Digests of recent works for extended Higgs models

[1] Full NLO calculations for $h(125)$ decays in non-minimal Higgs models

arXiv:1906.10070, arXiv:1910.12769

[2] New physics effects on the production rate of $e^+e^- \to h\,\gamma$

arXiv:1808.10268

[3] 2-loop correction to the hhh coupling in non-minimal Higgs models

arXiv:1903.05417, arXiv:1911.11507

[4] Aligned CP violating 2HDM cancelling the EDM

arXiv:2004.03943

Shinya Kanemura (Osaka Univ.)

with

Johannes Braathen, Mitsunori Kubota, Mariko Kikuchi,

Kentaro Mawatari, Kodai Sakurai, Kei Yagyu

Contributions to SNOWMASS EF-02 WG Meeting on 12 June, 2020

[1] H-COUP: Program to evaluate full NLO decays of h(125) in non-minimal Higgs models

S. Kanemura, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu

Physics: Nucl. Phys. B949 (2019) 114791 (arXiv:1906.10070)
Manual: arXiv:1910.12769

Higgs Precision Measurements

- Determination of the structure of the Higgs sector is important to determine **new physics** beyond the SM.
- Discovery of the 125 GeV Higgs boson opened a new window to narrow down the structure of the Higgs sector from its **precision measurements**.
- Precise measurements of the 125 GeV Higgs will be done at future collider experiments such as **HL-LHC and the ILC250**.
- **Precise calculations** of the Higgs properties (couplings, width, BRs, cross sections) must be important to compare future precision measurements.

H-COUP can do the job!!

Public Tools

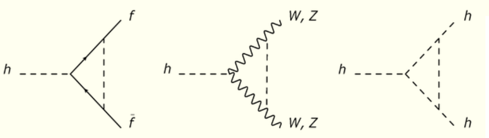
Here is a list of public tools to compute the Higgs decays for extended Higgs models.

- (ewN)2HDECAY : [M. Krause, M. Mühlleitner, M. Spira, 1810.00768][M. Krause, M. Mühlleitner, 1904.02103]
  - Model: 2HDMs, N2HDMs
  - Calculations of two-body-Higgs decays with full 1-loop EW and state-of-the-art QCD corrections in 17 renormalization scheme for mixing parameters
- Prophecy4f : [L. Altenkamp, S. Dittmaier, H. Rzehak,JHEP 1803 (2018) 110]
  - Model: SM,2HDMs, HSM
  - h → WW/ZZ → 4 fermions with NLO QCD and NLO EW corrections
- RECOLA2 : [A. Denner, J. N. Lang, S. Uccirati, CPC 224(2018)346]
  - Model: 2HDMs, HSM
  - Calculation to NLO amplitude for any process
- 2HDMC : [D. Eriksson, J. Rathsman, O. Stal CPC. 181 (2010) 189]
  - Model: 2HDMs
  - Calculations of decays of Higgs bosons with NLO QCD
- SHDECAY : [R. Costa, M. Mühlleitner, M. Sampaio, R. Santos, JHEP 06 (2016) 034]
  - Model: HSM (real and complex)
  - Calculations of decays of Higgs bosons with NLO QCD
- H-COUP : *Kanemura, Kikuchi, Sakurai, Yagyu, arXiv:1710.04603 (CPC)* *Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv:1910.12769*

What is H-COUP?

Kanemura, Kikuchi, Sakurai, Yagyu, arXiv:1710.04603 (CPC)
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv:1910.12769

H-COUP



H-COUP is a set of Fortran program to calculate couplings, decay rates and BRs for h(125) in various non-minimal Higgs models.

Model

- Higgs Singlet model
- Two Higgs doublet models
  Type I, II, X, Y
- Inert doublet model

Observables

✓ hff, hVV, hhh vertex functions (v1.0)
with NLO EW

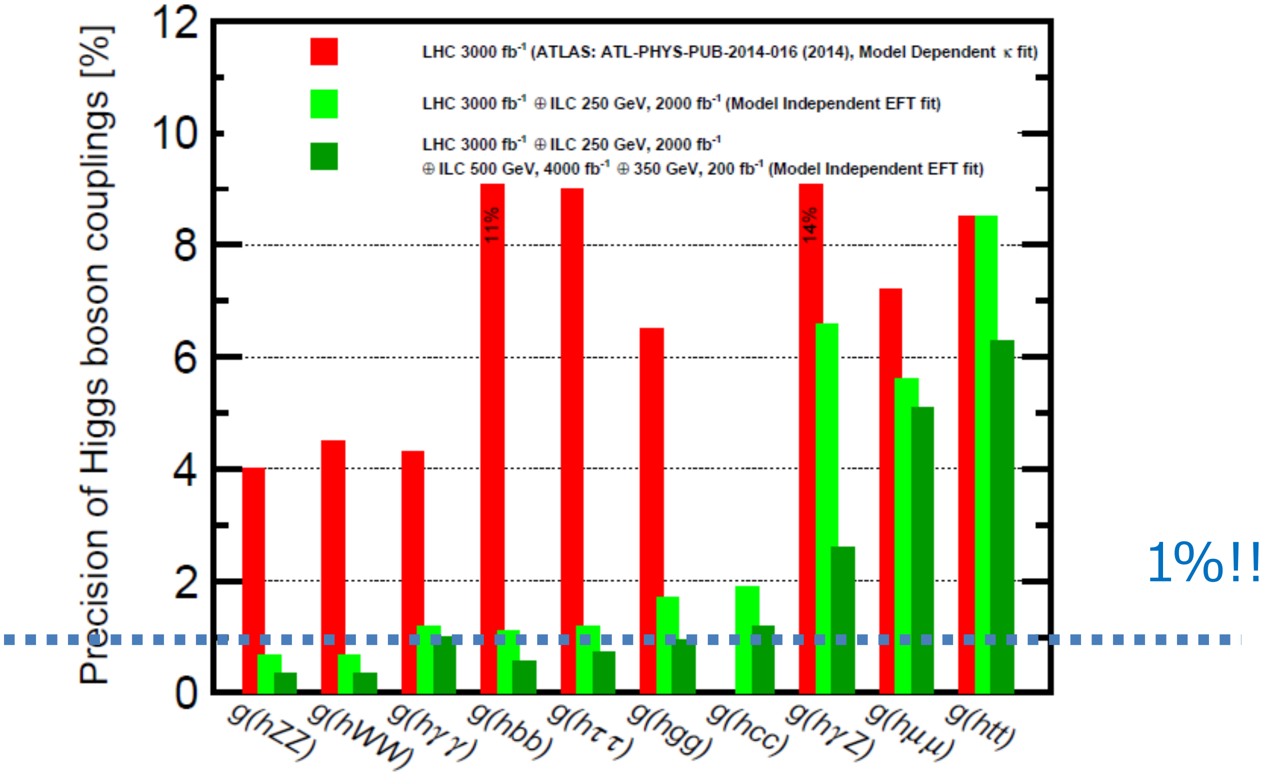
✓ $\mathrm{BR}(h \to ff), \mathrm{BR}(h \to VV^*)$, (v2.0)
$\mathrm{BR}(h \to \gamma\gamma), \mathrm{BR}(h \to Z\gamma), \mathrm{BR}(h \to gg)$
with NNLO QCD + NLO EW

What is New?

- ☐ All these decay rates (2 body, 3 body, loop induced processes) are calculated in the **improved EW on-shell scheme** without gauge dependence.
- ☐ These calculations are systematically applied to **various extended Higgs models**.

Prospects of the future measurements

Fujii et al, 1710.07621 [hep-ph]



- Accuracy of the measurements can be **O(1)% level** at HL-LHC+ILC250.
- Evaluations of systematic calculations with higher-order corrections are necessary.

Fingerprinting Higgs sectors by using H-COUP

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv:1906.10070 (NPB)

- **Fingerprinting** of the Higgs sector can be done by using H-COUP.

$$\Delta\mu_{XX} \equiv \frac{\mathrm{BR}(h \to XX)_{\mathrm{NP}}}{\mathrm{BR}(h \to XX)_{\mathrm{SM}}} - 1$$

・Colored points show predictions in each Higgs model

HSM: Higgs singlet model

Type-I, II, X, Y: two Higgs doublet models

IDM: inert doublet models

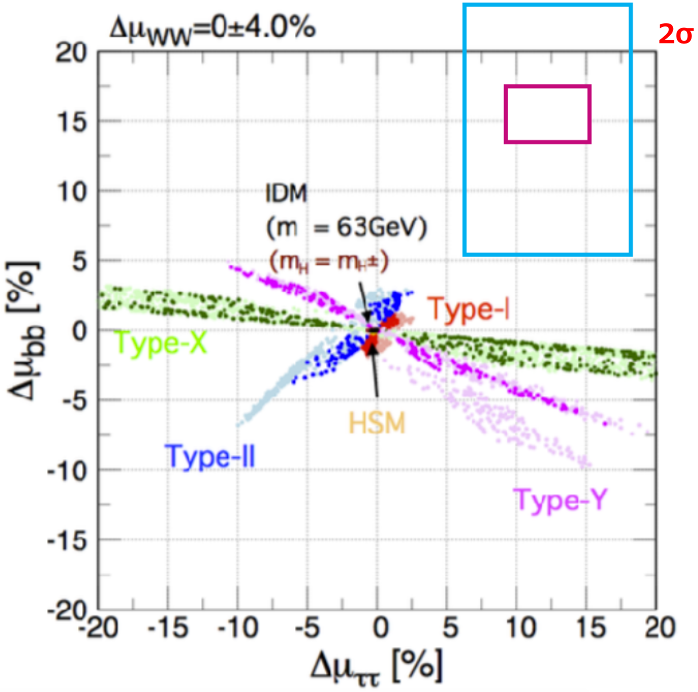
・Lighter (Darker) points show the case for

m_Φ > 300 (600) GeV

(m_Φ : Mass of extra Higgs bosons (degenerated))

2σ at HL-LHC

2σ at ILC250



If $|\Delta\mu_{\tau\tau}| \gtrsim 5\%$, 4 types of THDMs can be separated.

Fingerprinting the Higgs sector

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv:1803.01865 (PLB)

- **Fingerprinting** the Higgs sector can be done by using H-COUP.
- **Scale of the second Higgs boson** can be extracted.

Colored areas show predictions in each model

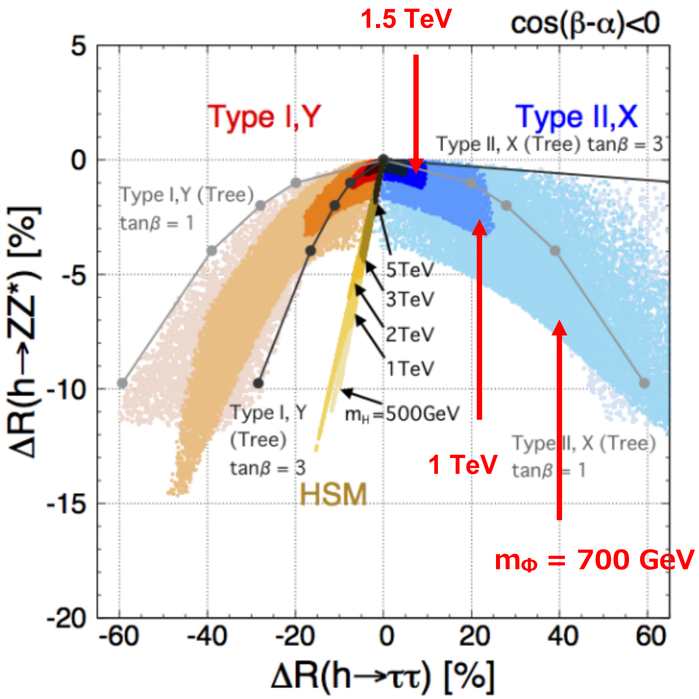
HSM: Higgs Singlet Model,

Type-I, II, X, Y: Two Higgs doublet models

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma_{SM}(h \to XX)} - 1$$

Darker colors show larger masses of extra Higgs bosons.

(m_Φ : Mass of extra Higgs bosons)



Models can be separated using direction of the deviations

If $|\Delta R(h \to ZZ^*)| \gtrsim 4$ (2)%, the second Higgs should appear below 1 (1.5) TeV!

Summary for the H-COUP projects

- Precise calculations of the observables of $h(125)$ are quite important to determine the structure of the Higgs sector, which can show the direction of BSMs.

- H-COUP systematically evaluates couplings, decay rates & BRs for $h(125)$ with higher order corrections in various extended Higgs models.

- By using H-COUP, fingerprinting of the Higgs sector is possible including NLO EW and NNLO QCD corrections.

- The scale of the second Higgs boson can be explored from the size of deviations in the decay rates of $h(125)$.

See also Nucl. Phys. B949 (2019) 114791 (arXiv:1906.10070) arXiv:1910.12769 for details

[2] Single Higgs production in association with a photon at electron-positron colliders in extended Higgs models

S. Kanemura, K. Mawatari, K. Sakurai

Phys. Rev D99 (2019) 035023 (arXiv:1808.10268)

Introduction: hγ production at e^+e^- colliders

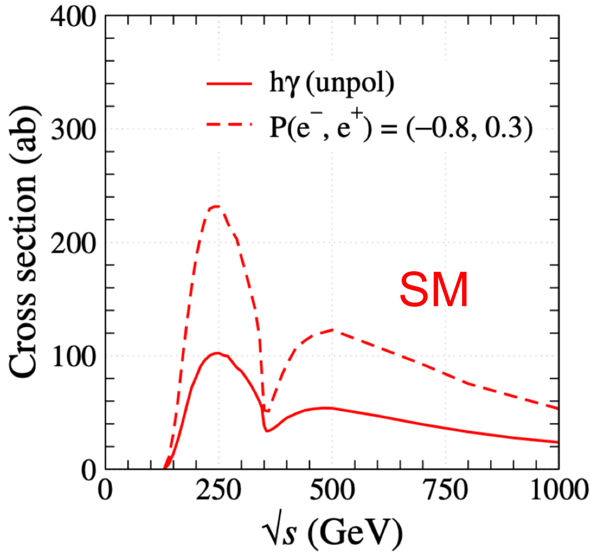
- The cross section peaked around E = 250 GeV
- Beam polarization can enhance the cross section
- The signal is clean: a monochromatic photon

$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{m_h^2}{s}\right)$$

$$\sim 93.8\text{GeV} \ @\sqrt{s} = 250\text{GeV}$$

- One-loop induced

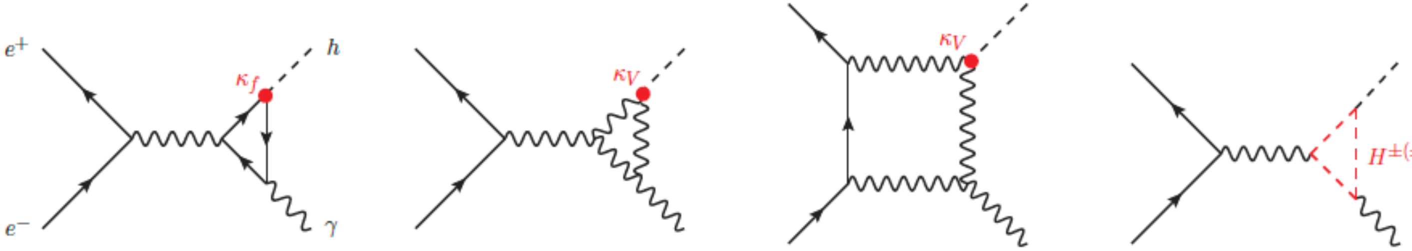
→ Small cross section but sensitive to new physics!



We investigate how much new physics effects can enhance the production rate using H-COUP

- 2HDMs
- Inert doublt model (IDM)
- Inert triplet model (ITM)

3 benchmark extended Higgs models



$$\kappa_X = \frac{g_{hXX}^{\rm NP}}{g_{hXX}^{\rm SM}}$$

	κ_f (=t)	κ_V	H^+	H^{++}
IDM (Inert doublet model)	1	1	○	×
ITM (Y=1) (Inert triplet model)	1	1	○	○
THDM (Two Higgs doublet model)	$s_{\beta\text{-}\alpha} - c_{\beta\text{-}\alpha}/t_\beta$	$s_{\beta\text{-}\alpha}$	○	×

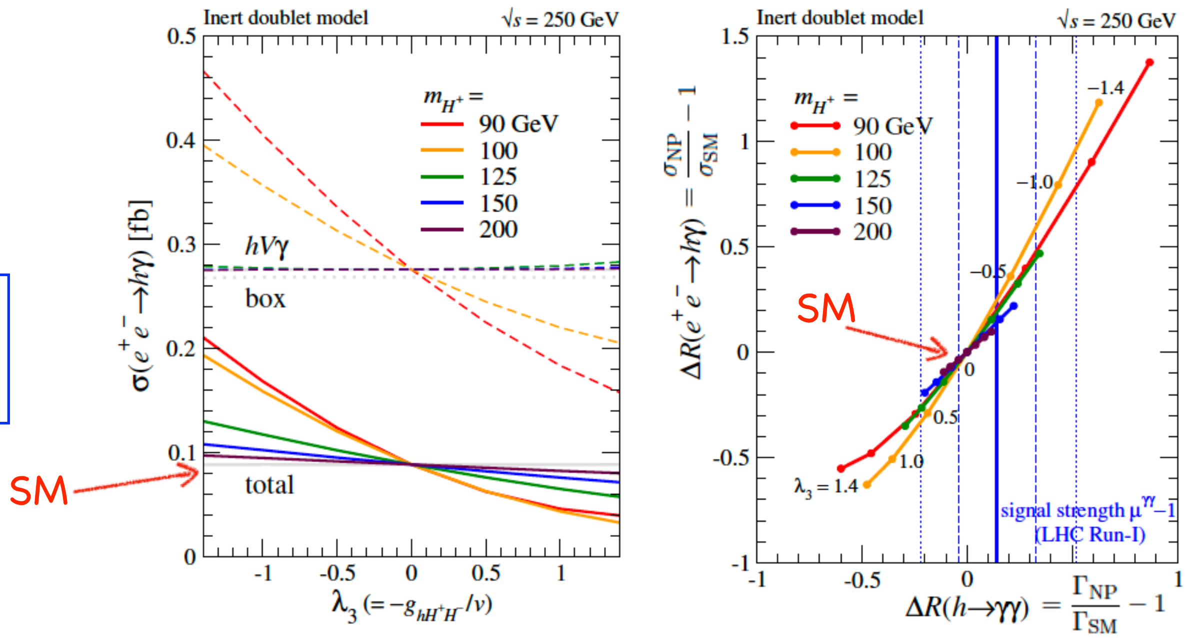
We employ H-COUP program to compute the loop amplitudes in each model

H-COUP v1: Kanemura, Kikuchi, Sakurai, Yagyu [1710.04603, CPC]
H-COUP v2: Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu [1910.12769]

$e^+e^- \to h\,\gamma$ in the IDM

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

$\lambda_3 > -1.4$ from the theoretical constraints



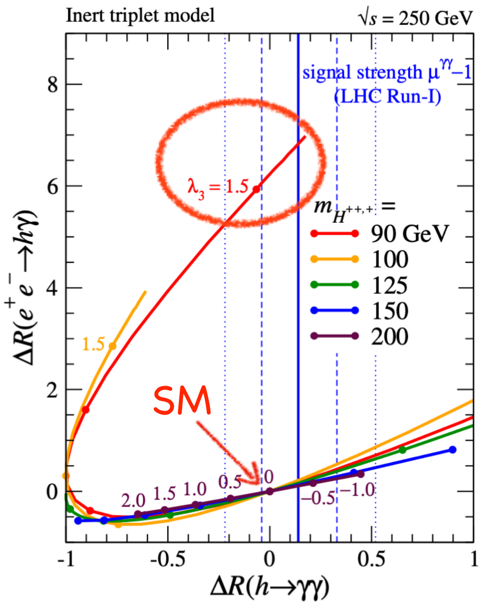
Ligter H^+ with negative λ_3 can enhance the production rate

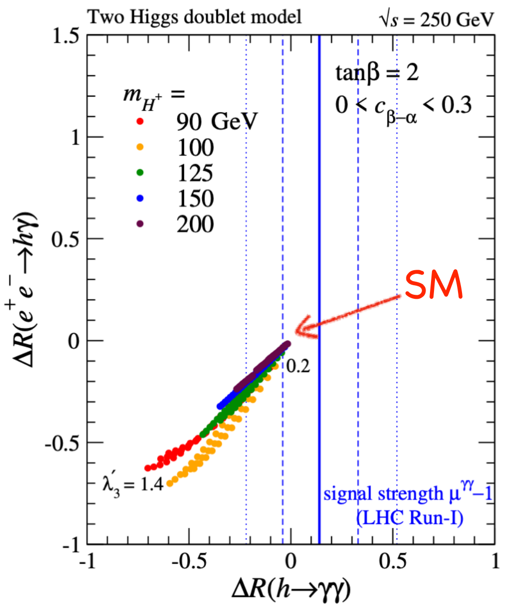
Strong positive correlation with $h\to\gamma\gamma$
⇨ Constrained for lighter H^+ by LHC

$e^+e^- \to h\gamma$ in the ITM and the THDM

$$V = \mu_1^2|\Phi|^2 + \mu_2^2\mathrm{Tr}[\Delta^\dagger\Delta] + \frac{1}{2}\lambda_1|\Phi|^4 + \frac{1}{2}\lambda_2(\mathrm{Tr}[\Delta^\dagger\Delta])^2 + \lambda_3|\Phi|^2\mathrm{Tr}[\Delta^\dagger\Delta] + \frac{1}{2}\lambda_4\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\{\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\}$$



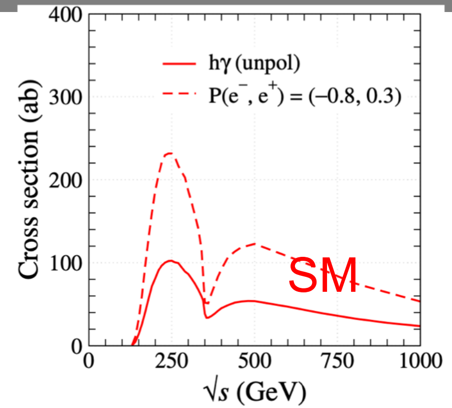


We can find a particular parameter region where the hγ production significantly, but the $h \to \gamma\gamma$ decay still remains at in the SM

Qualitative begaviours are similar to the case with the IDM but the enhanced parameter region is excluded by the theory constraints

Summary for $h\gamma$ production at e^+e^- colliders

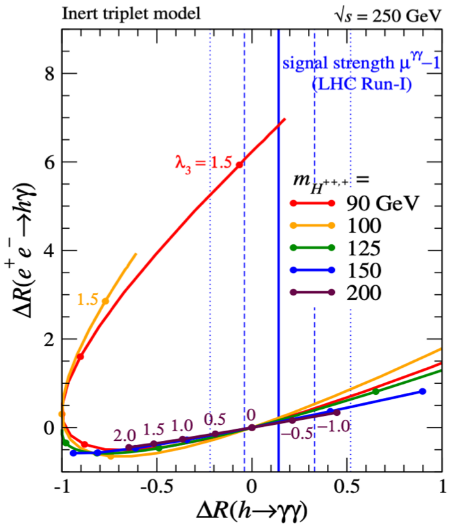
- In SM, the cross section peaked around E = 250 GeV
- Beam polarization can enhance the cross section
- The signal is clean: a monochromatic photon $E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{m_h^2}{s}\right)$ $\sim 93.8\text{GeV}\ @\sqrt{s} = 250\text{GeV}$
- One-loop induced
  → Small cross section but sensitive to new physics!



We studied IDM, ITM, 2HDM as bench mark models using H-COUP

Light charged scalars can enhance the event rates by a factor 2 under current theoretical and experimental constraints

For ITM, thanks to doubly charged scalars, a particular parameter region is found where the hγ production significantly increases, but $h\to\gamma\gamma$ does not.



See also Kanemura, Mawatari, Sakurai Phys. Rev. D99 (2019) 03523 for details

[3] Leading two-loop corrections to the *hhh* couplings in non-minimal Higgs model

Johannes Braathen and Shinya Kanemura

PLB 796 (2019) 38-46 & EPJC 80 (2020) 3, 227

Intro: Why investigate the Higgs trilinear coupling λ_{hhh}?

- **To probe the shape of Higgs potential and nature of EWPT**:
  - The Higgs is responsible for EWSB, but we don't know the shape of its potential away from the EW vacuum → this is determined by λ_{hhh}
  - In turn, λ_{hhh} determines the strength of the EWPT (crucial e.g. for EW Baryogenesis scenario)

- **To distinguish aligned scenarios with or without decoupling**:

  2HDM scenarios with alignment (i.e. SM-like tree-level Higgs couplings) seem strongly favoured by experimental results → why?

  - One (boring) explanation is **decoupling**, i.e. BSM states are out of reach.
  - Instead if there is **alignment without decoupling**, Higgs boson properties, e.g. λ_{hhh}, might **deviate significantly** from SM predictions because of large **non-decoupling effects** (NDE) in BSM loops!
  - Large NDE are known to appear in 2HDM at one loop [Kanemura, Okada, Senaha, Yuan '04] → what happens at two loops? Does pert. theory break down? Are huge new effects possible?
  - Currently there is still room for large deviations in λ_{hhh}: $-3.7 < \lambda_{hhh} / (\lambda_{hhh})^{SM} < 11.5$ (95% CL) [ATLAS-CONF-2019-049] → but potential deviations can be probed at **future colliders**!

Setup of our two-loop calculation for the 2HDM

- We consider a CP-conserving 2HDM, with (softly broken) Z_2 symmetry to avoid tree-level FCNCs

- 5 physical Higgs mass eigenstates: *h*, *H*: CP-even; *A*: CP-odd; $H^{\pm}$: charged

- BSM scalars (Φ = *H*, *A*, $H^{\pm}$) in 2HDM have **2 sources of mass**:
  (1) Higgs VEV *v*
  (2) soft Z_2 breaking scale *M*

$$\Rightarrow M_\Phi^2 = M^2 + \lambda_\Phi v^2$$

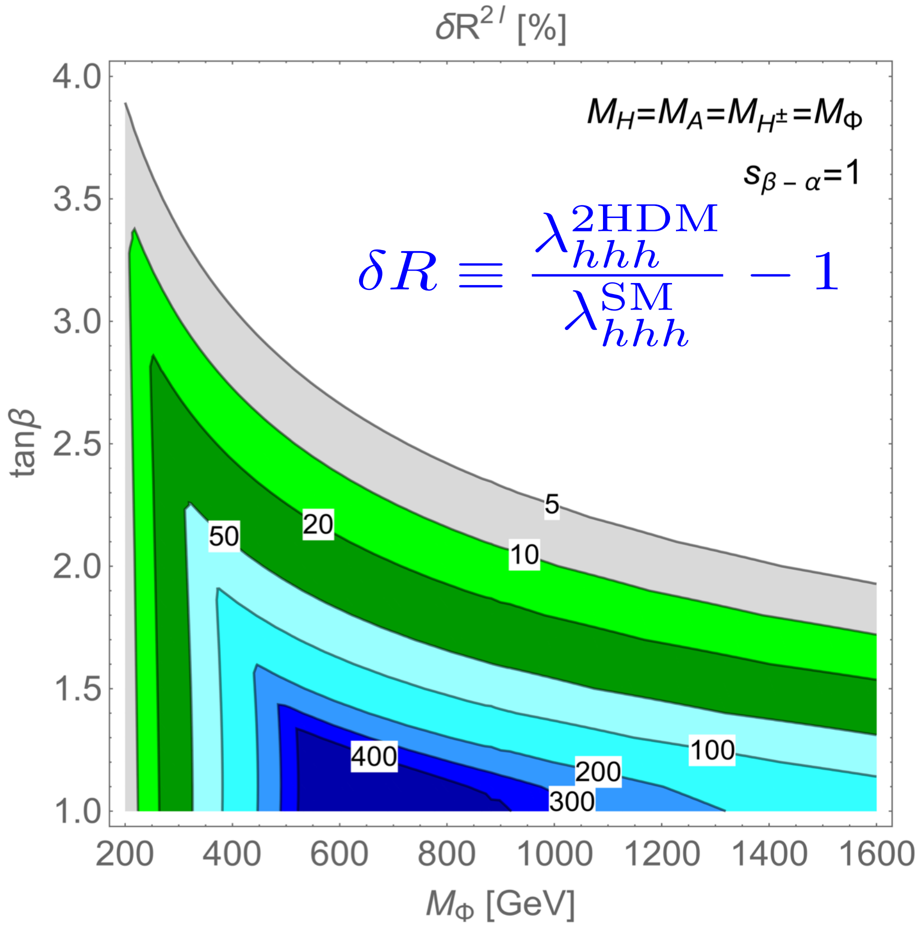
(λ_Φ : some combination of quartic couplings)

- We compute the **dominant two-loop corrections**, from top quark and additional BSM scalars (Φ=*H*, *A*, $H^{\pm}$)

  - Effective potential approx. → neglect sub-leading external momenta effects
  - Neglect sub-leading effects from light fermions, gauge bosons, and light scalars
  - Alignment limit (sin(β-α)=1) → evade/relax experimental constraints

Example of results: maximal possible BSM corrections in the 2HDM

- We plot the maximal deviation δR at (1+2) loops, allowed under criterion of tree-level unitarity
- Max. deviations for low tanβ and M_Φ~600-800 GeV → BSM scalars acquire all their mass from the Higgs VEV and become heavy
  - 1 loop: up to ~300% deviation at most
  - 2 loops: extra 100% (for same points)
- For increasing tanβ, unitarity constraints become more stringent → smaller effects
  - **Blue region**: probed already at HL-LHC (which can reach 50% accuracy on λ_{hhh})
  - **Green region**: probed at ILC (50% acc. at 250 GeV; 27% at 500 GeV; 10% at 1 TeV)



Summary for the hhh coupling at 2 loop

- **First two-loop calculation of λ_{hhh} in 2HDM**, in a scenario with alignment

- Two-loop corrections are typically 10-20% of one-loop contributions (max. 30%)
  - Non-decoupling effects found at one loop are not drastically changed.
  - Possible BSM deviations in λ_{hhh} are **accessible at future colliders**: HL-LHC (50% accuracy) and ILC (down to 10% at 1 TeV).
  - In the future perspective of precise measurements of λ_{hhh}, computing corrections beyond one loop will be necessary!

- Precise calculation of Higgs couplings (e.g. λ_{hhh}) can allow **distinguishing aligned BSM scenarios with or without decoupling**, by accessing non-decoupling effects!

See also Braathen and Kanemura, PLB 796 (2019) 38-46 & EPJC 80 (2020) 3, 227 for details

[4] Aligned CP-violating 2HDM canceling the electric dipole moment

Shinya Kanemura, Mitsunori Kubota and Kei Yagyu

arXiv:2004.03943

Introduction to aligned CPV 2HDM

Sakharov (1967); Kuzmin, Rubakov, Shaposhnikov (1985); Huet and Sather (1995); Kajantie, Laine, Rummukainen, Shaposhnikov (1996)

Baryogegnesis requires the Sakharov's conditions:

1. B violation 2. C and CP violation 3. Departure from equilibrium.

SM cannot satisfy them:

Kobayashi-Maskawa phase is numerically not sufficient.

Phase transition is not first-order getting out of equilibrium.

Extended Higgs model with extra CP-phases and modifications to Higgs potential can realize electroweak baryogenesis.

However, such a CP-phase is normally strongly constrained by the current data for the electric dipole moment (EDM).

We investigate a scenario with O(1) CP-phases in 2HDM but avoiding the EDM constraint

Aligned CPV 2HDM and EDM

- general 2HDM

$$\mathcal{V} = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - \left[\mu_3^2(\Phi_1^\dagger\Phi_2) + h.c.\right] + \tfrac{1}{2}\lambda_1|\Phi_1|^4 + \tfrac{1}{2}\lambda_2|\Phi_2|^4$$
$$+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left\{\left[\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2) + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right](\Phi_1^\dagger\Phi_2) + h.c.\right\}$$

$$\mathcal{L}_\mathrm{Y} = -\bar{Q}_L\left(\sqrt{2}\frac{M_d}{v}\Phi_1 + \rho_d\Phi_2\right)d_R + \ldots$$

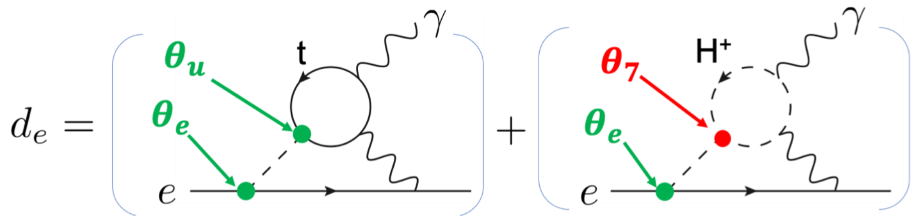
- We assume two kinds of alignment:
  - No mixing among the neutral Higgs bosons, such that the lightest one is treated as *h*(125). It leaves only one physical CPV-phase $\theta_7 = \arg[\lambda_7] - \arg[\lambda_5]/2$ in the potential.
  - No off-diagonal element of Yukawa interaction avoiding dangerous flavor changing neutral currents. It is realized by the following equation.

Pich and Tuzon, PRD (2009)

$$\rho_d = \frac{\sqrt{2}}{v}M_d\zeta_d \;, \text{ where } \zeta_d = |\zeta_d|e^{i\theta_d}$$

ρ_u and ρ_e are in a similar way.

- Remaining CP-phases, θ_f (f=u, d, e) and θ_7, give the contributions to the electron EDM (d_e) They can be destructive.



Barr and Zee, PRL (1990)

Numerical Results for EDM

- We calculate the contour plot of the electron EDM d_e as a function of θ_u and θ_7.
- Input:

$$|\zeta_u| = 0.01, |\zeta_d| = 0.1, \quad m_{H^+} = 230[\mathrm{GeV}]$$
$$|\zeta_e| = 0.5, |\lambda_7| = 0.3 \quad m_{H_2^0} = 280[\mathrm{GeV}]$$
$$m_{H_3^0} = 230[\mathrm{GeV}]$$

- Output:

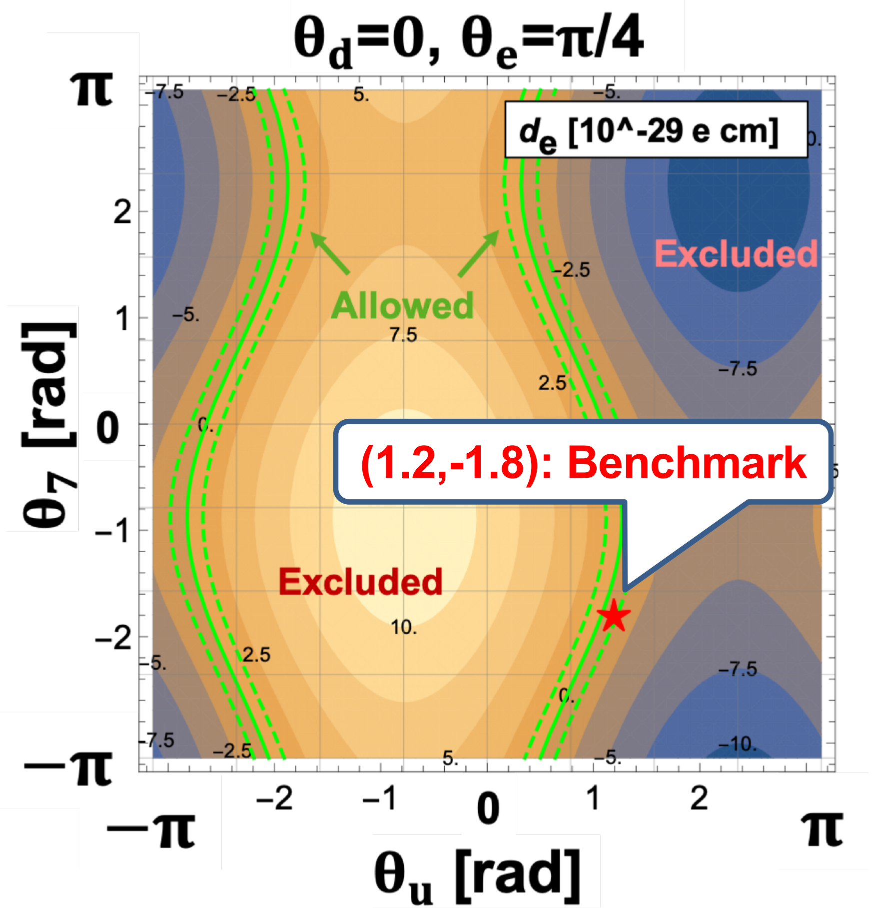
— : $d_e = 0$
- - -: Latest EDM bound

  - Area between the green dashed lines is allowed.
  - At the Benchmark point (1.2, -1.8):

$$d_e = -0.96 \ [10^{-29} \ \mathrm{e\ cm}]$$
$$|d_e^{\mathrm{exp.}}| < 1.1 \ \ [10^{-29} \ \mathrm{e\ cm}]$$

[ACME collaboration, Nature (2018)]

- CP-phases can be O(1) without large electron EDM.



Summary for CPV 2HDM cancelling EDM

We discussed CPV 2HDM cancelling the EDM

EDM data can be satisfied by the destructive interference between the contributions from multiple O(1) CP-phases in the Yukawa sector and in the Higgs sector.

Such O(1) CPV phases can be the source of the baryon number asymmetry of the Universe.

Note: In our paper [arXive: 2004.03943], we also obtain the following conclusions:

- CP-phases can be tested by the angular distributions of decays of extra Higgs bosons.
- Destructive interference can be conserved until the high scales at least $O(10^7)$ GeV, so stable.

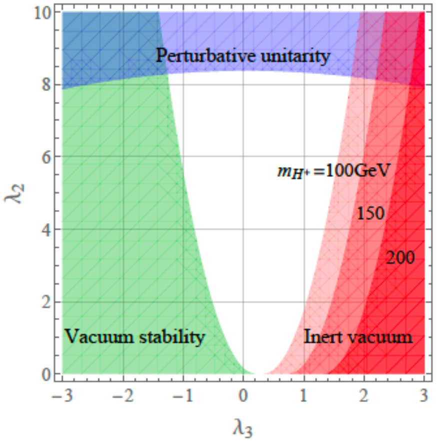
Buck-up slides

Supplement: Theoretical constraints

IDM

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

Inert doublet model (λ_4=λ_5=−0.1)

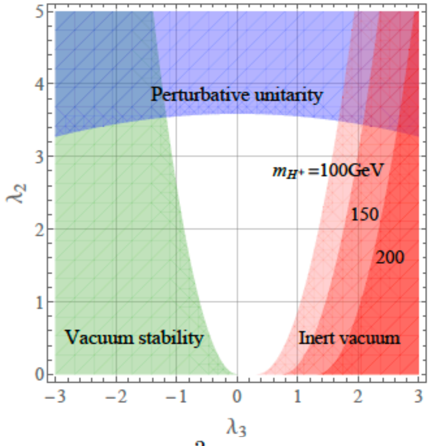


$$g_{hH^+H^-} = -\frac{2}{v}(m_{H^+}^2 - \mu_2^2) = -v\lambda_3$$

ITM

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\{(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\}$$

Inert triplet model (λ_2=λ_4, λ_5=0)



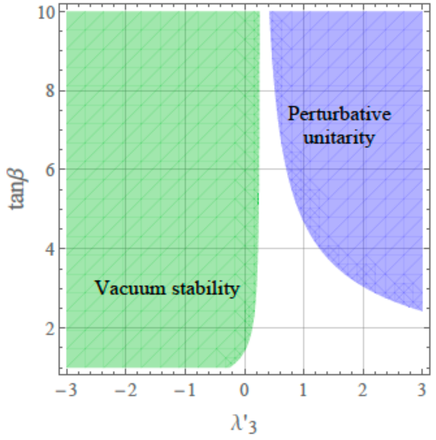
$$g_{hH^{++}H^{--}} = -\frac{2}{v}(m_{H^{++}}^2 - \mu_2^2) = -v\lambda_3$$

$$g_{hH^+H^-} = -\frac{2}{v}\left\{\frac{1}{2}(m_{H^{++}}^2 + m_H^2) - \mu_2^2\right\} = -v\left(\lambda_3 + \frac{1}{2}\lambda_5\right)$$

2HDM

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\{(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\}$$

Two Higgs doublet model (m_H=m_A=m_{H^+}, $c_{\beta-\alpha}$=0)



$$g_{hH^+H^-} = -\frac{2}{v}\left\{(m_{H^+}^2 - M^2 + \frac{1}{2}m_h^2)s_{\beta-\alpha} - (M^2 - m_h^2)\cot 2\beta\, c_{\beta-\alpha}\right\} \equiv -v\lambda'_3$$