イナート二重項模型における ヒッグス二光子崩壊の2ループ補正計算

愛甲 将司 (都城工業高等専門学校)

共同研究者：Johannes Braathen (DESY), 兼村晋哉（大阪大学）

Eur. Phys. J. C85 (2025) 5

PPP2026 (Progress in Particles Physics 2026)（2026/08/25 京都大学基礎物理学研究所）

独立行政法人国立高等専門学校機構
都城工業高等専門学校
National Institute of Technology(KOSEN), Miyakonojo College

Introduction

Problems in the SM

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

SM must be extended to solve these problems.

Introduction

Problems in the SM

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

SM must be extended to solve these problems.

Scalar DM models

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, Higgs signals etc.

We study the Inert Double Model (IDM) as a prototype scalar DM model.

Inert Doublet Model (IDM)

The model with two scalar doublets (Φ_1, Φ_2) with Z_2 symmetry.

c.f. Radiative neutrino mass models
E. Ma, PRD73 (2006),
M. Hirsch et al. JHEP1310 (2013) etc.

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

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

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

c.f. H and A can be interchanged.

c.f. Radiative neutrino mass models
E. Ma, PRD73 (2006),
M. Hirsch et al. JHEP1310 (2013) etc.

The model with two scalar doublets (Φ_1, Φ_2) with Z_2 symmetry.

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

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

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

c.f. H and A can be interchanged.

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

Mass scale irrelevant

Typical mass scale of inert scalars $m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$

The model with two scalar doublets (Φ_1, Φ_2) with Z_2 symmetry.

c.f. Radiative neutrino mass models
E. Ma, PRD73 (2006),
M. Hirsch et al. JHEP1310 (2013) etc.

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

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

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

c.f. H and A can be interchanged.

Parameters

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

Typical mass scale of inert scalars $m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$

DM scenario

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

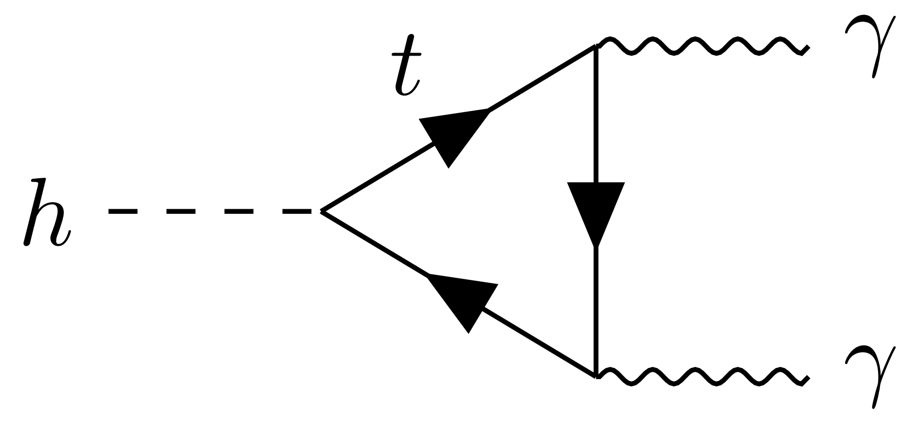
A. Arhrib et al. JCAP06 (2014), A. Balyaev et al. PRD97 (2018)

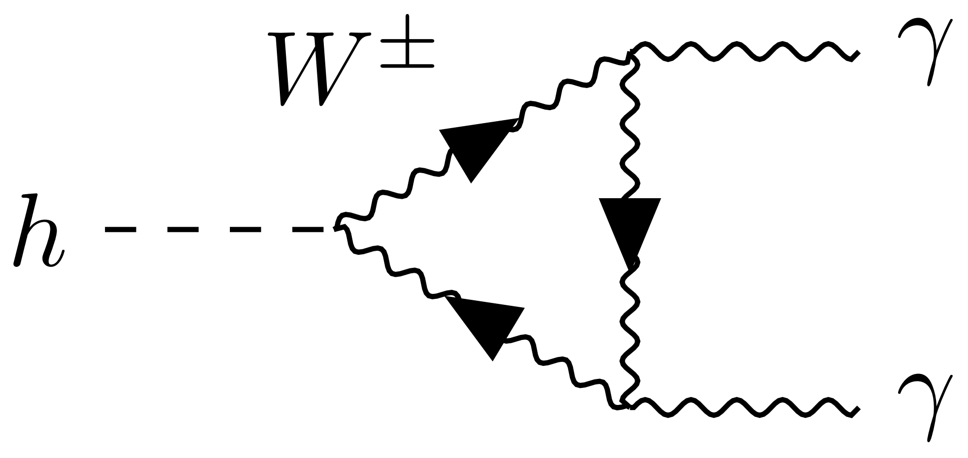
1. Higgs resonance scenario ($m_H \approx m_h/2$)
2. Heavy mass scenario ($500\ \mathrm{GeV} \lesssim m_H$)

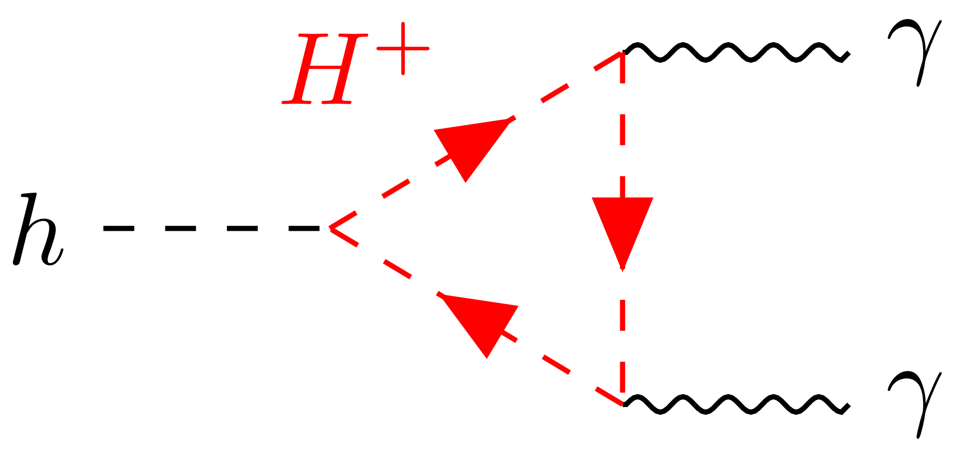
We discuss the testability of these scenarios via Higgs diphoton decay.

Higgs diphoton decay (1-loop)

Higgs diphoton decay is sensitive to quantum effects of new particles.

$i\mathcal{M} \sim$ 

$+$ 

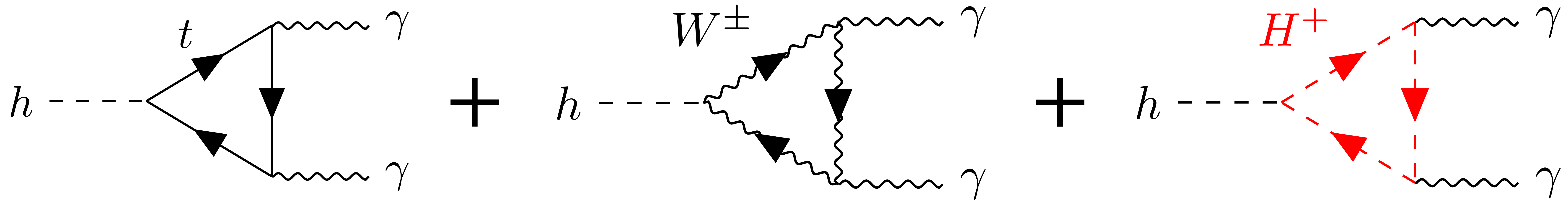
$+$ 

c.f. tree-level Higgs couplings are the same as those in the SM thanks to the Z_2 symmetry.

Higgs diphoton decay (1-loop)

Higgs diphoton decay is sensitive to quantum effects of new particles.

$i\mathcal{M} \sim$



Wilson coefficient

c.f. tree-level Higgs couplings are the same as those in the SM thanks to the Z_2 symmetry.

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4} C_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h, \quad C_{h\gamma\gamma} = \frac{\alpha_{\text{em}}}{4\pi} \left[\sum_f N_c^f Q_f^2 I_F(\tau_f) + I_V(\tau_W) - \frac{\lambda_{hH^+H^-}}{v} I_S(\tau_{H^\pm}) \right]$$

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

$$\lambda_{hH^+H^-} v = 2(\mu_2^2 - m_{H^\pm}^2)$$

In the Higgs resonance scenario ($\mu_2 \sim m_H \approx m_h/2$),

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

The mass splitting between the DM and charged Higgs boson induces a non-decoupling effect.

Higgs diphoton decay (1-loop)

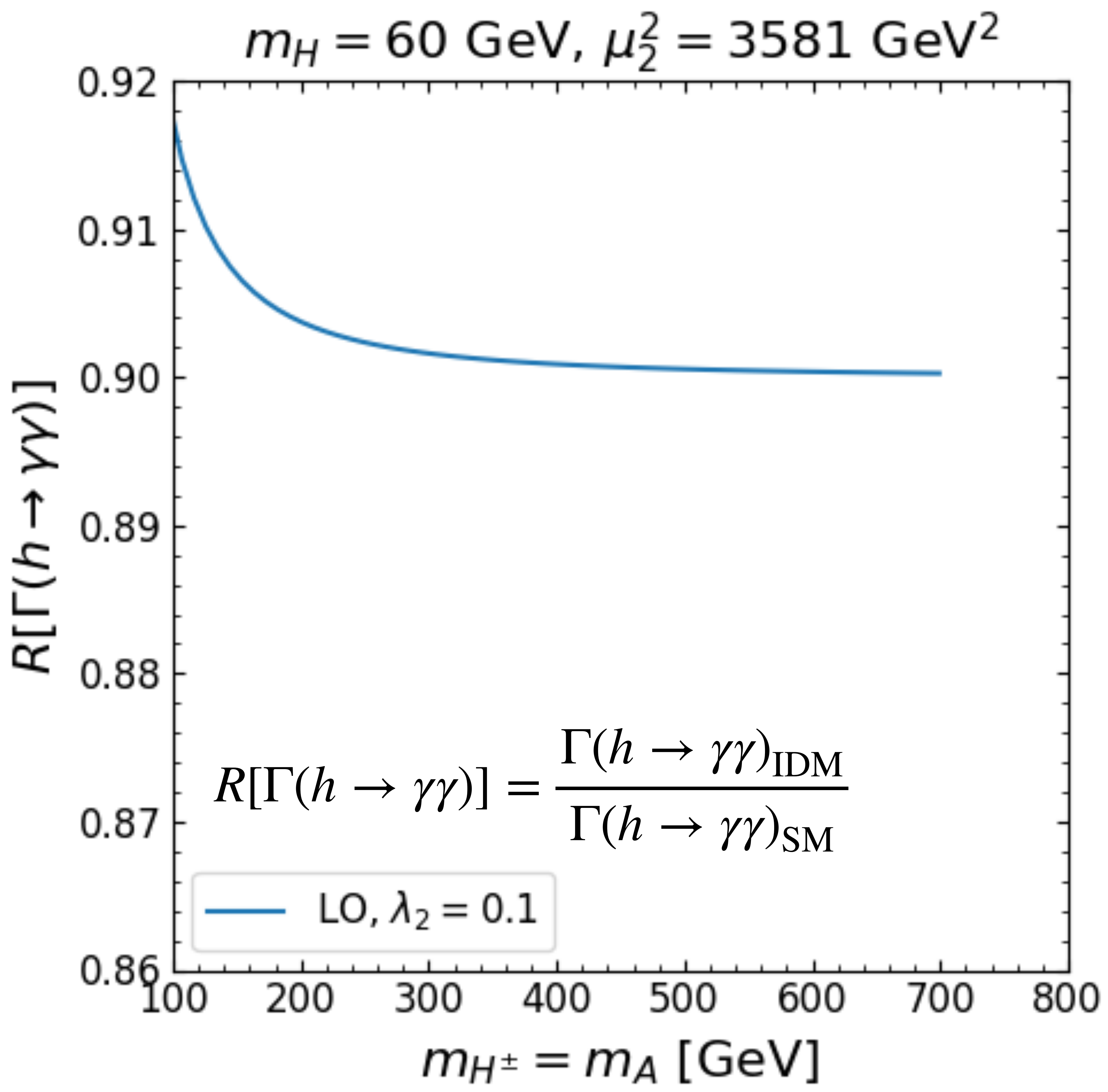
Higgs resonance scenario ($\mu_2 \sim m_H \approx m_h/2$),

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

$H^\pm \to W^{\pm *}H$ search: $\quad m_{H^\pm} \gtrsim 90 \text{ GeV}$

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

About 10% deviation in the decay rate.



μ_2^2 is determined by the DM relic abundance.

micrOMEGAs, CPC176 (2007)

Higgs resonance scenario ($\mu_2 \sim m_H \approx m_h/2$),

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

$H^\pm \to W^{\pm *}H$ search: $\quad m_{H^\pm} \gtrsim 90\ \text{GeV}$

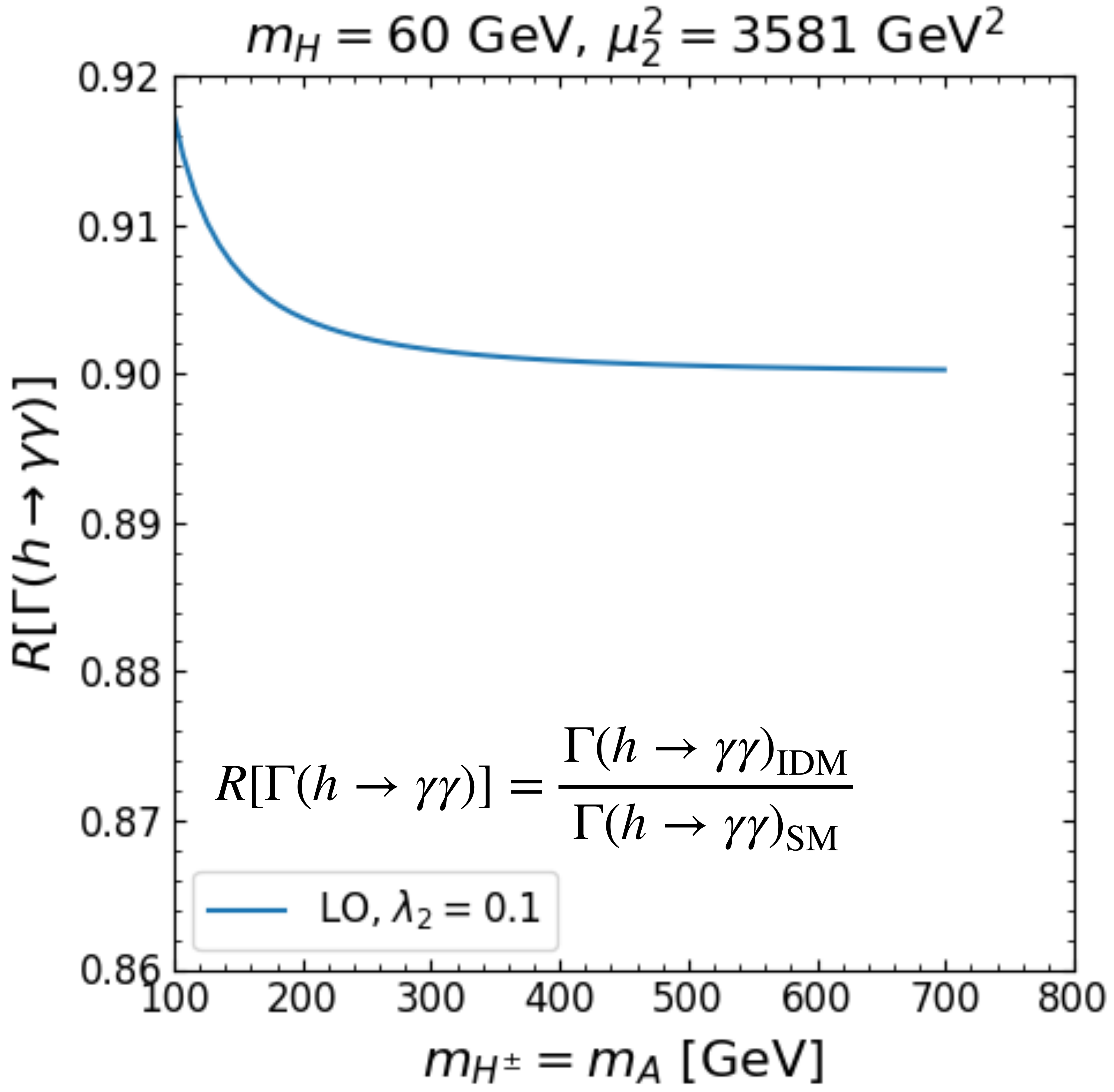
G. Abbiendi et al. EPJC35 (2004), A. Pierce and J. Thaler, JHEP08 (2007)

About 10% deviation in the decay rate.

$$\kappa_\gamma^{\text{LHC-Run2}} = (5.3, 6.0)\ [\%]$$ ATLAS-CONF-2021-053, CMS, Nature 607 (2022)

$$\kappa_\gamma^{\text{HL-LHC}} = (3.7, 2.9)$$ CYRM-2019-007.221

What is the impact of two-loop effects?



μ_2^2 is determined by the DM relic abundance.

micrOMEGAs, CPC176 (2007)

Leading corrections can be evaluated using the Higgs low-energy theorem (HLT).

J. Ellis et al. Nucl. Phys. B106 (1976)
M. Shifman et al. Sov. J. Nucl. Phys. 30 (1979)

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

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

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

Higgs Low-energy Theorem

Leading corrections can be evaluated using the Higgs low-energy theorem (HLT).

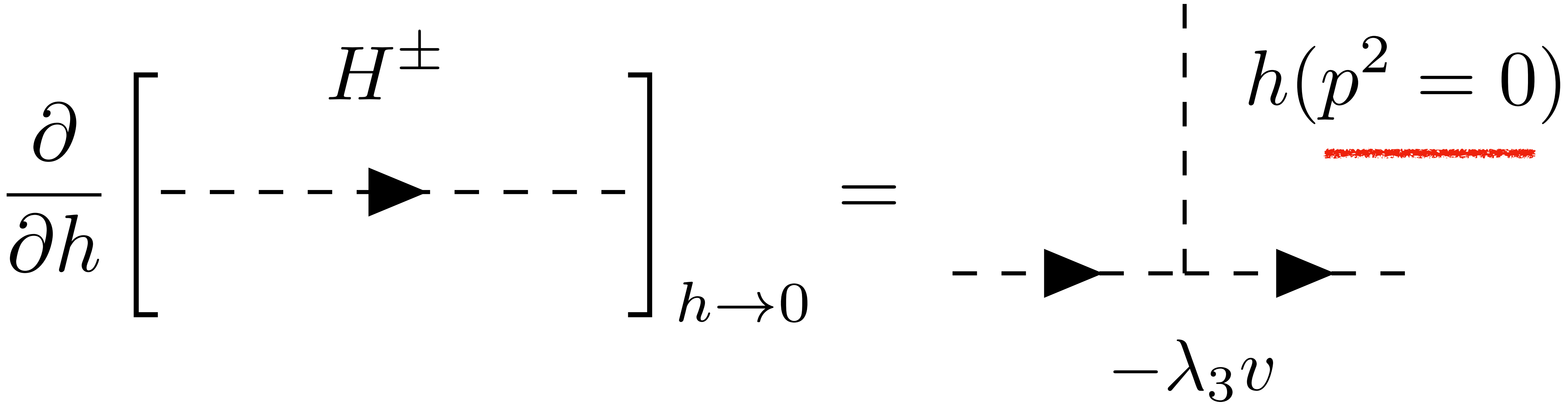
J. Ellis et al. Nucl. Phys. B106 (1976)
M. Shifman et al. Sov. J. Nucl. Phys. 30 (1979)

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

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

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

Naive proof: taking the higgs-field derivative corresponds to the insertion of zero-momentum Higgs leg.



Higgs-filed dependent mass

$$m_{H^\pm}^2(h) = \mu_2^2 + \frac{1}{2}\lambda_3(v+h)^2$$

We should be careful about the gauge dependences.

Gauge-dependence problem

B. Kniehl and M. Spira, Z. Phys. C69 (1995)

Feynman gauge at one-loop: $$\left(\frac{e^2}{16\pi^2}\right)^{-1}\Pi^{(1),\mathrm{1PI}}_{\gamma\gamma}(0)'_V = -3\left(\Delta_{\mathrm{UV}} - \ln\frac{m_W^2}{Q^2}\right) - \frac{2}{3}, \qquad \Delta_{\mathrm{UV}} = \frac{1}{\epsilon} + \gamma_E - \ln 4\pi$$

$$\to \left(\frac{e^2}{16\pi^2 v}\right)^{-1} C^{(1)}_{h\gamma\gamma,V} = \underline{6}$$ obtained by HLT.

It is inconsistent with the 1-loop $h\gamma\gamma$ vertex: $$\left(\frac{e^2}{16\pi^2 v}\right)^{-1} C^{(1)}_{h\gamma\gamma,V} = \underline{14}$$

This occurs because the two-point function is gauge-dependent.

c.f. calculation of beta functions,
Electroweak STU parameters etc.

Gauge-dependence problem

B. Kniehl and M. Spira, Z. Phys. C69 (1995)

Feynman gauge at one-loop: $\left(\frac{e^2}{16\pi^2}\right)^{-1}\Pi^{(1),\mathrm{1PI}}_{\gamma\gamma}(0)'_V = -3\left(\Delta_{\mathrm{UV}} - \ln\frac{m_W^2}{Q^2}\right) - \frac{2}{3}, \quad \Delta_{\mathrm{UV}} = \frac{1}{\epsilon} + \gamma_E - \ln 4\pi$

$$\to \left(\frac{e^2}{16\pi^2 v}\right)^{-1} C^{(1)}_{h\gamma\gamma,V} = \underline{6}$$ obtained by HLT.

It is inconsistent with the 1-loop $h\gamma\gamma$ vertex: $\left(\frac{e^2}{16\pi^2 v}\right)^{-1} C^{(1)}_{h\gamma\gamma,V} = \underline{14}$

This occurs because the two-point function is gauge-dependent.

c.f. calculation of beta functions, Electroweak STU parameters etc.

The gauge-independent two-point function can be obtained by

- Pinch technique (PT) — D. Binosi and J. Papavassiliou, PRD66 (2002), Phys. Rept. 479 (2009)
- Background field method (BFM) — A. Denner, G. Weiglein and S. Dittmaier, NPB440 (1995)

We performed two-loop calculations with those two different methods.

Two-loop calculation

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 (Our Work)

We calculated IDM corrections to the photon self-energy up to $\mathcal{O}(e^2)$.

We have checked

- **Ward-Takahashi identity**: $\Pi_{\gamma\gamma,T}(0) = 0$
- Cancelation of the **IR divergence** $(\ln m_W^2 \text{ and } \ln m_h^2)$
- Consistency between **PT**, **BFM** and **unitary-gauge** calculation in the Higgs-aligned Type-II 2HDM G. Degrassi and P. Slavich, EPJC83 (2023)

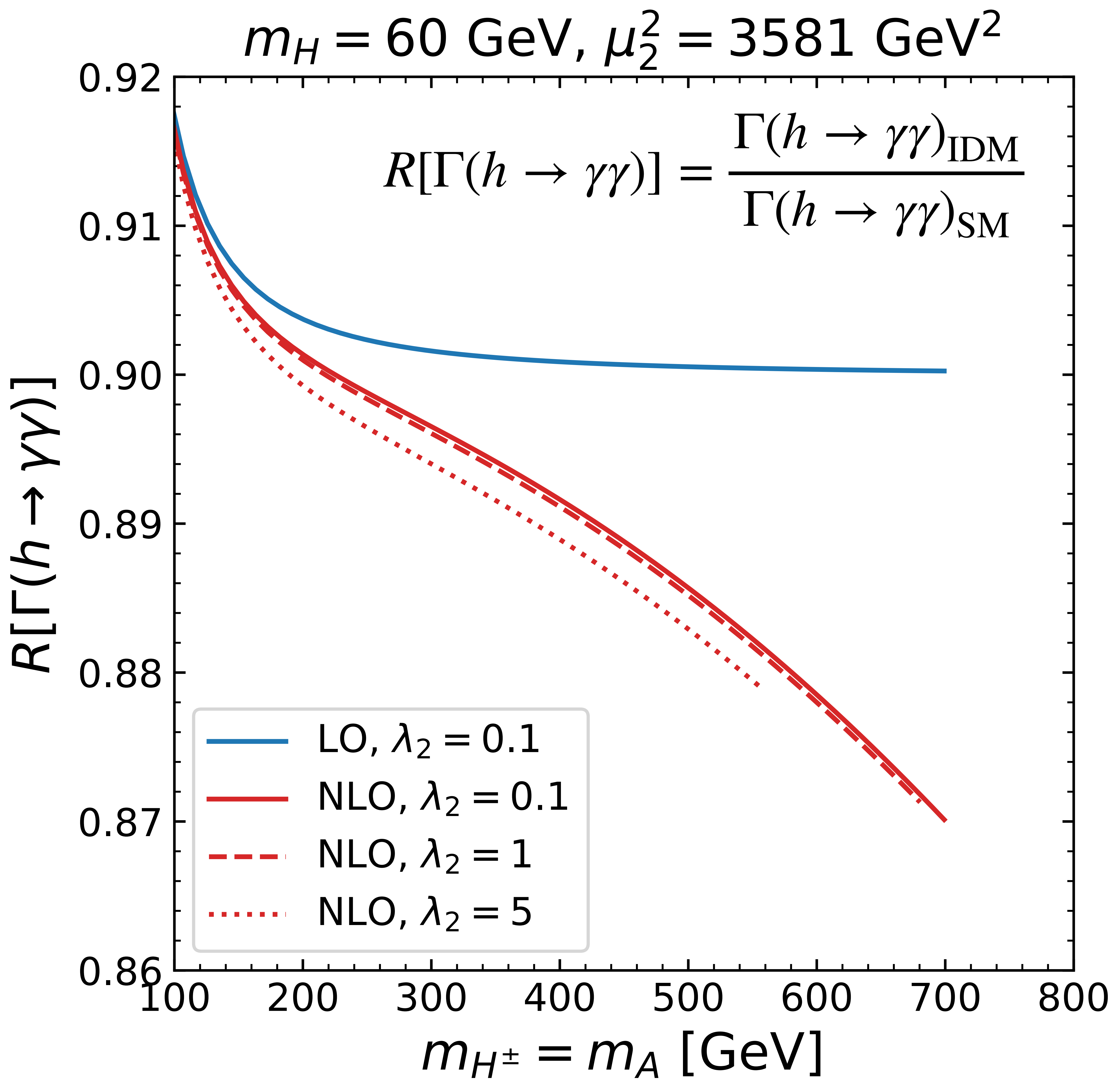
After taking the Higgs-field derivative, we performed the on-shell renormzalization and obtained **UV-finite** results.

S. Kanemura, M. Kikuchi and K. Sakurai, PRD94 (2016)
Braathen, Kanemura, PLB796 (2019) and EPJC80 (2020)
T. Abe and R. Sato, JHEP03 (2015), S. Banerjee et al. PRD104 (2021)

MA, Braathen, Kanemura, EPJC 85 (2025) 5

Numerical study

- Perturbative unitarity, vacuum stability, and inert vacuum conditions are imposed.
- μ_2^2 is determined by the DM relic abundance.
  micrOMEGAs, CPC176 (2007)
- Direct detection, collider search, and electroweak precision test are imposed.



MA, Braathen, Kanemura, EPJC 85 (2025) 5

Numerical study

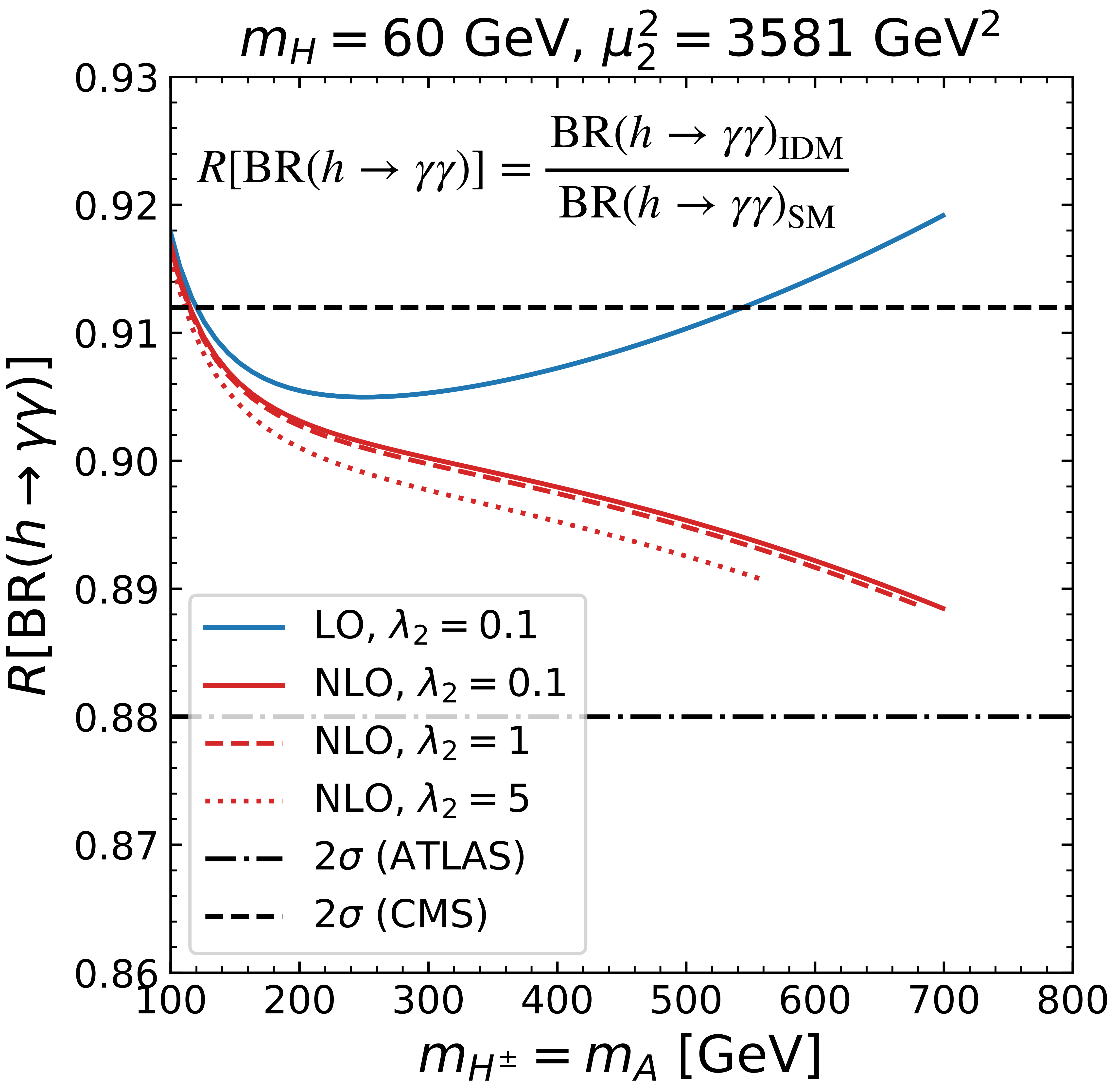
- Perturbative unitarity, vacuum stability, and inert vacuum conditions are imposed.
- μ_2^2 is determined by the DM relic abundance.
  micrOMEGAs, CPC176 (2007)
- Direct detection, collider search, and electroweak precision test are imposed.

HL-LHC expectation (2sigma)

CYRM-2019-007.221

$$\Delta R[\mathrm{BR}(h \to \gamma\gamma)] : 8.8\%\ (\mathrm{CMS}),\ 12\%\ (\mathrm{ATLAS})$$

Two-loop corrections are non-negligible to test the IDM at the HL-LHC.



MA, Braathen, Kanemura, EPJC 85 (2025) 5

The two-loop corrections to the Higgs triple coupling are calculated by the effective potential method. Braathen, Kanemura, PLB796 (2019) and EPJC80 (2020)

$$\kappa_\lambda = \lambda_{hhh}^{\mathrm{IDM}} / (\lambda_{hhh}^{\mathrm{SM}})^{(0)}$$

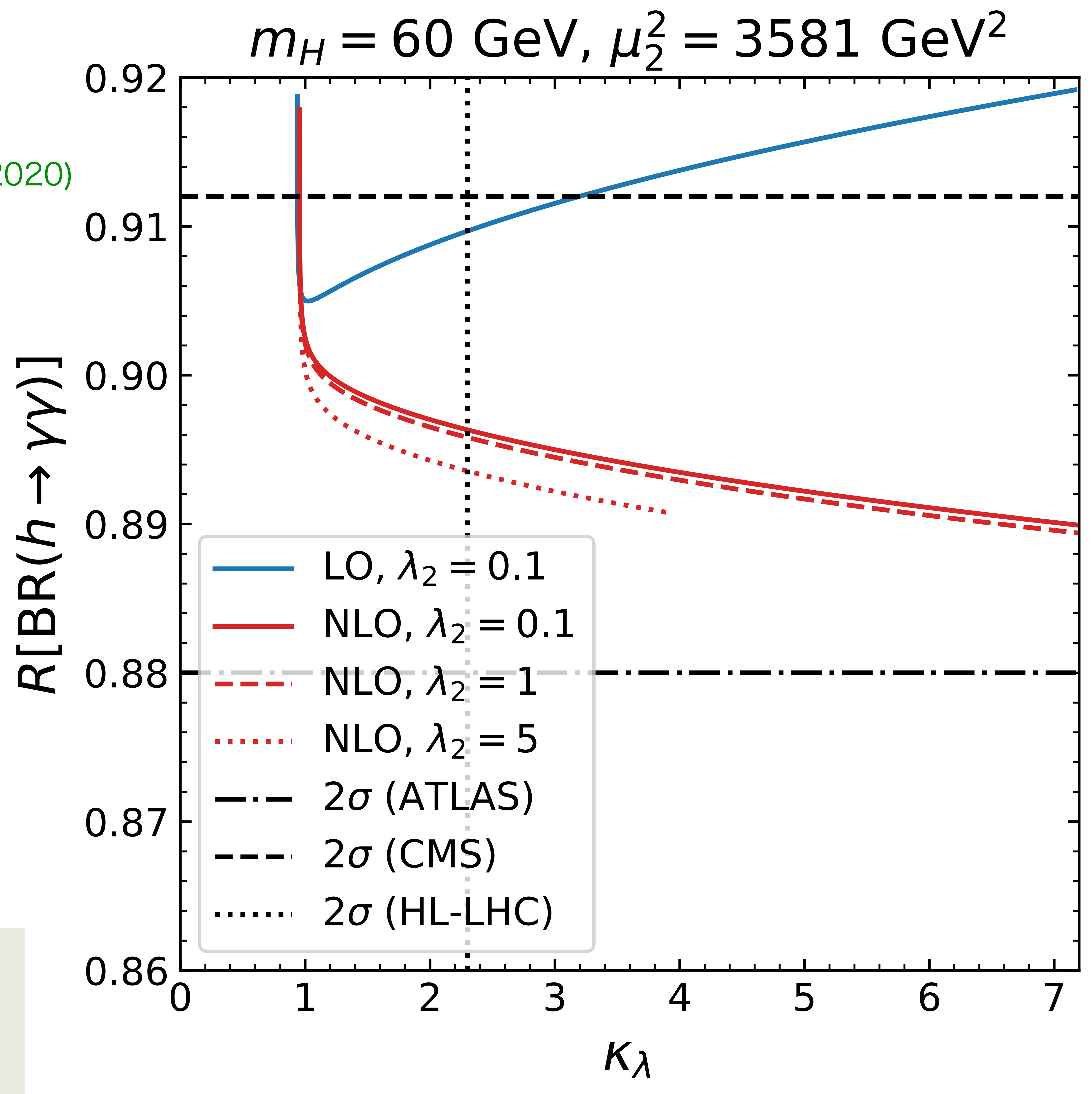
Their correlations are qualitatively changed from LO to NLO. The BSM corrections to $h \to \gamma\gamma$ grows faster, while κ_λ receives large corrections.

HL-LHC expectation

$$0.1 < \kappa_\lambda < 2.3$$ CYRM-2019-007.221 [hep-ph] 1902.00134

(New) $$0.48 < \kappa_\lambda < 1.58$$ [hep-ph] 2504.00672

For the resonance scenario, $h \to \gamma\gamma$ is powerfull, but κ_λ is useful to test the heavy mass scenario.

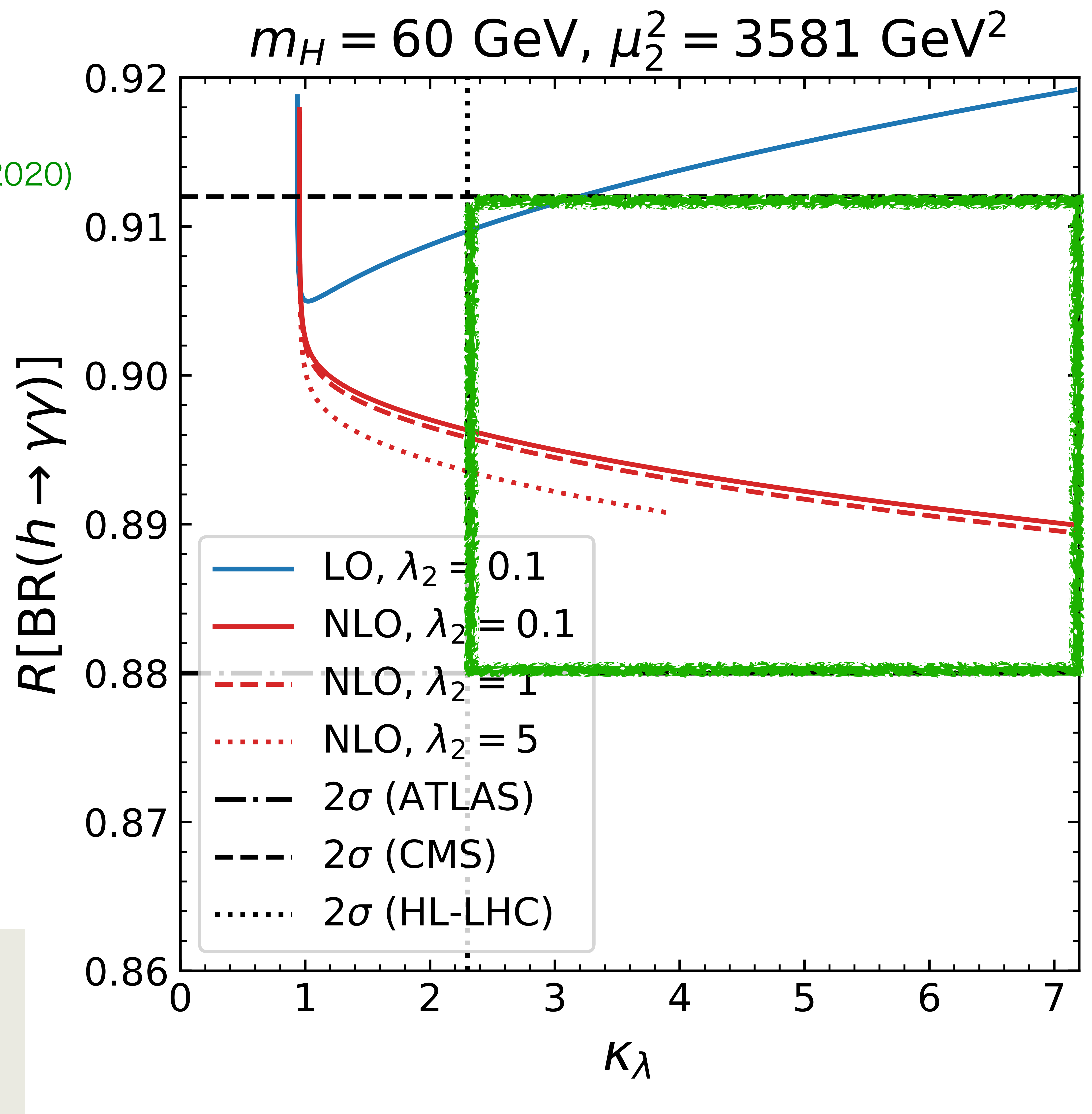


MA, Braathen, Kanemura, EPJC 85 (2025) 5

The two-loop corrections to the Higgs triple coupling are calculated by the effective potential method. Braathen, Kanemura, PLB796 (2019) and EPJC80 (2020)

$$\kappa_\lambda = \lambda_{hhh}^{\rm IDM}/(\lambda_{hhh}^{\rm SM})^{(0)}$$

Their correlations are qualitatively changed from LO to NLO. The BSM corrections to $h \to \gamma\gamma$ grows faster, while κ_λ receives large corrections.



HL-LHC expectation

$$0.1 < \kappa_\lambda < 2.3$$ CYRM-2019-007.221 [hep-ph] 1902.00134

(New) $$0.48 < \kappa_\lambda < 1.58$$ [hep-ph] 2504.00672

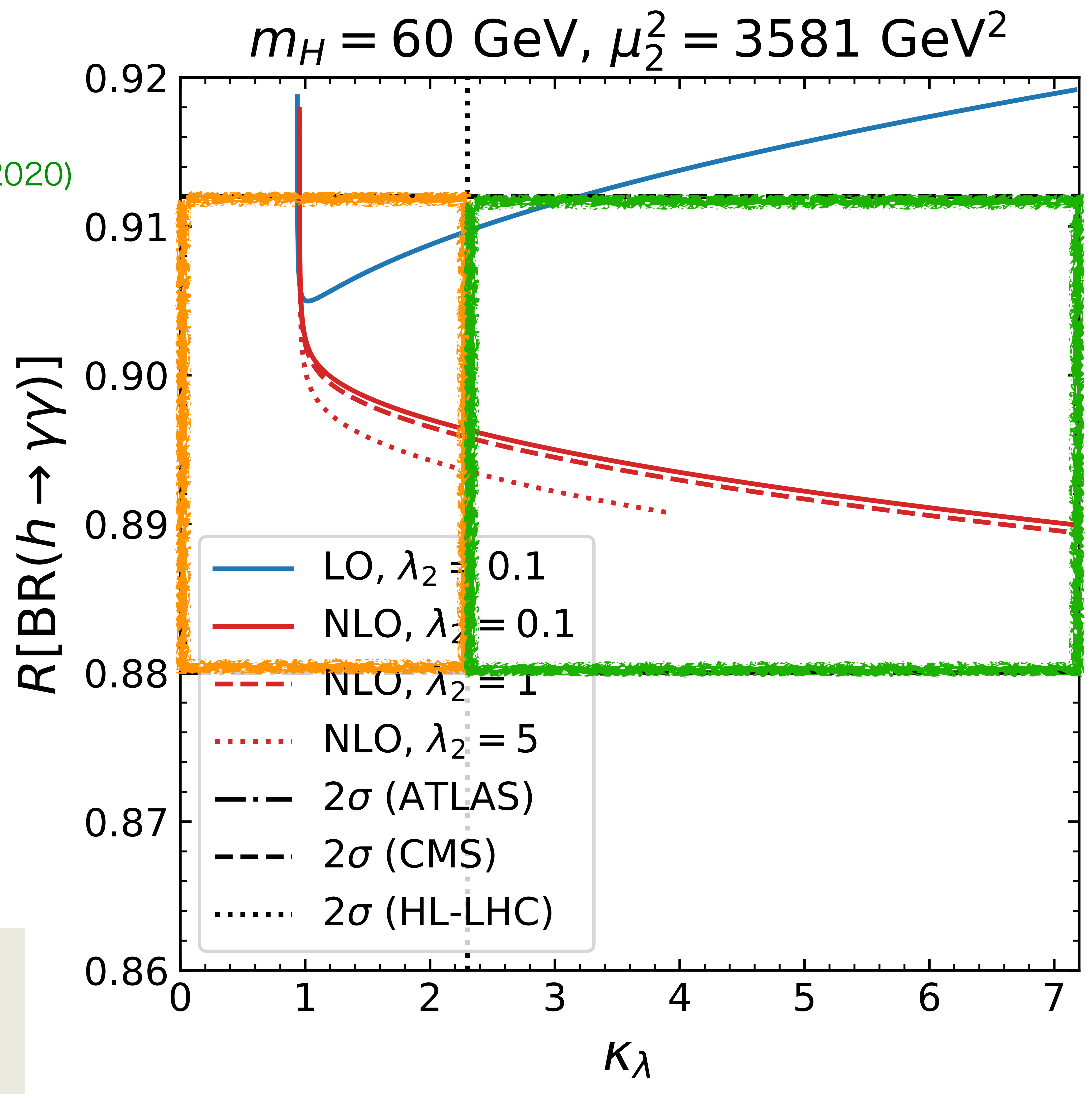
For the resonance scenario, $h \to \gamma\gamma$ is powerfull, but κ_λ is useful to test the heavy mass scenario.

MA, Braathen, Kanemura, EPJC 85 (2025) 5

The two-loop corrections to the Higgs triple coupling are calculated by the effective potential method. Braathen, Kanemura, PLB796 (2019) and EPJC80 (2020)

$$\kappa_\lambda = \lambda_{hhh}^{\mathrm{IDM}} / (\lambda_{hhh}^{\mathrm{SM}})^{(0)}$$

Their correlations are qualitatively changed from LO to NLO. The BSM corrections to $h \to \gamma\gamma$ grows faster, while κ_λ receives large corrections.



HL-LHC expectation

$$0.1 < \kappa_\lambda < 2.3$$ CYRM-2019-007.221 [hep-ph] 1902.00134

(New) $$0.48 < \kappa_\lambda < 1.58$$ [hep-ph] 2504.00672

For the resonance scenario, $h \to \gamma\gamma$ is powerfull, but κ_λ is useful to test the heavy mass scenario.

MA, Braathen, Kanemura, EPJC 85 (2025) 5

The two-loop corrections to the Higgs triple coupling are calculated by the effective potential method. Braathen, Kanemura, PLB796 (2019) and EPJC80 (2020)

$$\kappa_\lambda = \lambda_{hhh}^{\rm IDM}/(\lambda_{hhh}^{\rm SM})^{(0)}$$

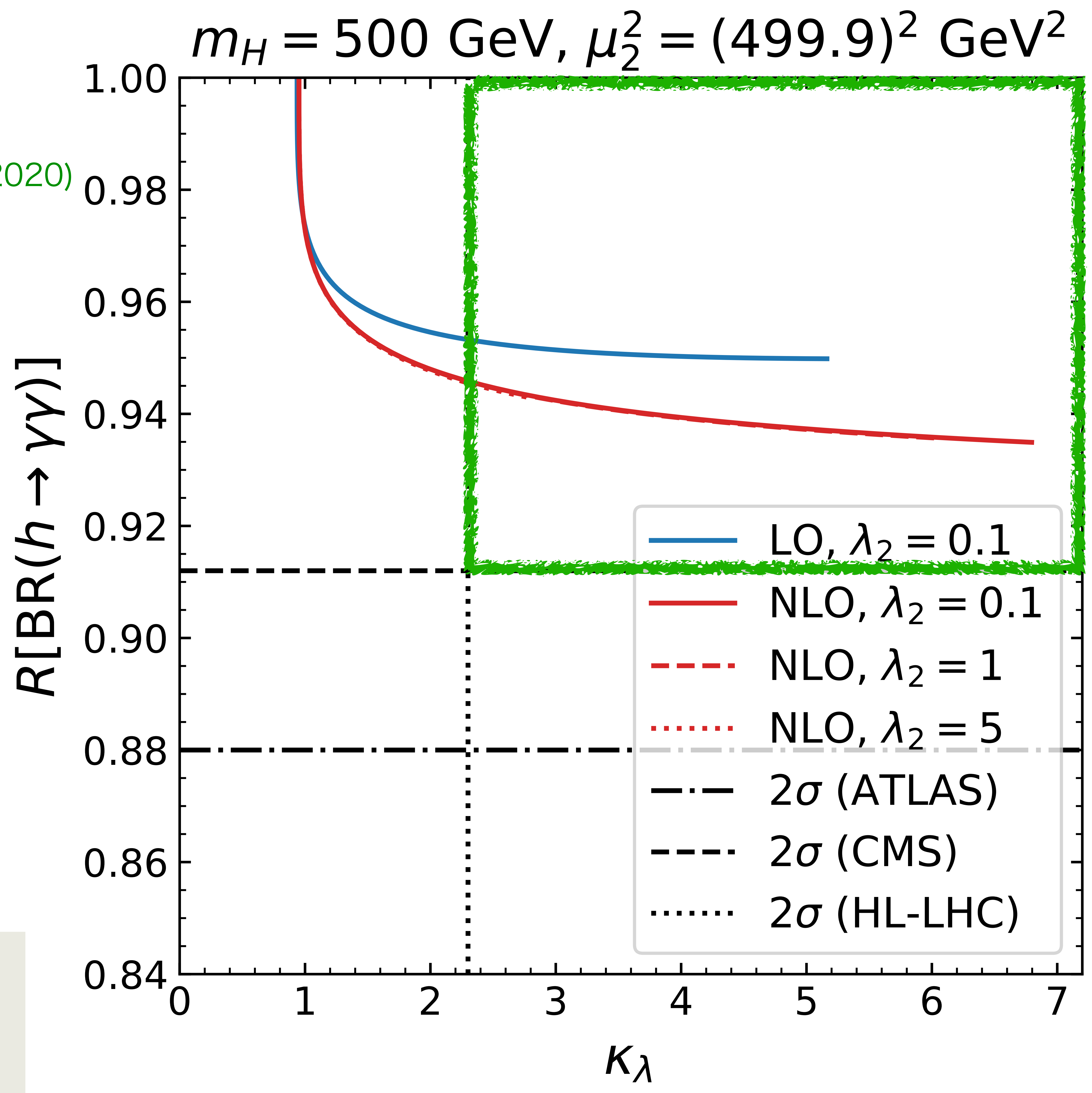
Their correlations are qualitatively changed from LO to NLO. The BSM corrections to $h \to \gamma\gamma$ grows faster, while κ_λ receives large corrections.

HL-LHC expectation

$$0.1 < \kappa_\lambda < 2.3$$ CYRM-2019-007.221 [hep-ph] 1902.00134

(New) $$0.48 < \kappa_\lambda < 1.58$$ [hep-ph] 2504.00672

For the resonance scenario, $h \to \gamma\gamma$ is powerfull, but κ_λ is useful to test the heavy mass scenario.



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 BSM contributions are calculated by using Higgs low-energy theorem in the gauge-invariant way (Pinch technique and background field method).

What we found

- Two-loop BSM contributions increase the deviation from the SM prediction, and it is important to include them to test the IDM at future colliders such as HL-LHC.