Light Higgs Decay
User Guide

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`Light Higgs Decay` is a package written in C++ and capable of calculating the decay widths and branching fractions of light CP-even and CP-odd Higgses. To explore in experiment a generic extension of the Standard Model (SM) that predicts BSM Higgses, the decays of BSM Higgs into SM particles are of special interest, and they are primarily governed by the Higgs couplings to the SM fermions and gauge bosons. The couplings to other BSM particles also matter since they influence the decay induced by loop diagrams. For instance, in the Two-Higgs-Doublet Model (2HDM), trilinear Higgs couplings such as $g_{HH^+H^-}$ affects the $H \to \gamma\gamma$ decay through $H^\pm$ running in the one-loop triangle diagram. In SUSY, more BSM particles such as charginos come into play.

`Light Higgs Decay` is dedicated to handle the light Higgs decay with modified Higgs couplings and the influences of several commonly seen BSM particles such as charged Higgs in the 2HDM and charginos in the MSSM. So it's able to handle the Higgs decay in a wide variety of scenarios including the neutral CP-even and CP-odd Higgses in the 2HDM, the minimal Suppersymmetric Model (MSSM) and the Next to Minimal Supersymmetric Model (NMSSM). The Higgs decay is fully determined by the parameters in the Lagragian of partonic fields

$$
\begin{aligned}
\mathcal{L} = &- \xi_{Huu}\frac{m_u}{v}H\bar{u}u - \xi_{Hcc}\frac{m_c}{v}H\bar{c}c - \xi_{Htt}\frac{m_t}{v}H\bar{t}t \\
&- \xi_{Hdd}\frac{m_d}{v}H\bar{d}d - \xi_{Hss}\frac{m_s}{v}H\bar{s}s - \xi_{Hbb}\frac{m_b}{v}H\bar{b}b \\
&- \xi_{Hee}\frac{m_e}{v}H\bar{e}e - \xi_{H\mu\mu}\frac{m_\mu}{v}H\bar{\mu}\mu - \xi_{H\tau\tau}\frac{m_\tau}{v}H\bar{\tau}\tau \\
&- \xi_{HZZ}\frac{2m_Z^2}{v}HZ^\mu Z_\mu - \xi_{HWW}\frac{2m_W^2}{v}HW^{+\mu}W^-_\mu \\
&+ C_H^\gamma \alpha \frac{H}{v}F_{\mu\nu}F^{H\nu} + C_H^g \frac{\alpha_s}{12\pi}\frac{H}{v}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{2}m_H^2 H^2 \\
&+ i\xi_{Auu}\frac{m_u}{v}A\bar{u}\gamma_5 u + i\xi_{Acc}\frac{m_c}{v}A\bar{c}\gamma_5 c + i\xi_{Att}\frac{m_t}{v}A\bar{t}\gamma_5 t \\
&+ i\xi_{Add}\frac{m_d}{v}A\bar{d}\gamma_5 d + i\xi_{Ass}\frac{m_s}{v}A\bar{s}\gamma_5 s + i\xi_{Abb}\frac{m_b}{v}A\bar{b}\gamma_5 b \\
&+ i\xi_{Aee}\frac{m_e}{v}A\bar{e}\gamma_5 e + i\xi_{A\mu\mu}\frac{m_\mu}{v}A\bar{\mu}\gamma_5 \mu + i\xi_{A\tau\tau}\frac{m_\tau}{v}A\bar{\tau}\gamma_5 \tau \\
&+ \frac{\alpha}{4\pi}C_A^\gamma A F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_s}{4\pi}C_A^g A G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{1}{2}m_A^2 A^2
\end{aligned}
\tag{1}
$$

where H and A denotes the CP-even and CP-odd Higgses, respectively. In this expression, $C^\gamma_{H/A}$ and $C^g_{H/A}$ are the effective $H/A-\gamma-\gamma$ and $H/A-g-g$ couplings, which are functions of the normalized Higgs couplings ξ, and also depend on the interactions with other non-SM particles.

In `Light Higgs Decay`, users are allowed to calculate the Higgs decay for arbitrary values of the parameters in Equation 1. However, a generic BSM of interest often implies certain relations among these parameter, which would significantly reduce the number of free parameters. For these reasons, we also embedded several popular BSMs, namely the four types of 2HDMs, the MSSM and the NMSSM in our package.

1 Initialize a Model

A physics model in `Light Higgs Decay` is encapsulate in a class dubbed `BSModel`. Various methods are declared in `Model.h` file to initialize a model and calculate the corresponding Higgs decay widths and decay branching fractions. A instance of a model class can be initialized in $0-6$ ways by invoking the

```
void set_model(int);
```

method, which corresponds to 7 different specific models. The input parameters for the $0-6$ modes are

- **mode 0**: In this mode, users can directly specify the parameter values in Equation 1. For those tree level decays, the decay widths are uniquely determined by the Higgs mass and the normalized couplings ξ. For those decay induced by the triangle diagrams at one-loop level, we consider all SM particles that would contribute. These parameters are to be initialized by invoking

```
void set_mA(double mA);
void set_mH(double mH);
void set_HffCoupling(double xiHtt, double  xiHbb, double xiHcc,
                     double xiHss, double  xiHuu, double xiHdd,
                     double xiHtata, double xiHmumu, double xiHee);
void set_AffCoupling(double xiAtt, double xiAbb, double xiAcc,
                     double xiAss, double xiAuu,double xiAdd,
                     double xiAtata, double xiAmumu, double xiAee);
void set_HVVCoupling(double xiHZZ, double xiHWW);
```

  The meaning of each method is self-explained.

  If the contribuition to the $H \to \gamma\gamma$ decay from a BSM charged Higgs through interaction

$$\mathcal{L}_{HH^+H^-} = g_{HH^+H^-} H H^+ H^- \tag{2}$$

  is interested, users can include it by specifying a nonzero charged Higgs mass $m_{H^\pm}$ and coupling strength $\lambda_{HH^+H^-}$ by invoking

```
void set_mHC(double mHC);
%void set_gHCC(double gHCC);
```

- **mode 1-4**: These four modes are reserved for four types of 2HDMs, with $1-4$ corresponding to Type-I, Type-II, Type-L and Type-F, respectively. The 2HDMs are governed by 6 free parameters

$$\cos(\beta-\alpha),\ \tan\beta,\ m_H,\ m_A,\ m_{H^\pm},\ \lambda v^2 \tag{3}$$

  which initialize through methods

```
void set_cosba(double cosba);
void set_tanb(double  tanb);
void set_mH(double mH);
void set_mA(double mA);
void set_mHC(double mHC);
void set_lambdav(double lambdav);
```

  their relation to the parameters in Equation 1 can be found in [].

- **mode 5**: This mode is reserved for the Minimal Supersymmetric Model (MSSM). The free parameters in MSSM are

$$\cos(\beta-\alpha),\ \tan\beta,\ m_H,\ m_A,\ m_{H^\pm},\ M_2,\ \mu_{\text{eff}} \tag{4}$$

  where M_2 and μ_{eff} are the wino mass and the effective μ-term coefficient.While the first five parameters initialize as they do in the previous modes, the last two parameters initialize via

```
void set_WinoMass(double WinoMass);
void set_mueff(double mueff);
```

  These two parameters govern the influence of charginos to the $H/A \to \gamma\gamma$ decay.

- **mode 6**: This mode is reserved for the Next to Minimal Supersymmetric Model (NMSSM). Other than the parameters in Equation 4, NMSSM contains two more parameters

$$\lambda_{HSS},\ P_{11} \tag{5}$$

  which govern the coupling strength of scalar singlet with the MSSM scalar doublet in the Higgs potential and the mixing of the neutral CP-odd Higgs component from the singlet with that from the doublet. They initialize via

```
void set_lambdaSHH(double lambdaSHH);
void set_P11(double P11);
```

  In the calculation of CP-odd Higgs decay, λ_{HSS} comes into play by modifying the CP-odd Higgs coupling with charginos, thus only affects the $H \to \gamma\gamma$ decay. When $\lambda_{HSS} = 0$, all couplings to CP-odd Higgs A are modulated by a factor of P_{11} based on those in MSSM.

2 Decay Width and Branching Fractions

Once an instance of model is initialized, `Light Higgs Decay` can calculate the decay branching width and branching fractions of CP-even Higgs H and CP-odd Higgs A through the following methods

CP-odd Higgs Decay Width

Method	Description
`double DecayWidth_Agaga();`	$A \to \gamma\gamma$
`double DecayWidth_Aee();`	$A \to e^+e^-$
`double DecayWidth_Amumu();`	$A \to \mu^+\mu^-$
`double DecayWidth_Atautau();`	$A \to \tau^+\tau^-$
`double DecayWidth_ATotalLepton();`	Total leptonic decay width
`double DecayWidth_APiPiPi();`	$A \to \pi\pi\pi$
`double DecayWidth_AEtaPiPi();`	$A \to \eta\pi\pi$
`double DecayWidth_AEtapPiPi();`	$A \to \eta'\pi\pi$
`double DecayWidth_AEtaEtaPi();`	$A \to \eta\eta\pi$
`double DecayWidth_AKKPi();`	$A \to KK\pi$
`double DecayWidth_AGammaPiPi();`	$A \to \gamma\pi\pi$
`double DecayWidth_AEtaEtapPi();`	$A \to \eta\eta'\pi$
`double DecayWidth_AEtapEtapPi();`	$A \to \eta'\eta'\pi$
`double DecayWidth_AEtaEtaEta();`	$A \to \eta\eta\eta$
`double DecayWidth_AEtaEtaEtap();`	$A \to \eta\eta\eta'$
`double DecayWidth_AEtaEtapEtap();`	$A \to \eta\eta'\eta'$
`double DecayWidth_AEtapEtapEtap();`	$A \to \eta'\eta'\eta'$
`double DecayWidth_AEtaKK();`	$A \to \eta KK$
`double DecayWidth_AEtapKK();`	$A \to \eta' KK$
`double DecayWidth_AQuark();`	$A \to q\bar{q}$
`double DecayWidth_AGluon();`	$A \to gg$
`double DecayWidth_ATotalHadron();`	Total hadronic decay width
`double DecayWidth_ATotal();`	Total decay width

CP-odd Higgs Decay Branching Fractions

Method	Description
`double BranchRatio_Agaga();`	$A \to \gamma\gamma$
`double BranchRatio_Aee();`	$A \to e^+e^-$
`double BranchRatio_Amumu();`	$A \to \mu^+\mu^-$
`double BranchRatio_Atautau();`	$A \to \tau^+\tau^-$
`double BranchRatio_AQuark();`	$A \to q\bar{q}$
`double BranchRatio_AGluon();`	$A \to gg$
`double BranchRatio_ATotalHadron();`	Total hadronic decay branching fraction

CP-even Higgs Decay Width

Method	Description
`double DecayWidth_Hgaga();`	$H \to \gamma\gamma$
`double DecayWidth_Hee();`	$H \to e^+e^-$
`double DecayWidth_Hmumu();`	$H \to \mu^+\mu^-$
`double DecayWidth_Htautau();`	$H \to \tau^+\tau^-$
`double DecayWidth_HPiPi();`	$H \to \pi\pi$
`double DecayWidth_HKK();`	$H \to KK$
`double DecayWidth_HPiPiPiPi();`	$H \to \pi\pi\pi\pi$
`double DecayWidth_Hcc();`	$H \to c\bar{c}$
`double DecayWidth_Hss();`	$H \to s\bar{s}$
`double DecayWidth_HGluon();`	$H \to gg$
`double DecayWidth_HTotal();`	Total decay width

CP-even Higgs Branching Fraction

Method	Description
`double BranchRatio_Hgaga();`	$H \to \gamma\gamma$
`double BranchRatio_Hee();`	$H \to e^+e^-$
`double BranchRatio_Hmumu();`	$H \to \mu^+\mu^-$
`double BranchRatio_Htautau();`	$H \to \tau^+\tau^-$
`double BranchRatio_HPiPi();`	$H \to \pi\pi$
`double BranchRatio_HKK();`	$H \to KK$
`double BranchRatio_HPiPiPiPi();`	$H \to \pi\pi\pi\pi$
`double BranchRatio_Hcc();`	$H \to c\bar{c}$
`double BranchRatio_Hss();`	$H \to s\bar{s}$
`double BranchRatio_HGluon();`	$H \to gg$