

# Higgs Phenomenology in Littlest Higgs Model with T-parity

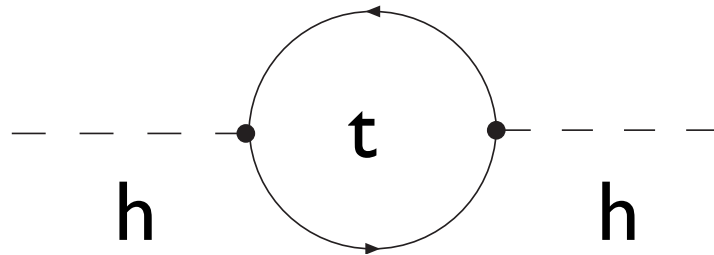
Kazuhiro Tobe (Michigan State University)

in collaboration with  
C.-R. Chen and C.-P. Yuan  
hep-ph/0602211

Pheno 06@Madison, May, 2006

# Motivation

## ● Naturalness problem in the Standard Model

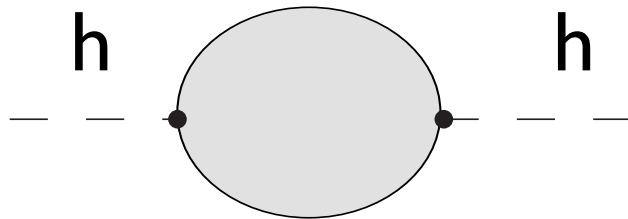


$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2} \Lambda^2 \sim (100 \text{ GeV})^2 ?$$

→  $\Lambda \sim 1 \text{ TeV}$  or fine tuning

not large enough to suppress  
dangerous higher dimensional operators

New physics



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

Cancellation?

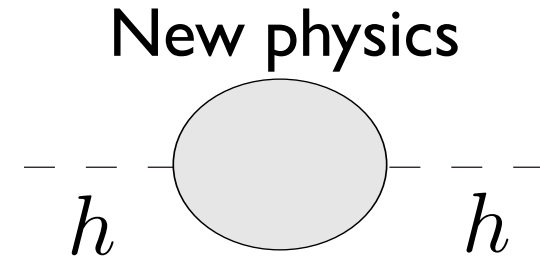
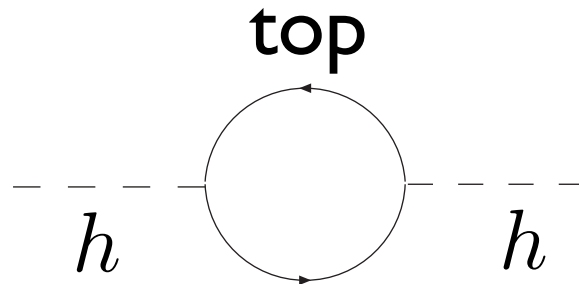
e.g. Supersymmetry

Little Higgs

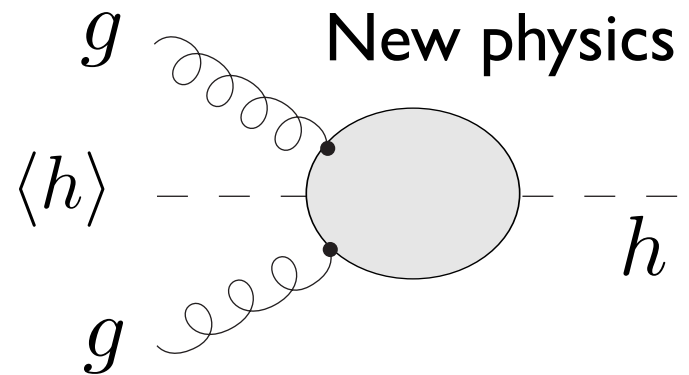
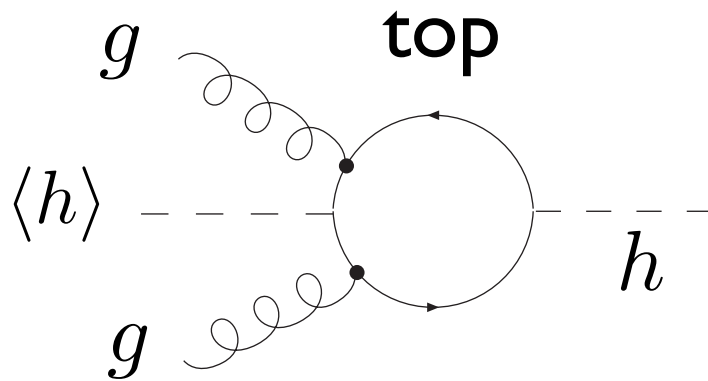
or String Landscape...?

Can we test the “cancellation” experimentally?

If there is “New physics” which cancels the  $\Lambda^2$  induced by top,



the “New Physics” likely affects gluon fusion process.



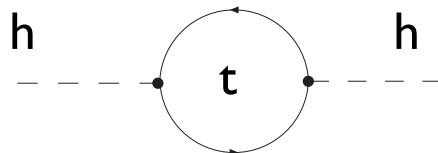
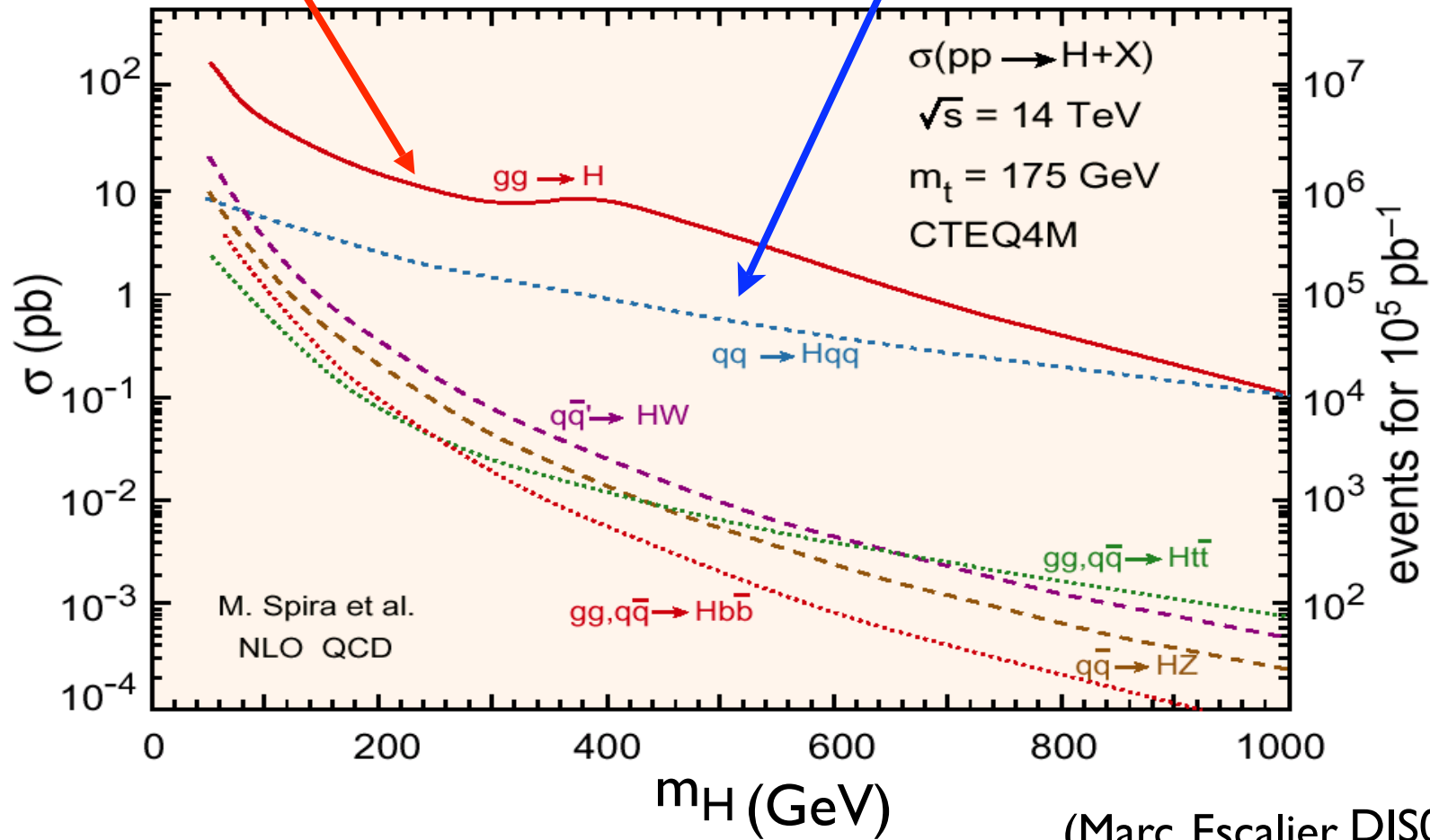
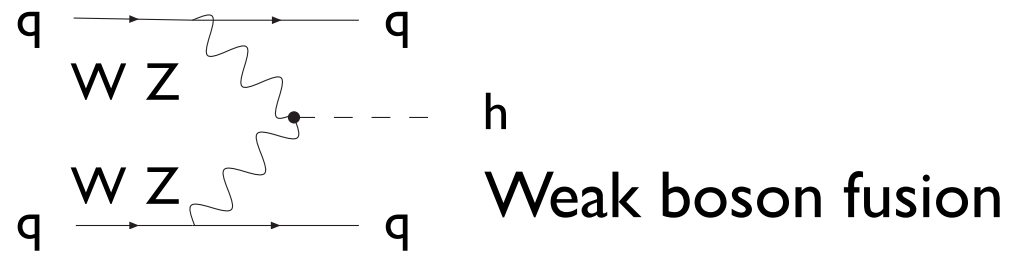
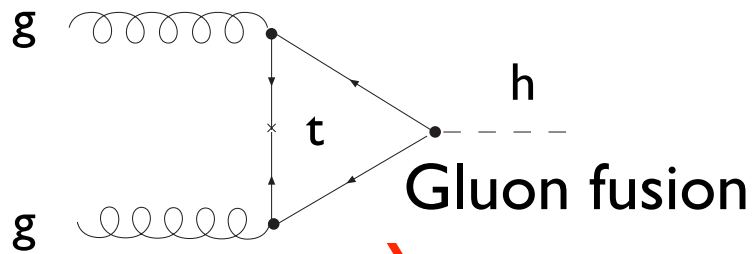
Since gluon fusion process is one of important production mechanisms of the SM Higgs, a study of the Higgs production and decay in this kind of “New Physics” at LHC will be very important.

“New Physics”



Little Higgs Model

# Remember SM Higgs production at LHC....



Higgs-top interaction induces gluon fusion

# Outline

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

# Littlest Higgs model with T-parity

# Littlest Higgs model with T-parity

## Little Higgs mechanism (collective symmetry breaking)

- Higgs boson is light because it is a pseudo Nambu-Goldstone boson 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 massless when either set of the interactions is absent:

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

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

# Littlest Higgs model with T-parity

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

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

$$SU(5) \xrightarrow{f} SO(5)$$

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

$$[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \longrightarrow SU(2) \times U(1)$$

Higgs boson is a pseudo Nambu-Goldstone boson

- Collective symmetry breaking mechanism

Large SM one-loop quadratic divergences in Higgs mass are canceled by new particles

- T-parity Cheng, Low hep-ph/0308199

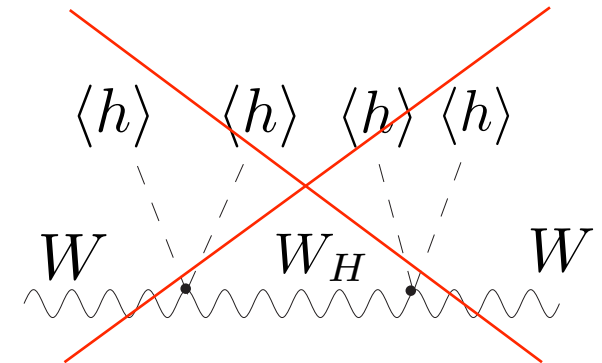
$$SU(2)_1 \times U(1)_1 \leftrightarrow SU(2)_2 \times U(1)_2$$

SM particles  $\rightarrow$  +SM particles

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

(heavy gauge bosons and Higgs)

$$q_- \rightarrow -q_- \quad (\text{T-odd doublet fermions})$$



- \* Contributions to EW observables are loop suppressed.

The new particle scale f can be much lower than 1 TeV.

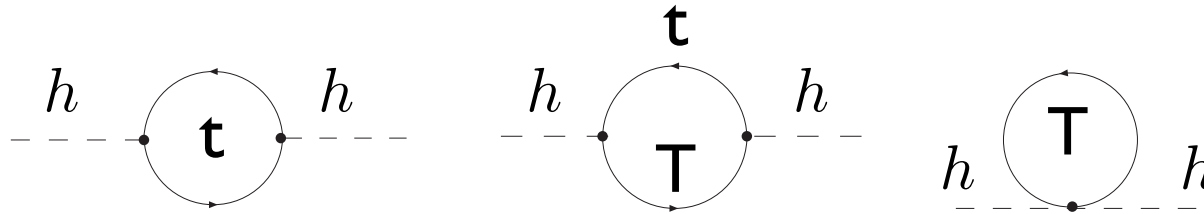
- \* The lightest T-odd particle can be a good dark matter candidate



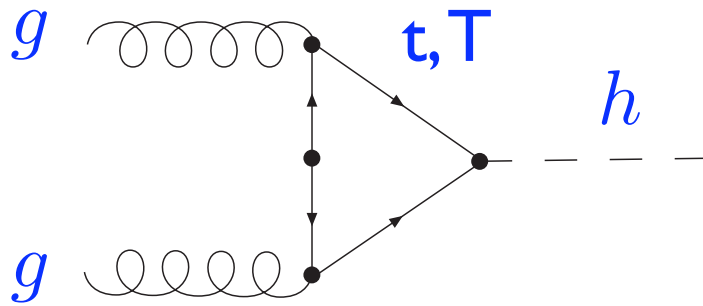
New Higgs interactions  
and gluon fusion process at 1-loop level

# Top-Yukawa interaction

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



$\Lambda^2$  is canceled !



Han, Logan, McElrath, Wang, hep-ph/0302188

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

for small Higgs mass

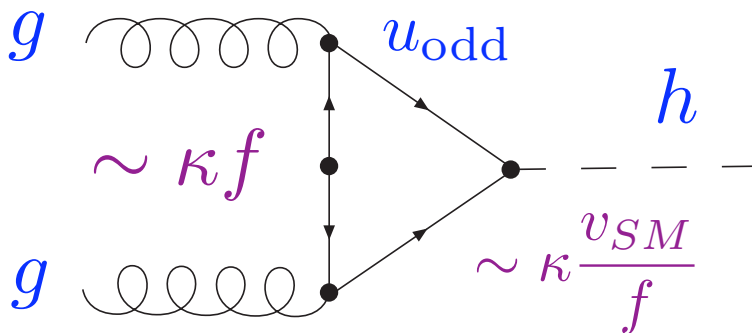
# T-odd Yukawa interaction

Low, hep-ph/0409025; Hubisz, Meade, hep-ph/0411264

T-parity  
 $q_1 \leftrightarrow q_2$

T-even: SM doublet

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



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

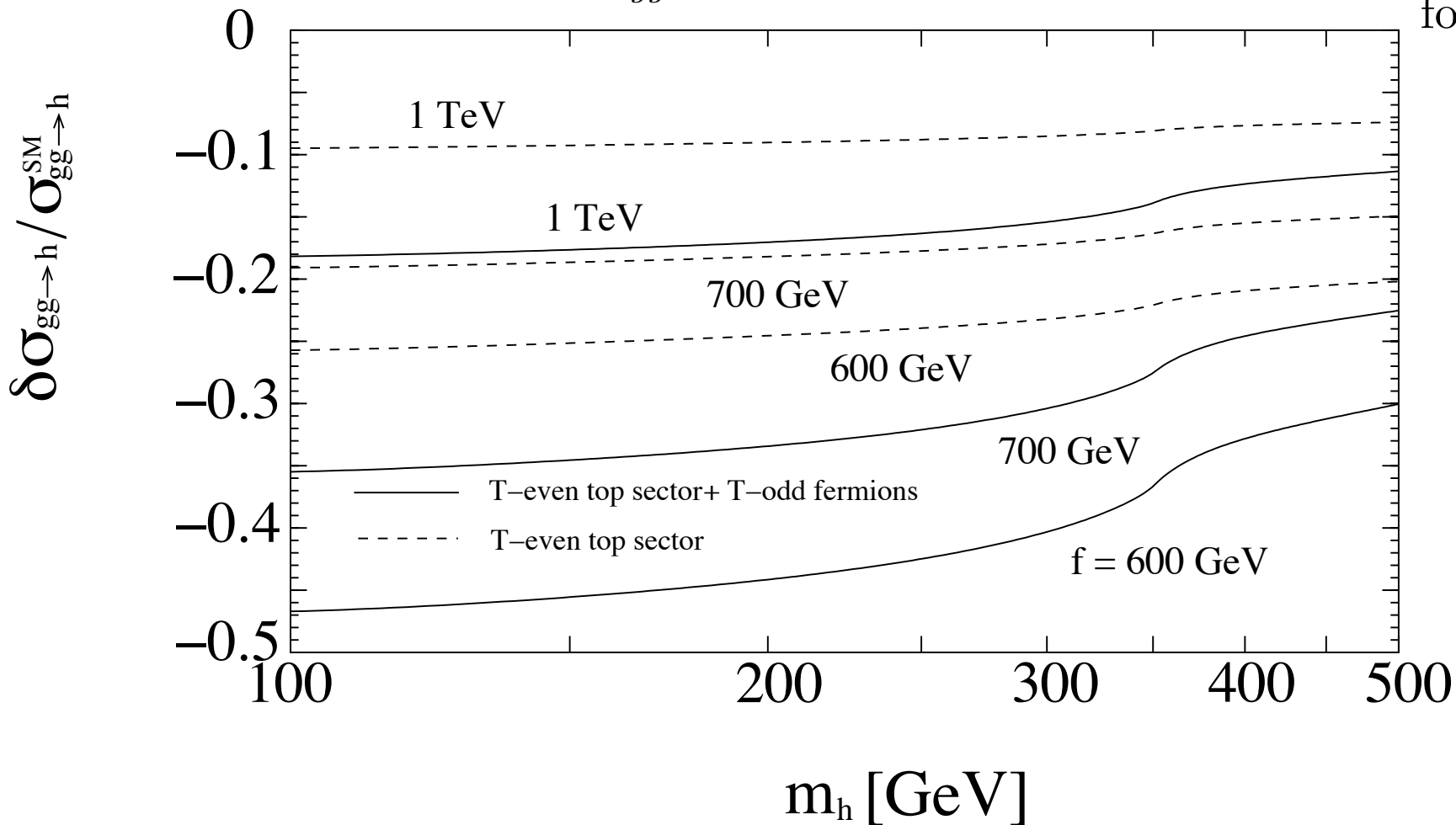
for small Higgs mass

# Correction to Higgs production cross section via gluon fusion process

$$\frac{\delta\sigma_{gg\rightarrow h}}{\sigma_{gg\rightarrow h}^{\text{SM}}} \quad (\text{where } \delta\sigma_{gg\rightarrow h} = \sigma_{gg\rightarrow h}^{\text{LH}} - \sigma_{gg\rightarrow h}^{\text{SM}})$$

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

for small  $m_h$

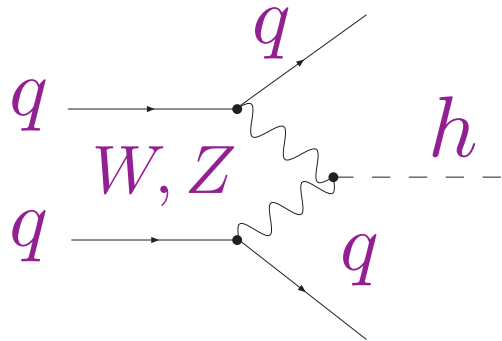


The production cross section can be significantly suppressed

# Other Higgs production and decay processes

# Production

weak boson fusion (VV)



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

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

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

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

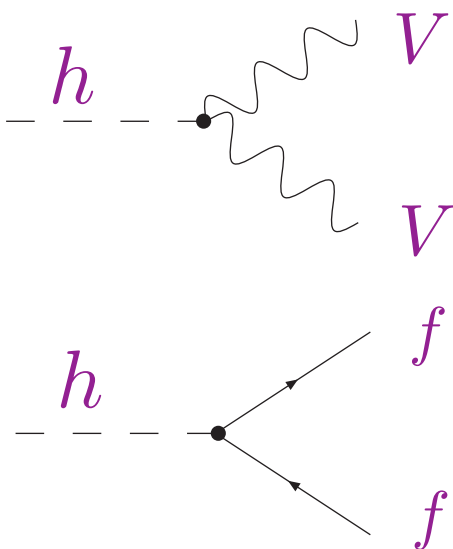
Down-type quark Yukawas Hubisz

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

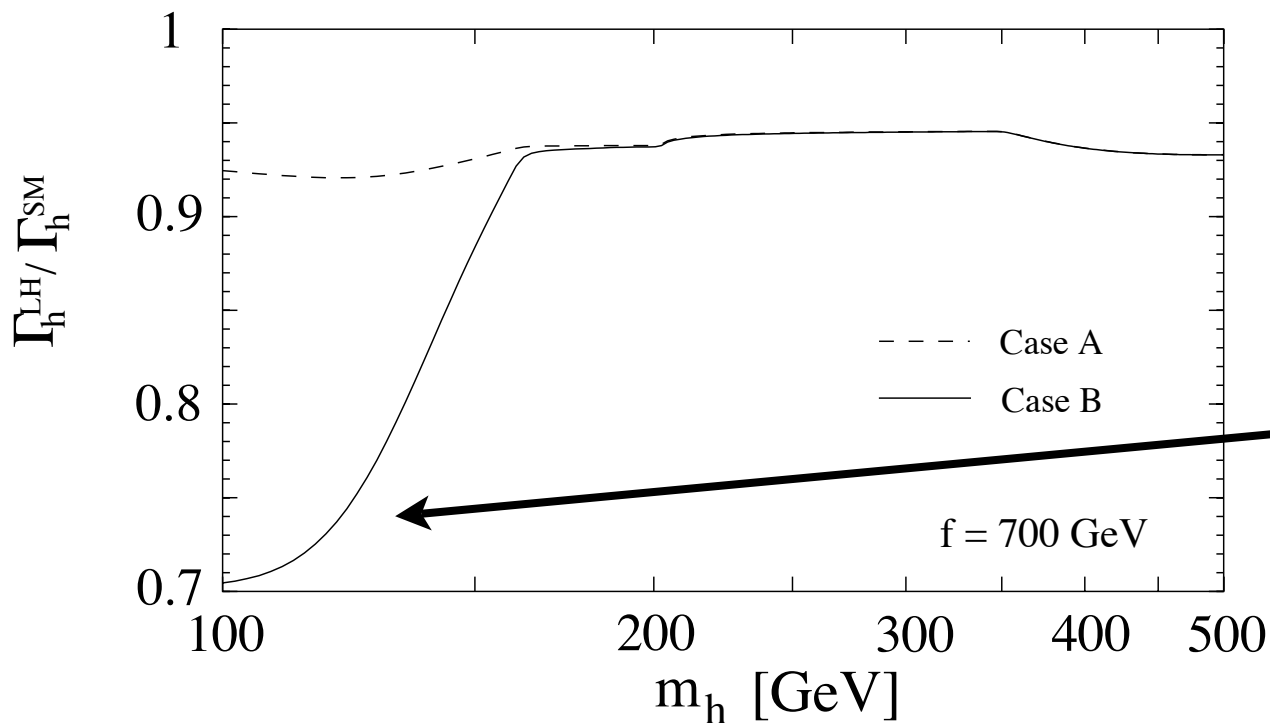
$$\simeq 1 - \frac{5}{4} \frac{v_{SM}^2}{f^2} \simeq \begin{cases} 0.84 & \text{for } f = 700 \text{ GeV,} \\ 0.92 & \text{for } f = 1000 \text{ GeV,} \end{cases} \quad \text{for Case B.}$$

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

# Decay

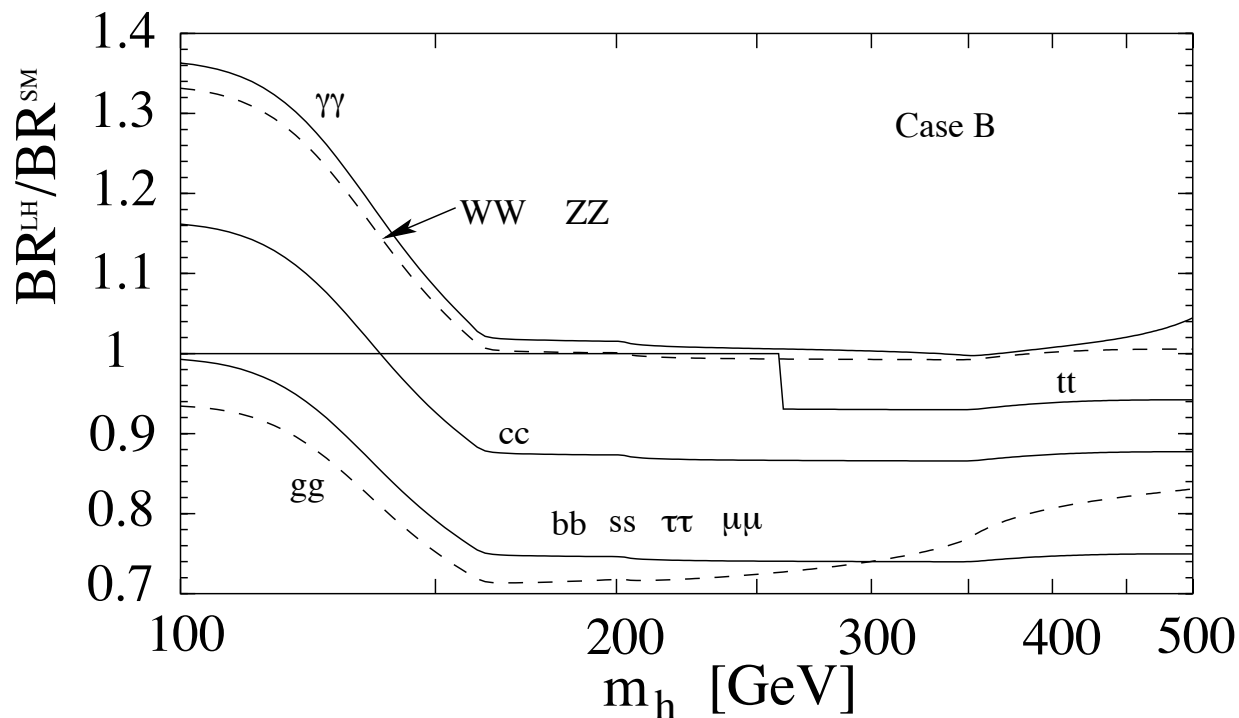


**all Higgs interactions are modified**



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.

$$R_{\sigma(X)} = \frac{\sigma^{\text{LH}}(X)}{\sigma^{\text{SM}}(X)}$$

$$R_{\text{BR}(Y)} = \frac{\text{BR}^{\text{LH}}(Y)}{\text{BR}^{\text{SM}}(Y)}$$

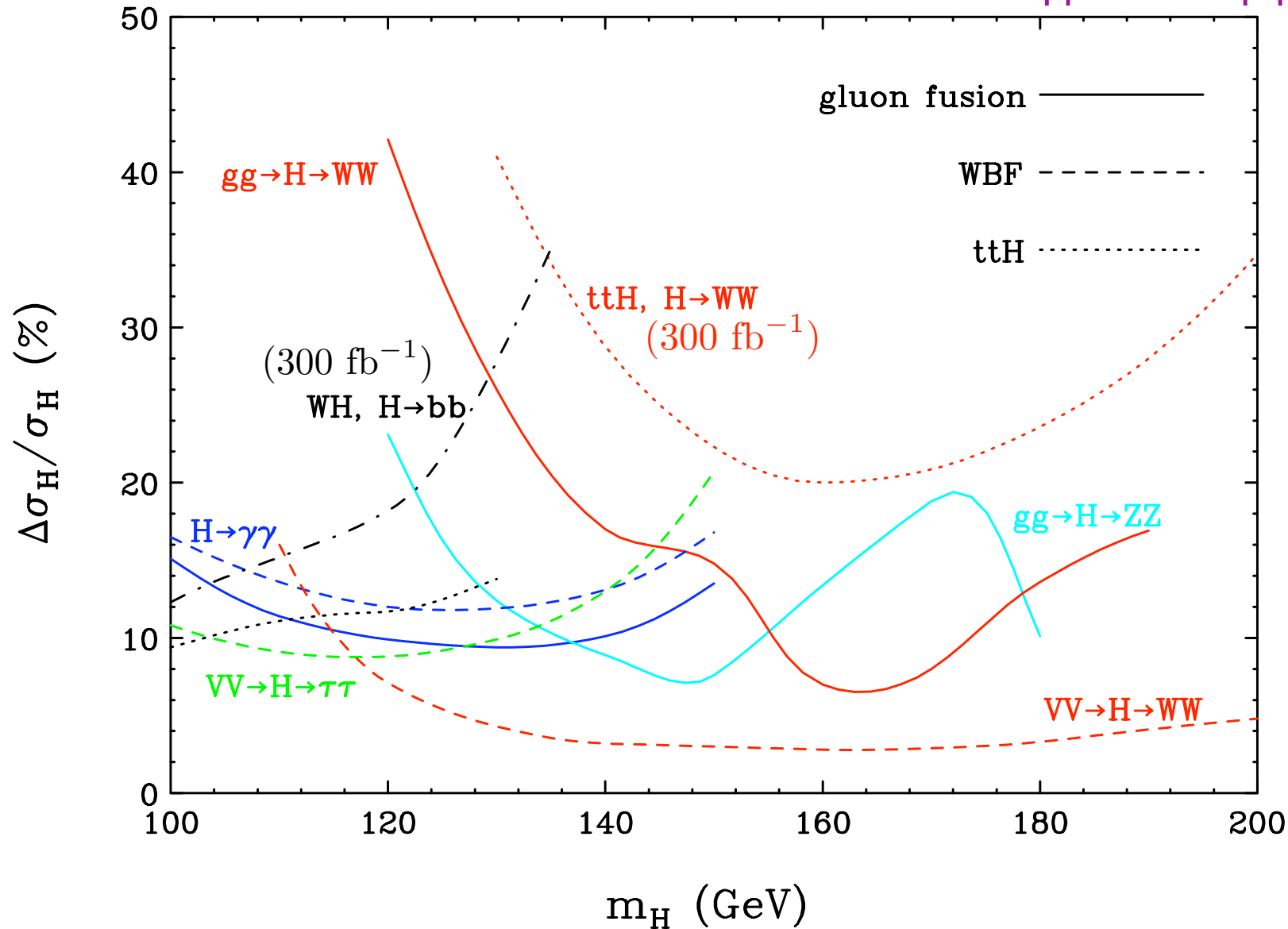
$$R_{\sigma(X)} \times R_{\text{BR}(Y)} \quad \text{for } f = (600, 700, 1000) \text{ GeV}$$

$m_h = 120 \text{ GeV}$	$R_{\text{BR}(\gamma\gamma)}$	$R_{\text{BR}(\tau\tau)}$	$R_{\text{BR}(b\bar{b})}$	$R_{\text{BR}(VV)}$
$R_{\sigma(gg)}$ (Case A)	<u>0.57, 0.68, 0.84</u>	0.56, 0.67, 0.83	—	<u>0.55, 0.66, 0.83</u>
(Case B)	<u>0.81, 0.86, 0.93</u>	0.51, 0.63, 0.81	—	<u>0.78, 0.84, 0.92</u>
$R_{\sigma(VV)}$ (Case A)	<u>0.97, 0.98, 0.99</u>	0.95, 0.96, 0.98	—	<u>0.94, 0.96, 0.98</u>
(Case B)	<u>1.34, 1.22, 1.09</u>	0.84, 0.89, 0.95	—	<u>1.30, 1.19, 1.08</u>
$R_{\sigma(t\bar{t}h)}$ (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	—
$m_h = 200 \text{ GeV}$	$R_{\text{BR}(\gamma\gamma)}$	$R_{\text{BR}(\tau\tau)}$	$R_{\text{BR}(b\bar{b})}$	$R_{\text{BR}(VV)}$
$R_{\sigma(gg)}$ (Case A)	—	—	—	<u>0.55, 0.67, 0.83</u>
(Case B)	—	—	—	<u>0.56, 0.67, 0.83</u>
$R_{\sigma(VV)}$ (Case A)	—	—	—	<u>0.90, 0.94, 0.97</u>
(Case B)	—	—	—	<u>0.90, 0.94, 0.97</u>

- 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 $\sigma \times \text{BR}$ for various Higgs search channels at the LHC with $200 \text{ fb}^{-1}$ 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.

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

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

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

$\sim 1.3$  for  $m_h = 120$  GeV and  $f = 600$  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.

**Back up slides**

# 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  $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$  to  $SU(2) \times U(1)$

$$\lambda_1 \mathcal{L}_1 \quad \lambda_2 \mathcal{L}_2$$

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

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

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

Higgs is exact NG boson under either SU(3)

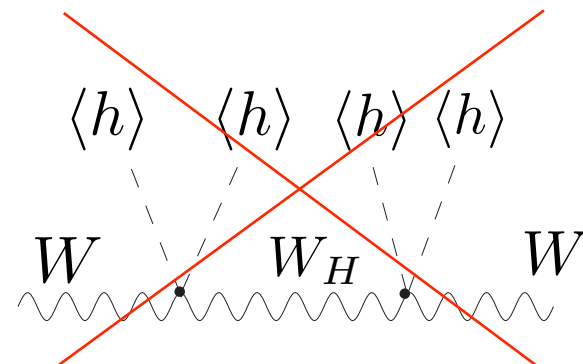
## T-parity

Cheng, Low hep-ph/0308199

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

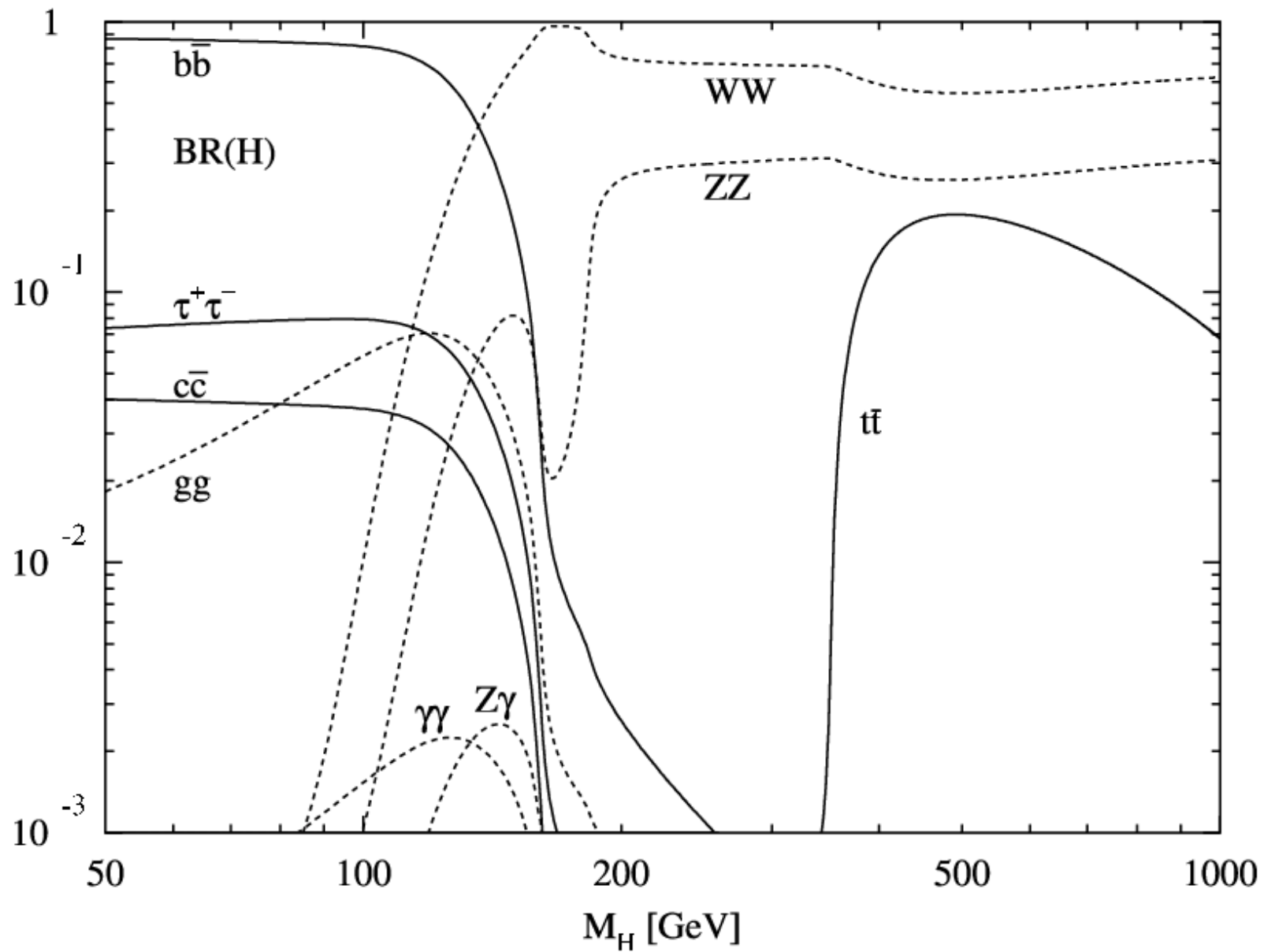
SM particles  $\rightarrow$  +SM particles

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

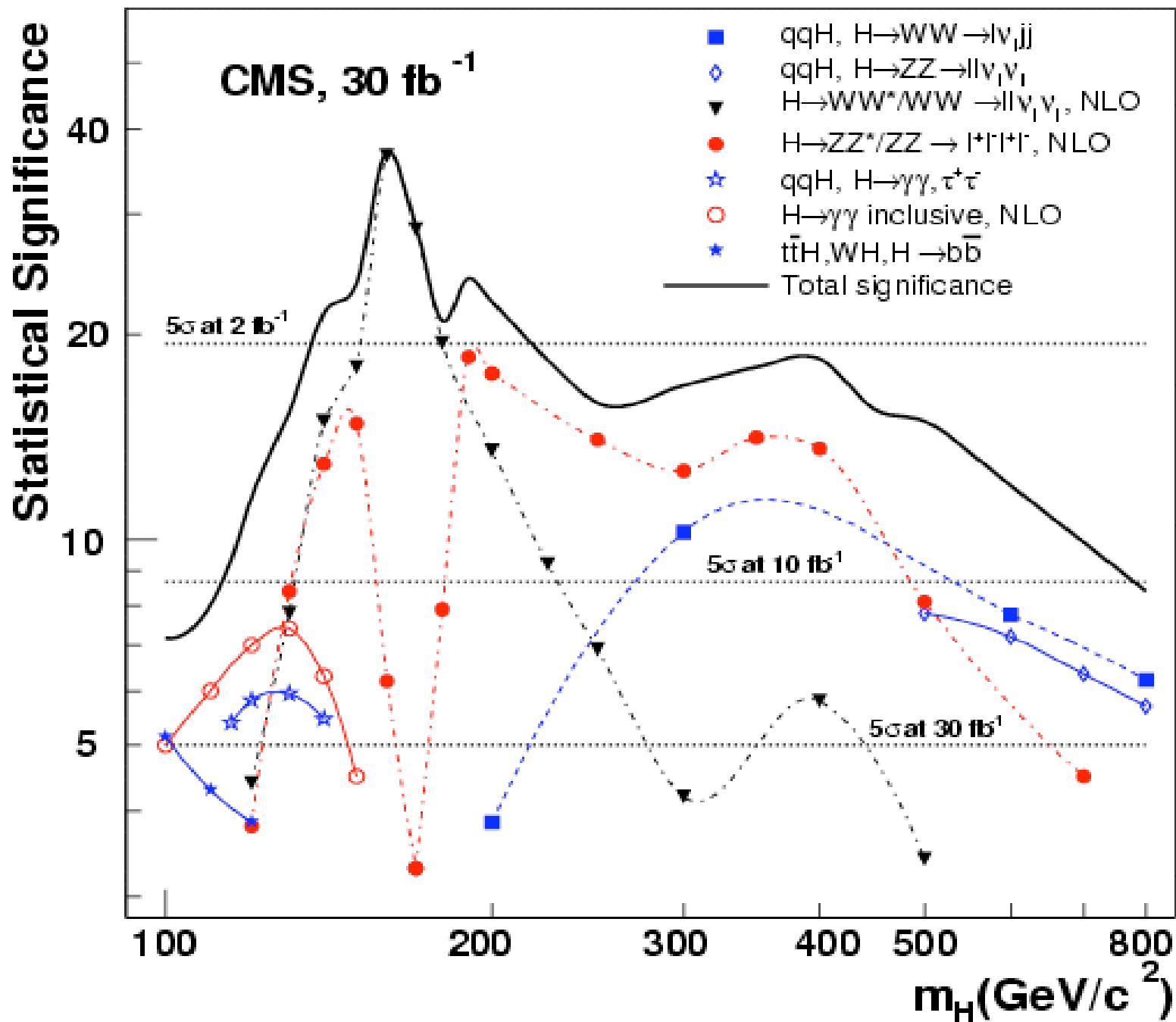


- Contributions to EW observables are loop suppressed. The new particle scale f can be much lower than 1 TeV.
- The lightest T-odd particle can be a good dark matter candidate

# SM Higgs decay branching ratios



# SM Higgs discovery potential



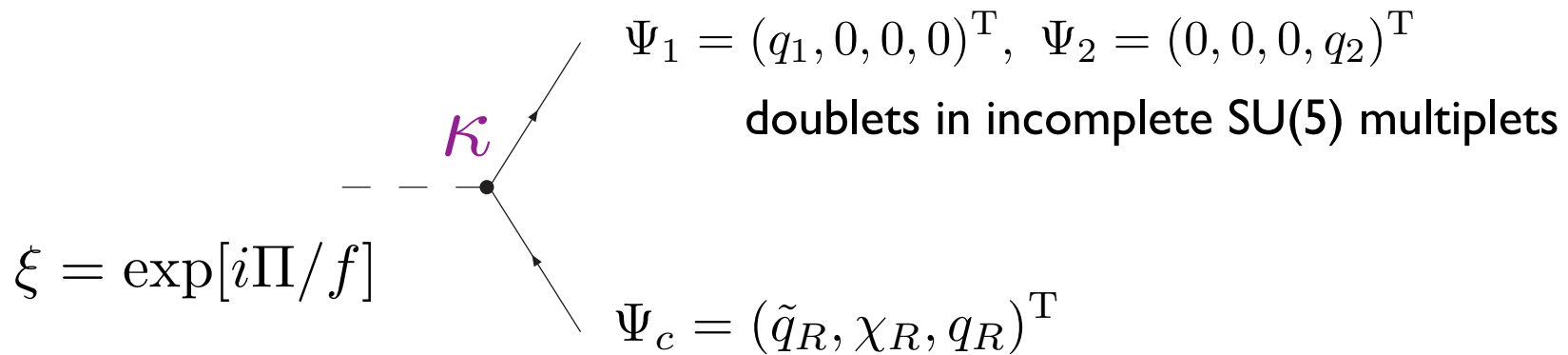
T-parity:  $q_i$  ( $i = 1, 2$ ) doublet under  $SU(2)_i$

T-parity

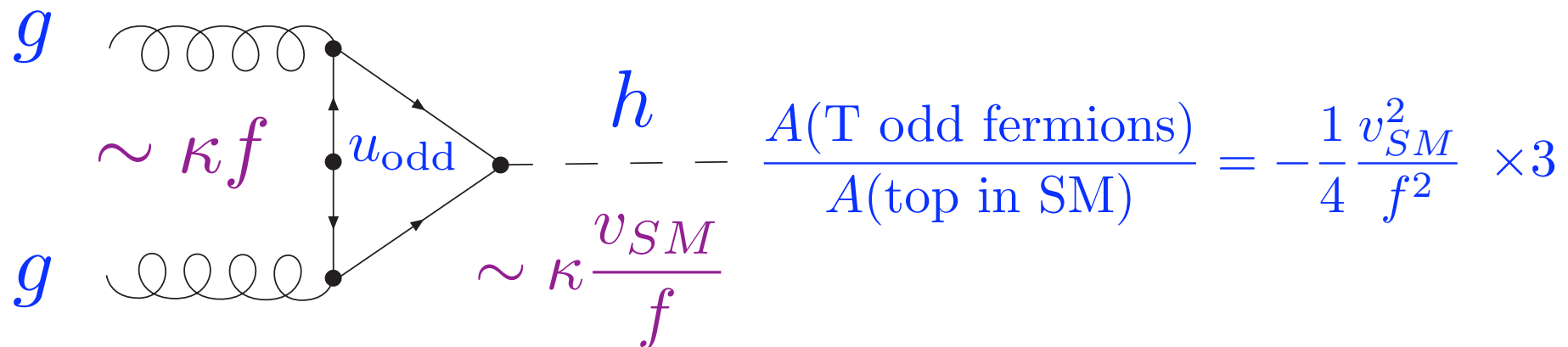
$$q_1 \leftrightarrow q_2$$

T-even: SM doublet

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



Note  $\xi$  contains Higgs boson  $h$



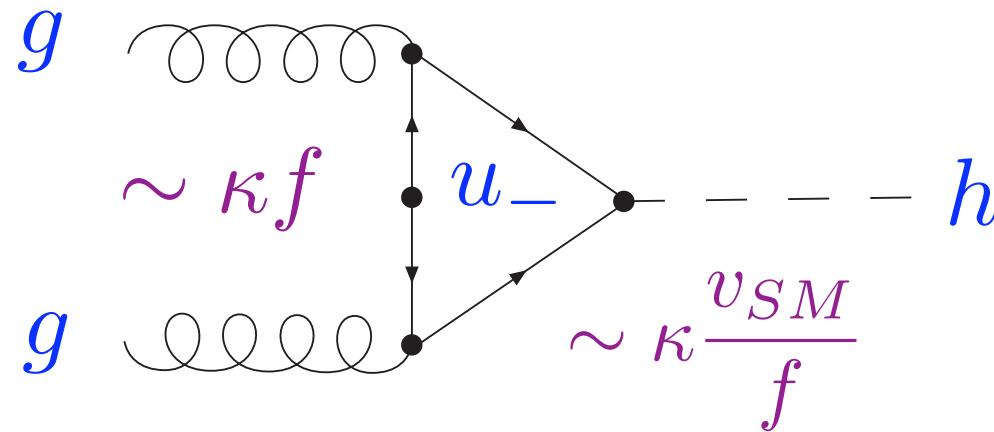
$\mathcal{L}_{\text{odd}}$  contains new Higgs interactions:

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

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

$q_-$  gets the Dirac mass with  $q_R$

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





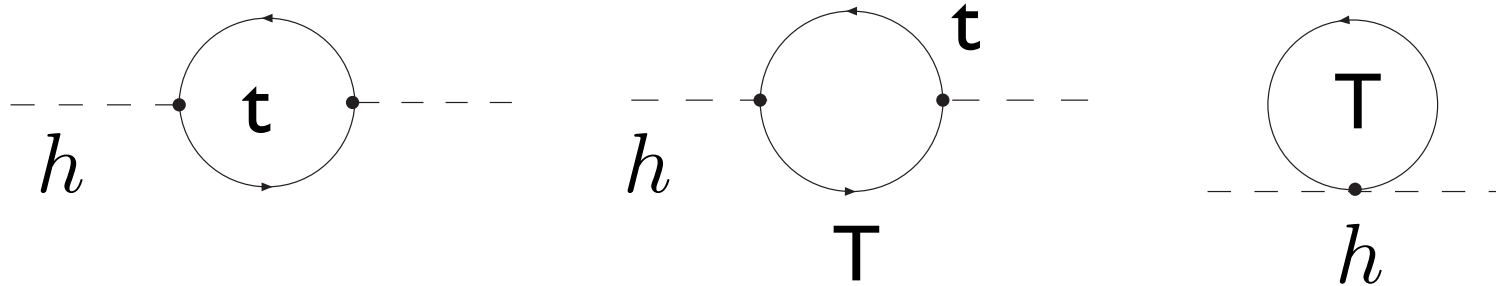
# Top Yukawa interaction

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

$$-\lambda_2 f (\bar{U}_1 U_{R1} + \bar{U}_2 U_{R2}) + \text{h.c.}$$

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

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



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

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

$$-\lambda_2 f (\bar{U}_1 U_{R1} + \bar{U}_2 U_{R2}) + \text{h.c.}$$

SU(3)<sub>1</sub>

SU(3)<sub>2</sub>

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

x,y summed over 4,5

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

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

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

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

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

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

$$R = \lambda_1 / \lambda_2$$

Top Yukawa is modified, and T<sub>+</sub> has the Yukawa coupling

# Down-type quark Yukawa couplings

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

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

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

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

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

Down-type quark Yukawa couplings are modified from those in the SM

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

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

The down-type Yukawa couplings can be significantly reduced in Case B.

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