Testing the Higgs triplet model via 125GeV Higgs boson decays with radiative corrections

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[2601.15983]

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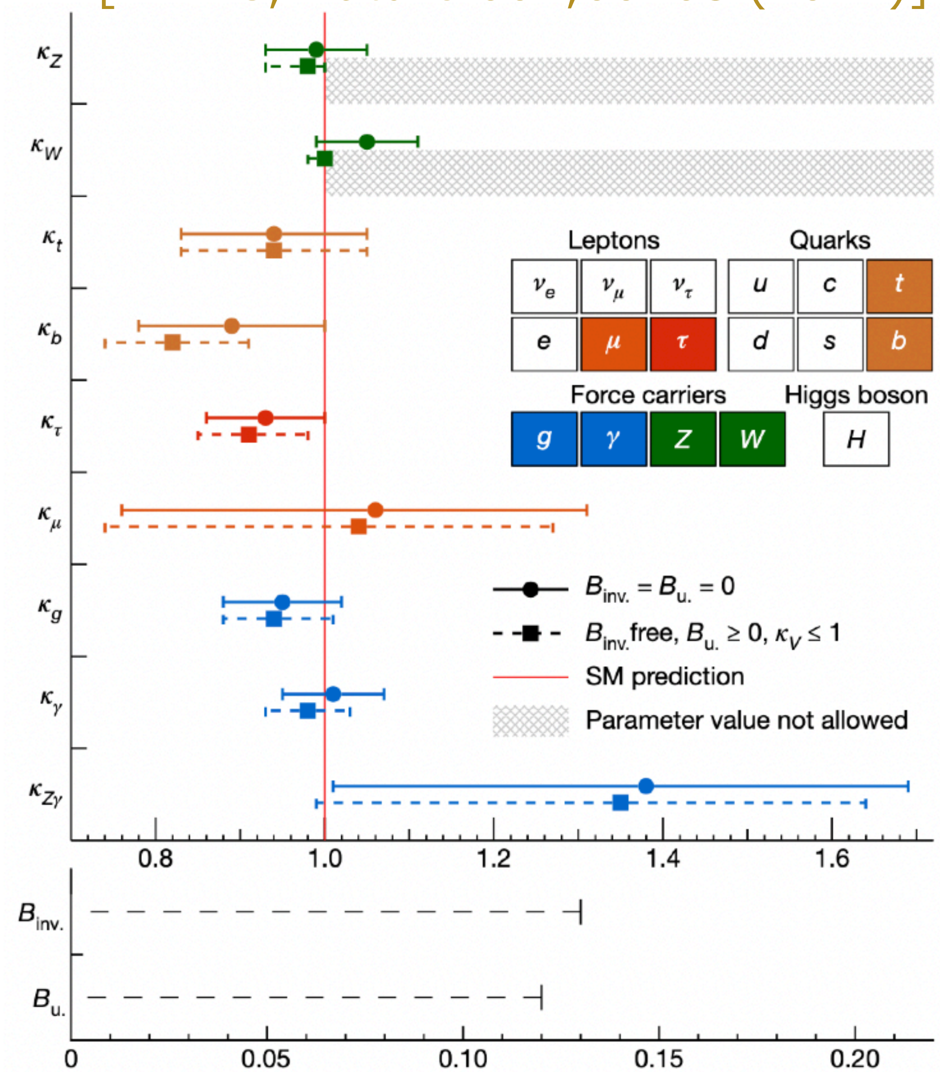
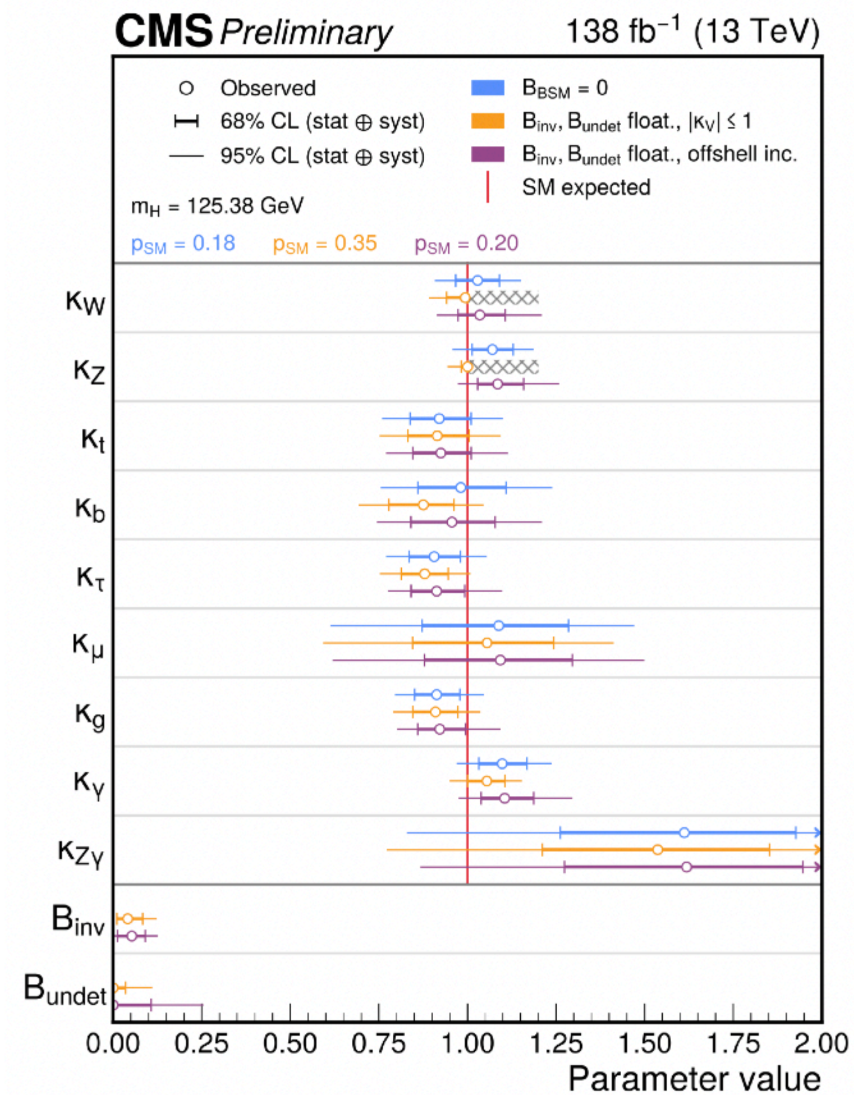
The shape of the Higgs sector is unknown

[ATLAS, Nature 607,60–68 (2022)]



[CMS PAS HIG-21-018]



The extended Higgs sector is an interesting possibility for new physics.

$$\Phi_{SM} + X \ldots$$

- Numbers, representation?
- Symmetries?
- Relation with BSM?

Reconstructing Higgs sector is an important task for new physics.

Probing Higgs sector with precision mesurement

$\rho_{\rm tree} \neq 1$

CHTM, RHTM, ⋯

$\rho_{\rm tree} = 1$

2HDM, HSM, IDM, ⋯

CHTM: Complex Higgs triplet model

RHTM: Real Higgs triplet model

- Distinguishability among models with $\rho_{\rm tree} = 1$ has been studied with radiative corrections. [Kanemura, Kikuchi, Mawatari, KS, Yagyu, PLB783 (2018), etc.]

- Testability of the exotic Higgs sector has also been studied at tree-level.

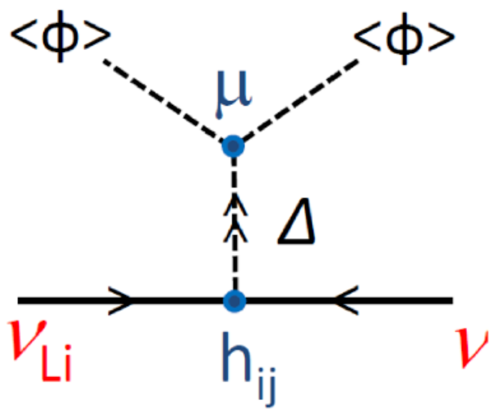
  [Kanemura, Tsumura, Yagyu, Yokoya, PRD90 (2014), etc.]

→ We will discuss how CHTM can be distinguished from other simple models by evaluating NLO corrections to 125 GeV Higgs decays.

Complex Higgs triplet model (CHTM) [1/2]

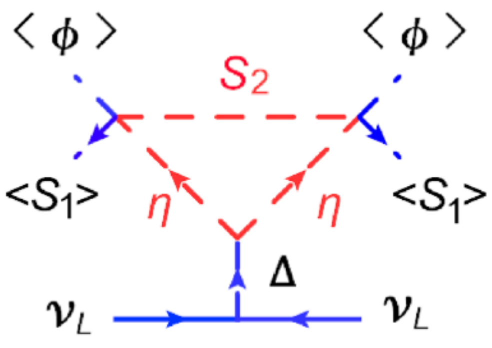
- A lot of motivations for BSM.
  - Neutrino masses

Type II seesaw



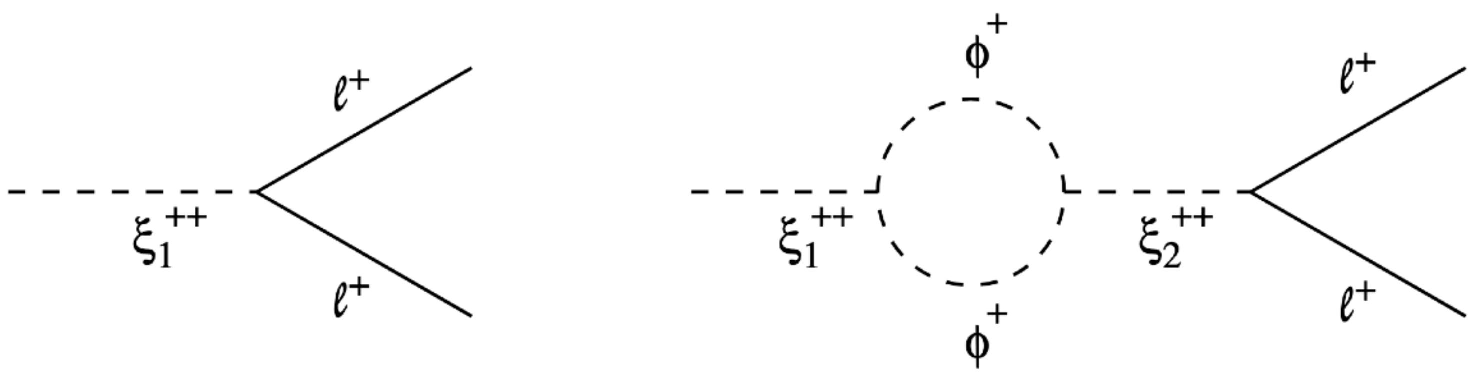
[Cheng,Li (1980); Schechter, Valle (1980); Magg, WeNerich,(1980)]

Radiative seesaw



[Kanemura, Sugiyama,PRD 86 (2012)]

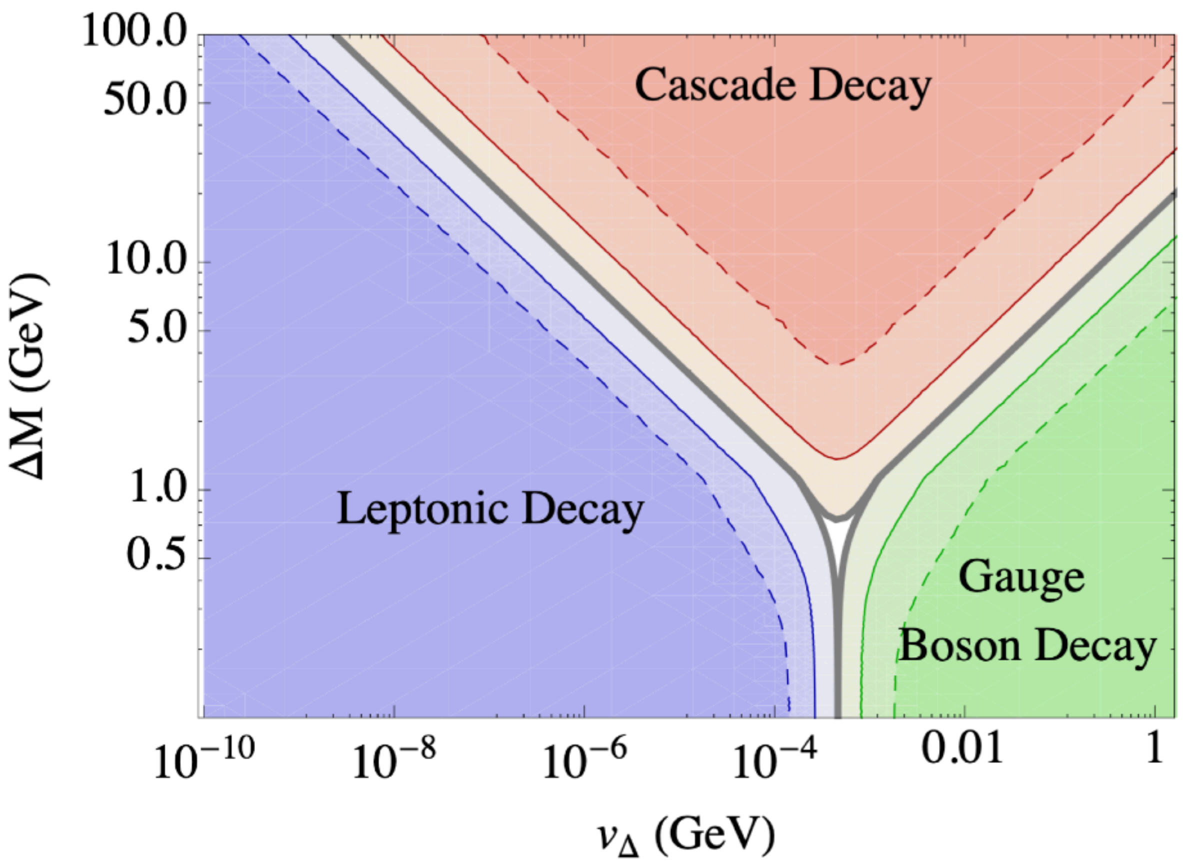
  - Leptogenesis: e.g., two triplet fields



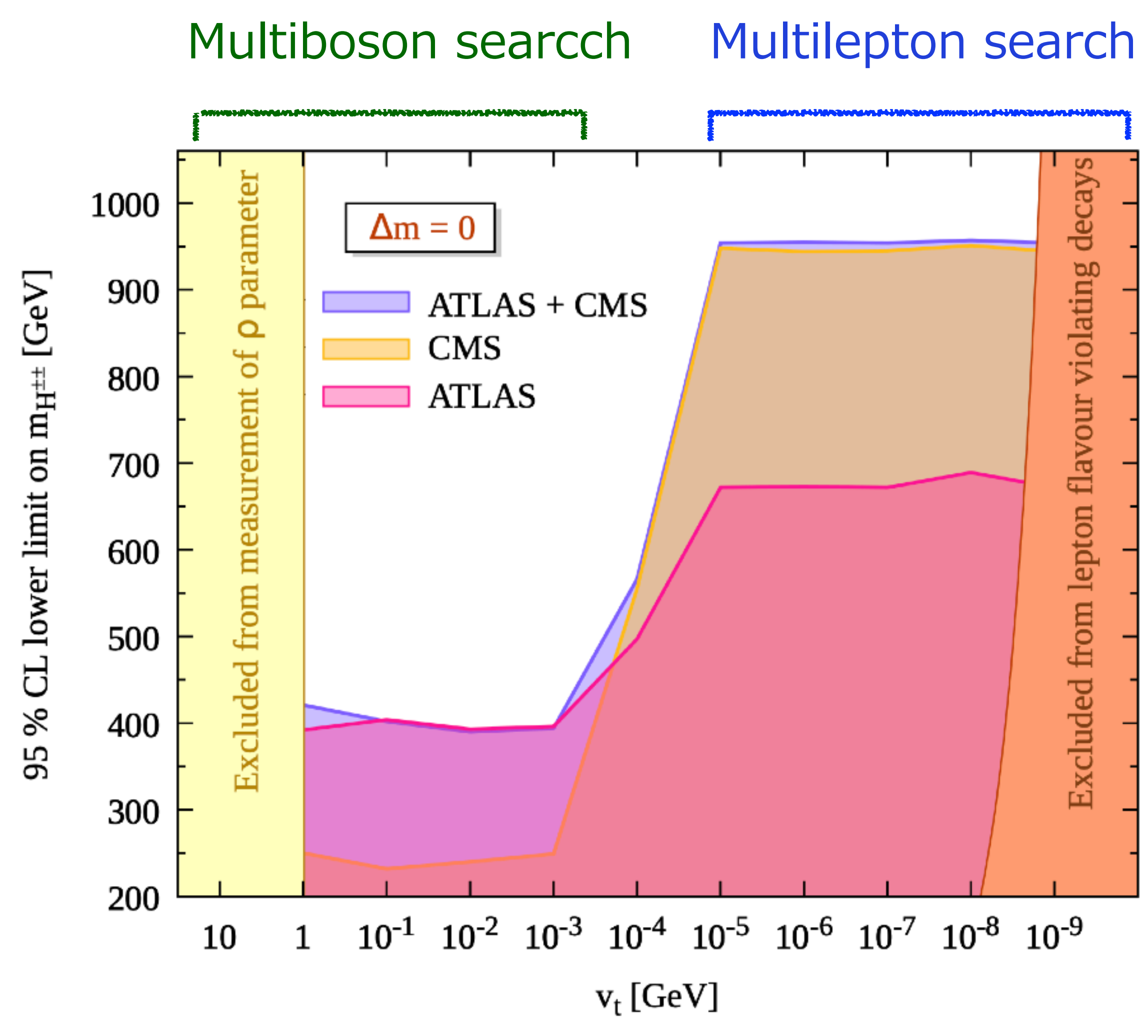
[Ma, Sarka, PRL 80 (1998)]

Complex Higgs triplet model (CHTM) [2/2]

- Rich phenomenorogy of doubly charged Higgs



[Melfo, Nemevšek, et.al., PRD85 (2012)]



[Ashanujjaman, Ghosh, JHEP 03 (2022)]

Set up

Field contents:

$$\Phi = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(\phi^0 + v_\phi + i\chi^0) \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+ & \Delta^{++} \\ \frac{1}{\sqrt{2}}(\delta^0 + v_\Delta + i\eta^0) & \Delta^+ \end{pmatrix}$$

$$\begin{pmatrix} \phi^\pm \\ \Delta^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} \chi \\ \eta \end{pmatrix} = R(\beta')\begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \begin{pmatrix} \phi \\ \delta \end{pmatrix} = R(\alpha)\begin{pmatrix} h \\ H \end{pmatrix}$$

125 GeV Higgs boson: h Heavy Higgs bosons: H, A, $H^\pm$, $H^{\pm\pm}$

Feature of the model:

$$\rho_{\rm tree} = \frac{m_W^2}{m_Z^2 \cos\theta_W^2} = \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2} \neq 1$$

- Custodial symmetry is not preserved.
- Strict restrictions for the model (e.g., $v_\Delta \lesssim \mathcal{O}(10)$ GeV.)

Limitations of mass spectrum: $m_{H^{\pm\pm}}^2 - m_{H^\pm}^2 = m_{H^\pm}^2 - m_A^2$, $m_H^2 = m_A^2$

Limitations of mixing angles: $\alpha, \beta, \beta' \ll 1$

Decoupling behaviors

$\rho_{\rm tree} = \dfrac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2}$ should be unitiy in the decoupling limit.

$$v_\Delta = \frac{\mu v_\phi^2}{\sqrt{2}\left[M^2 + (\lambda_2+\lambda_3)v_\Delta^2 + (\lambda_4+\lambda_5)v_\phi^2/2\right]}$$

Decoupling limit: $M^2 \to \infty$ and $\mu = \text{const.}$

$$V(\Phi,\Delta) = m^2\Phi^\dagger\Phi + M^2 \mathrm{Tr}(\Delta^\dagger\Delta) + [\mu\Phi^T i\sigma_2\Delta^\dagger\Phi + \mathrm{h.c.}] + (\text{quartirc term})$$

- $\rho_{\rm tree} = 1$
- Higgs couplings approaches to SM. (Mixing angles → 0)

$$\kappa_W = \cos\alpha\cos\beta + \sqrt{2}\sin\alpha\sin\beta, \qquad \kappa_f = \frac{\cos\alpha}{\cos\beta},$$

$$\kappa_Z = \frac{1}{\sqrt{1+\sin\beta^2}}(\cos\alpha\cos\beta' + \sqrt{2}\sin\alpha\sin\beta'),$$

$$\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}, \quad \tan\beta' = \frac{2v_\Delta}{v_\phi}$$

$$\sin\alpha \sim \frac{v_\Delta}{v_\phi}$$

Renormalization

Renormalization of gage sector is different from the SM due to an additional parameter.

CHTM:4 (e.g., $m_W, m_Z, \alpha_{\rm em}, v_\Delta$), SM:3 (e.g., $m_W, m_Z, \alpha_{\rm em}$)

Scheme in [Blank and Hollik (1998)]: $m_W, \quad m_Z, \quad \alpha_{\rm em}, \quad (s_W^{f=e})^2$

$$\hat{\Gamma}_{Zee} = \Gamma_{Zee}^{\rm tree}$$

- Decoupling of the triplet fields is not trivial since v_Δ is output. [Chen, S. Dawson, and T. Krupovnickas (2006)]

Scheme in [Aoki, Kanemura, Kikuchi, Yagyu (2012)]: $m_W, \quad m_Z, \quad \alpha_{\rm em}, \quad \beta'$

$$\Pi_{AG^0}(m_A^2) = 0$$

- Decoupling of the triplet fields is realized in the limit of $\beta' \to 0$.
- The CTs of scalar mixing angles (α, β, β') are gauge dependent. [Y. Yamada(2001)]

➡ We improved the latter scheme to have gauge-independent CTs by applying the pinch technique.

Calcurations of NLO corrections to *h* decays

- Radiative correcitons to *h* decays are computed:

$h \to f\bar{f}$	:	NLO EW +NNLO QCD corrections
$h \to VV^* \to Vf\bar{f}\ (V = Z, W)$	:	NLO EW +NLO QCD corrections
$h \to \gamma\gamma, \gamma Z, gg$	:	NNLO QCD corrections

- New phyics effects

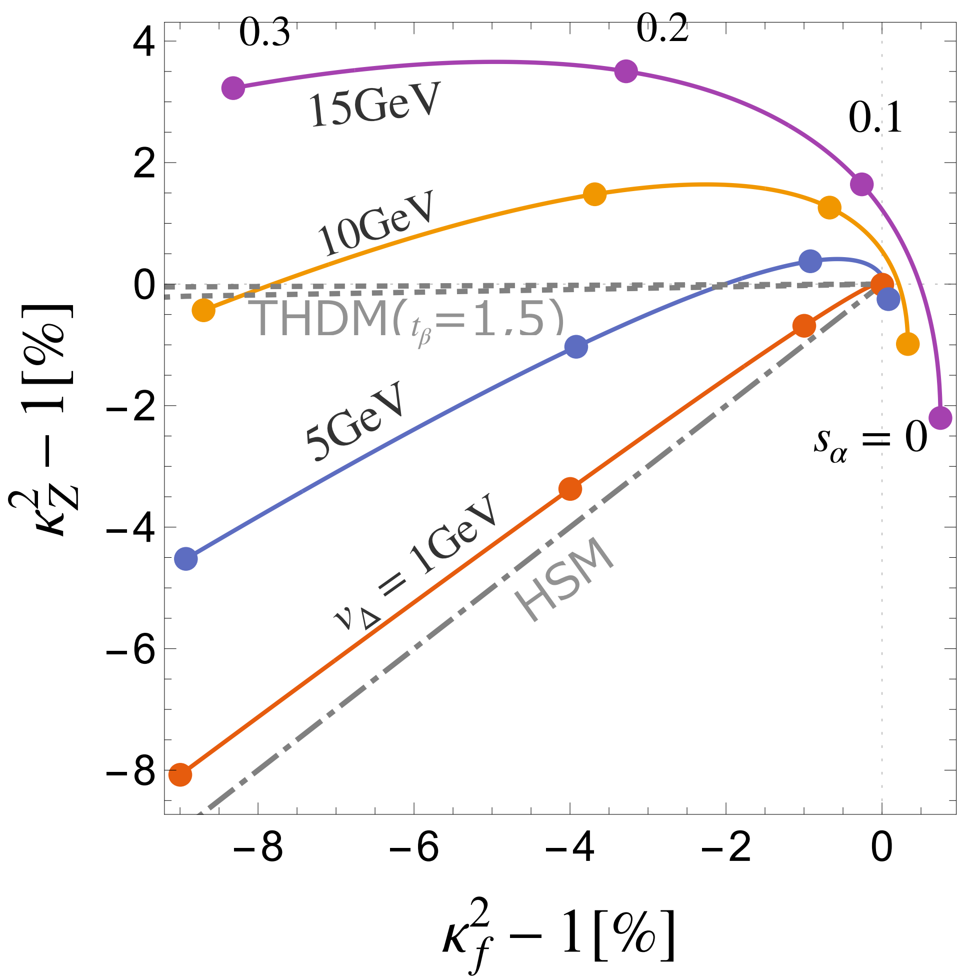
$$\mathcal{M}(h \to XX) = \underbrace{\mathcal{M}_{\text{tree}}}_{\ni \text{ mixing}} + \underbrace{\mathcal{M}_{1-\text{loop}} + \mathcal{M}_{\text{CT}}}_{\ni \text{ heavy Higgs loop}(\ H^{\pm\pm},\ H^{\pm},\ H,\ A\ )}$$

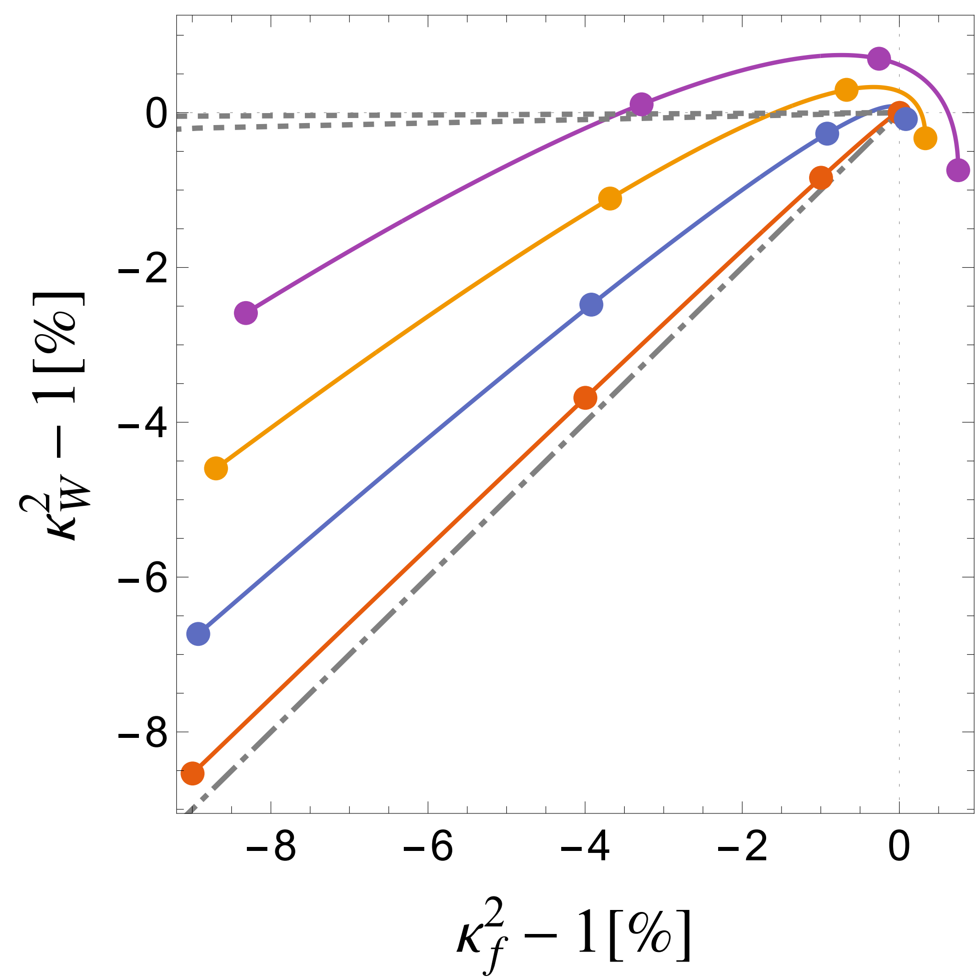
- Large v_Δ leads to sizable mixings and non-decoupling effects

- Doubly charged Higgs loop corrections is imporant espcially for $h \to \gamma\gamma$

The NLO corrections are typically of order a few percent,
comparable to the expected precision at future Higgs factories.

Higgs boson decay rates at LO





$$\kappa_W = \cos\alpha\cos\beta + \sqrt{2}\sin\alpha\sin\beta,$$

$$\kappa_Z = \frac{\cos\alpha\cos\beta' + \sqrt{2}\sin\alpha\sin\beta'}{\sqrt{1+\sin\beta^2}},$$

$$\kappa_f = \frac{\cos\alpha}{\cos\beta},$$

$$\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}, \quad \tan\beta' = \frac{2v_\Delta}{v_\phi},$$

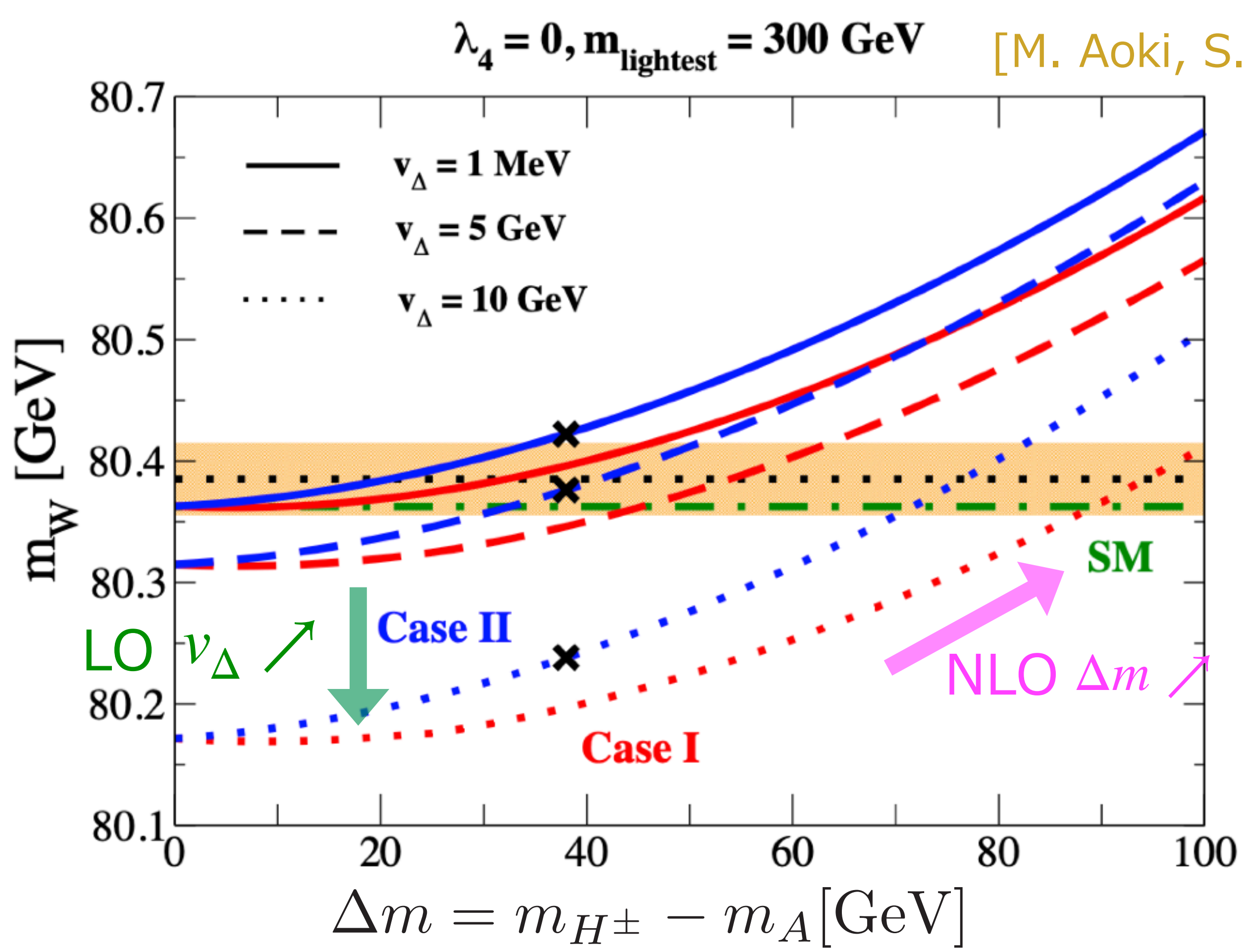
In the case of $v_\Delta \gg 1$, one obtains $\kappa_V > 1$ for CHTM.

→ $v_\Delta \gg 1$ is favored parameter regions where exisoticness ($\kappa_V > 1$) clearly appears.

Constrants 1: Electroweak precison mesurments

<u>*W* mass</u>:

[M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu, 1211.6



$$m_W^2 = \frac{m_Z^2(1+c_{\beta'}^2)}{4}\left[1+\sqrt{1-\frac{8\pi\alpha_{\rm em}}{\sqrt{2}G_F m_Z^2(1+c_{\beta'}^2)(1-\Delta r)}}\right]$$

LO NLO

$$\Delta r = \Delta\alpha + \Delta\rho + \Delta r_{\rm rem}$$

$$\Delta\rho \approx \frac{\sqrt{2}G_f}{12\pi^2\alpha_{\rm EM}}(m_A - m_H^{\pm})^2 + \ldots$$

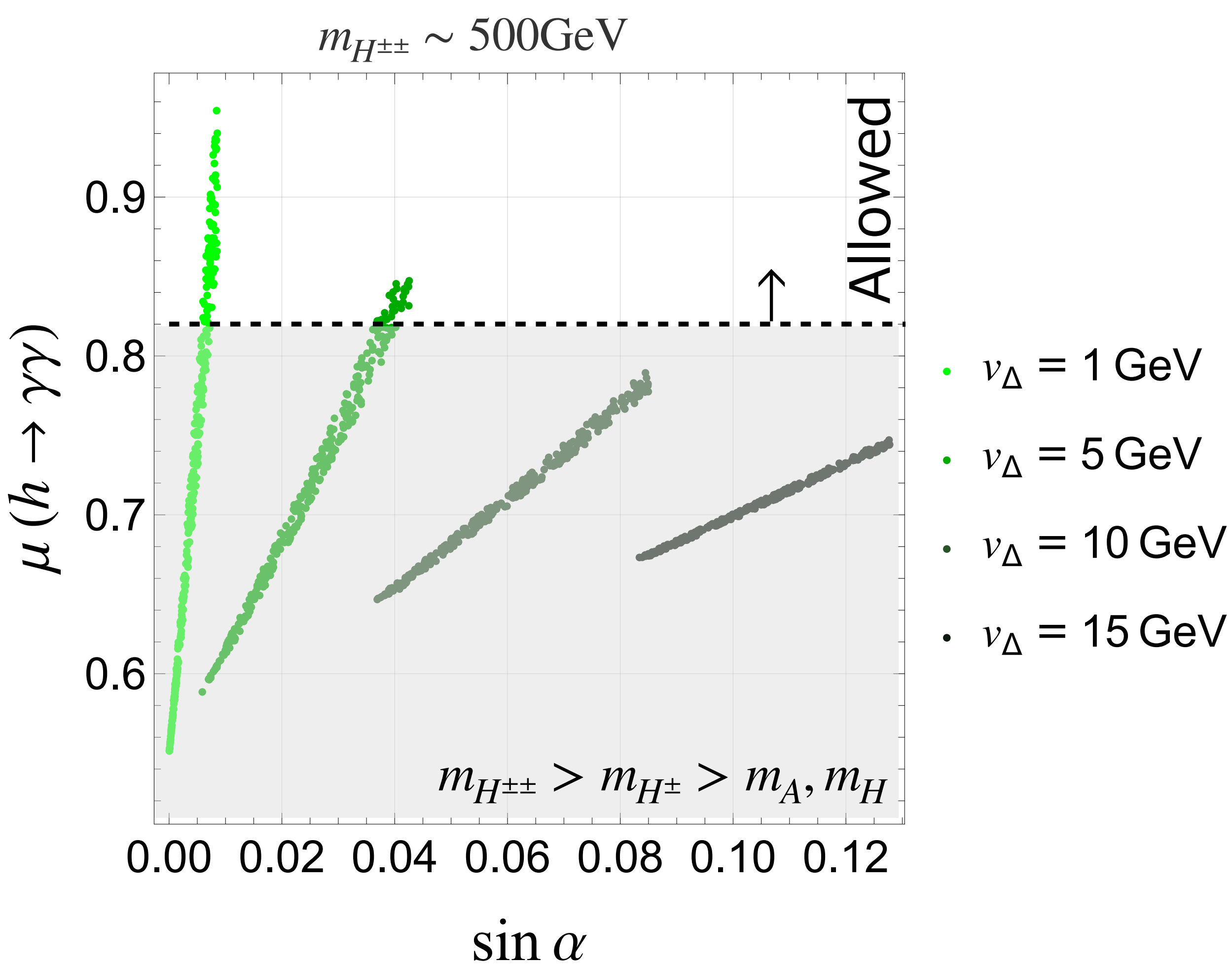
→ m_w requires large Δm in the case of $v_\Delta \sim \mathcal{O}(10)$ GeV.

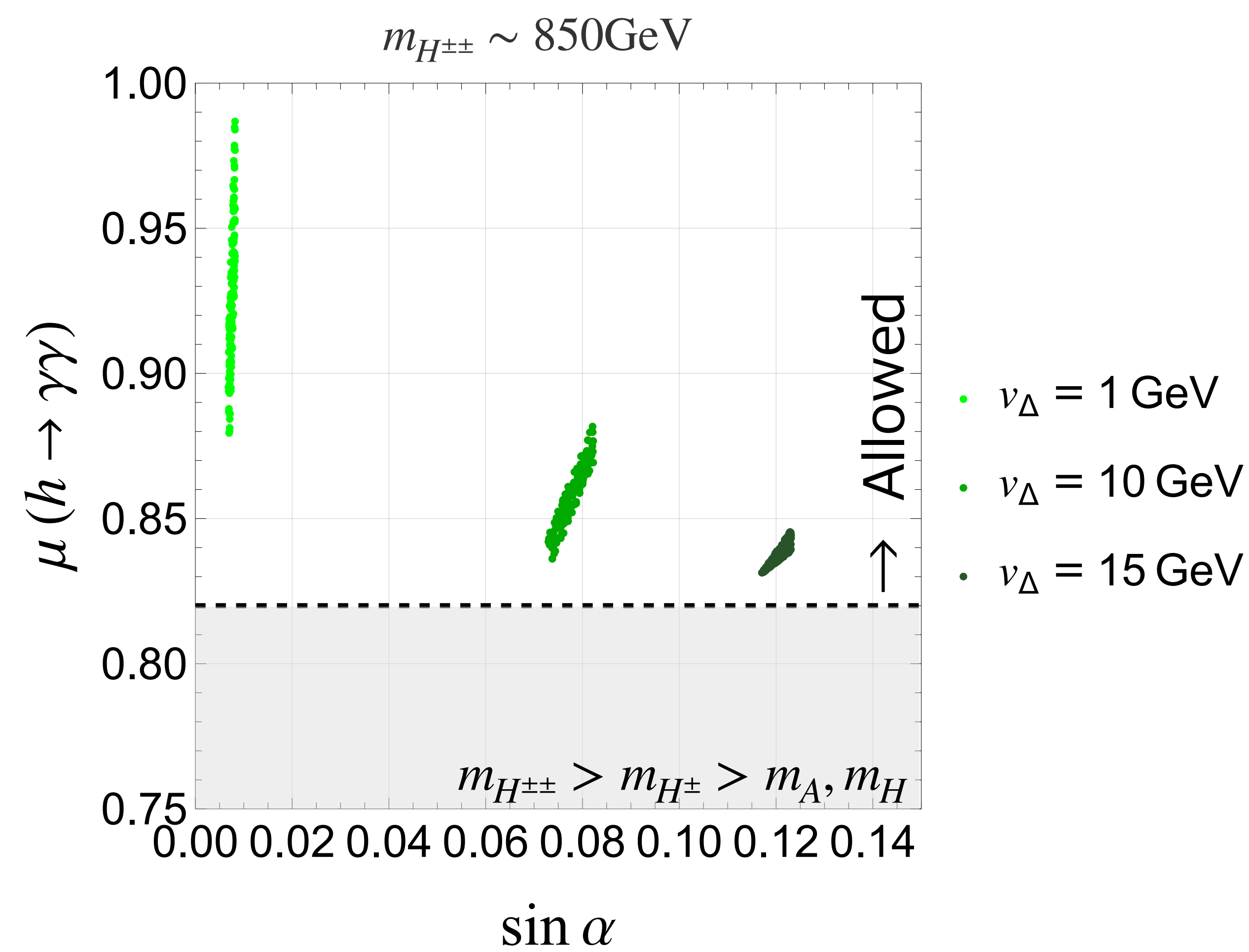
(For other observables, the same consequence is obtained.)

Constrants 2: $h \to \gamma\gamma$

[Aiko, Kanemura, Kikuchi, KS, Taniguchi, Yagyu]

$$\mu(h \to \gamma\gamma) = \frac{BR(h \to \gamma\gamma)^{CHTM}}{BR(h \to \gamma\gamma)^{SM}}$$





- Large v_Δ requires sizable mixing. This makes $h \to \gamma\gamma$ small.

- Doubly chaged Higgs loop corrections are suppressed by $1/m_{H^{\pm\pm}}^2$.

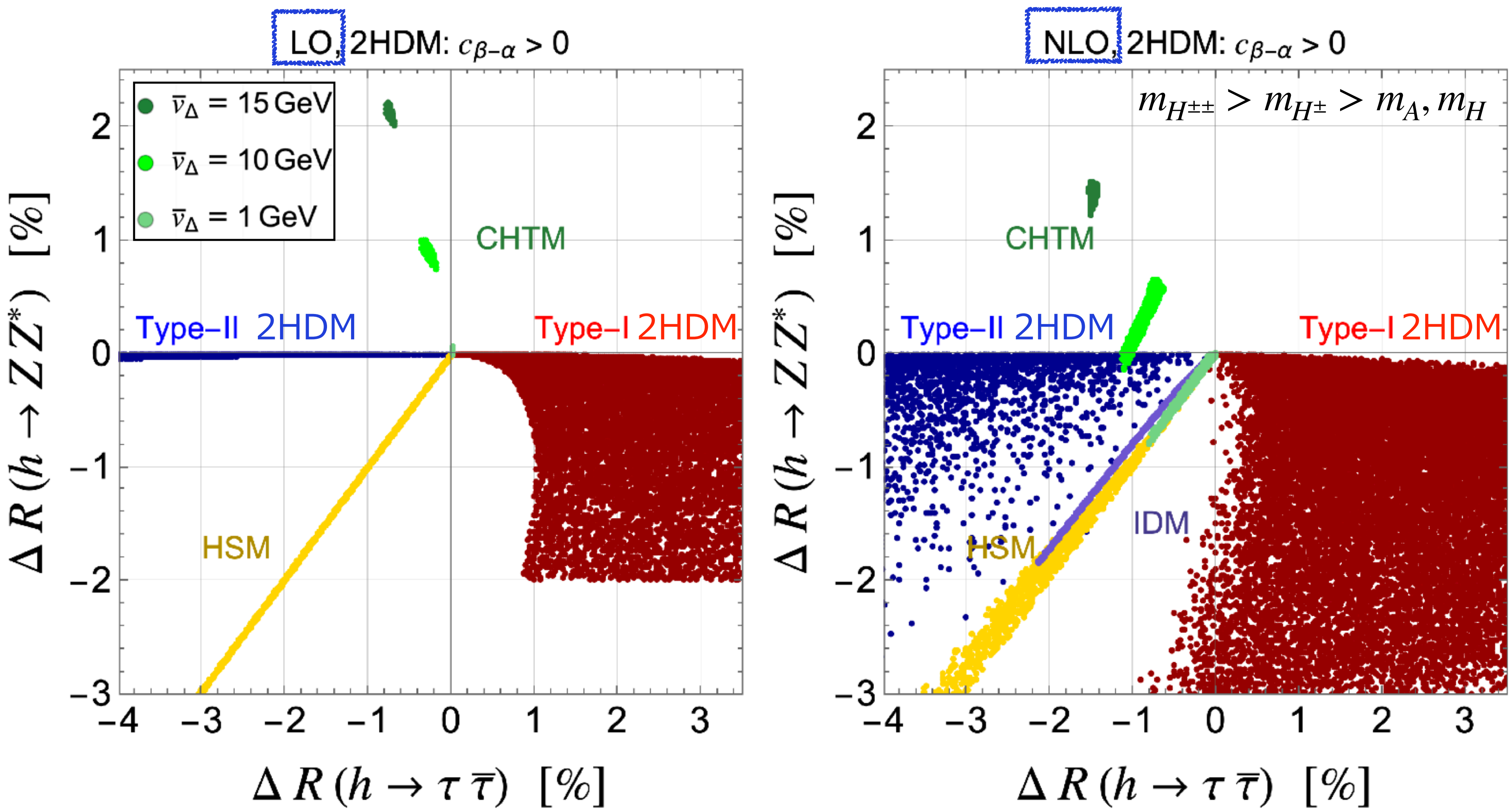
  $\to$ Heavier $H^{\pm\pm}$ is needed for a larger v_Δ regime.

  $700\text{GeV} \lesssim m_{H^{\pm\pm}} \lesssim 900\text{GeV}$ (the Heaviest $H^{\pm\pm}$ scenario)

  [Lower bounds for $m_{H^{\pm\pm}}$: $h \to \gamma\gamma$, upper bounds for $m_{H^{\pm\pm}}$: Perturbativity]

Decay rates of h at NLO [1/2]

$$\Delta R \equiv \frac{\Gamma(h \to XX)^{\rm HTM}}{\Gamma(h \to XX)^{\rm SM}} - 1$$



[Aiko, Kanemura, Kikuchi, KS, Taniguchi, Yagyu]

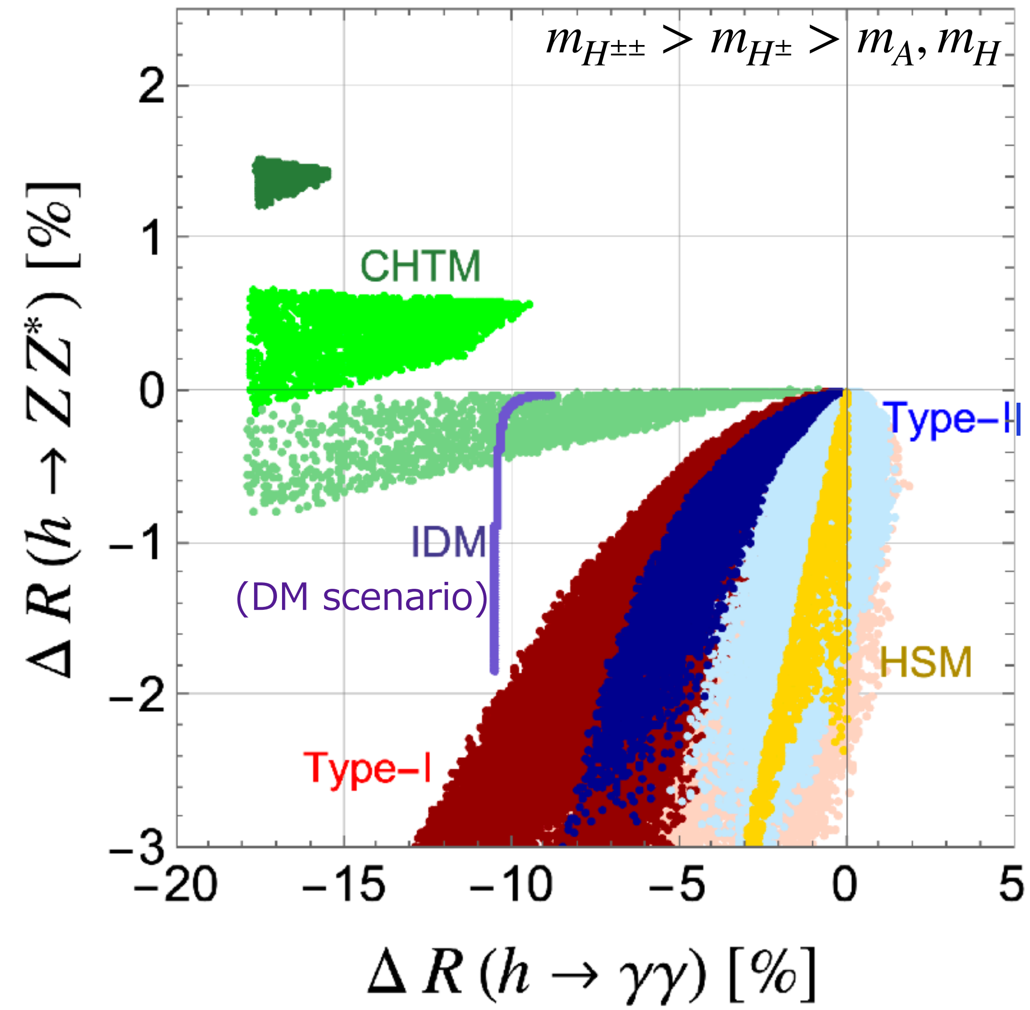
- Due to the loop corrections, ΔR deviate from LO with~-1%.

⟺ $\Gamma(h \to ZZ^*)$~0.44% , $\Gamma(h \to WW^*)$~0.58%, $\Gamma(h \to \tau\tau)$~1.3%
@ILC500 [Blas, et. al., JHEP01(2020)139]

- At NLO level, $\Delta R(h \to ZZ^*) \gtrsim 1\,\%$, by which CHTM is separable from other models.

Decay rates of *h* at NLO [2/2]

$$\Delta R \equiv \frac{\Gamma(h \to XX)^{\rm HTM}}{\Gamma(h \to XX)^{\rm SM}} - 1$$



[Aiko, Kanemura, Kikuchi, KS, Taniguchi, Yagyu]

- $h \to \gamma\gamma$ can be significantly deviated from the SM.

⟺ $\Gamma(h \to \gamma\gamma)$~2.6% @ HL-LHC [arXiv:2504.00672]

- One can identify CHTM if the positive deviation in $h \to ZZ^*$ and large deviations in $h \to \gamma\gamma$ are detected.

Summary

- We investigated the impact of NLO corrections to $h \to VV^*$ and $h \to ff$ in the complex Higgs triplet model.

- Characteristic deviations are the folloing:

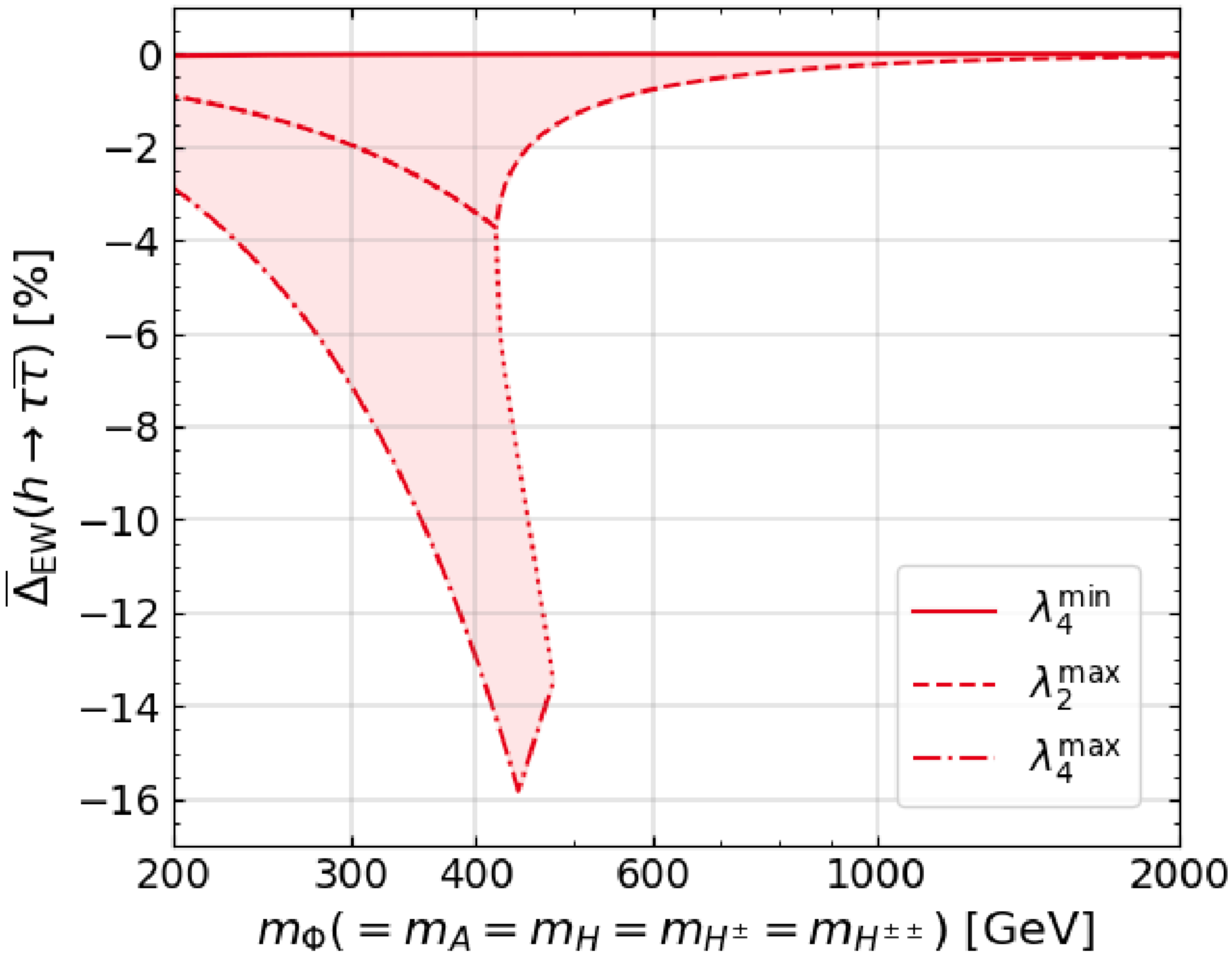
  - $\Delta R(h \to VV^*) \sim +1\,\%$, $\Delta R(h \to \gamma\gamma) \sim -20\,\%$ [Heaviest $H^{\pm\pm}$ scenario]

  - $\Delta R(h \to \gamma\gamma) \sim +10\,\%$ [Lightest $H^{\pm\pm}$ scenario]

(see the details in our paper)

- Loop corrections shift the deviations with the order of $\mathcal{O}(1)\,\%$.
  This may be detectable at the future collider experiments.

Decoupling behavior



Analytical formula for $h \to \gamma\gamma$

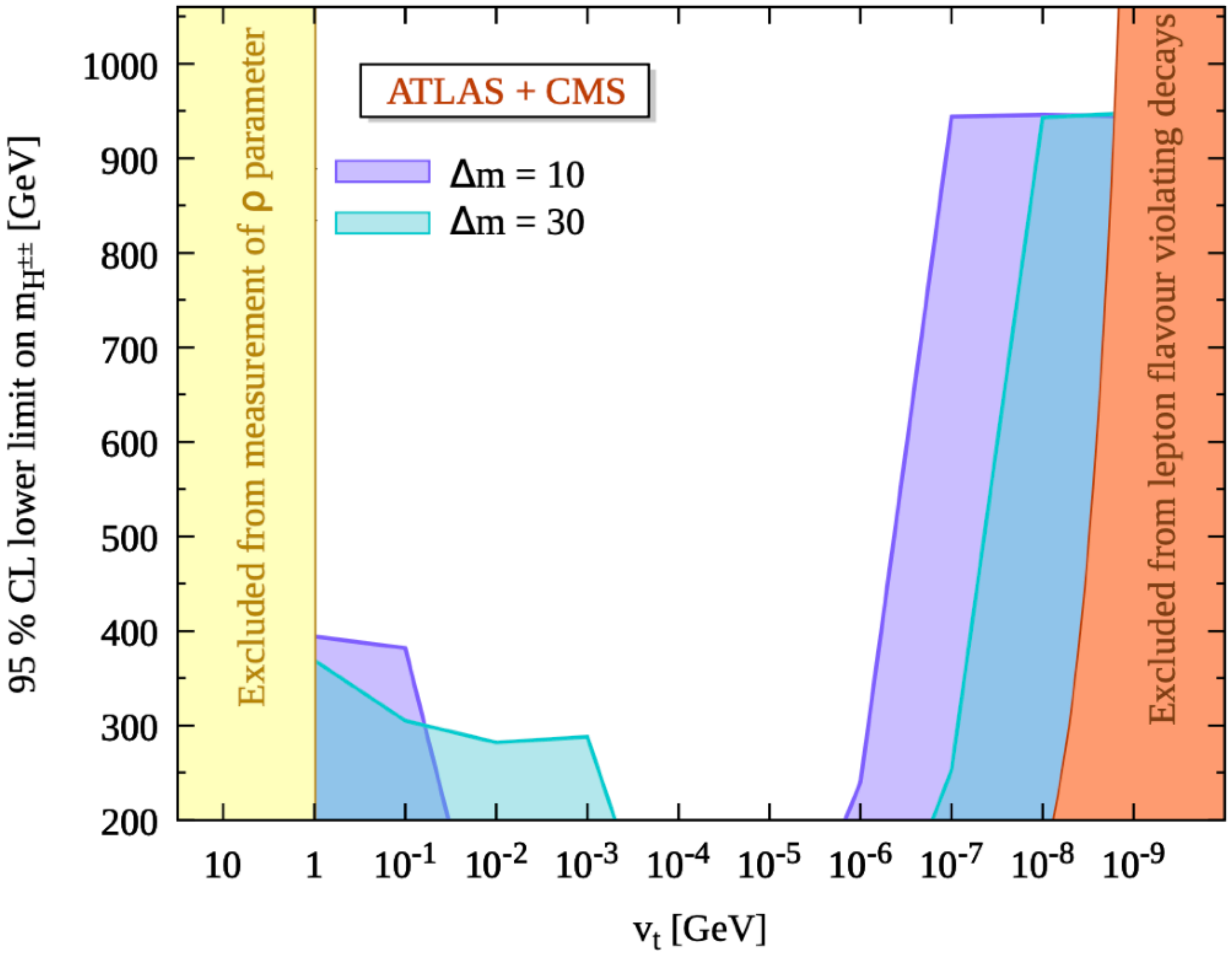
$$\Gamma_{h\to\gamma\gamma} = \frac{G_f \alpha^2 m_h^3}{128\sqrt{2}\pi^3}\left|4\frac{\lambda_{H^{++}H^{--}h}v}{12m_{H^{\pm\pm}}^2} + \frac{\lambda_{H^+H^-h}v}{12m_{H^\pm}^2} + (W, f\ \text{loop})\right|^2$$

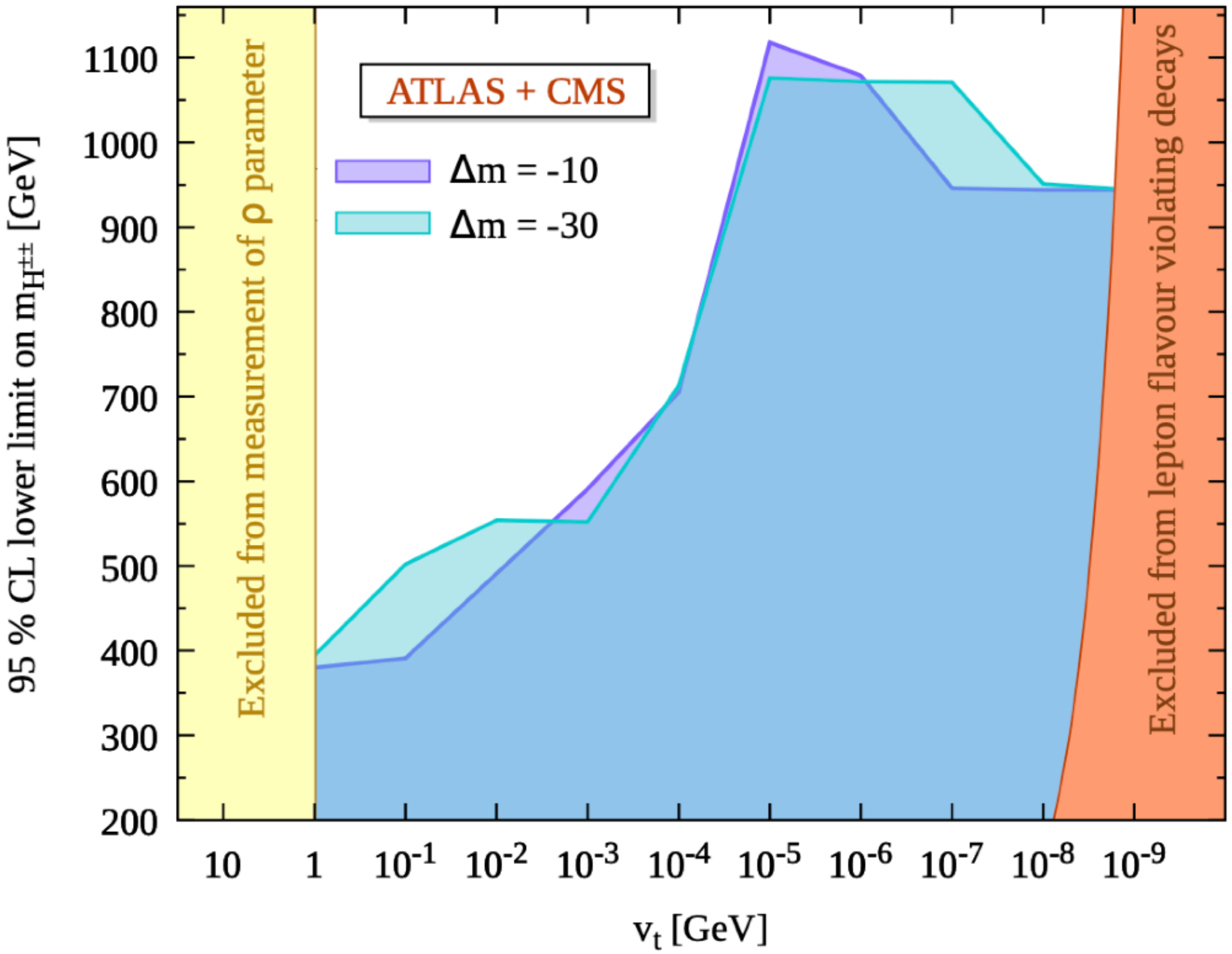
$$\lambda_{H^{++}H^{--}h}v \approx \lambda_4 v^2$$

$$V \ni \lambda_4 |\Phi^\dagger \Phi|^2 \mathrm{Tr}(\Delta^\dagger \Delta)$$

Direct searches of $H^{\pm\pm}$

[Ashanujjaman, Ghosh, JHEP 03 (2022)]



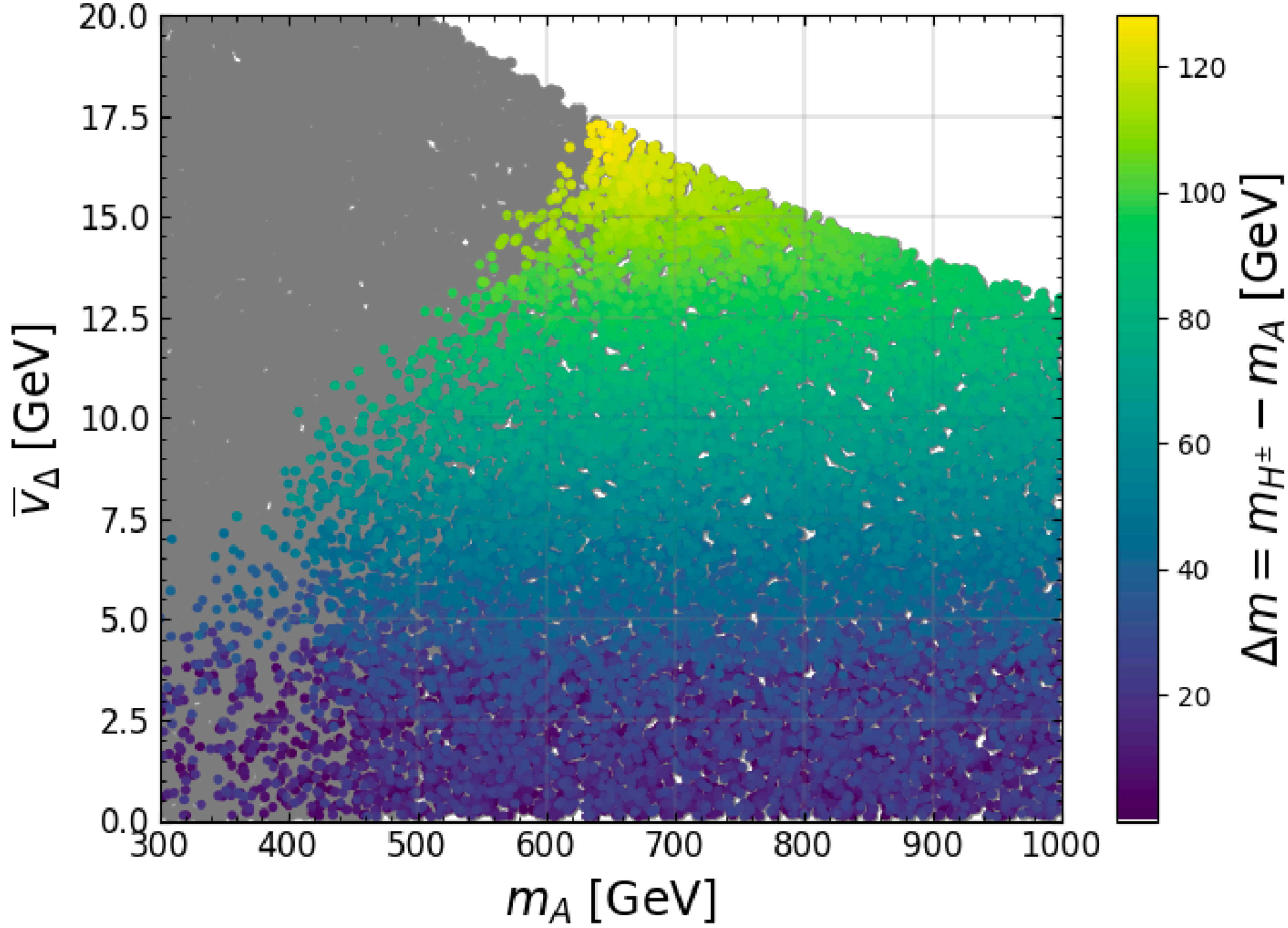


parameter scan

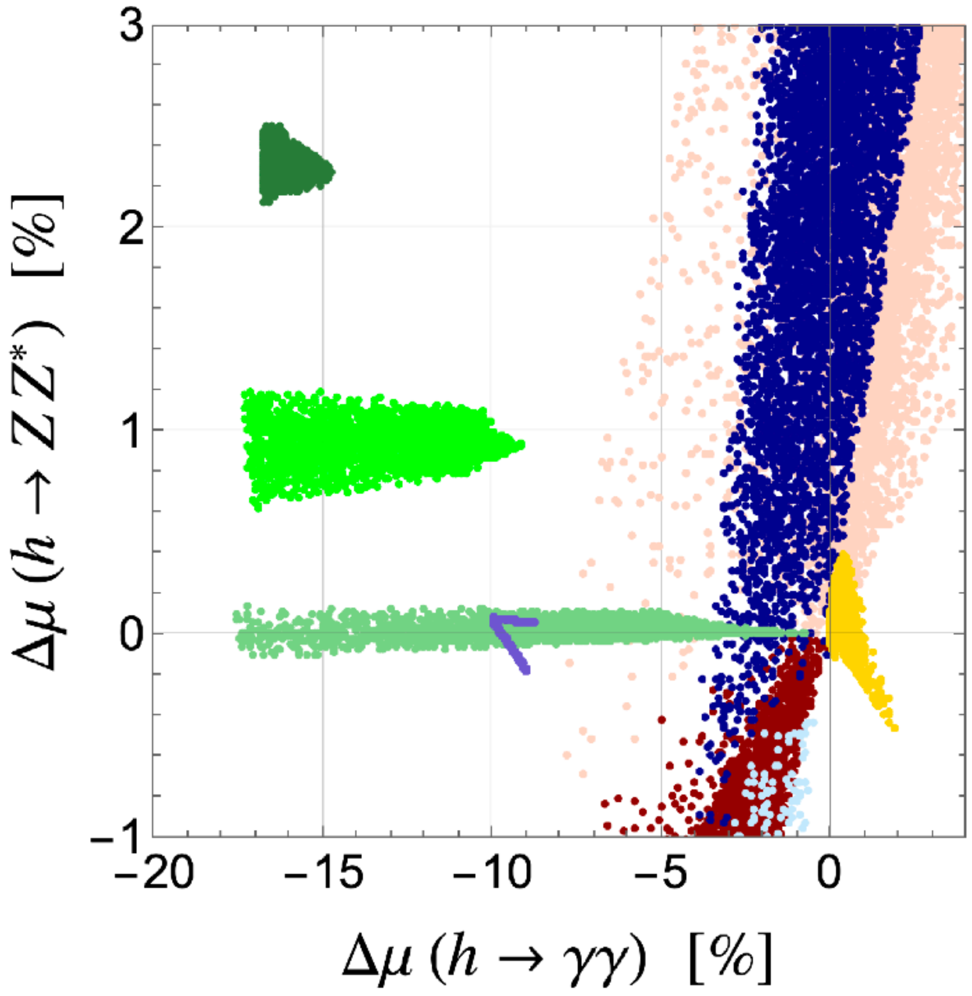
$$\text{HS: } 300\ \text{GeV} \le m_A \le 1000\ \text{GeV},\ 0 \le \lambda_4 \le 4\pi,\ 0 \le \Delta m \le 150\ \text{GeV},$$

$$\text{LS: } 400\ \text{GeV} \le m_{H^{\pm\pm}} \le 1000\ \text{GeV},\ -5 \le \lambda_4 \le 4\pi,\ 0 \le \Delta m \le 150\ \text{GeV},$$

Allowed parameter regions



Deviations in BRs



v_Δの繰り込み

BH scheme

- renormalization mW, mZ ,alpha, sW
- SWをinputにしている。そもそもSWをSM valueからずれた値をつかうとvDeltaは0にならない。
- SWをSM valueを inputとしても loop level で custdial violationを引き起こす項が生じる。自然にv_Delta → 0とするlimitがない。

  $v_\Delta \sim$ (correction with custdial symmetry violation)

AKKY scheme

- renormalization of mW, mZ ,alpha, beta'
- CP-odd Higgs mass matrixの off diagonal partがon-shell で0になることを要求
- CP-odd Higgs mass matrixの off diagonal partはv_Deltaに比例しているので、beta' → 0 limitは本質的にv_Delta->0に対応
- ただし、betaのカウンタータームがgauge depepnendetになるという別の困難が発生。