Higgs and Physics beyond the Standard Model (2)

岡田安弘(KEK/総合研究大学院大学)

京都大学理学研究科特別講義

2012年8月27日－29日

Higgs in new physics

- The Higgs particle is a window to new physics.
- Many new physics models predict a SM-like Higgs particle. Precise measurements of its properties are necessary to probe what is behind the Higgs boson.

(1) Higgs mass in the SM
(2) Higgs in SUSY models
(3) Strongly interacting Higgs sector

[1] Higgs mass in the Minimal SM

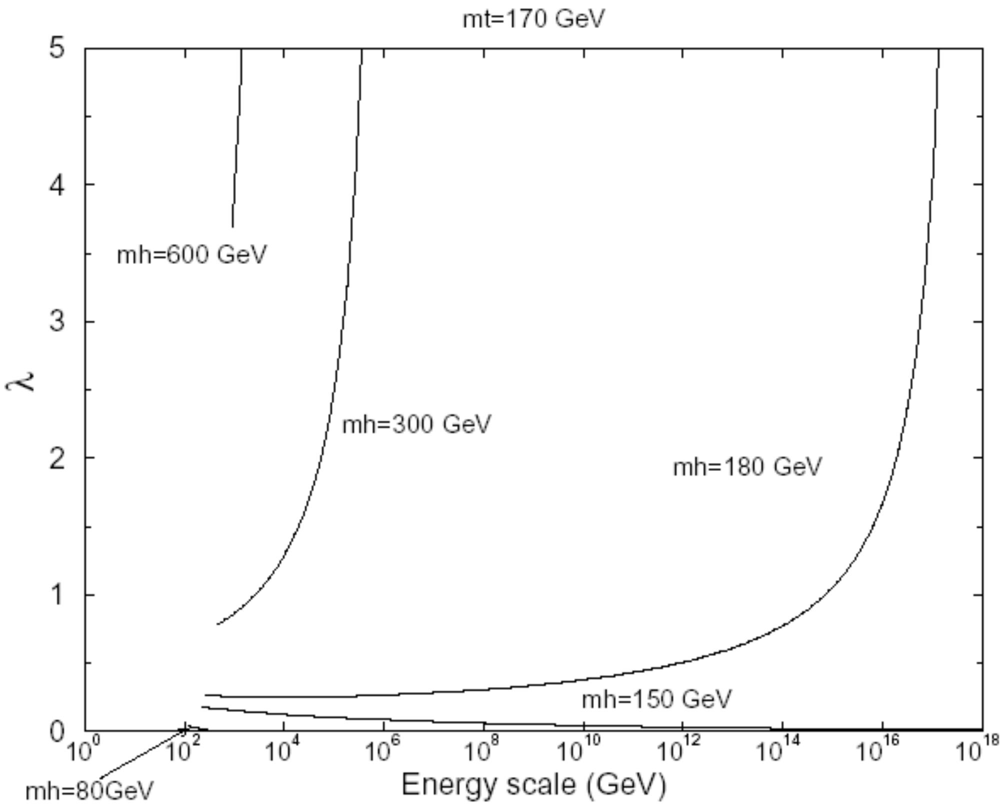
Large Higgs mass ⇔ Large self-coupling ⇔ Strong dynamics

$$\mu\frac{d}{d\mu}\lambda = \frac{1}{16\pi^2}(24\lambda^2 + 12y_t^2\lambda - 6y_t^4 + ...)$$

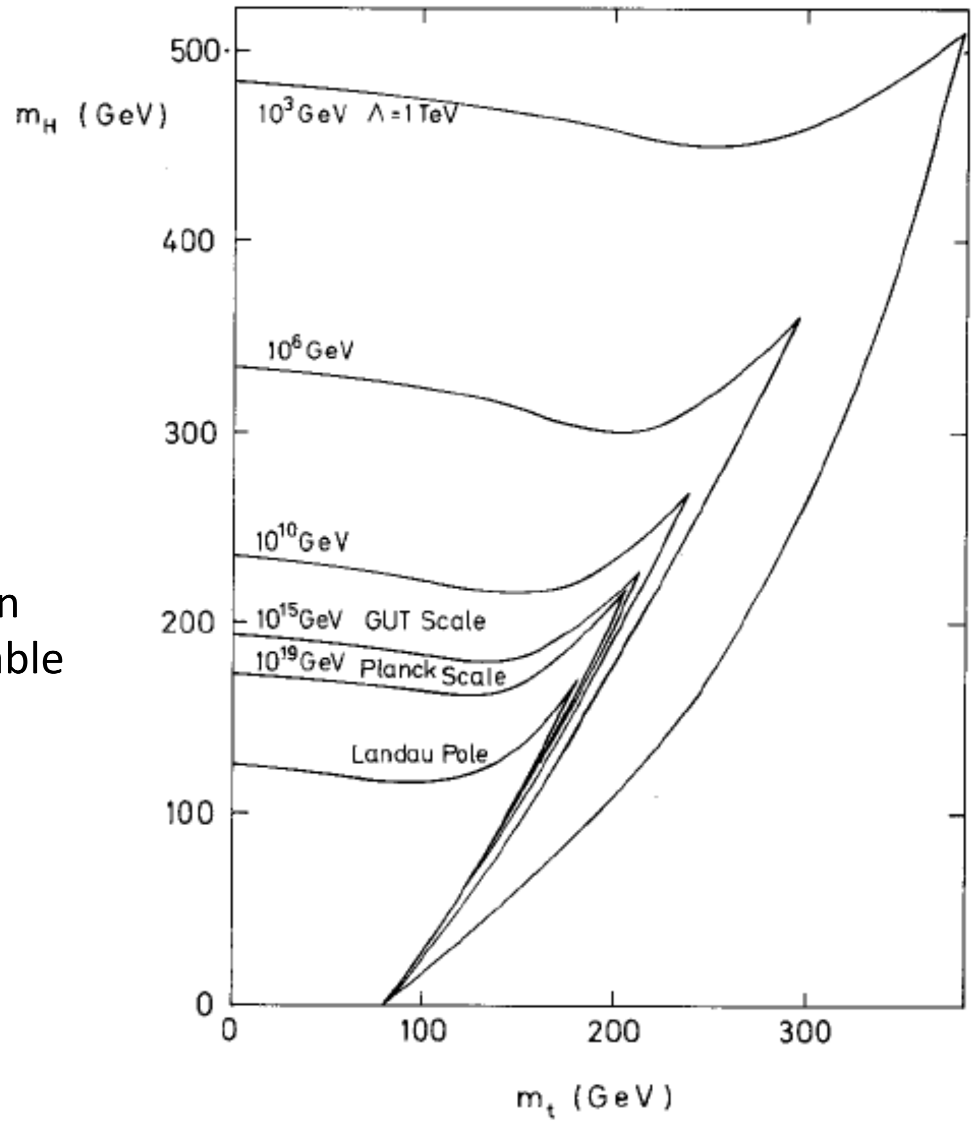
$$V = -\mu^2|\phi|^2 + \lambda|\phi|^4$$
$$m_h = \sqrt{2\lambda}v$$

If we require that the SM is valid up to 10^19 GeV,

130GeV$\leq m_h \leq$ 180 GeV



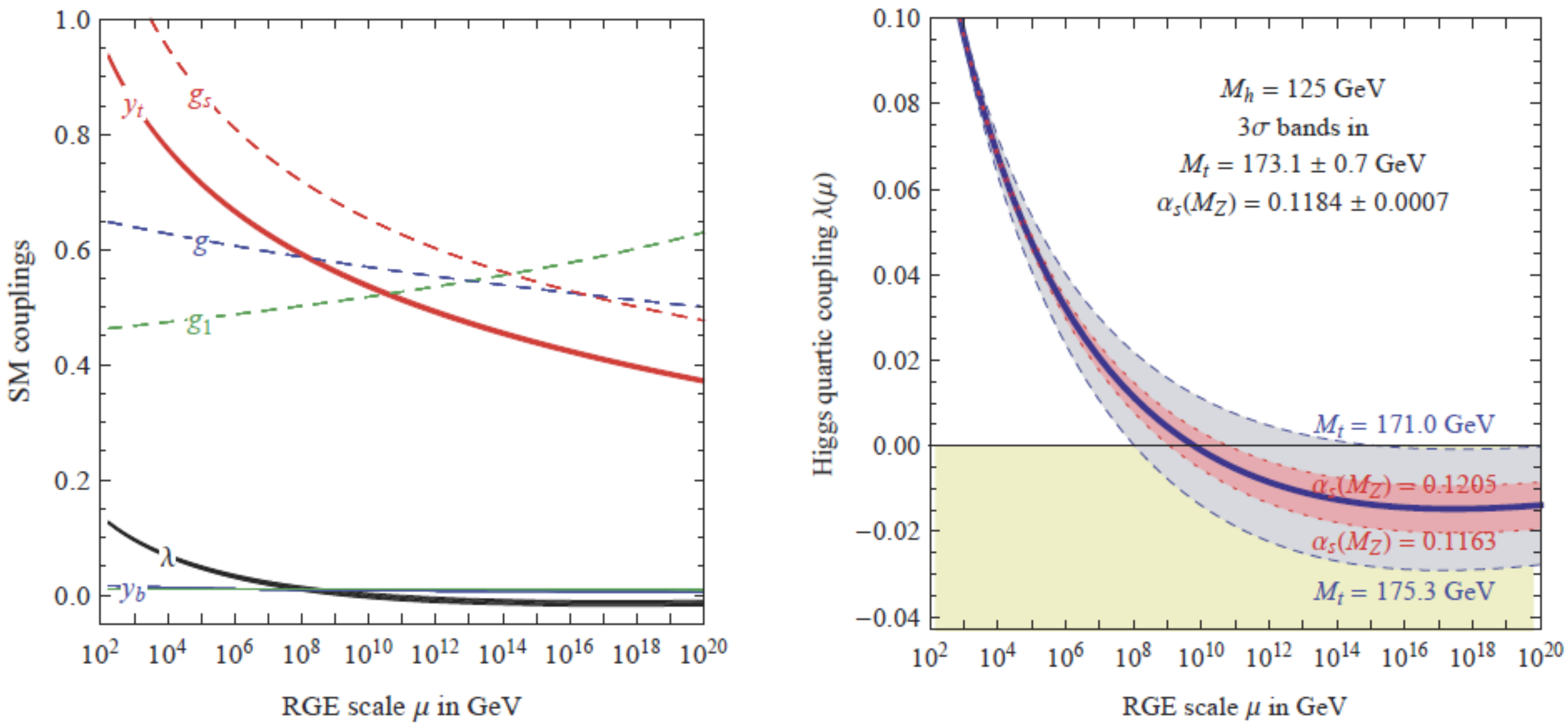
M.Lindner 1986



Lower values of the Higgs boson mass is permitted, if a meta-stable vacuum is allowed.

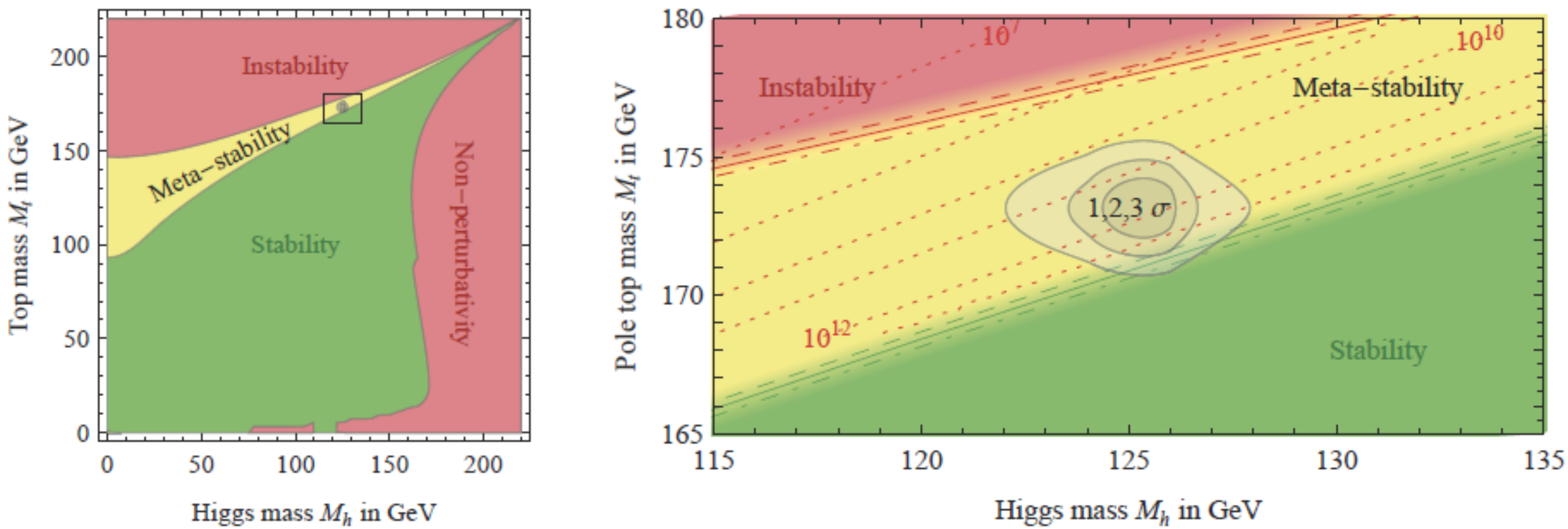
Giuseppe Degrassi[a], Stefano Di Vita[a], Joan Elias-Miró[b], José R. Espinosa[b,c], Gian F. Giudice[d], Gino Isidori[d,e], Alessandro Strumia[g,h]

arXive: 1205.6497



Giuseppe Degrassi[a], Stefano Di Vita[a], Joan Elias-Miró[b], José R. Espinosa[b,c],
Gian F. Giudice[d], Gino Isidori[d,e], Alessandro Strumia[g,h]

arXive: 1205.6497



[2] Higgs in SUSY models

- SUSY connect the weak scale and the Planck scale. (The weak scale is a derived quantity from the SUSY breaking physics.)
- Existence of bosons and fermions are required by symmetry.
- Stability of the Higgs potential is more or less guaranteed by the SUSY algebra.

Hierarchy problem and SUSY

String and GUT unification -> A cutoff scale ~ Planck scale (10^{19} GeV).
SUSY is the only known symmetry to avoid the fine tuning in the renormalization of the Higgs boson mass at the level of O(10^{34}).

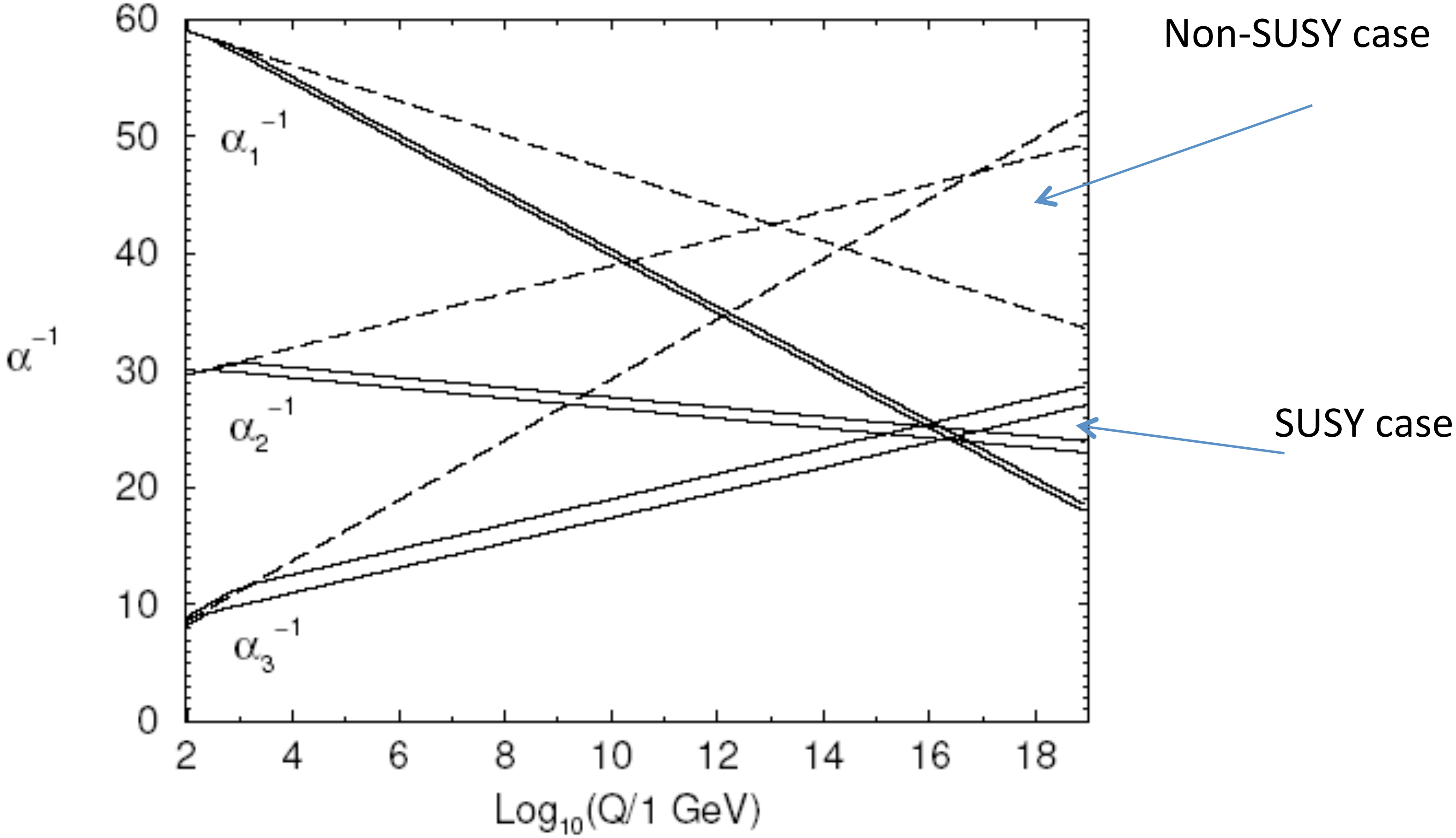
$$M_h^2 = M_{h,tree}^2 + c\frac{g^2}{4\pi^2}M_{pl}^2 \qquad (w/o\ SUSY)$$

$$M_h^2 = M_{h,tree}^2\left(1 + c'\frac{g^2}{4\pi^2}\ln(M_{pl}/M_W)\right) \qquad (with\ SUSY)$$

Three possibilities:

1. Some new dynamics associated with the electroweak symmetry breaking exists not far from the TeV scale.
2. Low energy SUSY exists.
3. Fine-tuning is realized by unknown reason.

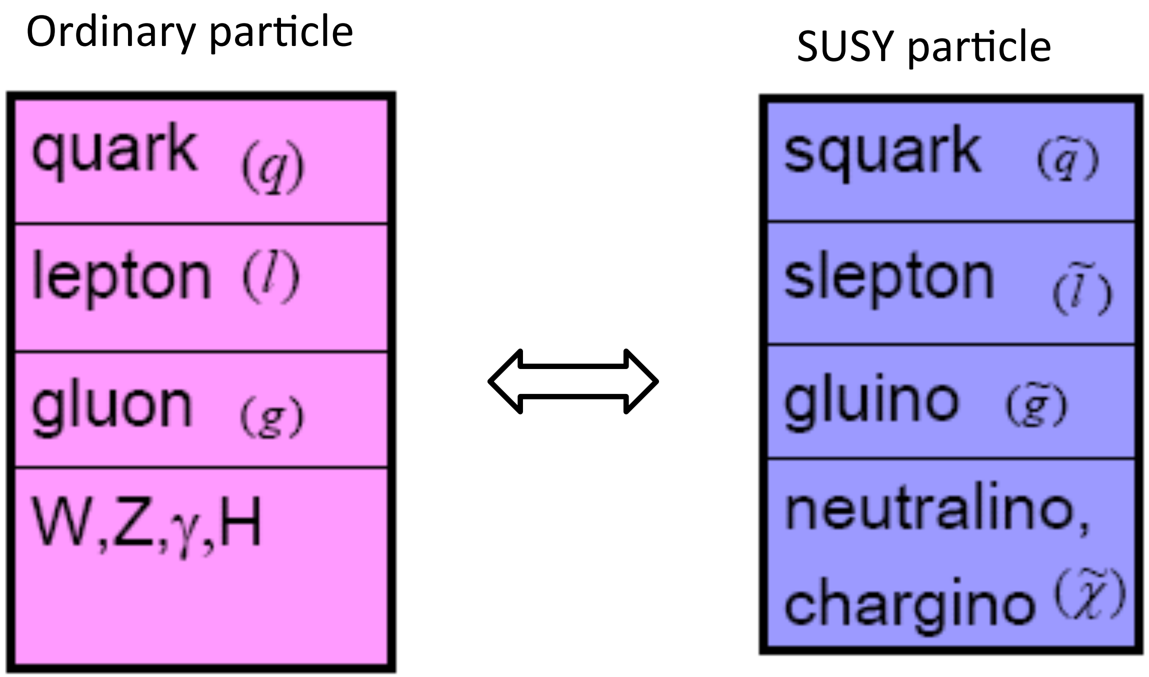
Gauge coupling unification



$$SU(3) \times SU(2) \times U(1) \subset SU(5)$$

MSSM

Minimal SUSY Standard Model: minimal particle contents



Super potential: Two Higgs doublet field with Y=1/2 and -1/2 to give mass terms for all quarks and leptons.

$$W = y_d H_1 \overline{D} Q + y_u H_2 \overline{U} Q + y_l H_1 \overline{E} L + \mu H_1 H_2$$

The MSSM particle content= Two Higgs doublet SM
+ scalar SUSY particles (squarks and sleptons)
+fermionic SUSY paricles (gluino, charginos, neutalinos)

New dimensionful parameters are introduced: about 100, mostly to give masses for SUSY particles.
Number of independent dimensionless coupling constants are one less than that of the SM.

The Higgs sector of the MSSM is a special case of Two Higgs doublet model.

At the tree level:
Type-II two Higgs doublet model
Higgs –potential id determined by gauge coupling constants.
(The lightest neutral Higgs mass is less that the Z boson mass at the tree-level)

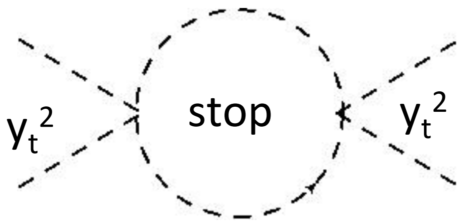
One loop correction raises the lightest Higgs boson upper bound

Physical Higgs bosons h, H (CP-even), A (CP-odd), $H^{\pm}$ (Charged Higgs)

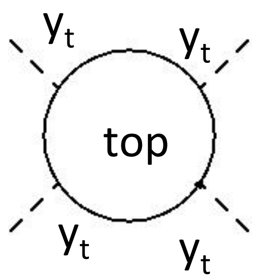
Higgs potential

$$
\begin{aligned}
V_{Higgs} &= m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1 \cdot H_2 + \bar{H}_1 \cdot \bar{H}_2) \\
&+ \frac{g_2^2}{8}(\bar{H}_1 \tau^a H_1 + \bar{H}_2 \tau^a H_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 \\
&+ \Delta V,
\end{aligned}
$$

ΔV =



\-



\+ ...

$$
m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{6}{(2\pi)^2} \frac{m_t^4}{v^2} \ln \frac{m_{stop}^2}{m_t^2}, \qquad \left(\tan\beta = \frac{<H_2^0>}{<H_1^0>}\right)
$$

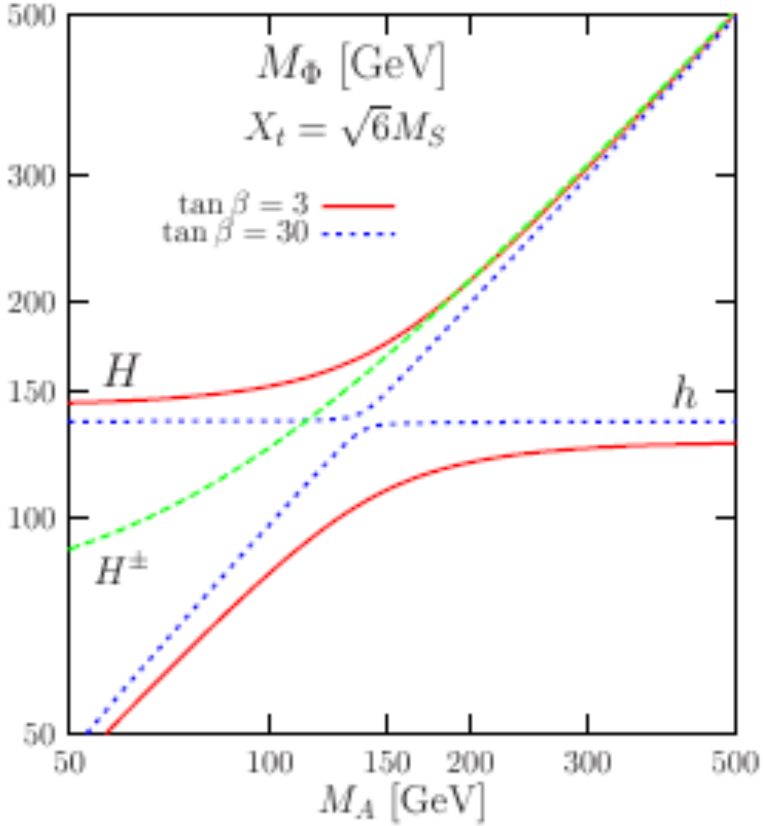
(for degenerate stops)

$$
m_h < 130\text{GeV}
$$

Y.Okada, M.Yamaguchi, T.Yanagida;
J.Ellis, G.Ridorfi, F.Zwirner;
H.Haber, R.Hempfling, 1991

Masses of five Higgs states

Masses of the CP even Higgs bosons (h,H) and charged Higgs boson
Is a function of CP-odd Higgs mass (MA), the vacuum angle (tan b) and
parameters in loop diagrams (stop masses, mixing, etc.)

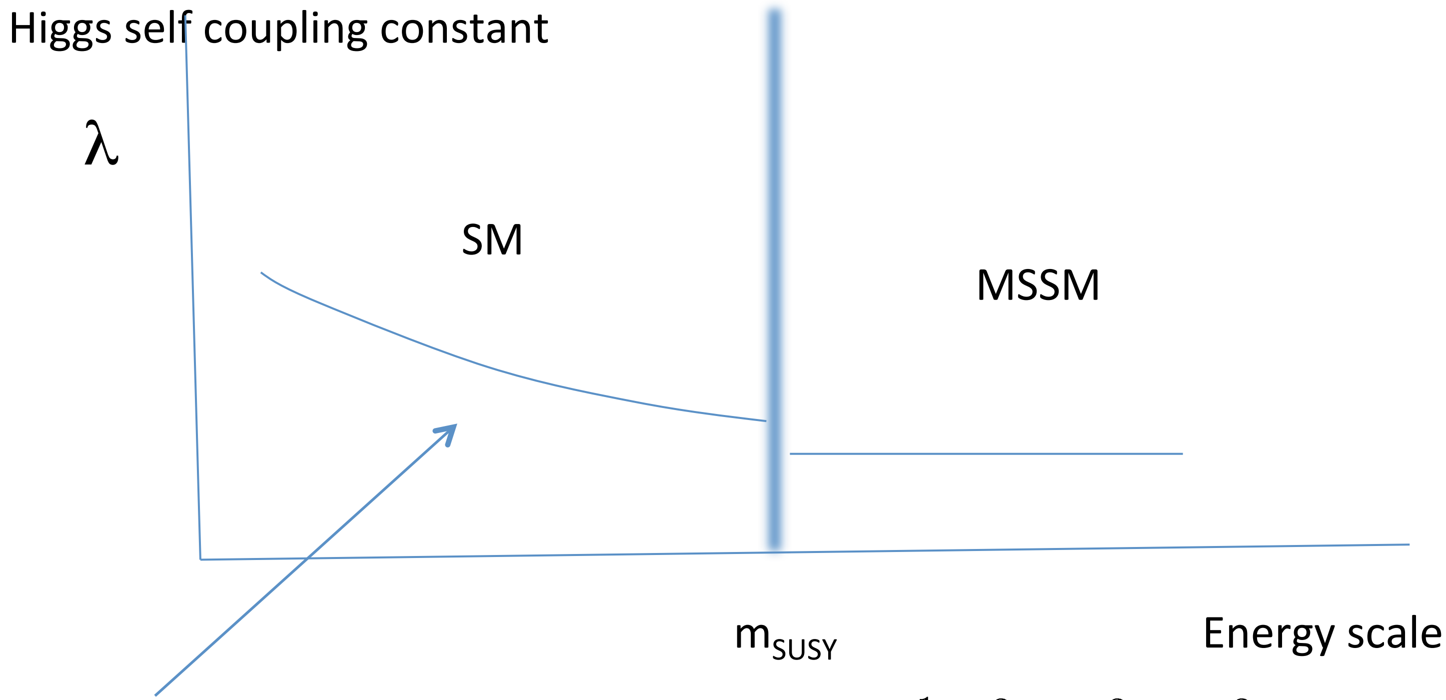


Precision SUSY Higgs measurements
are important even after SUSY is discovered.
Cf. Precision electroweak measurements
(mz, mw, $\sin^2\theta_W$, mt, mh)

Decoupling limit
(h becomes the SM-like Higgs boson)

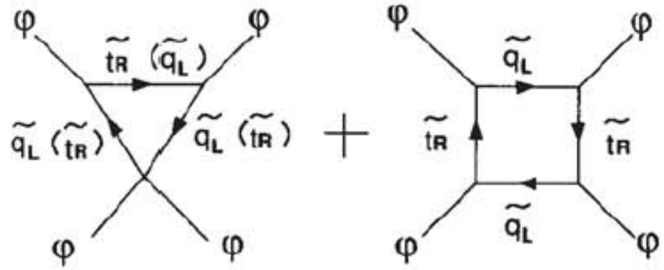
Understanding the origin of large radiative corrections

Consider the case that all extra particles decouples at m_{SUSY}



Running due to the SM top Yukawa coupling

$$\lambda(m_{SUSY}) = \frac{1}{8}(g_1^2 + g_2^2)\cos^2 2\beta + \delta\lambda$$

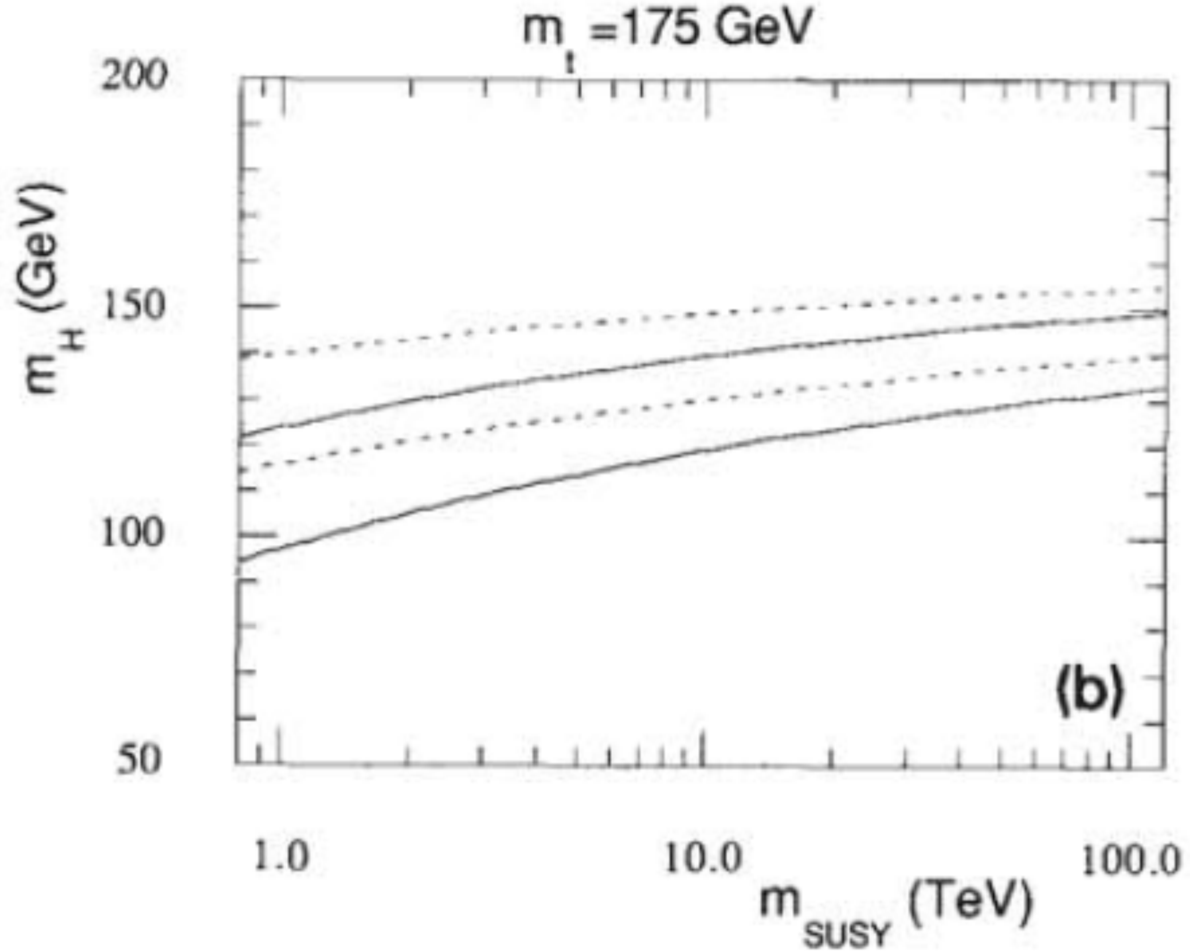


δλ is maximal when the stop LR mixing term is $\sqrt{6}m_{SUSY}$ (maximal stop mixing)

Y.Okada, M.Yamaguchi, and T.Yanagida, PLB262 (1991)

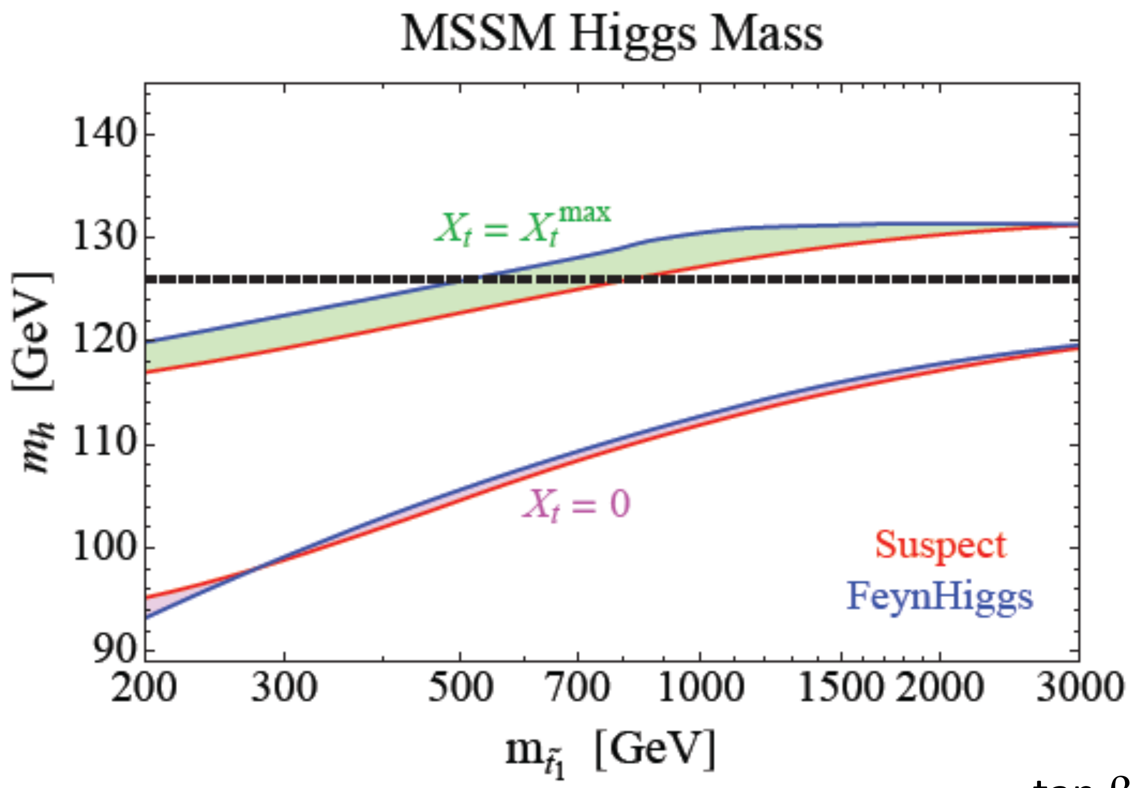
The lightest Higgs boson mass in the MSSM

solid: no stop mixing
dot: maximal stop mixing



Recent calculations

L.Hall, D.Pinner andJ.T.Ruderman, arXive1112.2703



tan β = 20

large stop mass and/or large stop mixing is needed for the Higgs mass to be near 126 GeV.

Global fit in CMSSM and NUHM1 after 1/fb LHC

O.Buchmuller,et al. arXiv: 1110.3568

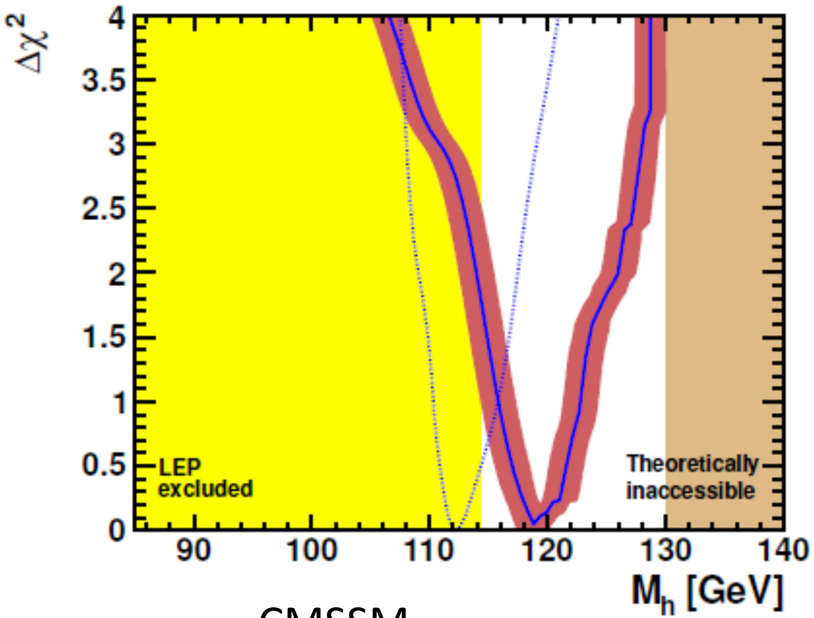
CMSSM

m_0 : Universal scalar mass at the GUT scale
$m_{1/2}$: Universal gaugino mass a the GUT scale
A_0: Universal triple scalar coupling
$\tan\beta$: The ratio of two Higgs VEV
All SUSY mass parameters can be determined by solving RGEs from the GUT to the weal scale.

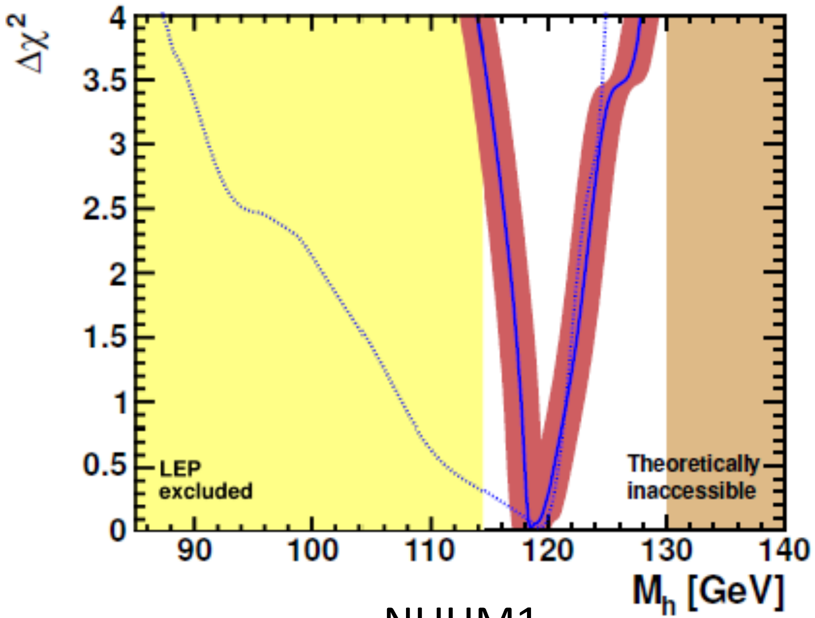
NUHM1

In addition to the CMSSM parameters, the soft SUSY breaking term for the Higgs fields is taken to be independent of m_0.

The lightest Higgs boson mass



CMSSM



NUHM1

Best fit point

Model	Minimum χ^2/d.o.f.	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (GeV) (no LEP)
CMSSM pre-LHC	21.5/20	37%	360^{+180}_{-100}	90^{+220}_{-50}	-400^{+730}_{-970}	15^{+15}_{-9}	$111.5^{+3.5}_{-1.2}$
CMSSM LHC$_{1/\mathrm{fb}}$	28.8/22	15%	780^{+1350}_{-270}	450^{+1700}_{-320}	-1100^{+3070}_{-3680}	41^{+16}_{-32}	$119.1^{+3.4}_{-2.9}$
Linear Δ BR$(b \to s\gamma)$	28.0/22	18%	720^{+1170}_{-230}	420^{+1270}_{-270}	-1100^{+2180}_{-2750}	39^{+18}_{-22}	$118.6^{+3.9}_{-1.9}$
$(g-2)_\mu$ neglected	21.3/20	38%	2000^{+}_{-}	1050^{+}_{-}	430^{+}_{-}	22^{+}_{-}	$124.8^{+3.4}_{-10.5}$
Both	20.5/20	43%	1880^{+}_{-}	1340^{+}_{-}	1890^{+}_{-}	47^{+}_{-}	$126.1^{+2.1}_{-6.3}$
NUHM1 pre-LHC	20.8/18	29%	340^{+280}_{-110}	110^{+160}_{-30}	520^{+750}_{-1730}	13^{+27}_{-6}	$118.9^{+1.1}_{-11.4}$
NUHM1 LHC$_{1/\mathrm{fb}}$	27.3/21	16%	730^{+630}_{-170}	150^{+450}_{-50}	-910^{+2990}_{-1170}	41^{+16}_{-24}	$118.8^{+2.7}_{-1.1}$
Linear Δ BR$(b \to s\gamma)$	26.6/21	18%	730^{+220}_{-90}	150^{+80}_{-20}	-910^{+2990}_{-1060}	41^{+16}_{-22}	$118.8^{+3.1}_{-1.3}$
$(g-2)_\mu$ neglected	20.3/19	38%	2020^{+}_{-}	1410^{+}_{-}	2580^{+}_{-}	48^{+}_{-}	$126.6^{+0.7}_{-1.9}$
Both	19.5/19	43%	2020^{+}_{-}	1410^{+}_{-}	2580^{+}_{-}	48^{+}_{-}	$126.6^{+0.7}_{-1.9}$

Tension between muon g-2 and LHC SUSY search
If muon g-2 is omitted, the fit becomes better and the SUSY mass spectrum and the Higgs boson mass tends to be heavier.

The Higgs sector of the phenomenological MSSM in the light of the Higgs boson discovery

ArXive: 12071348

A. Arbey[a,b,c], M. Battaglia[c,d,e], A. Djouadi[c,f] and F. Mahmoudi[c,g]

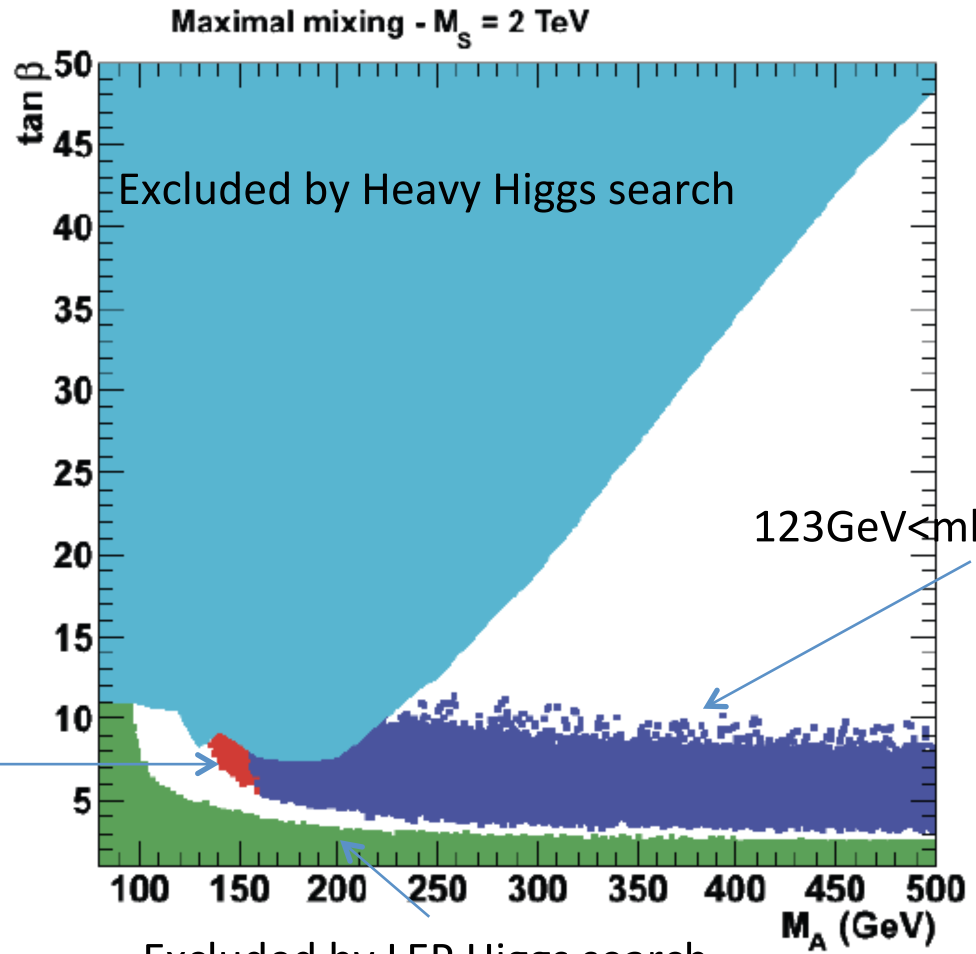
(1) Maximal mixing
 Xt= sqrt(6)*Ms

(2)Typical mxing
Xt=Ms

(3)No mixing
Xt=0

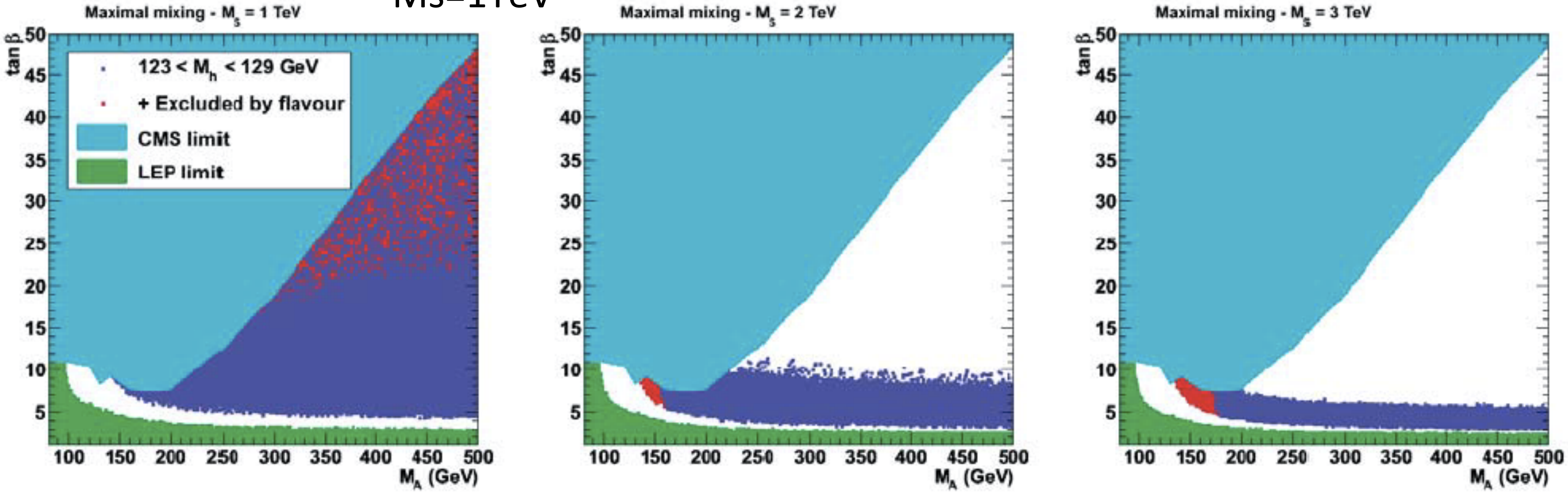
$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu \cot\beta$$

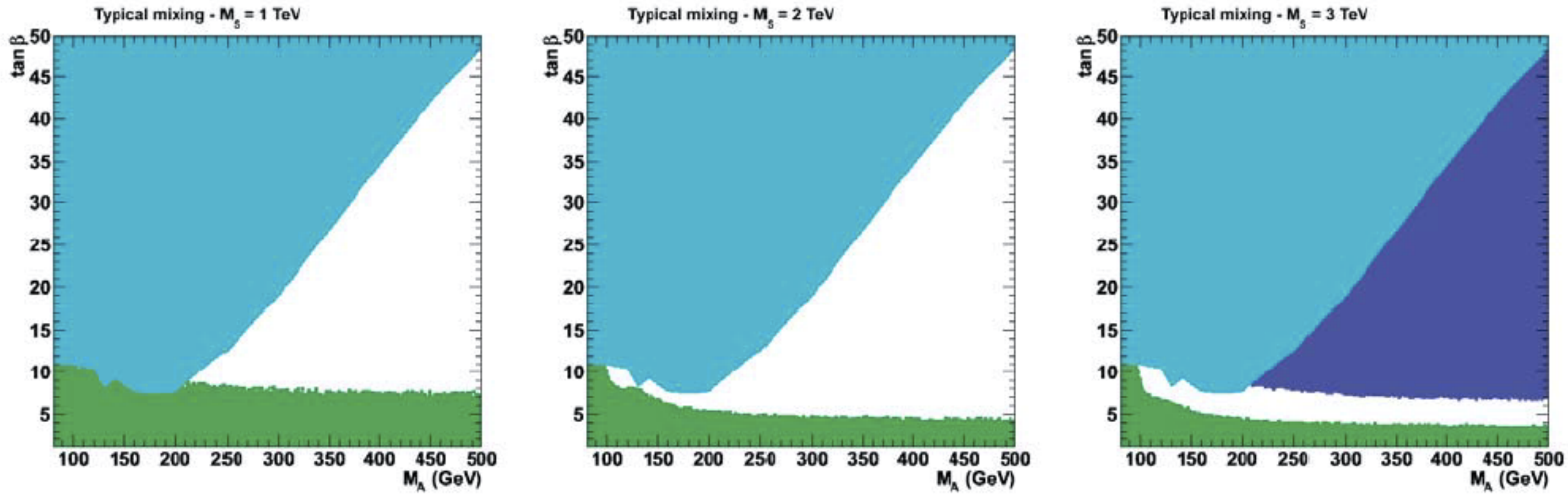


Maximal mixing

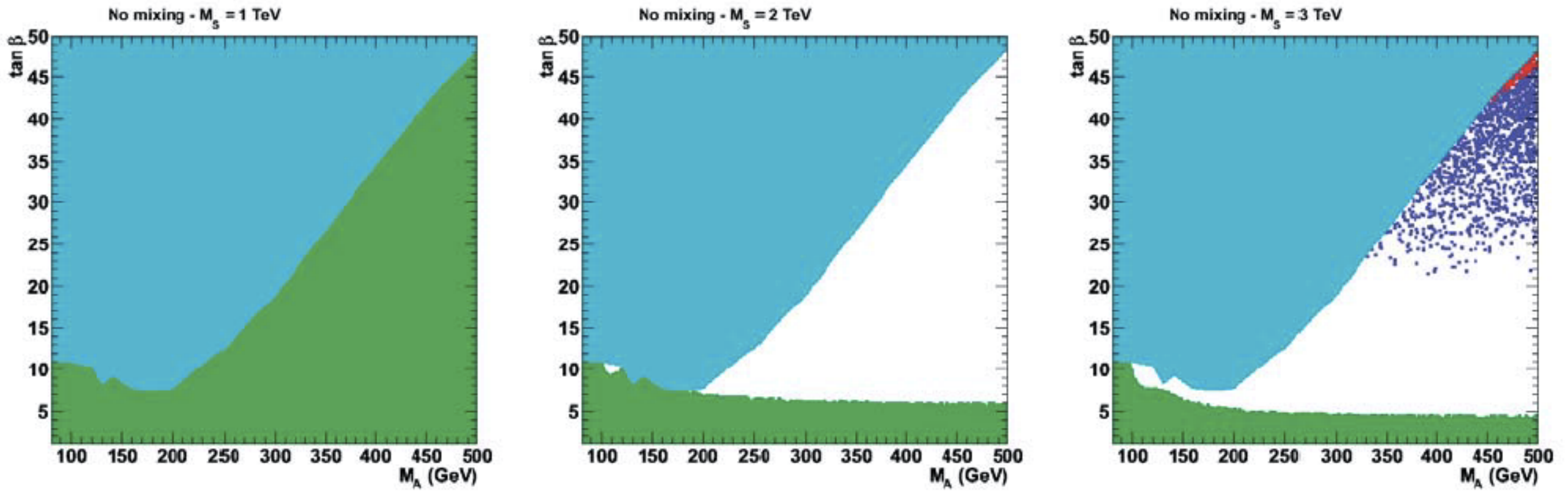
Ms=1TeV　　Ms=2TeV　　Ms=3TeV



Typical mixing

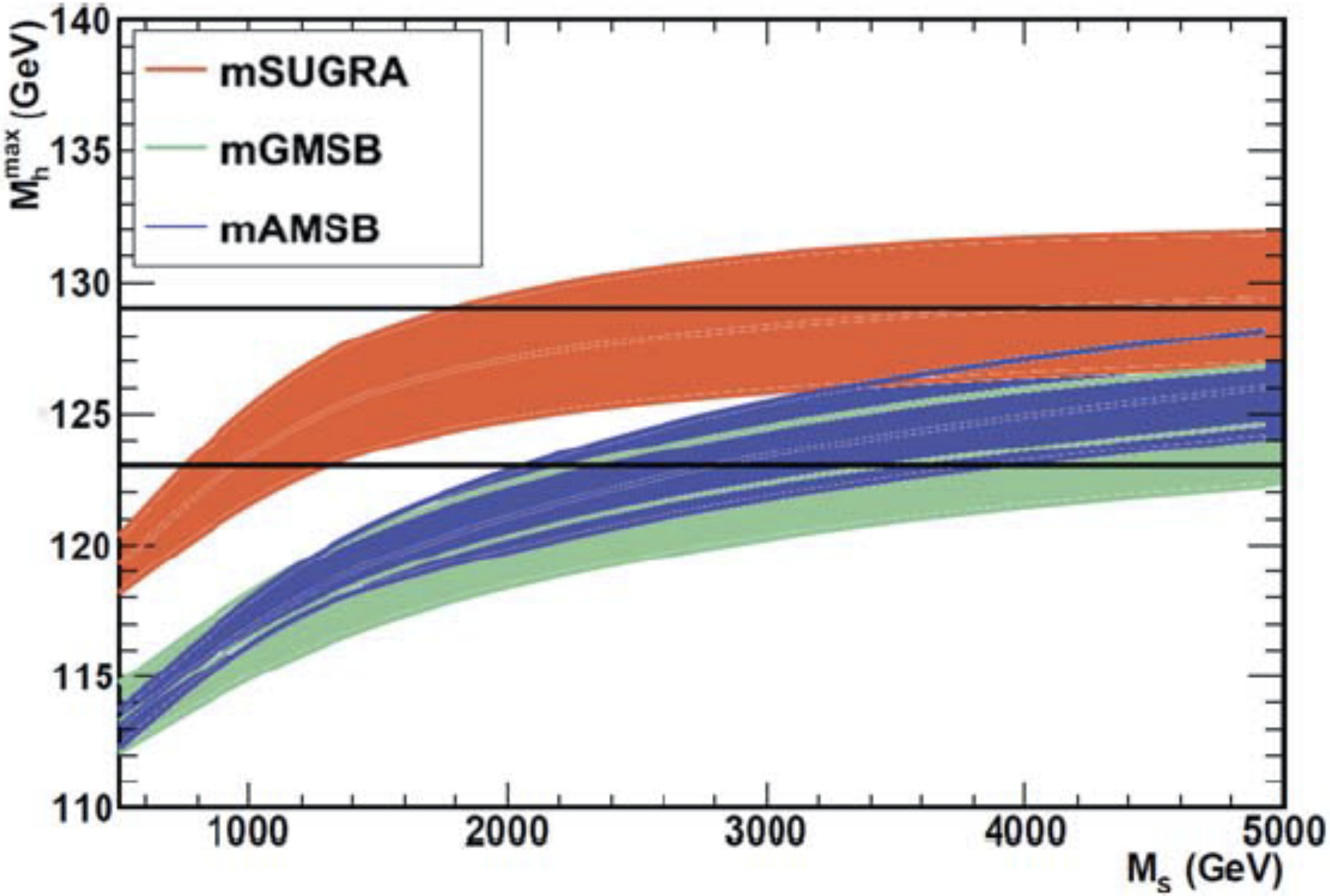


No mixing



No mixing - M_S = 1 TeV
No mixing - M_S = 2 TeV
No mixing - M_S = 3 TeV
tan β
50
45
40
35
30
25
20
15
10
5
100 150 200 250 300 350 400 450 500
M_A (GeV)

The lightest Higgs boson mass in various SUSY breaking scenarios



Including uncertainty from mt=170-176 GeV

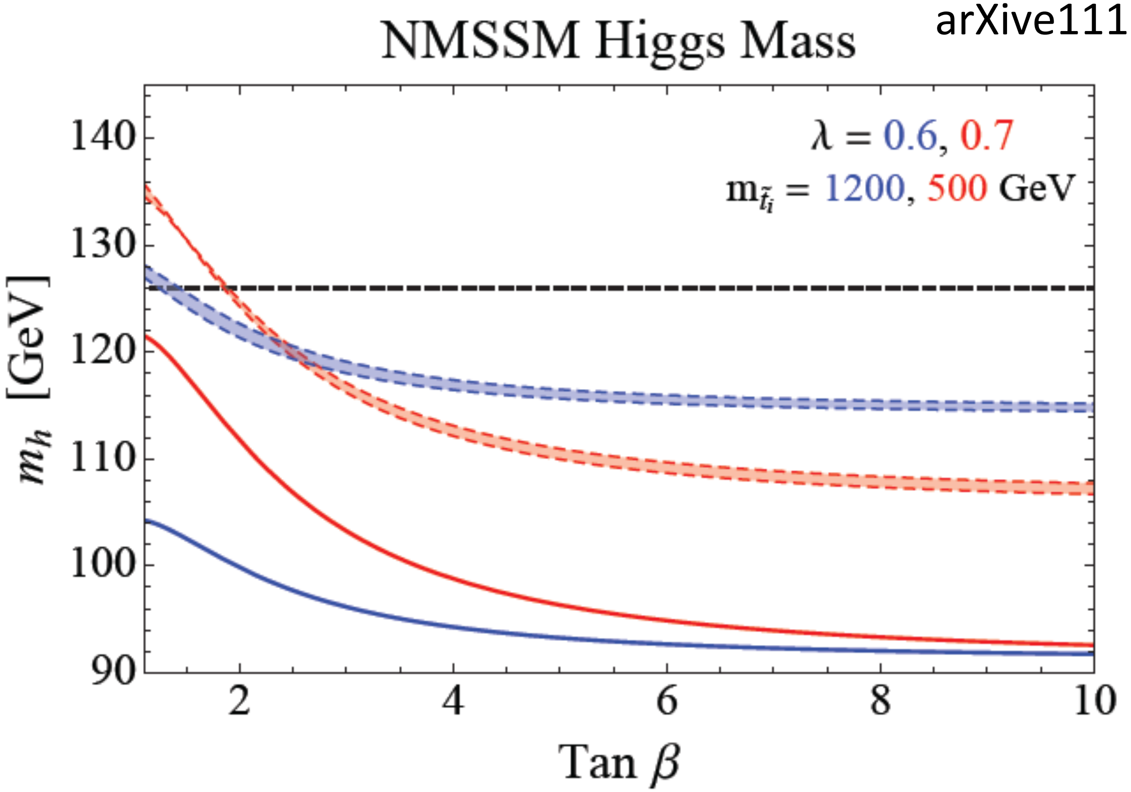
Higgs boson mass in other SUSY models

(1) Including gauge singlet Higgs field

$$\Delta W = \lambda S H_1 H_2 \rightarrow \Delta V = \lambda^2 |H_1 H_2|^2 + \ldots$$

$$m_h^2 \;=\; M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2 ,$$

L.Hall, D.Pinner andJ.T.Ruderman, arXive1112.2703



The Higgs mass can be as large as 126 GeV within the condition that λ does not blow up below the GUT scale.

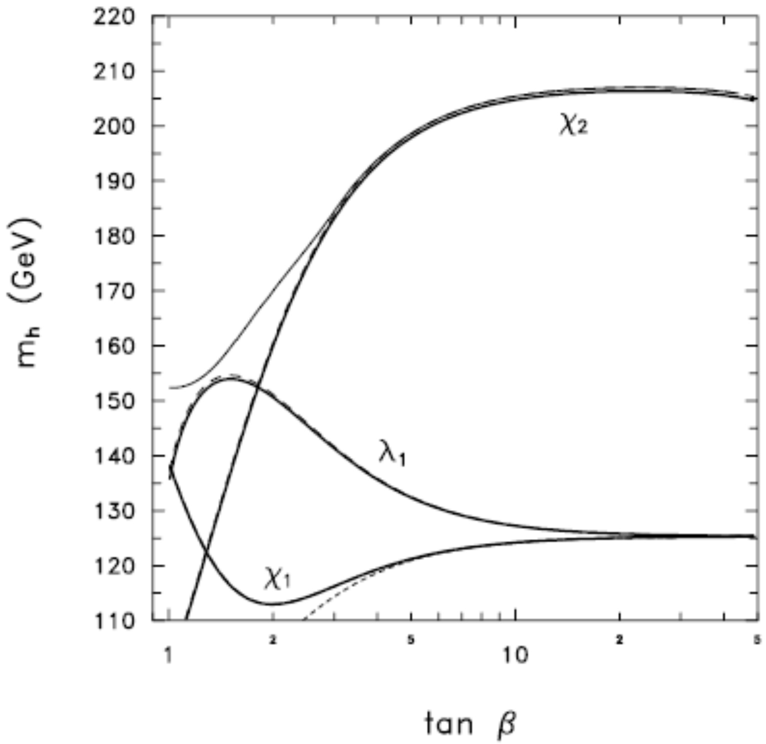
(2) General Higgs representation

J.R.Espinosa and M. Quiros PRL 81 (1998)

$$W = \lambda_1 H_1 \cdot H_2 S + \lambda_2 H_1 \cdot T_0 H_2 + \chi_1 H_1 \cdot T_1 H_1 + \chi_2 H_2 \cdot T_{-1} H_2$$

$$m_h^2/v^2 \leq \frac{1}{2}(g^2 + g'^2)\cos^2 2\beta + \left(\lambda_1^2 + \frac{1}{2}\lambda_2^2\right)\sin^2 2\beta + 4\chi_1^2 \cos^4\beta + 4\chi_2^2 \sin^4\beta .$$

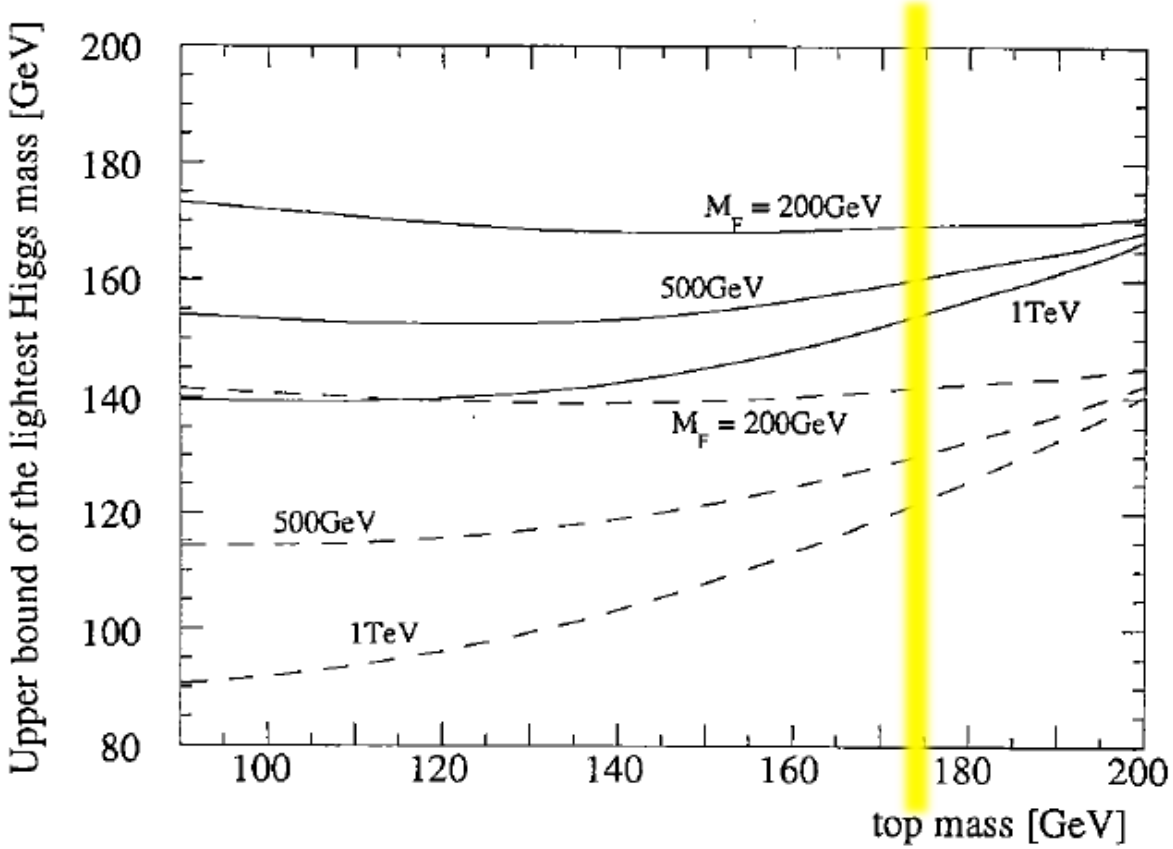
Upper bound of the lightest Higgs boson within no-blowup below GUT



Easy to have a large Higgs boson mass

(3) Loop effects of extra (vector-like) quarks

Upper bound of the lightest Higgs boson mass
with extra 10+10* representations of SU(5)



Maximal squark mixing

No squark mixing

T.Moroi and Y.Okada PLB 295(1992)

Squark mass scale = 1TeV

Strongly interacting Higgs sector

- It is a natural idea that the Higgs is identified as something like the pion in QCD, arising from some symmetry breaking of a new strong interacting sector. Such models generally predicts a Higgsless model or a heavy Higgs model.
- It is possible to consider that a whole Higgs doublet field generated as pseudo Nambu-Goldstone bosons, leading a light physical Higgs boson. Usually, this scenario does not work due to quadratic divergence in the Higgs mass term from gauge and top Yukawa corrections.
- Little Higgs models were invented to overcome this problem. In this model, quadratic divergence is cancelled at the one-loop level. A new strong interaction appears around 10 TeV, and still accommodate a light Higgs boson of about 100 GeV. This is a solution to the little hierarchy problem associated with electroweak precision measurements obtained in the LEP era.

N.Arkani-Hamed,A.G.Cohen, E.Katz, A.E.Nelson, T.Gregorie and J.G.Wacker,2002
N.Arkani-Hamed,A.G.Cohen, E.Katz,and A.E.Nelson,2002

The littlest Higgs Model

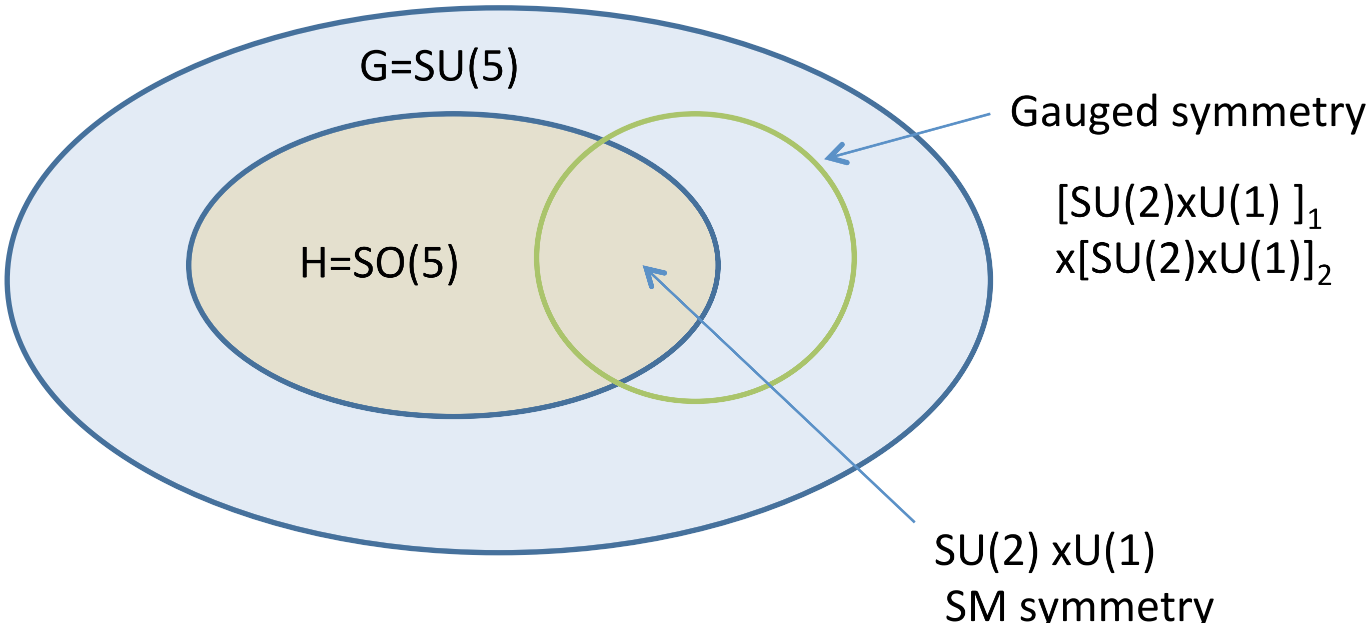
Based on a non-linear sigma model with a symmetry breaking (G/H)

$$\text{global:} \quad SU(5) \overset{f}{\Rightarrow} SO(5)$$

$$\cup \qquad\qquad \cup$$

$$\text{gauged:} \quad [SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \overset{f}{\Rightarrow} SU(2)\times U(1)$$

SM electroweak



Global SU(5) is broken to SO(5)
by VEV of symmetric tensor Σ.

$$\Sigma = \xi \Sigma_0 \xi^T$$

$$\langle \Sigma \rangle = \Sigma_0 = \left(\begin{array}{cc|c|cc} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ \hline 0 & 0 & 1 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{array}\right)$$

24-10=14 Nambu-Goldstone bosons are expressed by

f~O(1)TeV

$$\xi = \exp(i\Pi/f)$$

SM Higgs doublet H_{SM}

$$2\Pi = \left(\begin{array}{cc|c|cc} -\omega^0 - \frac{\eta}{\sqrt{5}} & -\sqrt{2}\omega^+ & -i\sqrt{2}\pi^+ & -i2\phi^{++} & -i\sqrt{2}\phi^+ \\ -\sqrt{2}\omega^- & \omega^0 - \frac{\eta}{\sqrt{5}} & h + i\pi^0 & -i\sqrt{2}\phi^+ & \sqrt{2}(\phi^P - i\phi^0) \\ \hline i\sqrt{2}\pi^- & h - i\pi^0 & \frac{4}{\sqrt{5}}\eta & -i\sqrt{2}\pi^+ & h + i\pi^0 \\ \hline i2\phi^{--} & i\sqrt{2}\phi^- & i\sqrt{2}\pi^- & -\omega^0 - \frac{\eta}{\sqrt{5}} & -\sqrt{2}\omega^- \\ i\sqrt{2}\phi^- & \sqrt{2}(\phi^P + i\phi^0) & h - i\pi^0 & -\sqrt{2}\omega^+ & \omega^0 - \frac{\eta}{\sqrt{5}} \end{array}\right)$$

Triplet Higgs field (ϕ)

Absorbed by heavy gauge bosons (ω, η)

Gauge symmetries

SU(5) translation

$$\Sigma \to V \Sigma V^T$$

Generators of gauge symmetries.

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$Y_1 = \frac{1}{10} \begin{pmatrix} 3 & & & & \\ & 3 & & & \\ & & -2 & & \\ & & & -2 & \\ & & & & -2 \end{pmatrix}$$

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^a * /2 \end{pmatrix}$$

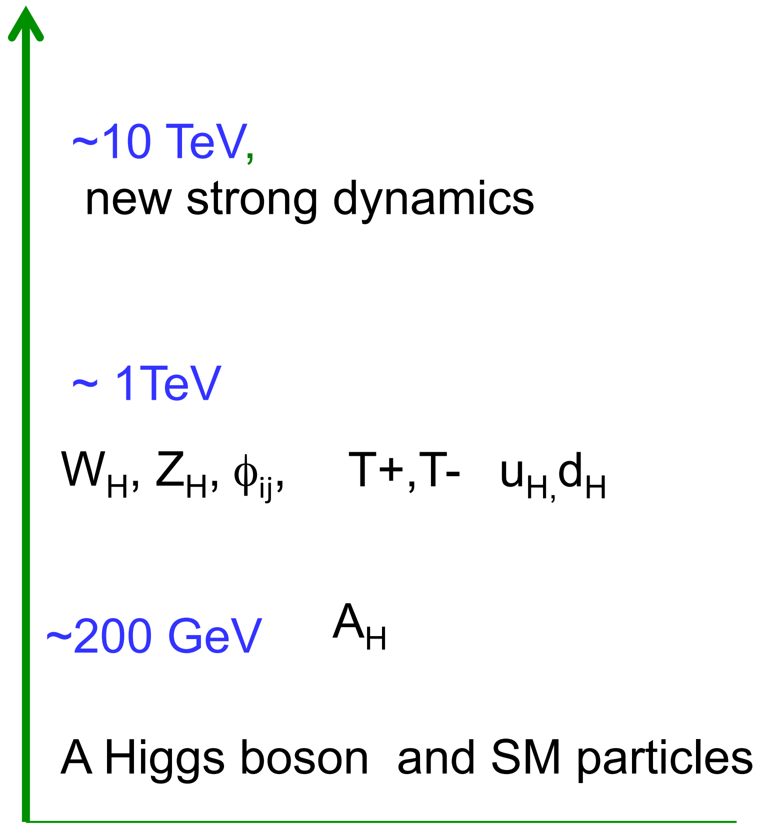
$$Y_2 = \frac{1}{10} \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

SM gauge symmetry : Q_1+Q_2, Y_1+Y_2

No quadratic divergence at the one loop level.
H_{SM} is massless if we put g_1=g'_1=0 (or g_2=g'_2=0)

- An effective Lagrangian below the cutoff scale is given by a non linear sigma model.
- The Higgs potential is obtained from the Coleman-Weinberg potential.
- Many extensions (T-parity, different group structure, etc.)

Particle content of the littlest Higgs model with T parity.



Strongly interacting light Higgs

Giuduce,Grojean, Pomarol, Rattazzi,2007

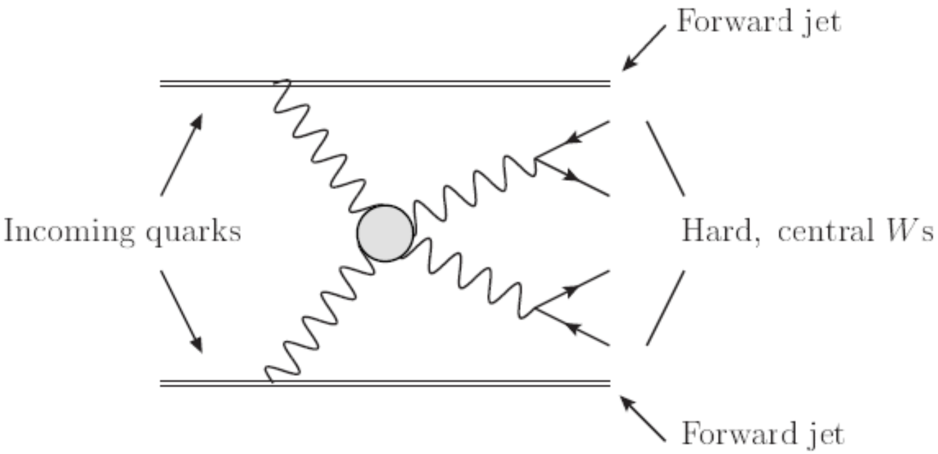
- A general framework describing the case that the Higgs double field (with a light physical Higgs boson) is associated with a symmetry breaking of a strongly interacting sector.

Dim 6 terms of the effective Lagrangian

$$\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} = & \frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right)\partial_\mu \left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right) \\
& + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}.
\end{aligned}$$

$V_L V_L$ scattering in strong interacting light Higgs

Even if a light Higgs boson exist, WW scattering is important to study the dynamics of the Higgs sector.



$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H),$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2},$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H(s+t)}{f^2},$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0.$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}.$$

High energy behaviors are related to these in the Higgsless case in the following way

$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = (c_H \xi)^2 \, \sigma\left(pp \to V_L V_L' X\right)_{\not{H}} \qquad (\xi = \frac{v^2}{f^2})$$

Even if a light Higgs boson is discovered, study of the high energy behavior of gauge boson scattering processes is important to reveal nature of the electroweak symmetry breaking.

Extension to the N Higgs-doublet case :
Y.Kikuta, Y.Okada, and Y.Yamamoto, arXive:1111.2120