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Type-X two Higgs doublet model in light of muon g-2: confronting the Higgs and collider data

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1. Motivation
2. Type-X 2HDM
3. Muon g-2 in Type-X
4. Other constraints
5. Results
6. Conclusions

1. Motivation

Very plausible signal of NP in the Fermilab muon g-2

Fermilab National Accelerator Laboratory (FNAL) Muon $g-2$ experiment

2104.03281, 2104.03247

$$\boxed{\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-11}.}$$

For the hadronic vacuum polarization
& hadronic light-by-light (HLbL) scattering,
data-driven (R-ratio) methods.

NP signal at 4.2σ

Active studies of NP effects in a very short time

1. SUSY:
   2104.07597, 2104.03839, 2104.03284, 2104.03262, 2104.03245, 2104.03274, 2104.03302, 2104.03491, 2104.03489, 2104.04458, 2104.03691, 2104.03259

2. two Higgs doublet model:
   2104.03367, 2104.03227, 2104.03275, 2010.03590, 2103.10632, 2010.02799, 2003.03386, 2104.03249

3. leptophilic boson model:
   2104.07680, 2104.03701

4. three Higgs doublet model:
   2104.07047

5. leptoquark model:
   2104.06656, 2104.05685

6. $L_\mu - L_\tau$ model:
   2104.05656, 2104.03340

7. $B - L$ or $B - 3L$ gauge model:
   2104.03542, 2103.13991

8. flavorful scalar model:
   2104.03238

9. 2HDM with a singlet scalar model:
   1909.03969

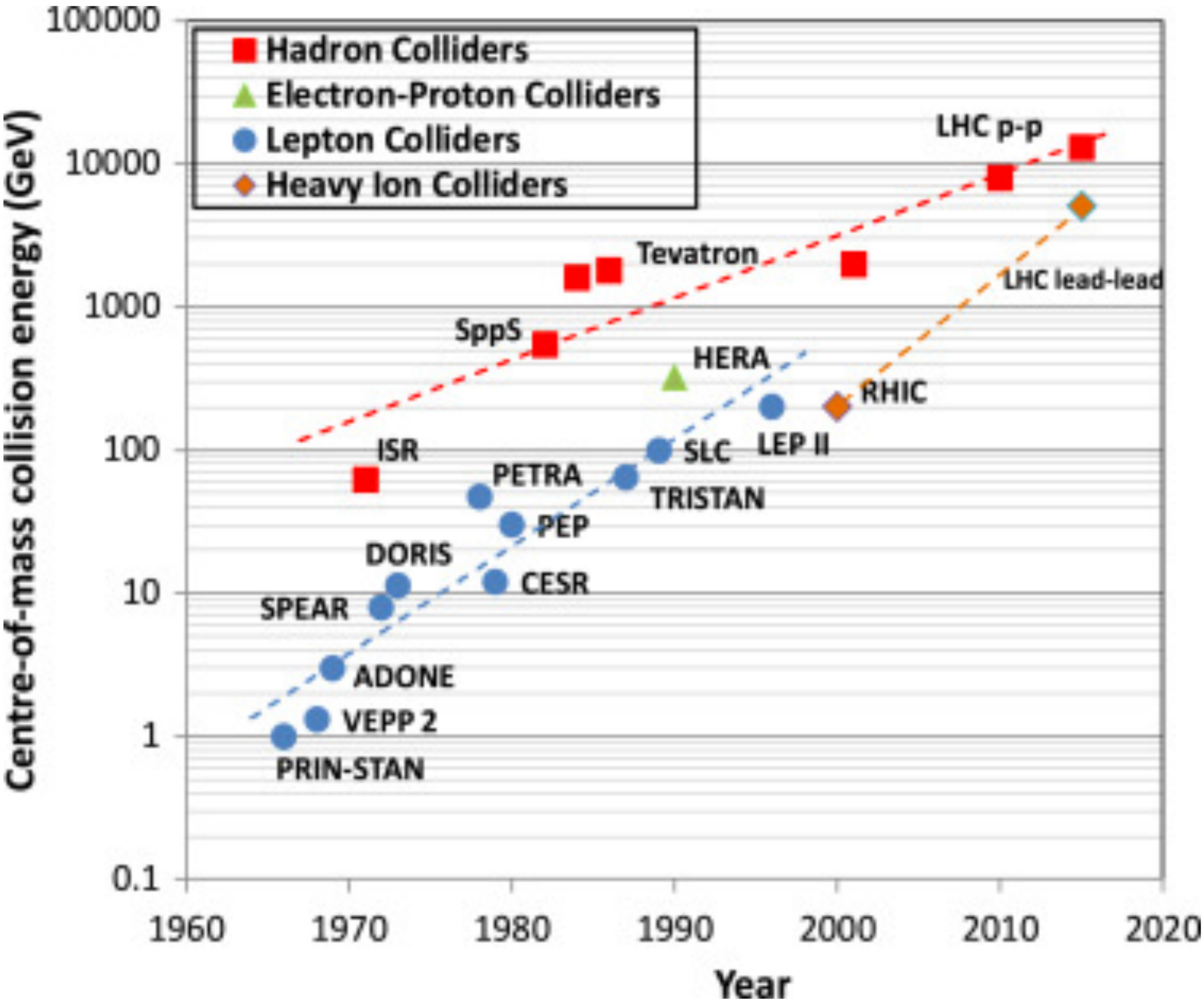
Study must go on!

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-11}.$$

Observation → Limiting a NP model

In fact, we are super-rich!

We have a vast amount of experimental data in particle physics.



No assumption but all the constraints
for each NP model

Type-X (Lepton-specific 2HDM)

2. Type-X 2HDM

Basic theory setup

2HDM

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \dfrac{v_i + h_i + i\eta_i}{\sqrt{2}} \end{pmatrix}, \quad i = 1, 2,$$

where $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV.

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$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$$

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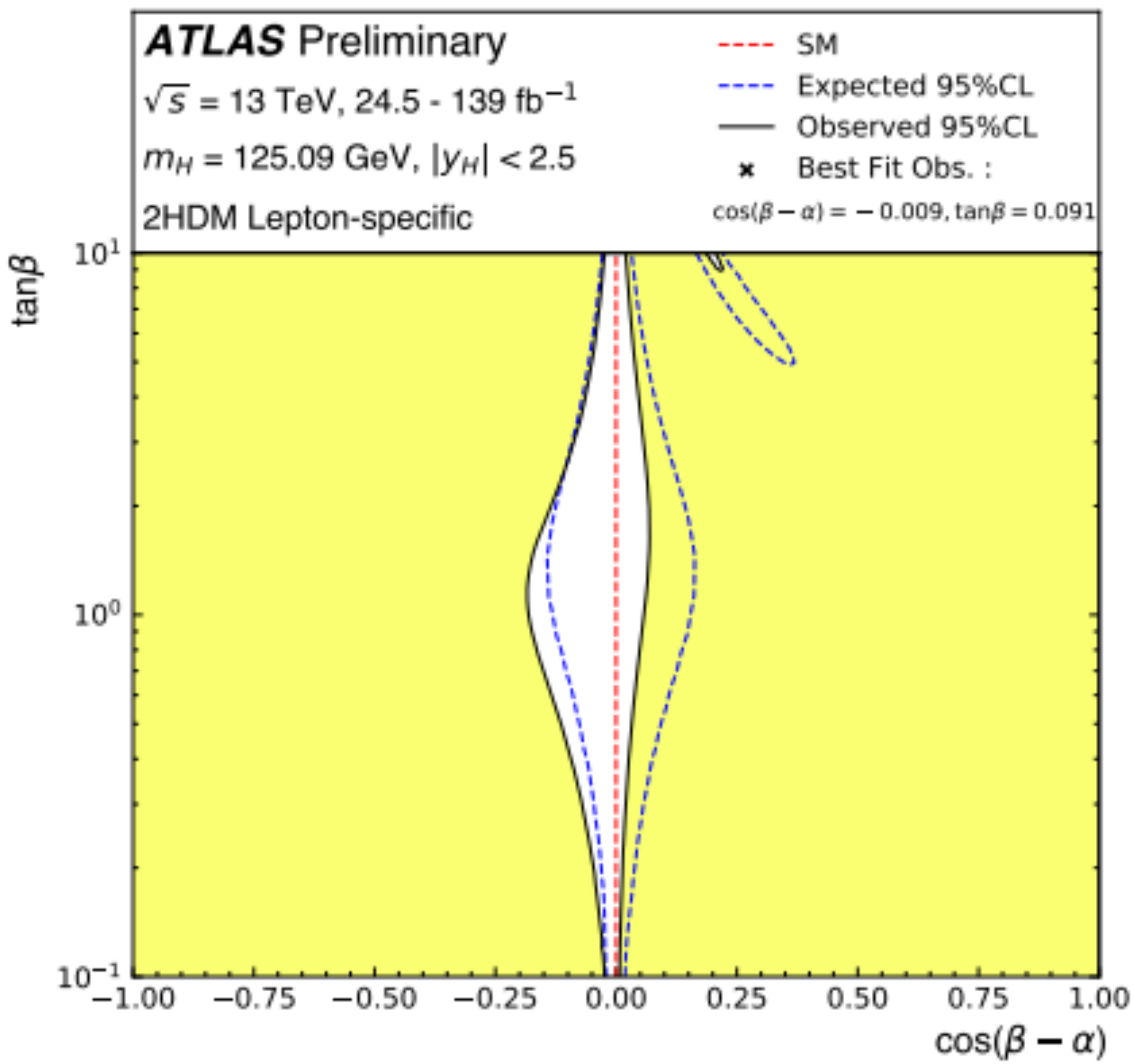
$$\boxed{\begin{aligned} V_\Phi = \; & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right], \end{aligned}}$$

Higgs precision data require the Higgs alignment limit.

$$\boxed{\Delta a_\mu \Longrightarrow \text{ huge } t_\beta \text{ \& light } M_A}$$



ATLAS-CONF-2020-027

Model parameters and basic setup

$$\{m_{\varphi^0},\ M_A,\ M_{H^\pm}, M^2,\ t_\beta\}$$

normal scenario (NS)	inverted scenario (IS)
$h_{\rm SM} = h, \quad \varphi^0 = H$	$h_{\rm SM} = H, \quad \varphi^0 = h$
$y_f^{h_{\rm SM}} = 1, \quad s_{\beta-\alpha} = 1$	$y_f^{h_{\rm SM}} = 1, \quad s_{\beta-\alpha} = 0$
$y_t^A = -y_t^{\varphi^0} = \frac{1}{t_\beta}, \quad y_\ell^A = y_\ell^{\varphi^0} = t_\beta$	$y_t^A = y_t^{\varphi^0} = \frac{1}{t_\beta}, \quad y_\ell^A = -y_\ell^{\varphi^0} = t_\beta$

$$y_t^{\varphi^0} y_\tau^{\varphi^0} < 0$$

Theoretical stabilities require strong constraints due to chain reaction.

$$\lambda_1 = \frac{1}{v^2}\left[m_{125}^2 + \boxed{t_\beta^2}\left(m_{\varphi^0}^2 - M^2\right)\right],$$

$$\lambda_2 = \frac{1}{v^2}\left[m_{125}^2 + \frac{1}{t_\beta^2}\left(m_{\varphi^0}^2 - M^2\right)\right],$$

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$$\lambda_4 = \frac{1}{v^2}\left[M^2 + M_A^2 - 2M_{H^\pm}^2\right],$$

$$\lambda_5 = \frac{1}{v^2}\left[M^2 - M_A^2\right],$$

$$\boxed{M^2 = m_{12}^2/(s_\beta c_\beta)}$$

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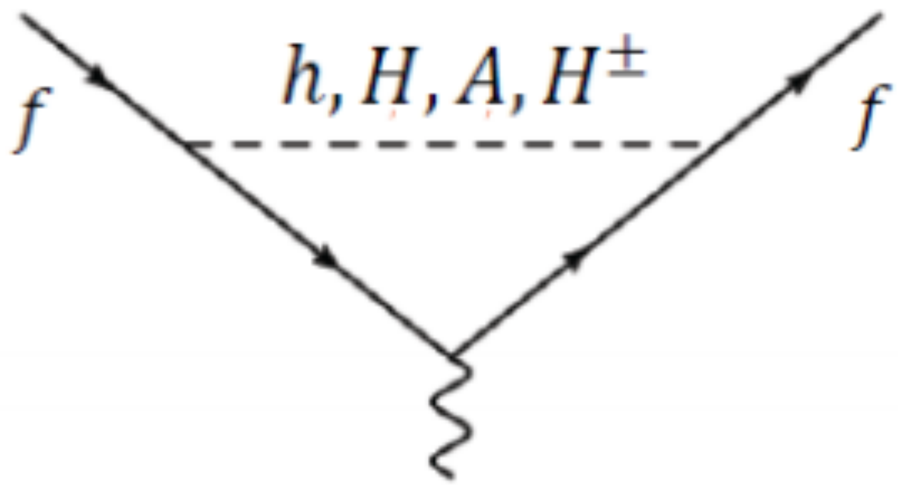
\end{aligned}
$$

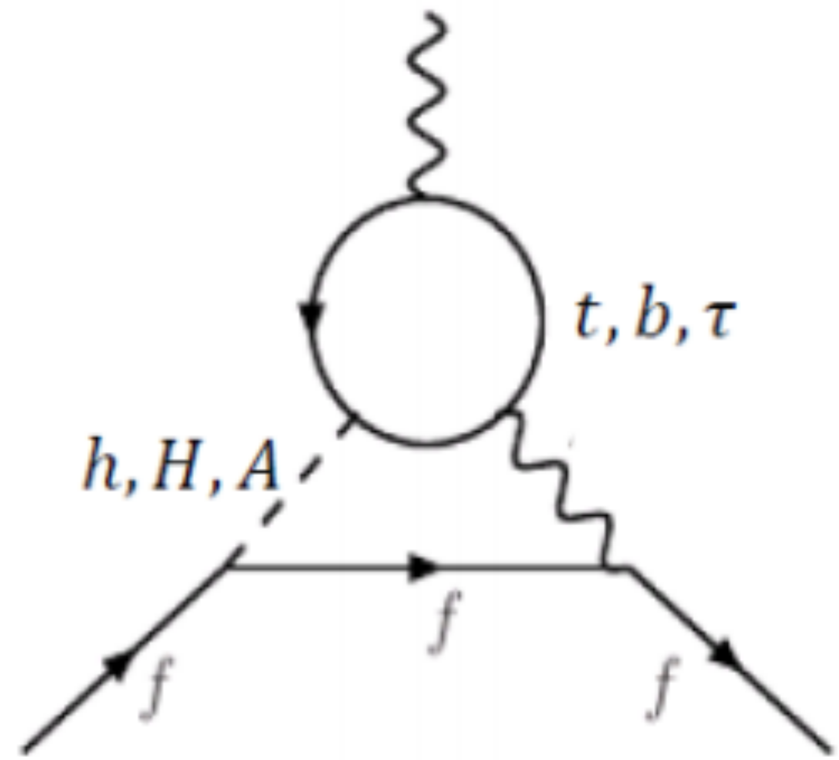
$$
\boxed{M_A \sim M_{H^\pm} \sim M \approx m_{\varphi^0}.}
$$

3. Muon g-2 in Type-X 2HDM

Two kinds of contributions

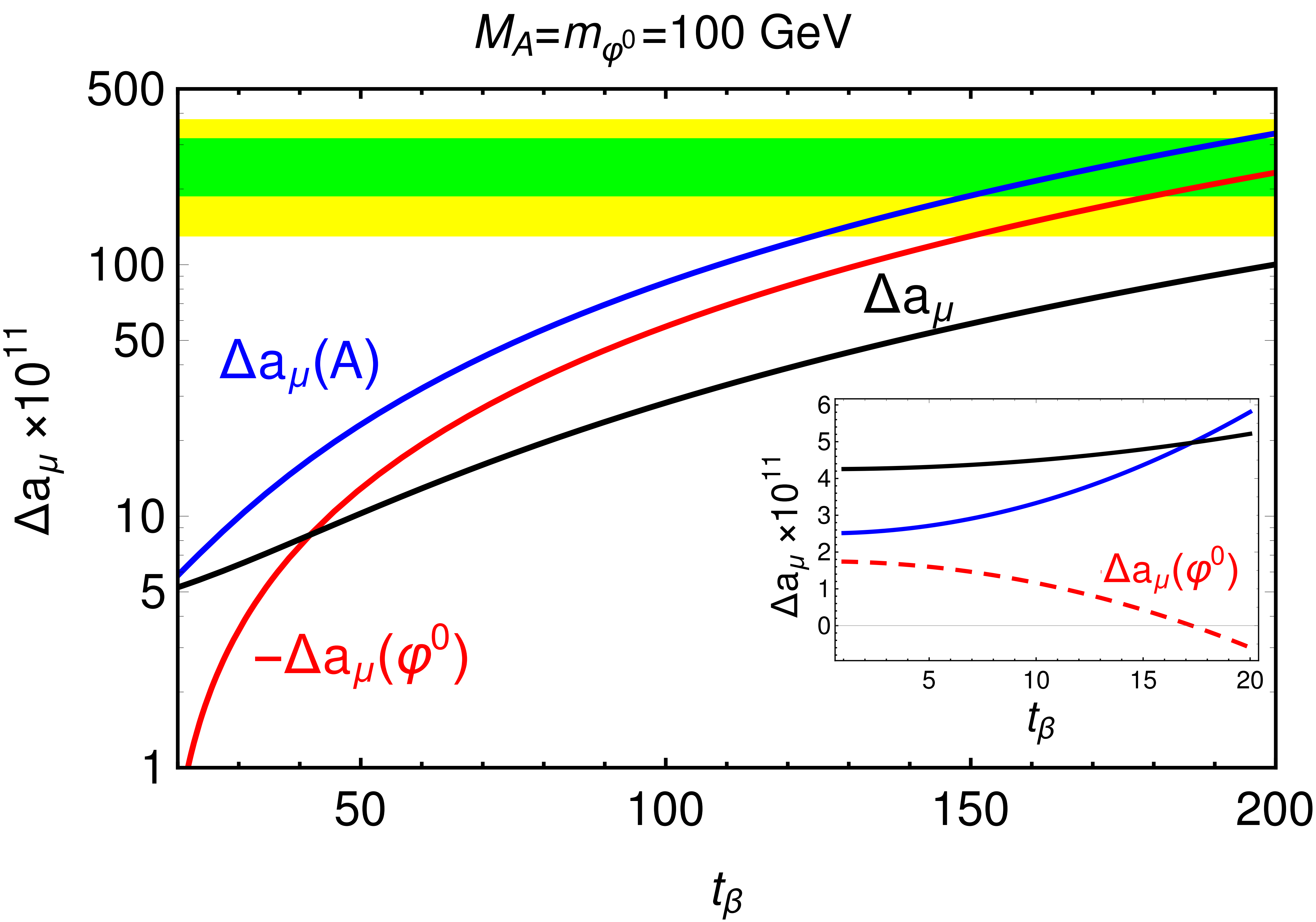


1-loop

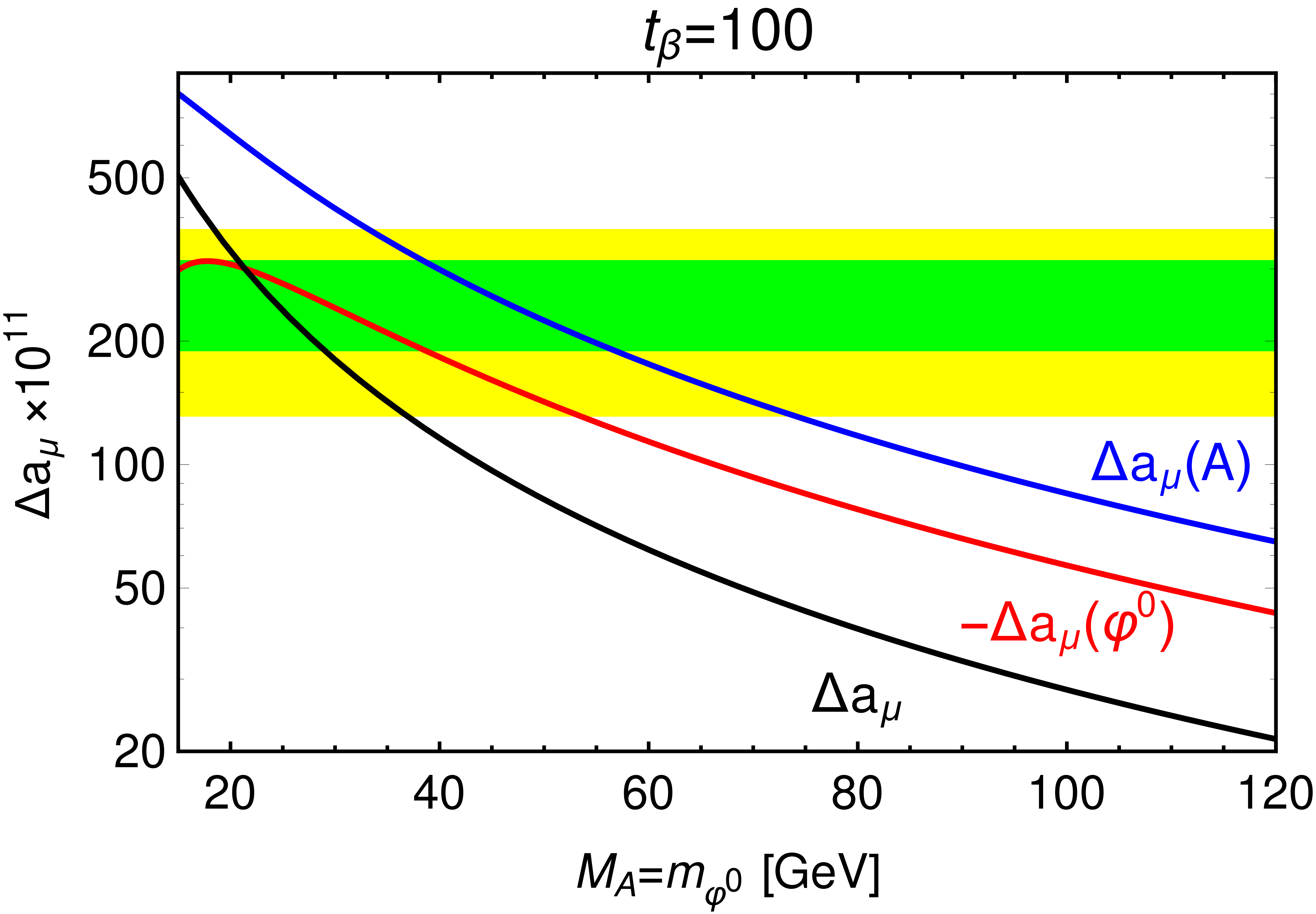


Barr-Zee 2-loop

Very large tanβ is required. And CP-even scalar cannot explain the observed muon g-2.



A light pseudo scalar A are required.



4. Other constraints

Scan strategy in 3 steps

Step I: Δa_μ at 2σ.

Step II: Theory+EWPD after Step I

1. Theoretical stabilities:
   Higgs potential being bounded from below, unitarity of scalar-scalar scatterings, perturbativity, vacuum stability.
2. Peskin-Takeuchi electroweak oblique parameters.

Step III: Collider bounds after Step II

1. Higgs precision data by using `HiggsSignals`.
2. Direct searches for new scalars at the LEP, Tevatron, and LHC, by using `HiggsBounds`.

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HiggsBounds provide powerful checkup.

HiggsBounds currently incorporates results from LEP [1–15], the Tevatron [16–50], and the ATLAS [51–123] and CMS [124–194] experiments at the LHC.

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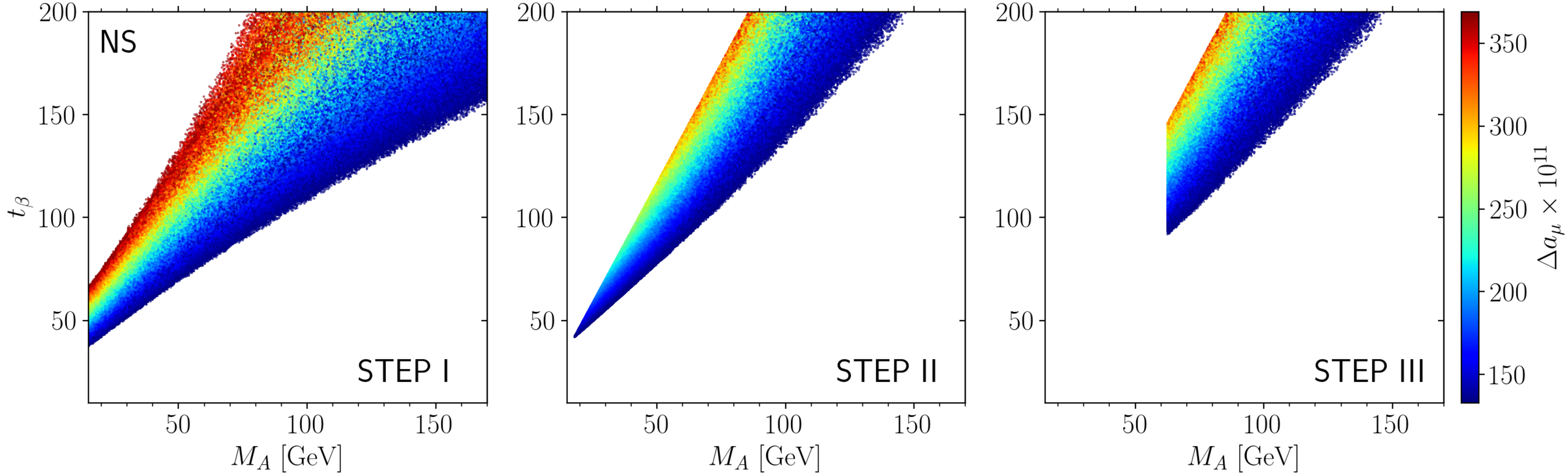
The inverted scenario has much stronger constraints from the collider data.

- For each scenario, we obtained 5×10^5 parameter sets satisfying Step II.
- After Step III,
  - Normal scenario: $\sim 80\%$ survived.
  - Inverted scenario: $\sim 1.8\%$ parameter sets survived.

5. (1) Results in the normal scenario

Other constraints play an important role.

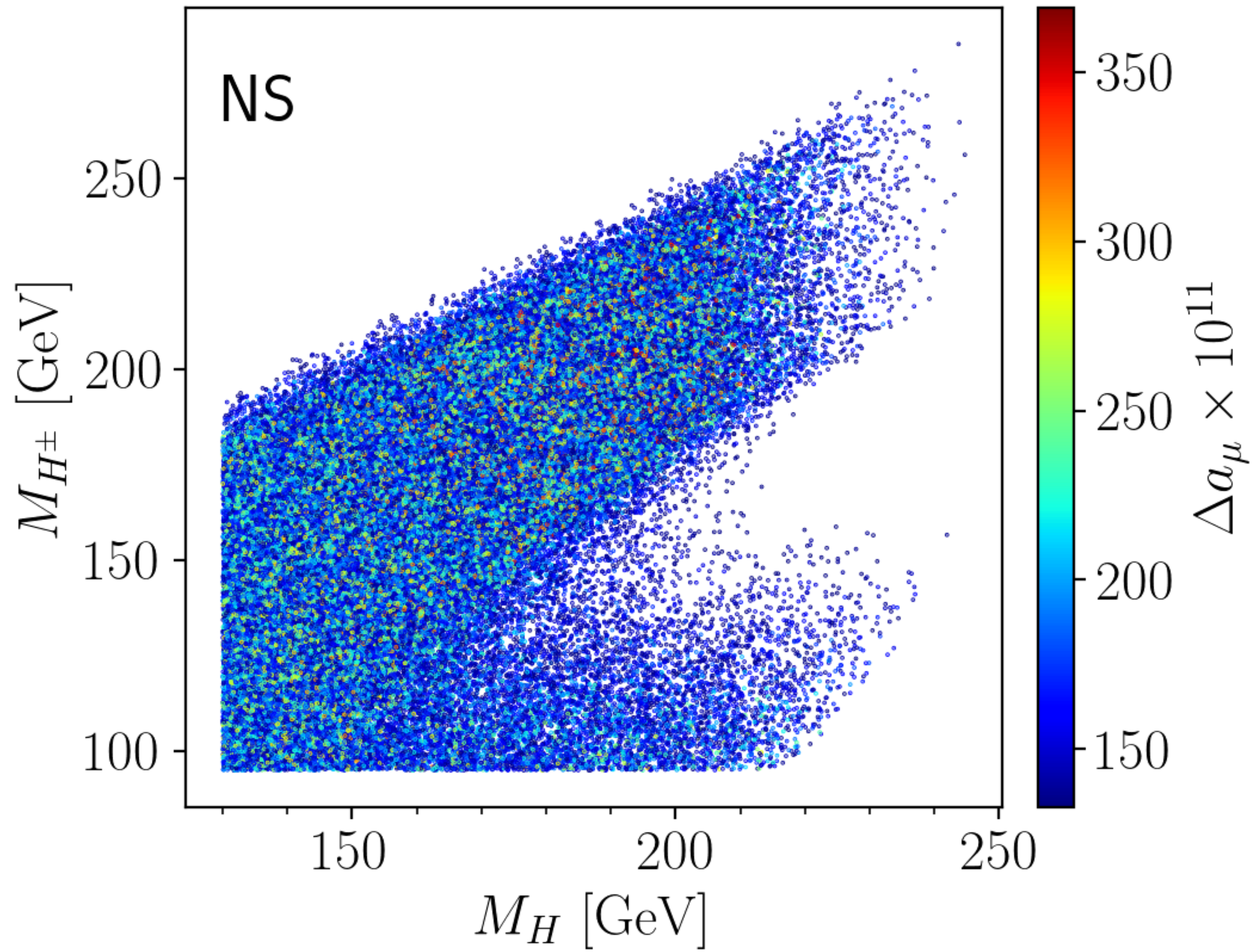


Step I+Theory+EWPD

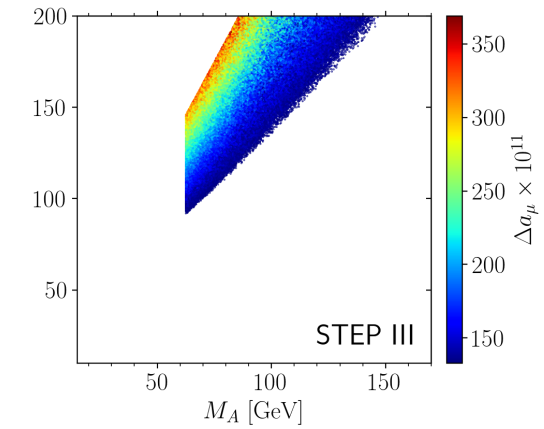
Step II+Collider

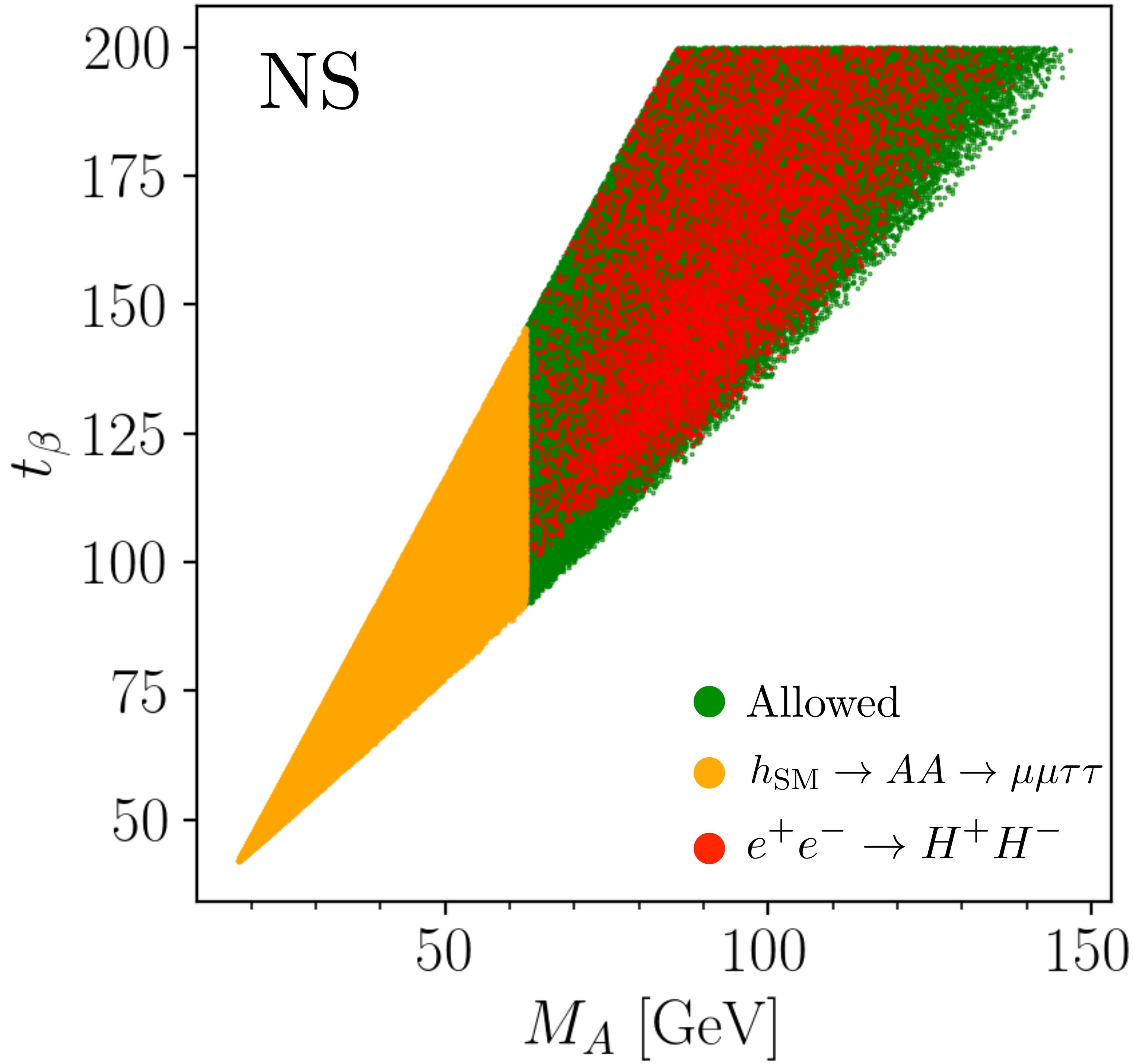
$$\boxed{t_\beta \gtrsim 100, \quad \text{intermediate-mass } A^0}$$

The other parameters are also limited. (i) Not too heavy MH and charged Higgs



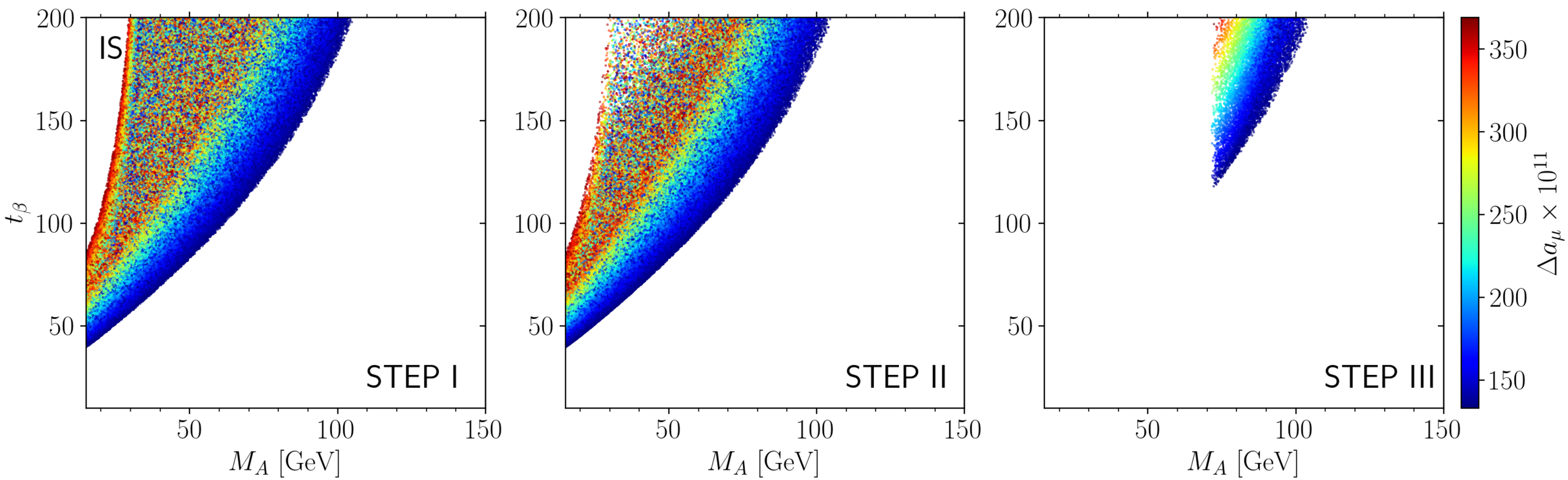
Exotic Higgs decay removes light A.

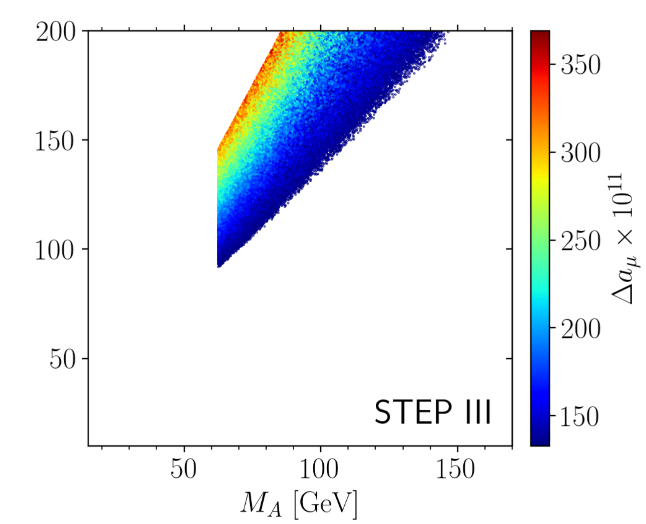




5. (2) Results in the inverted scenario

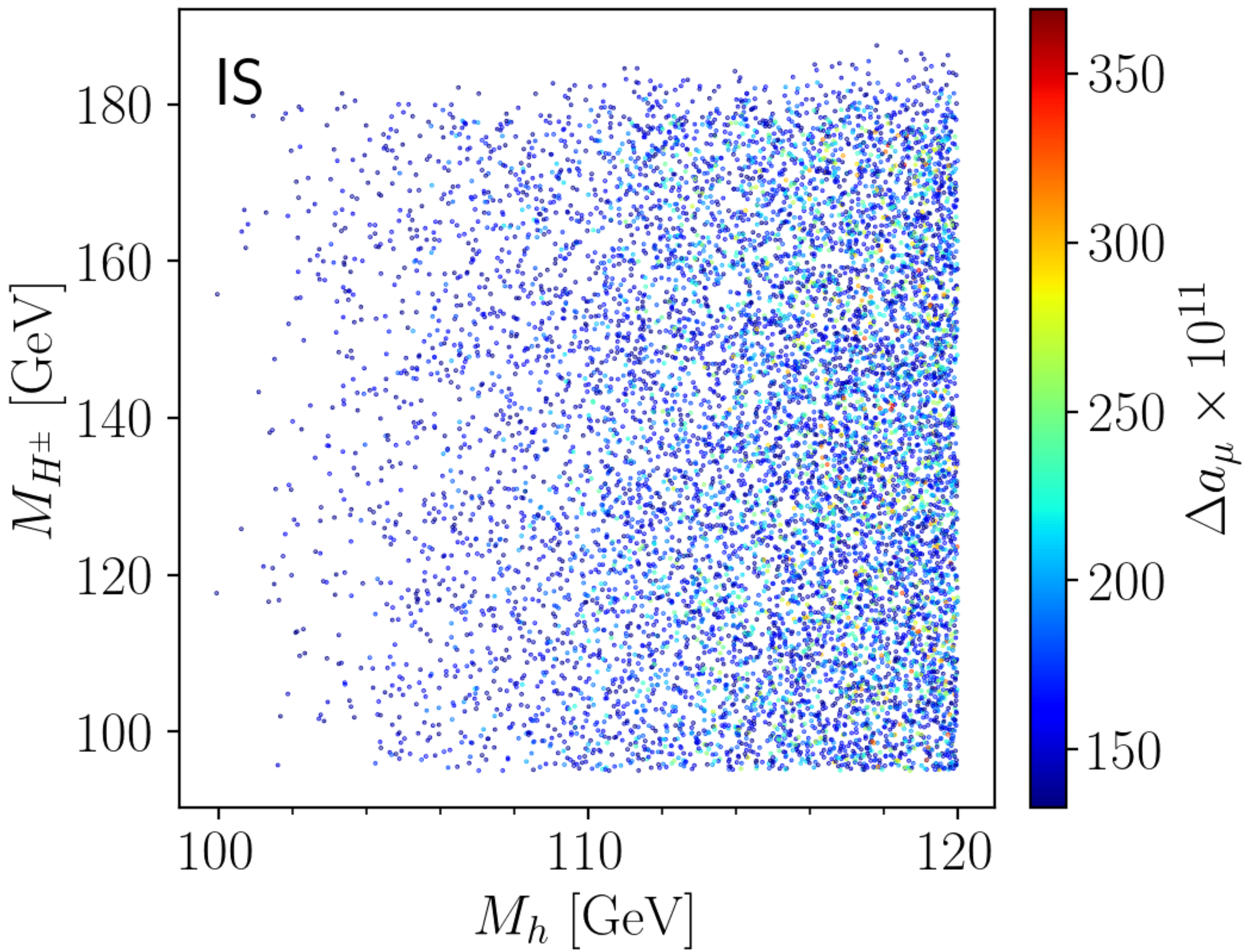
Slightly stronger constraints for the inverted scenario



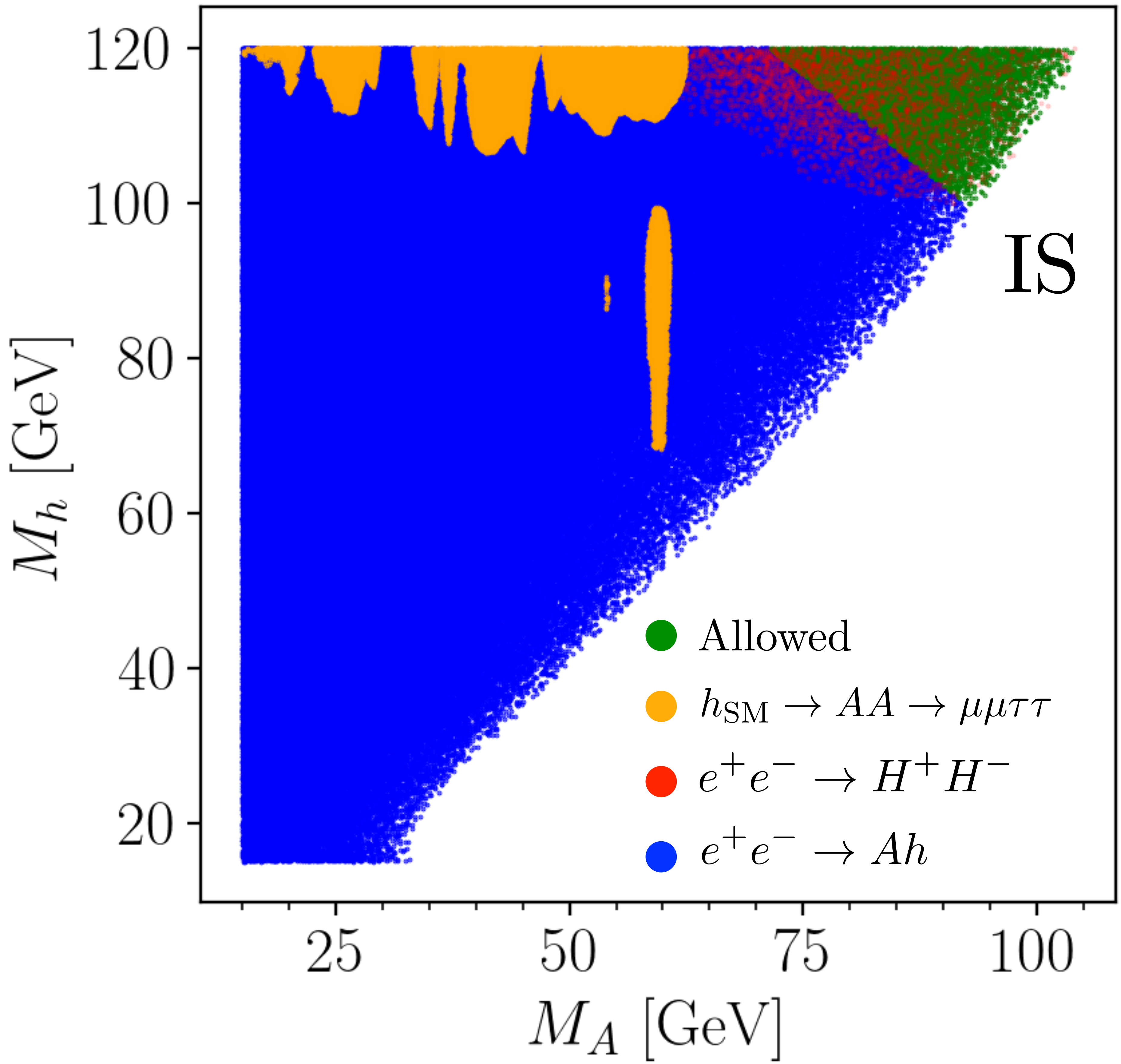


$$\boxed{t_\beta \gtrsim 100, \qquad \text{lighter } A^0}$$

The other parameters are also limited. (i) lighter MH and charged Higgs

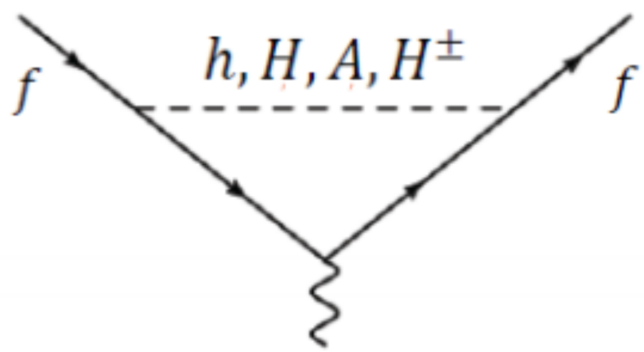


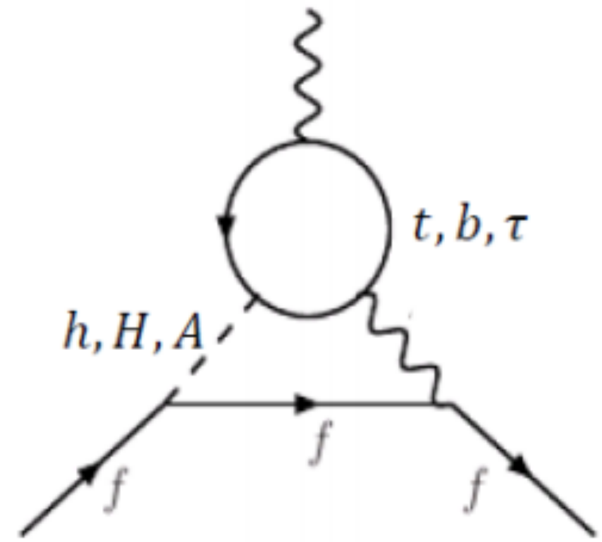
The other parameters are also limited. (ii) LEP search for Ah was crucial.



5. (3) Electron anomalous magnetic moment

In Type-X, the same contributions to the muon/electron g-2 except for mass.





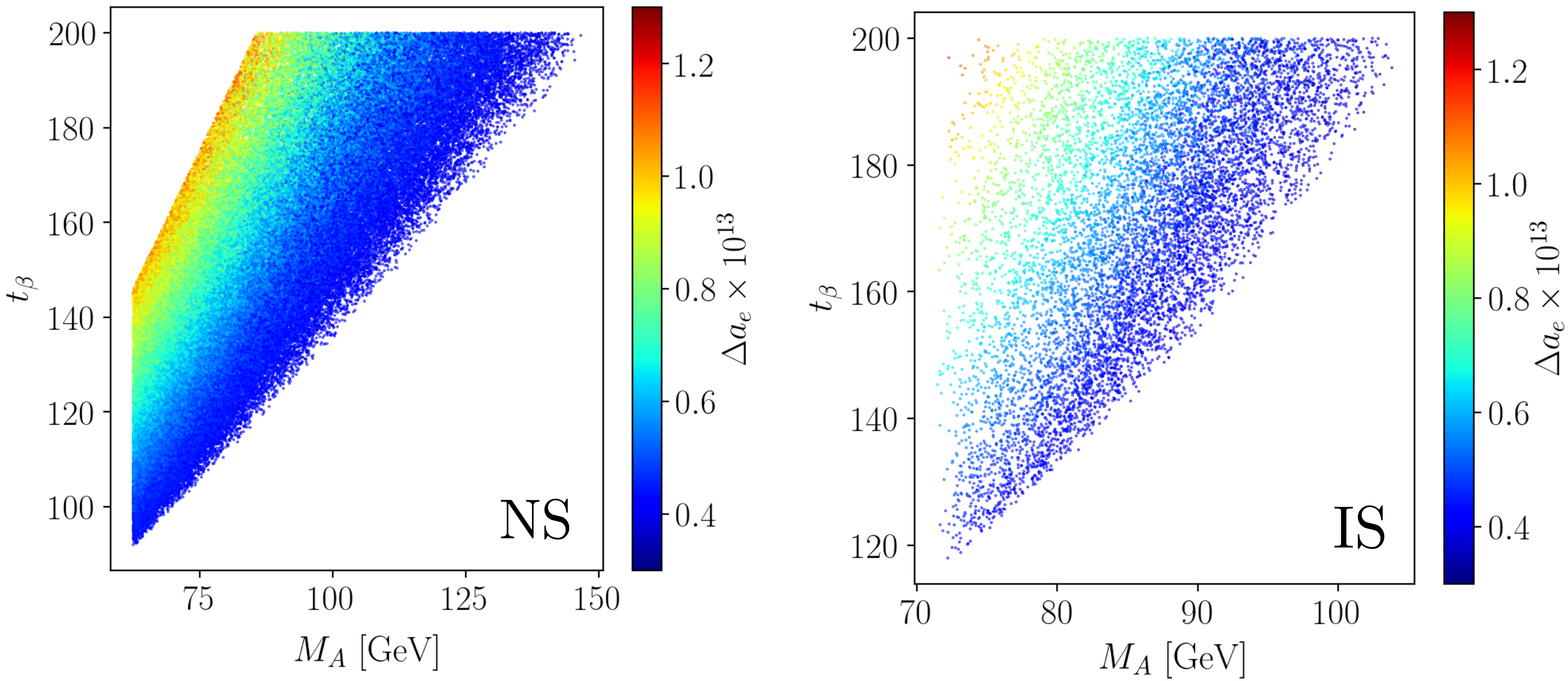
Δa_e is sensitive to the value of the fine structure constant α

$$\Delta a_e^{\mathrm{Cs}} = -8.8(3.6) \times 10^{-13},$$ Science 360 (2018)

$$\Delta a_e^{\mathrm{Rb}} = 4.8(3.0) \times 10^{-13}.$$ Nature 588 (2020)

The electron g-2 observation is consistent with Type-X.

$$\Delta a_e^{\mathrm{Cs}} = -8.8(3.6) \times 10^{-13},$$
$$\Delta a_e^{\mathrm{Rb}} = 4.8(3.0) \times 10^{-13}.$$



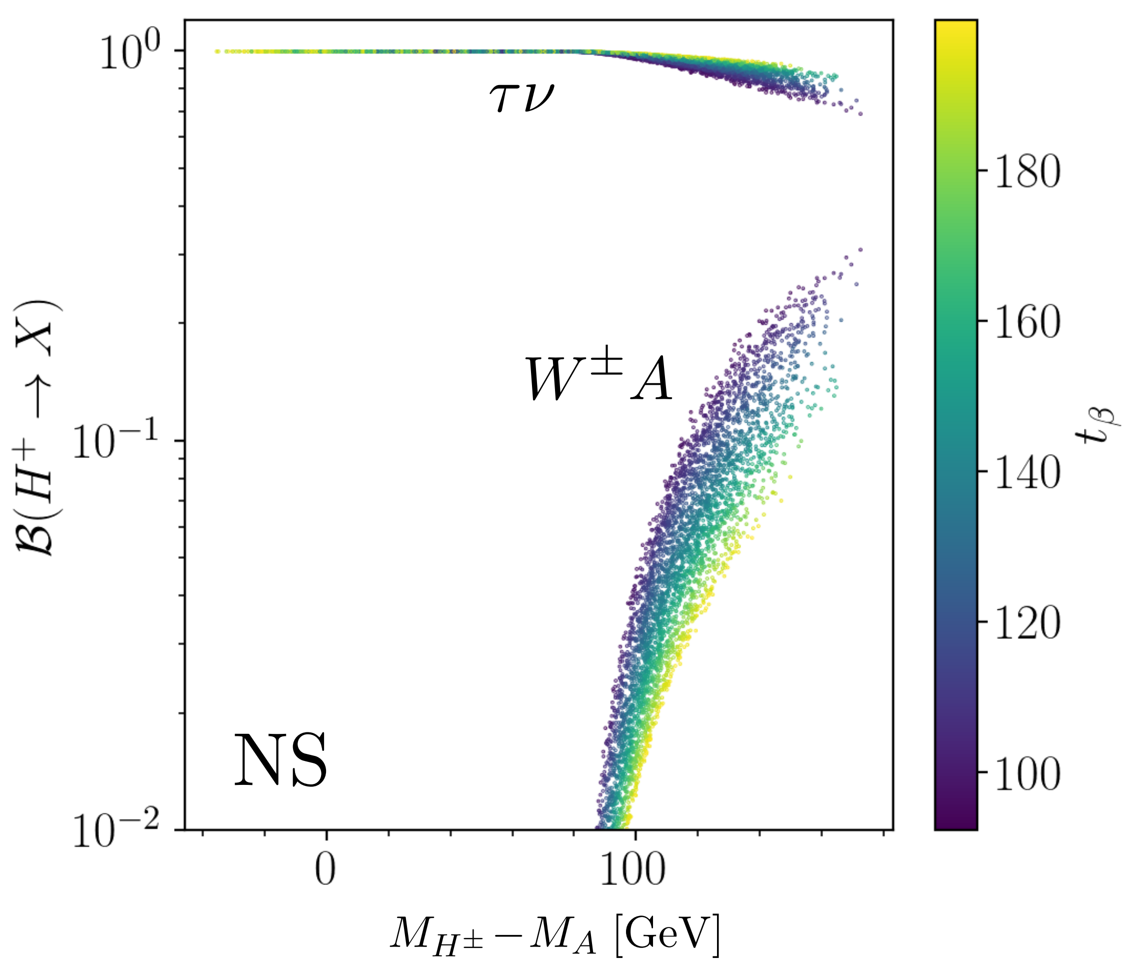
Δa_e^{Rb} at 2σ

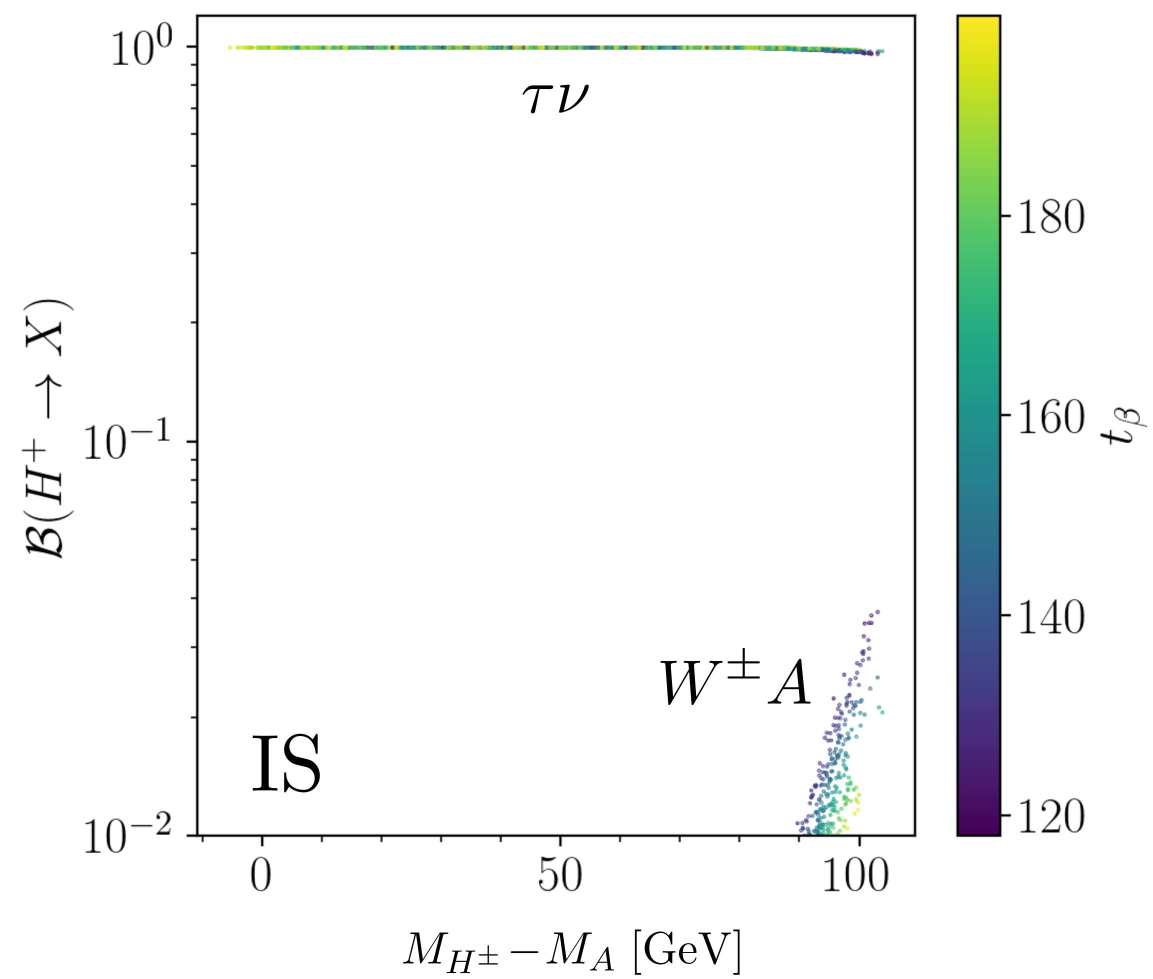
Δa_e^{Cs} at 3σ

5. (4) hadro-phobic new scalars at the LHC

For the final surviving points, new scalar bosons are hadro-phobic,

$$\mathcal{B}(A/\varphi^0 \to \tau^+\tau^-) \sim 1$$



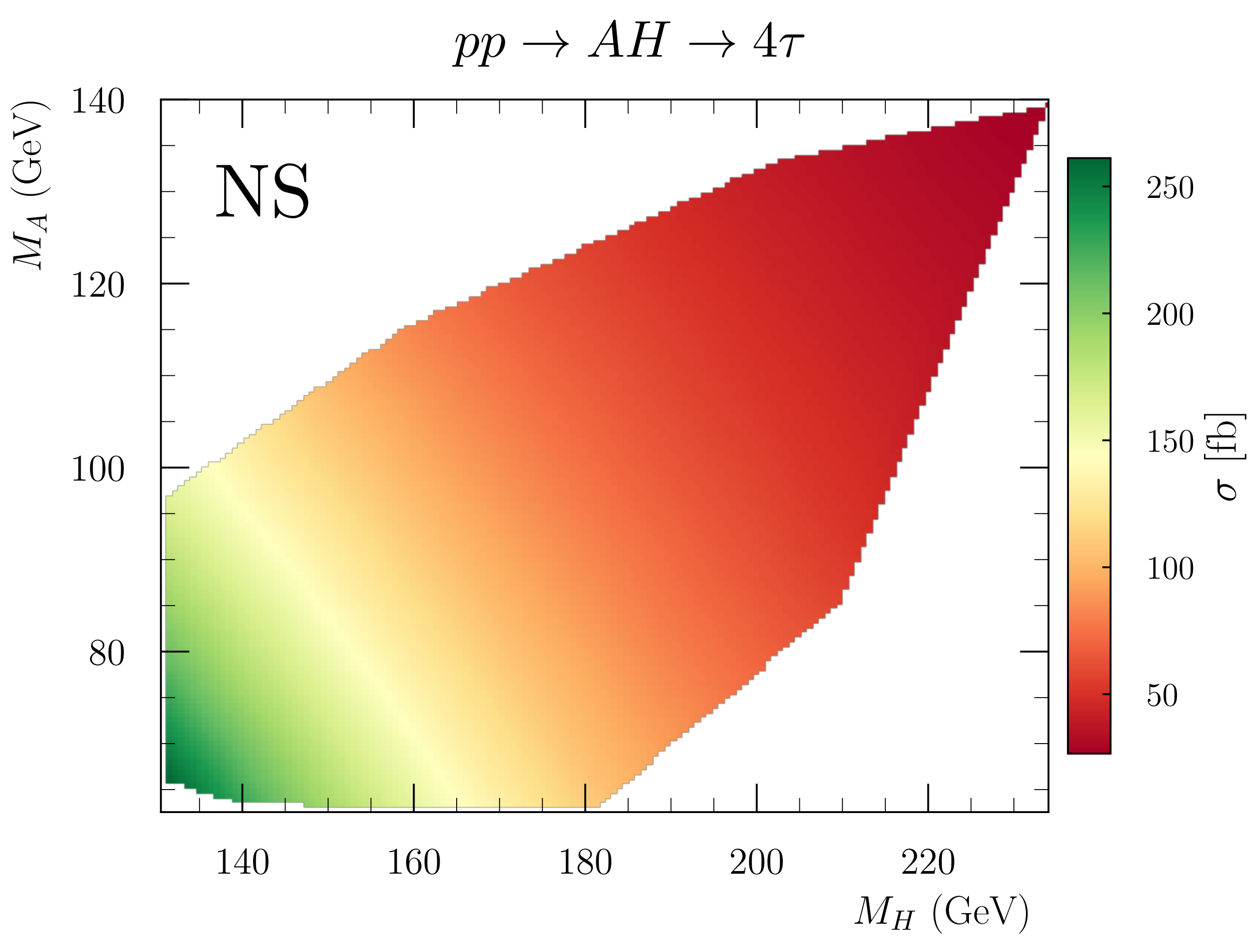


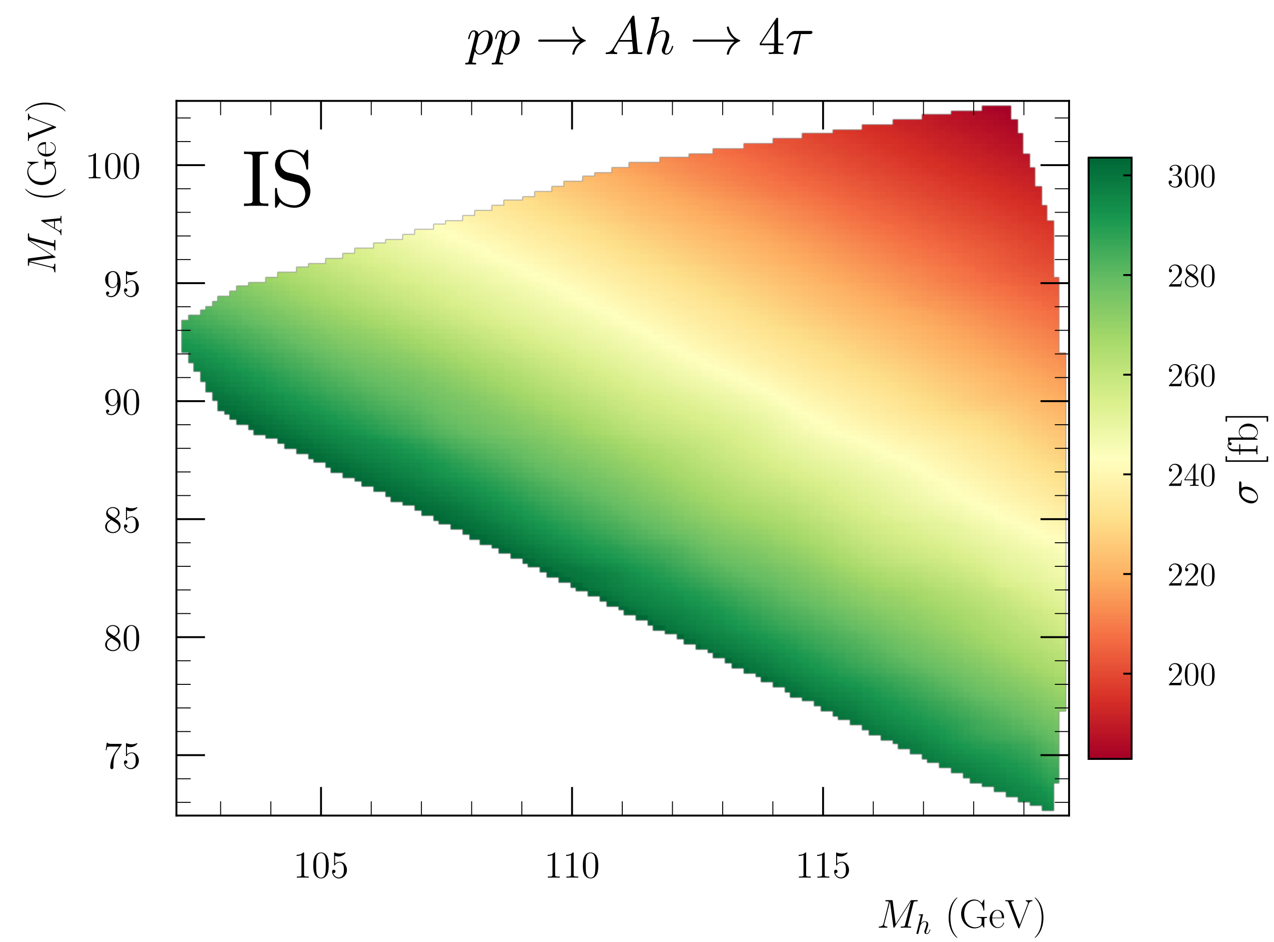
Two golden channels at the LHC.

$$q\bar{q} \to Z^* \to A\varphi^0 \to \tau^+\tau^-\tau^+\tau^-,$$

$$pp \to H^+H^- \to \tau^+\nu\tau^-\nu,$$

Four tau lepton channel: very promising

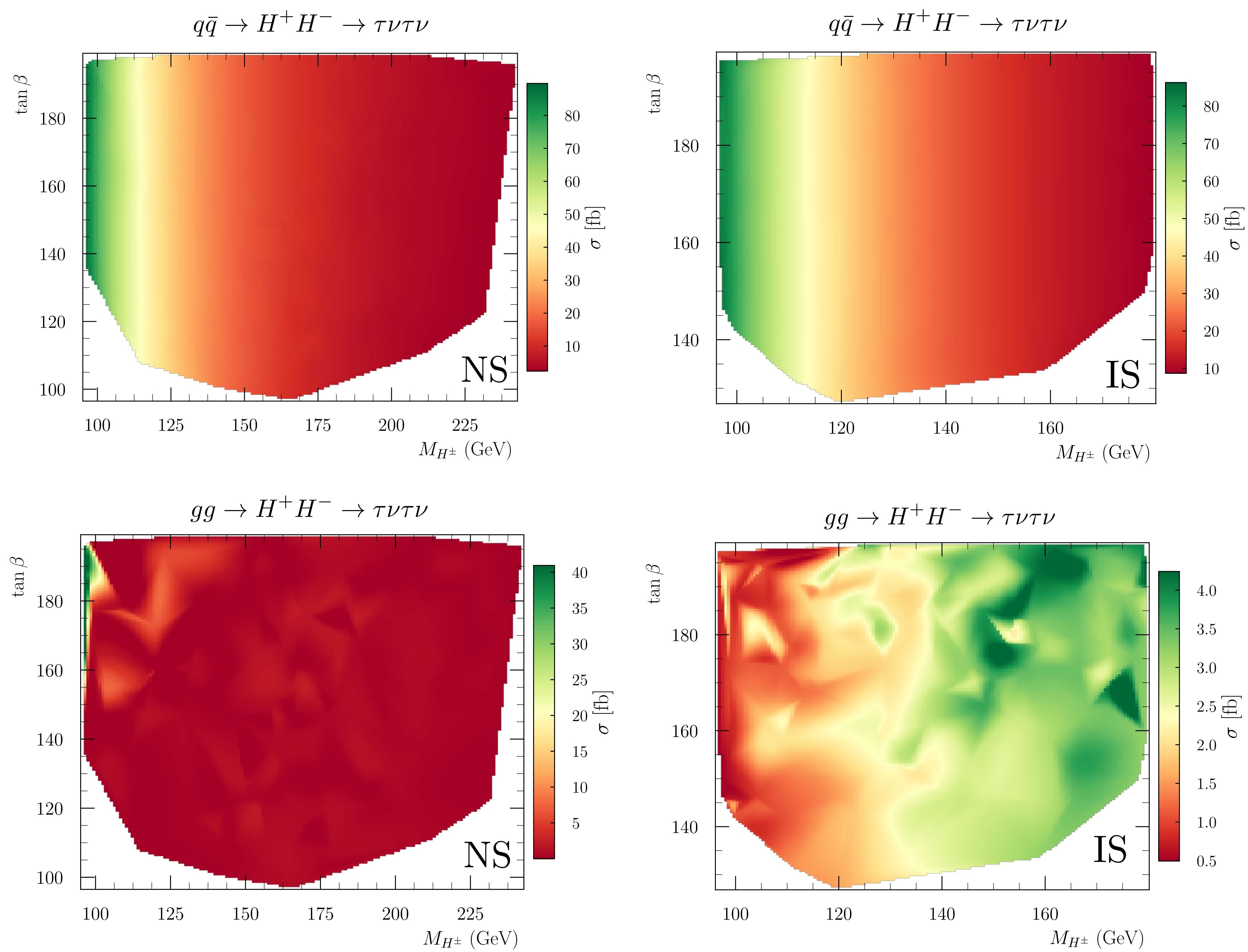




$$\sigma(pp \to ZZ \to 4\tau) \sim 17 \text{ fb at the 13 TeV LHC}$$

1507.06257, 1512.05314

Two tau lepton plus missing ET channel



$$\sigma_{\text{tot}}^{\text{SM}}(pp \to W^+W^- \to \tau\nu\tau\nu) \simeq 1.7 \text{ pb} \quad \text{arXiv:1905.04242},$$

$$\sigma_{\text{tot}}^{\text{SM}}(pp \to ZZ \to \tau^+\tau^-\nu\nu) \simeq 0.1 \text{ pb} \quad \text{arXiv:1507.06257}$$

6. Conclusions

- **In the normal scenario**
  - $\mathbf{t}_\beta \gtrsim \mathbf{90}$ **and** $\mathbf{M_A} \in [\mathbf{m_{125}/2}, \mathbf{145}]$ GeV;
  - $\mathbf{M_H} \in [\mathbf{130}, \mathbf{245}]$ GeV **and** $\mathbf{M_{H^\pm}} \in [\mathbf{95}, \mathbf{285}]$ GeV.
- **In the inverted scenario**
  - $\mathbf{t}_\beta \gtrsim \mathbf{120}$ **and** $\mathbf{M_A} \in [\mathbf{70}, \mathbf{105}]$ GeV;
  - $\mathbf{M_H} \in [\mathbf{100}, \mathbf{120}]$ GeV **and** $\mathbf{M_{H^\pm}} \in [\mathbf{95}, \mathbf{185}]$ GeV;
  - $\mathbf{M_A} + \mathbf{M_h} \gtrsim \mathbf{190}$ GeV.