Grand Unified Theories and Higgs Physics

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based on :

- PRD**84**, 115016 (2011) (arXiv:1106.3229)
- work in progress

  w/ M.Kakizaki, S.Kanemura, H.Tanigucji (U. of Toyama)

outline

GUT-breaking via Hosotani mechanism

= "grand gauge-Higgs unification"

K.Kojima, K.Takenaga & T.Y. (2011)

SUSY version (SGGHU)

- ✓ natural Doublet-Triplet (DT) splitting
- ✓ general & *testable* prediction

T.Y. (2011)

We may get a hint of the GUT-breaking @LHC&ILC.

M.Kakizaki, S.Kanemura, H.Taniguchi & T.Y. in progress

plan

- outline
- introduction
- SUSY grand GHU (SGGHU)
- phenomenology of SGGHU
- summary

introduction

126GeV resonance consistent w/ Higgs

✓ The SM is now being confirmed,
as an effective theory valid below TeV.

What's next?

introduction

- problems/puzzles in SM
  - charge quantization ← GUT, string,
  - hierarchy problem ← SUSY, XD, composite,
  - dark matter
  - neutrino masses ← seesaw,
  - Baryon asymmetry ← leptogenesis,
  - gen. #, quantum gravity, etc. ← string ???

Grand Unified Theories

- Unification of forces

$$G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

G : semi-simple ⇨ Charge Quantization

⇩

- Unification of Matters

SU(5)

$$\mathbf{10} \quad \boxed{\begin{matrix} U^c & Q \\ & E^c \end{matrix}} \qquad \bar{\mathbf{5}} \quad \boxed{\begin{matrix} D^c \\ L \end{matrix}} \qquad \mathbf{1} \quad \boxed{N^c}$$

wrong GUT relation

$$M_D = M_E^T$$

cf) $SU(3)_W$ unification
not fit so beautifully

Grand Unified Theories

- Unification of forces

$$G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

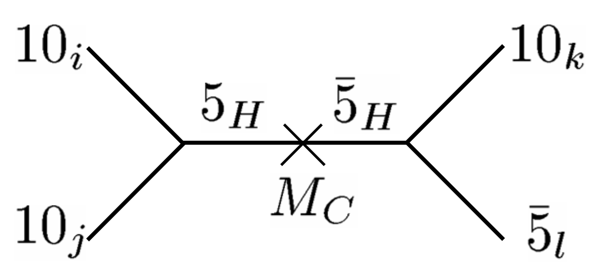
G : semi-simple $\Rightarrow$ Charge Quantization

$\Downarrow$

- How about Higgs?

$$\mathbf{5}\ \boxed{\begin{matrix} H^C \\ H \end{matrix}} \longrightarrow$$

if SUSY
Proton decay



Grand Unified Theories

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- How about Higgs?

$$\mathbf{5} \quad \boxed{\begin{matrix} H^C \\ H \end{matrix}} \quad \begin{matrix} \longleftarrow \gg M_G \sim 10^{16}\mathrm{GeV} \\ \longleftarrow M_W \sim 10^{2}\mathrm{GeV} \end{matrix}$$

Doublet-Triplet (DT) Splitting Problem

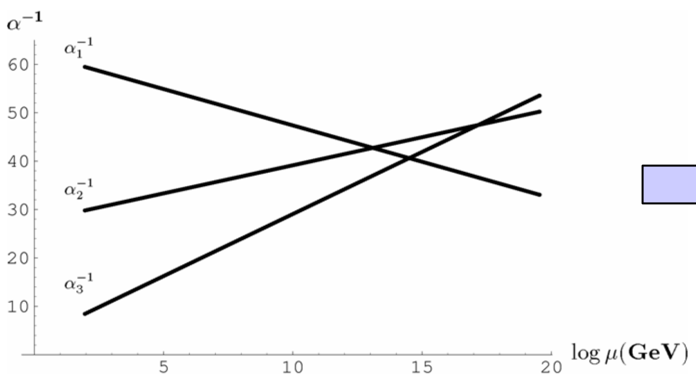
SUSY-GUTs

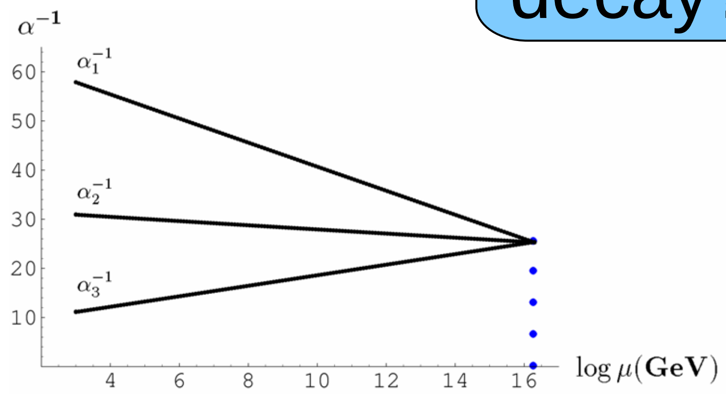
- probable extension of SM
  - beautiful unifications of forces and of matters
  - charge quantization
  - stabilization of the weak scale
  - gauge coupling unification (GCU)

Yukawa?

Higgs?

Proton decay?





$\Lambda_G \sim 2 \times 10^{16}\mathbf{GeV}$

SUSY-GUTs

- model building

theoretical issues

• doublet-triplet splitting

experimental issues $\boxed{\text{126GeV Higgs}}$

• wrong GUT relation ($Y_d = Y_e^T$)

• proton decay v.s. GCU

no longer success, but a constraint

GCU

requiring that models reduce to (N)MSSM

→ just restrict param. region on (N)MSSM

not easy to test

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SUSY grand GHU

- Hosotani mechanism   Y. Hosotani (1983)
  - symmetry breaking by a extra dim. component of the gauge field (A_5).

gauge-Higgs unification

- low energy prediction   T.Y. (2011)
  - A_5 (= adjoint Higgs) is massless @tree level, & acquires a mass of $O(m_{SB})$ via loop.

⇨ Its superpartners can have masses of $O(m_{SB})$.

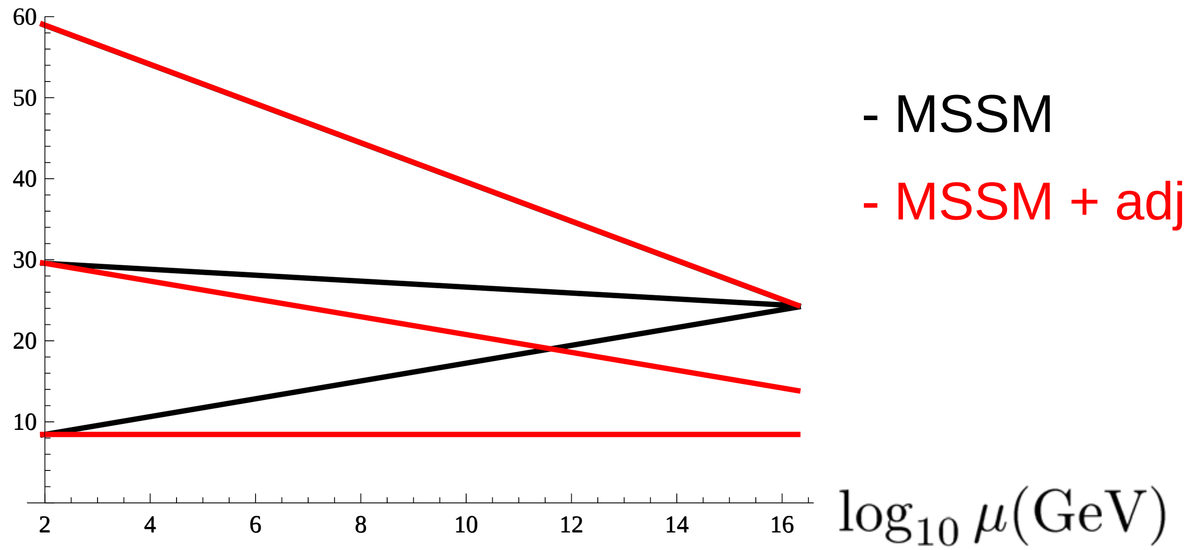
Light adjoints, $\mathbf{\Sigma_1}$, $\mathbf{\Sigma_2}$, $\mathbf{\Sigma_3}$ are predicted.

- Z_2-symm. : $\Sigma_i \to -\Sigma_i$ ⇨ SUSY inert triplet model

SUSY grand GHU

T.Y. (2011)

- gauge coupling unification
  - The adjoint matters : $\delta_{adj} b = (0, 2, 3)$



SUSY grand GHU

T.Y. (2011)

- gauge coupling unification

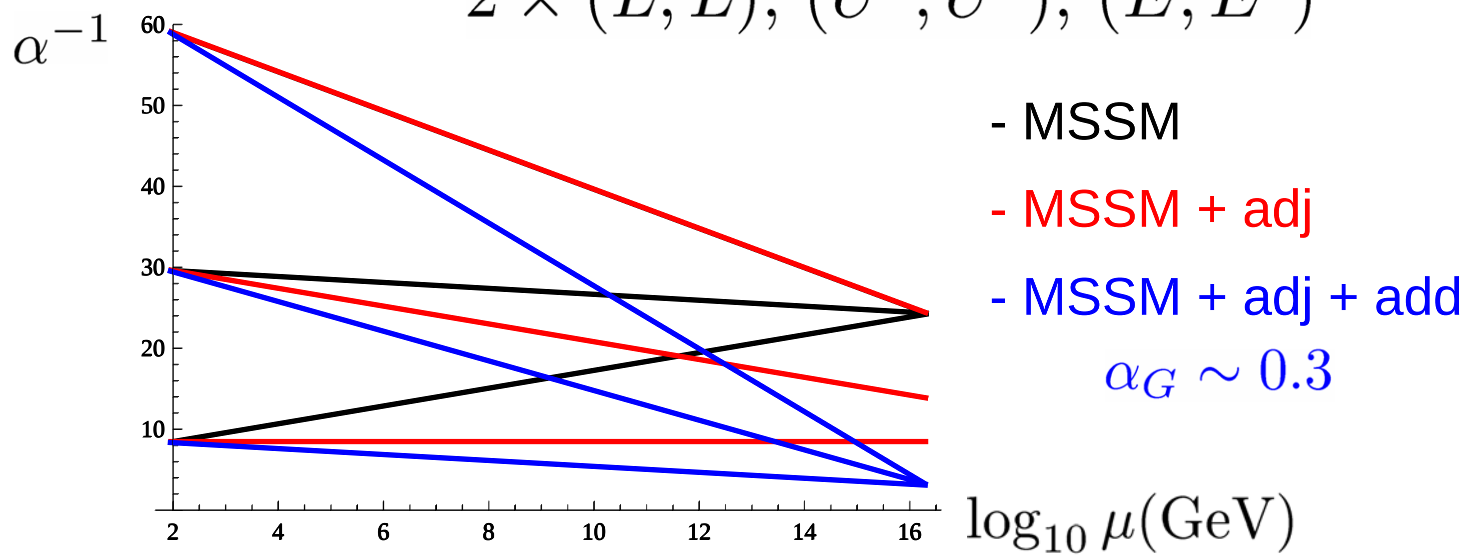
$n \lesssim 2$ to remain perturbative

  - The adjoint matters : $\delta_{adj} b = (0, 2, 3)$

⇨ recovered w/ $\delta_{add} b = (3+n, 1+n, n)$

ex1) additional matters for $\delta_{add} b = (4, 2, 1)$:

$$2 \times (L, \bar{L}), (U^c, \bar{U}^c), (E, \bar{E}^c)$$



SUSY grand GHU

- low energy effective theory
  - *SU*(3) is no longer asymptotically free,
    & remains strong @high energy
    ⇨ squarks & octet become rather heavy.
  - colorless fields : singlet & triplet
    ⇨ extended higgs sector

e.g. NMSSM-like contribution ⇨ heavier higgs

Higgs couplings are corrected at a few % level.

M.Kakizaki, S.Kanemura, H.Taniguchi & T.Y. in progress

poster by Taniguchi-kun

ILC

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phenomenology of SGGHU

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in progress

- Higgs sector extended

  H_u, H_d + $S\ (=\Sigma_1 : (\mathbf{1},\mathbf{1})_0)$ & $\Delta\ (=\Sigma_2 : (\mathbf{1},\mathbf{3})_0)$

  ⇨ 2 more [CP even, CP odd, charged] modes.

- superpotential

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

predictive!!

✓ no self couplings for S & Δ

✓ λ_Δ & λ_S are related to the gauge couplings

phenomenology of SGGHU

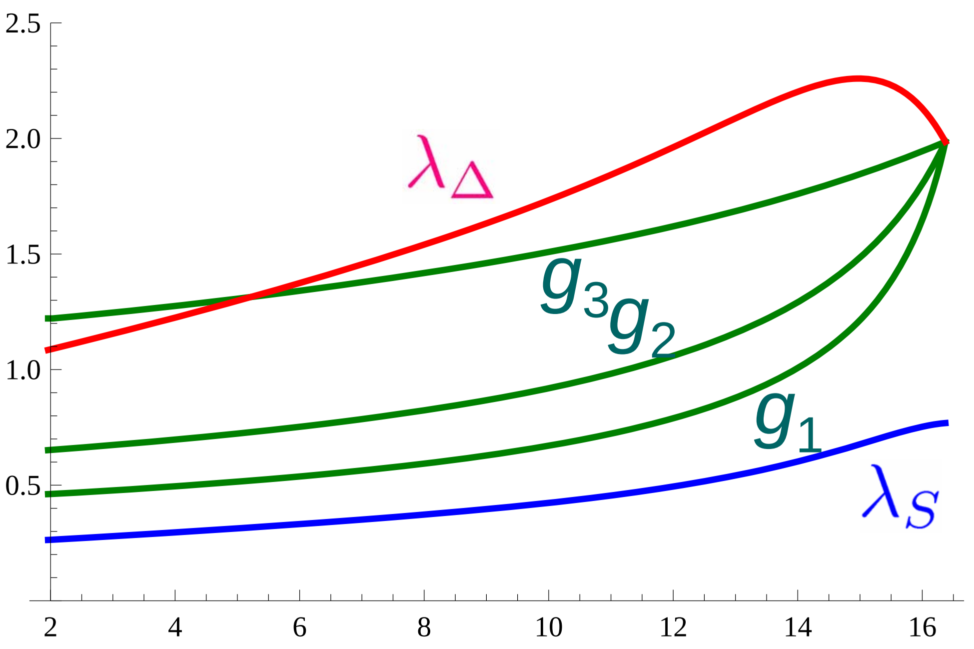
M.Kakizaki, S.Kanemura, H.Taniguchi & T.Y. in progress

- RG running
  - fix a model ⇨ gauge coupling unification
  - set $\lambda_\Delta = 2\sqrt{5/3}\lambda_S = g_{1,2,3}$ @ GUT scale
  - solve the RGE

ex1)

$\lambda_\Delta = 1.1 \quad \lambda_S = 0.26$

@ weak scale



phenomenology of SGGHU

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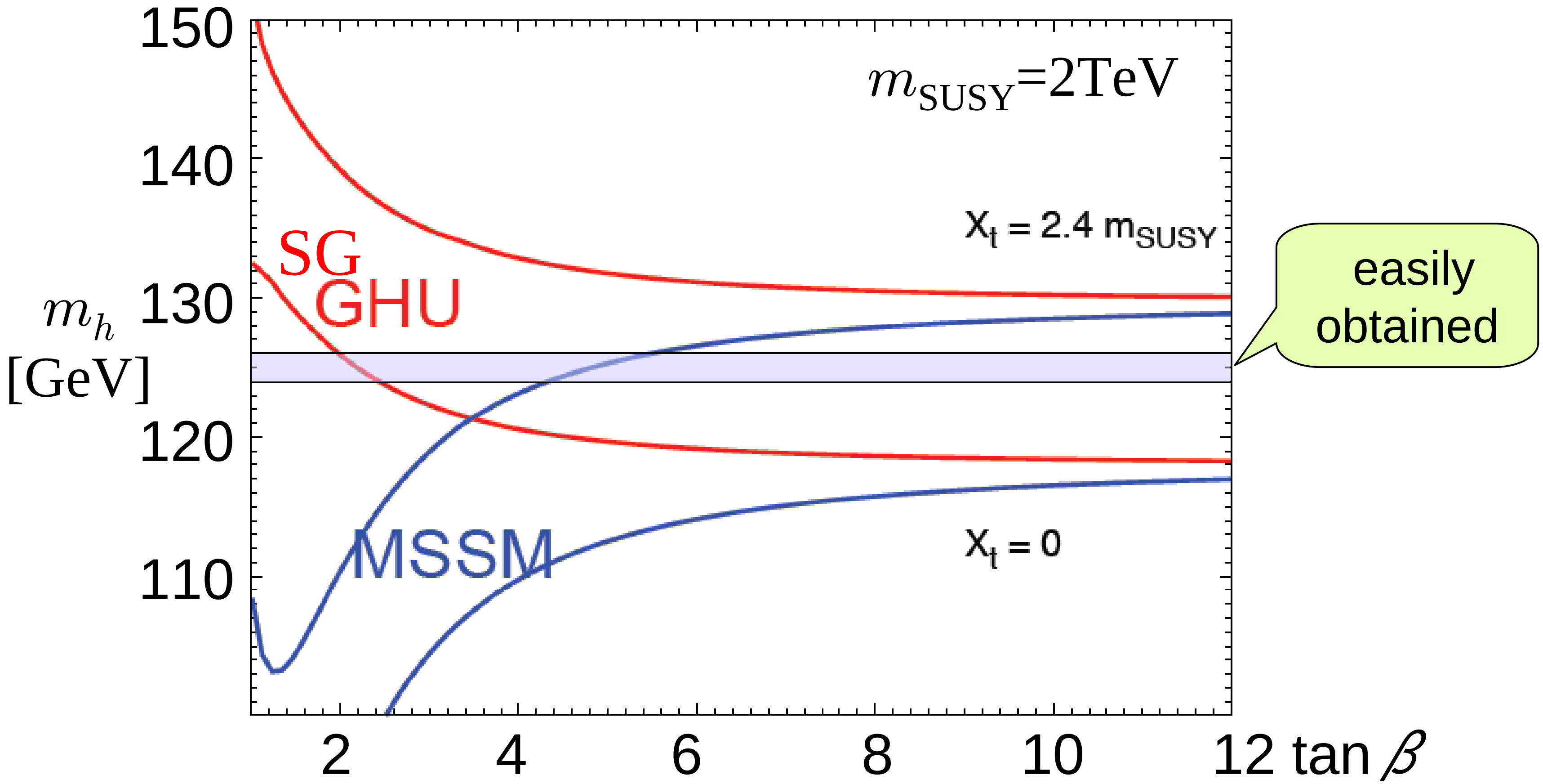
H.Taniguchi & T.Y.
in progress

- higs mass
  - NMSSM-like *F*-term contributions @tree



phenomenology of SGGHU

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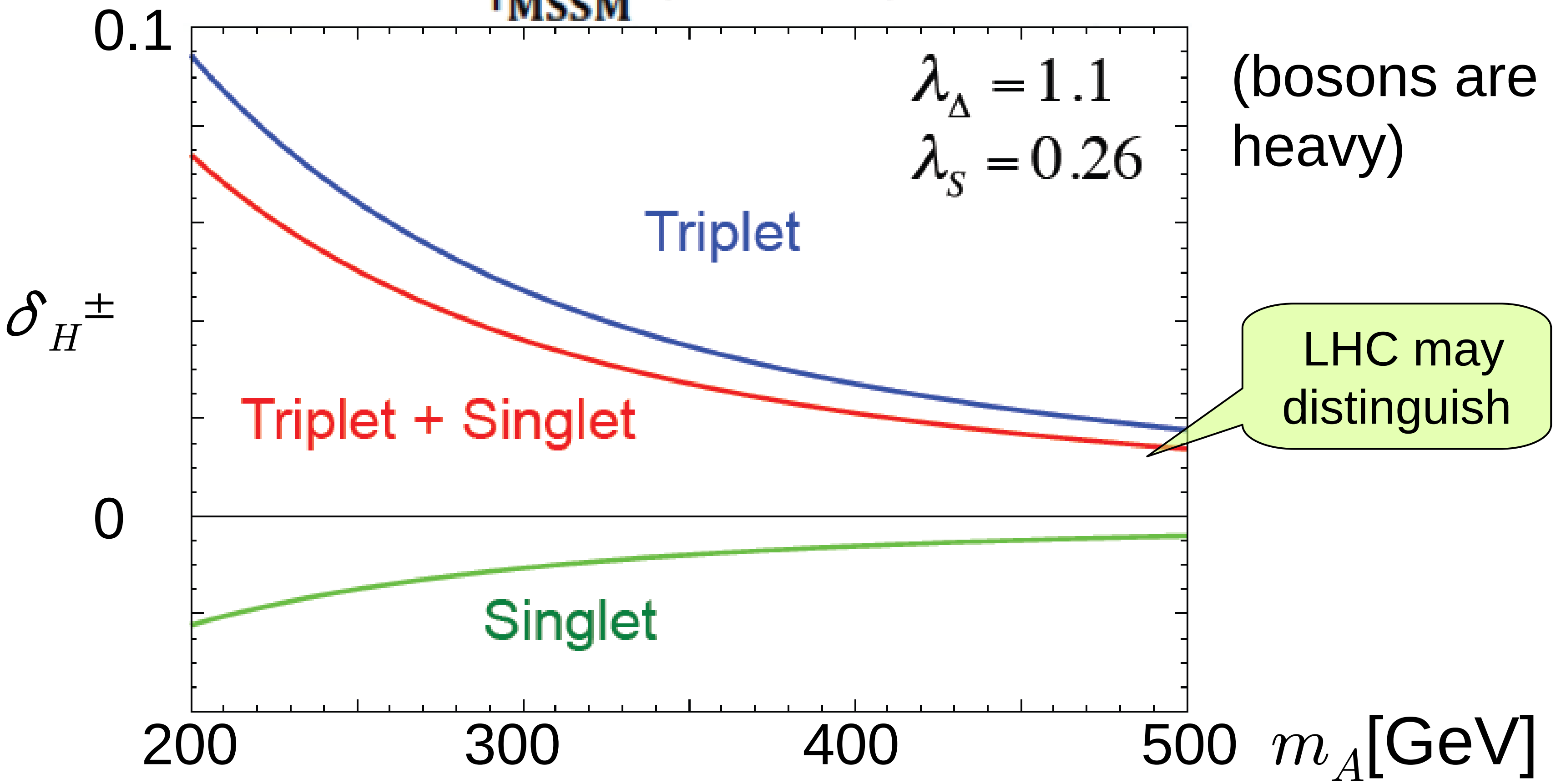
in progress

- charged Higgs mass

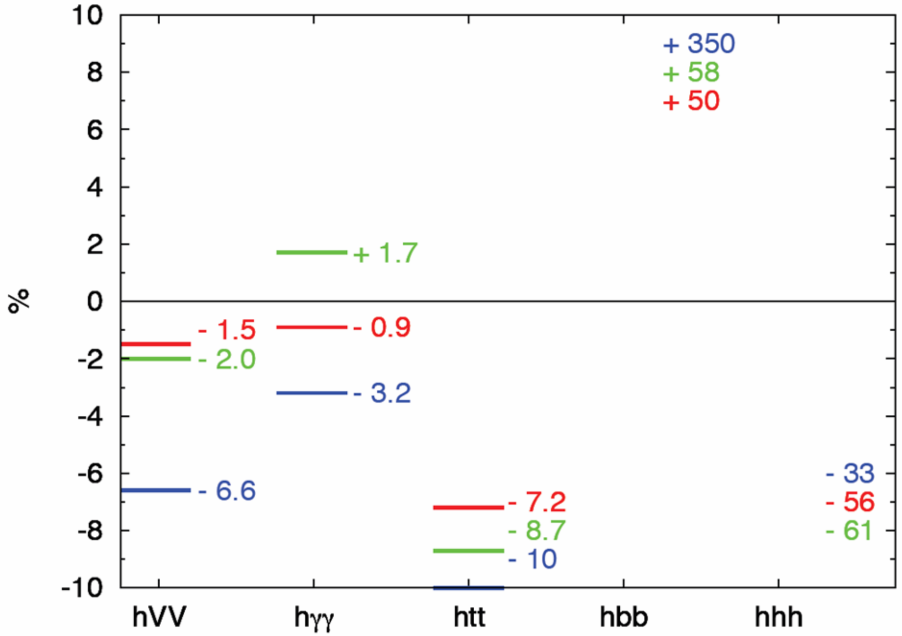
$$m_{H^\pm} = m_{H^\pm}\Big|_{\text{MSSM}} (1 + \delta_{H^\pm})$$

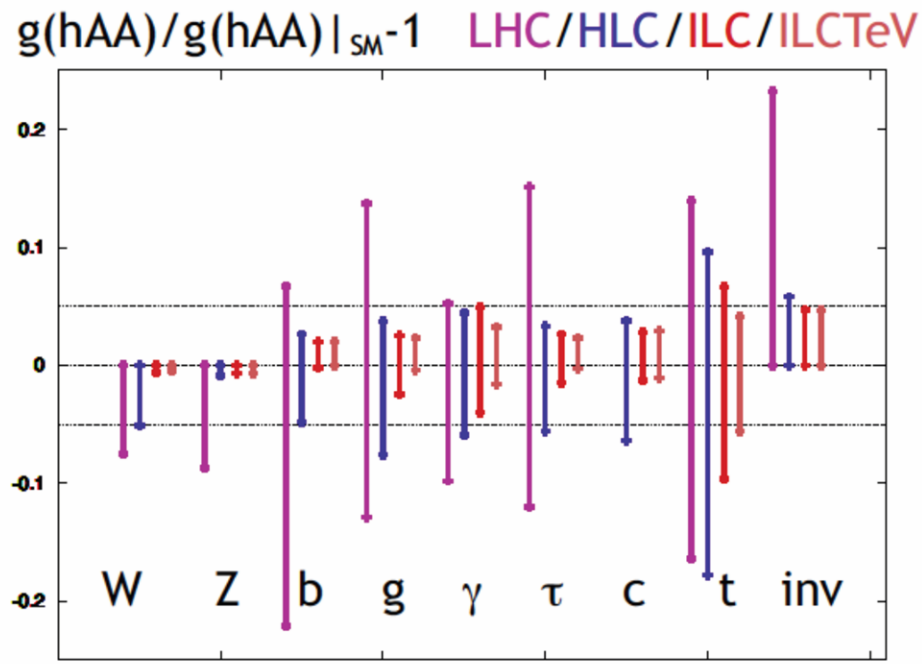


(bosons are heavy)

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]

MSSM:
NMSSM:
GHU:

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

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

We can distinguish models using LC precision measurements

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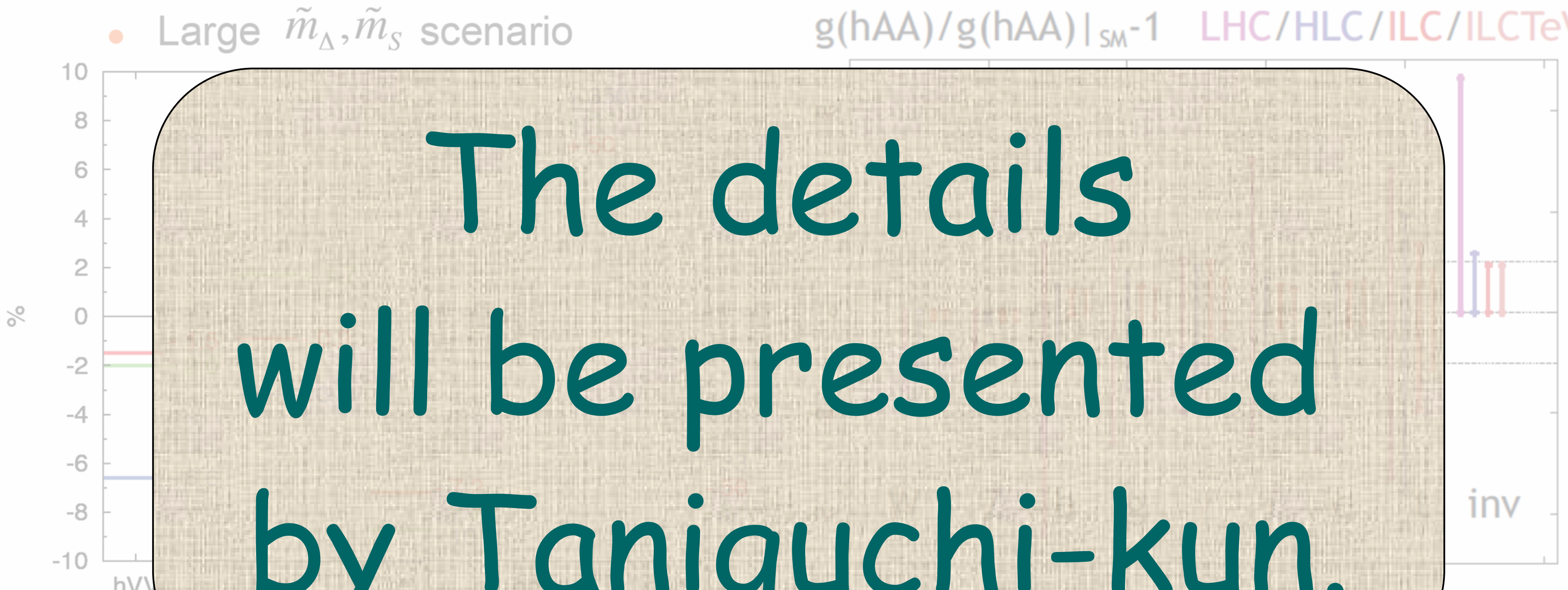

The details will be presented by Taniguchi-kun.

MSSM:

NMSSM:

GHU:

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

We can distinguish models using LC precision measurements

summary

- SUSY grand GHU

T.Y. (2011)

predictive!!

  - ✓ natural doublet-triplet splitting
    - ⇨ theoretically well motivated
  - ✓ generally predicts light adjoint chiral matters
    - ⇨ the Higgs sector is extended, S & Δ
- phenomenological study

M.Kakizaki, S.Kanemura, H.Taniguchi & T.Y. in progress

  - ✓ heavier Higgs mass
  - ✓ distinguishable charged Higgs mass
  - ✓ a few % deviations from the SM/MSSM
    - ⇨ can be a reasonable target of the ILC

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back up

Hosotani mechanism & DT Splitting

symmetry breaking by a continuous Wilson loop

$\sim$ VEV of zero-mode of A_5

gauge-Higgs unification

- The order parameter, $W \equiv \mathcal{P} \exp\left(i \int_C A_5 dy\right)$, is *valued on the group* (instead of the algebra).

special ⇐ traceless

$$\langle W \rangle = \mathrm{diag}(1,1,1,-1,-1) \equiv P_W$$

(inversely) missing VEV

$$\sim \mathrm{diag}(0,0,0,v,v)$$

⇒ DT Splitting [2] T.Y.

Hosotani mechanism & DT

- basis transformation

  (broken) gauge transformation w/ $\alpha^{(-)} =$

  ⇨ $\langle A_5 \rangle \to 0$ ⇨ $\langle W \rangle \to \mathbf{1}$

  - BCs around $y = y_\pi$ are modified:

    ex) $\Psi(y_\pi - y) = \eta_\pi^{\Psi} \gamma_5 \quad \Psi(y_\pi + y)$

    $P_W = \mathrm{diag.}(1,1,1,-1,-1)$

    ⇨ symmetry breaking by BCs,
    as in the orbifold breaking

$$\mathbf{5}: \begin{pmatrix} (+,-) \\ (+,-) \\ (+,-) \\ (+,+) \\ (+,+) \end{pmatrix}$$
$$y = y_0, y_\pi$$

- DT splitting [2] T.Y.

  "anti-periodic" **5** chiral ⇨ massless doublet

grand gauge-Higgs unification

- difficulty

[1] K.Kojima, K.Takenaga & T.Y.

  - orbifold action projects out adjoint scalars

    due to the opposite orbifold BCs.

  - this difficulty is shared w/ heterotic string

    - very well studied, classified w/ Kac-Moody level
    - ``diagonal embedding" method

Kuwakino's talk

K.R.Dienes & J.March-Russel (1996)

We borrow this in our pheno. models.

grand gauge-Higgs unification

- diagonal embedding (in field theory) [1] K.Kojima, K.Takenaga & T.Y.

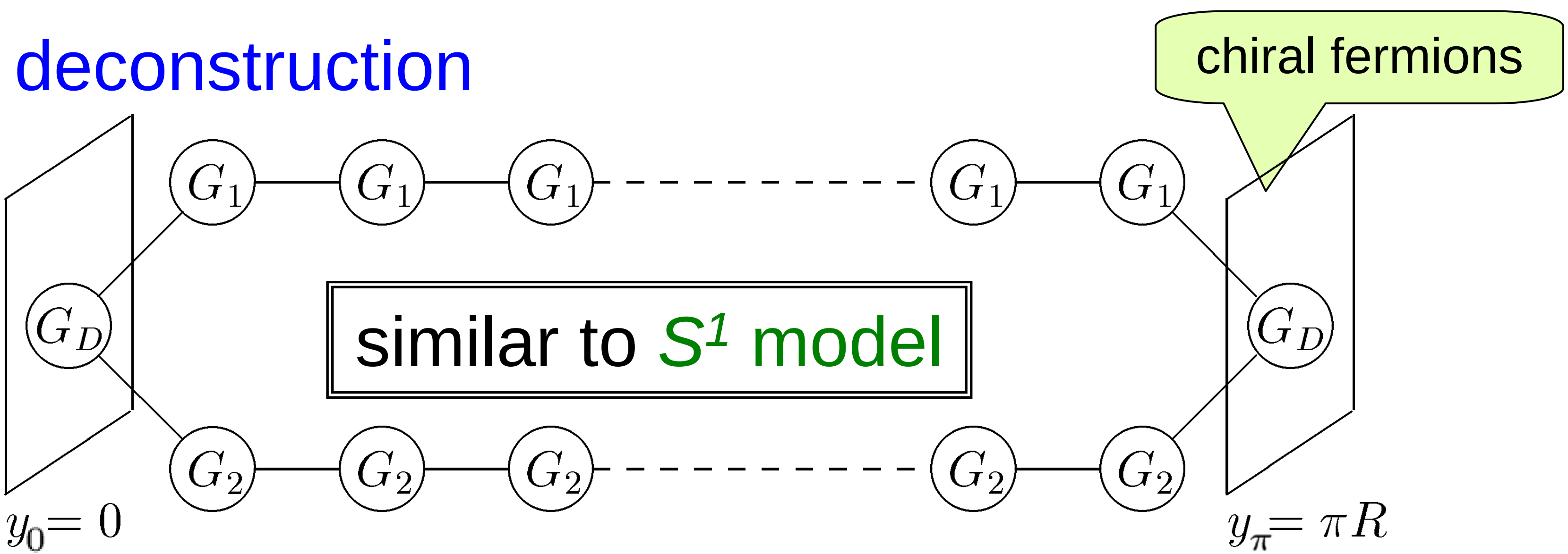
ex) S^1/Z_2 $(G \times G \to G_D)$ $y_0 = 0 < y < y_\pi = \pi R$

$A_\mu^{(1)}(x^\mu, y_i - y) = A_\mu^{(2)}(x^\mu, y_i + y)$

⇒ $A_5^{(+)} = (A_5^{(1)} - A_5^{(2)})/\sqrt{2}$ has a zero-mode.

This provides a way to "introduce" chiral fermions in S^1 models!!

- deconstruction



grand gauge-Higgs unification

- matter content
  - bulk fields → $\boxed{H_u \,\&\, H_d}$
    - similar to S^1 model : vector-like
    - couple to W.L. : $SU(5)$ incomplete multiplets
  - boundary fields → $\boxed{\text{chiral matter}}$
    - essentially 4D fields : chiral
    - not couple to W.L. : $SU(5)$ full multiplets