Revisiting the decoupling limit of the Georgi-Machacek model with a scalar singlet

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OUT LINE

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Summary

Model Review

[Georgi and Machacek, 1985]

Georgi-Machacek (GM) + Real scalar (S) → GM-S model

DM

[PRD 95 (2017) 016005]

- **Two SU(2) triplet scalar :** $\xi_{Y=0} = (\xi^+, \xi^0, \xi^-)^T$ **and** $\chi_{Y=2} = (\chi^{++}, \chi^+, \chi^0)^T$
- $\langle \xi^0 \rangle = \langle \chi^0 \rangle = v_\chi$ → **Custodial symmetry at tree level**

Scalar potential:

$$V(\Phi, X) = \frac{\mu_2^2}{2}\mathrm{Tr}\left[\Phi^\dagger\Phi\right] + \frac{\mu_3^2}{2}\mathrm{Tr}\left[X^\dagger X\right] + \lambda_1\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 + \lambda_2\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\mathrm{Tr}\left[X^\dagger X\right] + \lambda_3\mathrm{Tr}\left[X^\dagger X X^\dagger X\right] + \lambda_4\left(\mathrm{Tr}\left[X^\dagger X\right]\right)^2 - \lambda_5\mathrm{Tr}\left[\Phi^\dagger\tau^a\Phi\tau^b\right]\mathrm{Tr}\left[X^\dagger t^a X t^b\right] - M_1\mathrm{Tr}\left[\Phi^\dagger\tau^a\Phi\tau^b\right]\left(UXU^\dagger\right)_{ab} - M_2\mathrm{Tr}\left[X^\dagger t^a X t^b\right]\left(UXU^\dagger\right)_{ab}$$

Written in terms of bi-doublet Φ and a bi-triplet X

$$V(S) = \frac{\mu_S^2}{2}S^2 + \lambda_a S^2\,\mathrm{Tr}\left(\Phi^\dagger\Phi\right) + \lambda_b S^2\,\mathrm{Tr}\left[X^\dagger X\right] + \lambda_S S^4$$

Scalar Spectrum

Custodial Multiplets

- **Fiveplet** $H_5^{++} = \chi^{++}, \quad H_5^{+} = \frac{1}{\sqrt{2}}\left(\chi^{+} - \xi^{+}\right), \quad H_5^{0} = \sqrt{\frac{2}{3}}\,\xi^{0,r} - \sqrt{\frac{1}{3}}\,\chi^{0,r}$
- **Triplet** $H_3^{+} = -\,s_H\,\phi^{+} + \frac{1}{\sqrt{2}} c_H \left(\xi^{+} + \chi^{+}\right), \quad H_3^{0} = -\,s_H\,\phi^{0,i} + c_H\,\chi^{0,i}$
- **Singlet** $h = c_\alpha \phi^{0,r} - s_\alpha H_1^{0'}, \quad H = s_\alpha \phi^{0,r} + c_\alpha H_1^{0'}$

$$c_H \equiv \cos\theta_H = \frac{v_\phi}{v}, \quad s_H \equiv \sin\theta_H = \frac{2\sqrt{2}v_\chi}{v}.$$

s_α = CP-even Higgs mixing

SM- Higgs

$V_\chi \leq 1$ GeV (decoupling limit)

[*JHEP* 01 (2013) 026]

For $s_H \to 0$, $\lambda_{2,4}$ diverge, which can be avoided by $s_\alpha = 0$

$$\lambda_1 = \frac{M_h^2}{8v^2c_H^2}, \lambda_2 = \frac{M_{H_3}^2 + M_{H_5}^2 - M^2}{4v^2}, \lambda_3 = \frac{M_{H_5}^2 - M^2}{v^2},$$

$$\lambda_4 = \frac{M_{H_3}^2 - M_{H_5}^2 + M^2 + \overline{M}^2}{2v^2} \quad \lambda_5 = \frac{-(M_{H_3}^2 - M_{H_5}^2 + M^2)}{v^2}$$

→ $M^2 \equiv 3\sqrt{2}s_H v M_2$

$\{M_{H_5}, M_{H_3}\}$ → mass of fiveplet,triplet

- **Mass of CP-even BSM Higgs**

$$M_H^2 = \frac{1}{2}\left(3M_{H_3}^2 - M_{H_5}^2 + 3s_H^2\overline{M}^2\right)$$

Free parameters

GM sector:

M_{H_3} [GeV]	$[10^2, 10^3]$
M_{H_5} [GeV]	$[10^2, 10^3]$
M [GeV]	$[10^1, 10^3]$
$\overline{M}$ [GeV]	$[10^1, 10^6]$
v_χ [GeV]	$[10^{-4}, 10^0]$

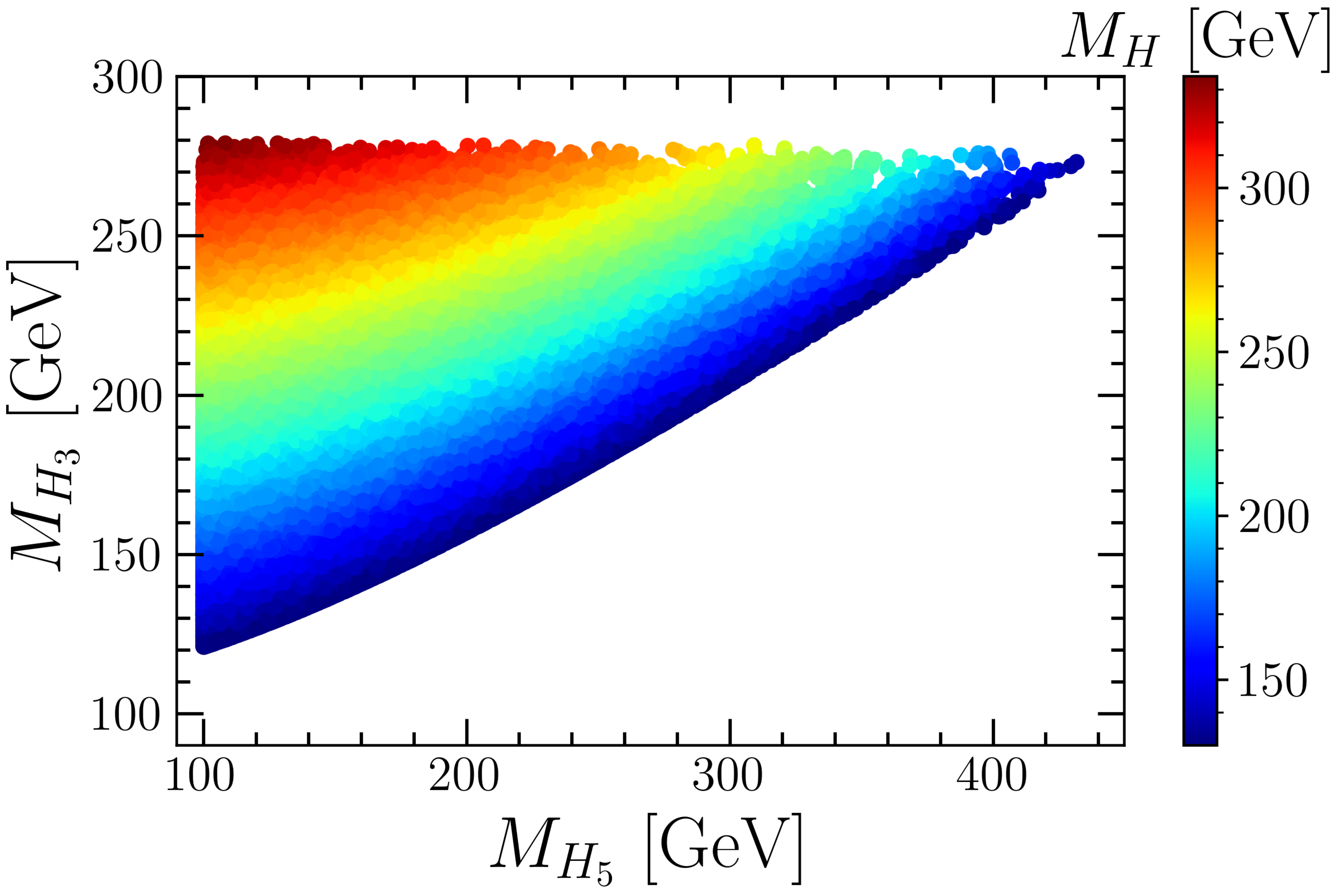
DM →

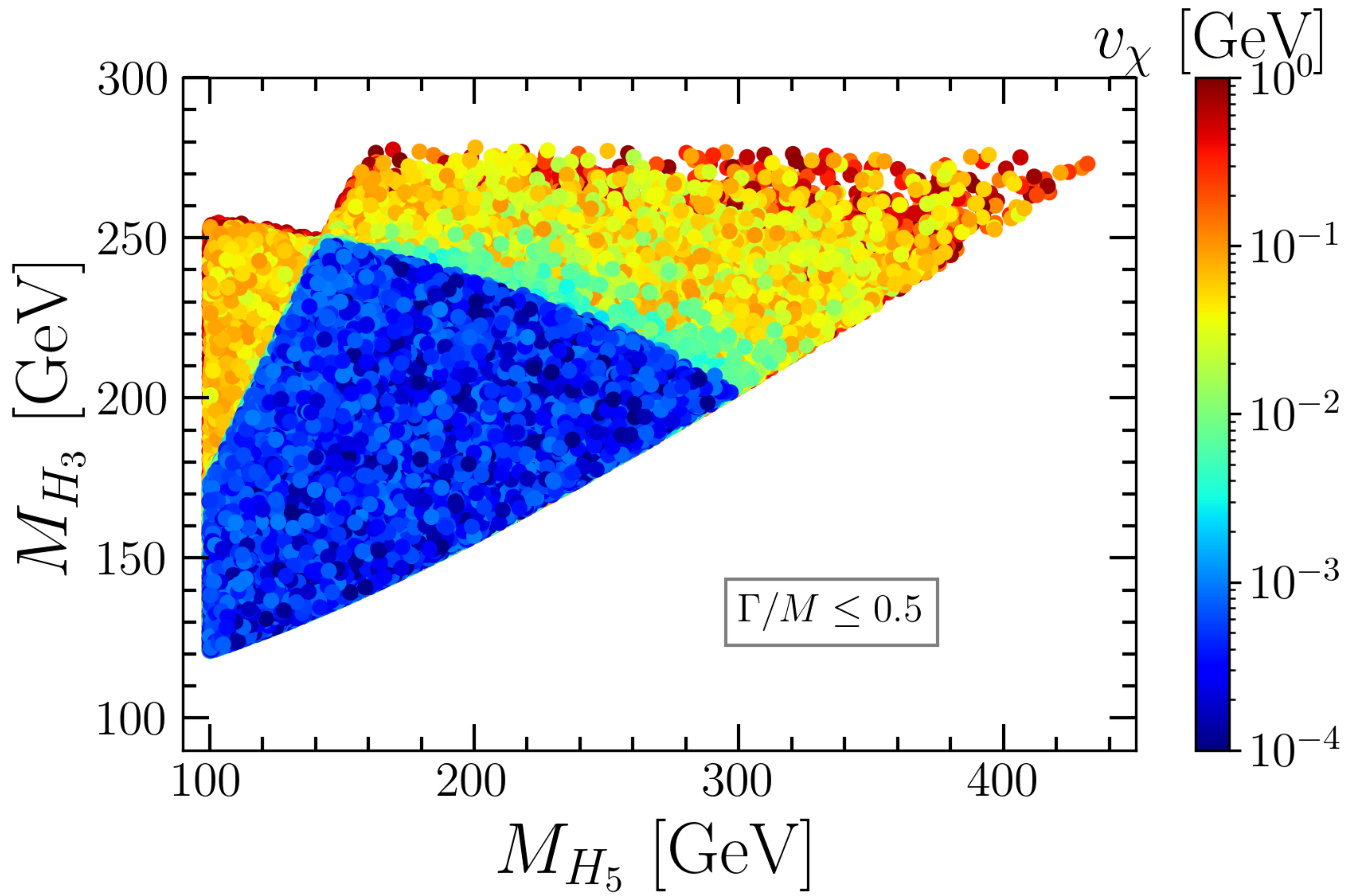
$\lambda_a, \lambda_b, \lambda_S$	$[10^{-4}, 10^0]$
M_S [GeV]	$[10^2, 10^3]$

Theoretical constraints

- **Mass of CP-even BSM Higgs,** $M_H > 130$ **GeV**
- **Perturbative unitarity exclude**

  $\rightarrow M_{H_3} > 280\ \mathrm{GeV}, \mathrm{M}_{\mathrm{H}_5} > 435\ \mathrm{GeV}$





- **Trilinear scalar coupling has a term** M^2/v_χ

  $\rightarrow$ large Γ/M **for** H and H_5^0

  via $H_i \rightarrow H_j H_j, H_i \rightarrow \gamma\gamma$

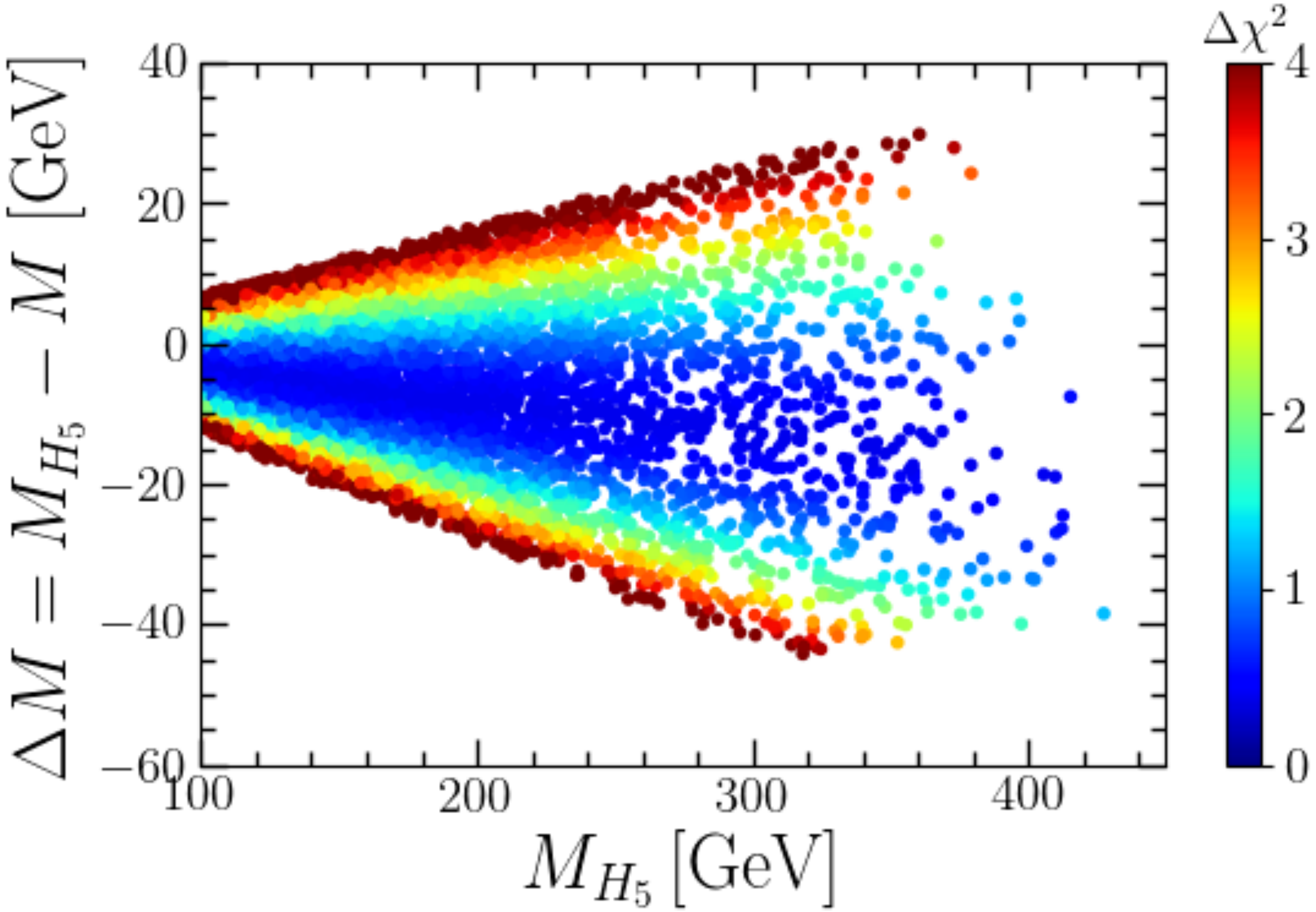
Exp. constraints : $h \to \gamma\gamma$

[*JHEP* 07 (2023) 088, *JHEP* 07 (2021) 027]

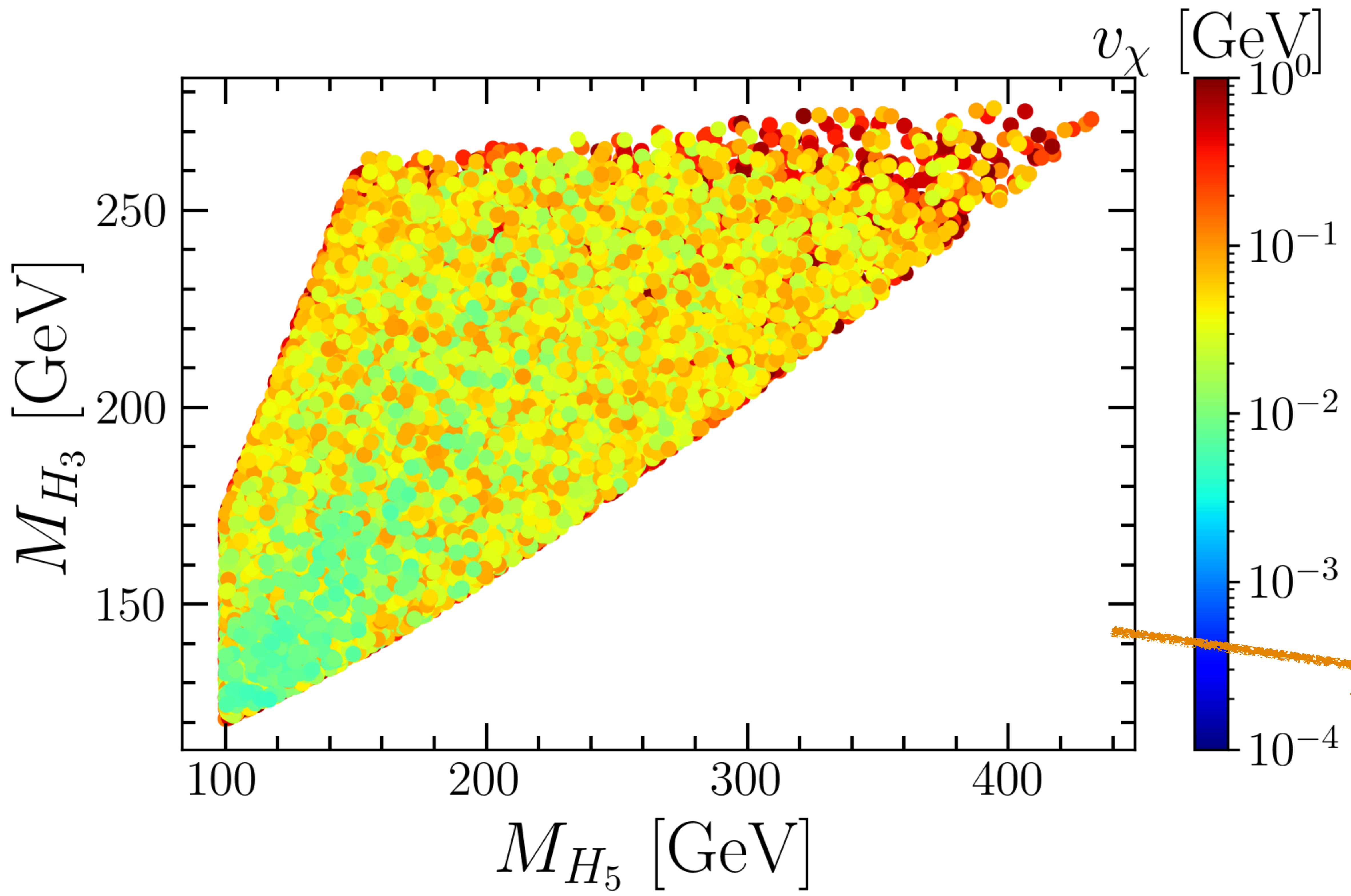
- $h \to \gamma\gamma$ **signal strength**

  $\mu_{\mathrm{ATLAS}} = 1.04^{+0.1}_{-0.09}, \qquad \mu_{\mathrm{CMS}} = 1.12 \pm 0.0$

- **BSM charged Higgs mediates** $h \to \gamma\gamma$ **via loop**
- $C_{H_5^+ H_5^- h} \sim (M_{H_5}^2 - M^2)$



Strong limit on ΔM



$v_\chi < 4.8 \times 10^{-3}$ GeV excluded

$H_5^{\pm\pm} \to W^{\pm}W^{\pm}$ search

[JHEP 06 (2021) 146]

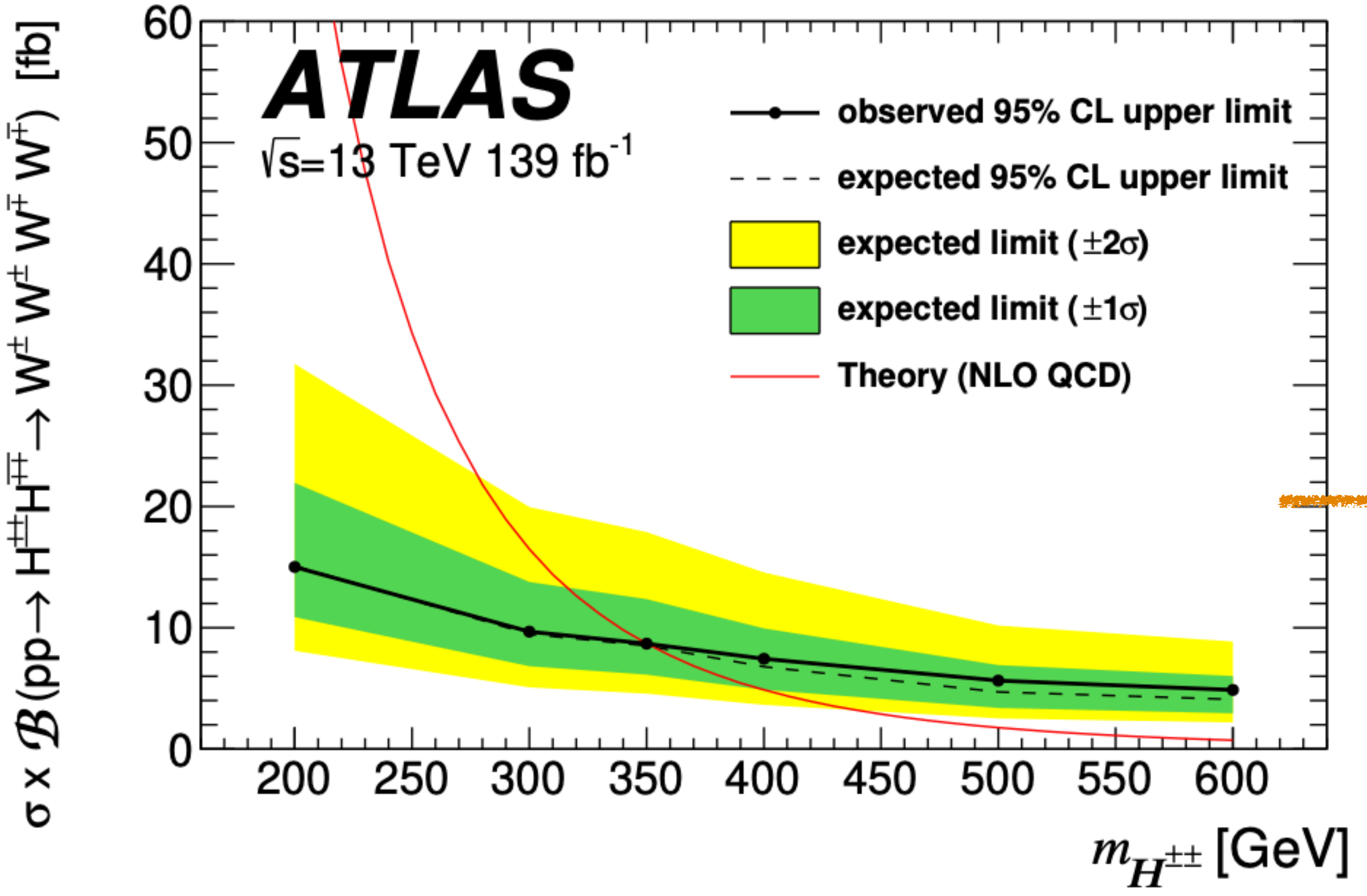
- **ATLAS search for**

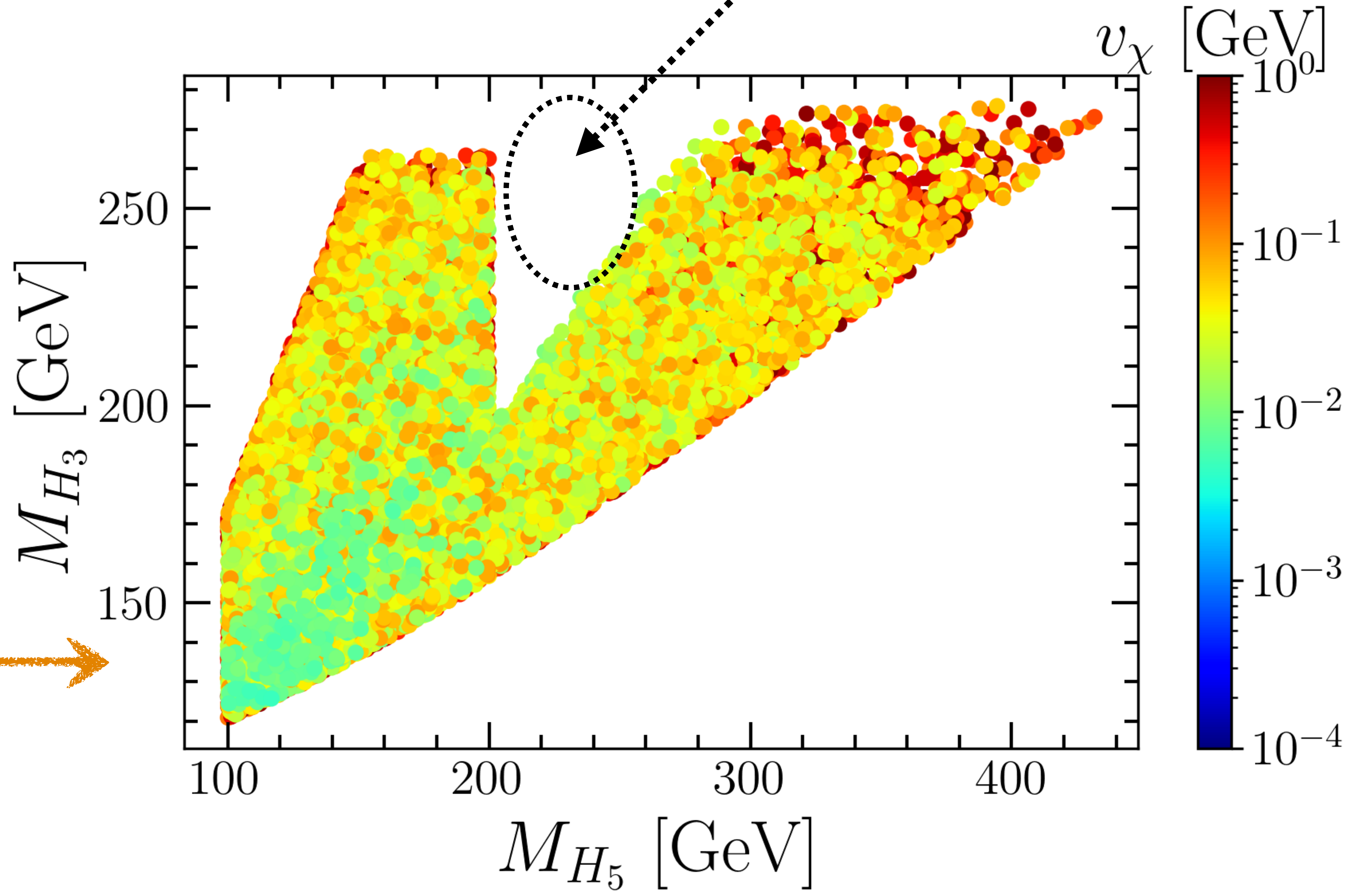
  $pp \to H_5^{\pm\pm}H_5^{\mp\mp},\ H_5^{\pm\pm} \to W^{\pm}W^{\pm}$

- **Other decay mode**

  $H_5^{\pm\pm} \to W^{\pm}H_3^{\pm}/W^{\pm\star}H_3^{\pm}$

$Br(H_5^{\pm\pm} \to W^{\pm}W^{\pm}) \sim 1$



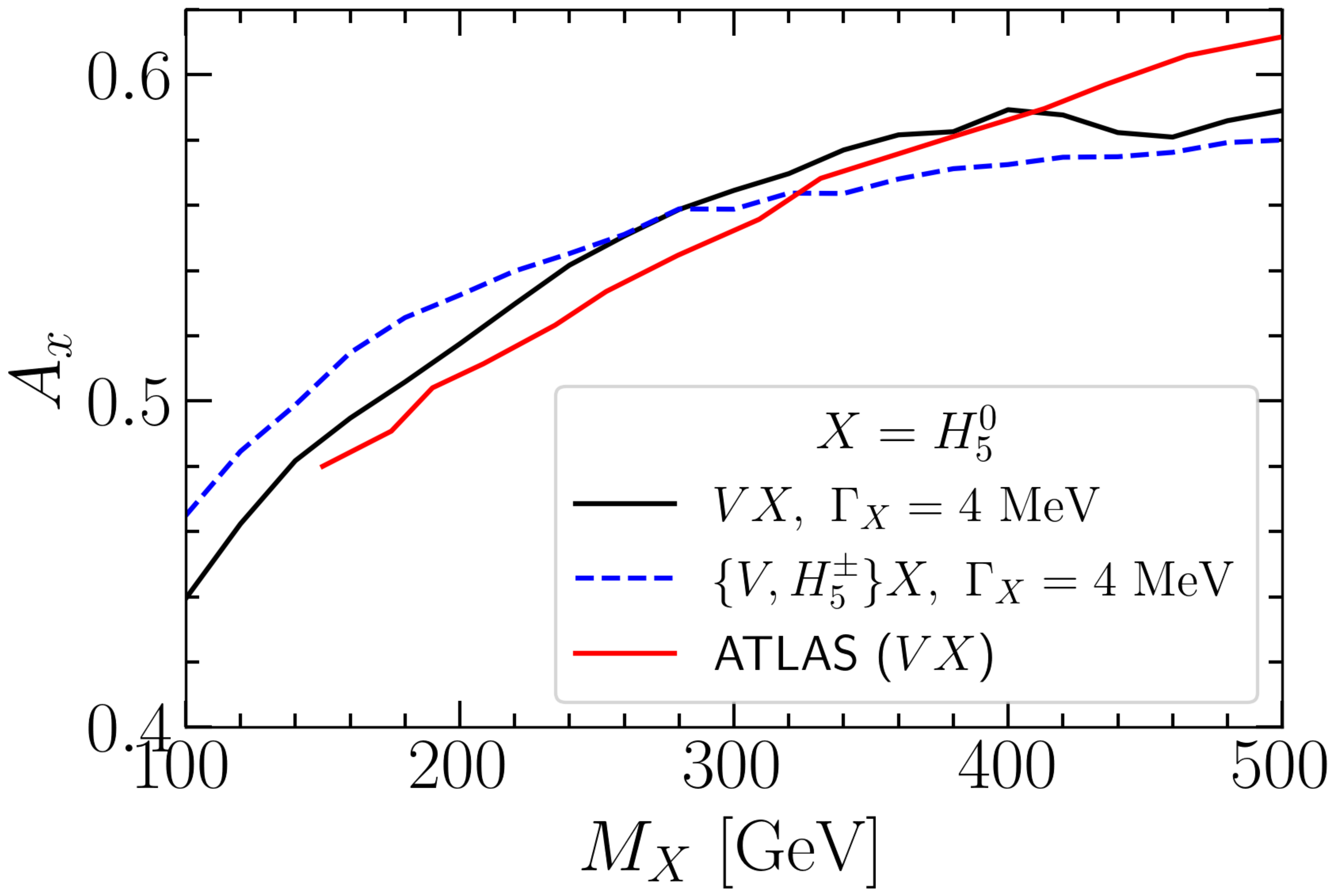


$H_5^0 \to \gamma\gamma$

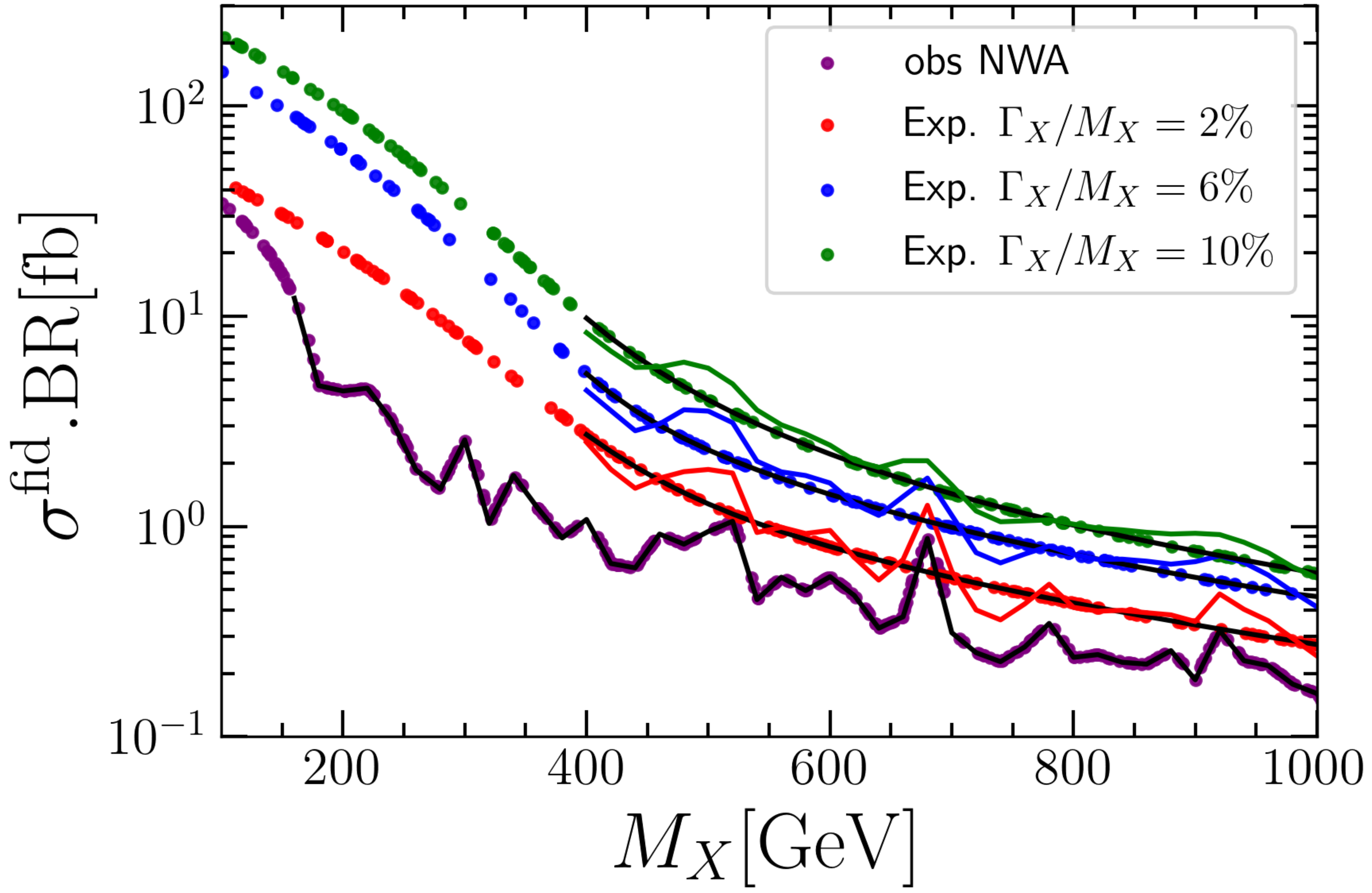
[PLB 822 (2021) 136651, MadGraph5, Pythia8]

- **ATLAS searched for spin-0 BSM resonances in the diphoton final state**
- $pp \to H_5^0 + \{V, H_5^\pm, H_3^0, H_3^\pm\}$
- $H_5^0 \to \gamma\gamma, H \to \gamma\gamma$ **via loop. vertex factor ~** M^2/v_χ

Diphoton selection cut efficiency

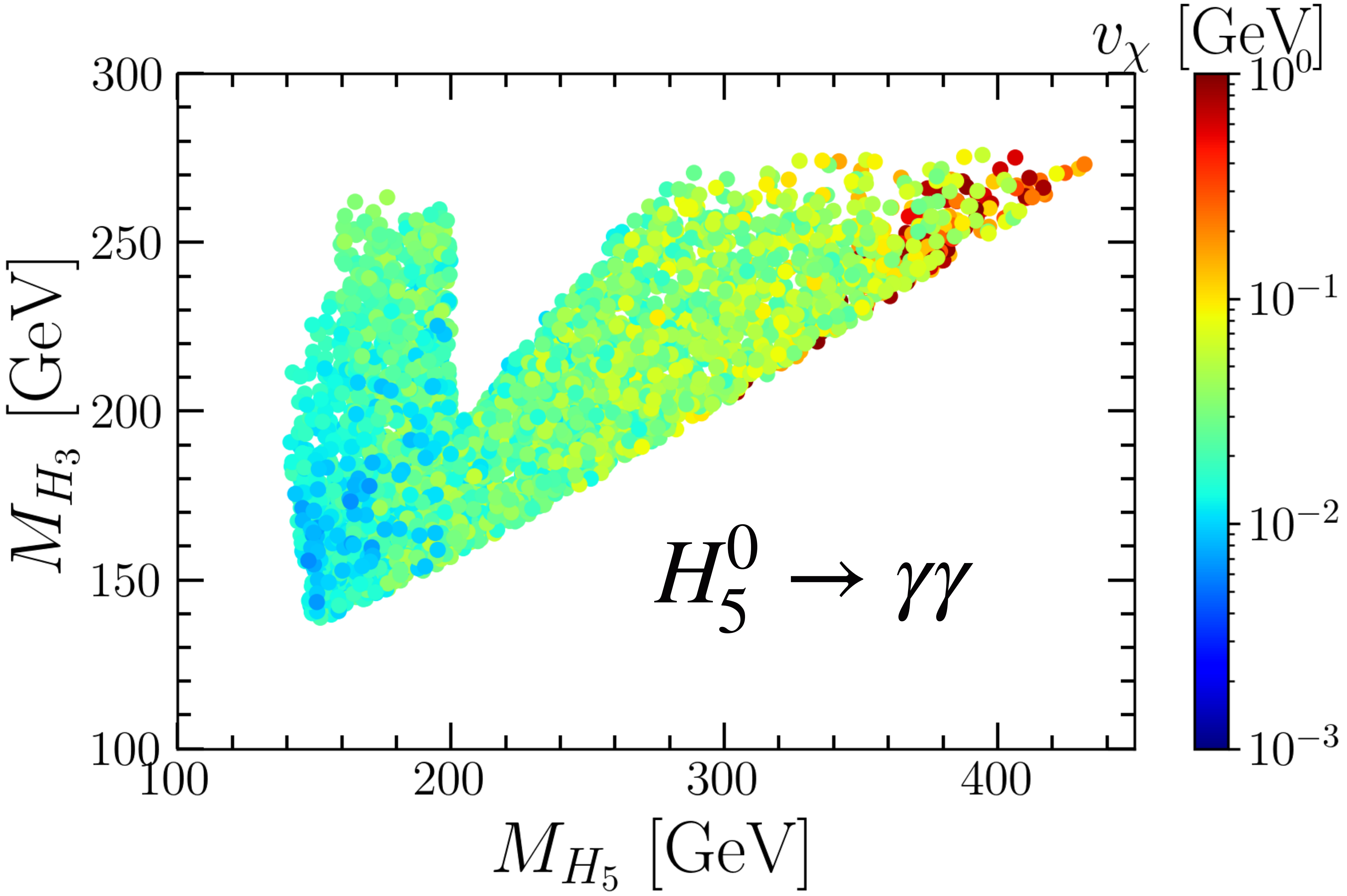


ATLAS limit

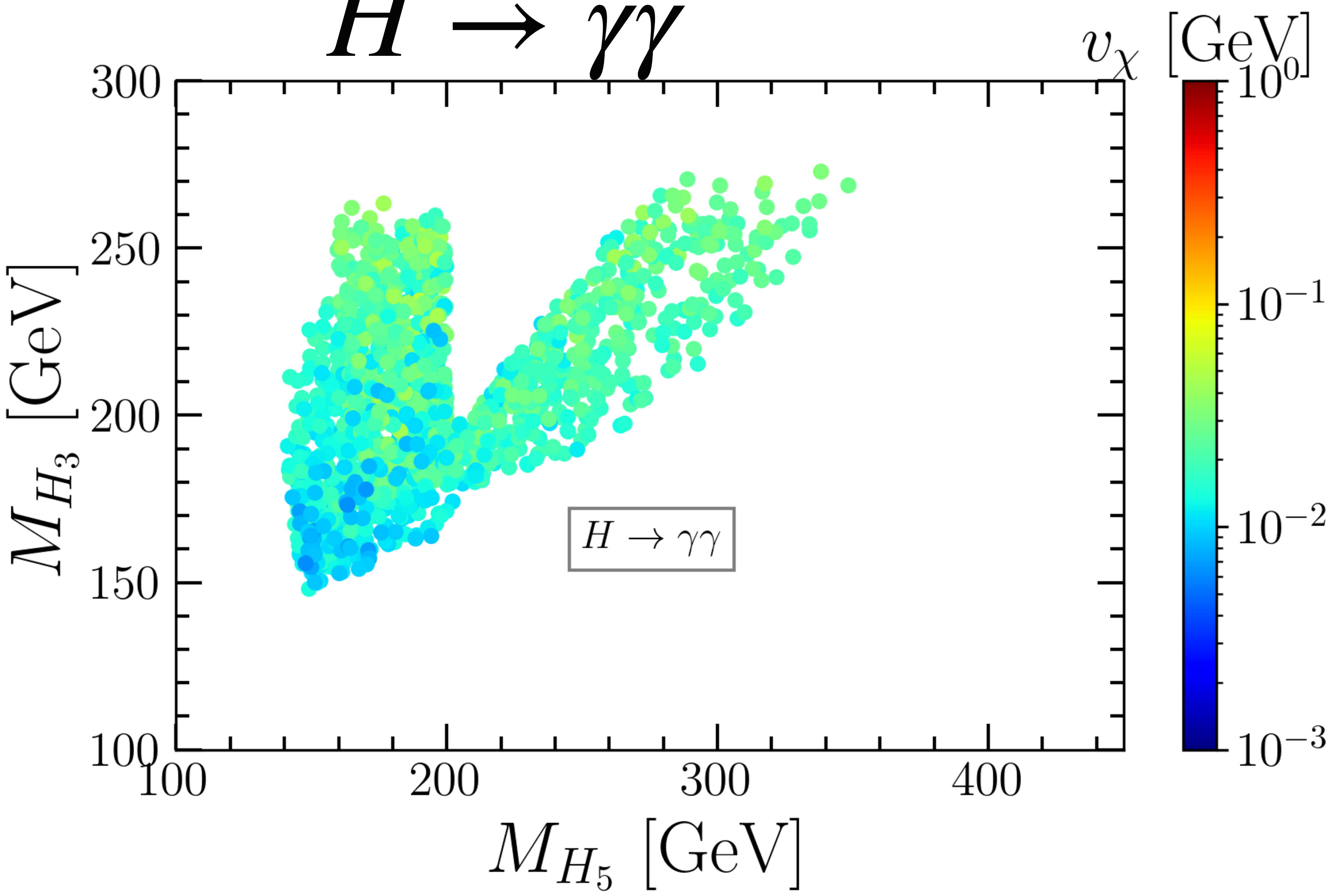


Observed limit is stronger for narrow resonance

Higher v_χ strongly constrained as H_5^0 $(or\ H)$ is a narrow resonance for which obs. limit is stronger.



$H \to \gamma\gamma$

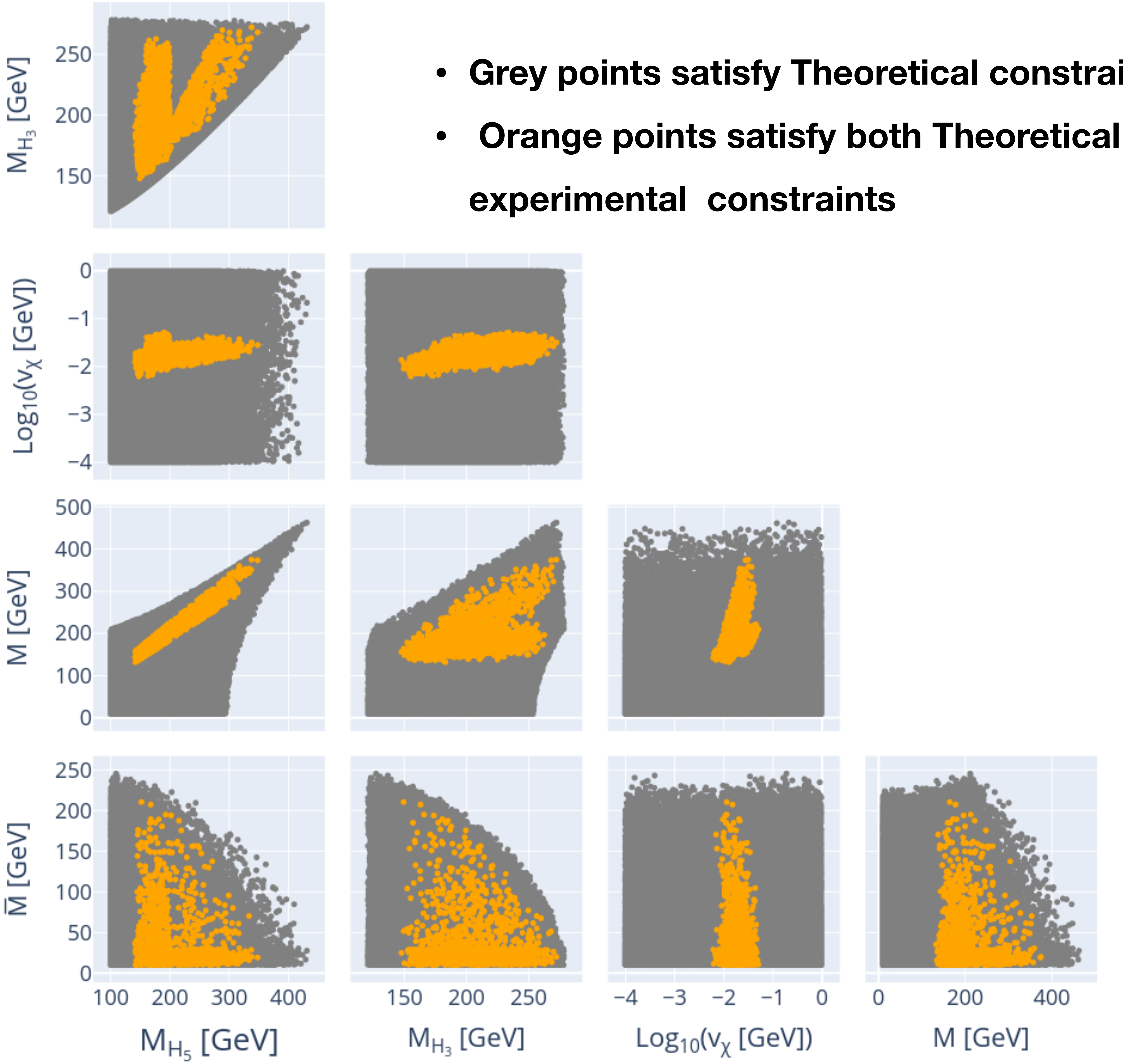


- $v_\chi > 0.05\ GeV$ **is excluded**

After all bounds

Allowed range

- $M_{H_5} < 350\ GeV,\ 145 < M_H < 300\ GeV$
- $150\ GeV < M_{H_3} < 270\ GeV$
- $4.8 \times 10^{-3}\ GeV < v_\chi < 0.05\ GeV$

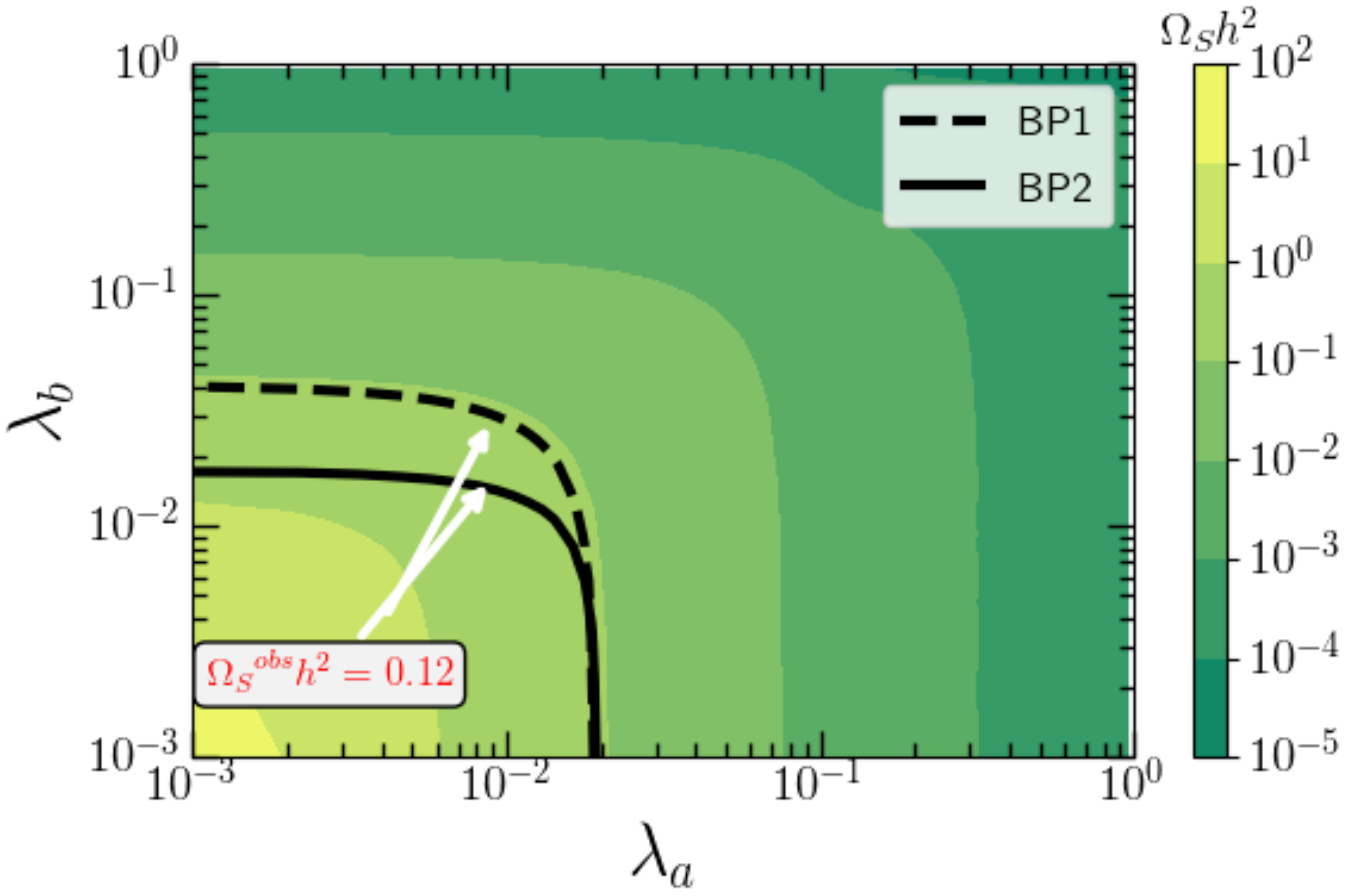


- **Grey points satisfy Theoretical constraints**
- **Orange points satisfy both Theoretical + experimental constraints**

DM relic density

[Feynrule, micrOMEGAs,CalcHEP]

- $S\ S \rightarrow SM\ SM \longrightarrow \lambda_a$
- $S\ S \rightarrow H_5\ H_5,\ H_3\ H_3,\ H\ H \longrightarrow \lambda_b$



BP1: $M_{H_5} = 300\,\text{GeV},\ M_{H_3} = 254\,\text{GeV},\ M_H = 227\,\text{GeV},\ v_\chi = 0.036\,\text{GeV}$
$M = 335\,\text{GeV},\ \overline{M} = 43\,\text{GeV}$ and $M_S = 280\,\text{GeV}$

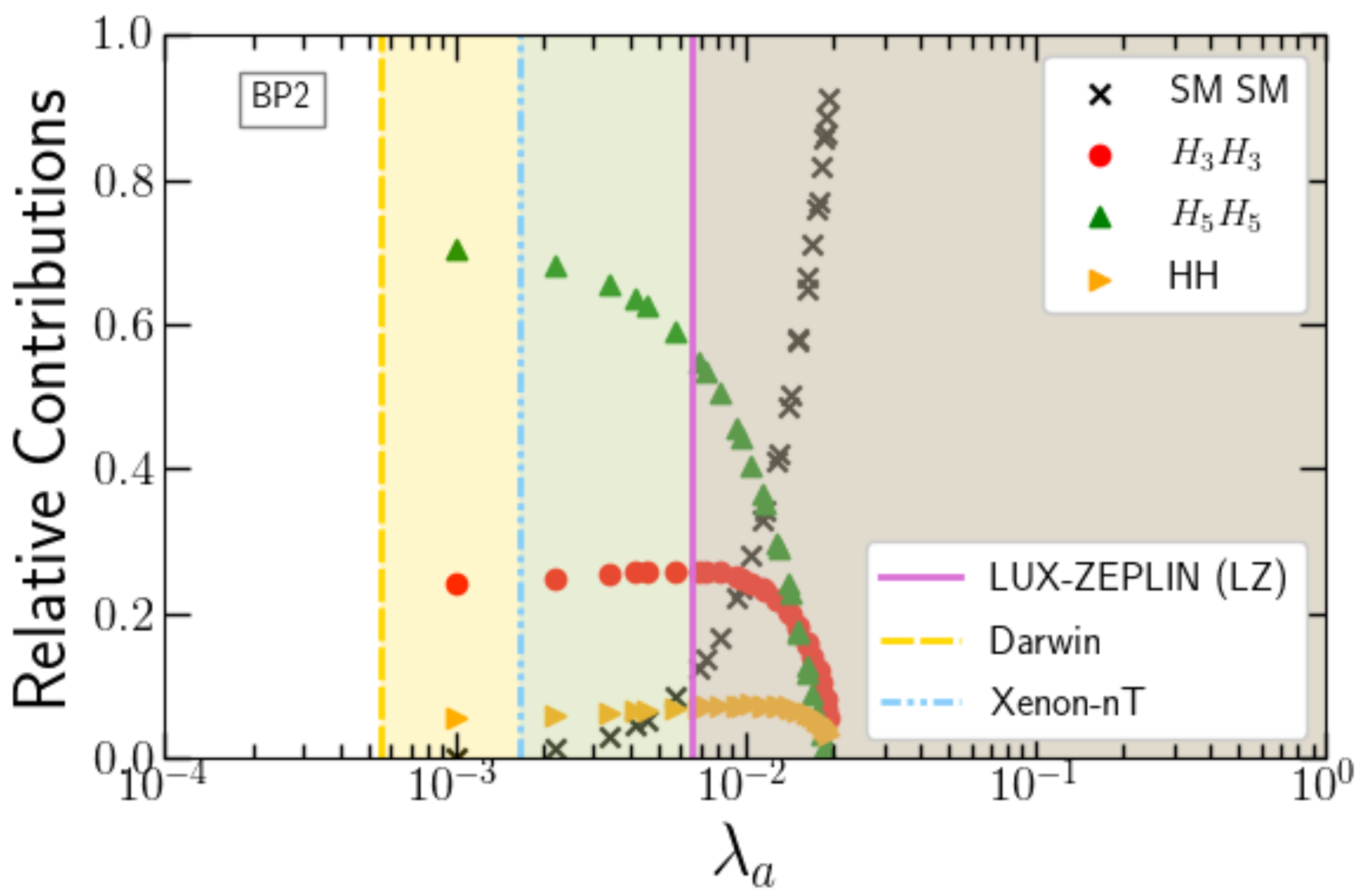
BP2: $M_{H_5} = 190\,\text{GeV},\ M_{H_3} = 234\,\text{GeV},\ M_H = 253\,\text{GeV},\ v_\chi = 0.05\,\text{GeV}$
$M = 210\,\text{GeV},\ \overline{M} = 10\,\text{GeV}$ and $M_S = 280\,\text{GeV}$

Direct and Indirect detection

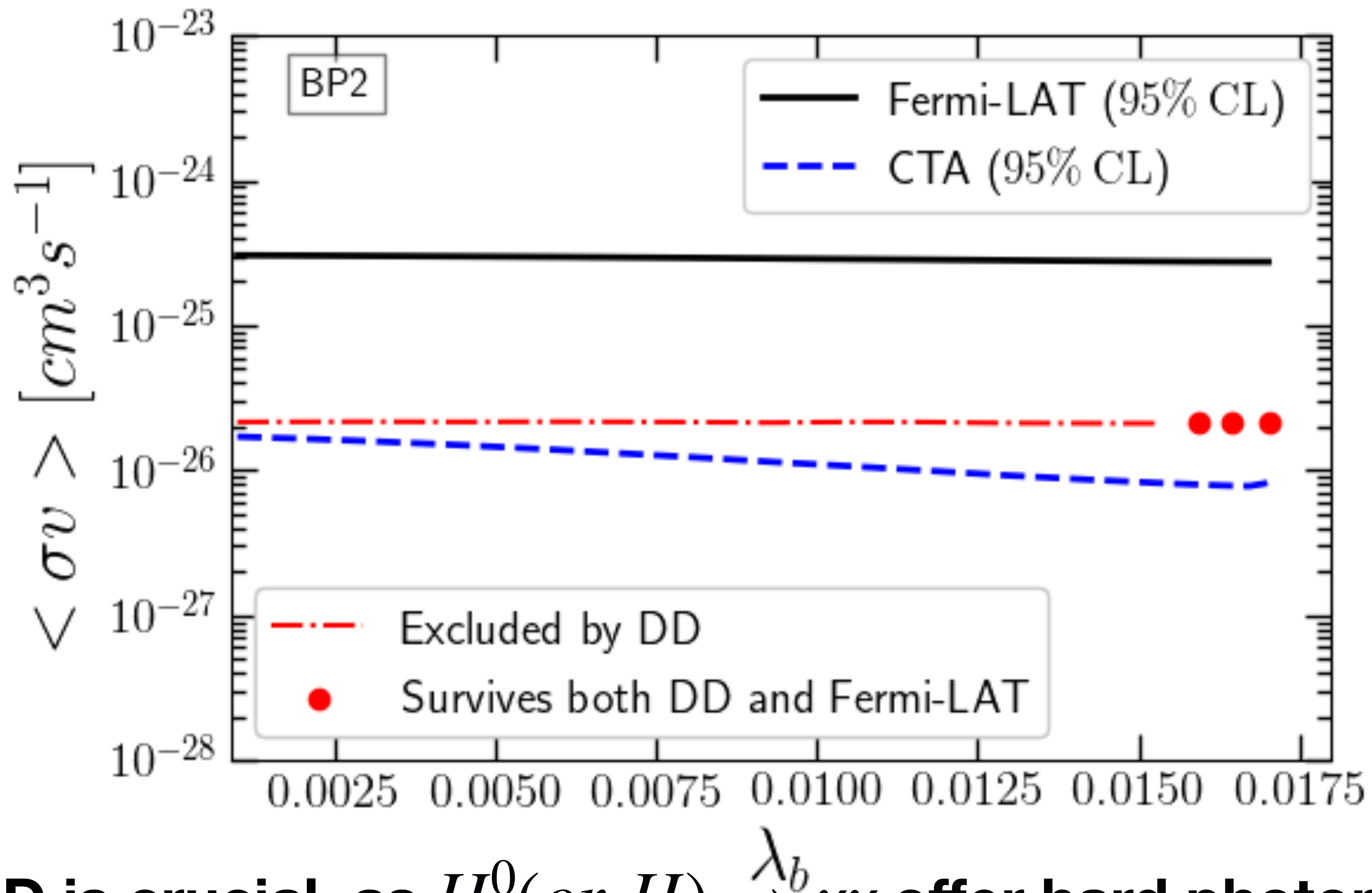
[PRL 131 (2023) 041002; *JCAP* 11 (2016) 017]

- **λ_b is tuned to satisfy observed relic density**
- **For lower λ_a, DM annihilation to BSM Higgs set relic density**

Direct detection

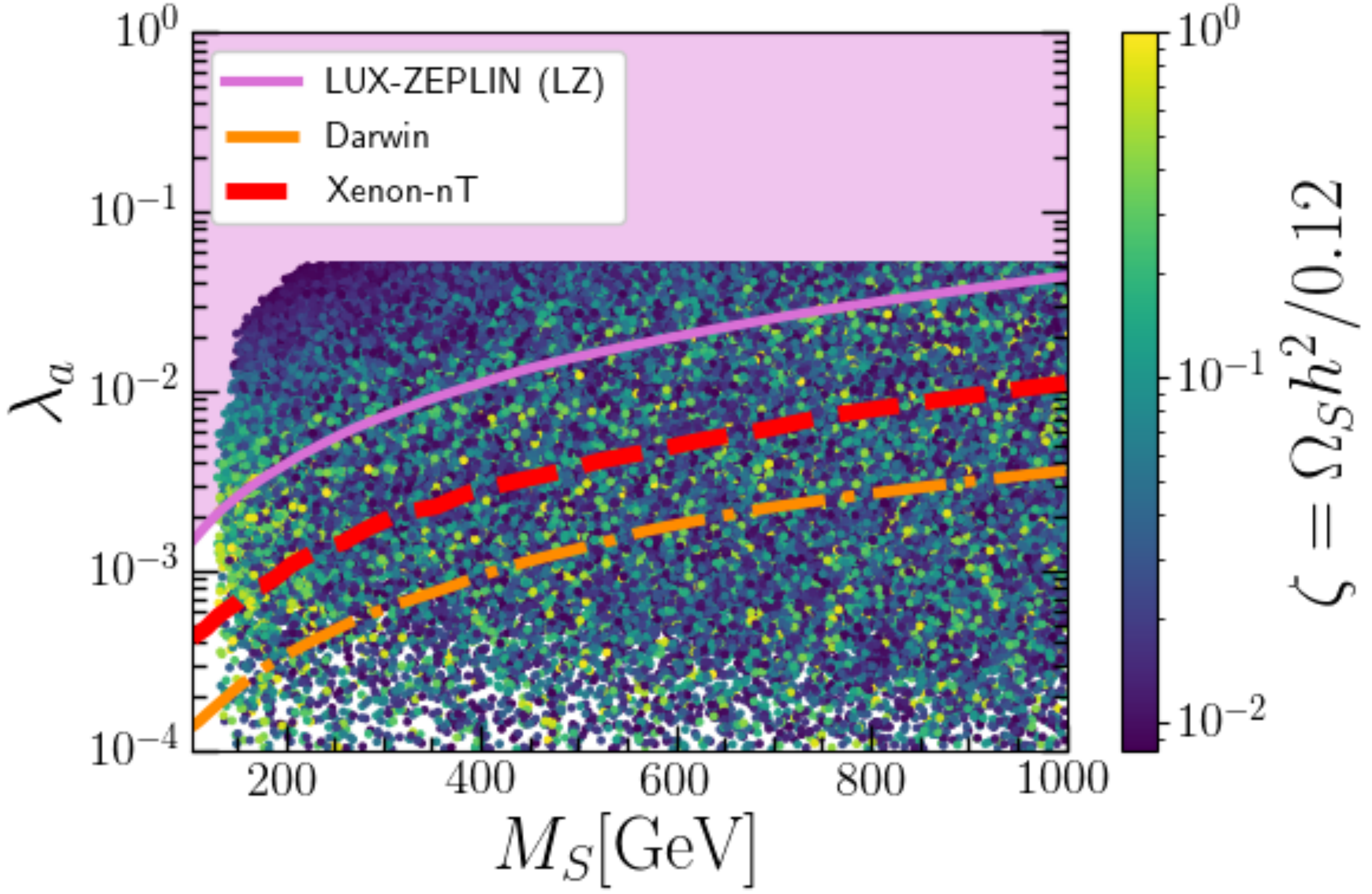


Indirect detection

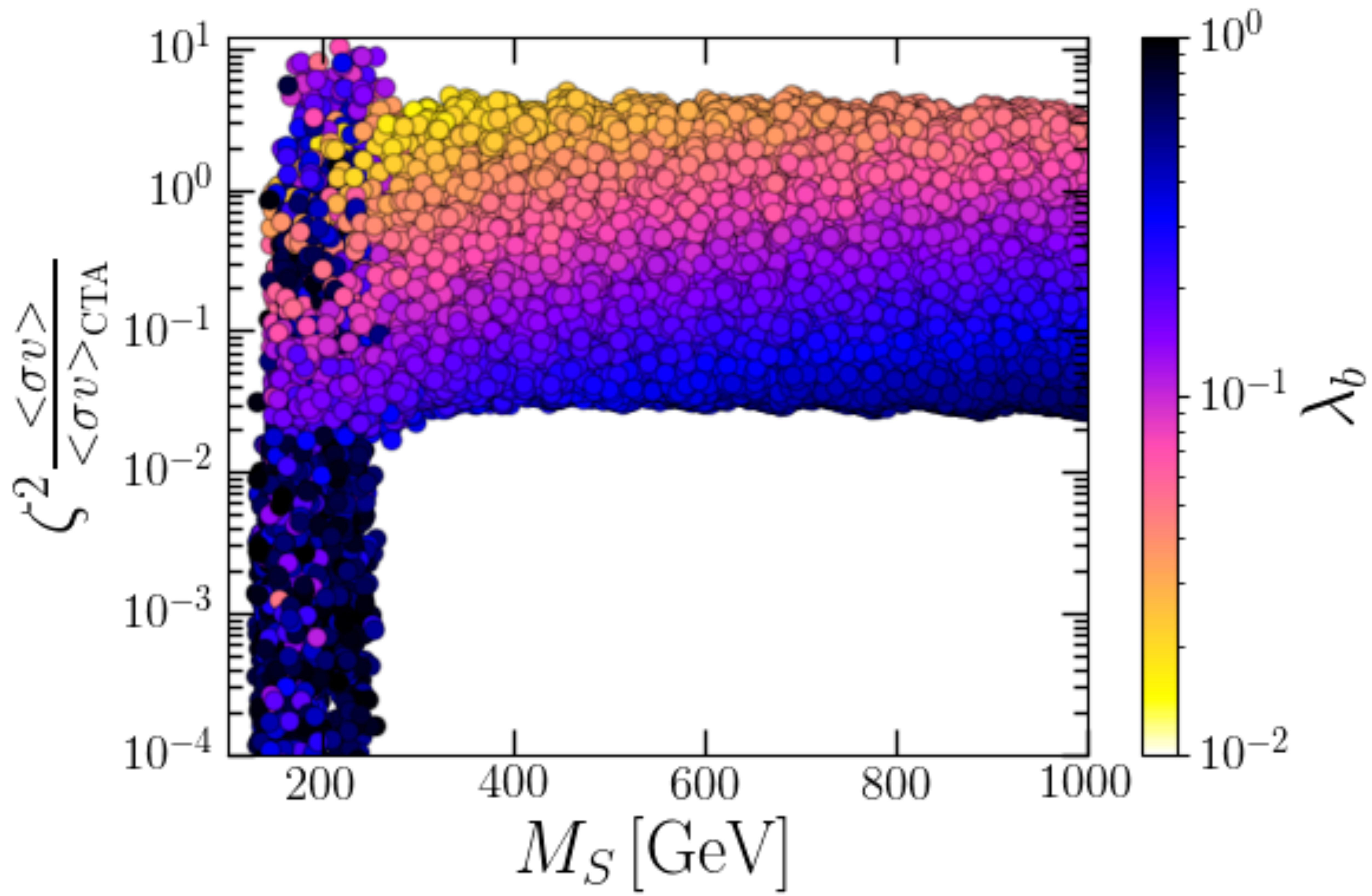


- **ID is crucial, as $H_5^0(or\ H) \to \gamma\gamma$ offer hard photon spectra**
- **NO limit from Fermi-LAT there exist weaker limit for DM heavier than 100 GeV**
- **With in CTA reach**

Global scan



Sensitivity at CTA

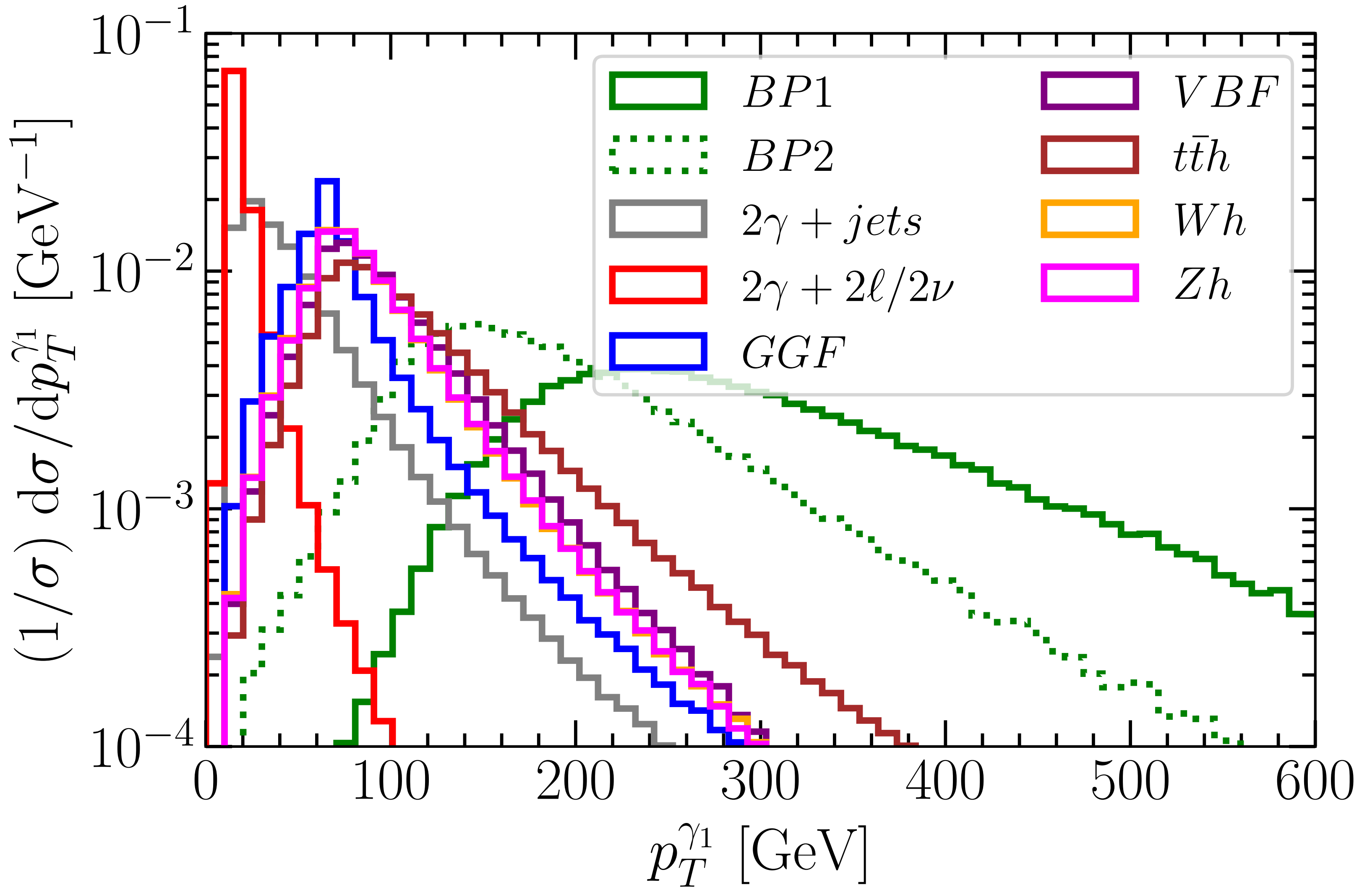


Diphoton signal @HL-LHC

$$pp \to H_5^0 + X, H_5^0 \to \gamma\gamma$$

σ^s (pb)		σ^b (pb)						
BP1	BP2	GGF	VBF	Zh	Wh	$t\bar{t}h$	$\gamma\gamma + 2\ell(2\nu)$	$\gamma\gamma + jets$
0.0167	0.0976	49.6	4.26	0.9	1.5	0.6	156.8	128.34

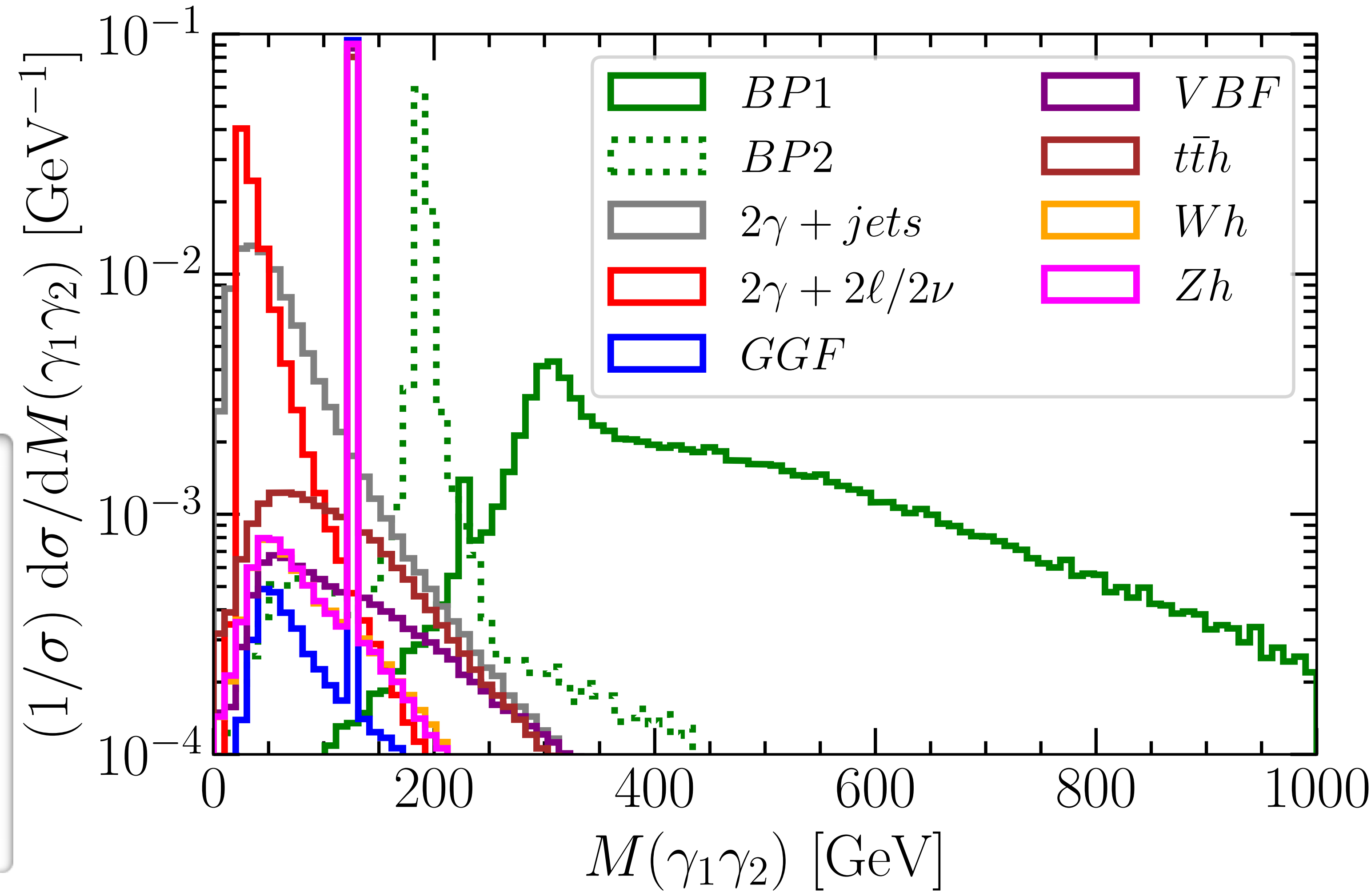
Dominant background



Selection cuts

- $p_T^{\gamma_{1,2}} \geq 80{,}30\ GeV$
- $|M(\gamma_1\gamma_2) - M_{H_5}| = 20\ GeV$

Events with $\mathcal{L} = 3000$/fb, $\mathcal{S} = N^s/\sqrt{N^s + N^b + (N^b\delta b)^2}$	
BP1	BP2
$N^s = 5711,\ N^b = 1032684,\ \mathcal{S} = 0.55$	$N^s = 164434, N^b = 3758548, \mathcal{S} = 4.36$



HL-LHC can probe BP2

Summary

- **We study the collider and dark matter phenomenology of the GM-S model in the decoupling limit.**
- **There exist a viable parameter space that can be probed by the future experiments.**
- **DM annihilation to the BSM Higgs play a crucial role to set relic density, while evading the strong DD limit.**
- **As the BSM scalars decay to diphoton final state, it offers good sensitivity at CTA as well as at the HL-LHC.**

Thank You!