Higgs Production and Decay in Little Higgs Models with T-parity

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in collaboration with
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hep-ph/0602211

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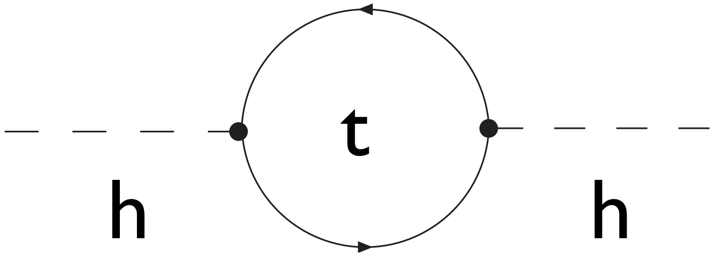
Motivation

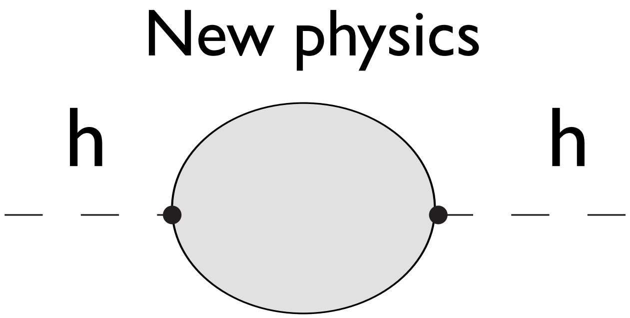
- Naturalness problem in the Standard Model



$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2 \sim (100\ \mathrm{GeV})^2\ ?$$

$\longrightarrow$ $\Lambda \sim 1\ \mathrm{TeV}$ or fine tuning

not large enough to suppress
dangerous higher dimensional operators



$$\delta m_h^2 \sim - \frac{y_t^2}{16\pi^2}\Lambda^2$$

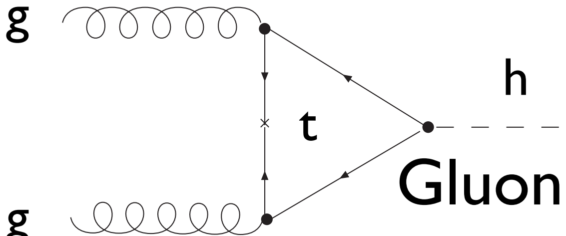
Cancellation?

e.g. Supersymmetry
Little Higgs

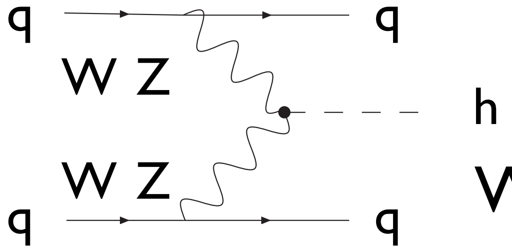
or String Landscape...?

Can we somehow test the "cancellation" experimentally?

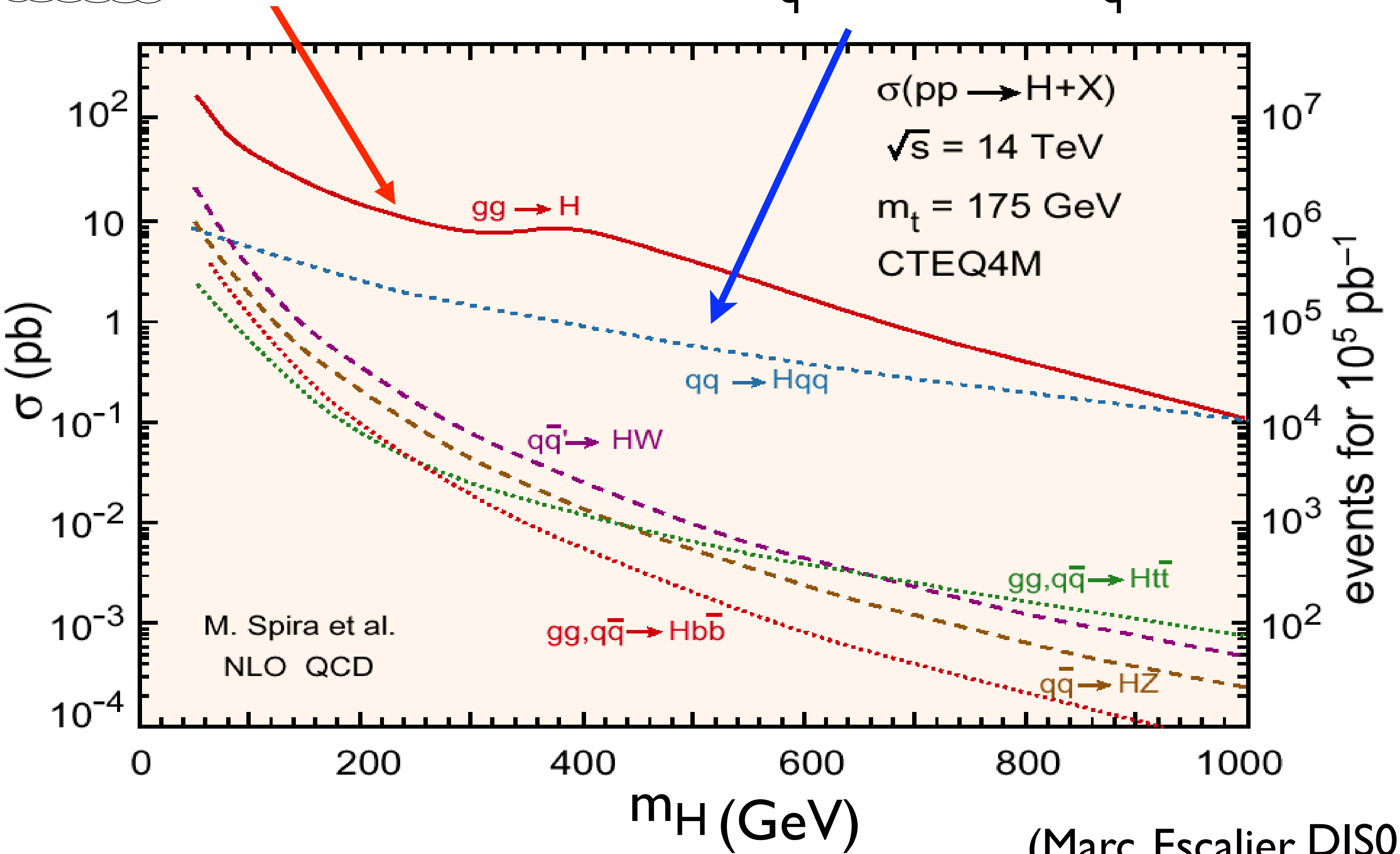
Let me remind you of SM Higgs production at LHC....



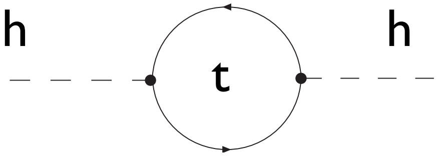
Gluon fusion



Weak boson fusion



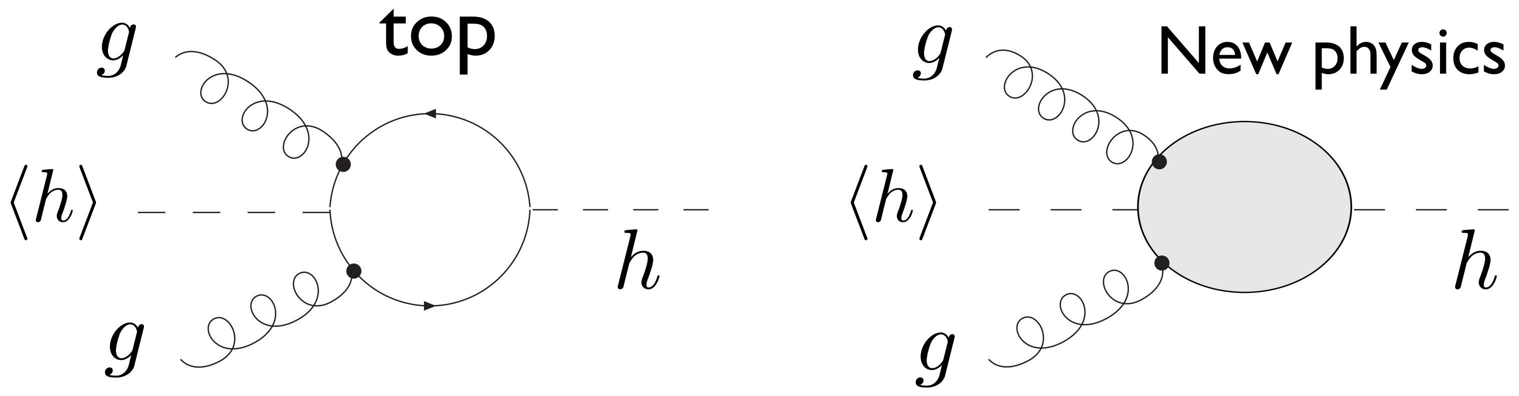
(Marc Escalier DIS05)



Same Higgs-top interaction induces gluon fusion

If there is “New physics” which cancels the Λ^2 induced by top to solve the naturalness problem,

the “New Physics” likely affects gluon fusion process.



Since gluon fusion process is one of important production mechanisms of the SM Higgs, a study of the Higgs production and decay in this kind of “New Physics” at LHC will be very important.

“New Physics” → Little Higgs Model

Outline

- Motivation
- Littlest Higgs Model with T-parity
- New Higgs Interactions and gluon fusion process $(gg \to h)$ at one-loop level
- Other Higgs production and decay processes
- Summary

Littlest Higgs model with T-parity

Little Higgs mechanism (collective symmetry breaking)

Higgs boson is a pseudo Nambu-Goldstone boson which is light because of approximate global symmetries.

Global symmetries are broken explicitly by two sets of interactions.

Arkani-Hamed, Cohen, Georgi hep-ph/0105239

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

The Higgs is a massless when either set of the interactions is absent:

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

$$\sim [O(100)\mathrm{GeV}]^2 \text{ for } \Lambda \sim 10 \text{ TeV}$$

Littlest Higgs models

Arkani-Hamed, Cohen, Katz, Nelson hep-ph/0206021

SU(5)/SO(5) non-linear sigma model

$$SU(5) \xrightarrow[\Sigma_0]{f} SO(5)$$

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

The VEV breaks $\underset{\lambda_1 \mathcal{L}_1}{[SU(2) \times U(1)]_1} \times \underset{\lambda_2 \mathcal{L}_2}{[SU(2) \times U(1)]_2}$ to $SU(2) \times U(1)$

$$\Sigma = \exp(i\Pi/f)\Sigma_0$$

$$\mathbf{1_0} \oplus \mathbf{3_0} \oplus \underline{\mathbf{2_{\pm 1/2}}} \oplus \mathbf{3_{\pm 1}}$$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \Phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \Phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

Higgs is exact NG boson under either SU(3)

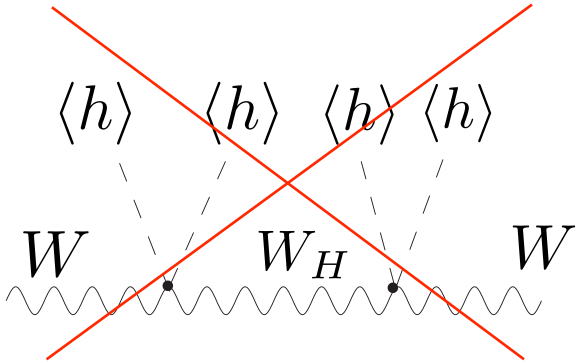
T-parity

Cheng, Low hep-ph/0308199

$$SU(2)_1 \times U(1)_1 \leftrightarrow SU(2)_2 \times U(1)_2$$

$$\text{SM particles} \to +\text{SM particles}$$

$$(W_H,\ Z_H,\ A_H,\ \Phi) \to -(W_H,\ Z_H,\ A_H,\ \Phi)$$

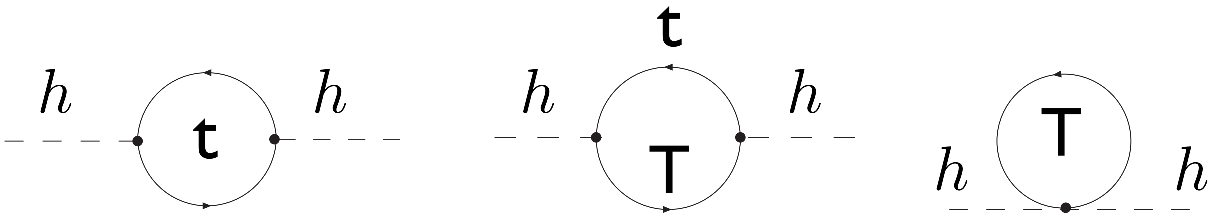


- Contributions to EW observables are loop suppressed. <u>The new particle scale f can be much lower than 1 TeV.</u>
- The lightest T-odd particle can be a good dark matter candidate

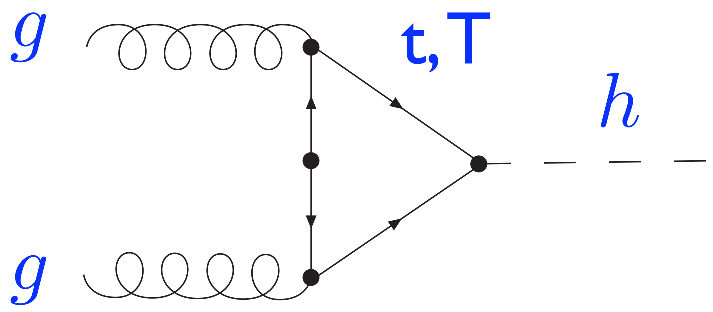
New Higgs interactions and gluon fusion process at 1-loop level in the Little Higgs model with T-parity

Top-Yukawa interaction

$$\chi_i = (q_i, T_i),\ \ \mathrm{SU}(3)_i\ \ i = 1, 2$$



Λ^2 is canceled !



$$\frac{\delta A(\text{top sector})}{A(\text{top in SM})} = -\frac{3}{4}\frac{v_{SM}^2}{f^2}$$

for small Higgs mass

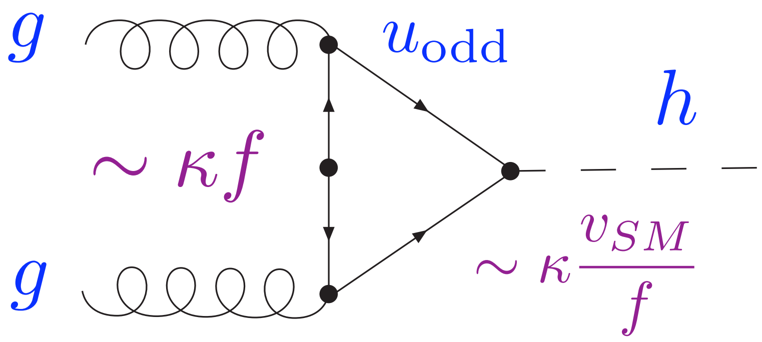
T-odd Yukawa interaction

T-parity

$$q_1 \leftrightarrow q_2$$

T-even: SM doublet

T-odd: T-parity partner: need a heavy mass



$$\frac{A(\text{T odd fermions})}{A(\text{top in SM})} = -\frac{1}{4}\frac{v_{SM}^2}{f^2} \times 3$$

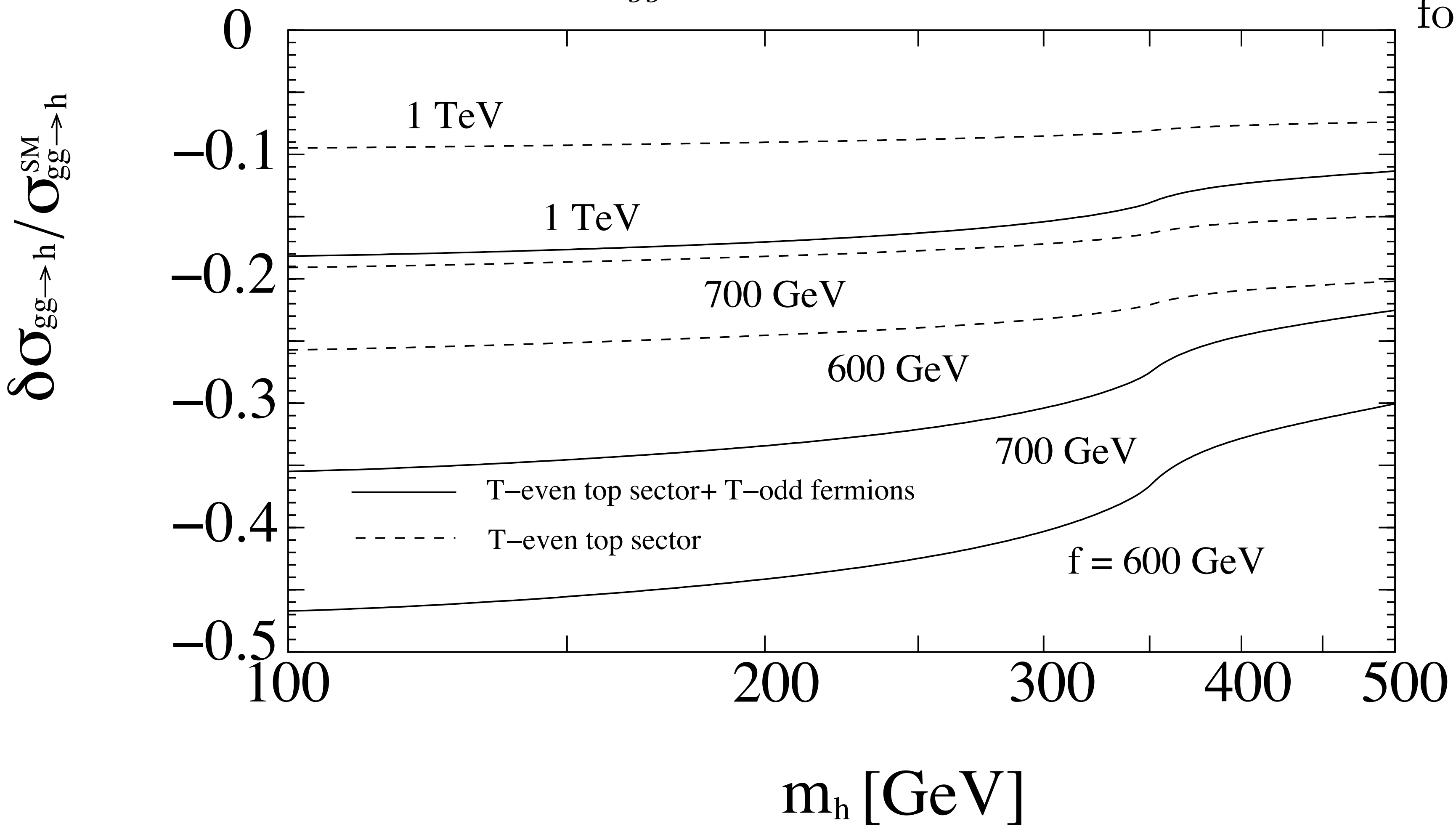
for small Higgs mass

Correction to Higgs production cross section via gluon fusion process

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \quad (\text{where } \delta\sigma_{gg\to h} = \sigma^{\rm LH}_{gg\to h} - \sigma^{\rm SM}_{gg\to h})$$

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \simeq -3\frac{v_{SM}^2}{f^2} \simeq \begin{cases} -37\% \text{ for } f = 700 \text{ GeV}, \\ -18\% \text{ for } f = 1000 \text{ GeV}. \end{cases}$$

for small m_h

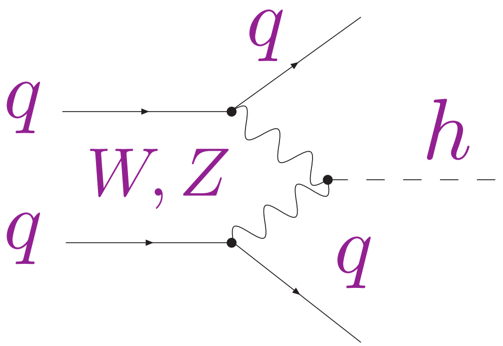


The production cross section can be significantly suppressed

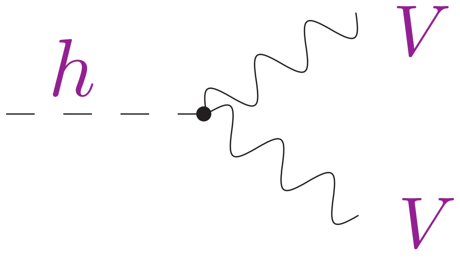
Other Higgs production and decay processes

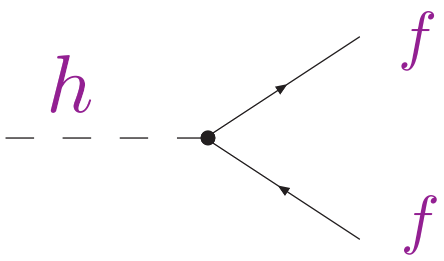
Production

weak boson fusion (VV)



Decay





Higgs interactions with SM gauge bosons (V=W, Z)

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} \simeq 1-\frac{1}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.97 & \text{for } f=700\ \text{GeV},\\ 0.98 & \text{for } f=1000\ \text{GeV}.\end{cases}$$

Up-type quark Yukawas (1st and 2nd generations)

$$\frac{g_{huu}}{g_{huu}^{\rm SM}} \simeq 1-\frac{3}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.90 & \text{for } f=700\ \text{GeV},\\ 0.95 & \text{for } f=1000\ \text{GeV}.\end{cases}$$

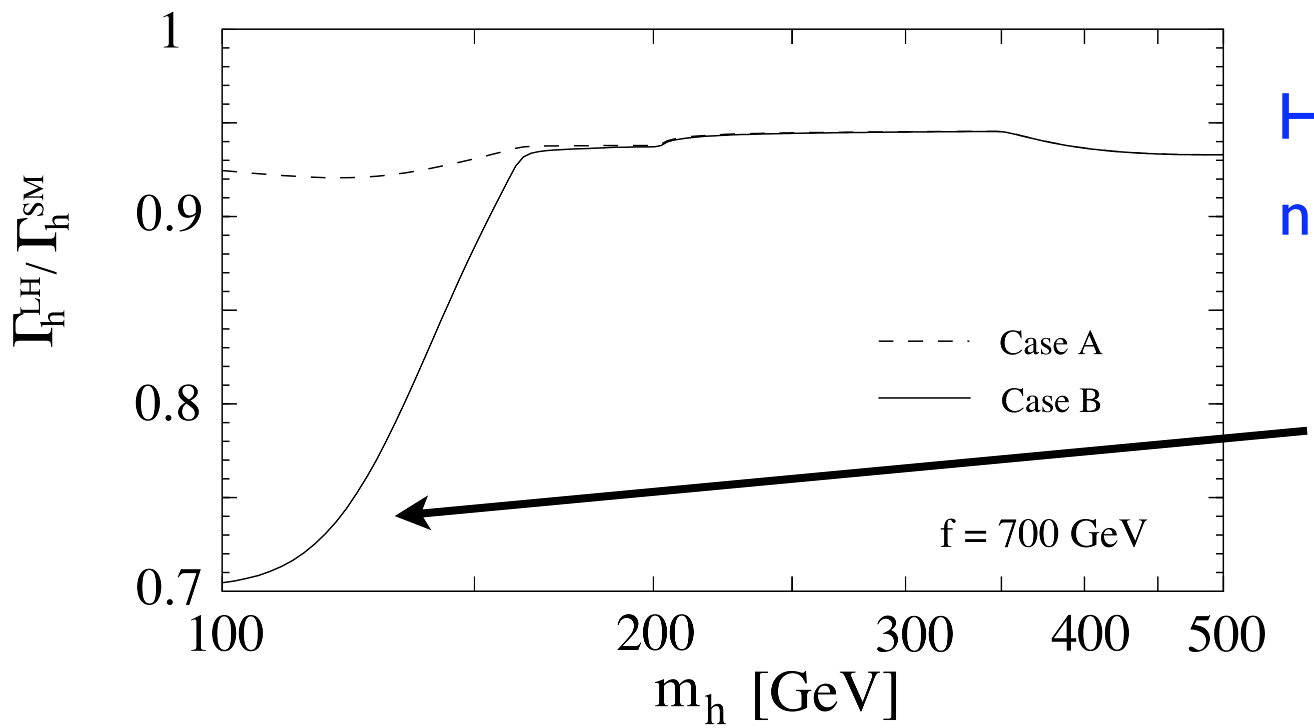
Down-type quark Yukawas

$$\frac{g_{hdd}}{g_{hdd}^{\rm SM}} \simeq 1-\frac{1}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.97 & \text{for } f=700\ \text{GeV},\\ 0.99 & \text{for } f=1000\ \text{GeV},\end{cases} \quad \text{for Case A,}$$

$$\simeq 1-\frac{5}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.84 & \text{for } f=700\ \text{GeV},\\ 0.92 & \text{for } f=1000\ \text{GeV},\end{cases} \quad \underline{\text{for Case B.}}$$

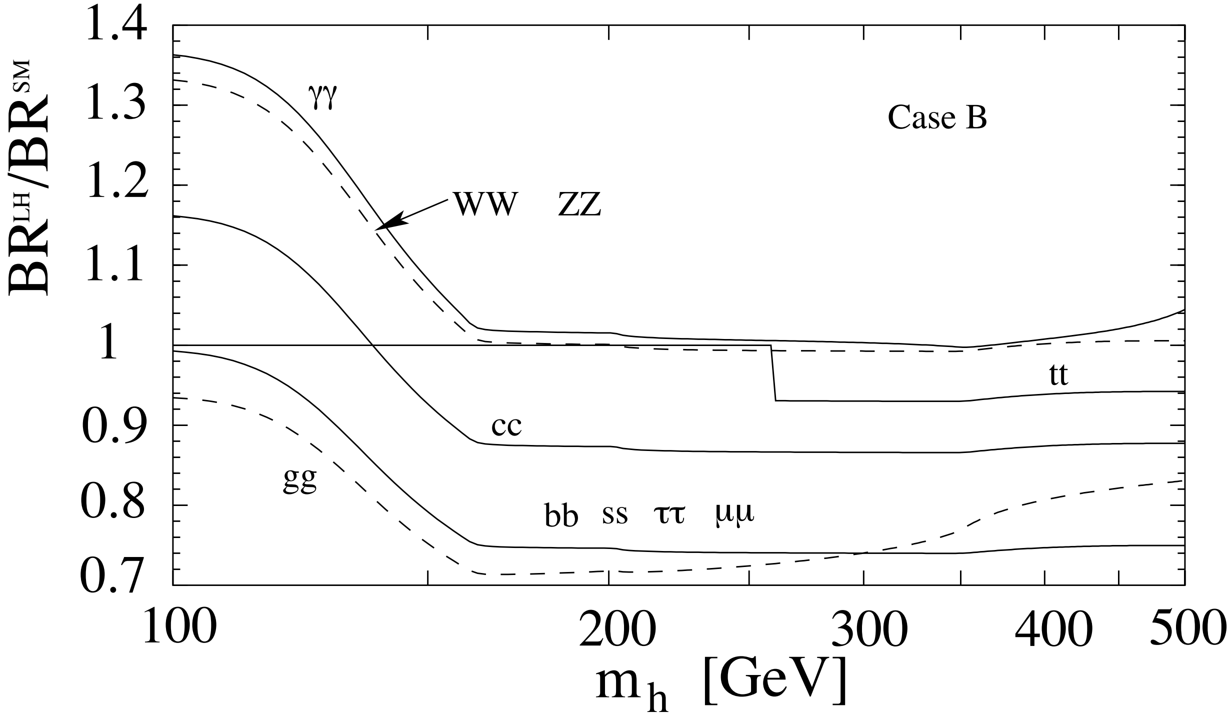
(We consider the same Yukawa structures in lepton sector,
as in quark sector.)

all Higgs interactions are modified



Higgs total decay width normalized by the SM value

$b\bar{b}, \ \tau^+\tau^-$ decay modes are dominant.



Higgs decay branching ratios, normalized by the SM values

In Case B, because of the largely reduced total decay width in small Higgs mass region, some of the Higgs boson decay branching ratios are increased.

$$R_{\sigma(X)} = \frac{\sigma^{\rm LH}(X)}{\sigma^{\rm SM}(X)} \qquad R_{{\rm BR}(Y)} = \frac{{\rm BR}^{\rm LH}(Y)}{{\rm BR}^{\rm SM}(Y)}$$

$$R_{\sigma(X)} \times R_{{\rm BR}(Y)} \qquad \text{for } f = (600,\ 700,\ 1000)\ \text{GeV}$$

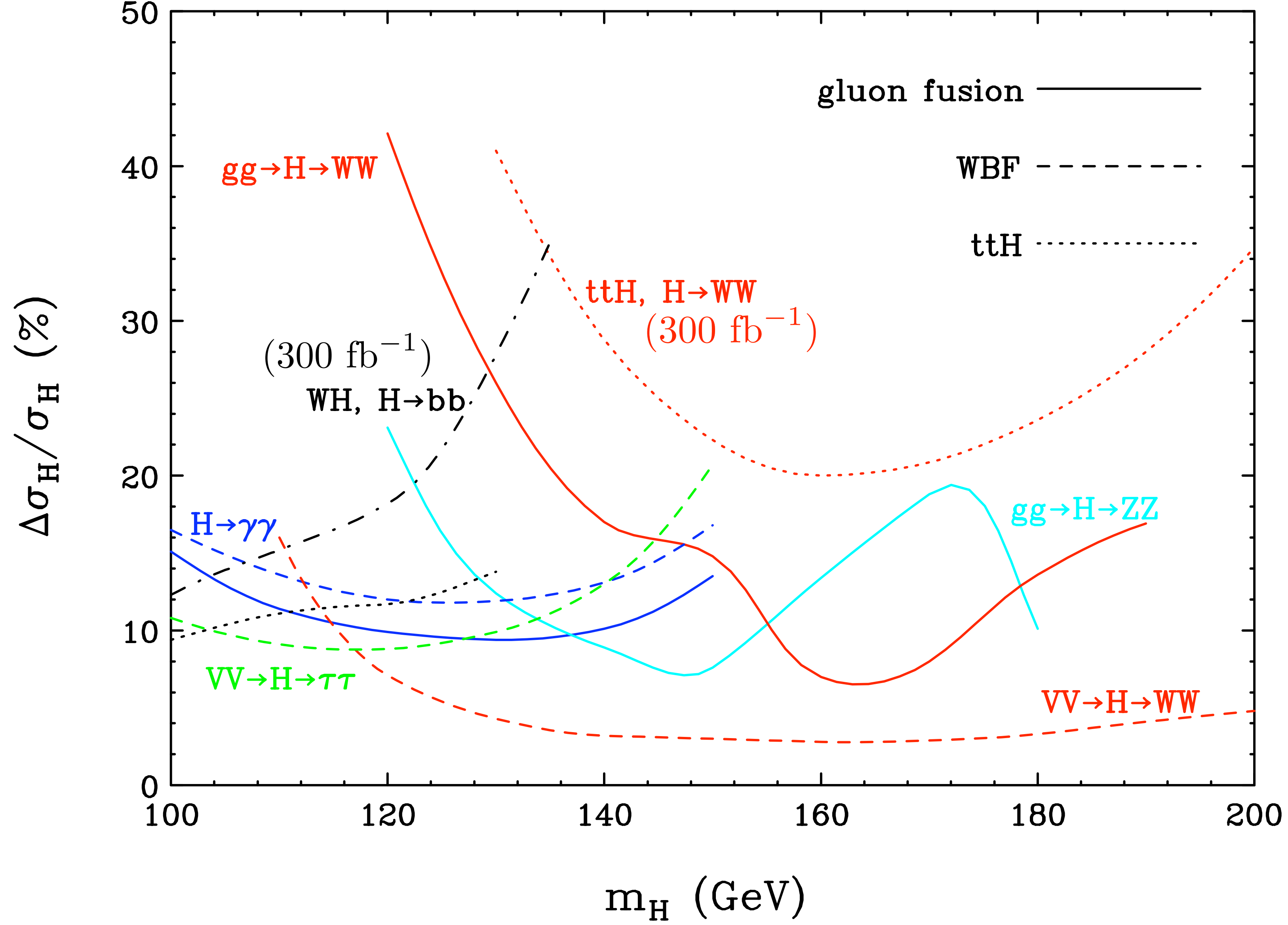
$m_h = 120$ GeV		$R_{{\rm BR}(\gamma\gamma)}$	$R_{{\rm BR}(\tau\tau)}$	$R_{{\rm BR}(b\bar{b})}$	$R_{{\rm BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	0.57, 0.68, 0.84	0.56, 0.67, 0.83	–	0.55, 0.66, 0.83
	(Case B)	0.81, 0.86, 0.93	0.51, 0.63, 0.81	–	0.78, 0.84, 0.92
$R_{\sigma(VV)}$	(Case A)	0.97, 0.98, 0.99	0.95, 0.96, 0.98	–	0.94, 0.96, 0.98
	(Case B)	1.34, 1.22, 1.09	0.84, 0.89, 0.95	–	1.30, 1.19, 1.08
$R_{\sigma(t\bar{t}h)}$	(Case A)	–	0.87, 0.90, 0.95	0.87, 0.90, 0.95	–
	(Case B)	–	0.77, 0.83, 0.92	0.77, 0.83, 0.92	–
$R_{\sigma(Vh)}$	(Case A)	0.97, 0.98, 0.99	–	0.95, 0.96, 0.98	–
	(Case B)	1.34, 1.22, 1.09	–	0.84, 0.89, 0.95	–

$m_h = 200$ GeV		$R_{{\rm BR}(\gamma\gamma)}$	$R_{{\rm BR}(\tau\tau)}$	$R_{{\rm BR}(b\bar{b})}$	$R_{{\rm BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	–	–	–	0.55, 0.67, 0.83
	(Case B)	–	–	–	0.56, 0.67, 0.83
$R_{\sigma(VV)}$	(Case A)	–	–	–	0.90, 0.94, 0.97
	(Case B)	–	–	–	0.90, 0.94, 0.97

- Higgs production via gluon fusion is suppressed.
- $\gamma\gamma,\ VV$ decay modes via weak boson fusion can be enhanced in small Higgs mass region in Case B.

Expected relative error on the determination of $\sigma \times \mathrm{BR}$ for various Higgs search channels at the LHC with 200 fb^{-1} of data

Zeppenfeld hep-ph/0203123



Needless to say, the improvement of the theoretical calculation is always important.

Summary

Littlest Higgs model with T-parity

★The fermionic partner of top quark (T) cancels the large quantum correction to the Higgs mass parameter.

➡solve the "naturalness (little hierarchy) problem".

★T-parity avoids strong constraints from EW precision data.

➡new particle mass scale f much smaller than 1 TeV is still allowed.

★T-parity introduces new T-odd fermions which need the heavy masses.

➡ the mass terms also generate new Higgs interactions.

T and T-odd fermions affect significantly Higgs production via gluon fusion process if the scale f is smaller than 1 TeV.

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \simeq -0.45\ (-0.35, -0.2)\ \text{for}\ f = 600\ (700, 1000)\ \text{GeV}$$

In new physics which cancels the large correction to Higgs mass induced by top quark, the Higgs production via gluon fusion will be modified by the new physics contributions, in general.

Summary

★ All Higgs interactions are modified because the Higgs is originated from the non-linear sigma model field.

➡ all other Higgs production channels and decay modes are modified from the SM values

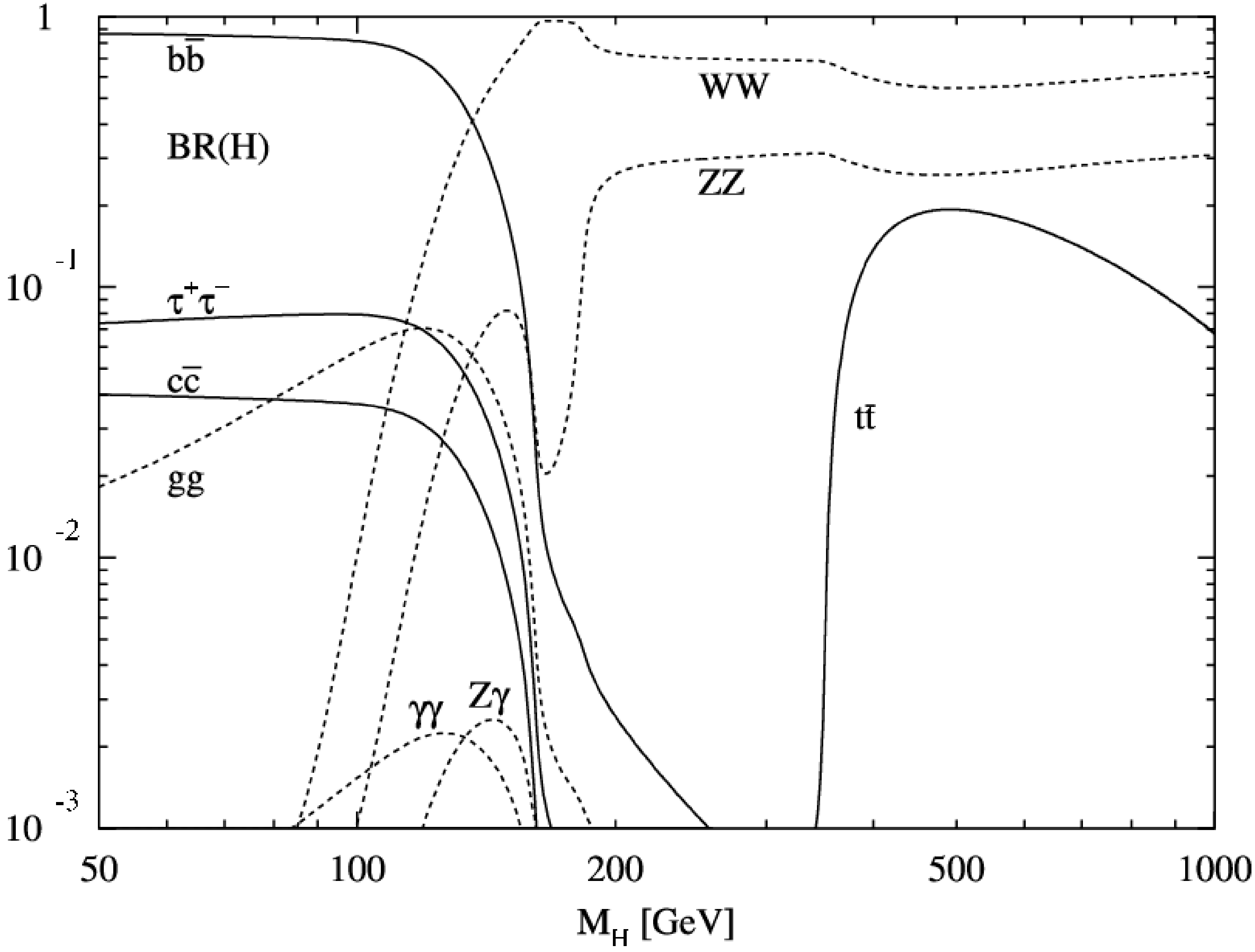
$$\frac{\sigma(VV)\times \mathrm{BR}(\gamma\gamma\ ,VV)_{\mathrm{LH}}}{\sigma(VV)\times \mathrm{BR}(\gamma\gamma\ ,VV)_{\mathrm{SM}}} \sim 1 \text{ in Case A}$$

$$\sim 1.3 \text{ for } m_h = 120 \text{ GeV and } f = 600 \text{ GeV in Case B.}$$

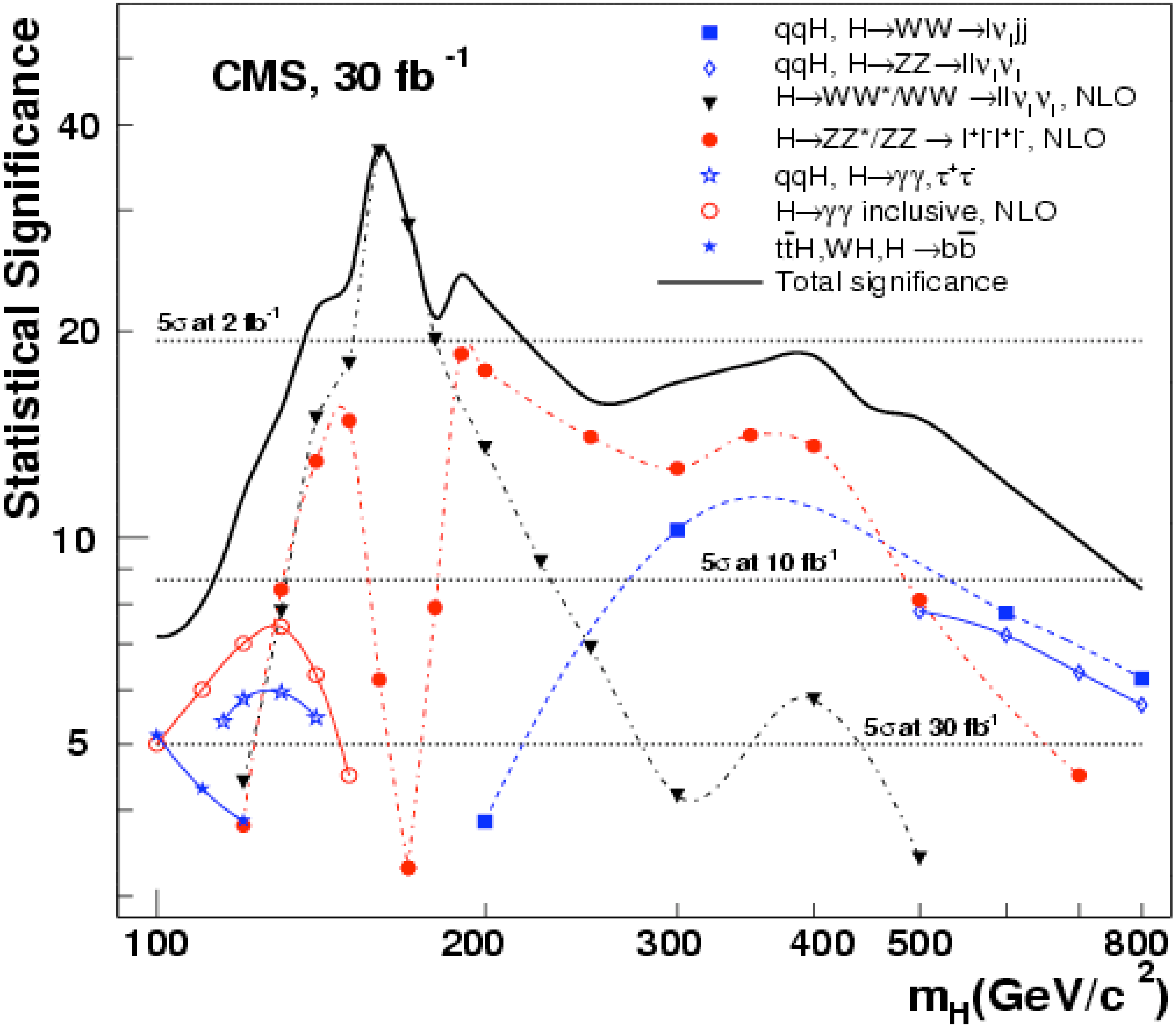
The discovery modes of Higgs boson produced via weak boson fusion will become more important in the LH than in the SM.

Searches for Higgs in various detection modes at the LHC will be very important to reveal the mechanism which solves the naturalness problem in the SM.

SM Higgs decay branching ratios



SM Higgs discovery potential



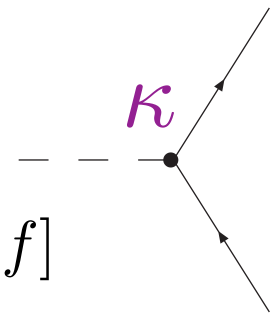
T-parity: $q_i \ (i = 1, 2)$ doublet under SU(2)$_i$

T-parity

$$q_1 \leftrightarrow q_2$$

T-even: SM doublet

T-odd: T-parity partner: <u>need a heavy mass</u>



$\Psi_1 = (q_1, 0, 0, 0)^{\mathrm{T}}, \ \Psi_2 = (0, 0, 0, q_2)^{\mathrm{T}}$

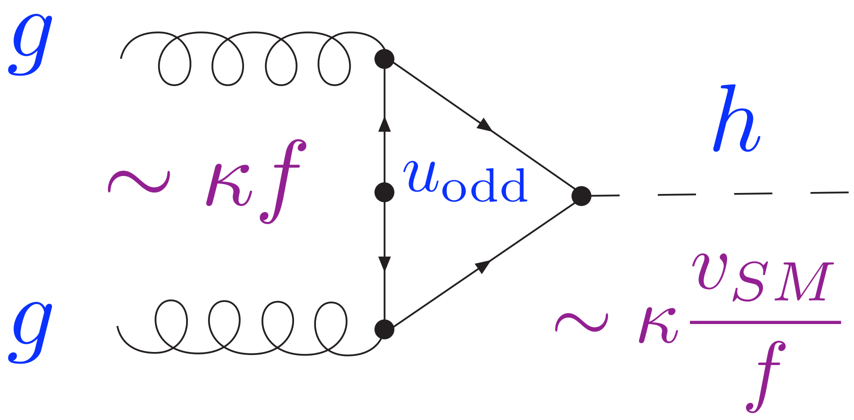
doublets in incomplete SU(5) multiplets

$\xi = \exp[i\Pi/f]$

$\Psi_c = (\tilde{q}_R, \chi_R, q_R)^{\mathrm{T}}$

<u>Note ξ contains Higgs boson h</u>

SO(5) multiplet transforming nonlinearly under SU(5)



$$\frac{A(\text{T odd fermions})}{A(\text{top in SM})} = -\frac{1}{4}\frac{v_{SM}^2}{f^2} \ \times 3$$

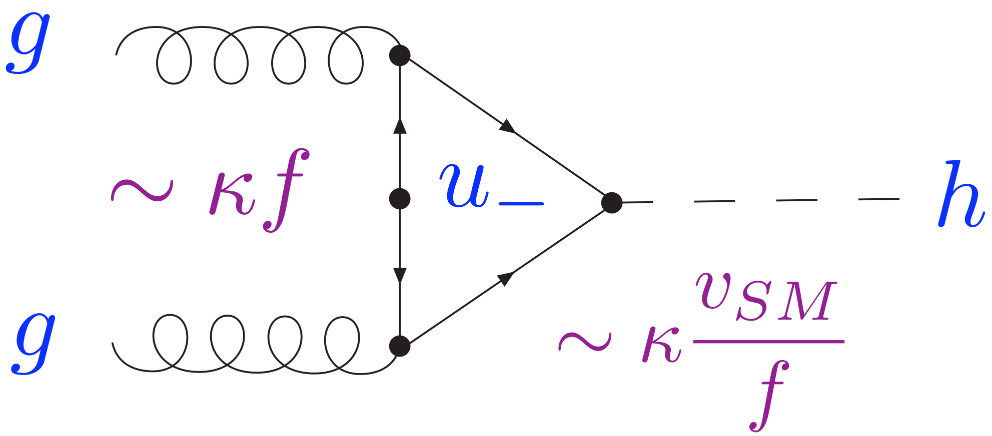
$\mathcal{L}_{\rm odd}$ contains new Higgs interactions:

$$\mathcal{L}_{\rm odd} \simeq -\sqrt{2}\kappa f\left[\bar{d}_{L-}d_{R-} + (1 - \frac{v^2}{8f^2})\bar{u}_{L-}u_{R-}\right] + \frac{\kappa v}{2\sqrt{2}f}h\bar{u}_{L-}u_{R-} + \cdots$$

$$q_- = -\sigma_2 \begin{pmatrix} u_{L_-} \\ d_{L_-} \end{pmatrix}$$

q_- gets the Dirac mass with q_R

This Higgs interaction is important for Higgs production via gluon fusion process



Top Yukawa interaction

SU(3)$_1$ SU(3)$_2$

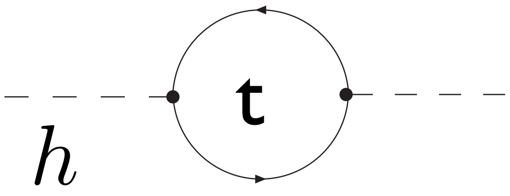
$$\mathcal{L}_t = -\frac{\lambda_1 f}{2\sqrt{2}}\epsilon_{ijk}\epsilon_{xy}\left[(\bar{Q}_1)_i\Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]u_R$$

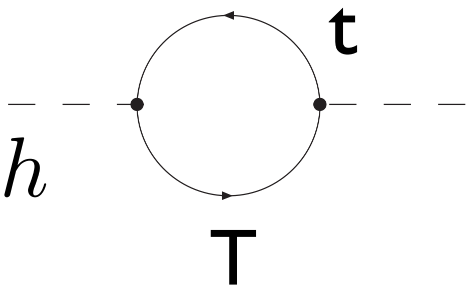
$$-\lambda_2 f\left(\bar{U}_1 U_{R_1} + \bar{U}_2 U_{R_2}\right) + \text{h.c.}$$

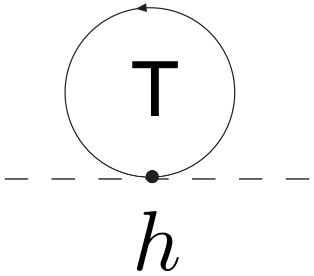
i,j,k summed over 1,2, 3
x,y summed over 4,5

$$Q_1 = (q_1, U_1, 0, 0)^{\mathrm{T}}, \quad Q_2 = (0, 0, U_2, q_2)^{\mathrm{T}}$$

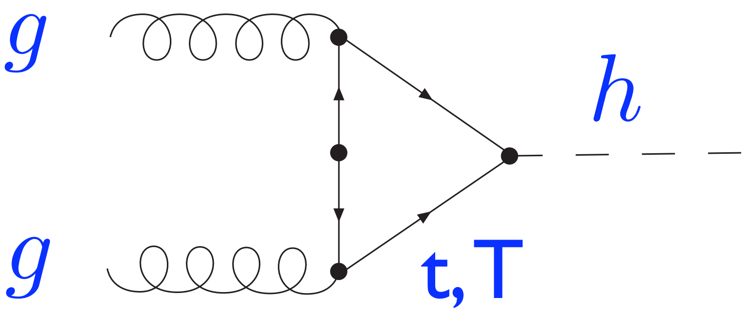
$$\Sigma \xrightarrow{\mathsf{T}} \tilde{\Sigma} \equiv \Sigma_0 \Omega \Sigma^\dagger \Omega \Sigma_0$$







The large quadratic divergence induced by top is canceled by the heavy fermionic partner of the top-quark, T



$$\frac{\delta A(\text{top sector})}{A(\text{top in SM})} = -\frac{3}{4}\frac{v_{SM}^2}{f^2}$$

Top Yukawa interaction

SU(3)$_1$ SU(3)$_2$

$$\mathcal{L}_t = -\frac{\lambda_1 f}{2\sqrt{2}}\epsilon_{ijk}\epsilon_{xy}\left[(\bar{Q}_1)_i\Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]u_R$$

$$-\lambda_2 f\left(\bar{U}_1 U_{R_1} + \bar{U}_2 U_{R_2}\right) + \text{h.c.}$$

i,j,k summed over 1,2, 3

x,y summed over 4,5

$$Q_1 = (q_1, U_1, 0, 0)^{\mathrm{T}}, \quad Q_2 = (0, 0, U_2, q_2)^{\mathrm{T}} \qquad \Sigma \xrightarrow{\mathrm{T}} \tilde{\Sigma} \equiv \Sigma_0\Omega\Sigma^\dagger\Omega\Sigma_0$$

$$m_t \simeq \frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}v_{SM} \qquad m_{T_+} \simeq \sqrt{\lambda_1^2+\lambda_2^2}f$$

$$m_{T_-} = \lambda_2 f$$

Top quark and T-even partner of top quark have the Yukawa interactions.

$$\mathcal{L}_{\text{Yukawa}} = -g_{htt}h\bar{t}t - g_{hTT}h\bar{T}_+T_+$$

$$g_{htt} \simeq \frac{m_t}{v_{SM}}\left\{1 - \frac{3+2R^2+3R^4}{4(1+R^2)^2}\frac{v_{SM}^2}{f^2} + \cdots\right\} \qquad g_{hTT} \simeq -\frac{m_t}{v_{SM}}\frac{R}{1+R^2}\frac{v_{SM}}{f}$$

$$R = \lambda_1/\lambda_2$$

Top Yukawa is modified, and T+ has the Yukawa coupling

Down-type quark Yukawa couplings

$$\mathcal{L}_{\rm down} = \frac{i\lambda_d f}{2\sqrt{2}} \epsilon_{ij}\epsilon_{xyz} \left[(\bar{\Psi}'_2)_x \Sigma_{iy}\Sigma_{jz} X - (\bar{\Psi}'_1 \Sigma_0)_x \tilde{\Sigma}_{iy}\tilde{\Sigma}_{jz}\tilde{X} \right] d_R$$

$$\Psi'_1 = (-\sigma_2 q_1, 0, 0, 0)^{\rm T}, \Psi'_2 = (0,0,0,-\sigma_2 q_2)^{\rm T}$$

In order to be gauge invariant, X has to be a singlet under SU(2) and its U(1) charges have to be $(Y_1, Y_2) = (-1/10, 1/10)$.

Here we consider the following two cases:

Jay Hubisz

$X = (\Sigma_{33})^{-1/4}$ (denoted as Case A)

$X = (\Sigma_{33}^\dagger)^{1/4}$ (denoted as Case B)

<u>Down-type quark Yukawa couplings are modified from those in the SM</u>

$$\frac{g_{hdd}}{g_{hdd}^{\rm SM}} \simeq 1 - \frac{1}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.97 & \text{for } f = 700 \text{ GeV}, \\ 0.99 & \text{for } f = 1000 \text{ GeV}, \end{cases} \quad \text{for Case A},$$

$$\simeq 1 - \frac{5}{4}\frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.84 & \text{for } f = 700 \text{ GeV}, \\ 0.92 & \text{for } f = 1000 \text{ GeV}, \end{cases} \quad \text{for Case B}.$$

<u>The down-type Yukawa couplings can be significantly reduced in Case B.</u>

We consider the same Yukawa structures in lepton sector, as in quark sector.