_H^2$$

$$\lambda_3 v^2 = -M^2 + 2M_{H^\pm}^2 + \frac{\sin 2\alpha}{\sin 2\beta}\left(M_H^2 - M_h^2\right)$$

$$\lambda_4 v^2 = M^2 + M_A^2 \cos^2\theta + M_a^2 \sin^2\theta - 2\, M_{H^\pm}^2$$

$$\lambda_5 v^2 = M^2 - M_A^2 \cos^2\theta - M_a^2 \sin^2\theta$$

Set(s) of free parameters

$$\left(M_H, M_{H^\pm}, M_A, M_a, \sin\theta\,, \cos(\beta-\alpha), \tan\beta, \lambda_3, \lambda_{1P}, \lambda_{2P}\right)$$

or

$$\left(M_H, M_{H^\pm}, M_A, M_a, \sin\theta\,, \cos(\beta-\alpha), \tan\beta, M, \lambda_{1P}, \lambda_{2P}\right)$$

EWPT

$$\Delta\rho \propto T$$
$$\propto \left[F\left(M_{H^\pm}^2, M_H^2\right) + \cos^2\theta\, F\left(M_{H^\pm}^2, M_A^2\right) + \sin^2\theta F\left(M_{H^\pm}^2, M_a^2\right) - \cos^2\theta F(M_A^2, M_H^2) - \sin^2\theta F(M_a^2, M_H^2)\right]$$

(for simplicity we quote the expression in the alignment limit)

$$F(x,y) = x + y - \frac{2xy}{x-y} log\left(\frac{x}{y}\right)$$

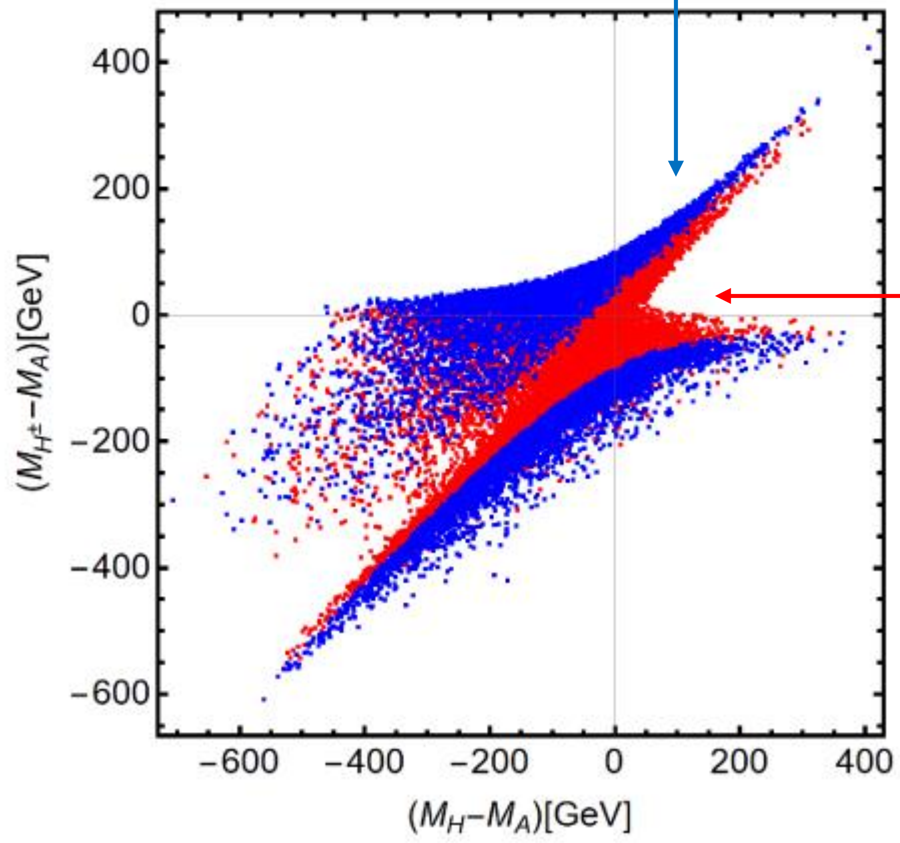
Deviation from the SM is due to
mass splitting between the BSM Higgs states.

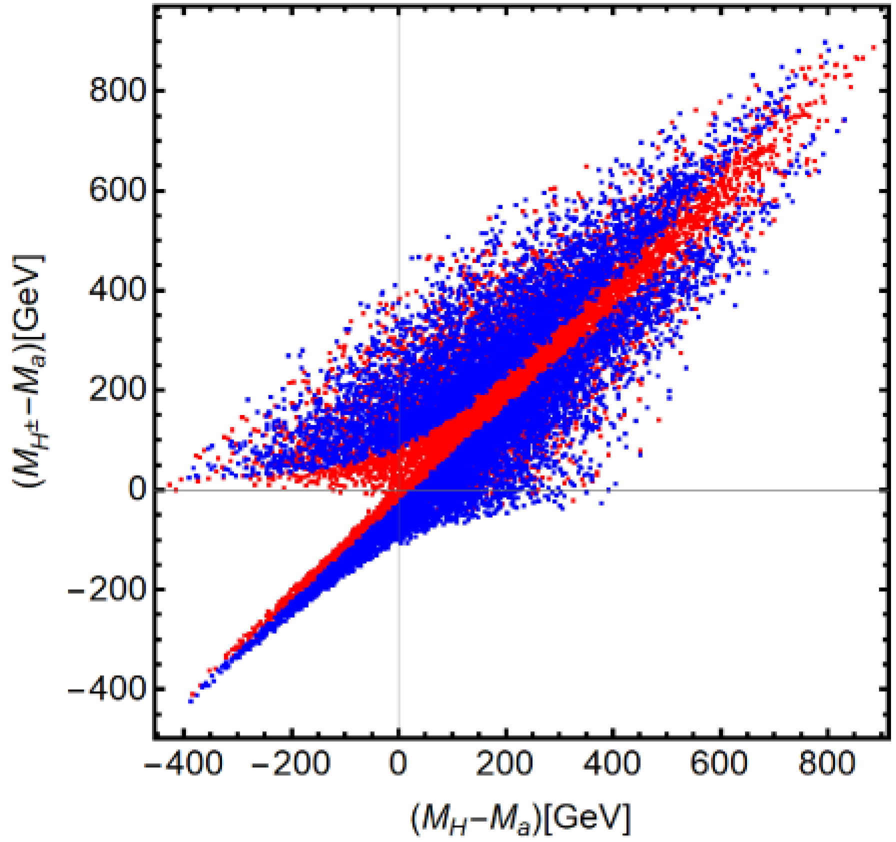
[Notice: Expression of $\Delta\rho$ provided for reference. Our analysis is based on EWPO S,T,U]

CDF Fit (arXiv:2204:05283)

see also e.g. Paul et al *Phys.Rev.D* 106 (2022) 1, 013008

J. De Blas et al *Phys.Rev.Lett.* 129 (2022) 27, 271801

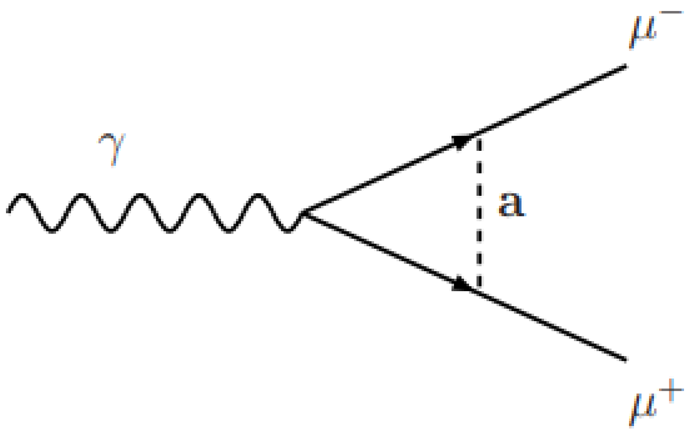




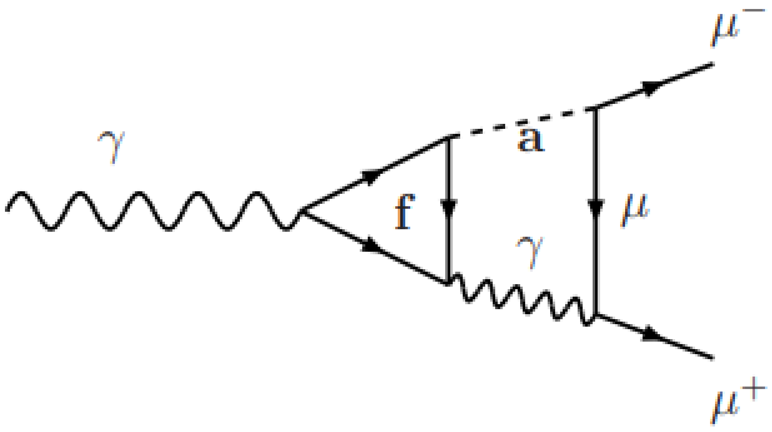
SM Fit

G.A., Nico Benicasa, A. Djouadi, K. Kannike arXiv:2212.14788

Connection with g-2



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



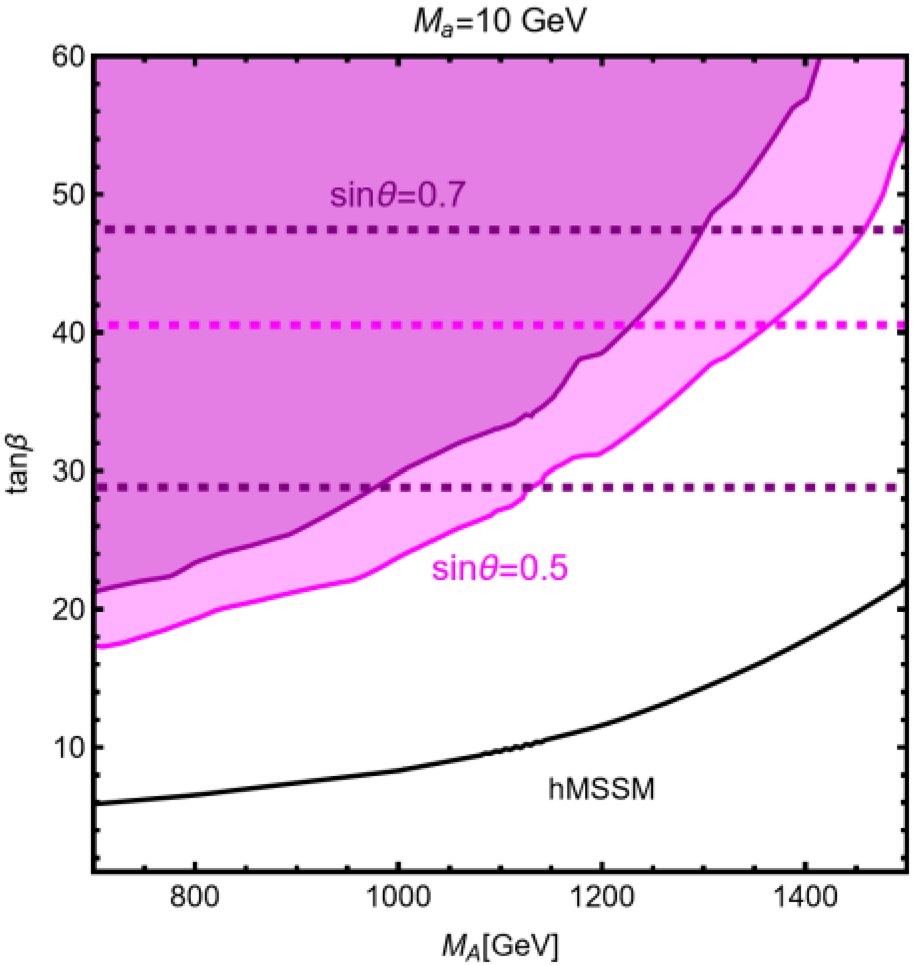
$$\Delta a_\mu^{2-loop} = \frac{\alpha^2}{8\pi^2 \sin^2\theta_W}\frac{m_\mu^2}{M_W^2} g_{a\mu\mu} \sum_f g_{aff} N_c^f Q_f \frac{m_f^2}{M_a^2} F\left(\frac{m_f^2}{M_a^2}\right)$$

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

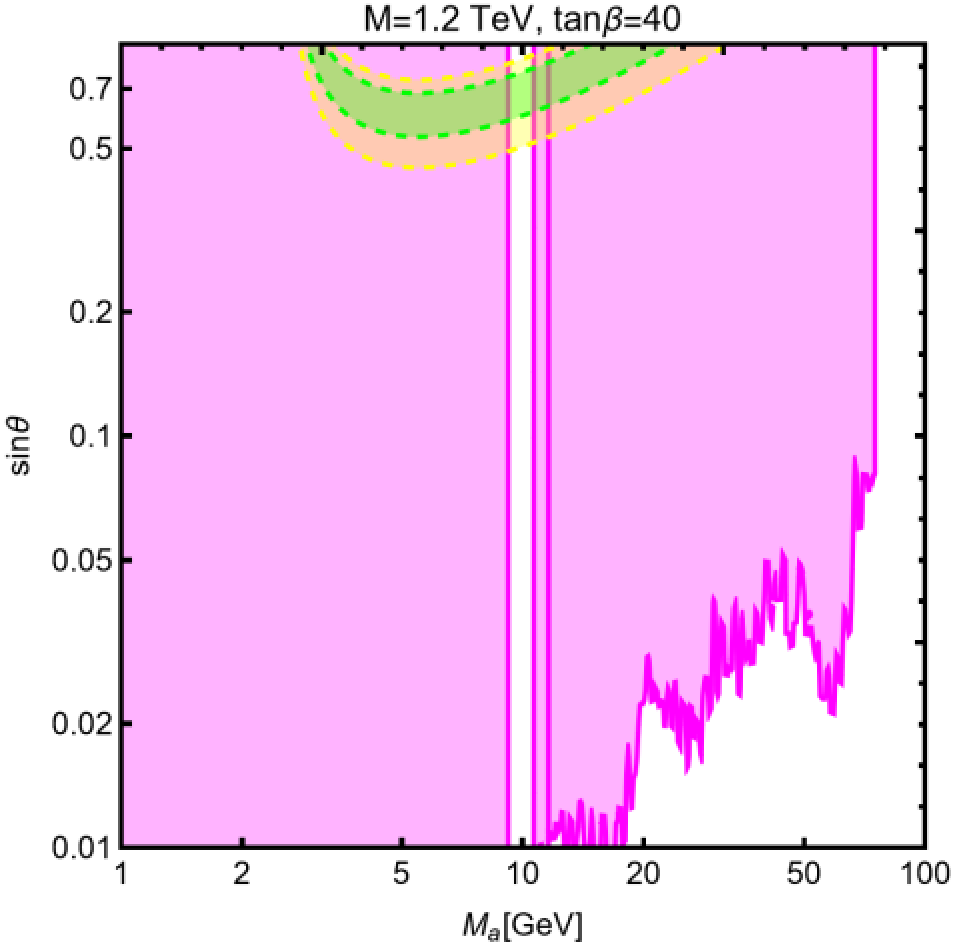
To have a sizable Δa_μ we need $g_{a\mu\mu} \propto tan\beta$. We need to go for Type-II or Type-X configurations.

LHC Constraints for Type-II configuration

$pp \to H/A \to \tau^+\tau^-$



$pp \to a \to \mu^+\mu^-$



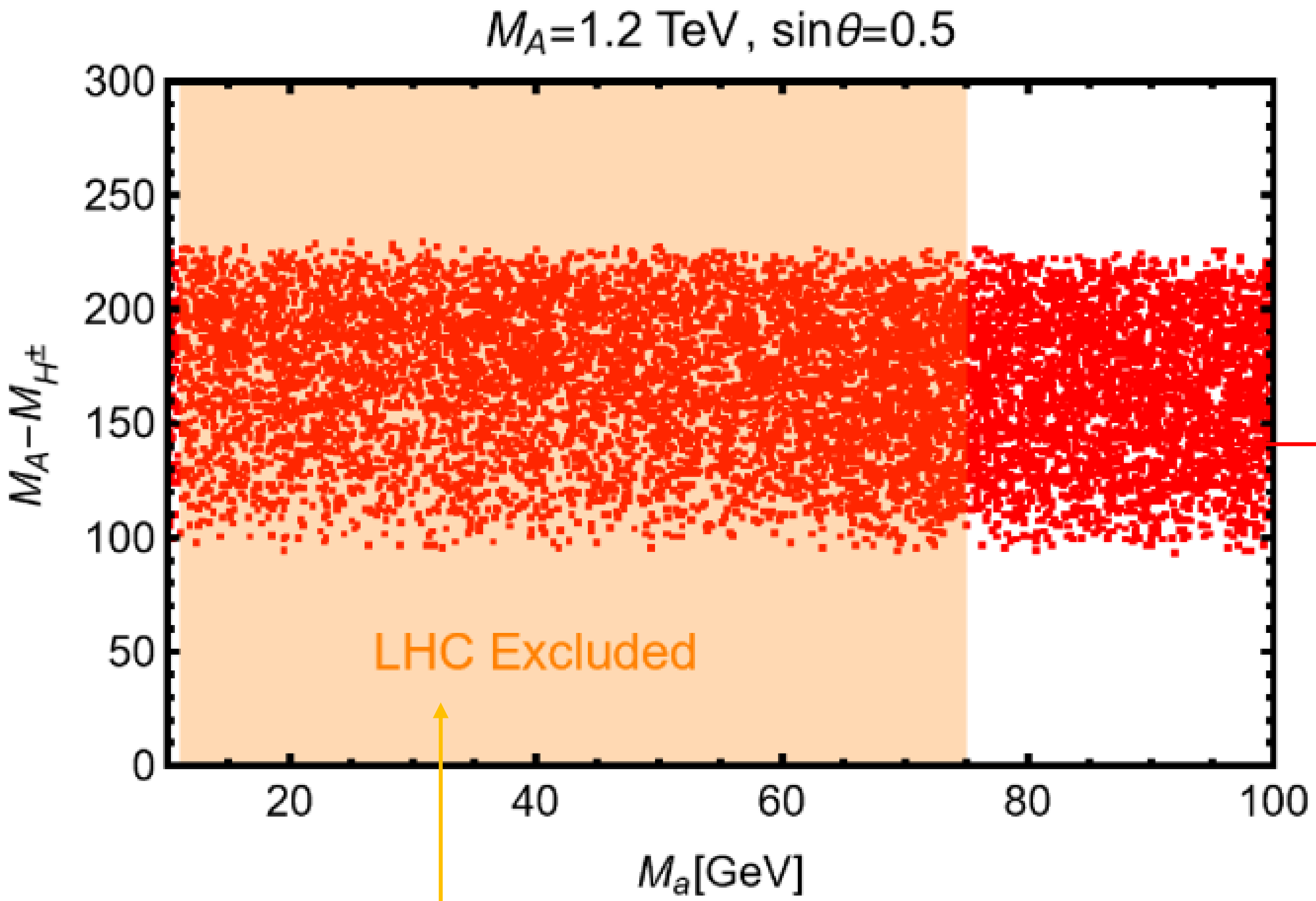
g-2 interpretation mostly ruled-out

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

Phys.Lett.B 834 (2022) 137436

Points with deviation of S,T compatible with CDF. No attempt for g-2.
Notice that big hierachy between M_a and M_A disfaclavored by perturbative unitarity.

D. Gonclaves et al. *Phys.Rev.D* 95 (2017) 5, 055027

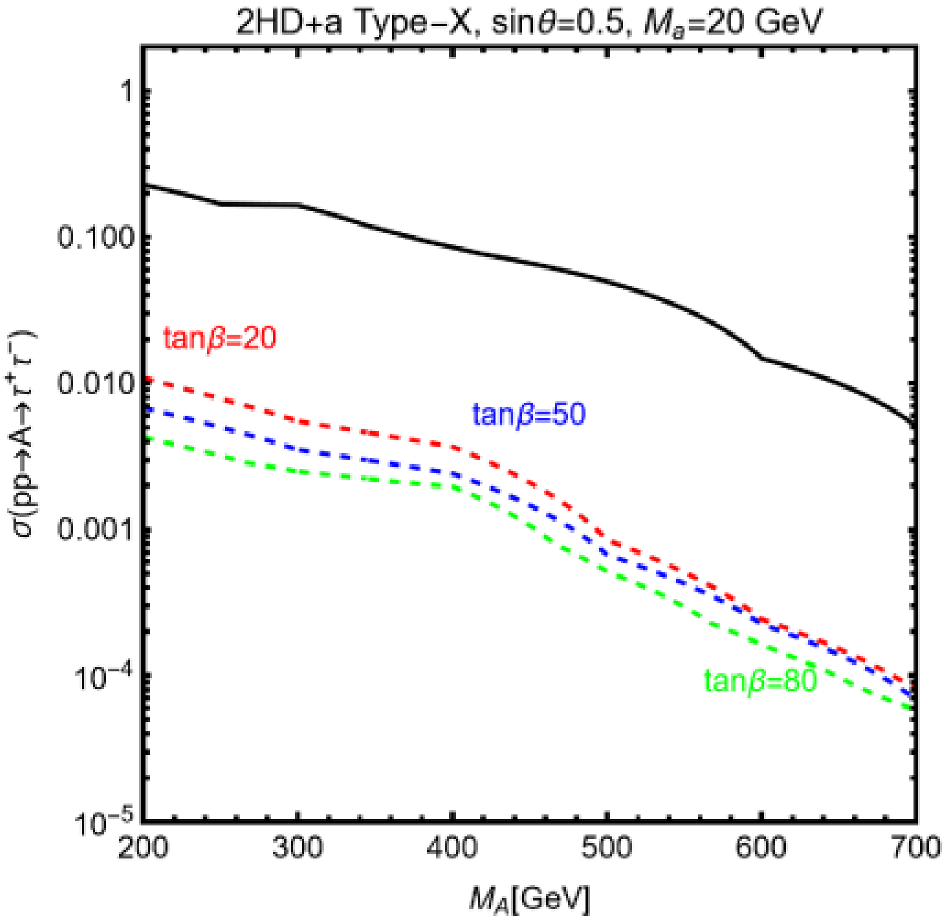


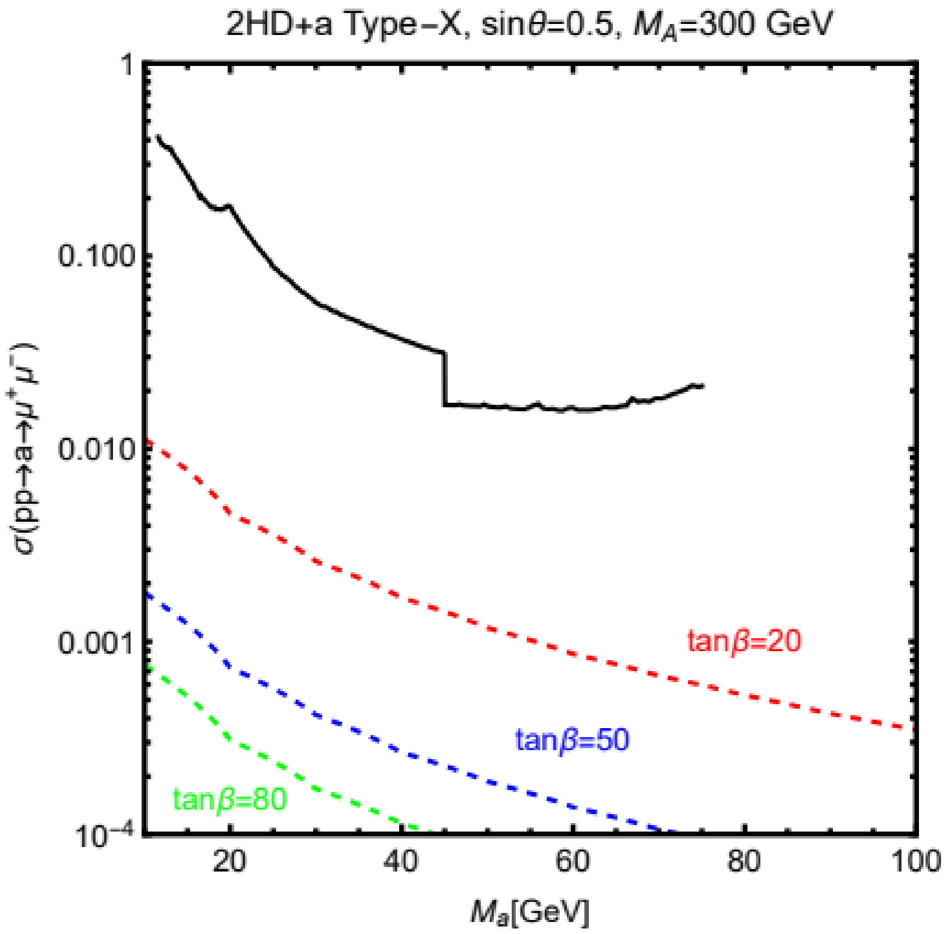
Searches of light resonances

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

LHC Constraints for Type-X configuration

Production cross-sections for both light and heavy resonances very suppressed and much below experimental limits in the high $tan\beta$ regime.





Constraints from decay of the Higgs

$$\Gamma(h \to aa) = \frac{|\lambda_{haa}|^2}{32\,\pi M_h}\sqrt{1-\frac{4M_a^2}{M_h^2}}$$

$$\lambda_{haa} = \frac{1}{v}\left[\left(M_h^2 - 2M_H^2 + 4M_{H^\pm}^2 - 2M_a^2 - 2\lambda_3 v^2\right)\sin^2\theta - 2(\lambda_{1P}\cos^2\beta + \lambda_{2P}\sin^2\beta)v^2\cos^2\theta\right]$$

To avoid a too large contribution to the width of the Higgs we have imposed:

$$\frac{\lambda_{haa}}{M_h} \leq O(10^{-3})$$

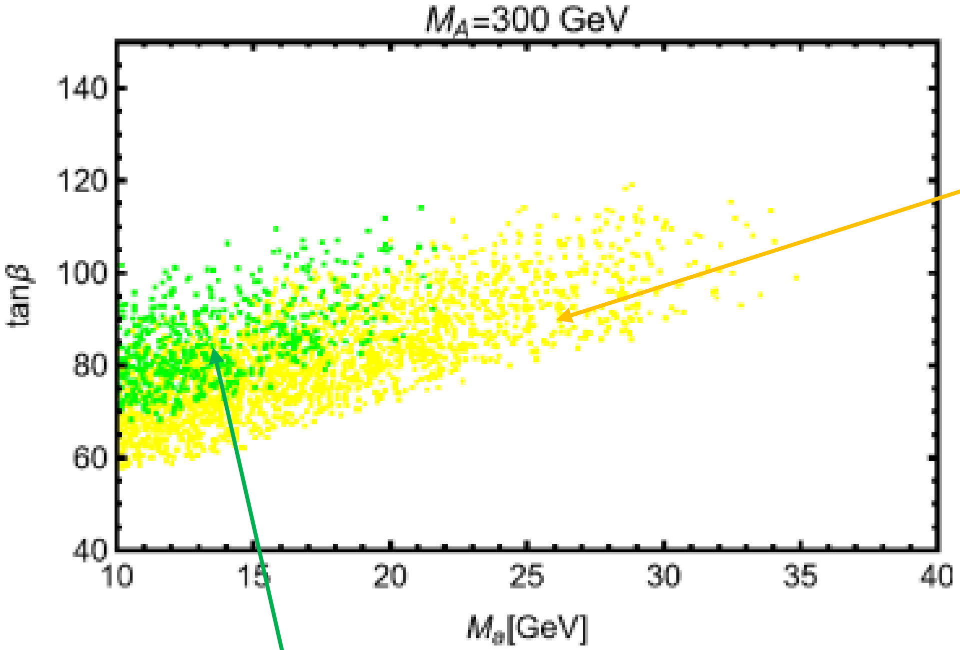
Parameter scan

M_A fixed to 300 GeV and 500 GeV

$M_a \in [10,100]\ GeV$ $\quad M_{H,H^\pm} \in [100,1000]\ GeV$

$\tan\beta \in [1,150]$ $\quad |\cos(\beta-\alpha)| < 0.2$

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

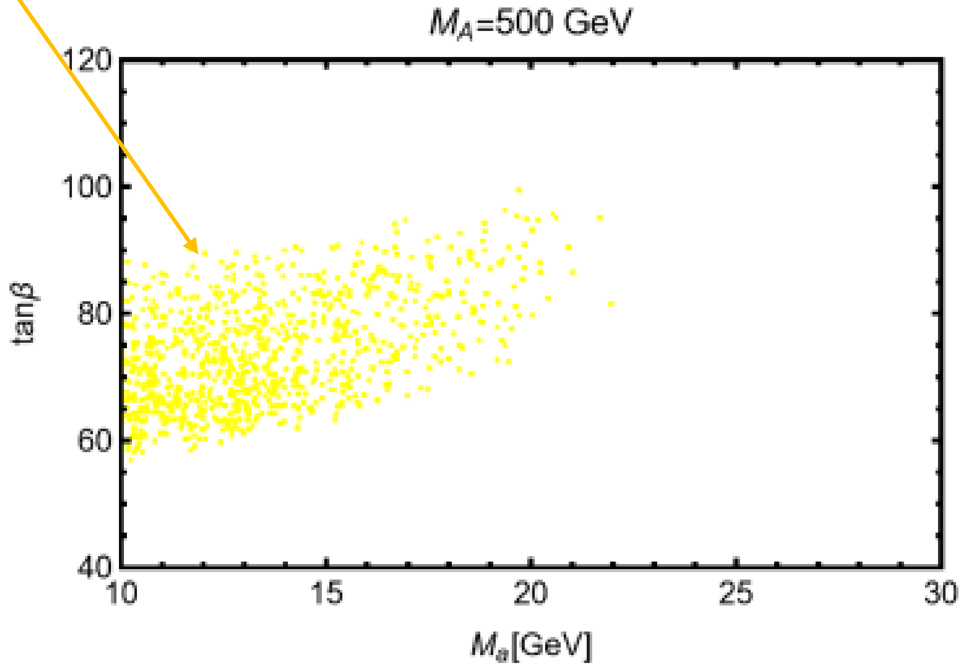


$\Delta a_\mu(2\,\sigma)$

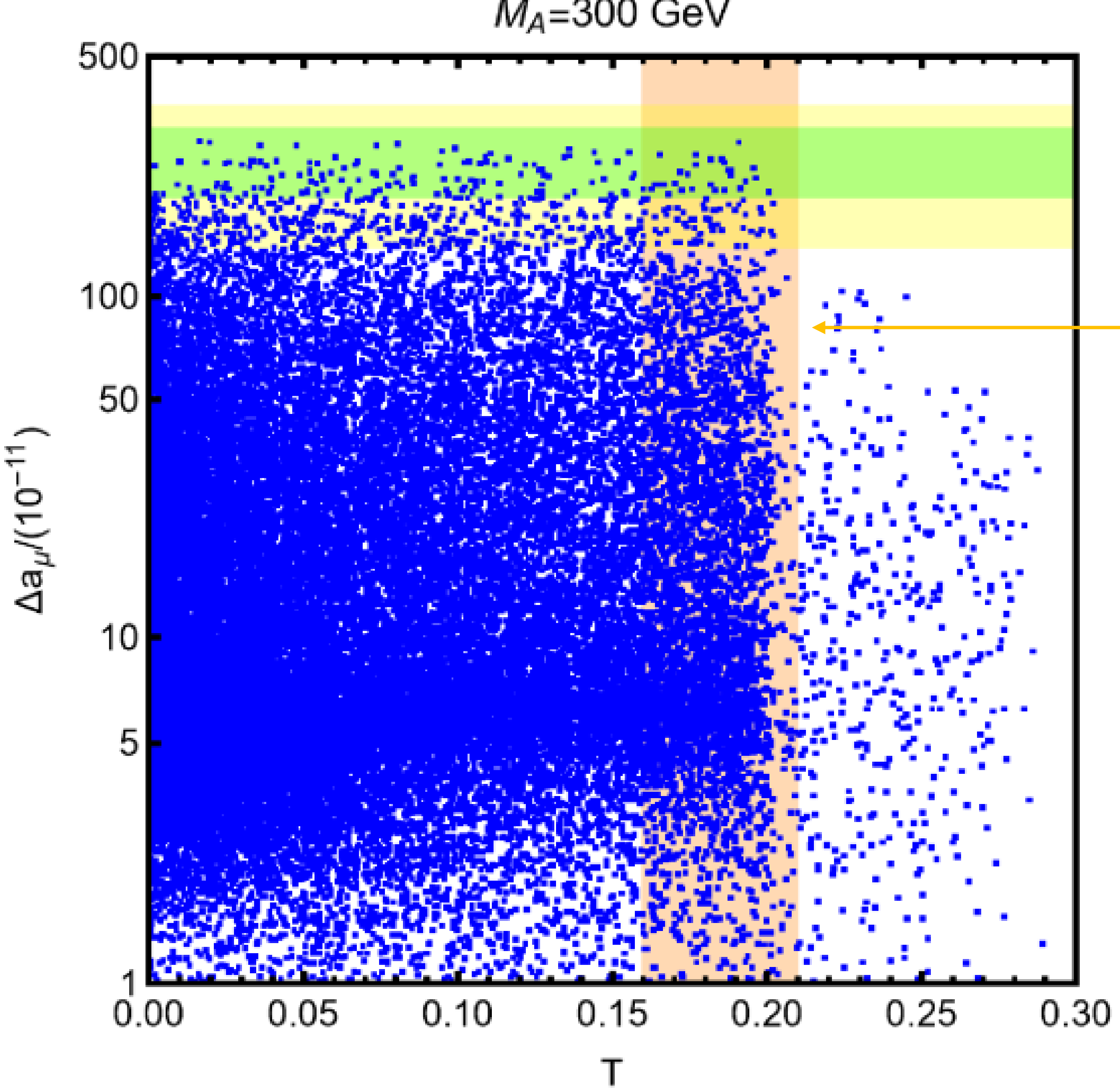
$\Delta a_\mu(1\,\sigma)$

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



$T \in [0.159, 0.210]$

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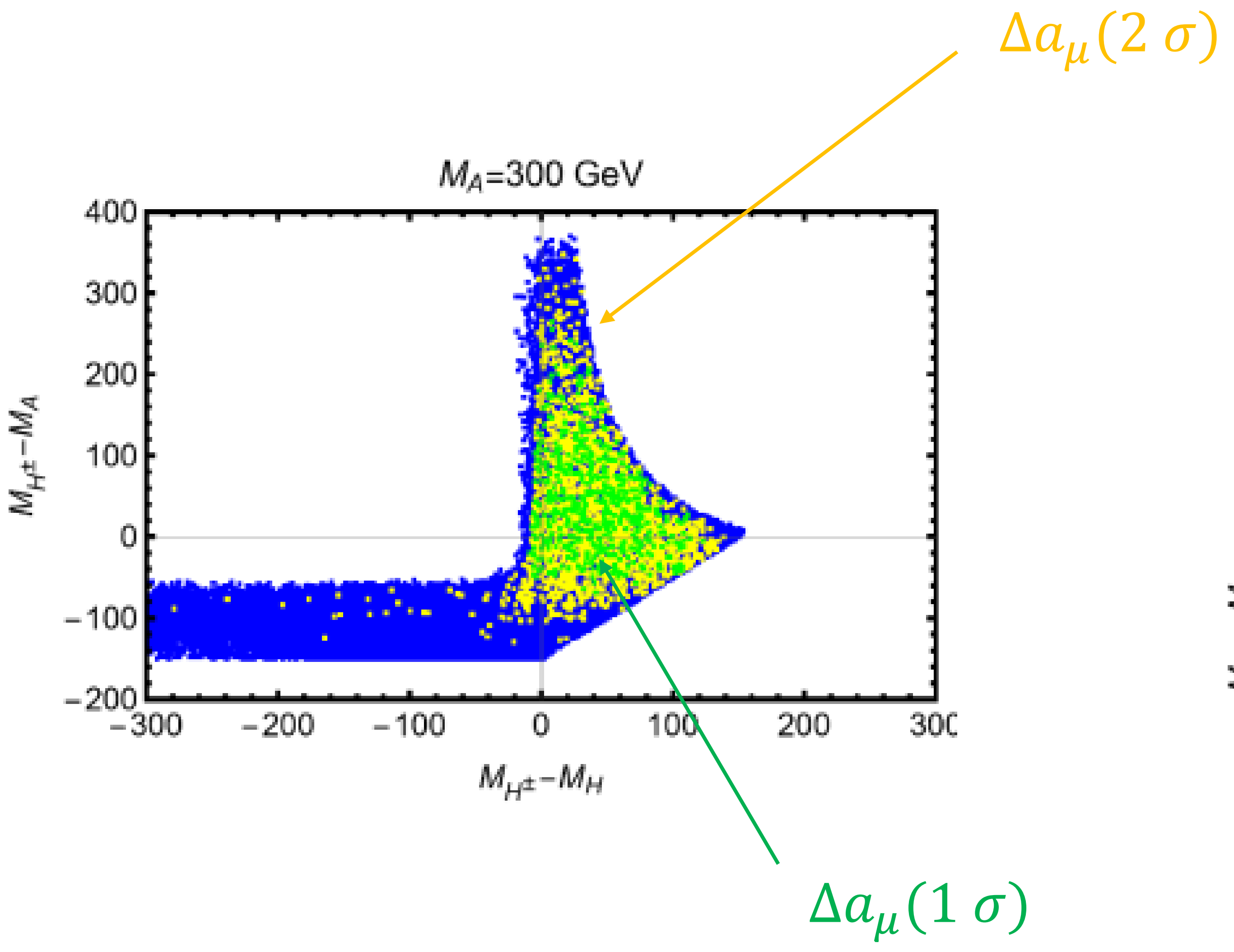
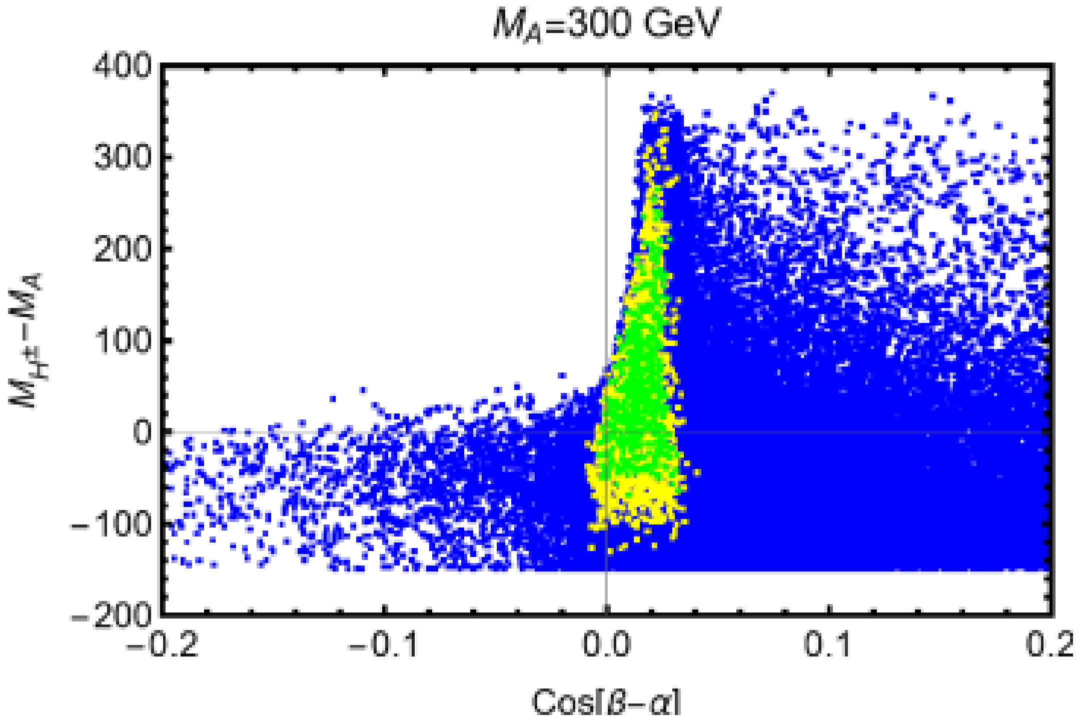
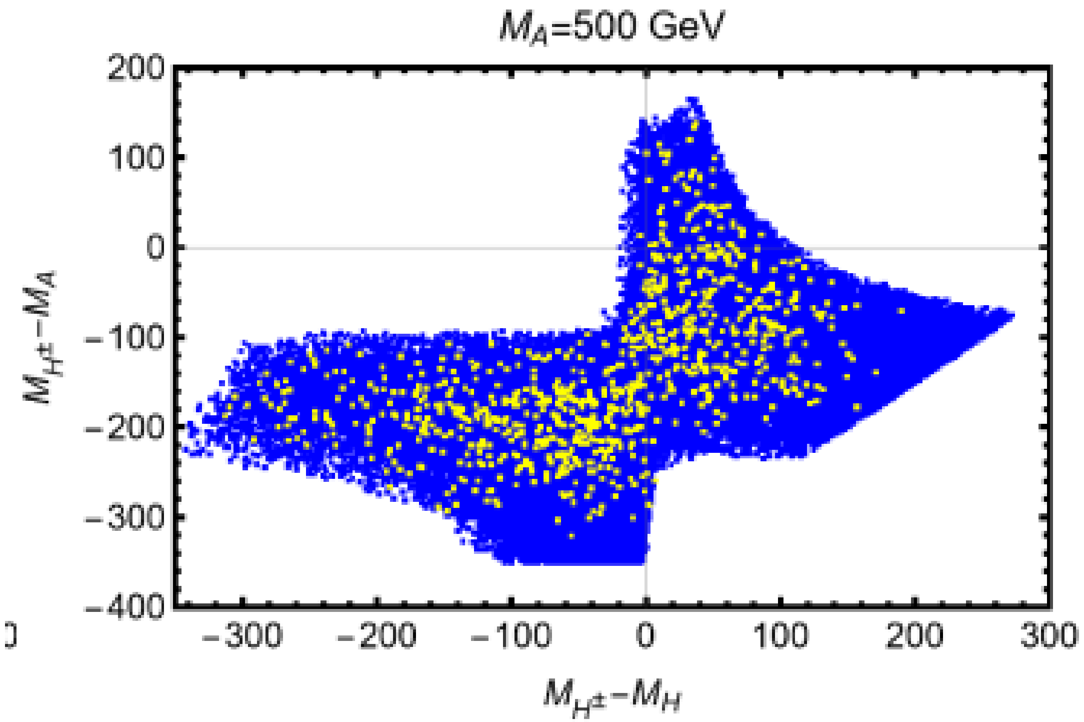
G.A. and A. Djouadi, *Phys.Rev.D* 106 (2022) 9, 095008

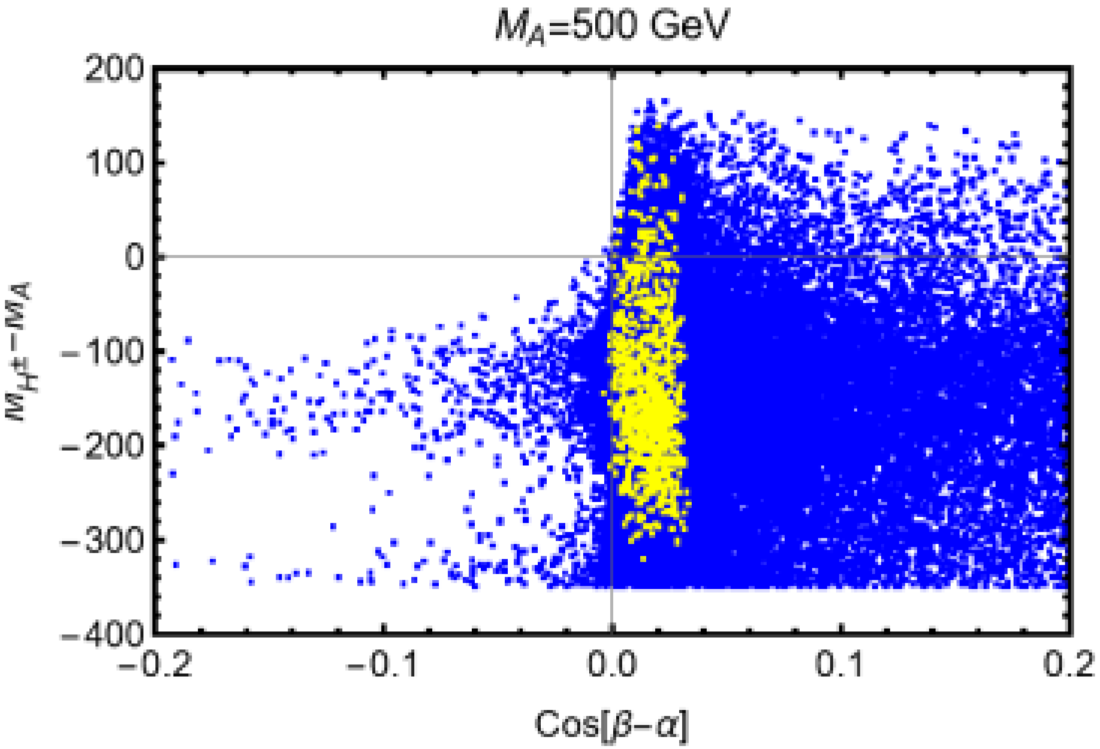
Combined results for type-X configurations







M_A=500 GeV
200
100
0
−100
−200
−300
−400
$M_{H^\pm}-M_A$
−300
−200
−100
0
100
200
300
$M_{H^\pm}-M_H$



M_A=500 GeV
200
100
0
−100
−200
−300
−400
$M_{H^\pm}-M_A$
−0.2
−0.1
0.0
0.1
0.2
Cos[β−α]

Connection with DM

We consider a SM singlet odd under an additional Z_2 symmetry.

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

Relic density

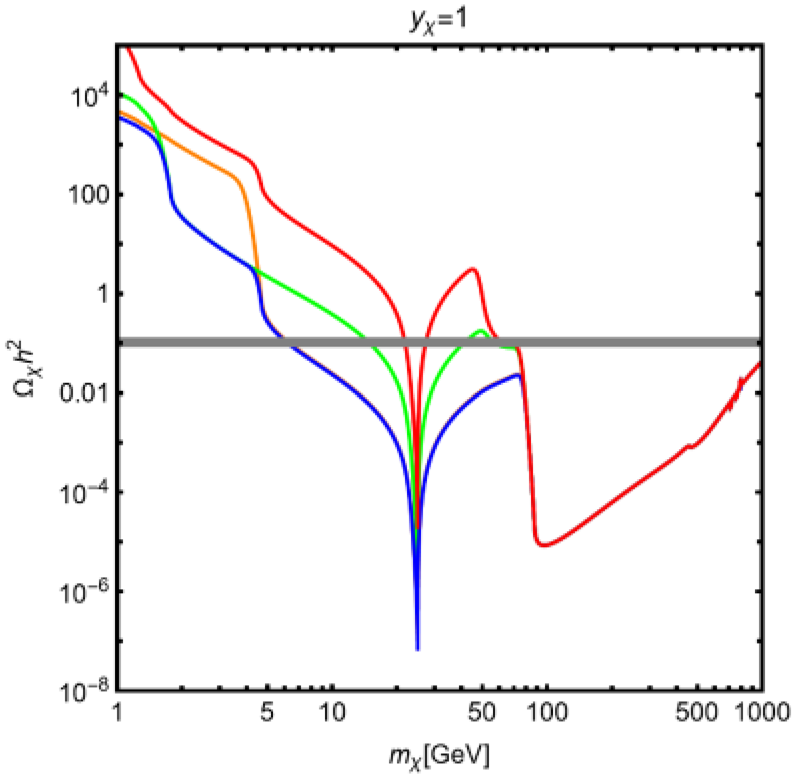
$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

$\langle \sigma v \rangle$

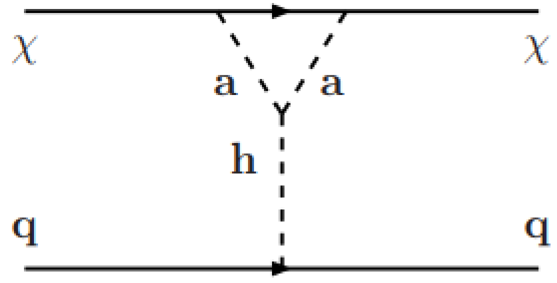
$\bar{\chi}\chi \to a\,/A \to \bar{f}f$

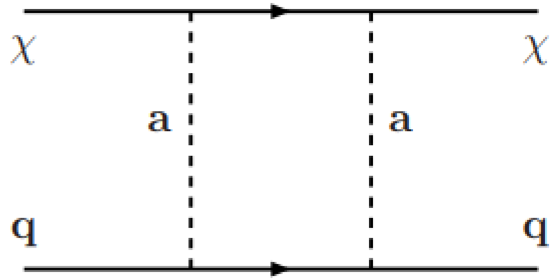
$\bar{\chi}\chi \to a\,/A \to ha(A)$

$\bar{\chi}\chi \to a\,/A \to a(A)a(A)$

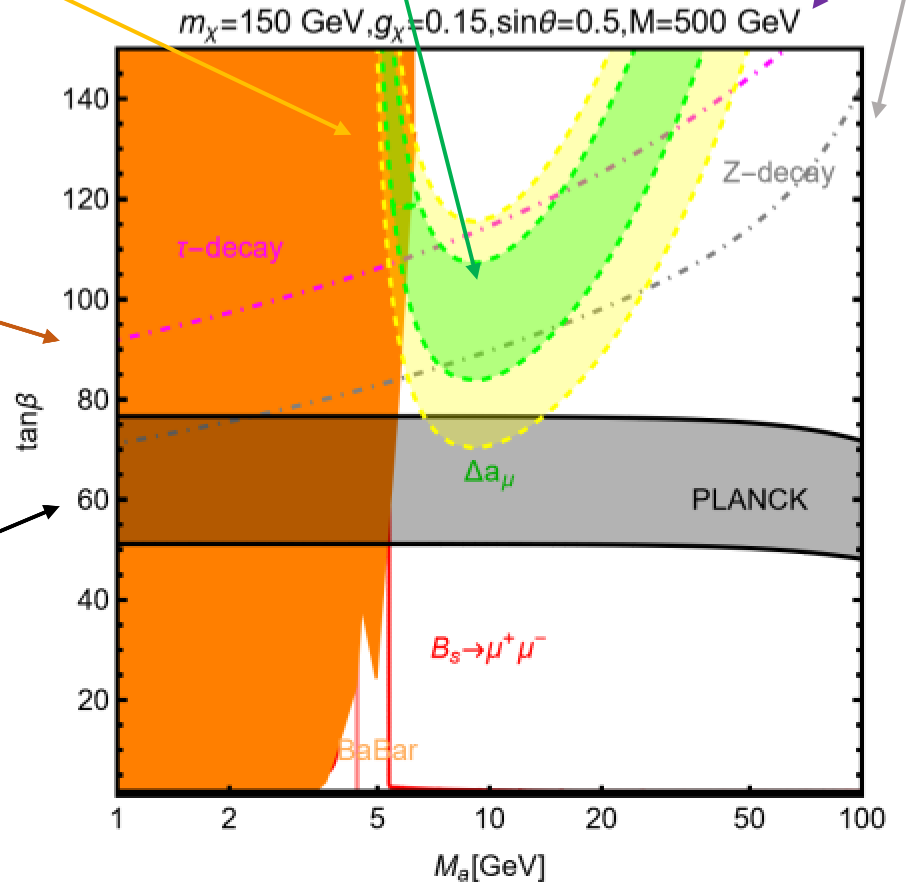


Direct Detection





Induced a one-loop



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

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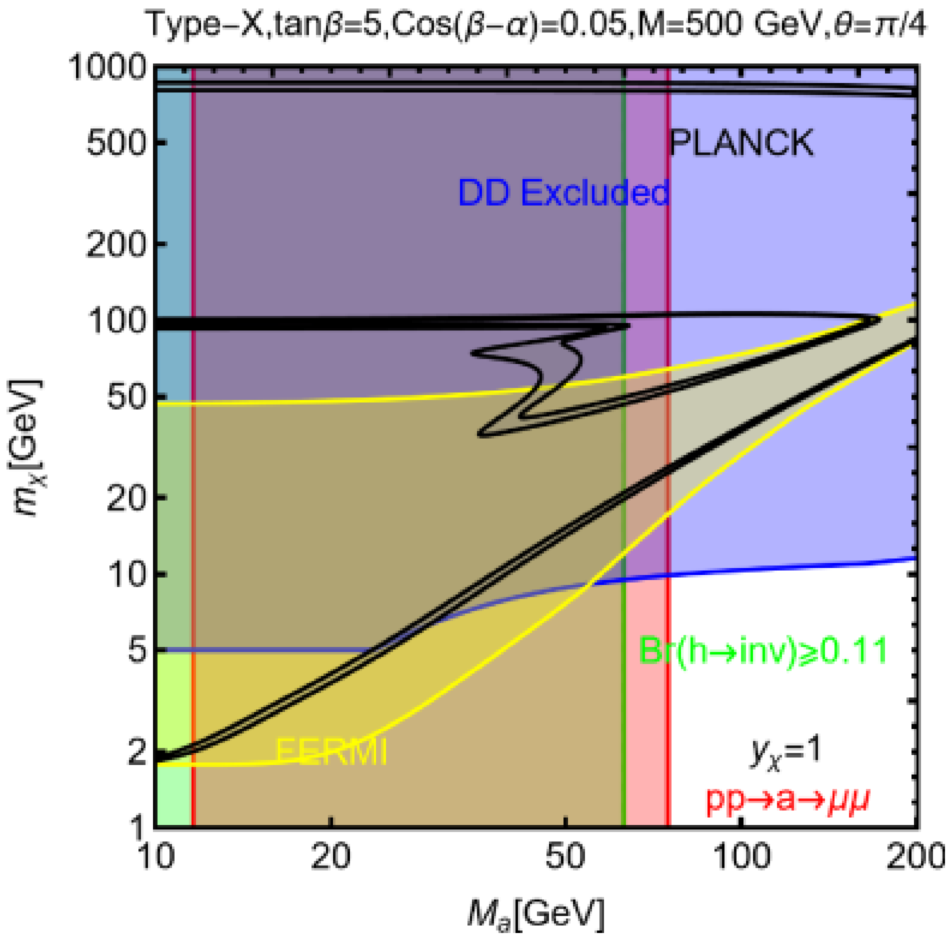
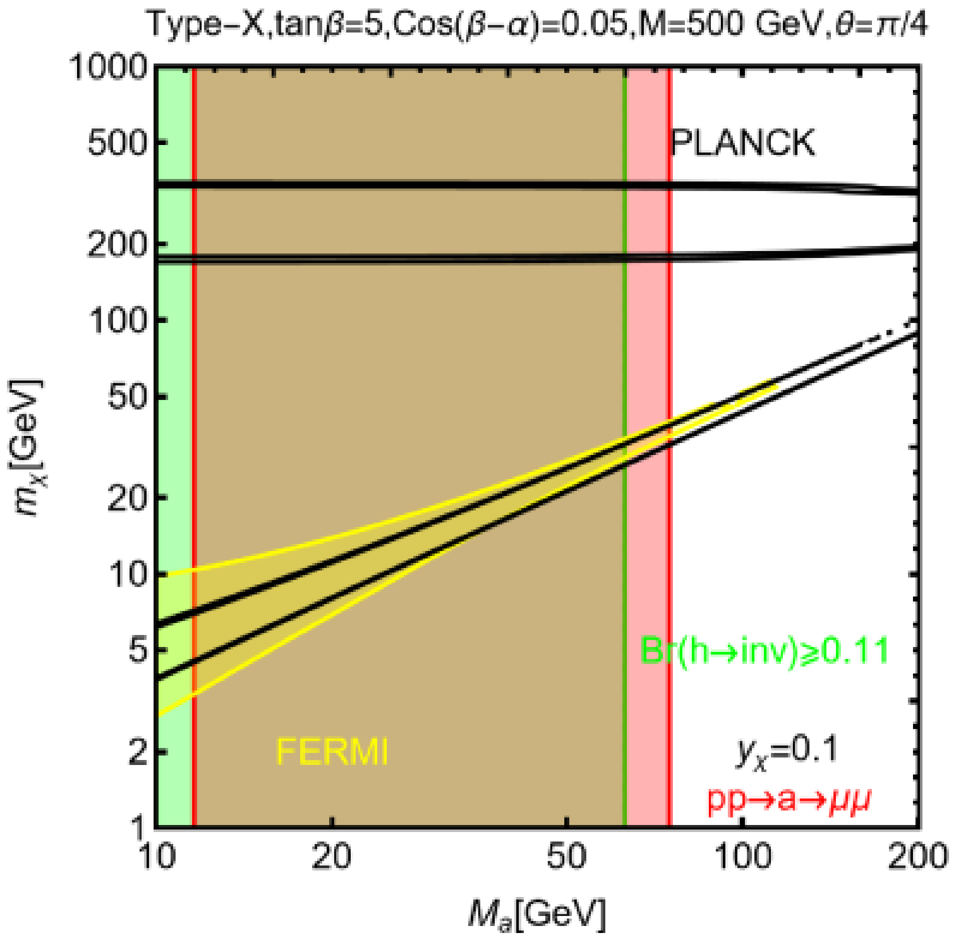
Conclusions

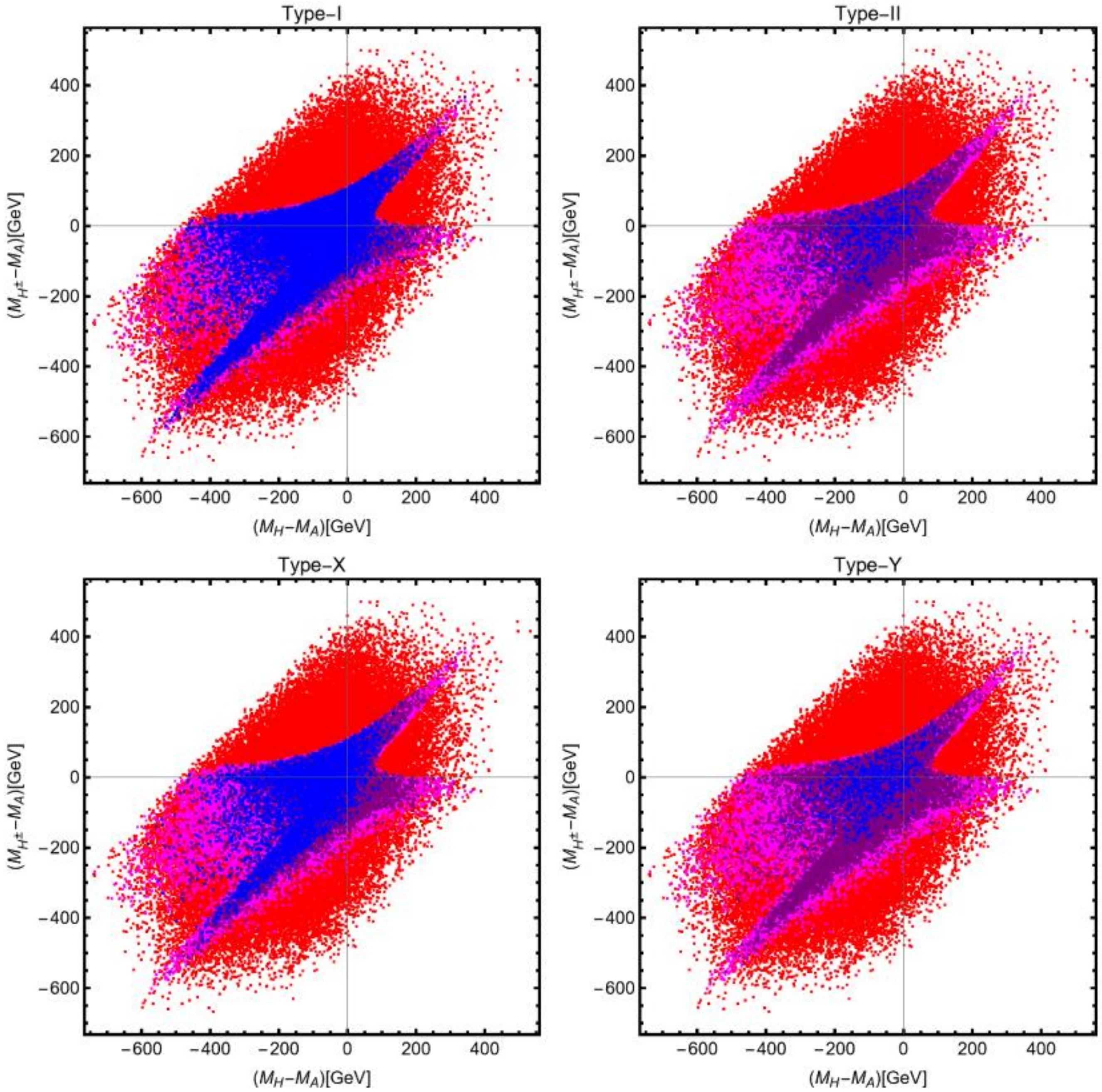
We have investigated the possibility of accommodating within the 2HDM+a, deviation from the SM fit of the S,T,U parameters, possibly complying with the anomaly reported by CDF last year, BSM interpretation of the measure of g-2 and finally provide a viable DM candidate.

Such task can be achieved by considering a scenario with type-X (lepton specific) configuration, light a boson ($M_a \leq 30\ GeV$) and few hundred GeV mass A boson.

Back up


Type−X,tanβ=5,Cos(β−α)=0.05,M=500 GeV,θ=π/4
PLANCK
DD Excluded
Br(h→inv)≥0.11
FERMI
y_χ=1
pp→a→μμ
m_χ[GeV]
M_a[GeV]


Type−X,tanβ=5,Cos(β−α)=0.05,M=500 GeV,θ=π/4
PLANCK
Br(h→inv)≥0.11
FERMI
y_χ=0.1
pp→a→μμ
m_χ[GeV]
M_a[GeV]


Type-I
Type-II
Type-X
Type-Y
$(M_{H^\pm}-M_A)$[GeV]
(M_H-M_A)[GeV]
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400