Leading two-loop corrections to the Higgs di-photon decay in the inert doublet model

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Work in progress

Higgs as a Probe of New Physics 2023 (2023/06/09 Osaka)

Problems in the SM

- Dark matter (DM)
- Baryon asymmetry of the universe
- Neutrino tiny mass etc.

SM must be extended to solve these problems.

Scalar DM

Discrete symmetry (e.g. Z_2 symmetry) stabilizes additional scalars.

- DM relic density can be explained via the freeze-out mechanism
- Testable through many channels
  - DM direct detection, collider search, indirect search, etc.

Scalar DM can be tested in current and future experiments.

The model with two scalar doublets Φ_1 and Φ_2 with unbroken Z_2 symmetry.

$$V(\Phi_1,\ \Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right],$$

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix},\quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

Inert scalars (H, A, and H^+) are Z_2 odd → We take H as a DM candidate.

Parameters v (=246 GeV), m_h (=125 GeV), m_H, m_A, $m_{H^\pm}$, μ_2^2, λ_2

DM scenario

There are two scenarios, where DM relic abundance can be explained under the bound of direct detection.

A. Arhrib et al. JCAP06 (2014), A. Balyaev et al. PRD97 (2018)

1. Higgs resonance scenario ($m_H \approx m_h/2$)
2. Heavy mass scenario ($500\ \mathrm{GeV} \lesssim m_H$)

→ We focus on the testability of the DM scenario via Higgs measurements.

S. Kanemura, M. Kikuchi and K. Sakurai, PRD94 (2016)

Higgs to diphoton decay is useful channel to study the IDM.

$$C_{h\gamma\gamma} = \frac{\alpha_{\rm em}}{4\pi}\left[\sum_f N_c^f Q_f^2 I_F(\tau_f) + I_V(\tau_W) - \frac{\lambda_{hH^+H^-}}{v} I_S(\tau_{H^\pm})\right]$$

$$\mathcal{L}_{\rm eff} = -\frac{1}{4} C_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h$$

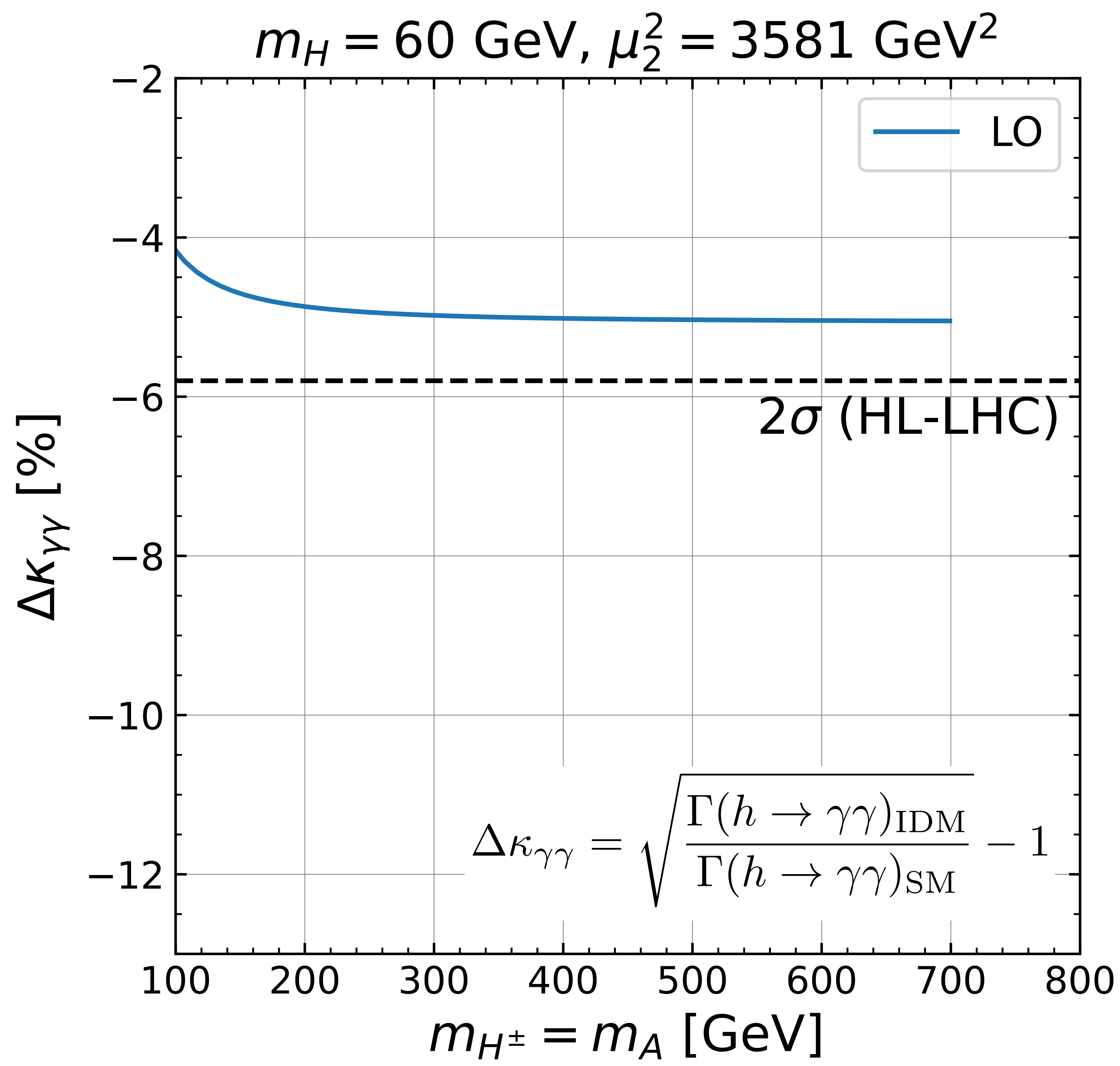
$$\tau_i = m_h^2/(4m_i^2)$$

Especially, in the Higgs resonance scenario,

- $m_H \approx m_h/2$
- $m_H^2 \approx \mu_2^2$ to avoid DM direct detection.

$$C_{h\gamma\gamma,S} \approx -\frac{\alpha_{\rm em}}{6\pi v}\left(1 - \frac{m_H^2}{m_{H^\pm}^2}\right) \quad \text{for} \quad \tau_{H^\pm} \ll 1$$

Additional Higgs contibutions do not decouple.



What is the impact of two-loop effects?

Higgs Low-energy Theorem

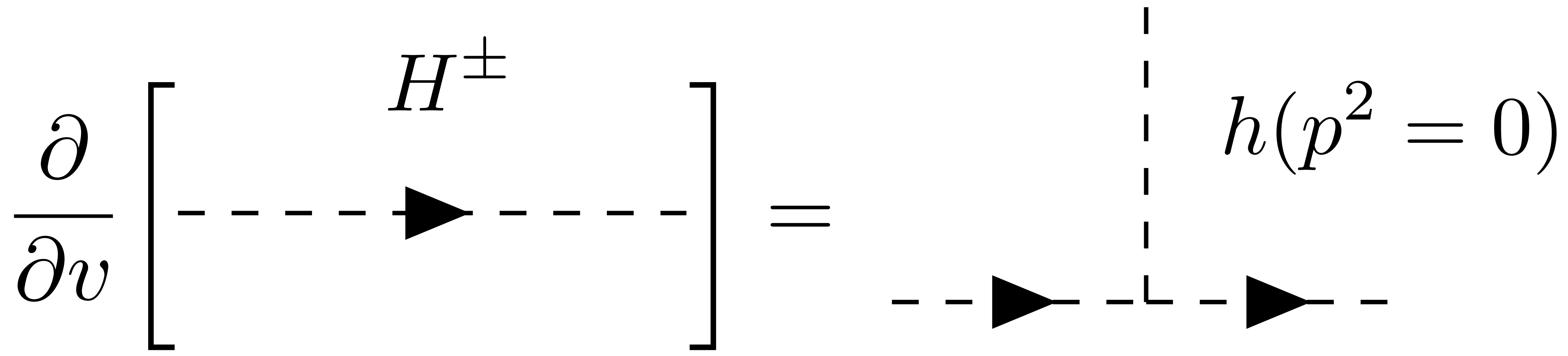
J. Gunion et al. The Higgs Hunter's Guide and refs. therein.
B. Kniehl and M. Spira, Z. Phys. C69 (1995)

Leading contributions can be evaluated by using the Higgs low-energy theorem.

$\Pi_{\gamma\gamma}(p^2)$: Transverse part of the photon two-point function

$$C_{h\gamma\gamma} = \frac{\partial}{\partial v}\Pi_{\gamma\gamma}(0)' \quad \text{in} \quad m_h^2 \to 0$$

Taking the derivative with respect to the vacuum expectation value corresponds to the insertion of the Higgs leg with zero-momentum.



We calculate purely scalar contributions to the photon two-point function at the two-loop level and apply the Higgs low-energy theorem.

Higgs to diphoton at two-loop

SM contributions

QCD: A. Djouadi, Phys. Rept. 457 (2008) and refs. therein
Two-loop EW: G. Degrassi, F. Maltoni, NPB724 (2005), S. Actis et al. NPB811 (2009)

Full two-loop EW contributions and higher-order QCD corrections are included.

IDM contributions

Purely scalar and fermion-scalar contributions are included.

Calculations are performed in the on-shell scheme, and we have checked

- Cancelation of the UV divergence
- Cancelation of the IR divergence ($\ln m^2_{G^\pm/G^0}$)
- Ward-Takahashi identity: $\Pi_{\gamma\gamma,T}(0) = 0$

We have taken the gauge-less limit ($g, g' \to 0$) while keeping the weak-mixing angle fixed.

S. Hessenberger and W. Hollik, EPJC77 (2017)

MA, Braathen, Kanemura, preliminary

Numerical analysis

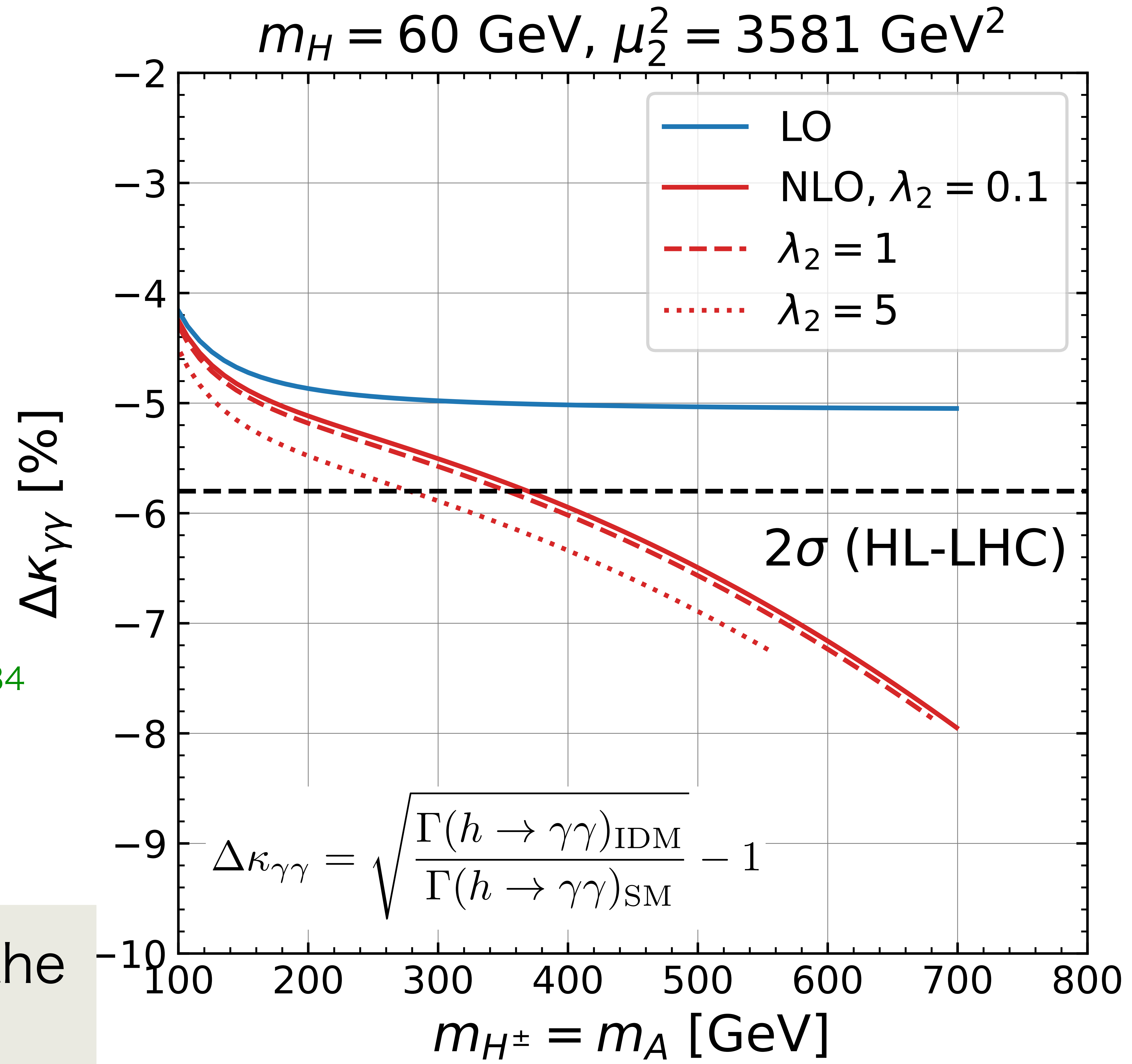
- Perturbative unitarity, vacuum stability, and inert vacuum condition are imposed.
- Value of μ_2^2 is determined so that DM relic abundance is satisfied. micrOMEGAs, CPC176 (2007)
- DM direct detection, collider searches, and electroweak precision tests are also imposed.

HL-LHC expectation

CYRM-2019-007.221, [hep-ph] 1902.00134

$$2.9\%\ (\mathrm{CMS}),\ 3.7\%\ (\mathrm{ATLAS})$$

Two-loop contributions are important to study the Higgs resonant scenario at the HL-LHC



Summary

Motivation

- Higgs to diphoton decay is useful channel to study the IDM, especially for the Higgs resonance scenario. $\Longrightarrow$ What is the impact of two-loop corrections?

New points

- Leading scalar and fermion-scalar contributions are calculated by using Higgs low-energy theorem

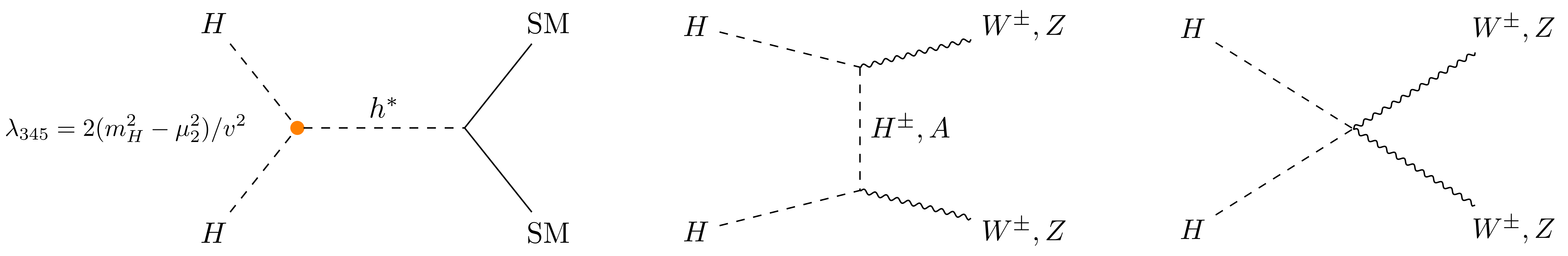
What we found

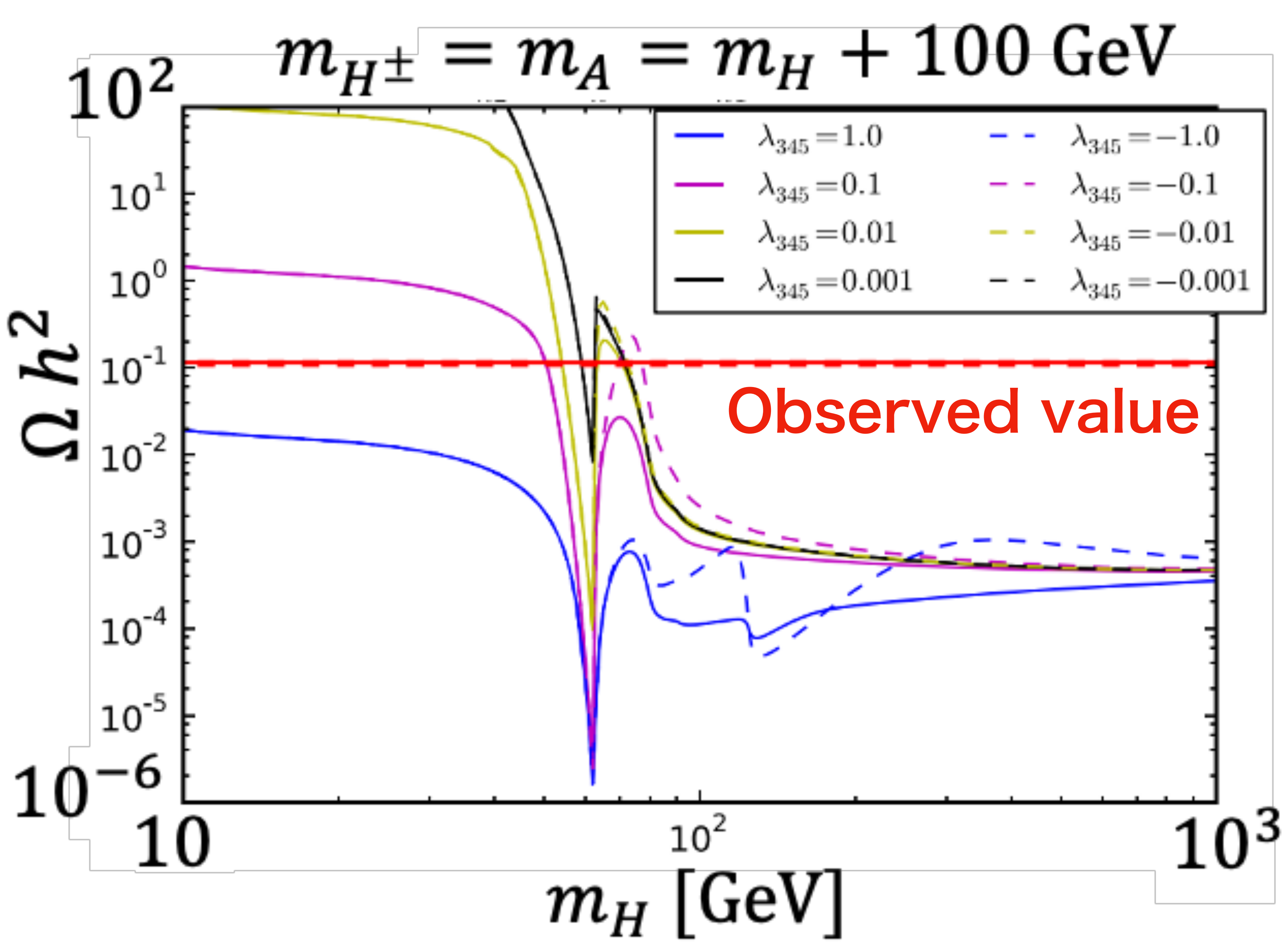
- Two-loop contributions increase the magnitude of $\Delta\kappa_{\gamma\gamma}$, and could be tested at future colliders such as HL-LHC.

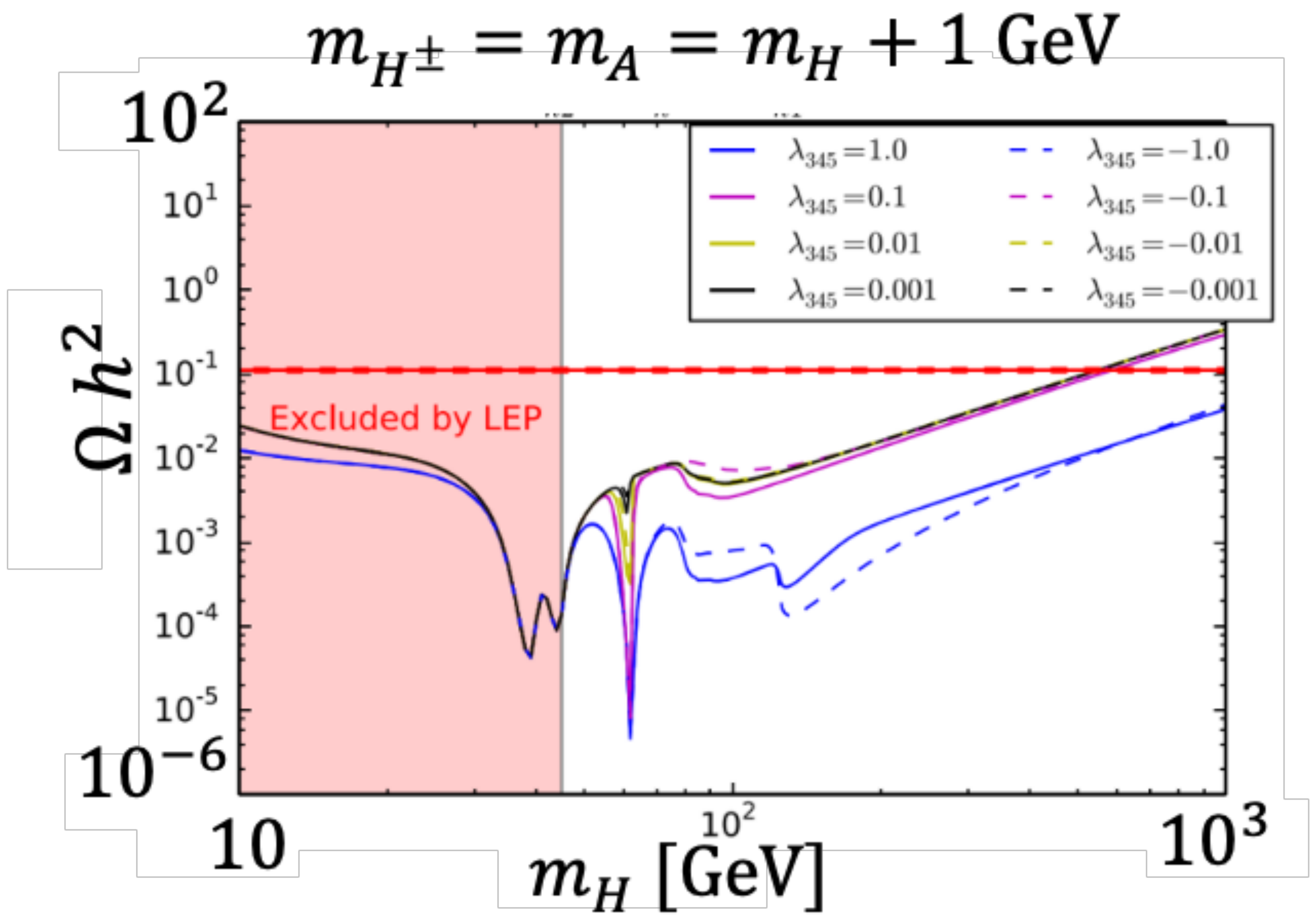
Backup

DM scenario

Relic abundance

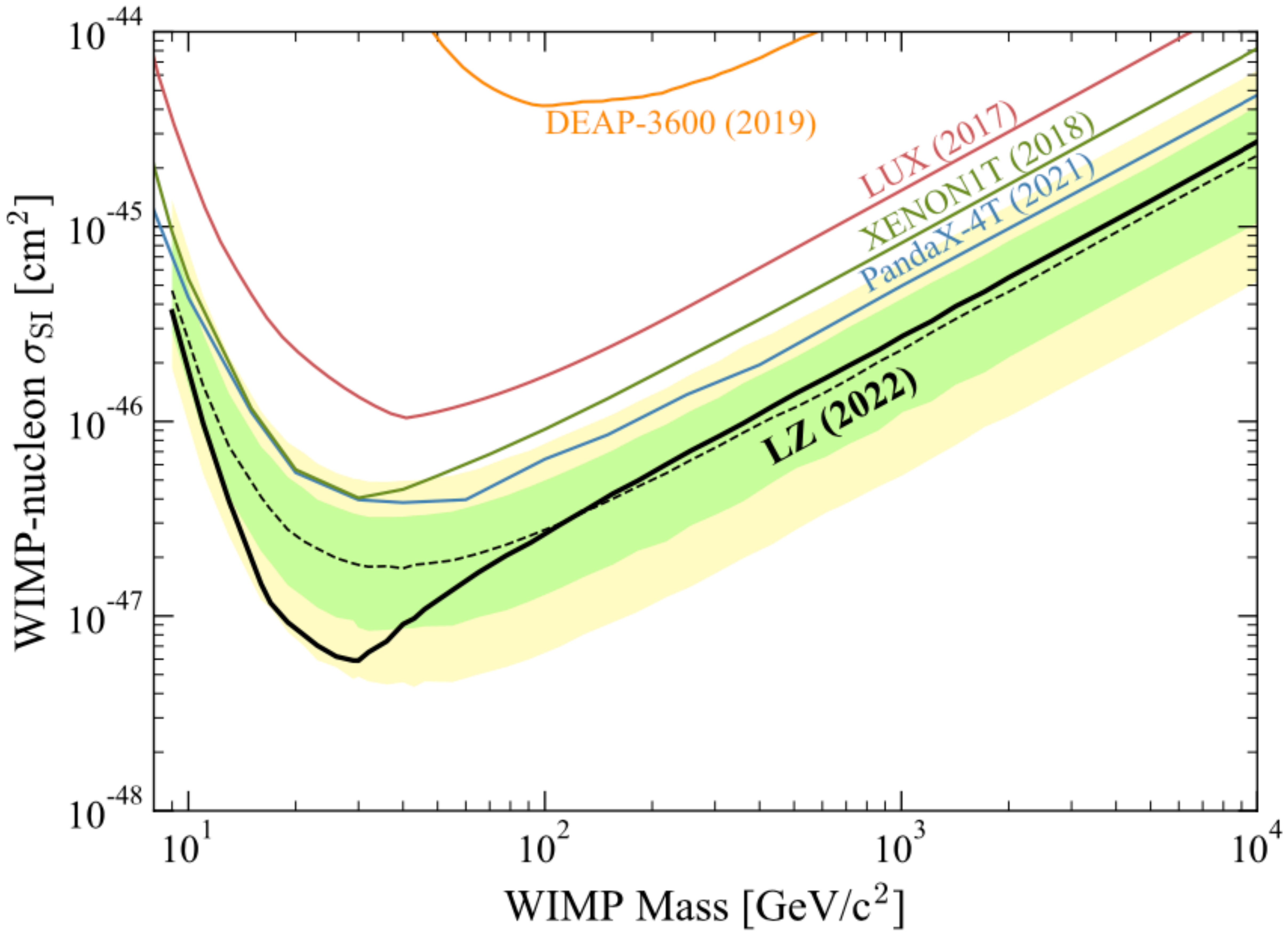




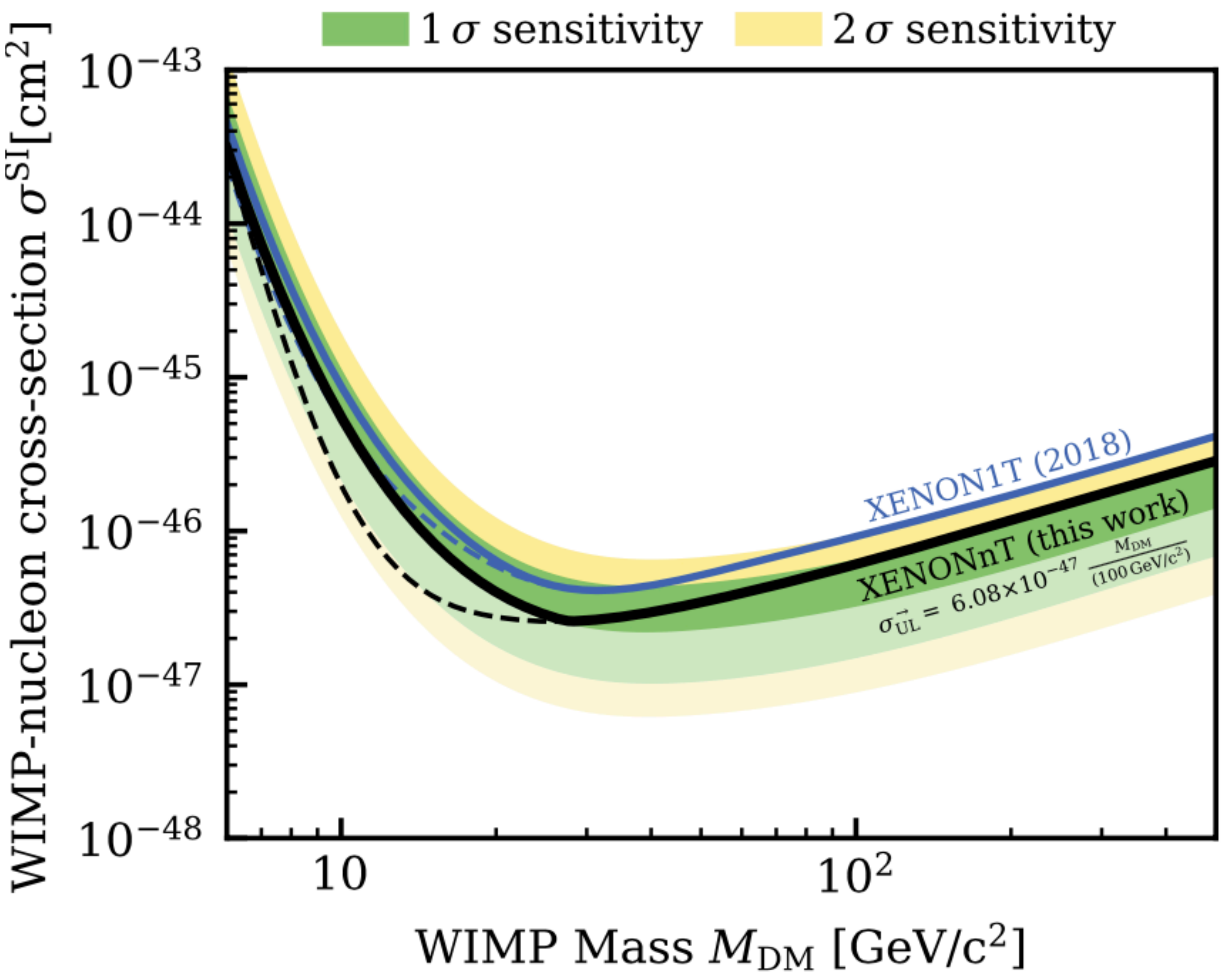


A. Balyaev et al. PRD97 (2018)

DM direct detection

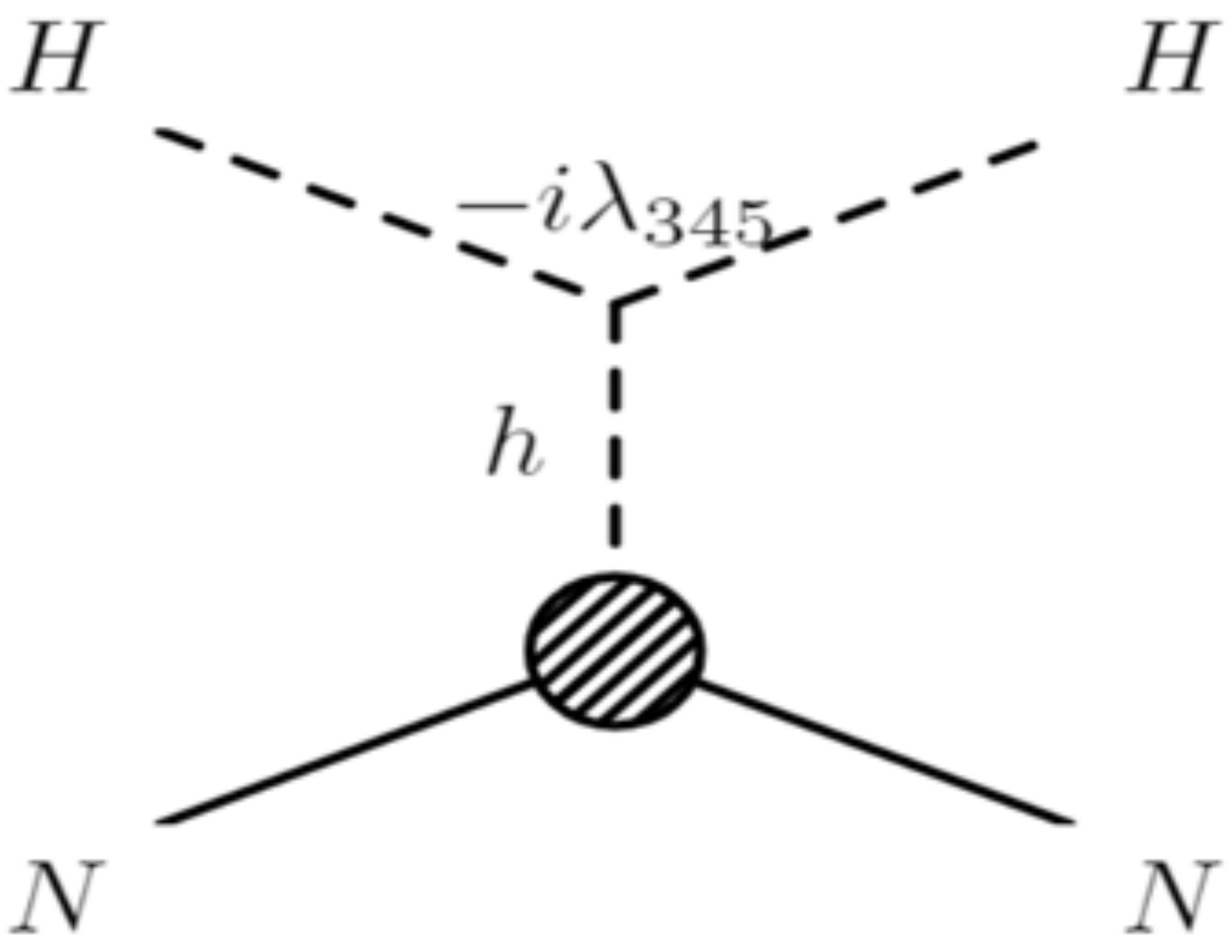


LZ Collaboration: 2207.03764 [hep-ex]

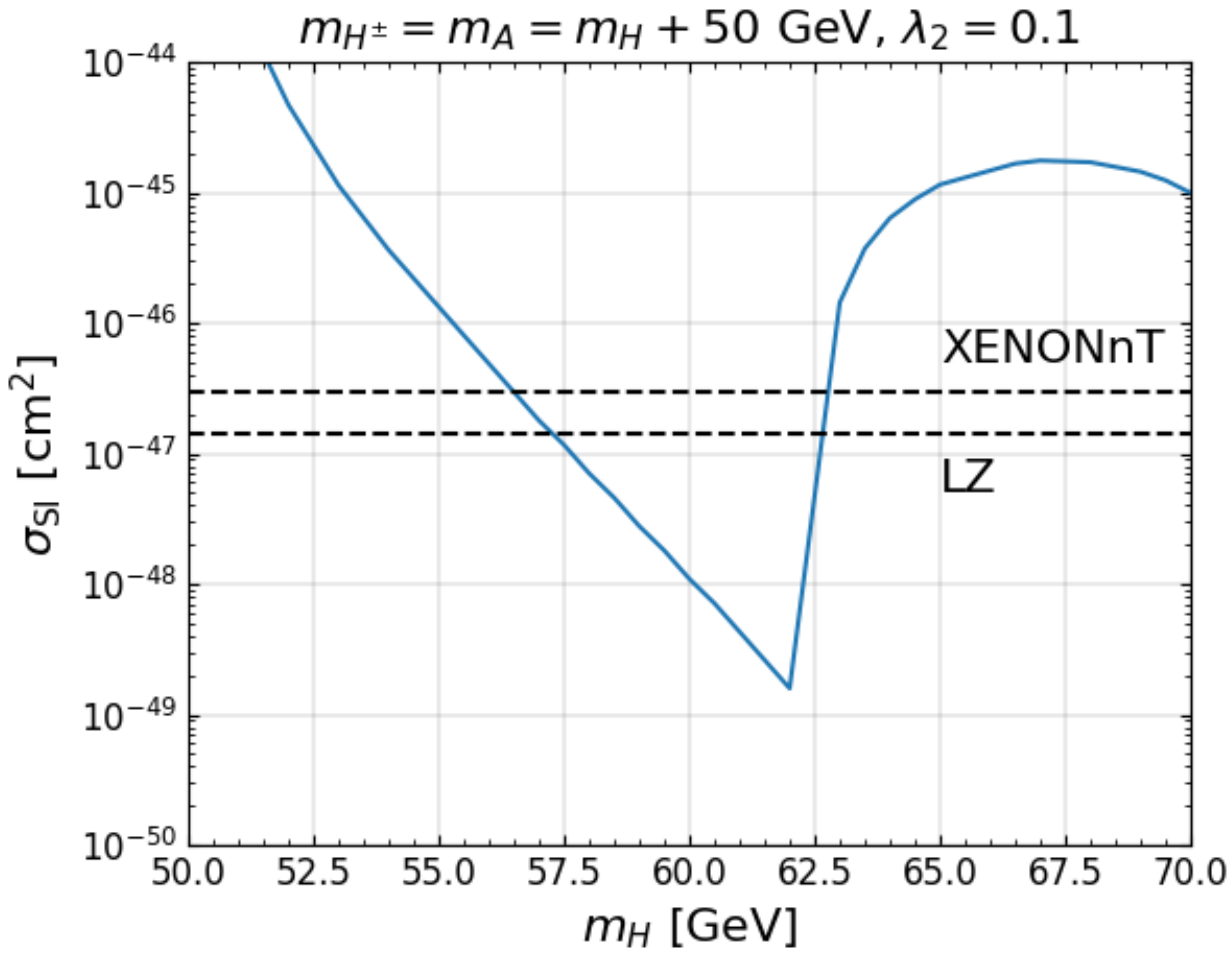


XENONnT, 2303.14729 [hep-ex]

DM direct detection



$$\lambda_{345} = 2(m_H^2 - \mu_2^2)/v^2$$



Collider bounds

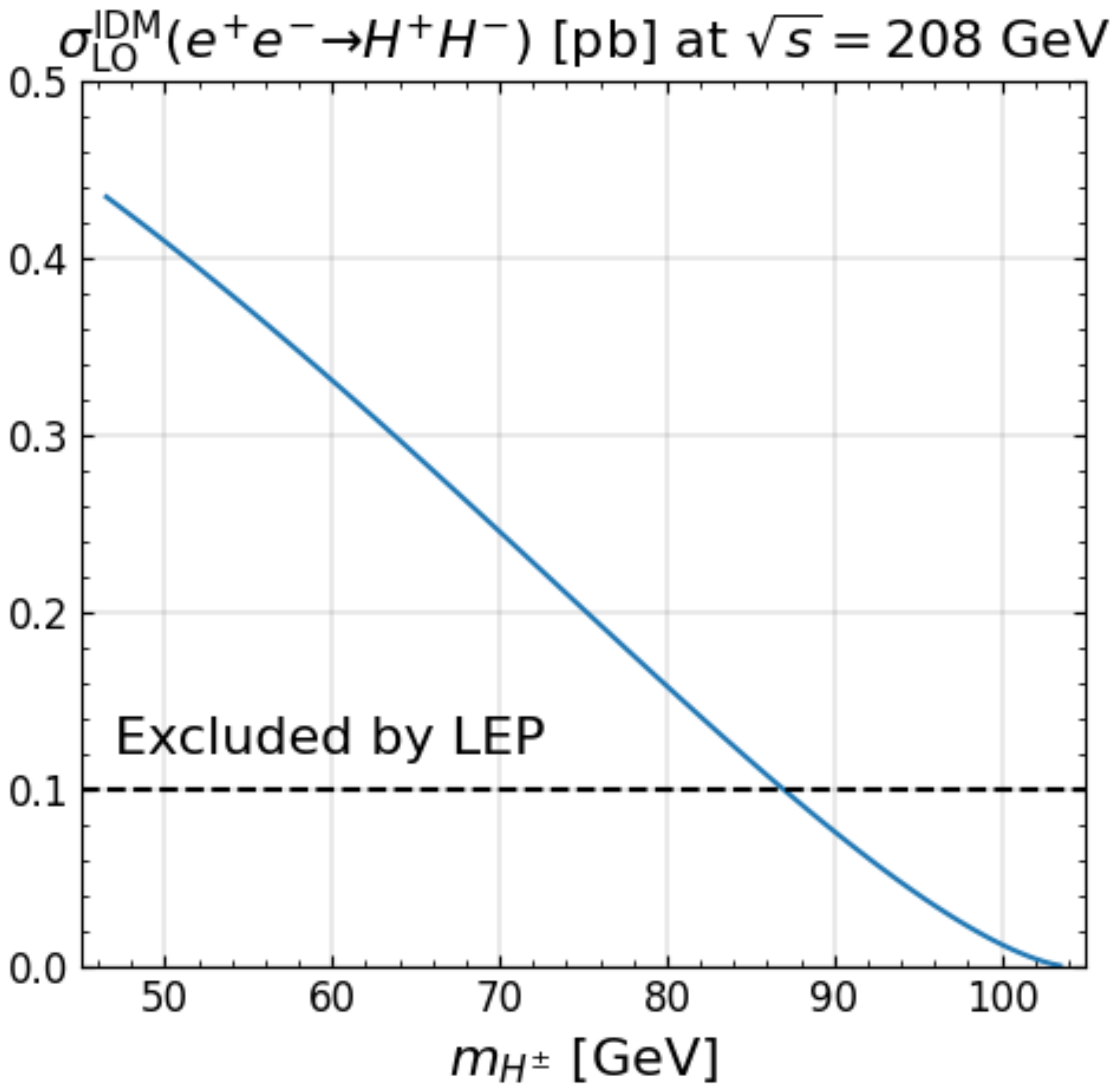
Direct searches at LEP

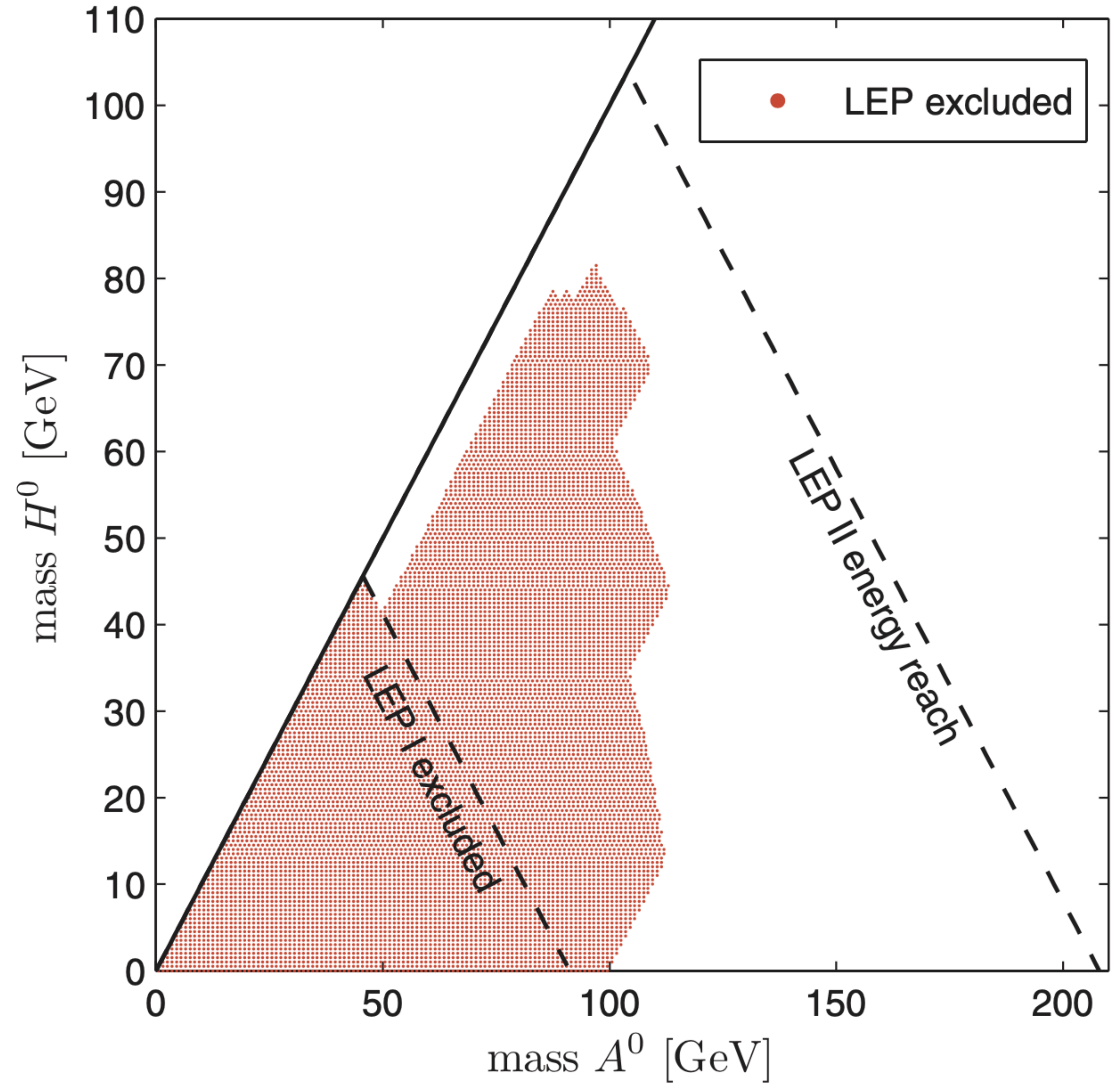
$e^+e^- \to H^+H^-$

G. Abbiendi et al. EPJC35 (2004)
A. Pierce and J. Thaler, JHEP08 (2007)

$e^+e^- \to HA$

E. Lundstrom et al. PRD79 (2009)

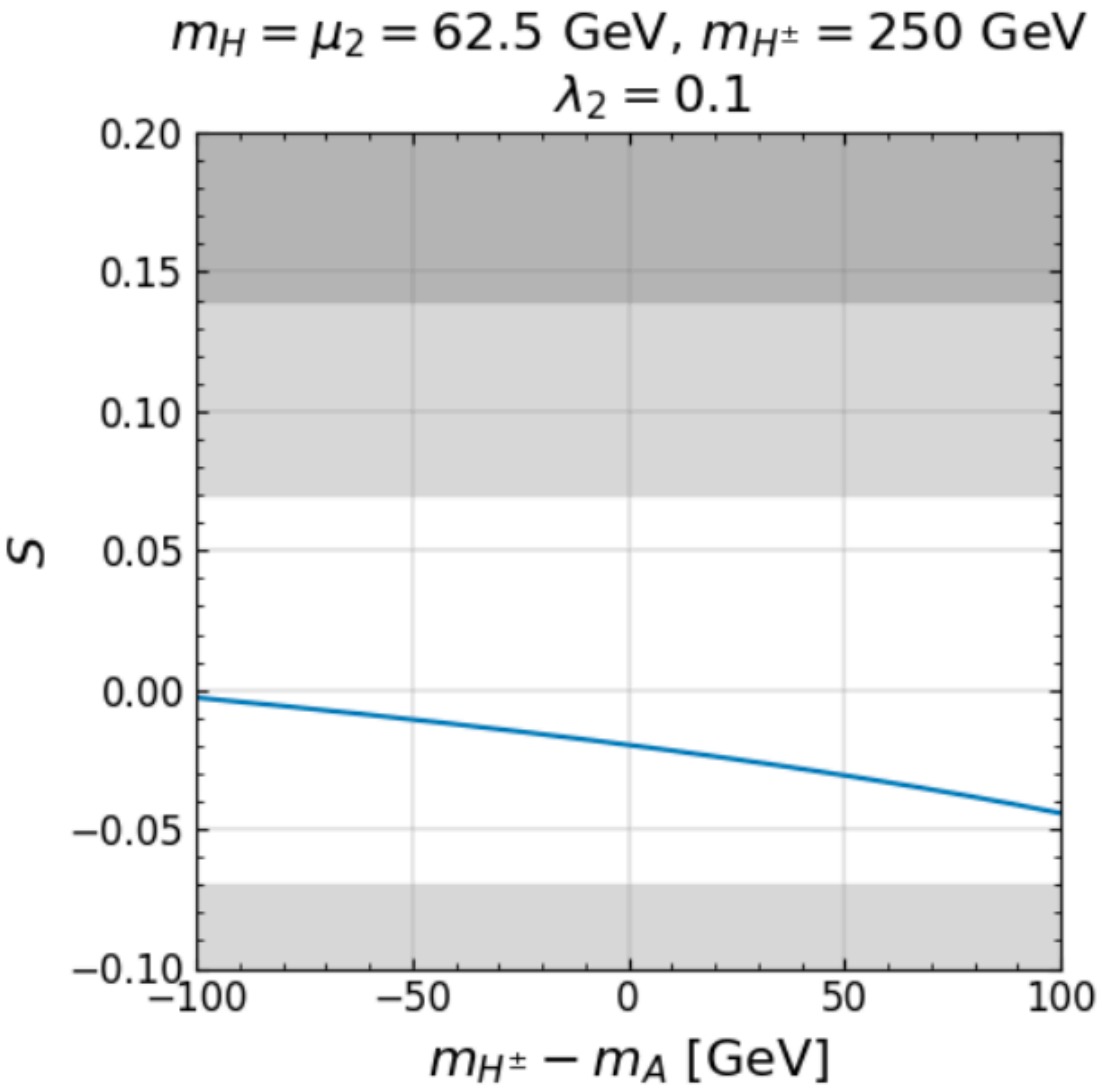


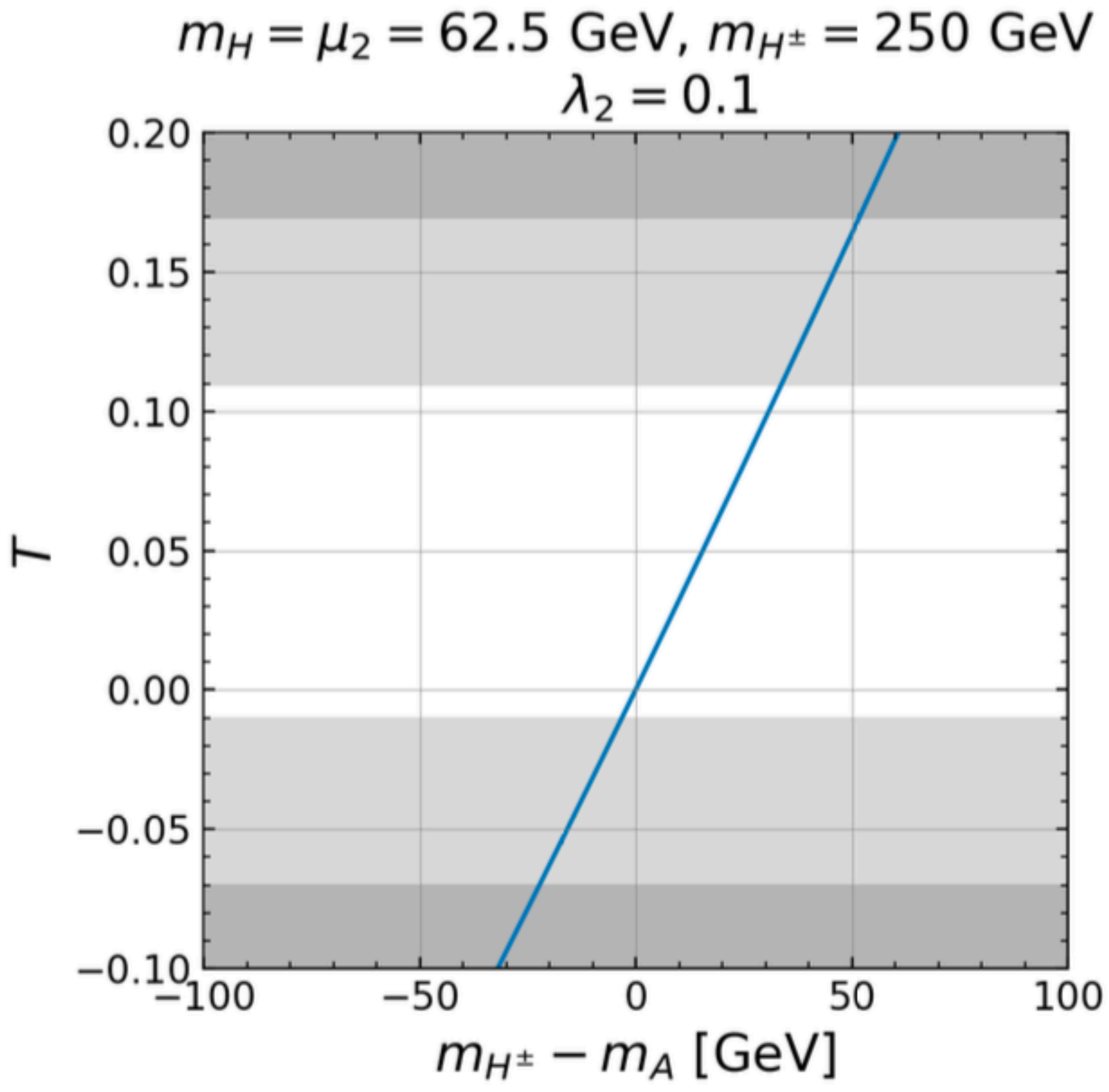


$m_{H^\pm} \gtrsim 90$ GeV

$m_A(> m_H) \gtrsim 100$ GeV or $m_A - m_H \lesssim 8$ GeV

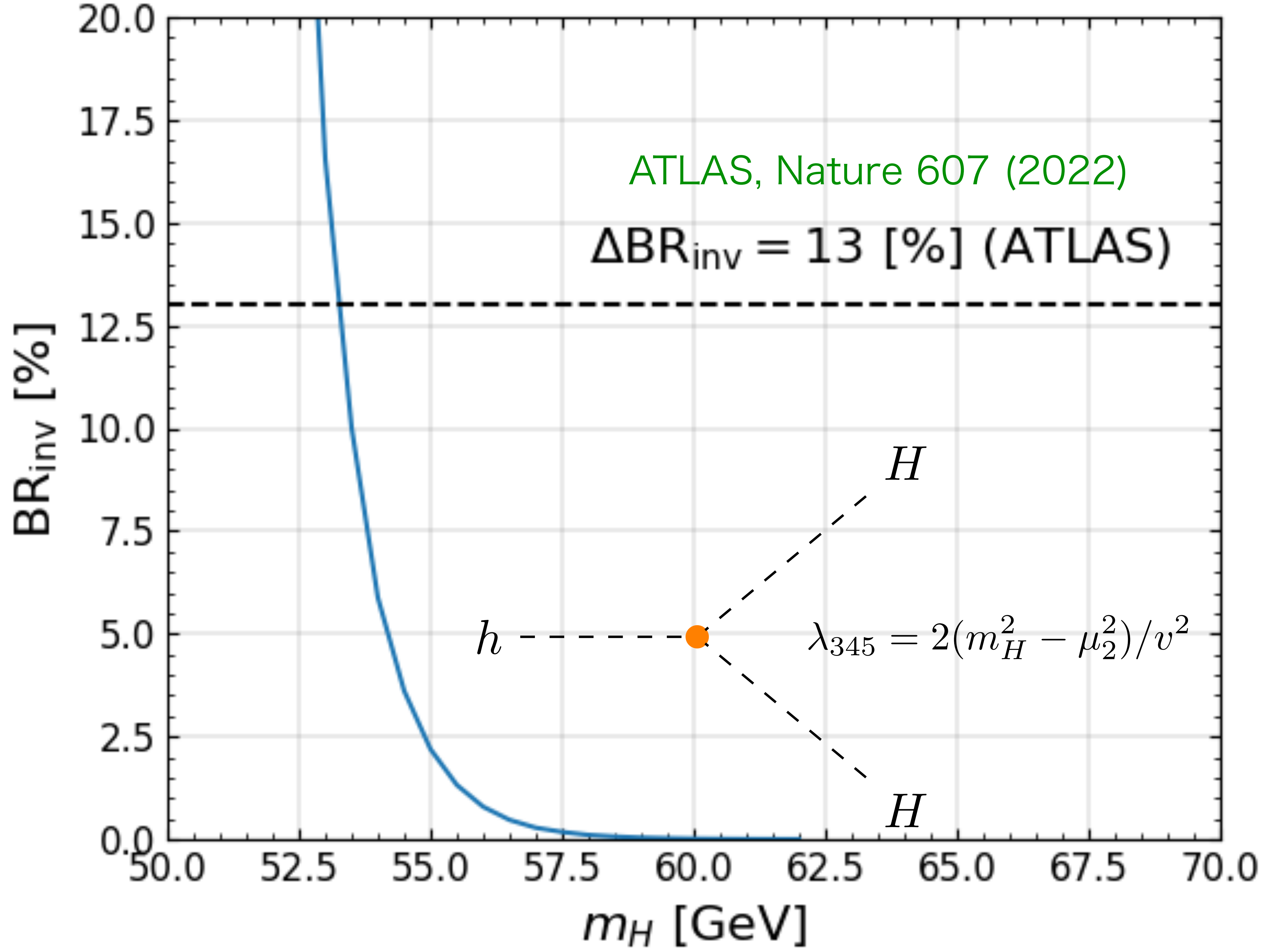
Electroweak precision test

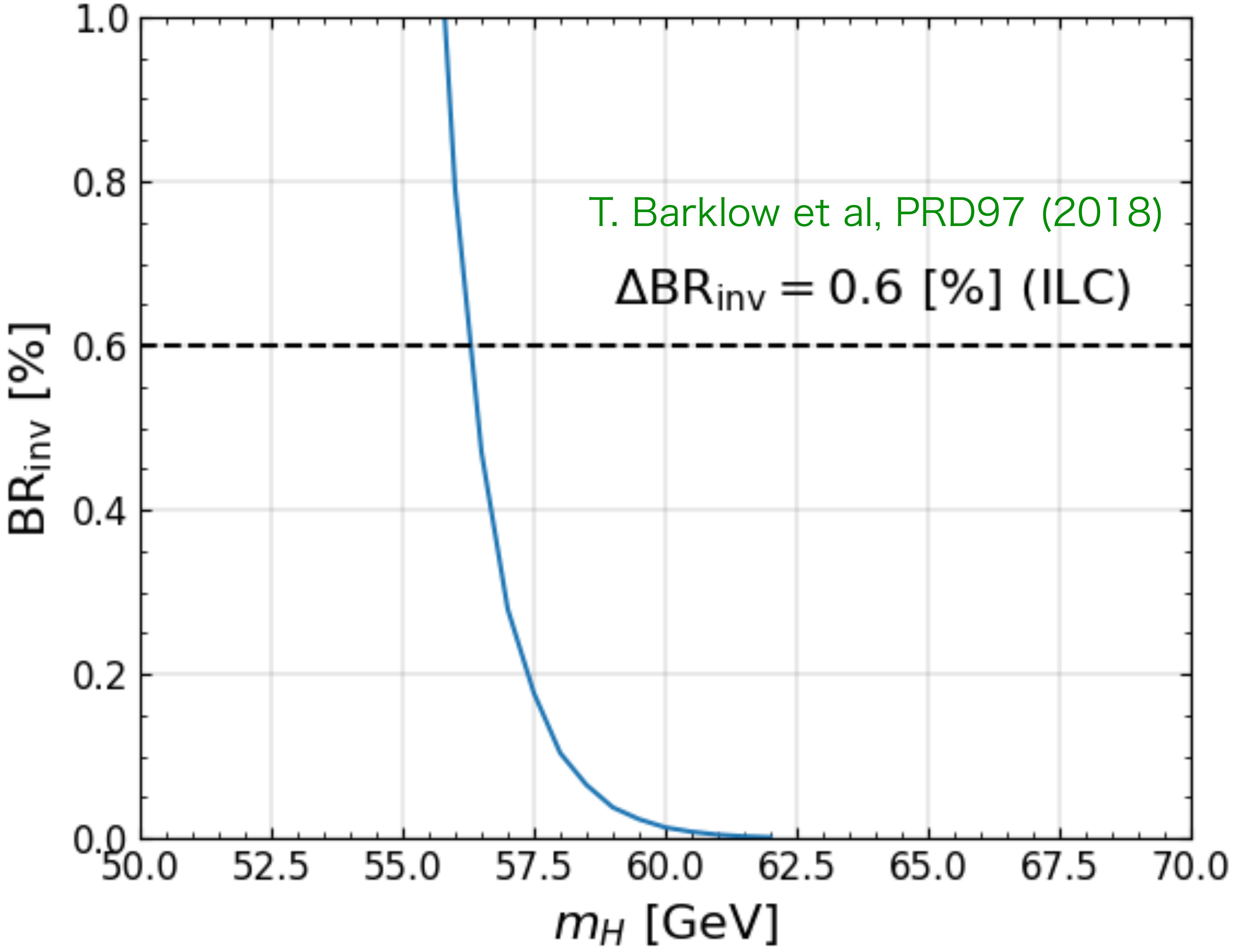




$$\Rightarrow m_{H^\pm} \simeq m_A$$

Higgs invisible decay





Higgs Triple coupling

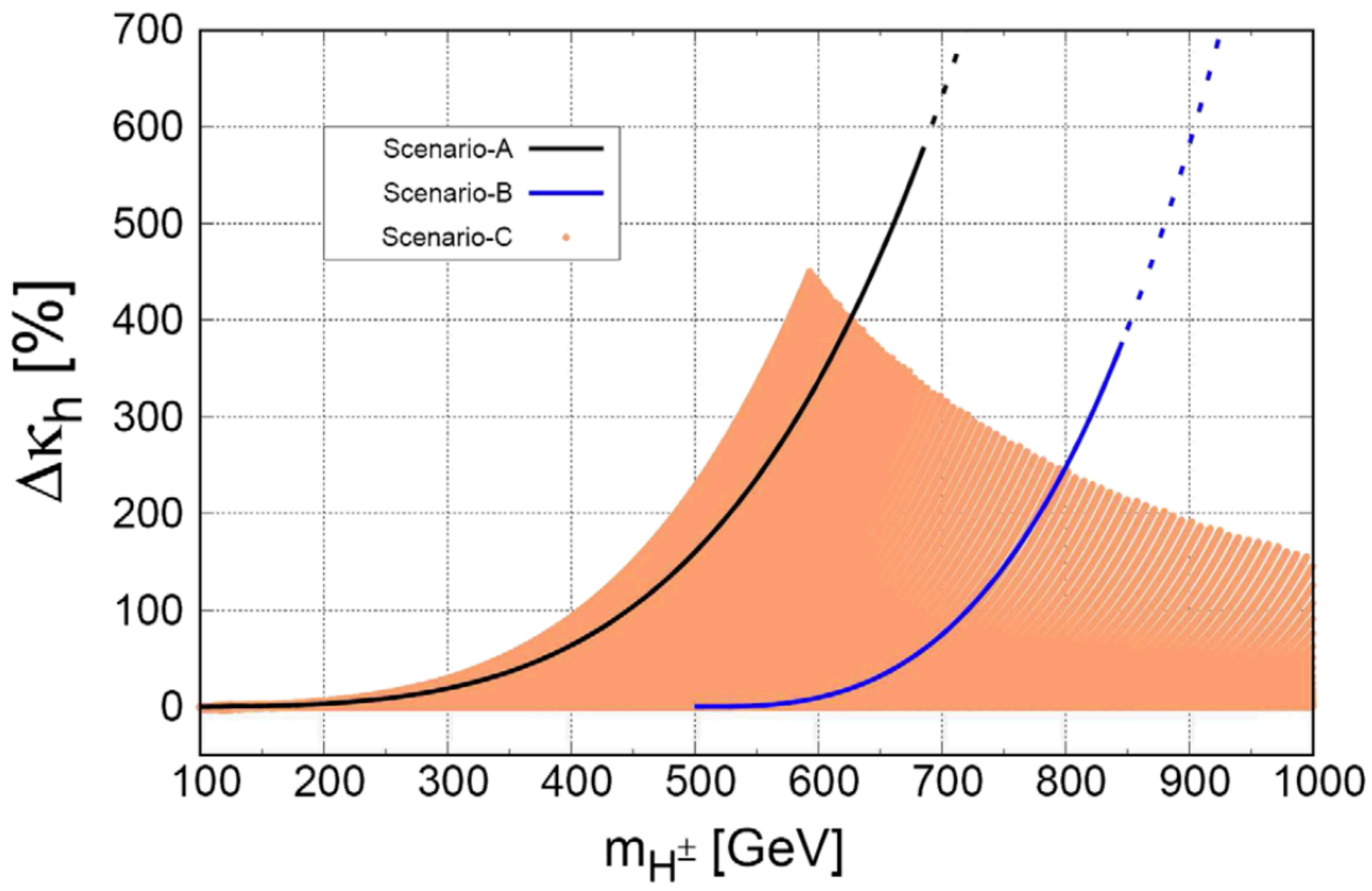
S. Kanemura, M. Kikuchi and K. Sakurai, PRD94 (2016)

Scenario-A

$$m_A = 63\ \mathrm{GeV},\ m_H = m_{H^\pm},$$
$$\mu_2^2 = (61.5)^2\ \mathrm{GeV}^2,\ \lambda_2 = 6.17 \times 10^{-3}$$

Scenario-B

$$m_A = 500\ \mathrm{GeV},\ m_H = m_{H^\pm},$$
$$\mu_2^2 = (499.9)^2\ \mathrm{GeV}^2,\ \lambda_2 = 4.97 \times 10^{-3}$$



$$\Delta\kappa_{\gamma\gamma} = \frac{\hat{\Gamma}_{hhh,\mathrm{IDM}}(m_h^2, m_h^2, 2m_h^2)}{\hat{\Gamma}_{hhh,\mathrm{SM}}(m_h^2, m_h^2, 2m_h^2)} - 1$$

Higgs to di-photon

Effective coupling at two-loop

$$C_{h\gamma\gamma} = C^{(1)}_{h\gamma\gamma,\mathrm{SM}} + C^{(2)}_{h\gamma\gamma,\mathrm{SM}} + C^{(2)}_{h\gamma\gamma,\mathrm{QCD}} + C^{(3)}_{h\gamma\gamma,\mathrm{QCD}} + C^{(1)}_{h\gamma\gamma,\mathrm{IDM}} + C^{(2)}_{h\gamma\gamma,\mathrm{IDM}}$$

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4} C_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h$$

$$C^{(1)}_{h\gamma\gamma,\mathrm{IDM}} = C_{\mathcal{O}(\lambda_3)},$$

$$C^{(2)}_{h\gamma\gamma,\mathrm{IDM}} = C_{\mathcal{O}(\lambda_3^2)} + C_{\mathcal{O}((\lambda_4+\lambda_5)^2)} + C_{\mathcal{O}((\lambda_4-\lambda_5)^2)} + C_{\mathcal{O}(\lambda_2)} + C_{\mathrm{WF\ and\ VEV}}$$

Higgs resonance scenario

$$\lambda_3 = \frac{2(m_{H^\pm}^2 - \mu_2^2)}{v^2} \simeq \frac{2(m_{H^\pm}^2 - m_H^2)}{v^2},$$

$$\lambda_4 + \lambda_5 = \frac{2(m_H^2 - m_{H^\pm}^2)}{v^2} \simeq -\lambda_3,$$

$$\lambda_4 - \lambda_5 = \frac{2(m_A^2 - m_{H^\pm}^2)}{v^2} \simeq 0$$

DM direct detection: $m_H^2 \simeq \mu_2^2$

T parameter

Renormalization of μ_2^2

In the $\overline{\text{MS}}$ scheme, $\mathcal{O}(\lambda_2)$ contributions do not decouple even if $m_\Phi \to \infty$.

$$C_{\mathcal{O}(\lambda_2)} = \frac{\lambda_2}{3m_{H^\pm}^2 v}\left[-(m_H^2 + m_A^2 + 4m_{H^\pm}^2) + \mu_2^2(\overline{\ln} m_H^2 + \overline{\ln} m_A^2 + 4\overline{\ln} m_{H^\pm}^2)\right]$$

We renormalize μ_2^2 so that $C_{\mathcal{O}(\lambda_2)}$ is independent of the renormalization scale and follows the decoupling theorem.

J. Braathen, S. Kanemura, EPJC80 (2020)

$$\delta\mu_2^2 = \frac{\lambda_2\mu_2^2}{2}\left[\frac{A(m_H)}{m_H^2} + \frac{A(m_A)}{m_A^2} + \frac{4A(m_{H^\pm})}{m_{H^\pm}^2}\right]$$

$$= 3\lambda_2\mu_2^2\Delta_{\text{UV}} - \frac{\lambda_2\mu_2^2}{2}\left[\overline{\ln} m_H^2 + \overline{\ln} m_A^2 + 4\overline{\ln} m_{H^\pm}^2 - 6\right]$$

$$C_{\mathcal{O}(\lambda_2)} = \frac{\lambda_2}{3m_{H^\pm}^2 v}\left[-(m_H^2 + m_A^2 + 4m_{H^\pm}^2) + 6\mu_2^2\right]$$

Numerical Results

$$C^{(1)}_{h\gamma\gamma,\mathrm{IDM}} = C_{\mathcal{O}(\lambda_3)},$$
$$C^{(2)}_{h\gamma\gamma,\mathrm{IDM}} = C_{\mathcal{O}(\lambda_3^2)} + C_{\mathcal{O}((\lambda_4+\lambda_5)^2)} + C_{\mathcal{O}((\lambda_4-\lambda_5)^2)} + C_{\mathcal{O}(\lambda_2)} + C_{\mathrm{WF\ and\ VEV}}$$

Higgs resonance scenario

$$C_{h\gamma\gamma} = \frac{\alpha_{\mathrm{em}}}{4\pi v}\mathcal{I}$$

$$m_H = 60\ \mathrm{GeV},\ m_A = m_{H^\pm} = 500\ \mathrm{GeV},\ \mu_2^2 = 3581\ \mathrm{GeV}^2,\ \lambda_2 = 0.1$$

$\mathcal{I}^{(1)}_{H^\pm}$	$\mathcal{I}^{(2)}_{\mathcal{O}(\lambda_3^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}((\lambda_4+\lambda_5)^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}((\lambda_4-\lambda_5)^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}(\lambda_2)}$	$\mathcal{I}^{(2)}_{\mathrm{WF\ and\ VEV}}$
-8.28×10^{-2}	-8.51×10^{-3}	-2.06×10^{-3}	0	-1.30×10^{-4}	-1.24×10^{-2}

Heavy mass scenario

$$m_H = 500\ \mathrm{GeV},\ m_A = m_{H^\pm} = 700\ \mathrm{GeV},\ \mu_2^2 = (499.9)^2\ \mathrm{GeV}^2,\ \lambda_2 = 0.1$$

$\mathcal{I}^{(1)}_{H^\pm}$	$\mathcal{I}^{(2)}_{\mathcal{O}(\lambda_3^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}((\lambda_4+\lambda_5)^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}((\lambda_4-\lambda_5)^2)}$	$\mathcal{I}^{(2)}_{\mathcal{O}(\lambda_2)}$	$\mathcal{I}^{(2)}_{\mathrm{WF\ and\ VEV}}$
-4.10×10^{-2}	-5.14×10^{-3}	-1.48×10^{-3}	0	-6.46×10^{-5}	-1.07×10^{-3}

Heavy mass scenario

MA, Braathen, Kanemura, preliminary