Higgs-pair Production and Decay in Simplest Little Higgs Model

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Based on arXiv:0908.1827, XFH, L. Wang, J. M. Yang

outline

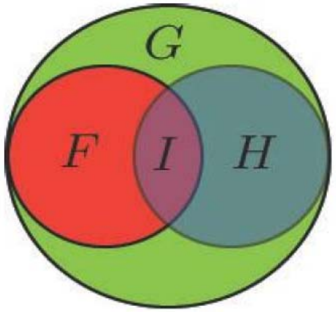
- Little Higgs Theory
- The Simplest Little Higgs Model
- Higgs-pair Production and Decay at LHC
- Conclusion

Little Higgs Theory

N. Arkani-Hamed, A. G. Cohen, H. Georgi, PLB 513, 232 (2001).

Idea: Higgs boson become PGB via mechanism of collective symmetry breaking.

$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$



- **Induce 2 couplings which break the global symmetry.**
- **Each individual coupling preserves enough of global symmetry to guarantee massless of GB.**
- **Combination of both couplings breaks global enough to allow GB to become a PGB.**

$$\Delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2$$

The quadratic divergences appear at two-loop level

Some breaking patterns of little Higgs theories:

Global Symmetries	Gauge Symmetries
$SU(5)/SO(5)$	$[SU(2)\otimes U(1)]^2$
$SU(3)^8/SU(3)^4$	$SU(3)\otimes SU(2)\otimes U(1)$
$SU(6)/SP(6)$	$[SU(2)\otimes U(1)]^2$
$SU(4)^4/SU(3)^4$	$SU(4)\otimes U(1)$
$SO(5)^8/SO(5)^4$	$SO(5)\otimes SU(4)\otimes U(1)$
$[SU(3)\otimes U(1)/SU(2)\otimes U(1)]^2$	$SU(3)\otimes U(1)$

The Simplest Little Higgs Model

Kaplan and Schmaltz, JHEP 0310,039(2003) ; Schmaltz, JHEP 0408,056(2004)

Based on $[SU(3)\otimes U(1)/SU(2)\otimes U(1)]^2$

$$SU(3)\otimes U(1)_X \xrightarrow{\langle\Phi_i\rangle = f_i} SU(2)\otimes U(1)_Y$$

The uneaten 5 PGBs can be parameterized as:

$$\Phi_1 = e^{it_\beta\Theta}\begin{pmatrix}0\\0\\f_1\end{pmatrix} \qquad \Phi_2 = e^{-it_\beta\Theta}\begin{pmatrix}0\\0\\f_2\end{pmatrix}$$

$$\Theta = \frac{1}{f}\left[\begin{pmatrix}0 & 0 & \\ 0 & 0 & H \\ & H^\dagger & 0\end{pmatrix} + \frac{\eta}{\sqrt{2}}\begin{pmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{pmatrix}\right]$$

$$f = \sqrt{f_1^2 + f_2^2}$$

$$t_\beta \equiv \tan\beta = f_2/f_1$$

The kinetic term in the non-linear sigma model

$$\mathcal{L}_\Phi = \sum_{j=1,2} \left| \left(\partial_\mu + igA_\mu^a T^a - i\frac{g_x}{3} B_\mu^x \right) \Phi_j \right|^2$$

$$g_x = g \tan\theta_W / \sqrt{1 - \tan^2\theta_W / 3}$$

Φ_1, Φ_2 **develop their VEVs, new heavy gauge bosons get their masses proportional to *f***

$$m_{W'_\pm}^2 = \frac{g^2}{2} f^2 \qquad m_{W'_{0,\bar{0}}}^2 = \frac{g^2}{2} f^2 \qquad m_{Z'}^2 = g^2 f^2 \frac{2}{3 - \tan^2\theta_W}$$

The quark Yukawa interactions for the third generation and the first two generations:

$$\mathcal{L}_3 = i\lambda_1^t t_1^c \Phi_1^\dagger Q_3 + i\lambda_2^t t_2^c \Phi_2^\dagger Q_3 + i\frac{\lambda_d^m}{\Lambda} d_m^c \varepsilon_{ijk} \Phi_1^i \Phi_2^j Q_3^k + h.c.$$

$$\mathcal{L}_{1,2} = i\lambda_1^{d_n} d_{1n}^c Q_n^T \Phi_1 + i\lambda_2^{d_n} d_{2n}^c Q_n^T \Phi_2 + i\frac{\lambda_u^{mn}}{\Lambda} u_m^c \varepsilon_{ijk} \Phi_1^{*i} \Phi_2^{*j} Q_n^k + h.c.$$

n = 1, 2 ; i, j, k = 1, 2, 3

$$Q_3 = \begin{pmatrix} t_L \\ b_L \\ iT_L \end{pmatrix} \qquad Q_n = \begin{pmatrix} d_{nL} \\ -u_{nL} \\ iD_{nL} \end{pmatrix}$$

d_m^c runs over $(d^c, s^c, b^c, D^c, S^c)$

u_m^c runs over (u^c, c^c, t^c, T^c)

d_{1n}^c and d_{2n}^c are linear combinations of d^c, D^c for n=1 and s^c, S^c for n=2

The Higgs boson interactions and the mass terms for three generations of quarks:

$$\mathcal{L}_t \simeq -f\lambda_2^t\left[x_\lambda^t c_\beta t_1^c\left(-s_1 t_L + c_1 T_L\right) + s_\beta t_2^c\left(s_2 t_L + c_2 T_L\right)\right] + h.c.$$

$$\mathcal{L}_{d_n} \simeq -f\lambda_2^{d_n}\left[x_\lambda^{d_n} c_\beta d_1^c\left(s_1 d_{nL} + c_1 D_{nL}\right) + s_\beta d_2^c\left(-s_2 d_{nL} + c_2 D_{nL}\right)\right] + h.c.$$

$$\mathcal{L}_q \simeq -\frac{\lambda_q}{\Lambda} f^2 s_\beta c_\beta s_3 q^c q_L + h.c. \qquad (q = u, c, b)$$

$$x_\lambda^t \equiv \frac{\lambda_1^t}{\lambda_2^t}, \quad x_\lambda^{d_n} \equiv \frac{\lambda_1^{d_n}}{\lambda_2^{d_n}}; \quad s_\beta \equiv \frac{f_2}{\sqrt{f_1^2 + f_2^2}}, \quad c_\beta \equiv \frac{f_1}{\sqrt{f_1^2 + f_2^2}}$$

$$s_1 \equiv \sin\frac{t_\beta(h+v)}{\sqrt{2}\, f}, \quad s_2 \equiv \sin\frac{(h+v)}{\sqrt{2}\, t_\beta f}, \quad s_3 \equiv \sin\frac{(h+v)(t_\beta^2+1)}{\sqrt{2}\, t_\beta f}$$

$$c_1 \equiv \cos\frac{t_\beta(h+v)}{\sqrt{2}\, f}, \quad c_2 \equiv \cos\frac{(h+v)}{\sqrt{2}\, t_\beta f}, \quad c_3 \equiv \cos\frac{(h+v)(t_\beta^2+1)}{\sqrt{2}\, t_\beta f}$$

The tree-level μ term:

$$-\mu^2\left(\Phi_1^{\dagger}\Phi_2 + h.c.\right) = -2\mu^2 f^2 s_\beta c_\beta \cos\left(\frac{\eta}{\sqrt{2}s_\beta c_\beta f}\right)\cos\left(\frac{\sqrt{H^\dagger H}}{s_\beta c_\beta f}\right)$$

The scalar potential:

$$V = -m^2 H^+ H + \lambda\left(H^+ H\right)^2 - \frac{1}{2}m_\eta^2\eta^2 + \lambda' H^+ H \eta^2 + \cdots$$

$$m^2 = m_0^2 - \frac{\mu^2}{s_\beta c_\beta}, \quad \lambda = \lambda_0 - \frac{\mu^2}{12 s_\beta^2 c_\beta^2 f^2}, \quad \lambda' = -\frac{\mu^2}{4 s_\beta^2 c_\beta^2 f^2}$$

m_0 and λ_0 are respectively the one-loop contributions to Higgs mass and quartic coupling.

$$m_0^2 = \frac{3}{8\pi^2}\left[\lambda_t^2 M_T^2 \ln\frac{\Lambda^2}{M_T^2} - \frac{g^2}{4}M_{W'}^2\ln\frac{\Lambda^2}{M_{W'}^2} - \frac{g^2}{8}(1+\tan^2\theta_W)M_{Z'}^2\ln\frac{\Lambda^2}{M_{Z'}^2}\right]$$

$$\lambda_0 = \frac{1}{3s_\beta^2 c_\beta^2}\frac{m_0^2}{f^2} + \frac{3}{16\pi^2}\left[\lambda_t^4\ln\frac{M_T^2}{m_t^2} - \frac{g^4}{8}\ln\frac{M_{W'}^2}{m_W^2} - \frac{g^4}{16}(1+\tan^2\theta_W)^2 M_{Z'}^2\ln\frac{M_{Z'}^2}{m_Z^2}\right]$$

from Kingman Cheung, PRD76, 035007(2007)

The parameters in Coleman-Weinberg potential:

$$f,\ x_\lambda^t,\ t_\beta,\ \mu,\ m_\eta,\ m_h,\ v$$

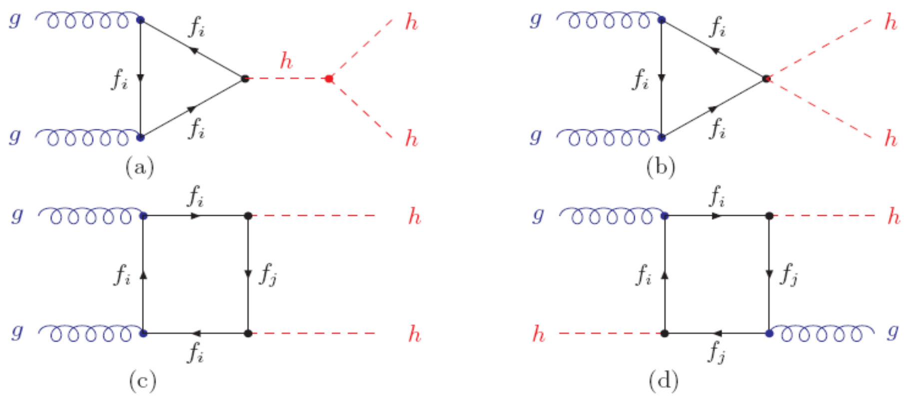
$$v^2 = \frac{m^2}{\lambda},\quad m_h^2 = 2m^2,\quad m_\eta^2 = \frac{\mu^2}{s_\beta c_\beta}\cos\left(\frac{v}{\sqrt{2}s_\beta c_\beta f}\right)$$

$$m^2 = m_0^2 - \frac{\mu^2}{s_\beta c_\beta},\quad \lambda = \lambda_0 - \frac{\mu^2}{12 s_\beta^2 c_\beta^2 f^2},\quad \lambda' = -\frac{\mu^2}{4 s_\beta^2 c_\beta^2 f^2}$$

$$v \simeq v_0\left[1 + \frac{v_0^2}{12f^2}\frac{t_\beta^4 - t_\beta^2 + 1}{t_\beta^2} - \frac{v_0^4}{180f^4}\frac{t_\beta^8 - t_\beta^6 + t_\beta^4 - t_\beta^2 + 1}{t_\beta^4}\right]$$

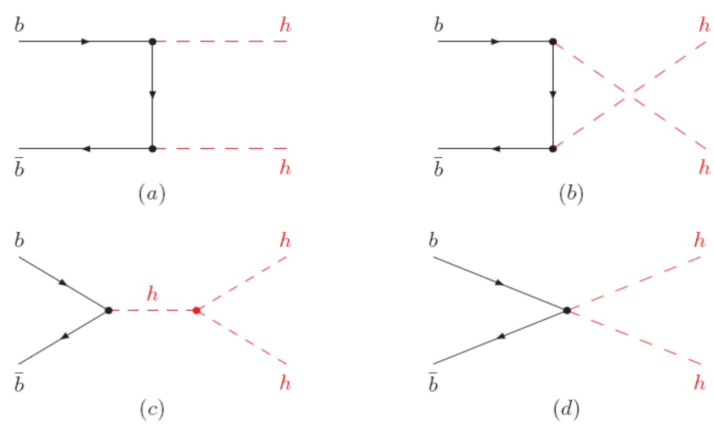
Higgs-pair Production and Decay at LHC (in SLHM)

gluon-gluon fusion

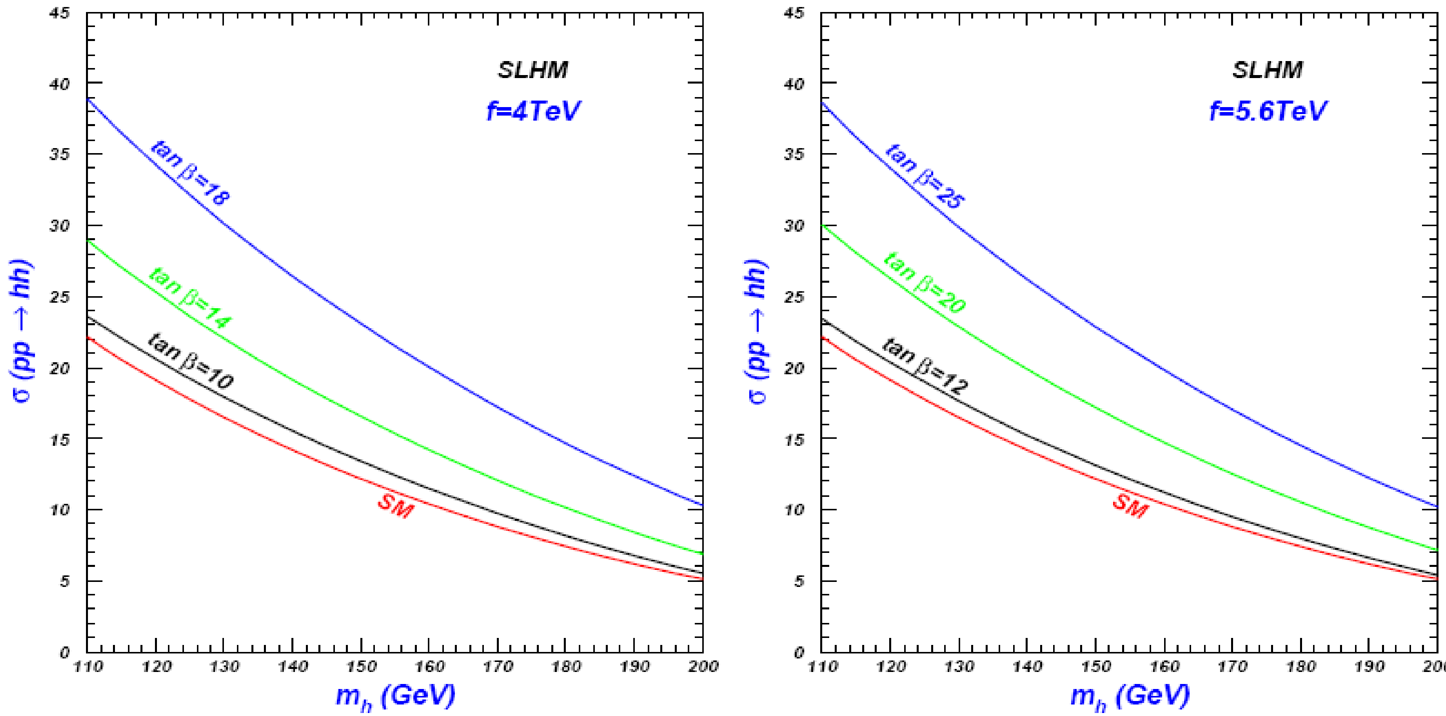


i, j =1, 2 with (f_1,f_2) denoting (t, T) or (d, D) or (s, S)

$b\bar{b}$ annihilation



Hadronic cross section of Higgs-pair production at the LHC versus the Higgs boson mass



The cross section can be significantly enhanced for a larger $\tan\beta$.

For the perturbation to be valid, $\tan\beta$ cannot be too large for fixed scale f.

Higgs Decays in Simplest Little Higgs Model

$h \to f\bar{f},\ WW,\ ZZ$

$$\Gamma(h \to XX) = \Gamma(h \to XX)_{SM} (g_{hXX} / g_{hXX}^{SM})^2$$

$h \to gg$

$$\mathcal{L}_{qua} = -\frac{m_t}{v} y_t \bar{t} t h - \frac{m_T}{v} y_T \bar{T} T h - \frac{m_D}{v} y_D \bar{D} D h - \frac{m_S}{v} y_S \bar{S} S h$$

$h \to \gamma\gamma$

$$\mathcal{L} = \mathcal{L}_{qua} + \frac{2m_W^2}{v} y_W W^+ W^- h + \frac{2m_{W'}^2}{v} y_{W'} W'^+ W'^- h$$

$h \to \eta\eta,\ Z\eta$

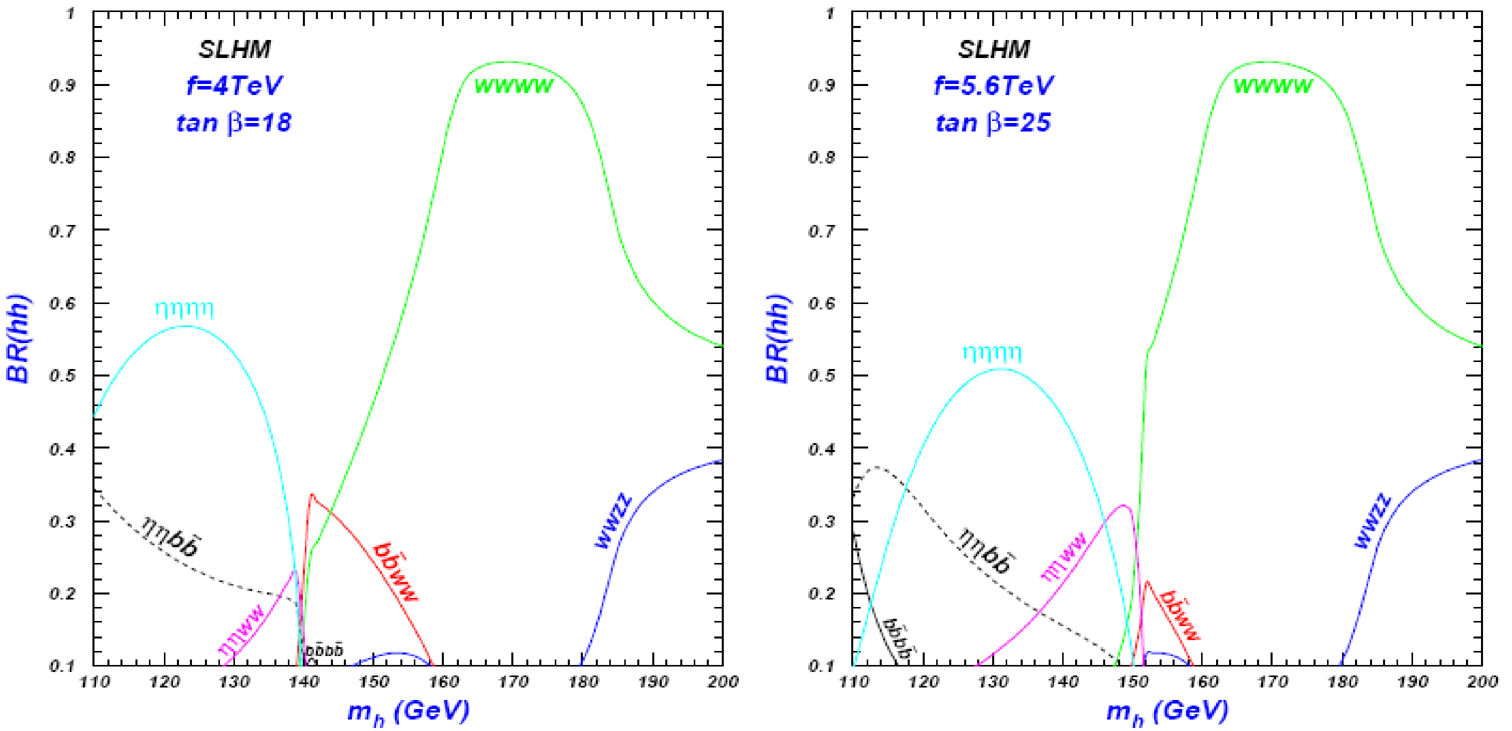
$$\Gamma(h \to \eta\eta) = \frac{\lambda'^2}{8\pi} \frac{v^2}{m_h} \sqrt{1 - x_\eta}$$

$$\Gamma(h \to Z\eta) = \frac{m_h^3}{32\pi f^2} \left(t_\beta - \frac{1}{t_\beta} \right)^2 \lambda^{3/2} \left(1, \frac{m_Z^2}{m_h^2}, \frac{m_Z^2}{m_h^2} \right)$$

$$x_\eta = 4m_\eta^2 / m_h^2, \quad \lambda(1, x, y) = (1 - x - y)^2 - 4xy$$

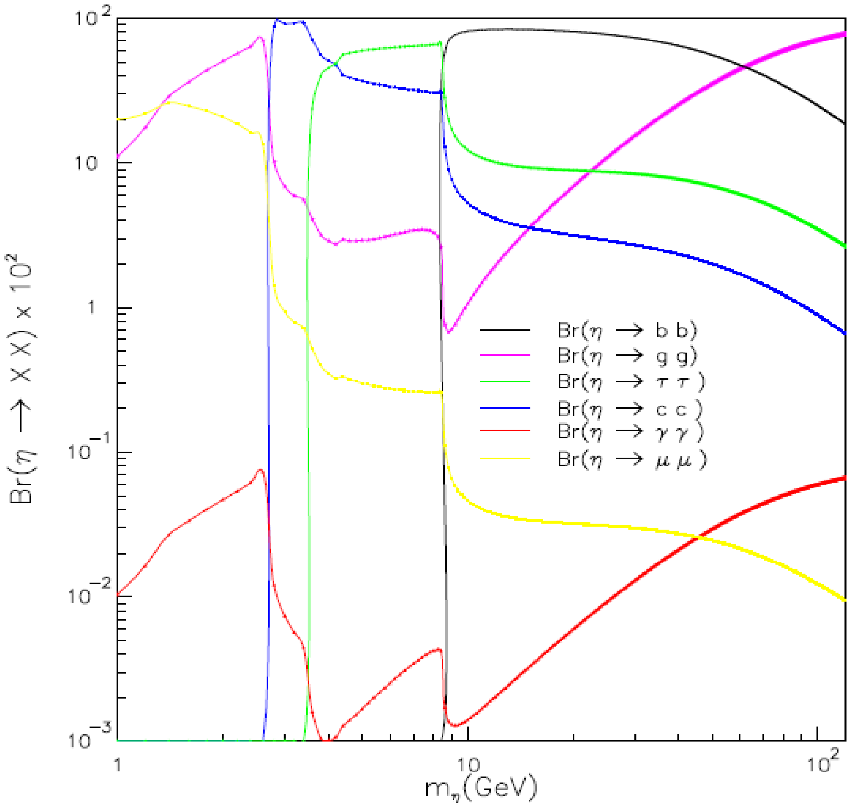
K. Cheung, J. Song, PRD 78, 055015 (2008)

The decay branching ratios (above 0.1) of Higgs-pair versus the Higgs boson mass



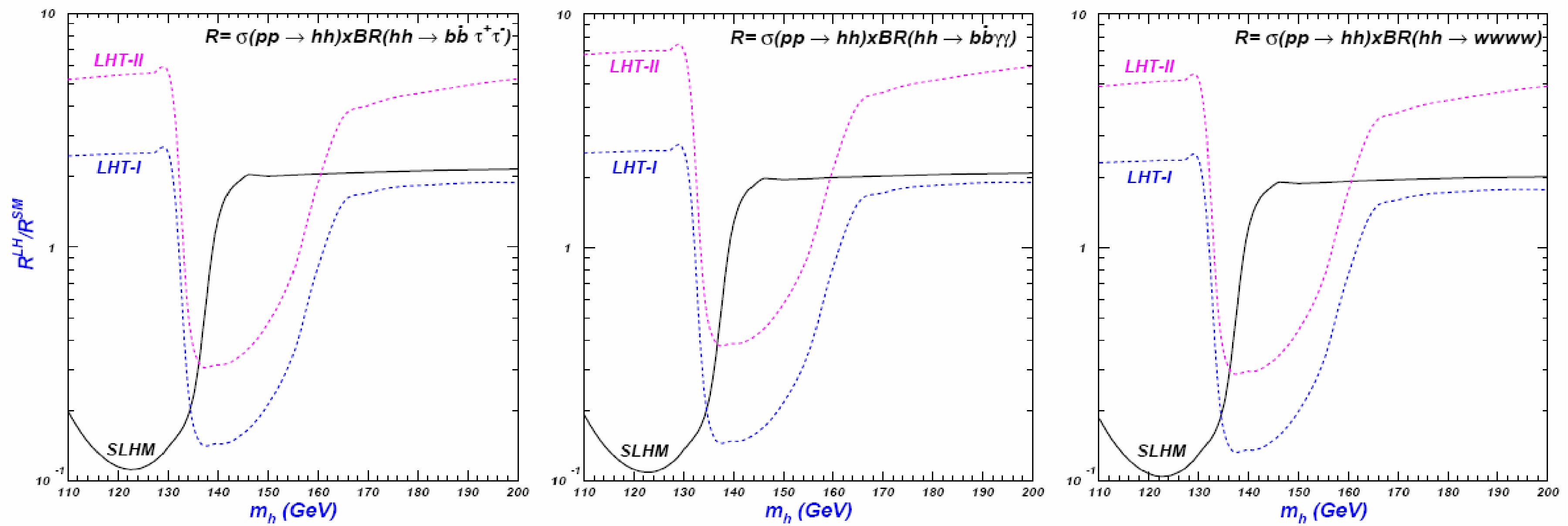
For $m_h \in [150GeV,\ 200GeV]$, the dominant decay channel is $hh \rightarrow WWWW$.

For $m_h < 140GeV$, the dominant decay channel is $hh \rightarrow \eta\eta\eta\eta$.



Branching ratio of η for $1\text{GeV} \le m_\eta \le 120$ GeV from Kingman Cheung *et al*., PRD78, 055015(2008)

The rates of different channels in LHT-I, LHT-II, and SLHM normalized to the SM prediction



For $m_h < 130GeV$, the rates of final states $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ can be enhanced sizably in LHT-I and LHT-II, but suppressed significantly in SLHM.

For $m_h \in [150GeV,\ 200GeV]$, the rate of $pp \to hh \to WWWW$ can be enhanced sizably in three models.

Conclusion

- **The Higgs-pair production rate in SLHM can be significantly larger than SM prediction.**

- **For a low Higgs mass, the dominant decay mode of Higgs-pair is** $hh \to \eta\eta\eta\eta$ **, while** $hh \to b\bar{b}\eta\eta$ **and** $hh \to b\bar{b}WW$ **may also have sizable ratios.**

- **For a light Higgs boson, the rate of** $pp \to hh \to b\bar{b}\tau^+\tau^-(b\bar{b}\gamma\gamma)$ **can be sizably enhanced in LHT-I/II but severely suppressed in SLHM; the rate of** $pp \to hh \to WWWW$ **can be sizably enhanced in both LHT-I/II and SLHM for an intermediately heavy Higgs.**

Thanks!