The 2021 CERN-CKC Theory Workshop:
BSM physics towards the end of the pandemic
2021. 6. 9.

Comprehensive study of Type-X 2HDM in light of the muon g-2

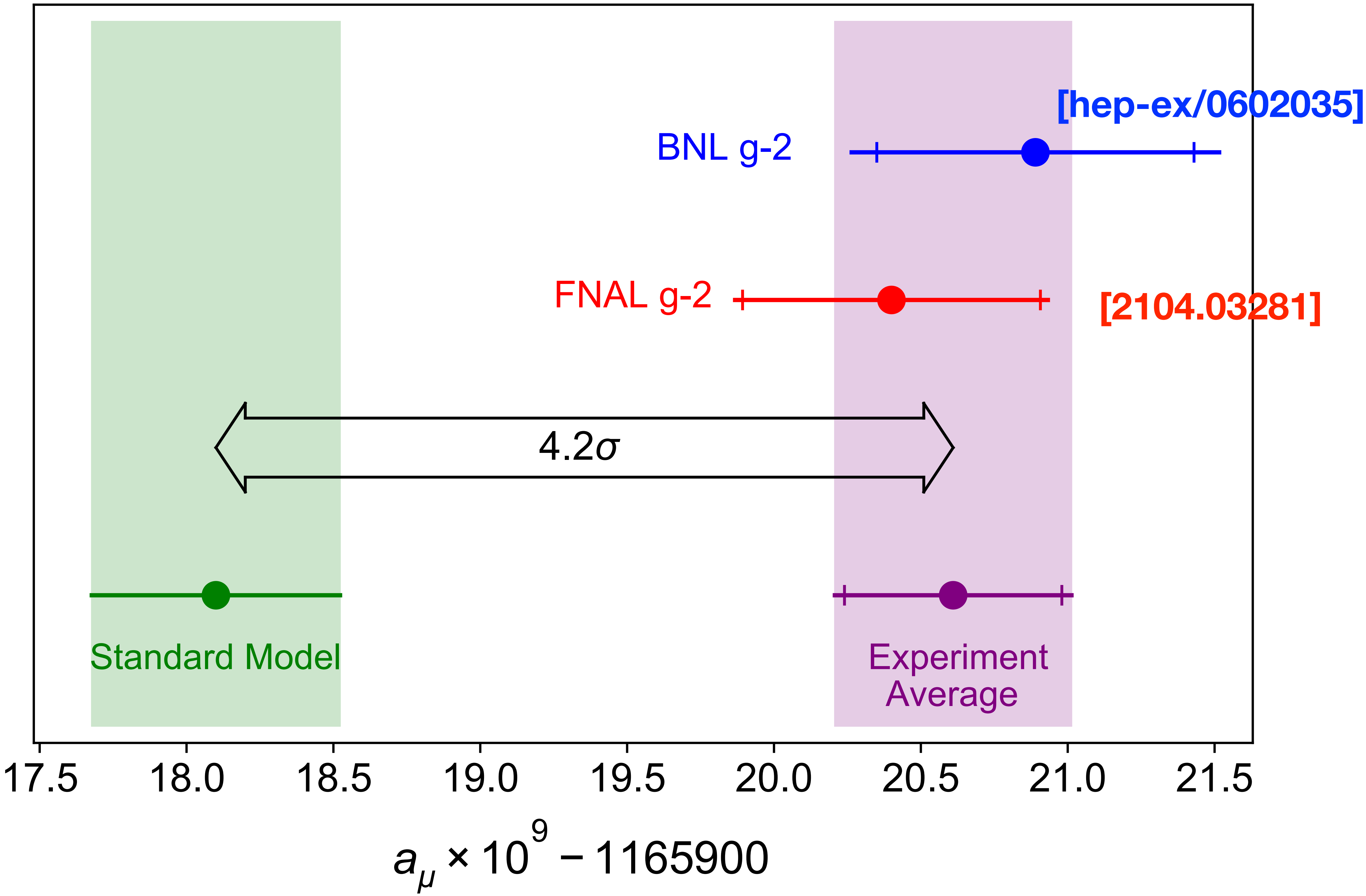
Jeonghyeon Song
(Konkuk University, Korea)

w/ A. Jueid, J. Kim, S. Lee, arXiv: 2104.10175

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

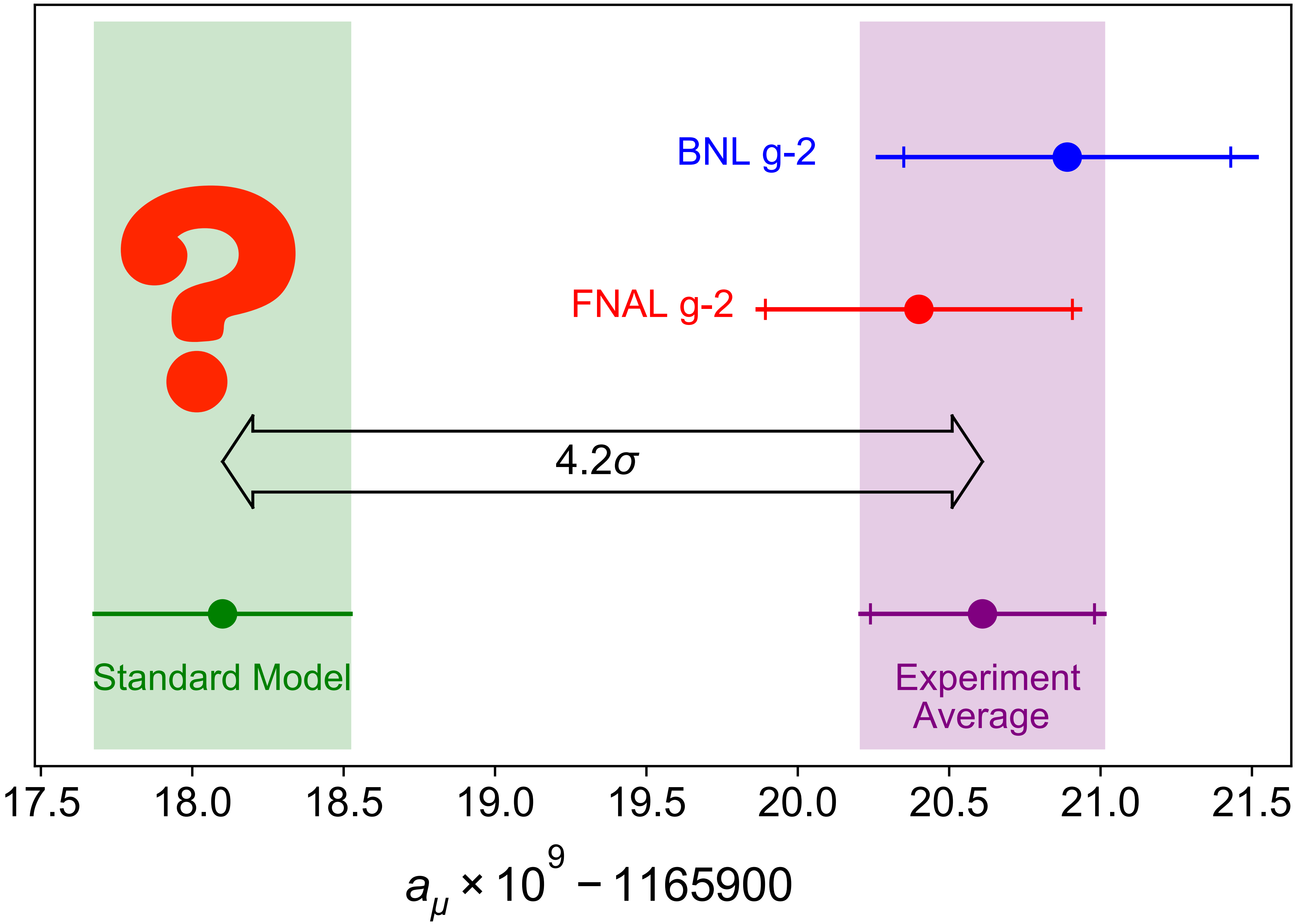
1. Motivation

Beautiful measurement of muon g-2 by BNL and Fermilab ➡ reduced error



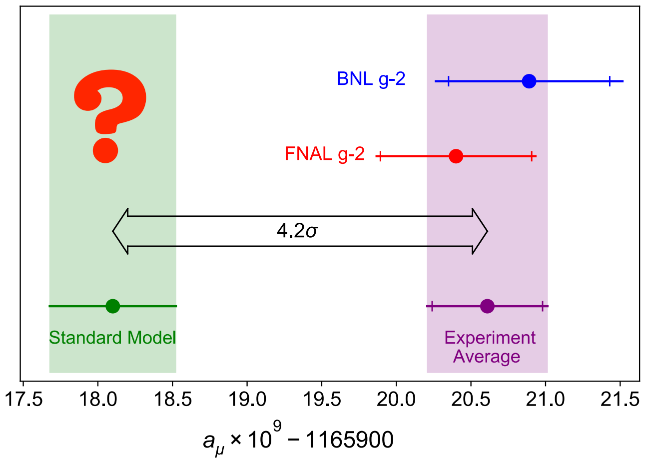
1. Motivation

The SM prediction is still controversial.

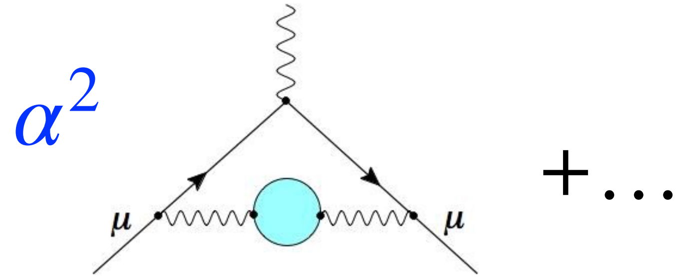


1. Motivation

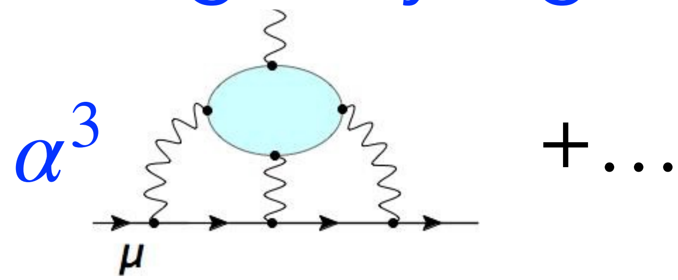
4.2σ from the White paper [2006.04822]: data-driven results for HVP & HLbL

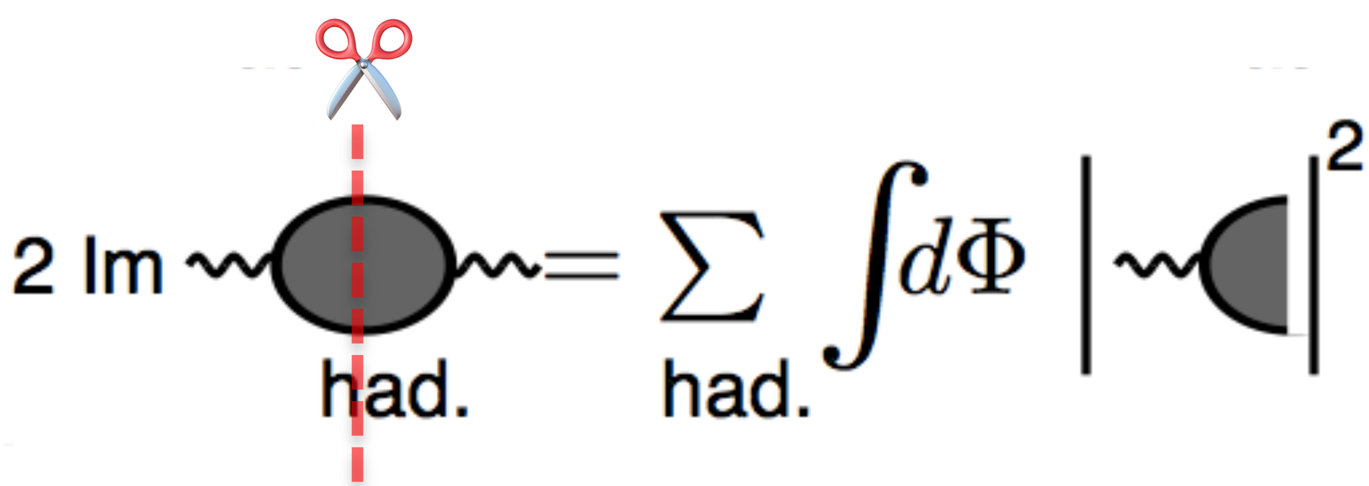


…Vacuum Polarization (HVP)



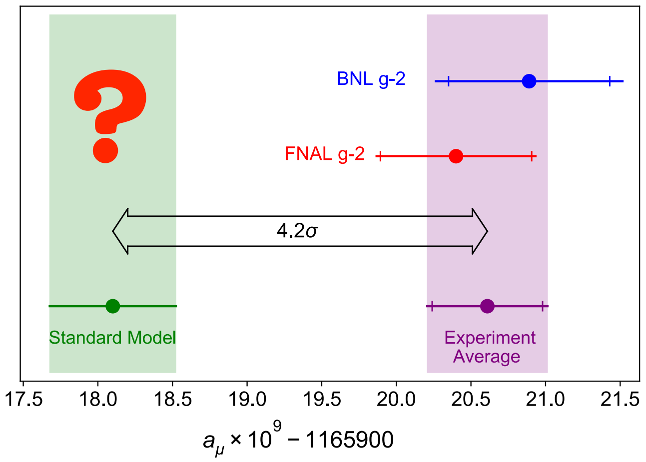
…Light-by-Light (HLbL)

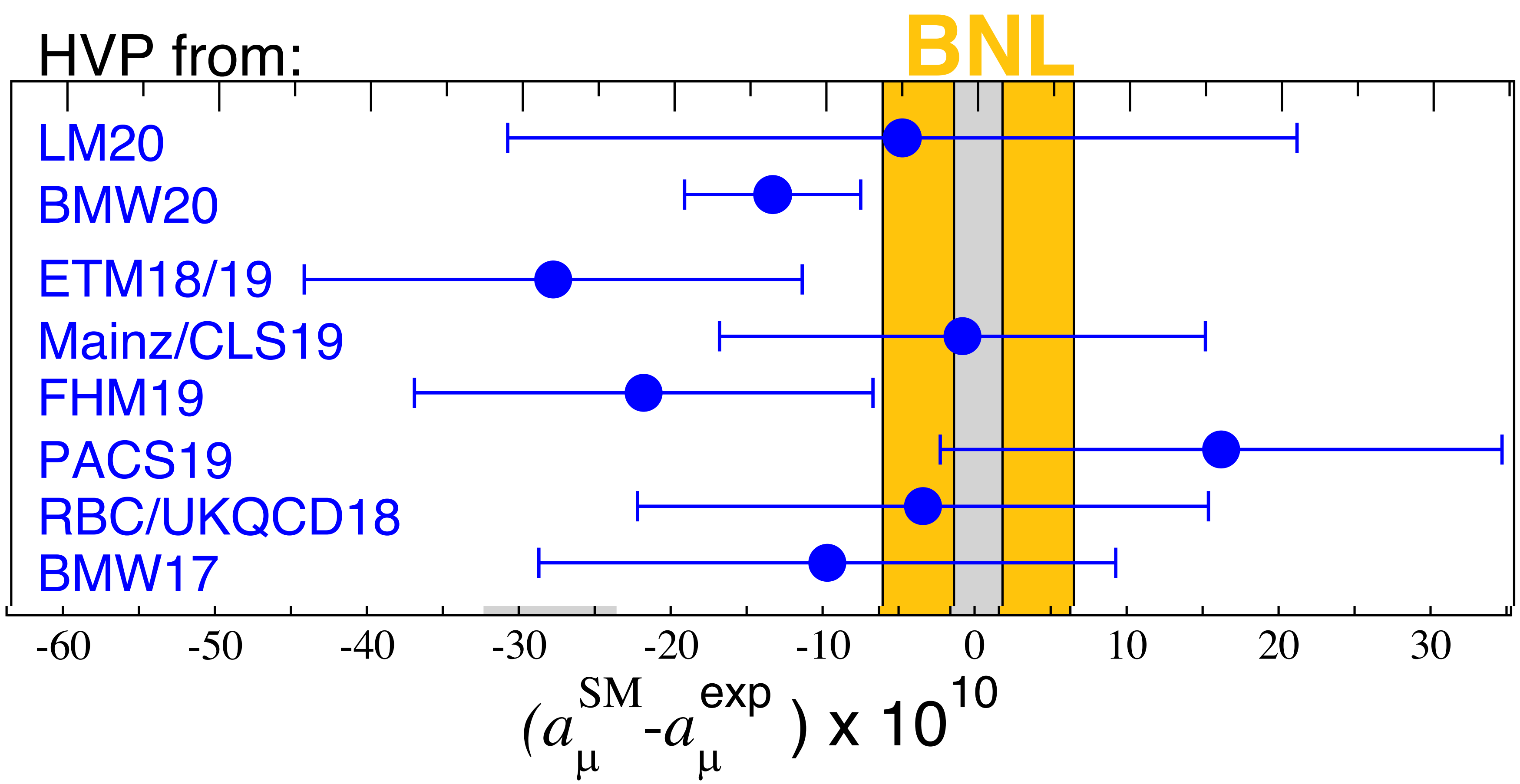




1. Motivation

If we take the Lattice results, the measurement is consistent with the SM.





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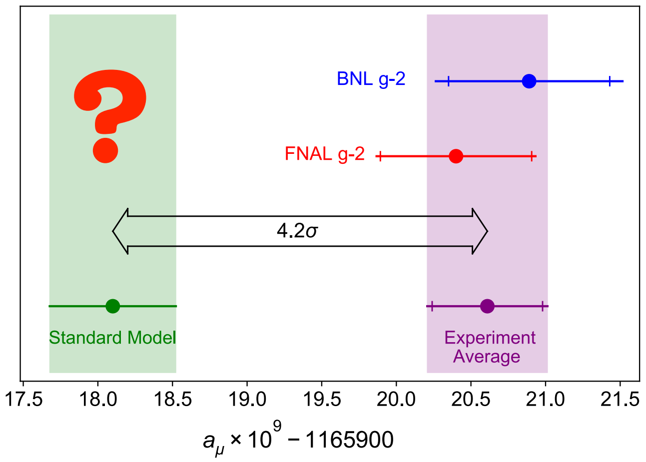
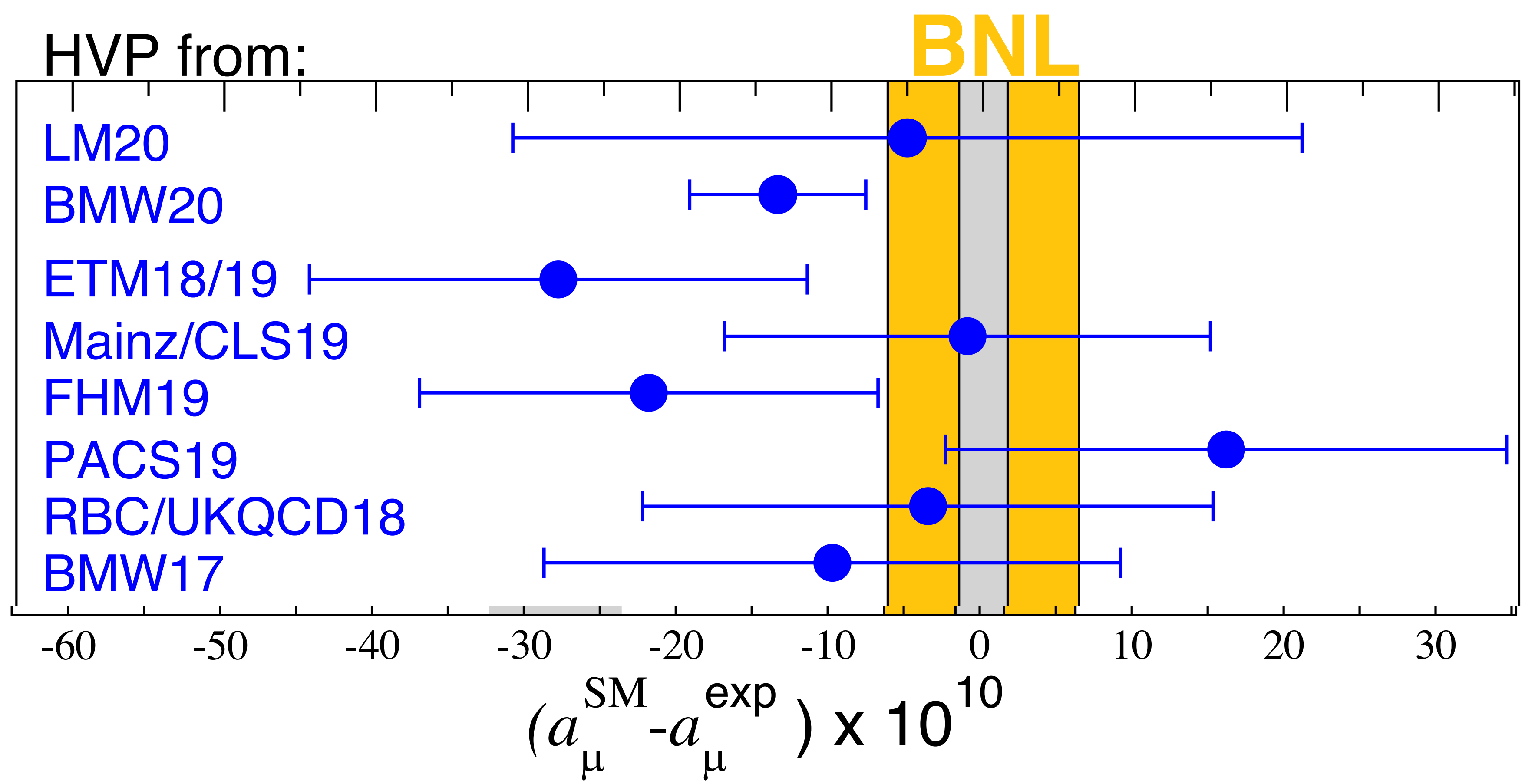


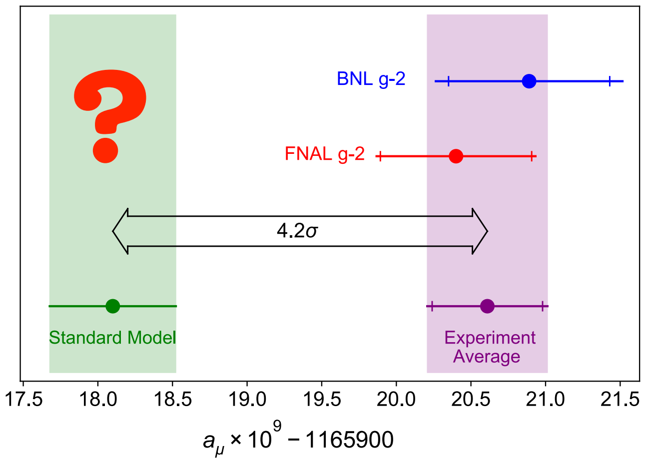


- Large spread between results
- Large systematic uncertainties
- Tension with EW precision data

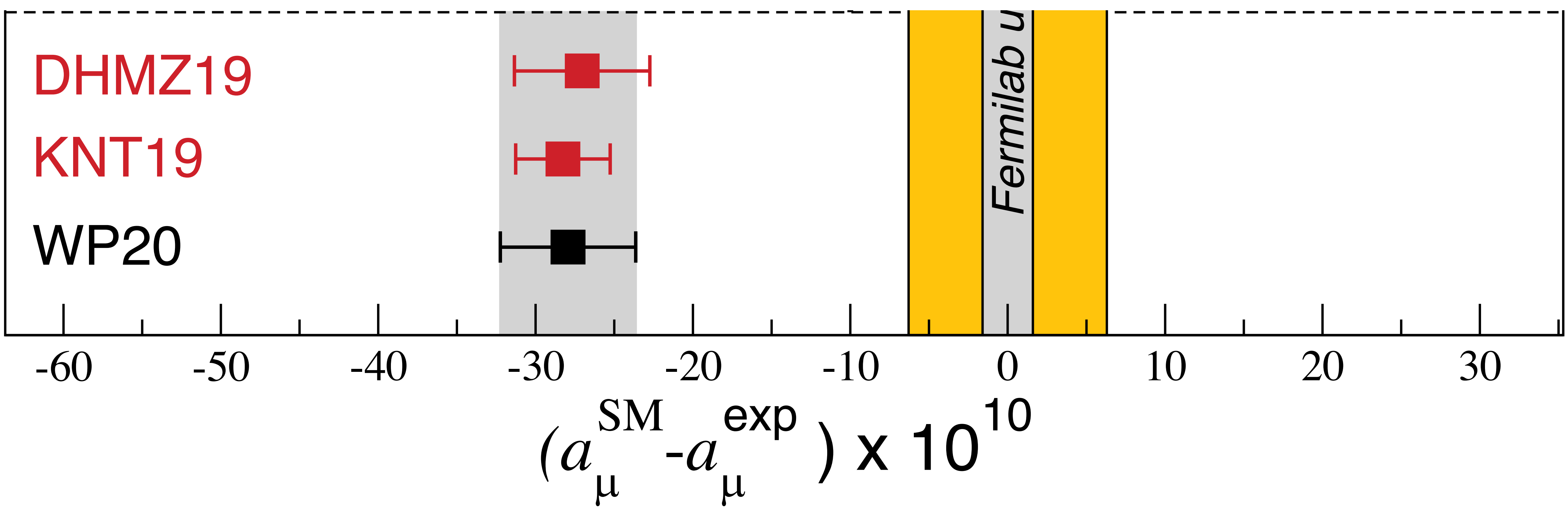
[2003.04886]

1. Motivation

The WP value is based on a conservative merging process!



Dispersive data-driven



1. Motivation

We take the muon g-2 anomaly as a NP signal.

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

> 0

NP signal at 4.2σ

1. Motivation

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

1. Motivation

Common factors of NP models

1. SUSY:
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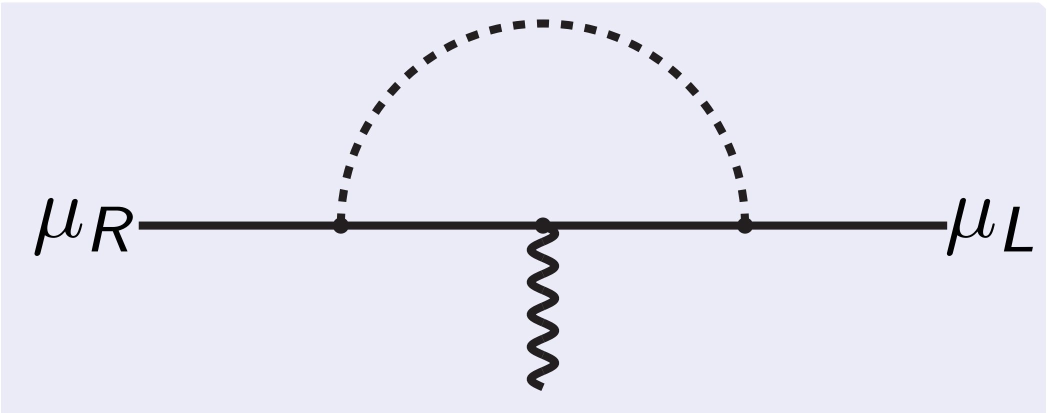
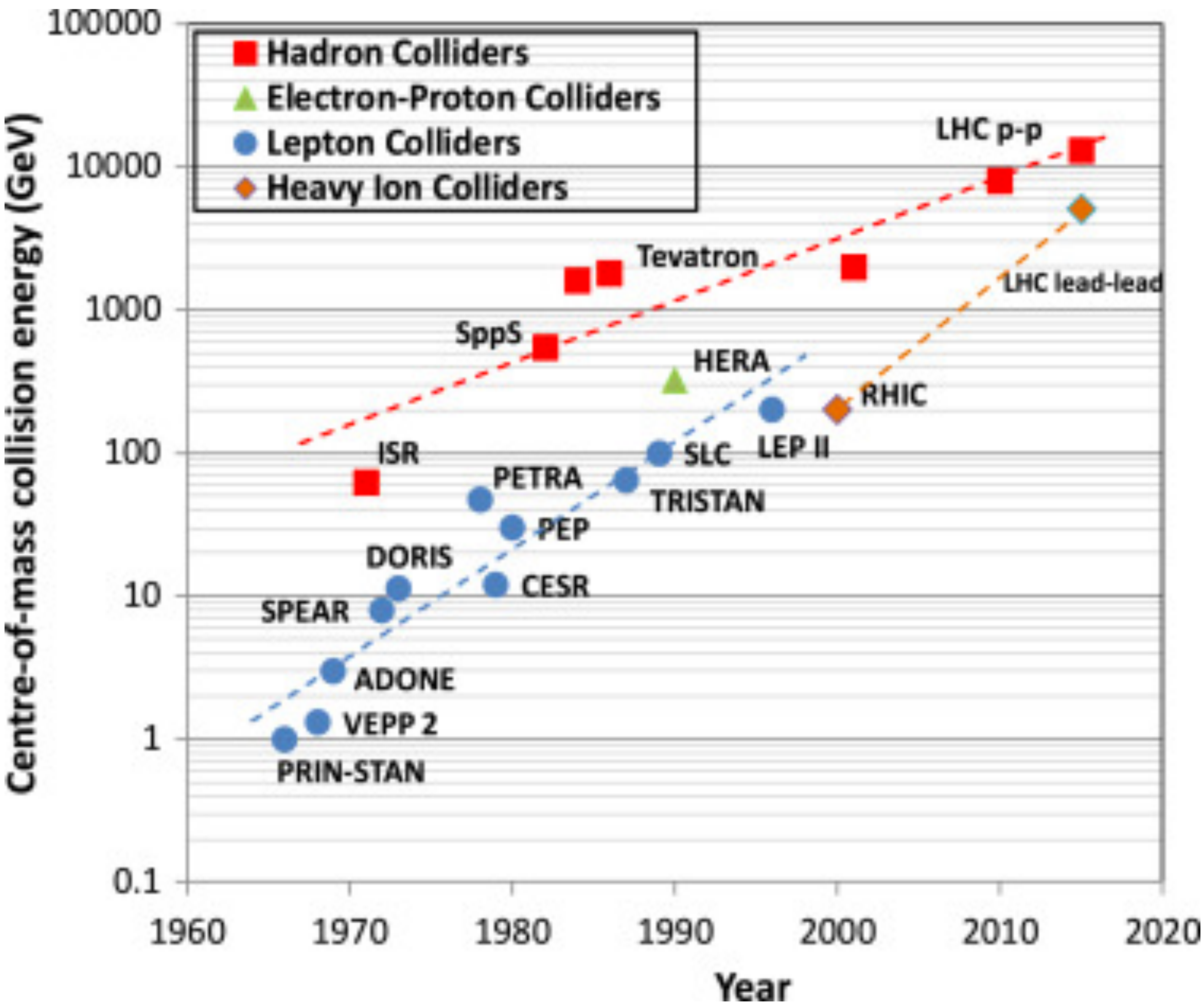
- Loop-induced
- CP- and Flavor-conserving
- Chirality-flipping



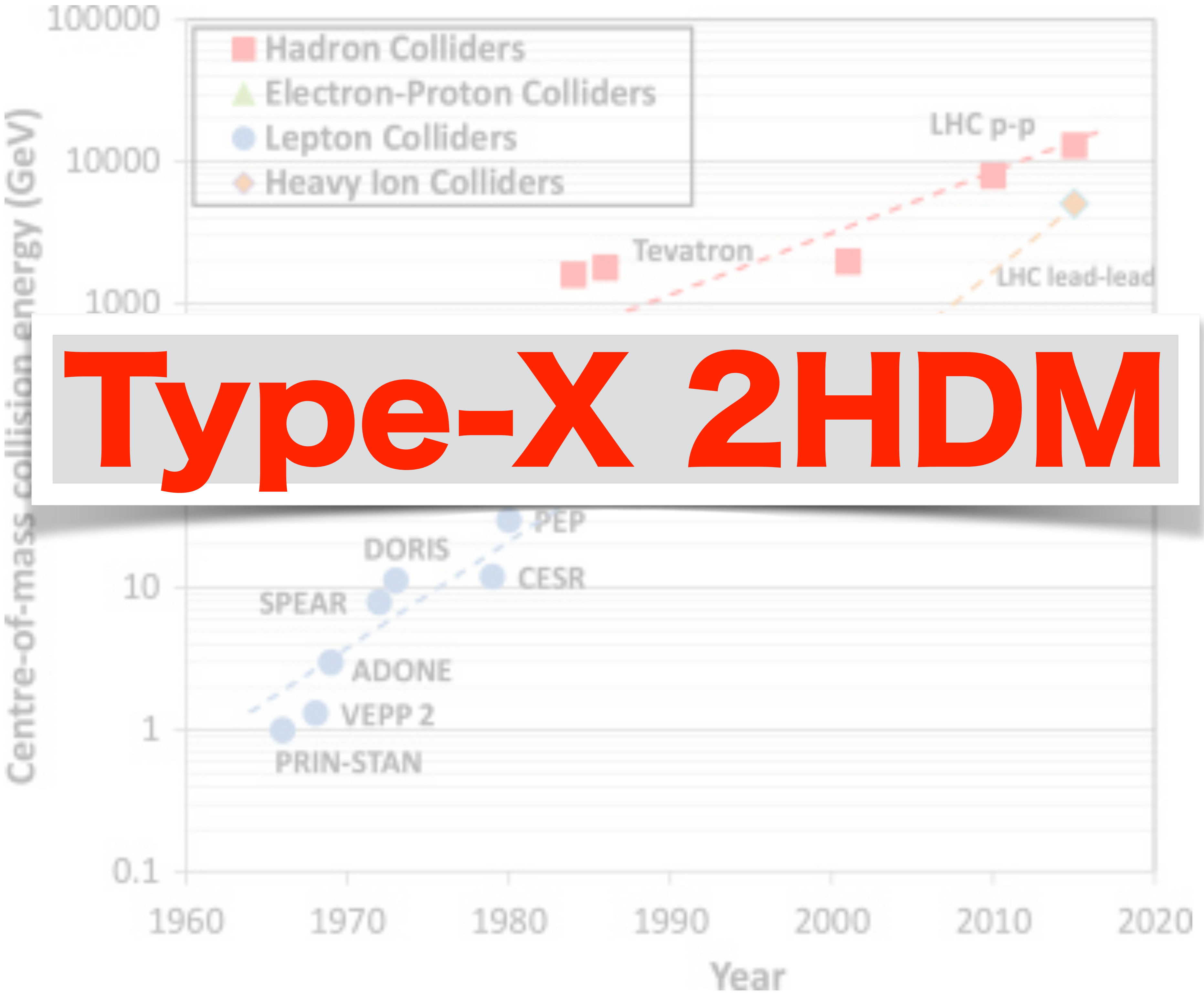
1. Motivation

Research must go on! We have a vast amount of experimental data.



1. Motivation

Beyond explaining the muon g-2.
Whole parameter space of one model for all the data



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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A discrete Z_2 symmetry for no tree level FCNC:

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

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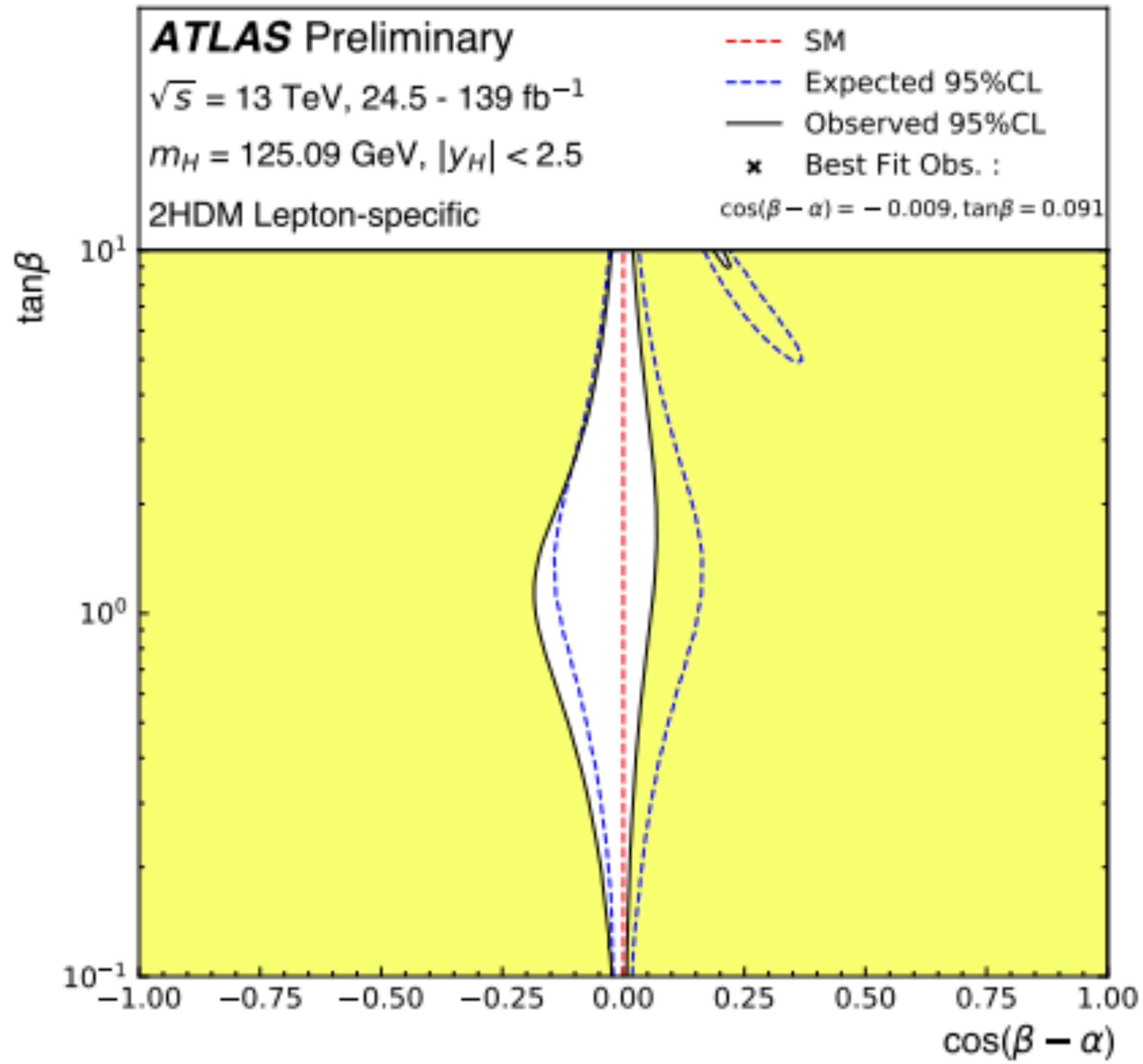
$$\boxed{\begin{aligned} V_\Phi = \;& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) \\ & + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger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

2. Type-X 2HDM

Minimal assumption from the Higgs precision data: alignment limit

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



ATLAS-CONF-2020-027

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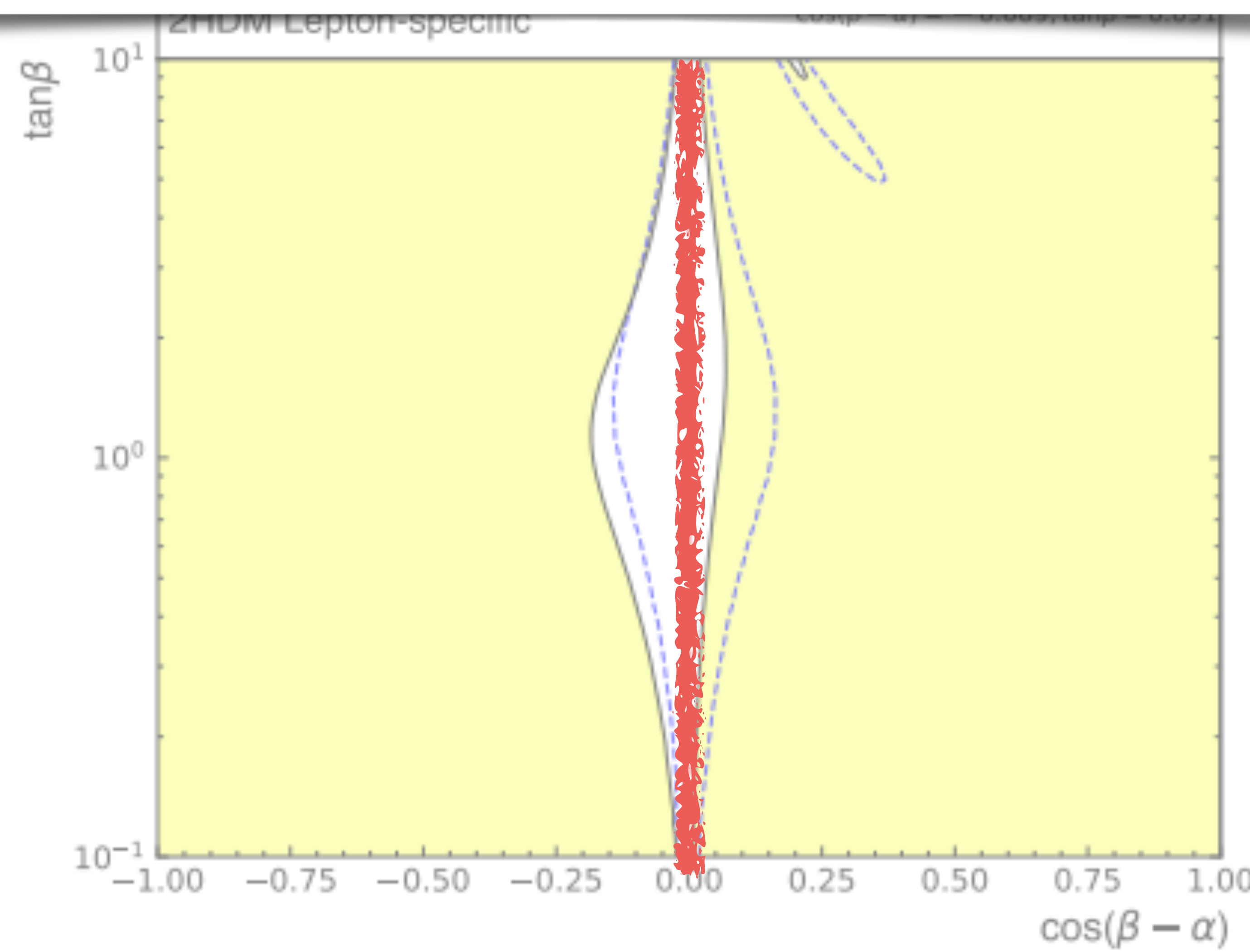
Alignment limit



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2. Type-X 2HDM

No arbitrary suppressions of h-A-A vertex in the alignment limit.

$$\lambda_{hAA} = \frac{1}{2v^2}\left[(2M^2 - 2m_A^2 - m_h^2)s_{\beta-\alpha} + (M^2 - m_h^2)(\cot\beta - \tan\beta)c_{\beta-\alpha}\right]$$

- If $M_A < m_h/2$,

$$\mathcal{B}(h_{\rm SM} \to AA) < 0.2 \Longrightarrow \lambda_{hAA} \lesssim 6 \times 10^{-3}$$

- Conspiracy of M_A, α, β, m_{12} to suppress λ_{hAA}?

$$\tan(\beta-\alpha) = \frac{M^2 - m_h^2}{2M^2 - 2m_A^2 - m_h^2}(\tan\beta - \cot\beta)$$?

- Stick to $s_{\beta-\alpha} = 1$.

2. Type-X 2HDM

Two scenarios & model parameters

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

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

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

New CP-even scalar boson

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

2. Type-X 2HDM

Theoretical stabilities require strong constraints due to chain reaction.

$$t_\beta \simeq 100$$

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

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

$$\lambda_3 = \frac{1}{v^2}\left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^\pm}^2\right],$$

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

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

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

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

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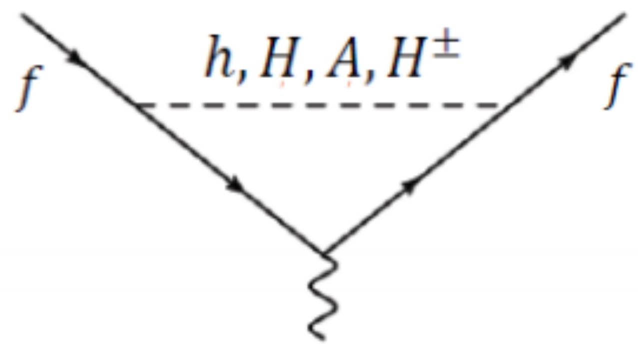
$$\lambda_5 = \frac{1}{v^2}\left[M^2 - M_A^2\right],$$

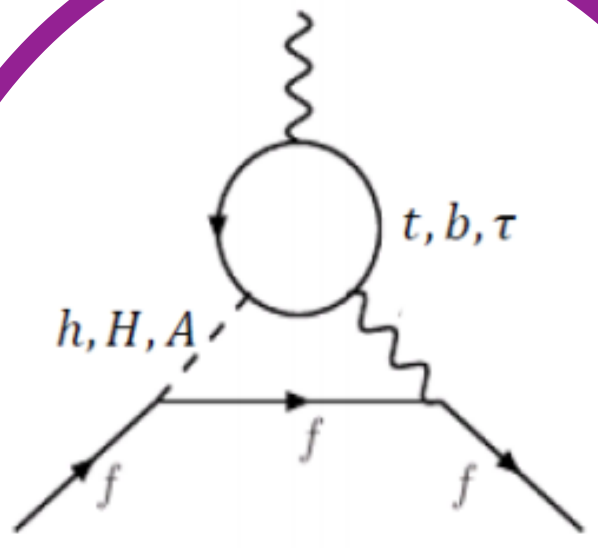
$$M_A \sim M_{H^\pm} \sim M \approx m_{\varphi^0}.$$

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

Two kinds of contributions



1-loop

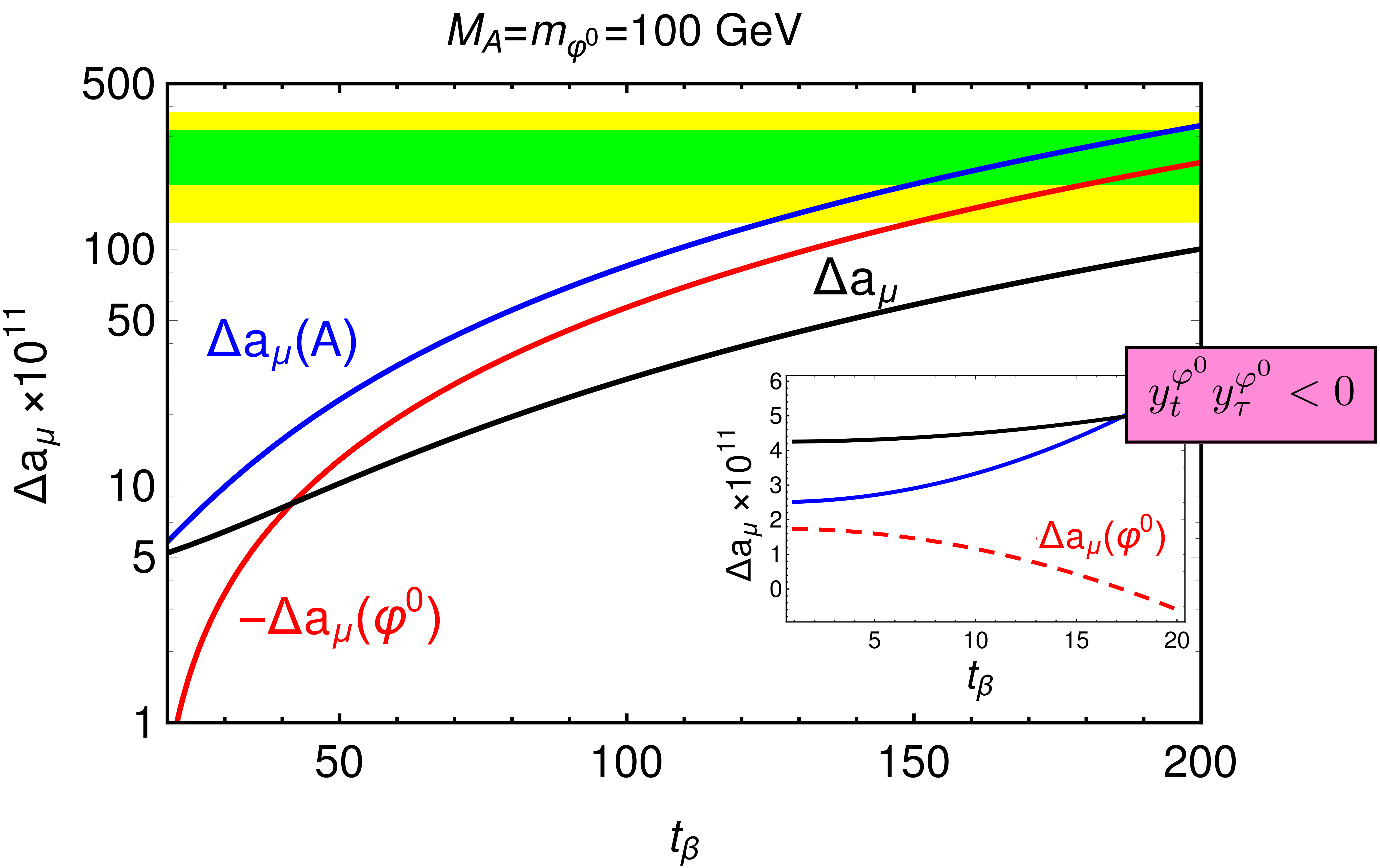


Barr-Zee 2-loop

Dominant

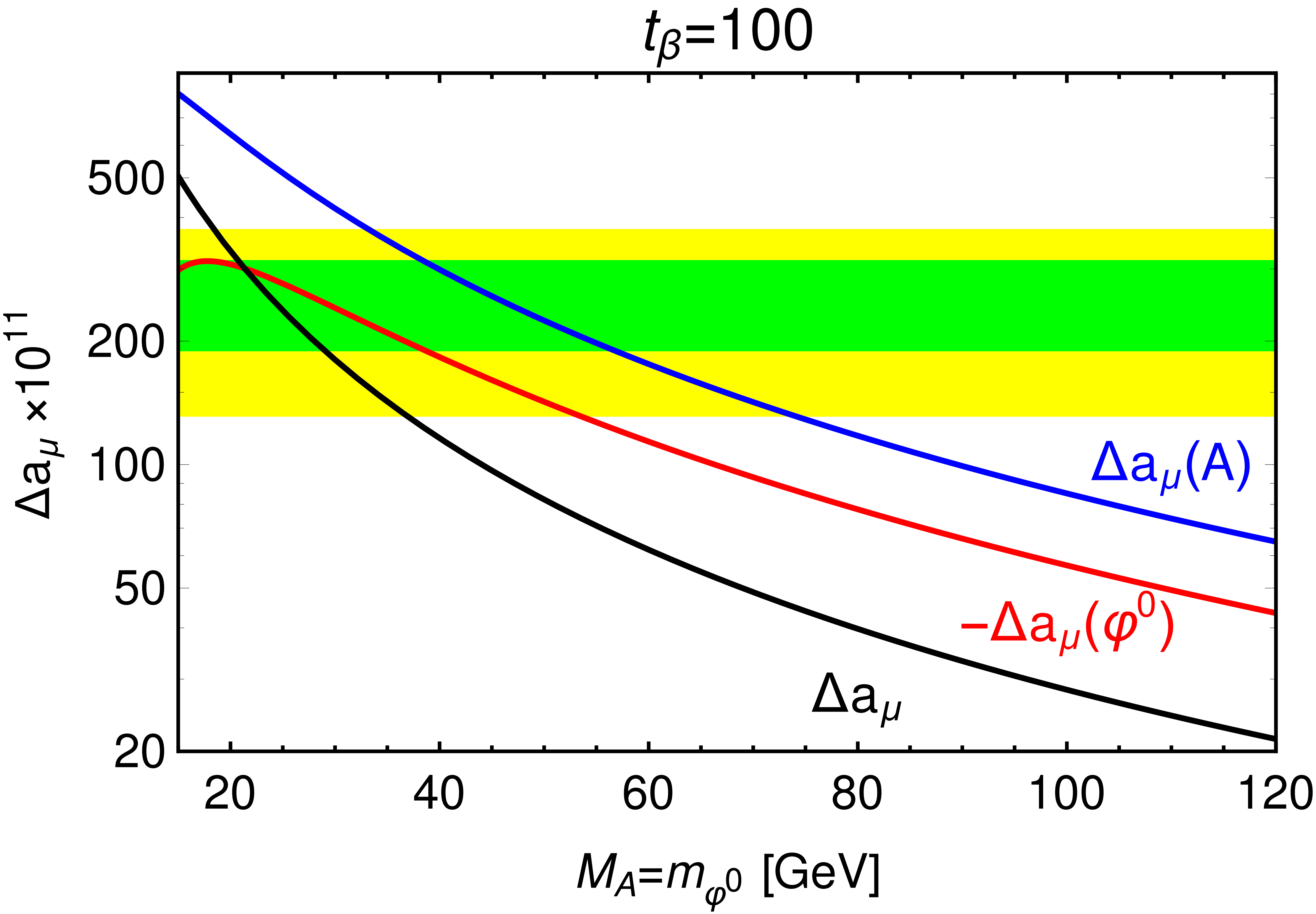
3. Muon g-2 in Type-X 2HDM

Large tanβ is required. CP-even scalar cannot explain the observed muon g-2.



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

A light pseudo scalar A helps, but a light CP-even scalar doesn't.



4. Other constrains

Scan strategy in three 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`.

4. Other constrains

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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HiggsBounds provide powerful checkup.

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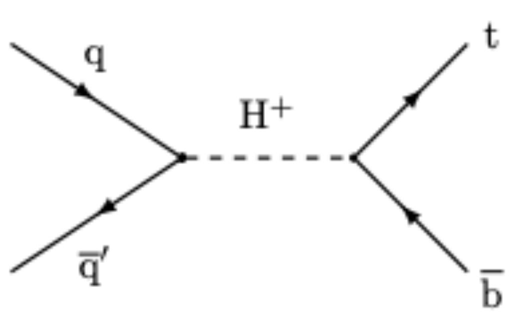

4. Other constrains

The inverted scenario survived harder, 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.

4. Other constrains

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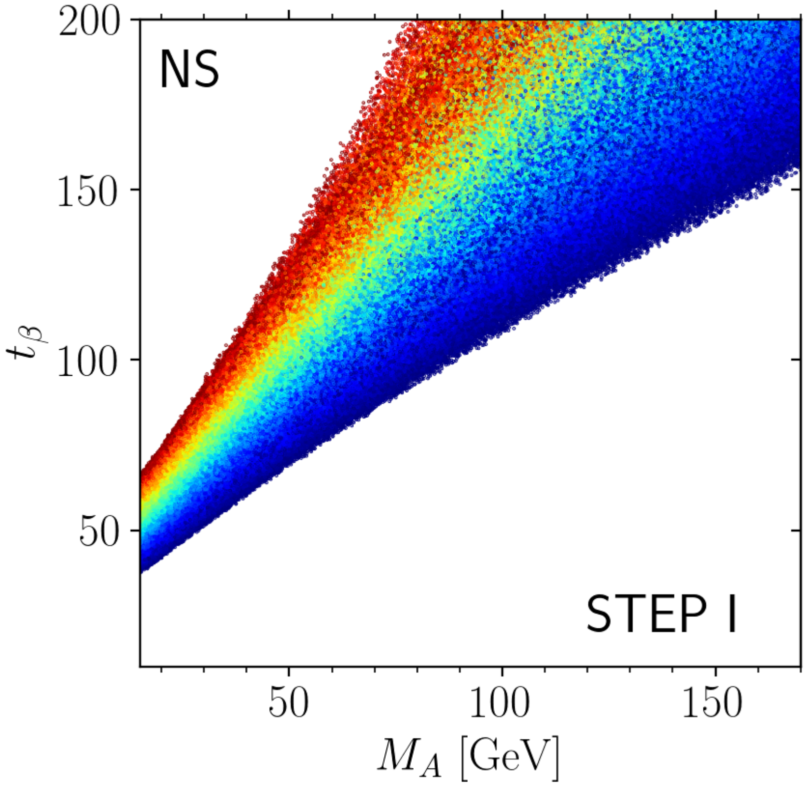
- For each scenario, we obtained 5×10^5 parameter sets satisfying Step II.
- After Step III,
  - Normal scenario: $\sim 80\%$ survived.
  - Inverted scenario: $\sim 1.8\%$ parameter sets survived.

The inverted scenario is not dead.

5. Results

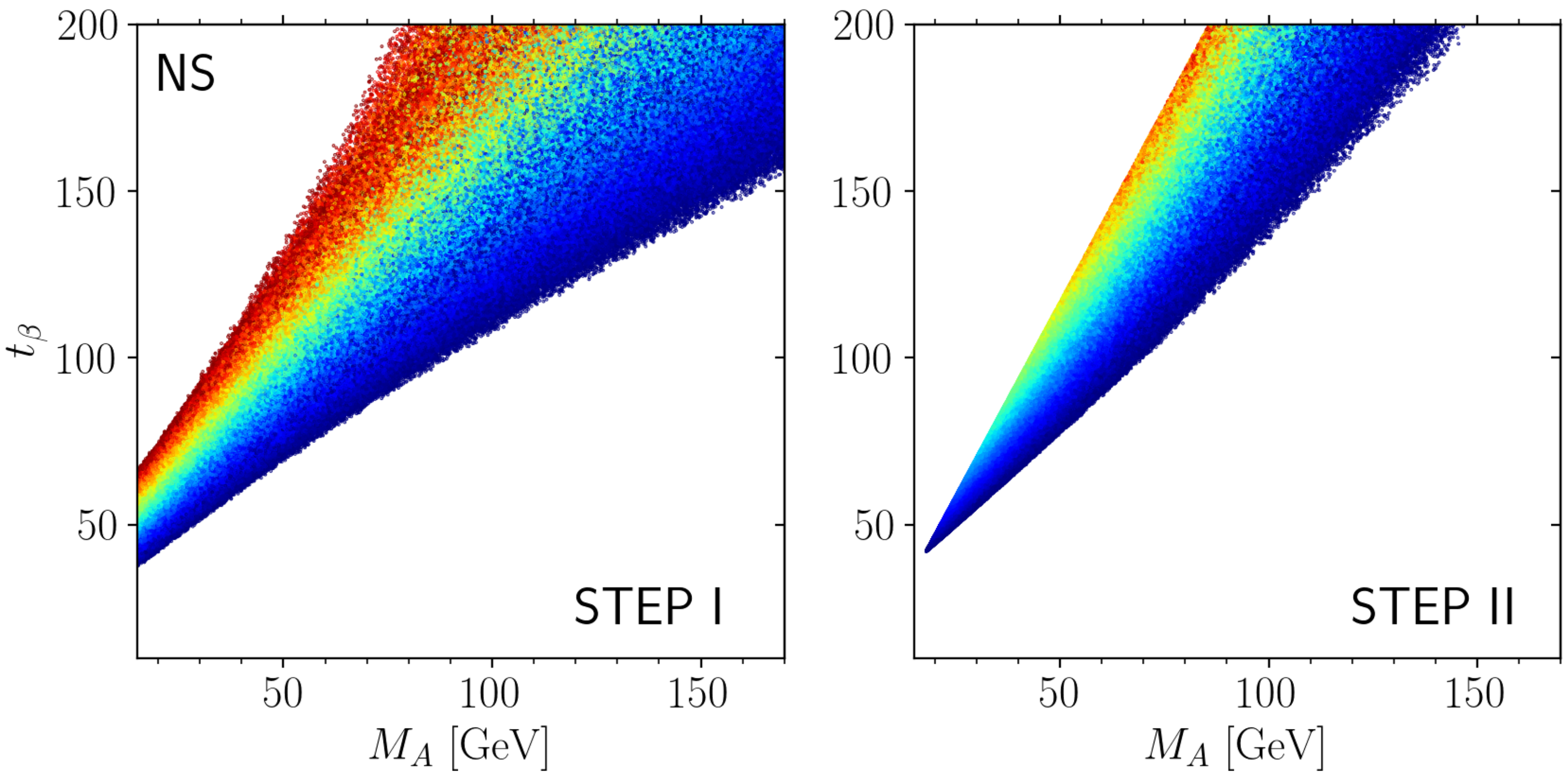
(1) In the normal scenario, collider data are crucial.



Δa_μ

5. Results

(1) In the normal scenario, collider data are crucial.



Δa_μ Step I+Theory+EWPD

5. Results

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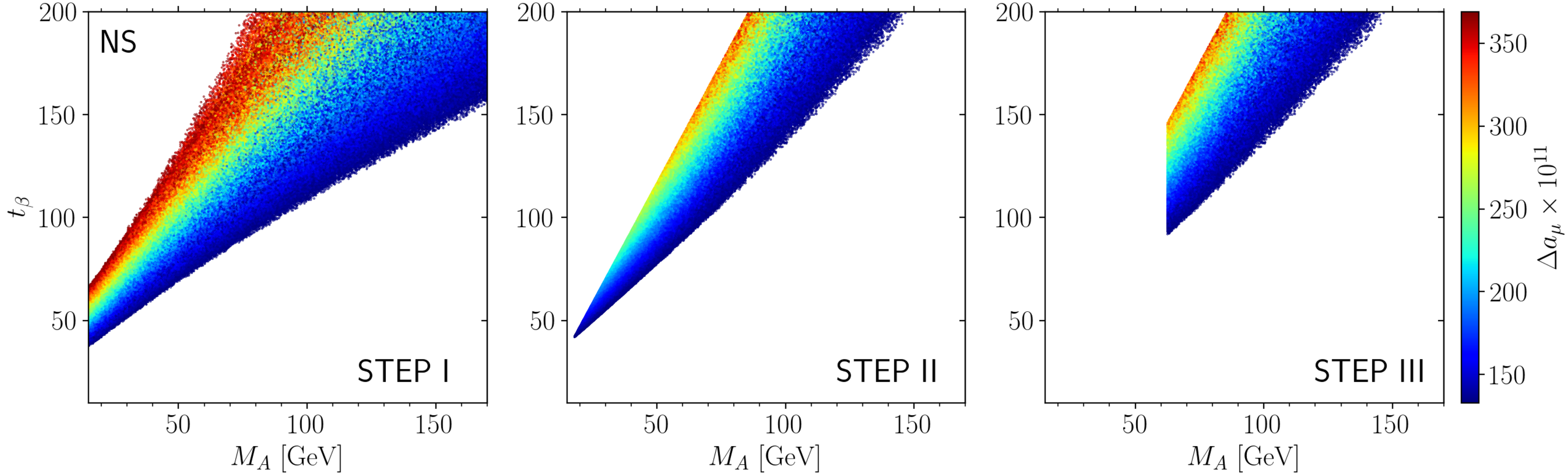


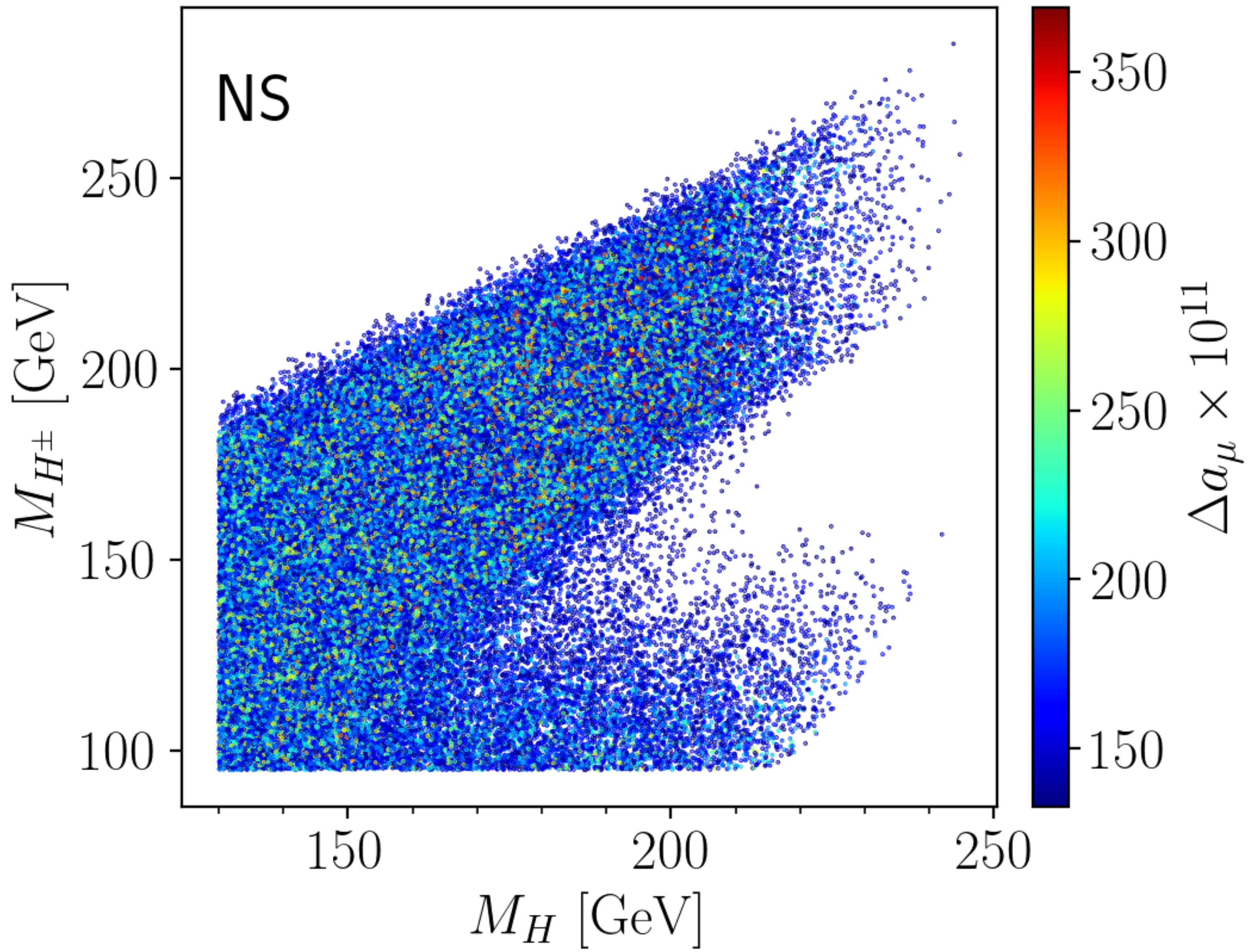
Δa_μ | Step I+Theory+EWPD | Step II+Collider

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

5. Results

Chain reaction ➽ Not too heavy MH and charged Higgs

$$\lambda_1 = \frac{1}{v^2}\left[m_{125}^2 + t_\beta^2\left(m_{\varphi^0}^2 - M^2\right)\right],$$
$$\lambda_2 = \frac{1}{v^2}\left[m_{125}^2 + \frac{1}{t_\beta^2}\left(m_{\varphi^0}^2 - M^2\right)\right],$$
$$\lambda_3 = \frac{1}{v^2}\left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^\pm}^2\right],$$
$$\lambda_4 = \frac{1}{v^2}\left[M^2 + M_A^2 - 2M_{H^\pm}^2\right],$$
$$\lambda_5 = \frac{1}{v^2}\left[M^2 - M_A^2\right],$$



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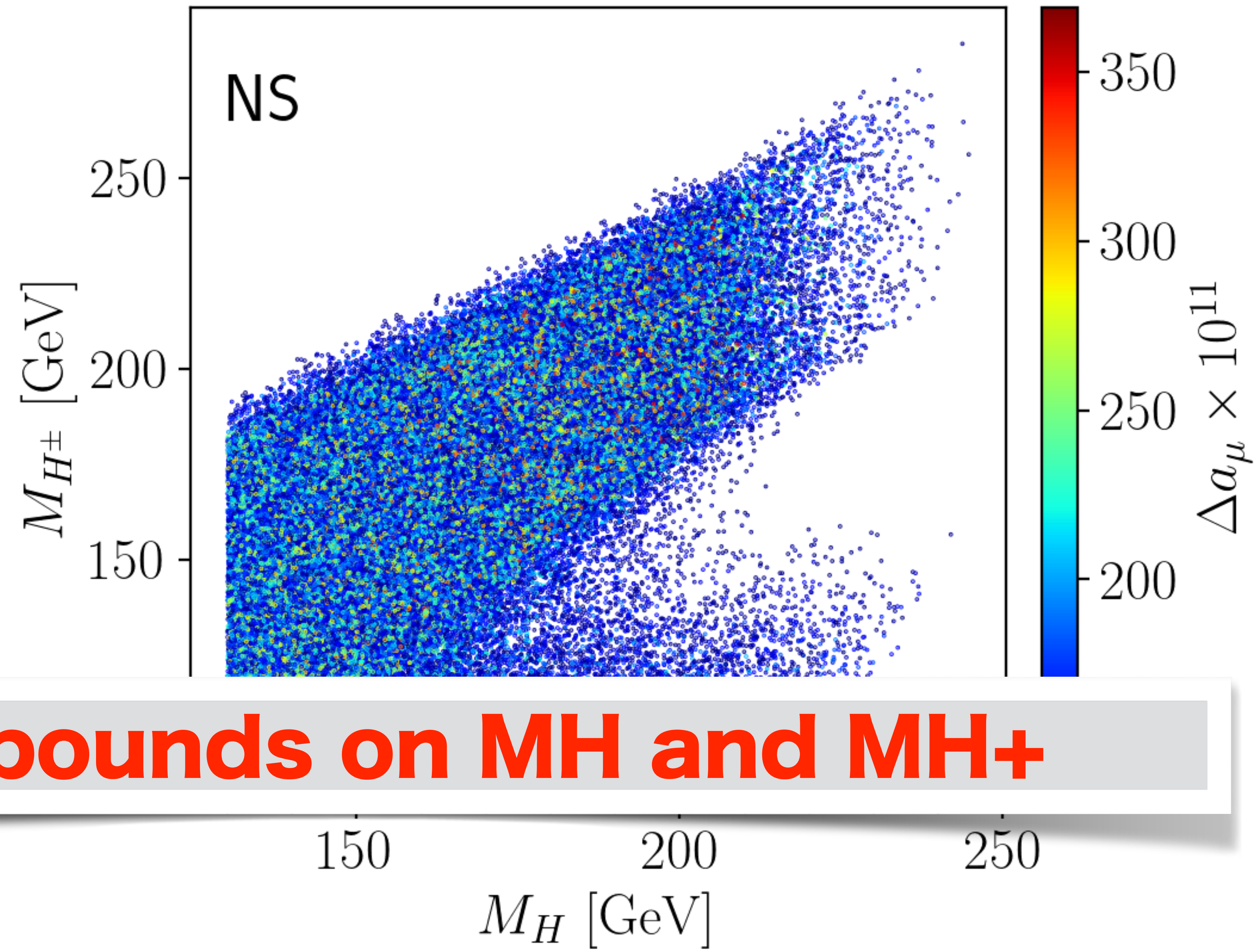
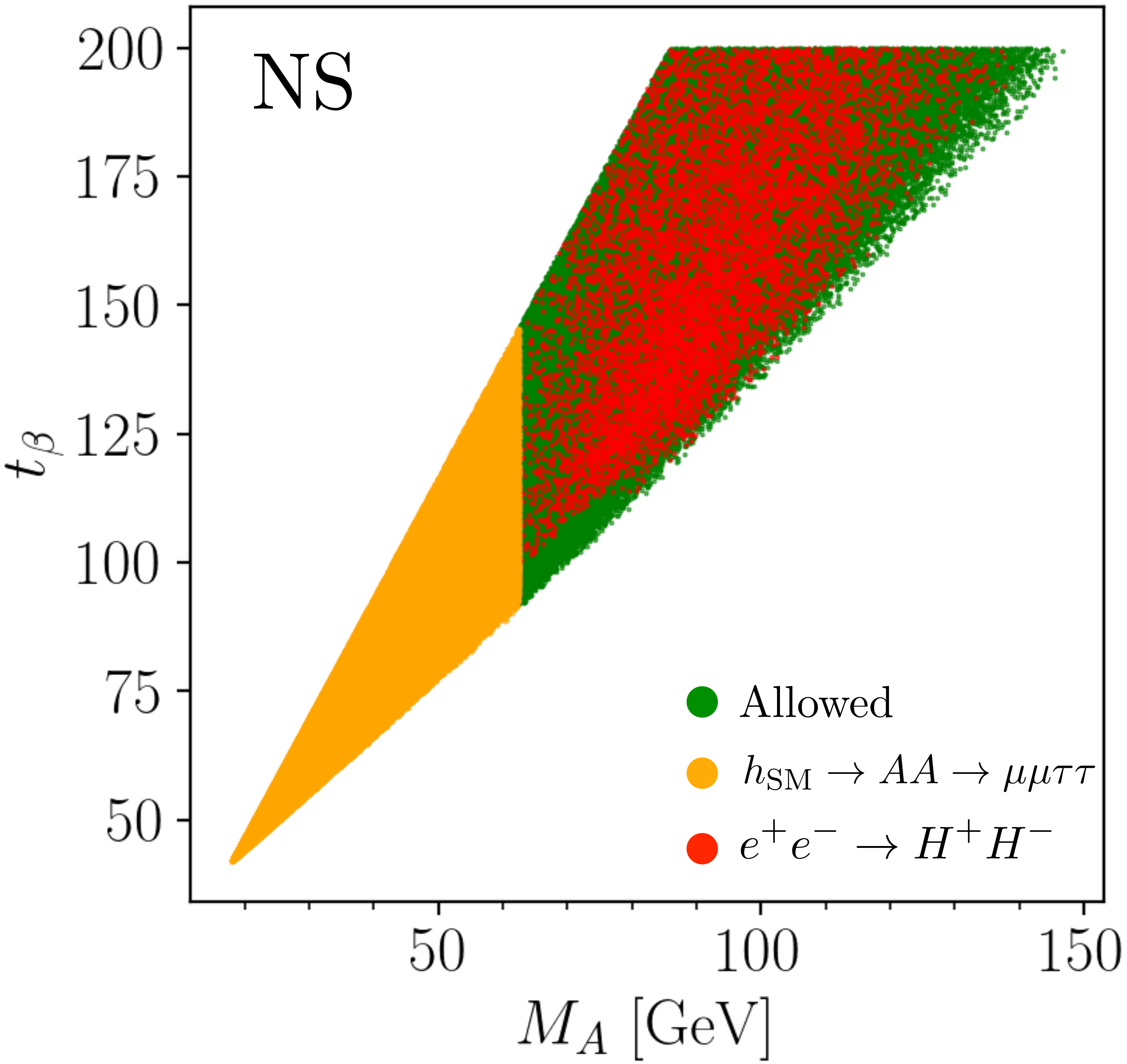
$$\lambda_5 = \frac{1}{v^2}\left[M^2 - M_A^2\right],$$

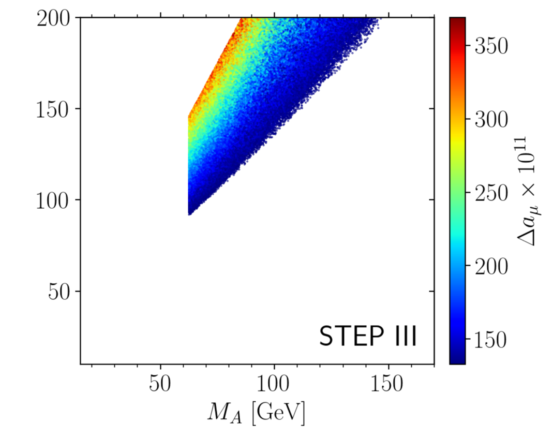


Upper bounds on MH and MH+

5. Results

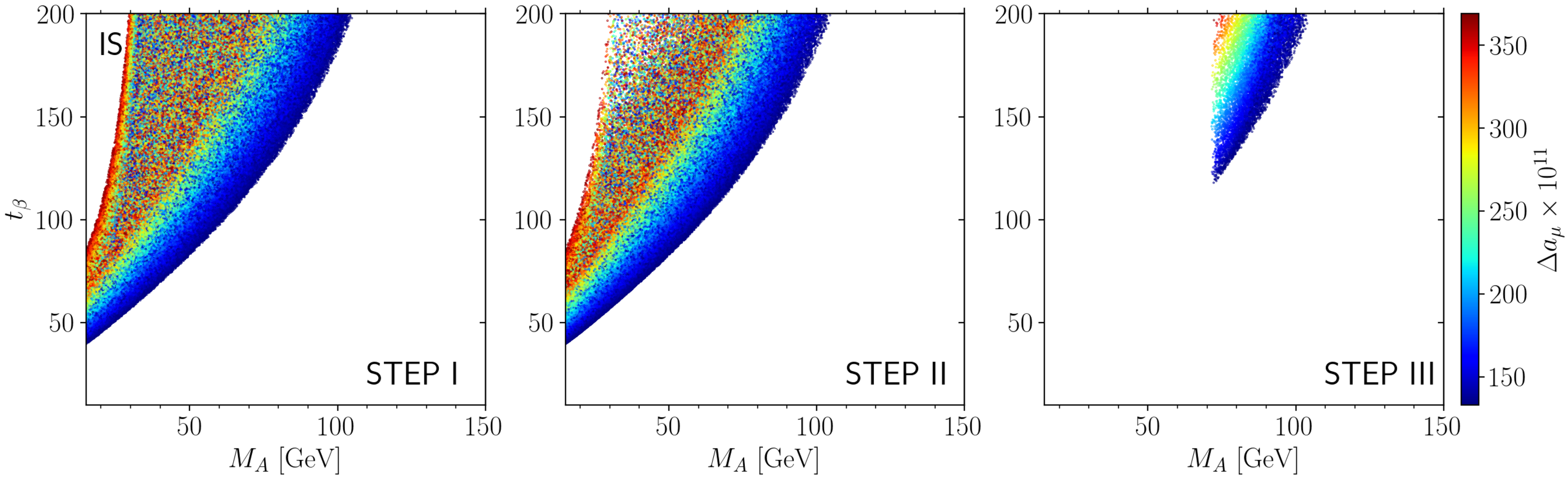
Exotic Higgs decay removes light A.



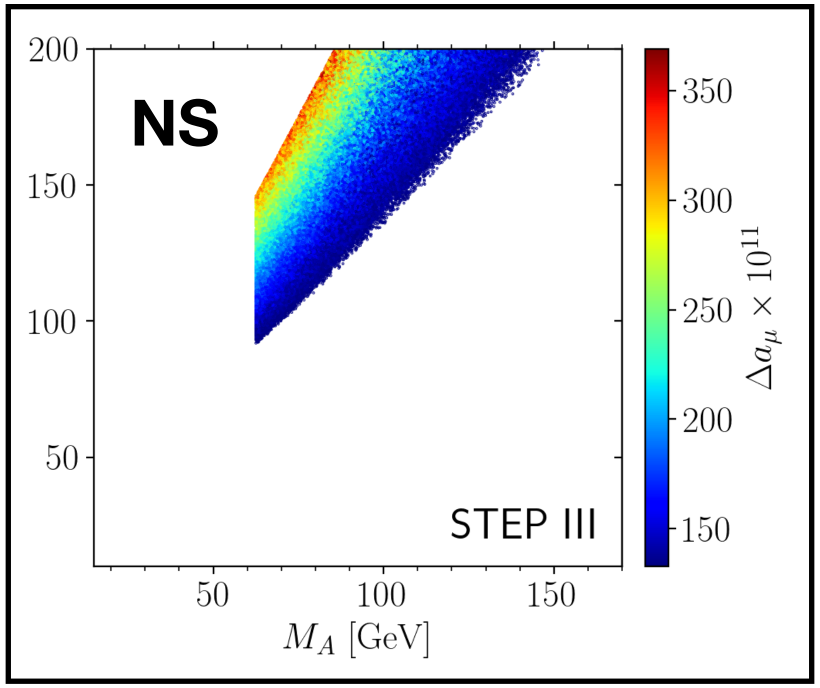


5. Results

(2) In the inverted scenario, collider data are more crucial.



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



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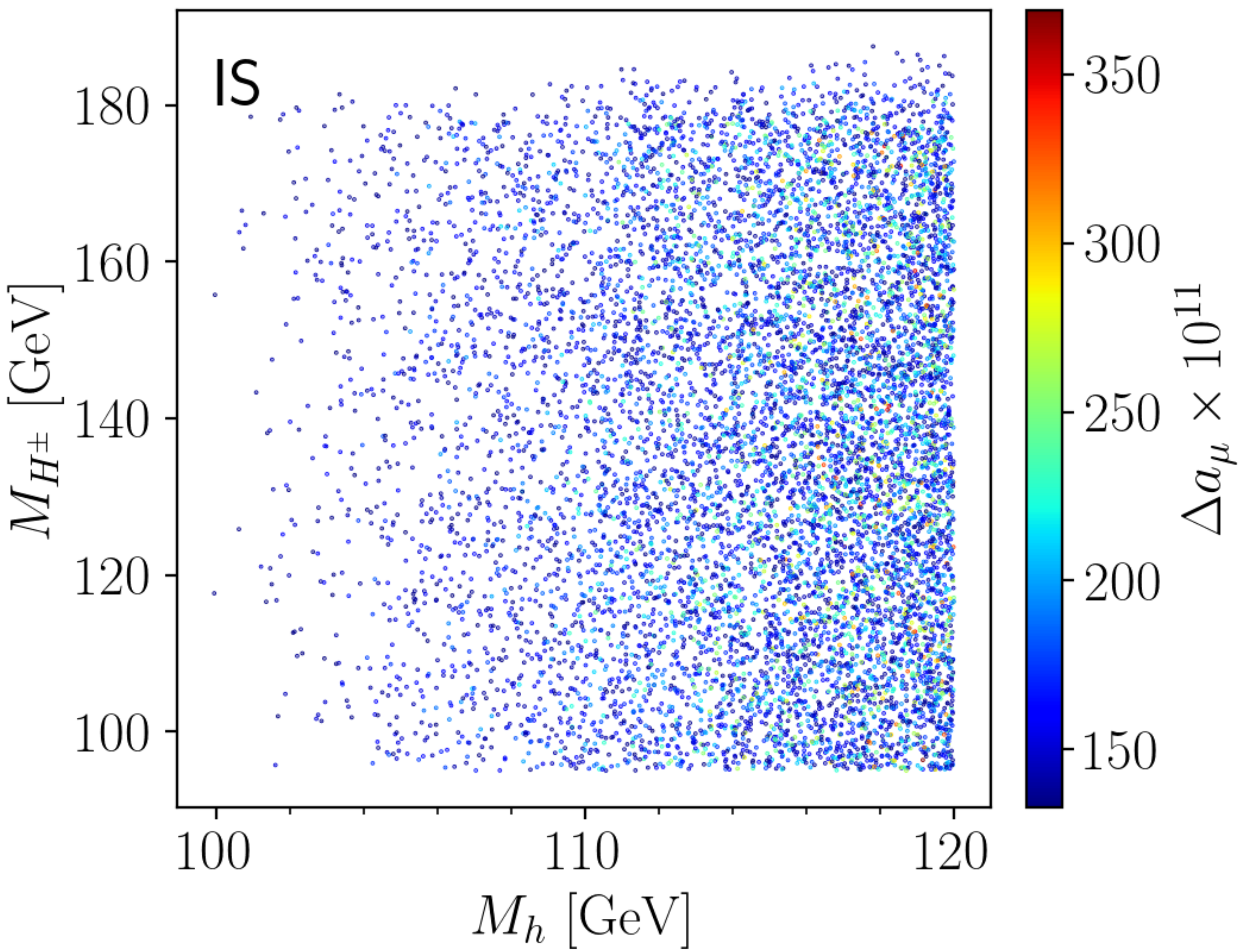
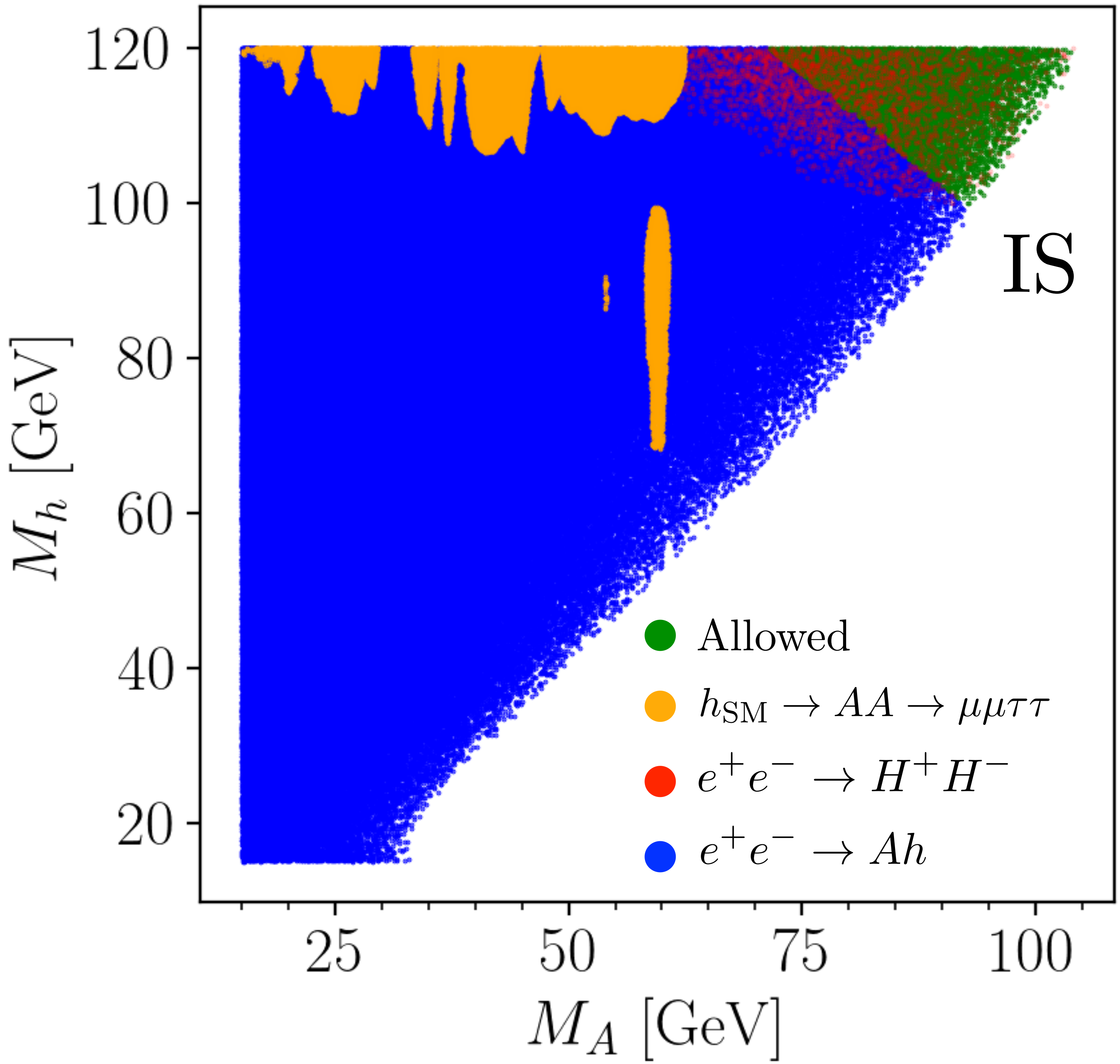
$$\lambda_4 = \frac{1}{v^2}\left[M^2 + M_A^2 - 2M_{H^\pm}^2\right],$$

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



5. Results

Exotic Higgs decay & LEP search for Ah are crucial.



6. Implications

What do the surviving parameters imply?

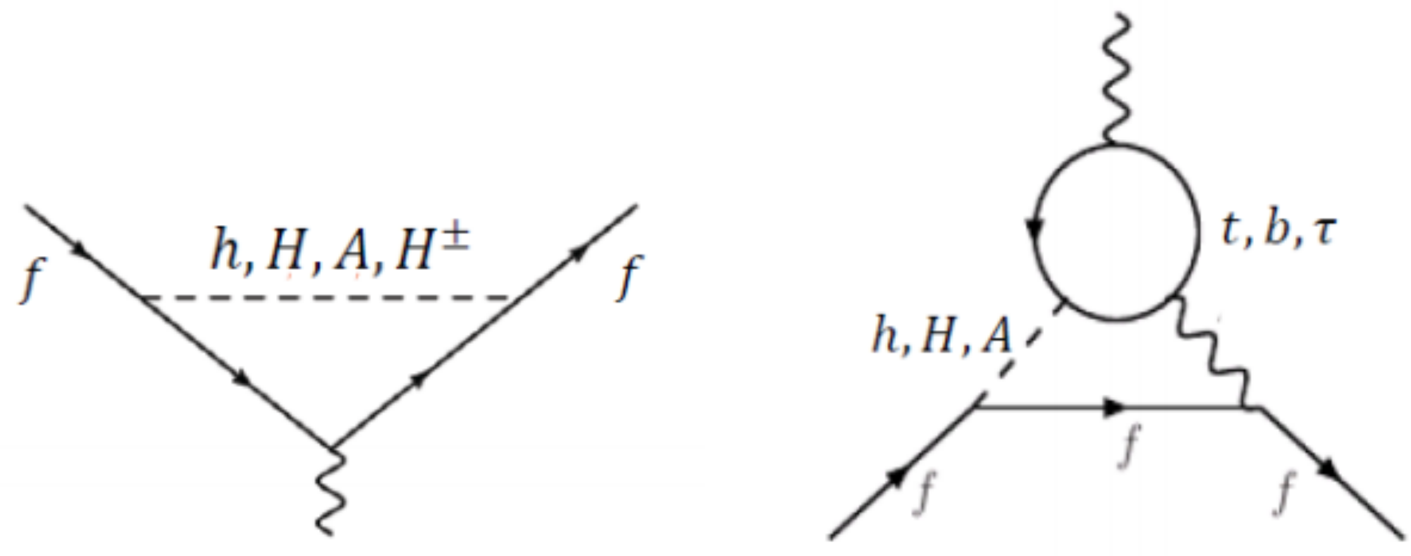
(1) Electron anomalous magnetic moment

(2) Lepton Flavor Universality in Z and τ decays

(3) Phenomenological signatures at the HL-LHC

6. Implications

(1) Electron anomalous magnetic moment:
the same contributions to the muon/electron g-2 except for mass.

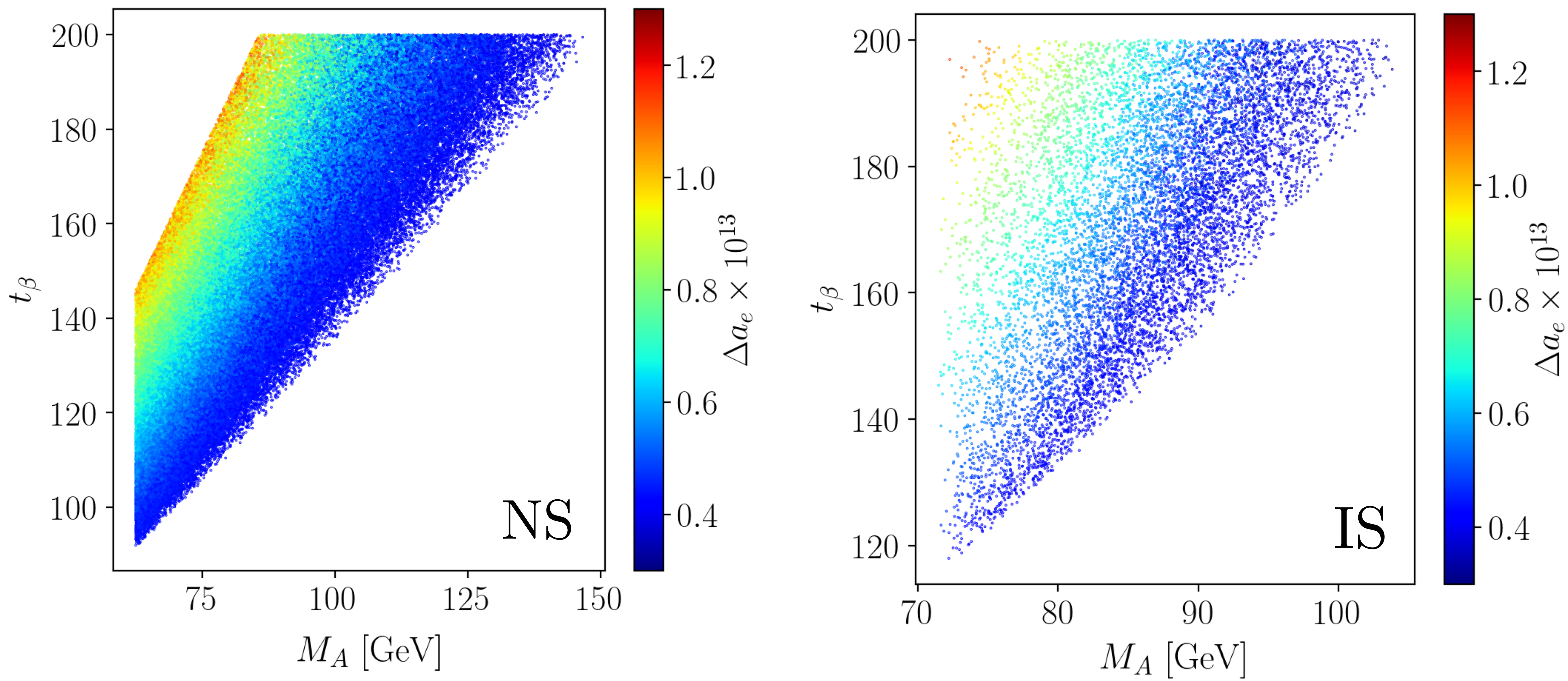


Δa_e is sensitive to the value of the fine structure constant α

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

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

(1) Electron anomalous magnetic moment is consistent with Type-X.



$\Delta a_e^{\rm Rb}$ at 2σ

$\Delta a_e^{\rm Cs}$ at 3σ

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

6. Implications

(2-1) Lepton Flavor Universality in Z decays:

$$\frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} \equiv 1 + \delta^Z_{\mu\mu} = 1.0009 \pm 0.0028,$$

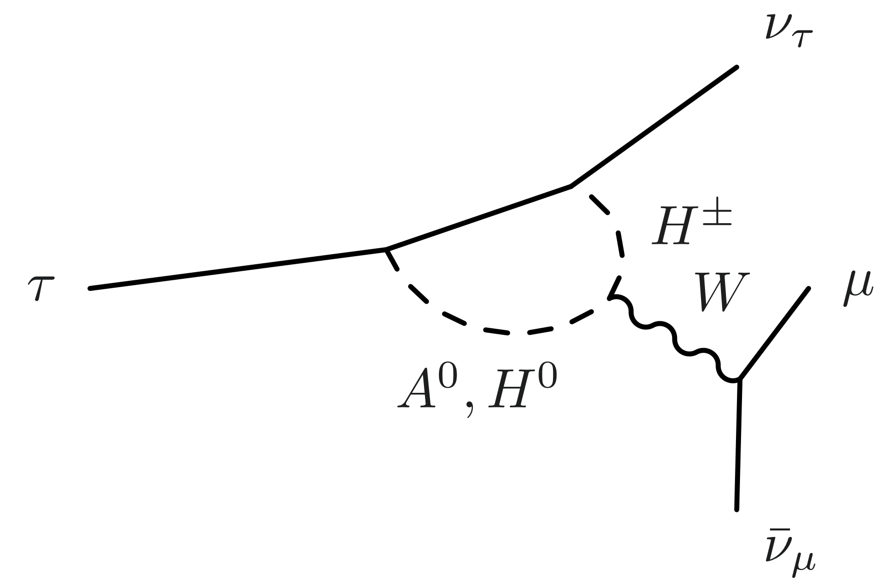
$$\frac{\Gamma(Z \to \tau^+\tau^-)}{\Gamma(Z \to e^+e^-)} \equiv 1 + \delta^Z_{\tau\tau} = 1.0019 \pm 0.0032,$$

[hep-ex/0509008]

With the correlation of +0.63

$$\delta^Z_{\tau\tau} \propto m_\tau^2 t_\beta^2$$

(2-2) Lepton Flavor Universality in $\boldsymbol{\tau}$ decays:



$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0010 \pm 0.0014,$$

$$\left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0014,$$

$$\left(\frac{g_\mu}{g_e}\right) = 1.0018 \pm 0.0014,$$

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9958 \pm 0.0026,$$

$$\left(\frac{g_\tau}{g_\mu}\right)_K = 0.9879 \pm 0.0063.$$

HFLAV [1909.12524]

$$(\rho_{ij}) = \begin{pmatrix} 1 & 0.51 & -0.50 & 0.23 & 0.11 \\ 0.51 & 1 & 0.49 & 0.25 & 0.10 \\ -0.50 & 0.49 & 1 & 0.02 & -0.01 \\ 0.23 & 0.25 & 0.02 & 1 & 0.06 \\ 0.11 & 0.10 & -0.01 & 0.06 & 1 \end{pmatrix}$$

6. Implications

(2-3) χ2 analysis of LFU in Z and τ decays:

- Type-X is better in explaining the LFU violation.

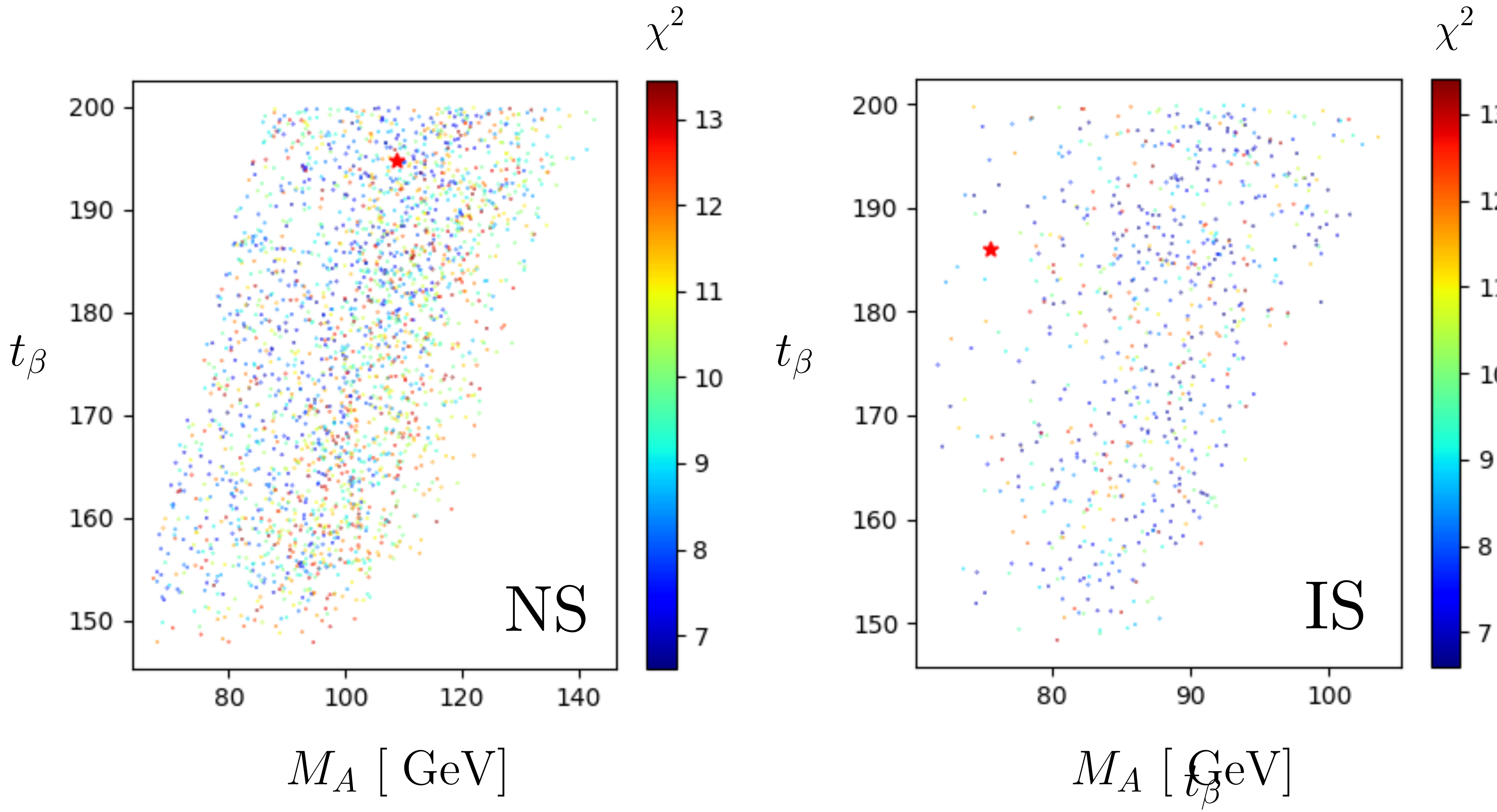
$$\chi^2_{\rm min} = 6.6, \quad \chi^2_{\rm SM} = 13.4$$

- $\chi^2_{\rm min}$ happens when

$$\begin{aligned} \text{NS:} \quad & t_\beta = 195, \quad M_A = 108.7\ \text{GeV}, \\ & M_H = 130.4\ \text{GeV}, \quad M_{H^\pm} = 121.7\ \text{GeV}, \quad M^2 = (130.4\ \text{GeV})^2, \\ \text{IS:} \quad & t_\beta = 186, \quad M_A = 75.6\ \text{GeV}, \\ & m_h = 116.7\ \text{GeV}, \quad M_{H^\pm} = 116.3\ \text{GeV}, \quad M^2 = (116.5\ \text{GeV})^2. \end{aligned}$$

6. Implications

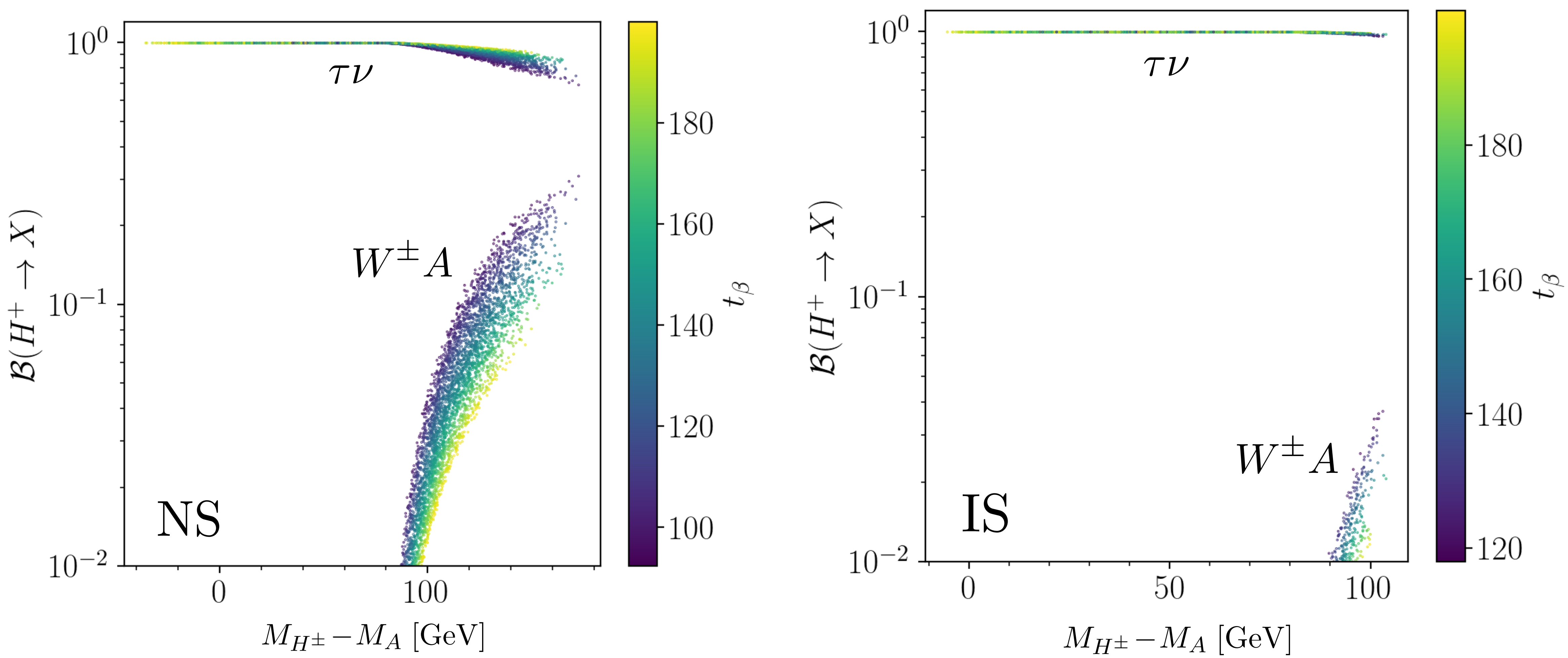
(2-3) Many parameters have $\chi 2$ less than $\chi 2_{SM}$



6. Implications

(3) LHC signatures? For the final surviving points, new scalar bosons are hadro-phobic.

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



6. Implications

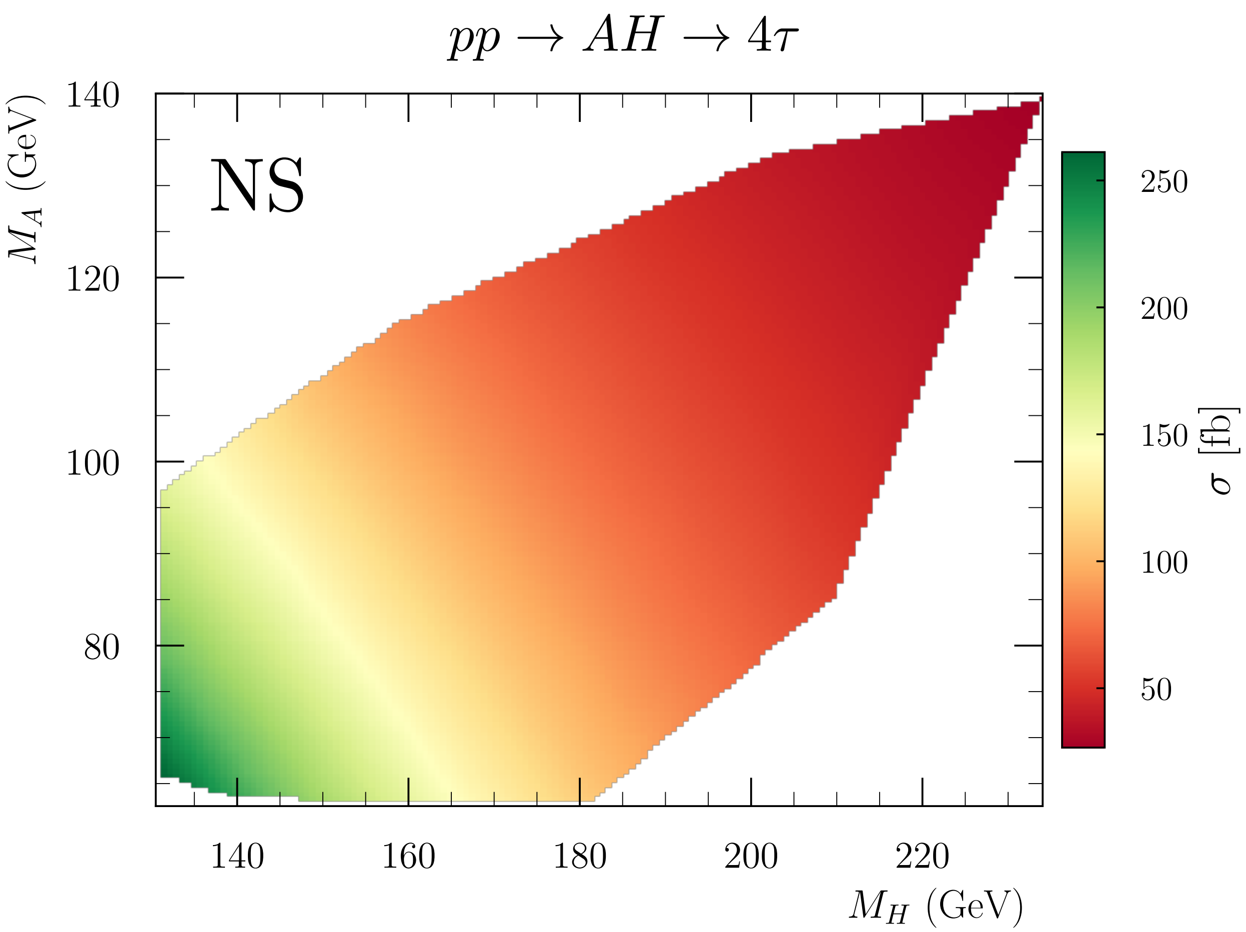
(3) Two golden modes at the HL-LHC

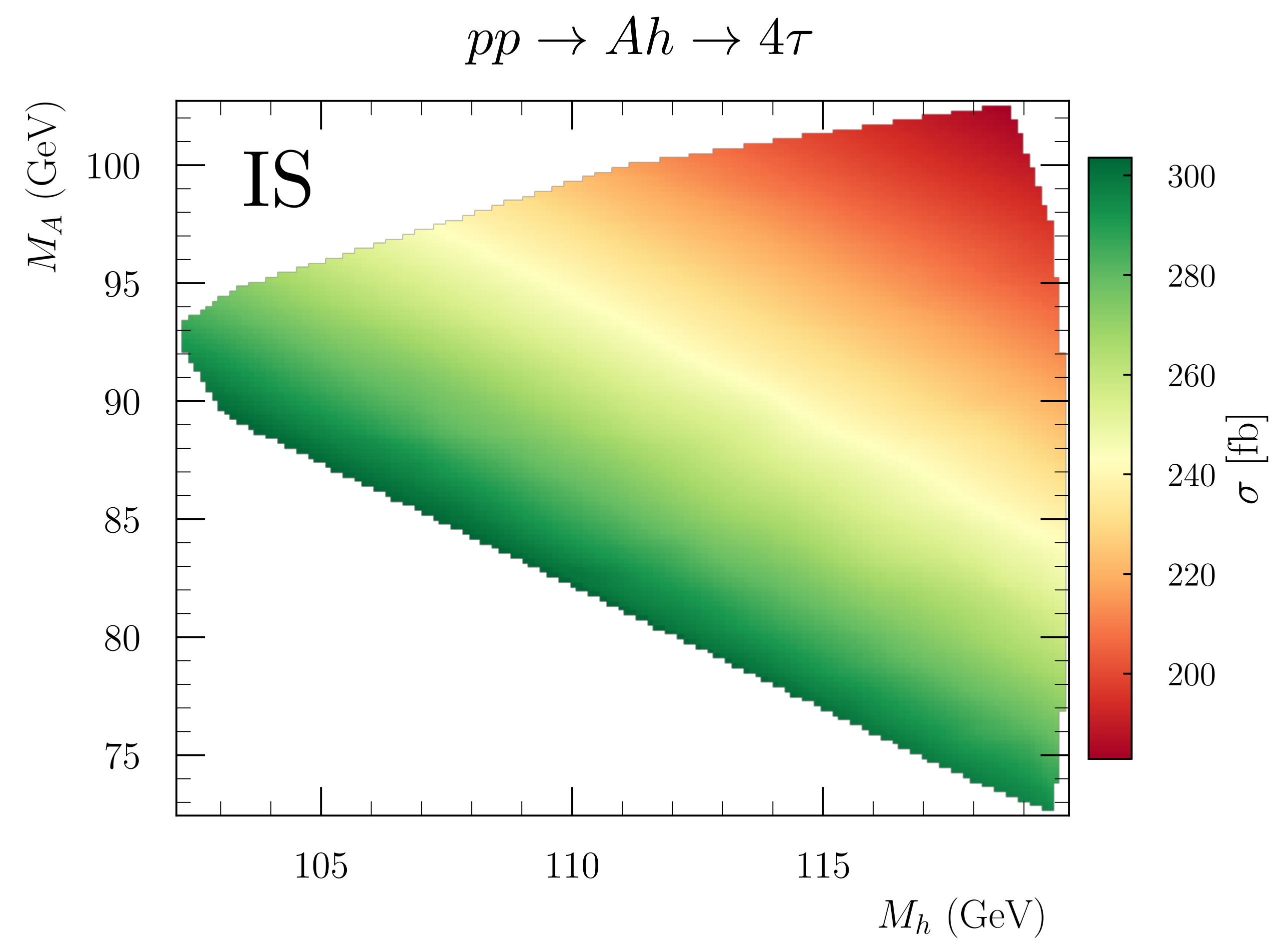
$$q\bar{q} \to Z^* \to A\varphi^0 \to \tau^+\tau^-\tau^+\tau^-,$$

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

6. Implications

(3) Four tau lepton channel: very promising





at the 14 TeV LHC

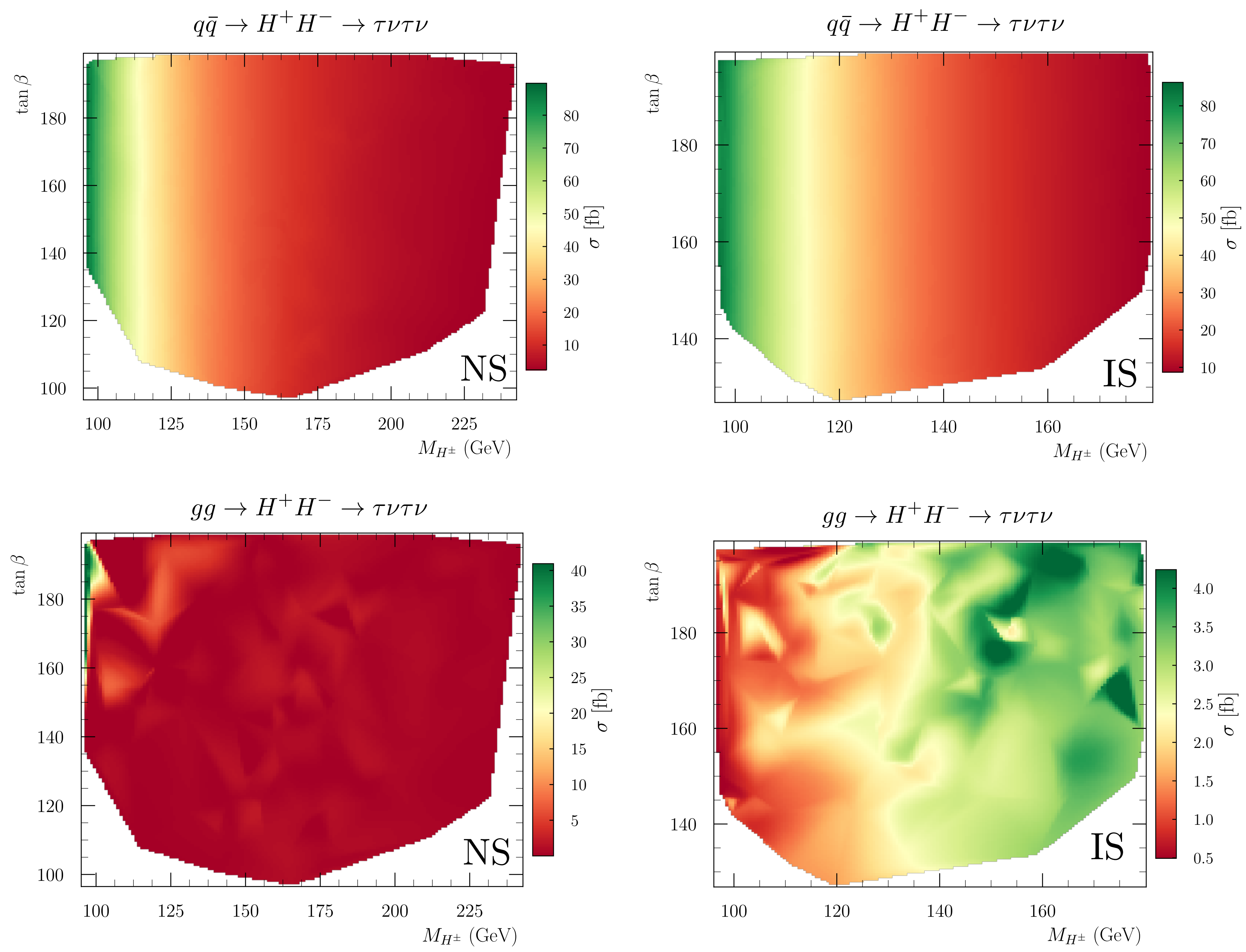
$$\sigma(pp \to ZZ \to 4\tau) \sim 17 \text{ fb at the 13 TeV LHC}$$

4 tau mode has a high potential.

[1507.06257] [1512.05314]

6. Implications

(3) 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

Type-X 2HDM is a viable model for the muon g-2 and other data.

- **In the normal scenario**
  - $\mathbf{t_\beta \gtrsim 90}$ **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**
  - $\mathbf{t_\beta \gtrsim 120}$ **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.