# Higgs phenomenology of the supersymmetric grand unified theory with the Hosotani mechanism

Mitsuru Kakizaki (University of Toyama)

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- In collaboration with
  Shinya Kanemura (U. of Toyama)
  Hiroyuki Taniguchi (U. of Toyama)
  Toshifumi Yamashita (Aichi Medical U.)
- Work in progress

# Contents

# 1. Motivations

- Conventional grand unified theories (GUTs): $M_{GUT} \sim 10^{16} GeV$
  - Decoupling theorem → Verifying GUTs is difficult
  - Tests of GUTs rely on relations among coupling constants
- Supersymmetric Grand Gauge-Higgs Unification (GHU):

  (Hosotani mechanism → Doublet-triplet splitting)

  [Kojima,Takenaga,Yamashita,PRD84,051701;Yamashita,PRD84,115016(2011)]

  - The existence of new light chiral adjoints is predicted:

    Color octet superfield: $O(8,1,0)$

    SU(2) triplet superfileld: $\Delta(1,3,0)$ } The Higgs sector is extended

    SU(2) singlet superfield: $S(1,1,0)$ }

We can test grand unification by exploring the Higgs sector

# 2. Model of Supersymmetric Grand Gauge-Higgs Unification (GHU)

- Higgs particles:

$H_d(1,2,-1/2)$ $\Delta(1,3,0)$
$H_u(1,2,1/2)$ $S(1,1,0)$

→

4 CP-even scalars: $h, H, S_R^0, \Delta_R^0$
3+1 CP-odd scalars: $A, S_I^0, \Delta_I^0, G$
3+1 charged scalars: $H^\pm, \Delta^\pm, \bar{\Delta}^\pm, G^\pm$

- GHU Higgs potential:

$$W = \mu H_u \cdot H_d + \mu_\Delta \mathrm{tr}(\Delta^2) + \frac{\mu_S}{2} S^2 + \xi_S S + \lambda_\Delta H_u \cdot \Delta H_d + \lambda_S S H_u \cdot H_d$$

The properties of the MSSM Higgs bosons are affected (← $\lambda_\Delta H_u \cdot \Delta H_d + \lambda_S S H_u \cdot H_d$)

$$V_{\mathrm{soft}} = \tilde{m}_{H_u}^2 |H_u|^2 + \tilde{m}_{H_d}^2 |H_d|^2 + 2\tilde{m}_\Delta^2 \mathrm{tr}(\Delta^\dagger \Delta) + \tilde{m}_S^2 |S|^2 + [B_\mu \mu H_u \cdot H_d + B_\Delta \mu_\Delta \mathrm{tr}(\Delta^2) + \frac{B_S \mu_S}{2} S^2 + A_\Delta \lambda_\Delta H_u \cdot \Delta H_d + A_S \lambda_S S H_u \cdot H_d + \bar{\xi}_S S + \mathrm{h.c.}]$$

- Features of the GHU:

$\Delta(1,3,0)$ $S(1,1,0) \supset$ 5th component of the gauge boson

→
- Trilinear couplings among $\Delta, S$ are absent
- $\lambda_S, \lambda_\Delta$ are related to the gauge couplings

# Running of coupling constants

- The existence of $O(8,1,0)$, $\Delta(1,3,0)$ would spoil the successful gauge coupling unification (GCU)
  - Extra vector-like matter multiplets are needed for GCU:

    $2\times L(1,2,-1/2)+U^C(\bar{3},1,-2/3)+E^C(1,1,1)$ @ SUSY scale

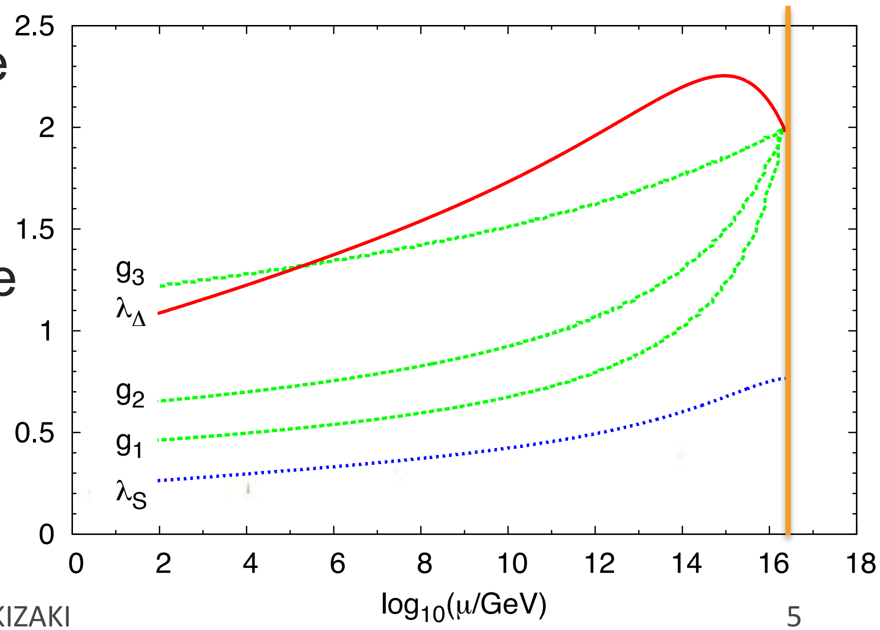
- Unification of the coupling constants:

$\lambda_\Delta = 2\sqrt{5/3}\lambda_S = g_{1,2,3}$ @ GUT scale

↓

$\lambda_\Delta = 1.1 \quad \lambda_S = 0.26$ @ Weak scale

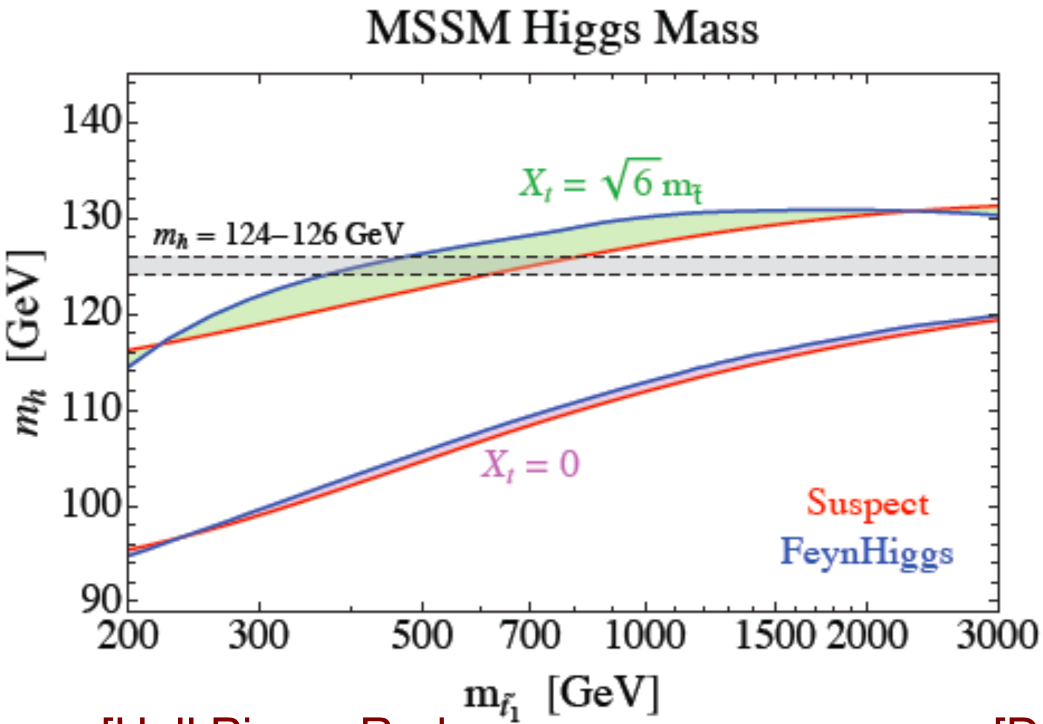
High predictability on the Higgs properties

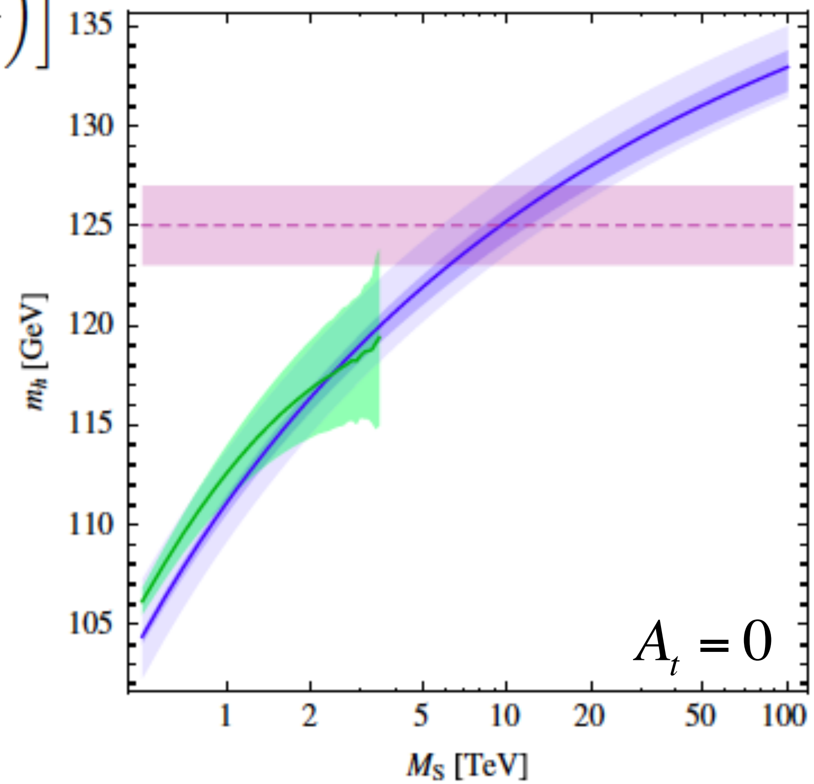


# 3. GHU Predictions of the phenomenology of the Higgs sector

- Mass of the light Higgs boson in the MSSM:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$




[Hall,Pinner,Ruderman, JHEP1204,131(2012),arXiv:1112.2703]

[Draper,Meade,Reece,Shih, PRD85,095007(2012),arXiv:1112.3068]

**To obtain a 126 GeV Higgs boson is not easy in the MSSM**

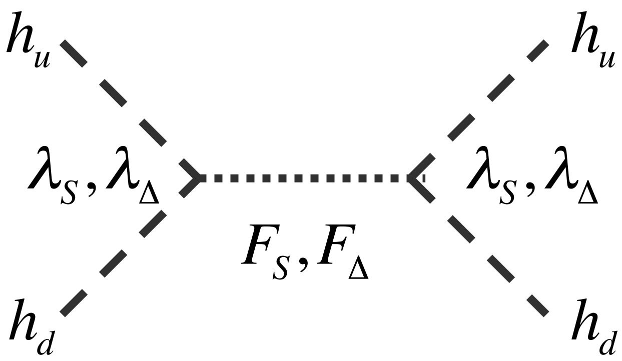
# GHU predictions of the mass of the Higgs boson

- Predicted mass of the light Higgs boson in the GHU:

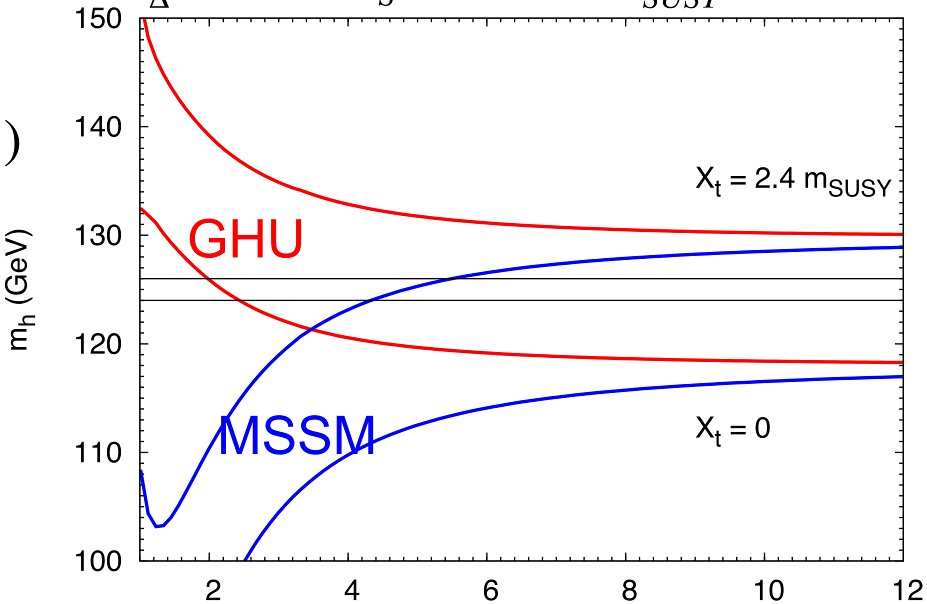
$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_t^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right] \quad \Big\} \text{ MSSM}$$

$$+\frac{1}{2}\lambda_S^2 v^2 s_{2\beta}^2 + \frac{1}{8}\lambda_\Delta^2 v^2 s_{2\beta}^2$$

Contributions from $S(1,1,0)$ $\Delta(1,3,0)$




$\lambda_\Delta = 1.1$ $\lambda_S = 0.26$ $m_{SUSY} = 2TeV$




A 126 GeV Higgs boson is realized without a large mixing (in particular for small $\tan\beta$ )

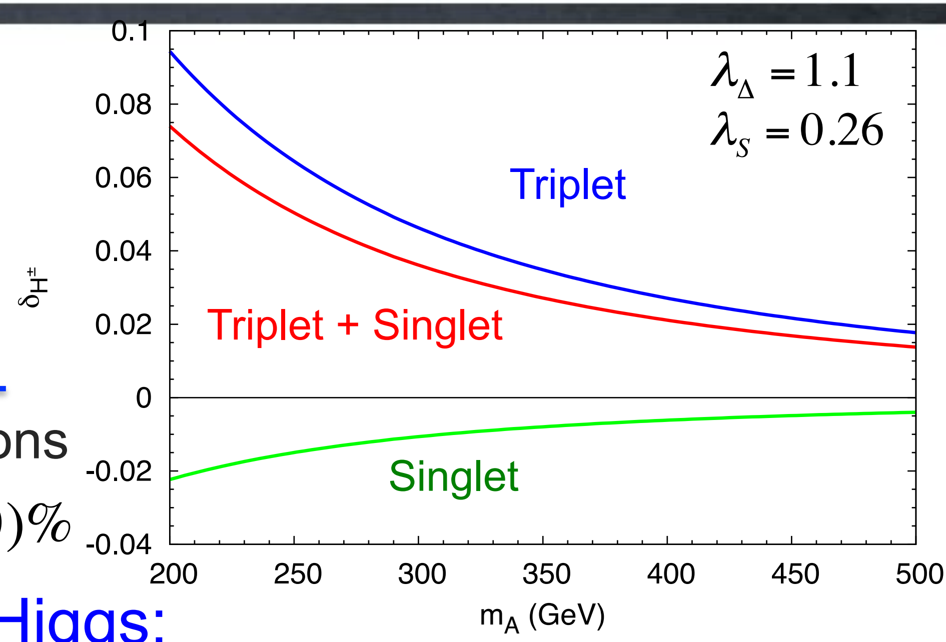
# Mass spectra of the MSSM Higgs particles

- Mass of the charged Higgs

$$m_{H^\pm}^2 = m_{H^\pm}^2|_{\rm MSSM}(1+\delta_{H^\pm})^2$$
$$\simeq m_A^2 + m_W^2 - \frac{\lambda_S^2}{2}v^2 + \frac{\lambda_\Delta^2}{8}v^2$$

for heavy triplet and singlet bosons

➡ Mass shifts: $O(1)\% \sim O(10)\%$




- Mass of the heavy CP-even Higgs:

$m_H \simeq m_H|_{\rm MSSM} \simeq m_H|_{\rm NMSSM}$ for heavy triplet and singlet bosons

➡ Very small mass shifts: $< 1\%$

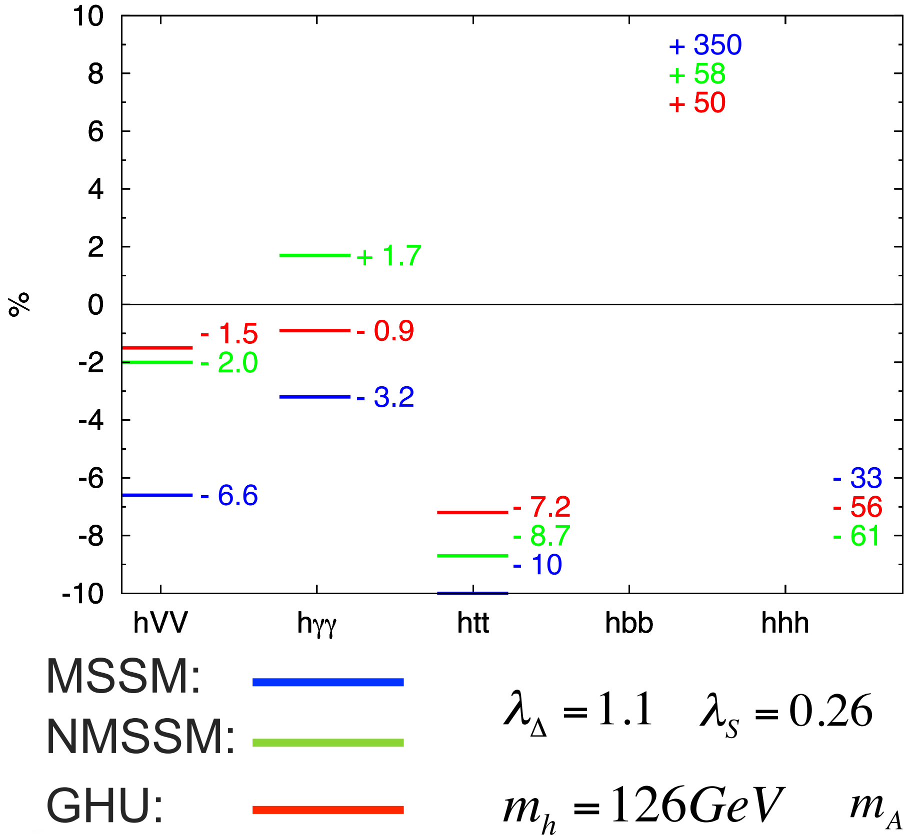
- N.B. For light $S, \Delta$, the order of the masses is altered via mixing
- Accuracy of LHC mass measurements: a few %

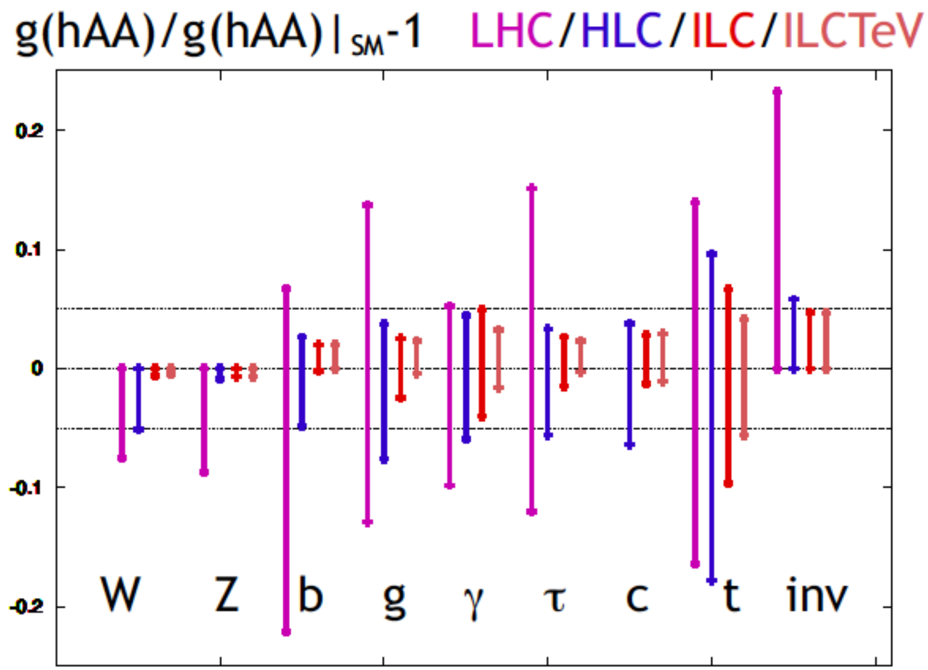
[see e.g. Assamagan,Coadou(2002)]

**We can distinguish models using LHC data to some extent**

# Couplings of the SM-like Higgs boson

- Deviations from the SM values: $g(hAA)/g(hAA)_{SM}-1$
  - Large $\tilde{m}_\Delta, \tilde{m}_S$ scenario




[Peskin,1207.2516]

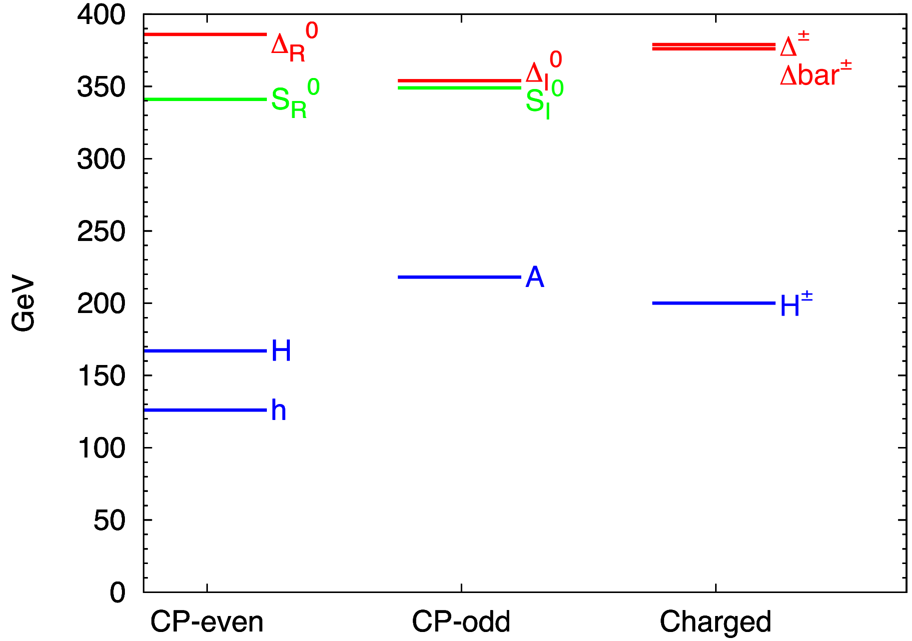
$\lambda_\Delta = 1.1 \quad \lambda_S = 0.26 \quad \lambda_{S,NMSSM} = 0.6 \quad \tan\beta_{MSSM} = 10 \quad \tan\beta_{GHU,NMSSM} = 3$

$m_h = 126GeV \quad m_A = \mu_{eff} = 150GeV \quad m_{SUSY} = 2TeV$

We can distinguish models using LC precision measurements

# Masses of the Higgs bosons for light $S, \Delta$

- Benchmark mass spectrum of the Higgs sector:




- Small soft triplet and singlet masses
  → Mixing between the MSSM and new Higgs bosons

$$\lambda_\Delta = 1.1 \quad \lambda_S = 0.26 \quad \tan\beta = 3$$

$$\mu_{eff} = 180GeV \quad \mu_\Delta = 330GeV \quad \mu_S = 150GeV$$

$$\tilde{m}_\Delta = 100GeV, \tilde{m}_S = 300GeV \quad m_{SUSY} = 2TeV$$

- E.g. Expected charged triplet channel at future linear colliders:

$$e^+e^- \to \Delta^\pm\Delta^\mp \to tbtb$$

$$e^+e^- \to \Delta^\pm\Delta^\mp \to tb\tau\nu$$

via large $H^\pm - \Delta^\pm(\bar{\Delta}^\pm)$ mixing

**The GHU remnant particles are directly probed at linear colliders**

# 4. Summary

- We have explored the Higgs phenomenology of the supersymmetric grand gauge-Higgs unification (GHU)
  - The predicted values of the Higgs sector observables deviates from those of the SM and MSSM by $O(1)\% \sim O(10)\%$
  - Future linear collider can directly probe light extra Higgs bosons

➡ By combining LHC and LC Higgs studies, we can differentiate among the varieties of new physics

- The GHU is a good illustration to show the capabilities of colliders for testing GUT scale physics

# Backup slides

# Higgs sector in SUSY extensions

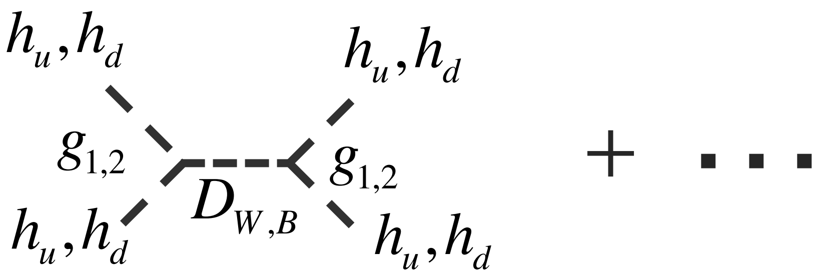
- Higgs doublet ⟷ higgsino doublet (chiral fermion)

  ➡ Two Higgs doublets are needed for anomaly cancellation

- Higgs chiral superfields:
  - $(h_u, \tilde{h}_u)$ $(1, 2, -1/2)$
  - $(h_d, \tilde{h}_d)$ $(1, 2, 1/2)$

    } MSSM
  - Singlet Higgs (NMSSM), triplet Higgs, ....

- Higgs four-point functions:



# MSSM Higgs potential

$$V_H = (|\mu|^2 + m_{H_1}^2)|H_1|^2 + (|\mu|^2 + m_{H_2}^2)|H_2|^2 - \mu B \epsilon_{ij}(H_1^i H_2^j + \text{h.c.})$$
$$+ \frac{1}{2}\lambda_1(h_1^\dagger h_1)^2 + \frac{1}{2}\lambda_2(h_2^\dagger h_2)^2 + \lambda_3(h_1^\dagger h_1)(h_2^\dagger h_2) + \lambda_4(h_2^\dagger \epsilon^T h_1^*)(h_1^T \epsilon h_2)$$
$$+ \left\{ \frac{1}{2}\lambda_5(h_1 \epsilon h_2)^2 + [\lambda_6(h_1^\dagger h_1) + \lambda_7(h_2^\dagger h_2)](h_1 \epsilon h_2) + \text{h.c.} \right\},$$

where

$$\overline{m}_1^2 = |\mu|^2 + m_{H_1}^2, \qquad \overline{m}_2^2 = |\mu|^2 + m_{H_2}^2, \qquad \overline{m}_3^2 = B\mu$$

$$\lambda_{1,2} = \frac{g_2^2 + g_1^2}{4} + \Delta\lambda_{1,2}, \quad \lambda_3 = \frac{g_2^2 - g_1^2}{4} + \Delta\lambda_3$$
$$\lambda_4 = -\frac{g_2^2}{2} + \Delta\lambda_4, \quad \lambda_{5,6,7} = \Delta\lambda_{5,6,7}.$$

MSSM Loop

# MSSM Higgs sector

- EW symmetry breaking: $\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}} \qquad \tan\beta = \frac{v_2}{v_1}$

  ➡ $\mathrm{Re}(h_u^0), \mathrm{Re}(h_d^0)$ mix: $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$

- Mass eigenvalues:

$$M_{h,H}^2 = \frac{1}{2}(M_A^2 + M_Z^2 + \epsilon)\left[1 \mp \sqrt{1 - 4\frac{M_Z^2 M_A^2 \cos^2 2\beta + \epsilon(M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta)}{(M_A^2 + M_Z^2 + \epsilon)^2}}\right]$$

MSSM loop

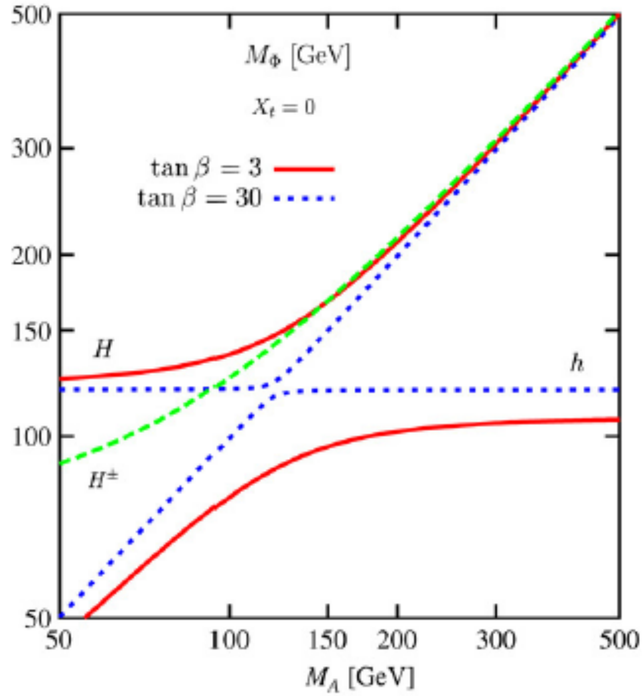
- Independent parameters:

  $M_A \qquad \tan\beta \qquad (\varepsilon)$

  $m_h = 126 GeV$ ➡ One parameter is fixed

- Decoupling limit: $M_A \to$ large

  $\beta \to \alpha + \pi/2$

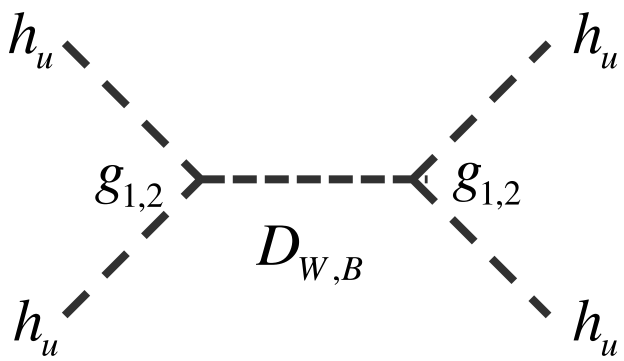


# Estimate of the light Higgs mass in the MSSM

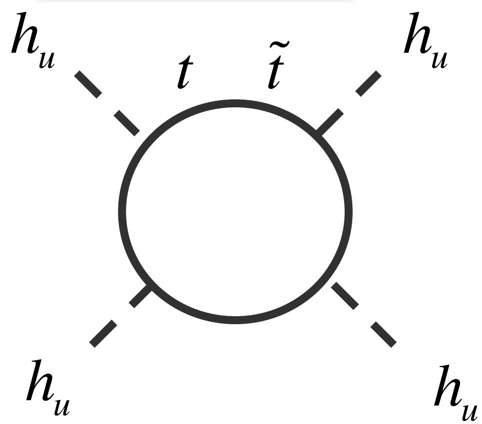
$(126GeV)^2$ → $m_h^2$ ; $(91GeV)^2$ → $m_Z^2$

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta \quad + \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

MSSM tree



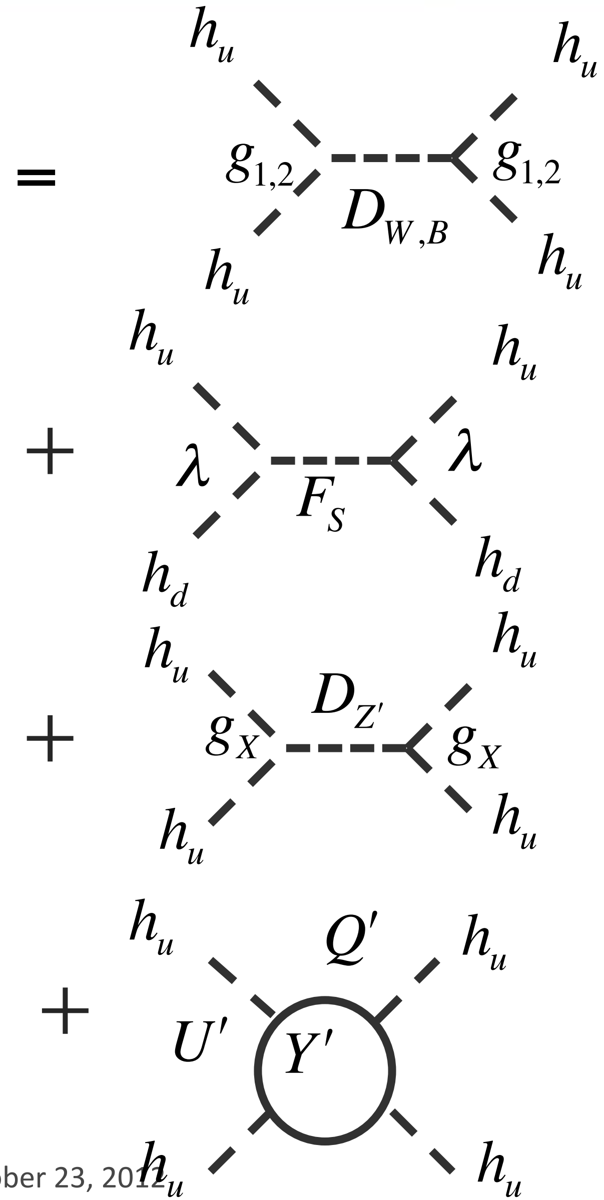

MSSM loop

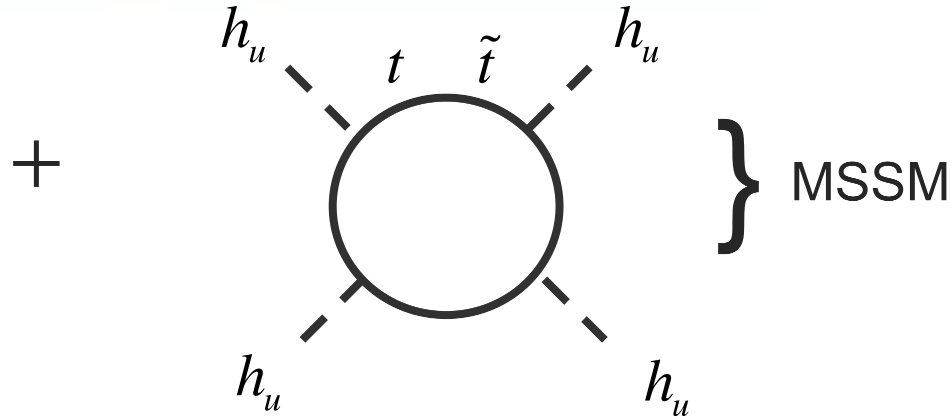



[Okada,Yamaguchi,Yanagida;
Ellis,Ridorfi,Zwirner;
Haber,Hempfling(1991)]

# Light Higgs mass in SUSY extensions

$m_h^2 =$

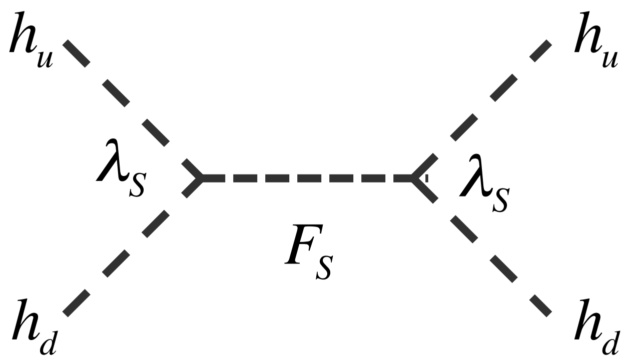


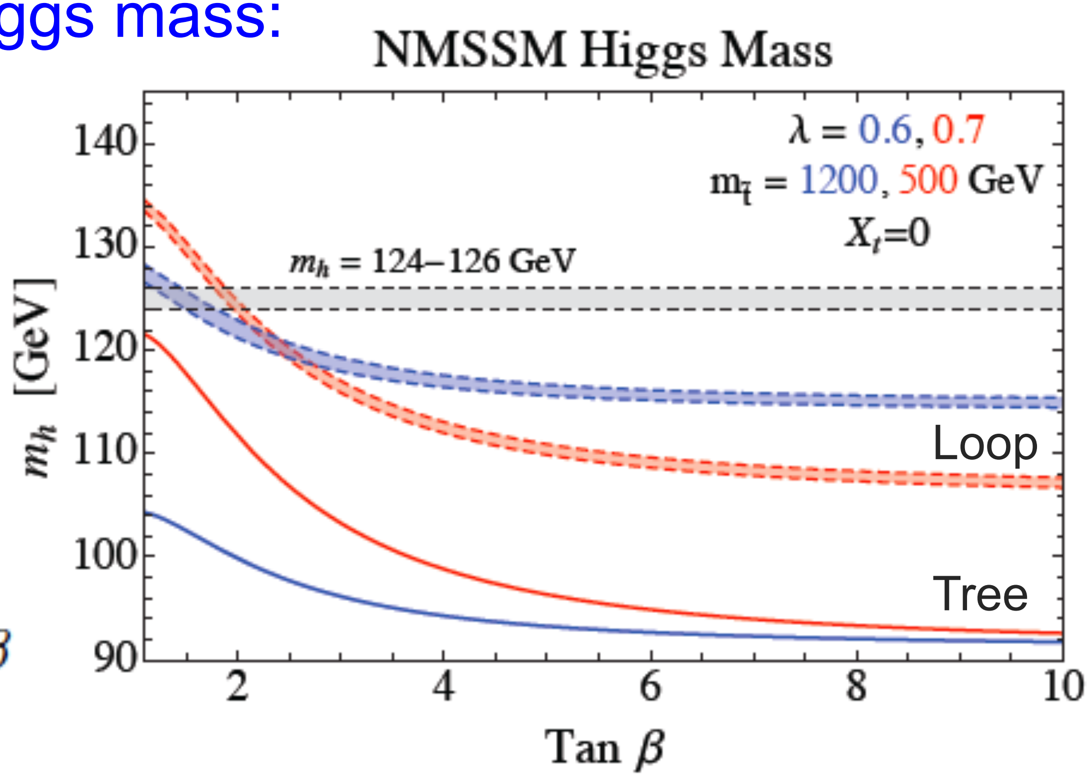

- F-term contributions:
  e.g.) NMSSM, Triplet Higgs
- D-term contributions:
  e.g.) U(1) extended MSSM
- Loop contributions:
  e.g.) Vector-like matter

# NMSSM (nMSSM)

- Particle contents: MSSM + Singlet $S$
- Superpotential: $W = W_{\text{MSSM}} + \lambda_S S H_u H_d + \mu H_u H_d + \frac{M_s^2}{2} S^2$
- Contributions to the Higgs mass:

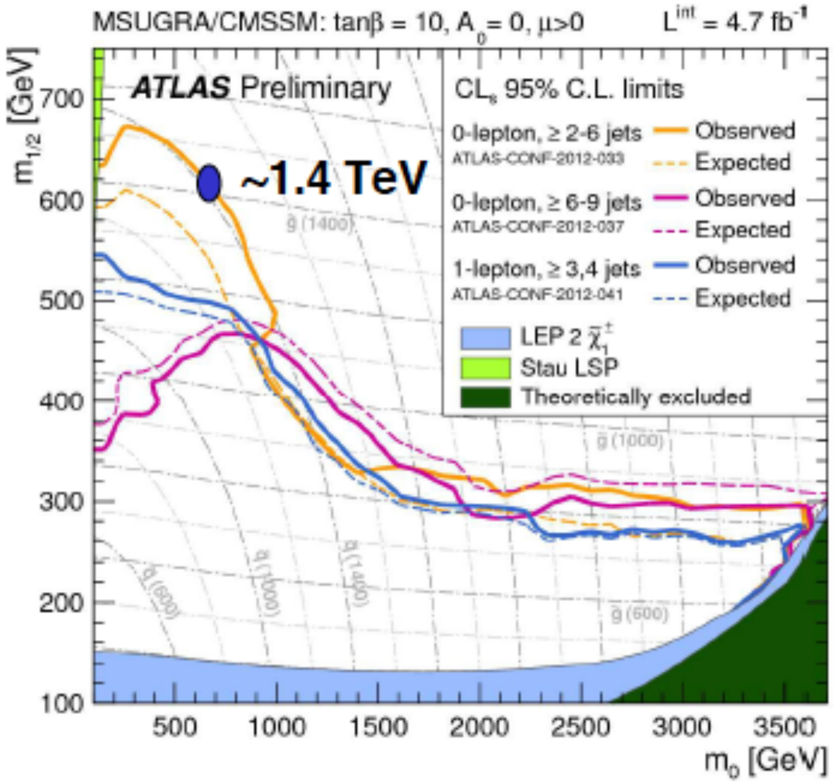



$$\Delta m_h^2 = \frac{\lambda_S^2 v^2}{2} \sin^2 2\beta$$

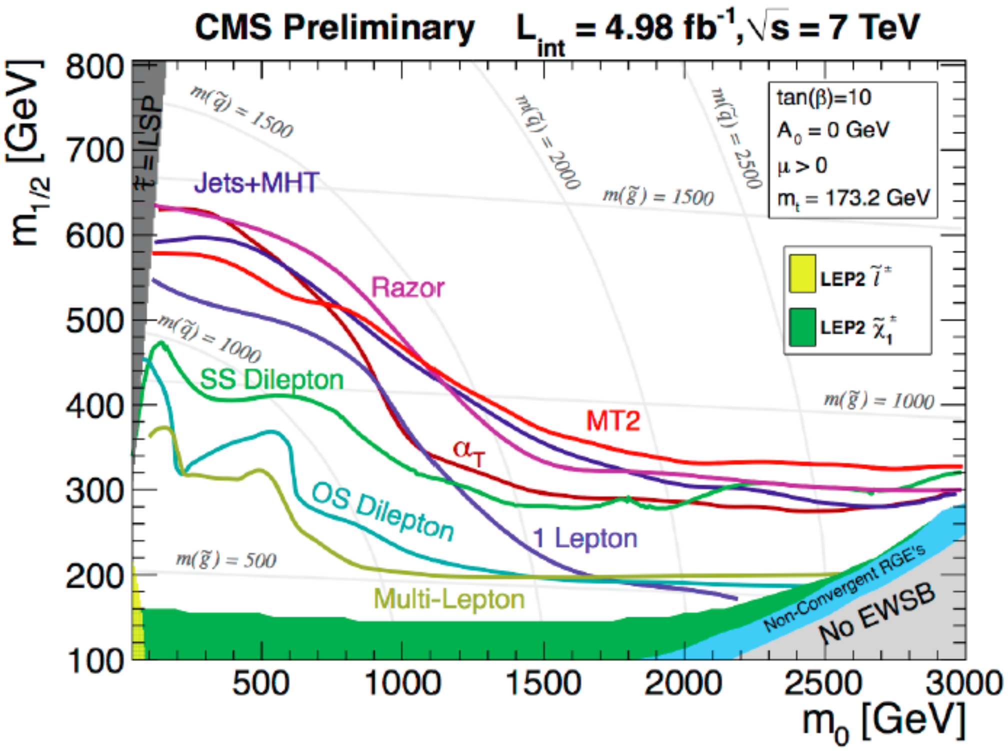



[Hall,Pinner,Ruderman,JHEP1204,131(2012),arXiv:1112.2703]

# SUSY searches

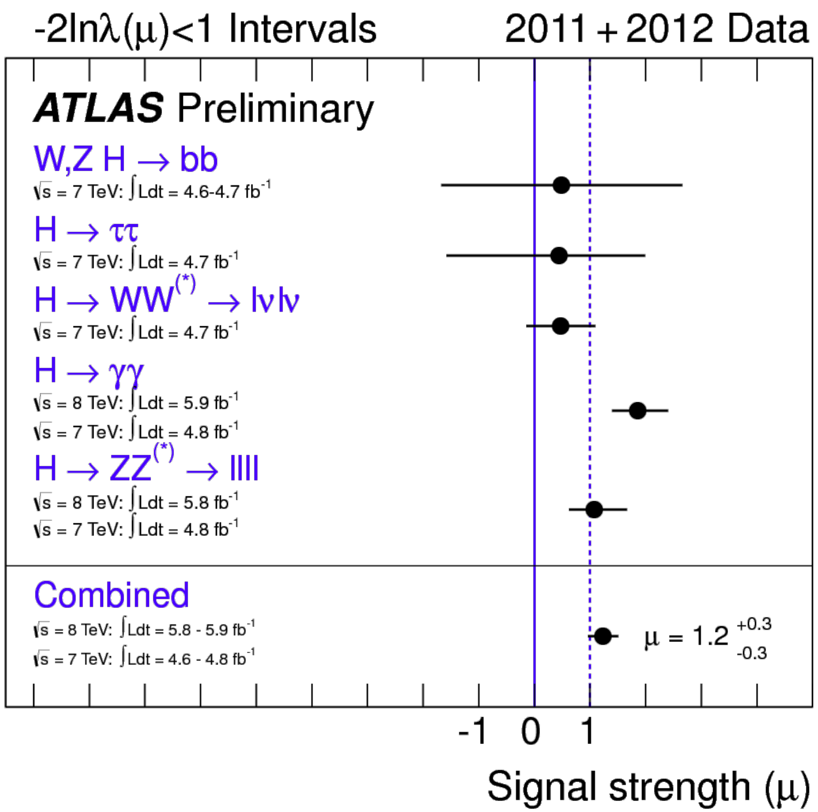



[Pralavorio,SUSY2012]

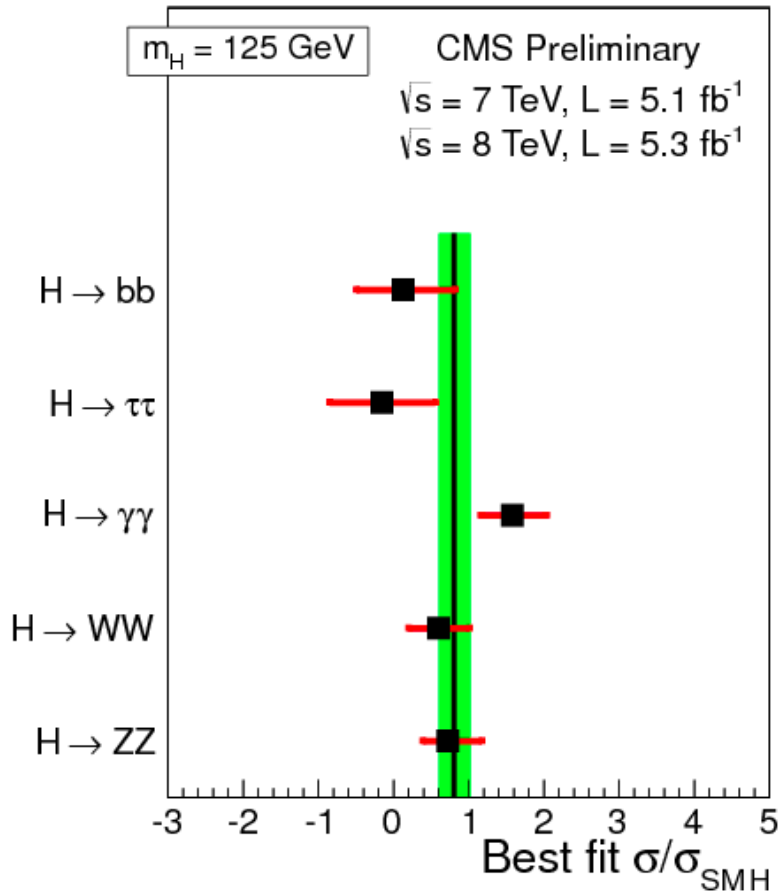



[Campagnari,SUSY2012]

# Higgs decay channels



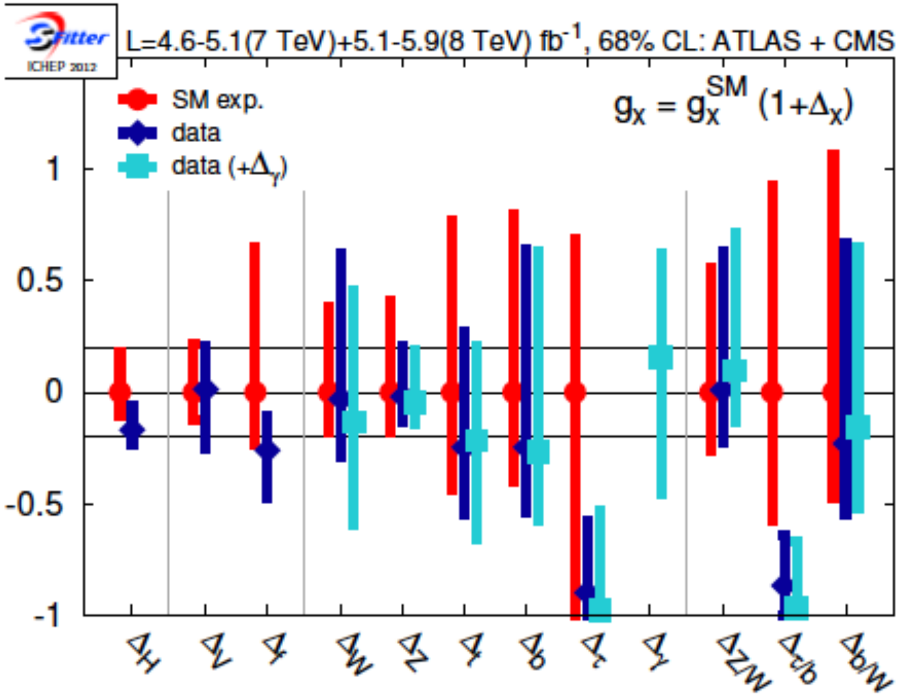

[Hawkings,talk at ICHEP2012]




[Incandela,talk at ICHEP2012]

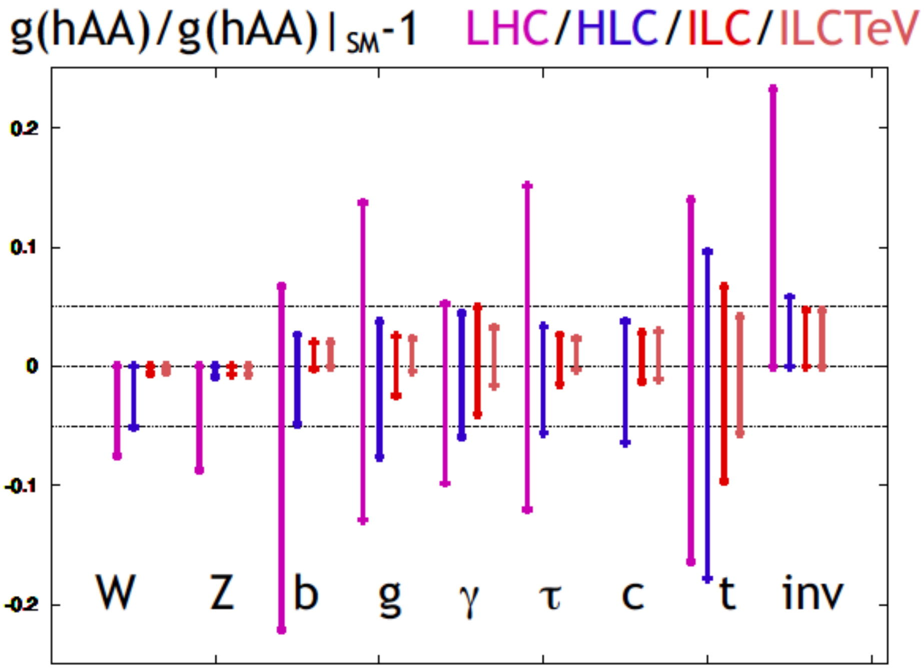
# Measuring the Higgs couplings

After ICHEP2012




[Plehn,Rauch,1207.6108]

In the future




[Peskin,1207.2516]

# SM-like Higgs couplings in the MSSM

$$g_{hVV} = \sin(\beta - \bar{\alpha})$$

$$g_{hbb} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$$

$$g_{htt} = \frac{\cos\alpha}{\sin\beta} = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$$

(Normalized to the SM counterparts)

[Djouadi,Phys.Rev.Rep.]