Higgs boson mass limits in perturbative unification theories

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Introduction

"Higgs boson"

electroweak symmetry breaking
fermion mass generation

→ main target f future experiments (LHC LC

◎ Standard Model

$$V \quad -m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{2} (\Phi^\dagger \Phi)^2$$

Higgs mass m_h λv^2 not predicted

◎ Present experimental limit

$$114.1 \text{ GeV} \leq m_h \leq 196 \text{ GeV} \ (95\% \text{ CL}$$

$\log_{10}(m_h/\text{GeV})$ $93^{+0.2}_{-0.23}$

"3σ (4σ)" limit → $m_h < 363 (589)$ GeV

new physics allows heavy Higg Peskin and Wells

e g SM with one extra generation

$m_h \sim 500$ GeV as good as the SM

He Polonsky and Su

Novikov Okun Rozanov and Vysotsky

Perturbative theory

$\rightarrow \lambda(\mu < \lambda_{\text{"Non Perturbative"}} \quad (\mu < \Lambda)$

$\rightarrow m_h^2 \quad \lambda v^2 <$ upper limit

© gauge coupling unification

★ Grand Unified Theories well studied

$\sqrt{\frac{5}{3}}\, g' \quad g \quad g_3 \quad \left(\sin^2\theta_W(\Lambda) = 3/8 \right)$

at Λ 2×10^{16} GeV (SUSY)

10^{13} GeV (non-SUSY)

★ SU(3) electroweak model Dimopoulos, Kaplan, Weiner Li, Liao, Hall, Nomura Csaki, Erlich, Kribs Terning

$\sqrt{3}\, g' \quad g_2 \quad \left(\sin^2\theta_W(\Lambda) = 1/4 \right)$

at $\Lambda \sim 4$ TeV (non SUSY) 0–100 TeV (SUSY

★ others $1/4 \leq \sin^2\theta_W(\Lambda) \leq 3/8$

or $10 \lesssim \Lambda < 10^{18}$ GeV

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Standard Model

$$m_h^2 = \underline{\underline{\lambda}}\, v^2 . \qquad v = 246\,\text{GeV}$$

perturbative up to scale Λ

$$\lambda < \lambda_0$$

"perturbativity condition"

$$\mu \frac{d\lambda}{d\mu} = \sum_i \beta_\lambda^{(i\ \text{loop})}$$

$$= \frac{12}{16\pi^2}\lambda^2 - \frac{78}{(16\pi^2)^2}\lambda^3 + \frac{897+5045(3)}{(16\pi^2)^3}\lambda^4 +$$

$$\boxed{\left|\beta_\lambda^{(j>i)}\right| < \left|\beta_\lambda^{(i)}\right|}$$

perturbative expansion is a good approximation

$\Longrightarrow \quad \lambda < \lambda_0 = 8.2$ (up to 3 loop level)

$\Longrightarrow \quad m_h$ upper limit

as a function of Λ fig

SM analysis

- two-loop RGEs for all gauge, top Yukawa and Higgs couplings
- using experimental data

$$\alpha^{-1} = 137.06$$
$$\Delta\alpha^{(5)}_{had}(m_Z) = 0.02761$$
$$\sin^2\theta_W^{lep}{}_{eff} = 0.23136$$
$$\alpha_s(m_Z) = 0.118$$

(LEP EW working group.)

$\longrightarrow$ $\overline{MS}$ gauge couplings

references

- S. Fanchiotti, B. Kniehl and A. Sirlin PRD48, 307 (1993)
  for $\alpha_{\overline{MS}}$ including $O(\alpha\alpha_s)$ two-loop corrections.
- G. Degrassi, P. Gambino and A. Sirlin PLB 394, 188 (1997)
  for $\sin^2\theta_W^{\overline{MS}}$ (two-loop $O(g^4 M_t^2/M_W^2)$)

- top Yukawa

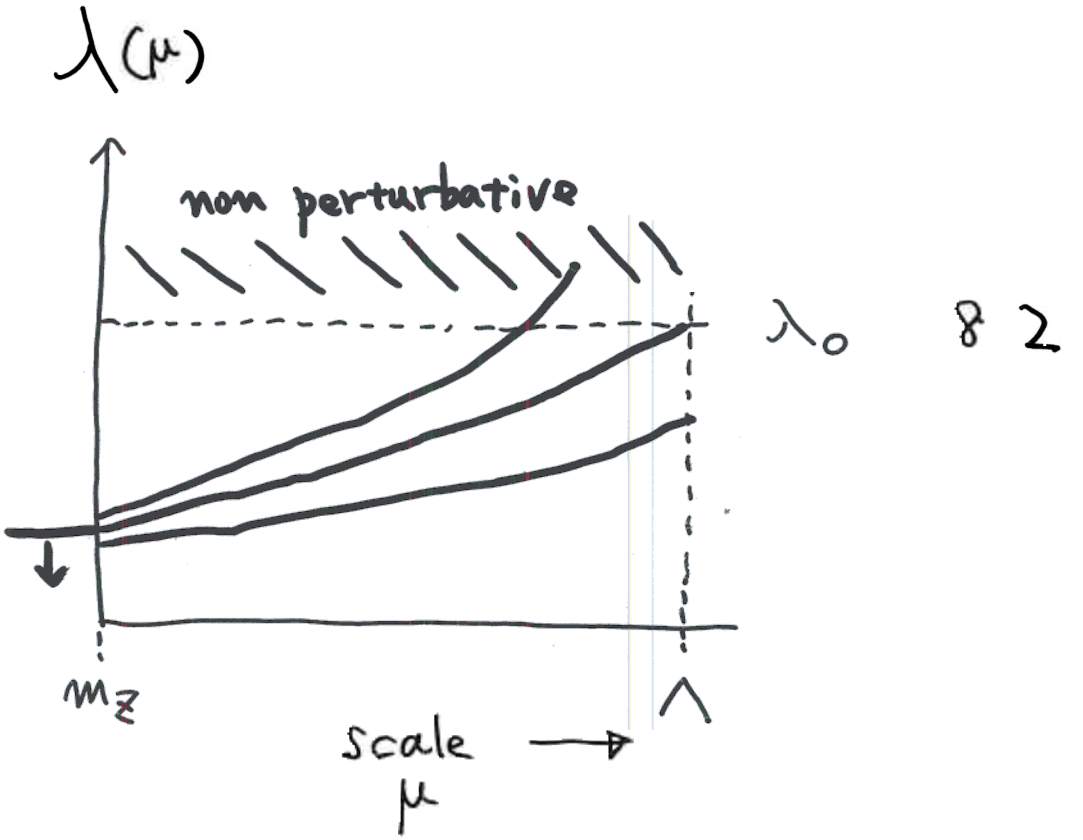
$$y_t^{\overline{MS}}(\mu) = 2^{\frac{3}{4}} G_F^{\frac{1}{2}} m_t \left(1 + \delta_t(\mu)\right) \qquad \mu = m_t$$

$\delta_t(\mu)$: one-loop correction
H. Hempfling and B. Kniehl, PRD 51, 1386 (1995)

- Higgs coupling

$$\lambda^{\overline{MS}}(\mu) = \sqrt{2}\, G_F M_H^2 \left(1 + \delta_H(\mu)\right)$$

$\delta_H(\mu)$: one-loop correction
A. Sirlin and R. Zucchini, NPB 266, 389 (1986)

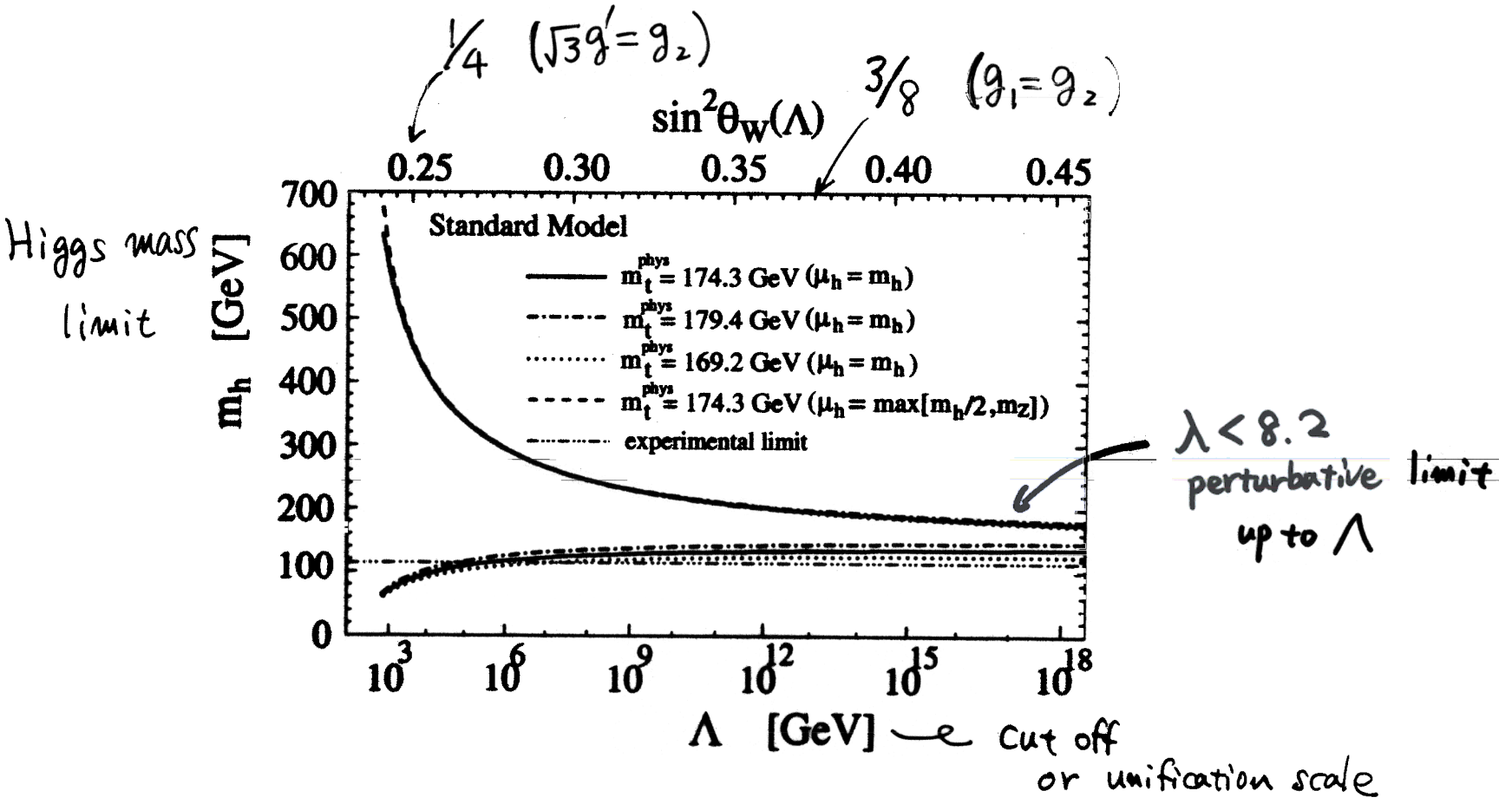


$$\lambda(\mu) < \lambda_0 \quad 8\ 2$$

$$m_Z < \mu < \Lambda$$

$\longrightarrow$ m_h upper limit

Standard Model



e.g.

- $\sin^2\theta_W(\Lambda) = 1/4$ ($\Lambda = 3.8$ TeV)
  $m_h < 460$ GeV
- $\sin^2\theta_W(\Lambda) = 3/8$ ($\Lambda = 10^{13}$ GeV)
  $m_h < 200$ GeV

See also
- Nierste, Riesselmann
- Hambye, Riesselmann

Non renormalzable operator

$$\mathcal{L}_{NR} = f \frac{|\Phi|^6}{\Lambda^2}$$

$$\rightarrow \Delta m_h^2 = f\left[3 \text{ GeV} \left(\frac{3.8 \text{ TeV}}{\Lambda}\right)\right]$$

if $m_h = 460$ GeV

$$m_h^2 + \Delta m_h^2 = (46 \text{ GeV})^2$$

tandard Model with one extra generation

$$\begin{pmatrix} N \\ E \end{pmatrix}_L \quad N_R \,, \quad \begin{pmatrix} U \\ D \end{pmatrix}_L \,, \quad U_R \quad D_R$$

m_N 50 GeV
m_E 100 GeV
m_U m_D 85 GeV

good fit for $m_h = 500$ GeV

Novikov, Okun, Rozanov and Vysotsky

See also He Polonsky and Su

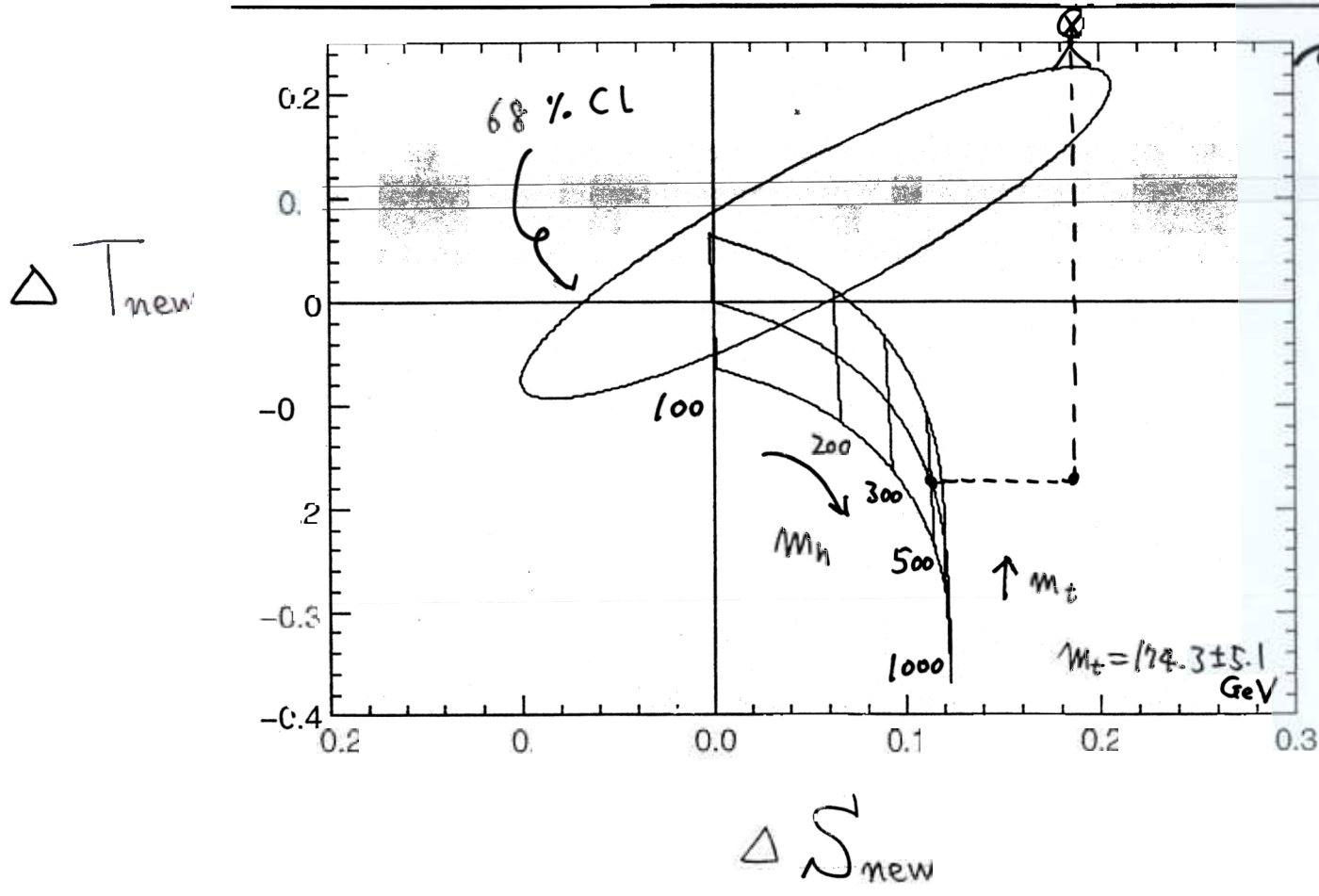
ΔS_{lepton}	0	05
ΔS_{quark}	0	2
ΔT_{new}	0	43

Standard Model with one extra generation

$$\begin{pmatrix} N \\ E \end{pmatrix}_L \quad N_R \quad \begin{pmatrix} U \\ D \end{pmatrix}_L \quad U_R \quad D_R$$

$m_N = 50\,\mathrm{GeV}$
$m_E = 100\,\mathrm{GeV}$

$m_U - m_D = 85\,\mathrm{GeV}$
$m_U + m_D = 500\,\mathrm{GeV}$



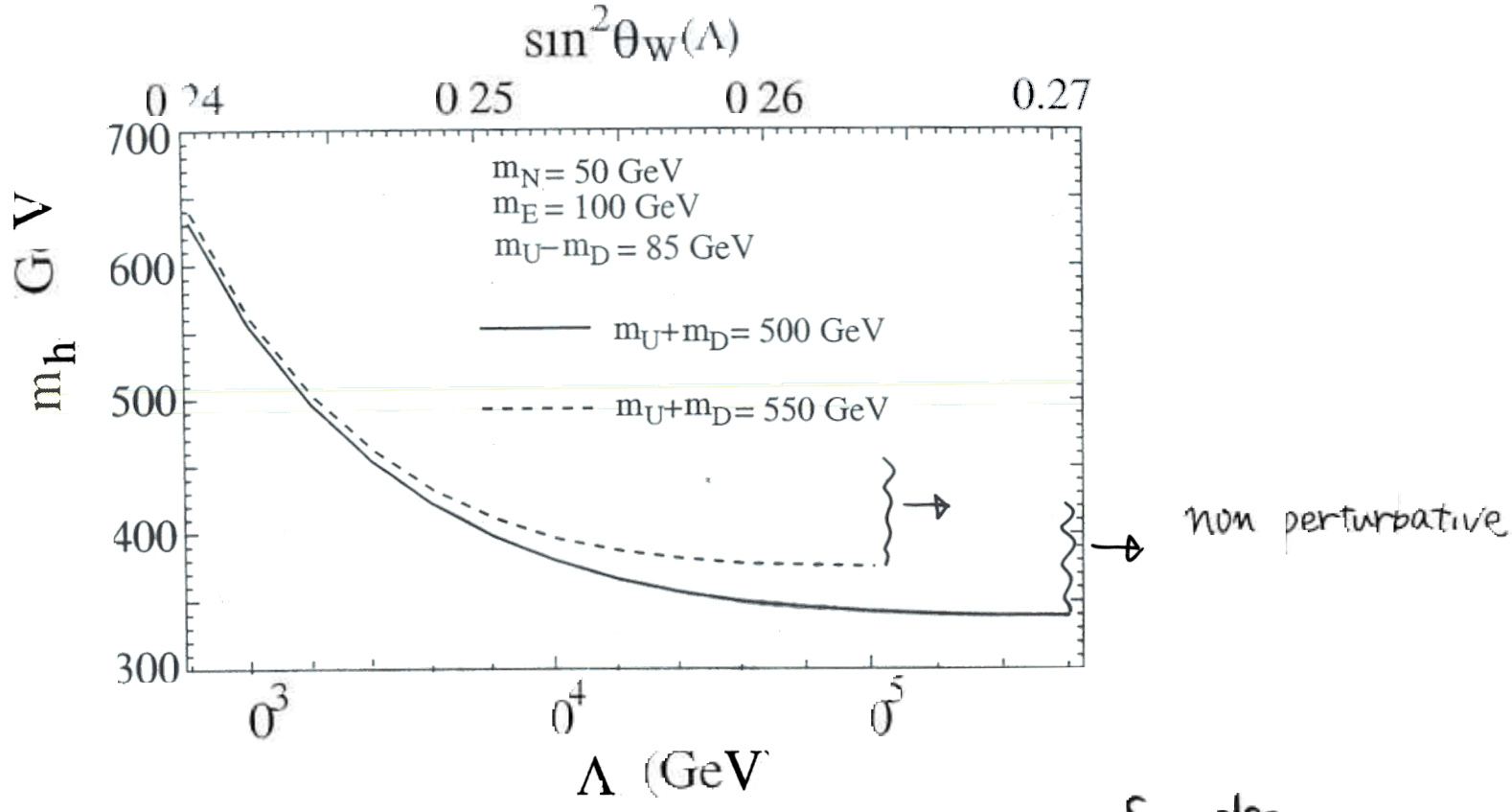
Peskin and Wells

extra generation

$\Delta S_{lepton} = -0.05$
$\Delta S_{quark} = 0.12$

$\Delta T_{lepton} = 0.04$
$\Delta T_{quark} = 0.39$

Standard Model with one extra generation



See also
Pirogov and Zenin

Supersymmetric theories

S. Martin talk

- Okada, Yamaguchi and Yanagida
- Haber and Hempfling
- Ellis, Ridolfi and Zwirner

⋮

minimal SUSY SM

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \eta \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2}$$

$\eta = 0.78$ for $\Delta_S = m_{\tilde{t}} = 1\,\text{TeV}$ and $X_t = 0$

2-loop suppression

<u>MSSM predicts a light Higgs</u>

next-to-minimal SUSY SM
(gauge singlet S)

$$W = \lambda_S S H_u H_d$$

$$\mu = \lambda_S \langle S \rangle$$

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \eta \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2} + \underline{\underline{\frac{\lambda_S^2}{2\sqrt{2} G_F} \sin^2 2\beta}}$$

perturbativity condition

$$\lambda_S < 5.1$$

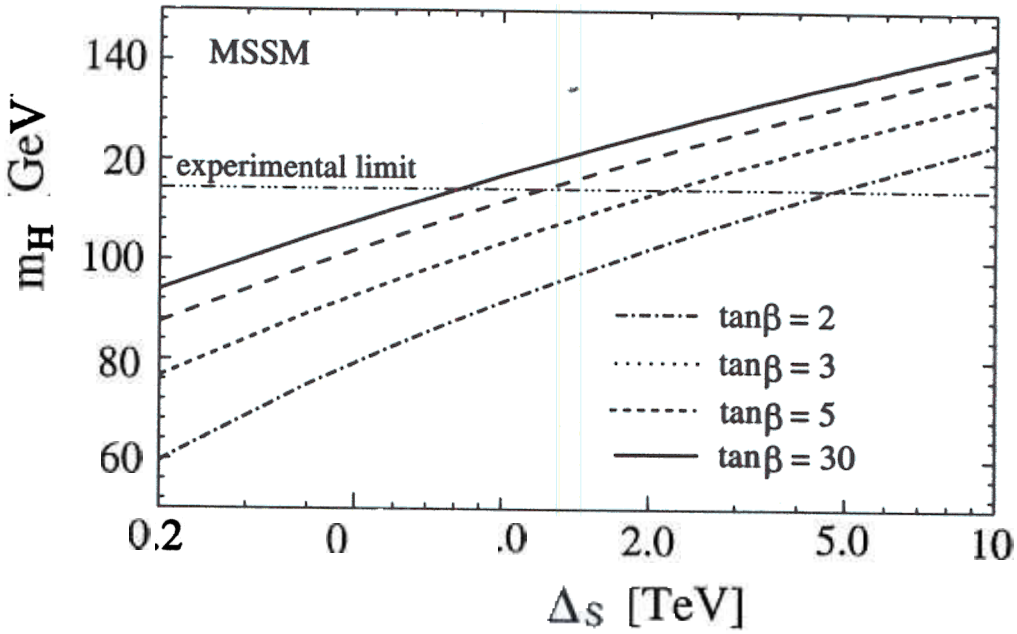
$$y_{top} < 4.9$$

up to Λ

Minimal SUSY SM

perturbativity $2 < \tan\beta < 65$

Λ 2×10 Ge



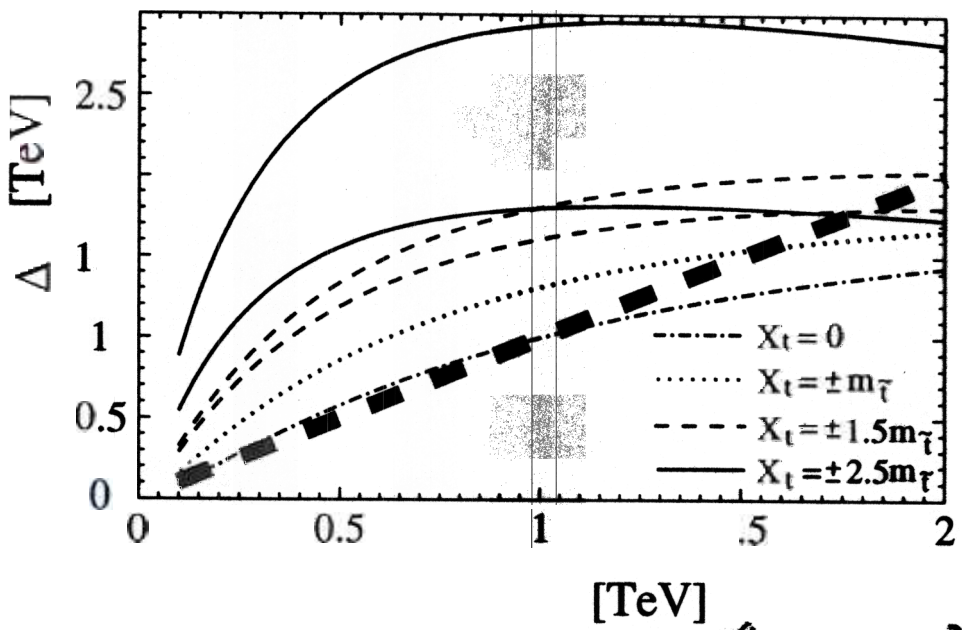
$O(\alpha_t \alpha_s)$ two loop result

Carena et. al hep-ph/000[illegible]

Espinosa et al hep-ph/9912231

$X_t - A_t \mu \cot\beta$

G Degrassi et al



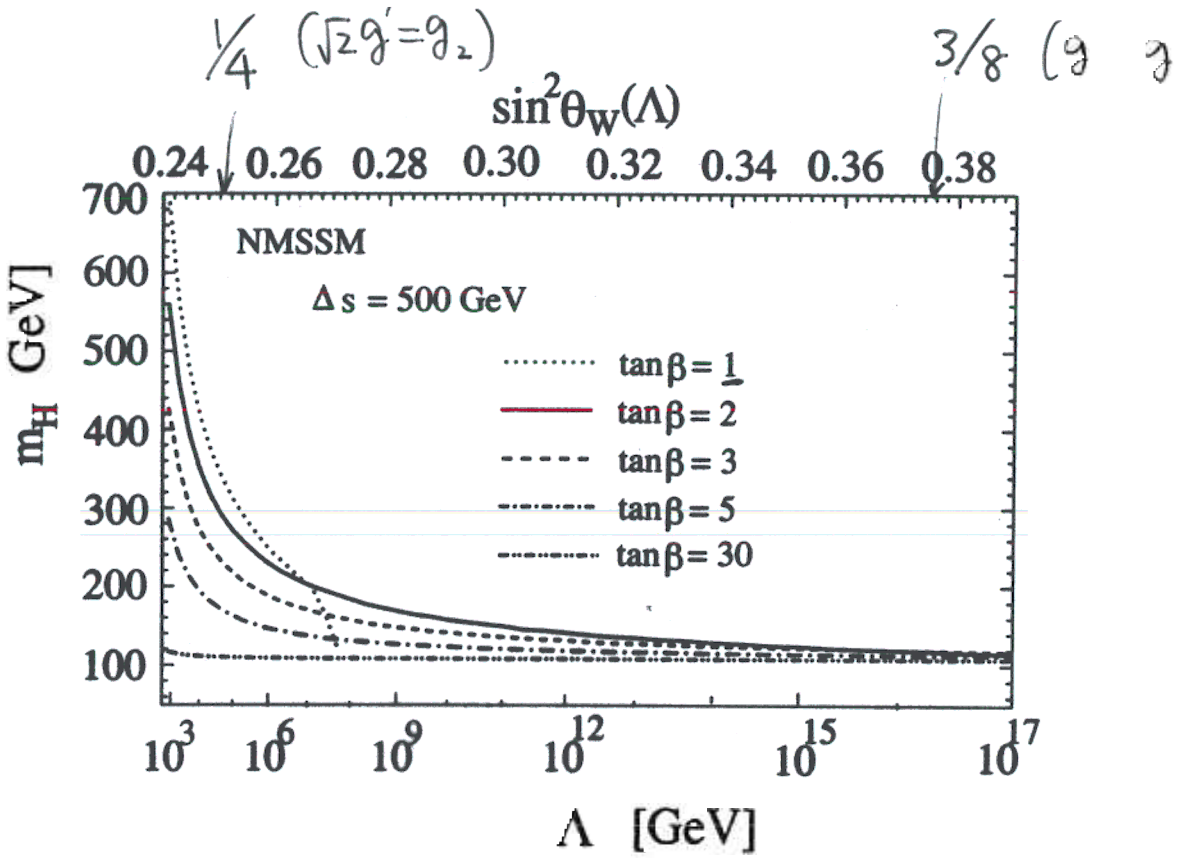
$$m_H^2 < m_Z^2 \cos 2\beta + \eta \frac{3 G_F m_t^4}{\sqrt{2}\,\pi^2} \ln \frac{\Delta_S^2}{m_t^2}$$

η 0 78 two loop suppression

Δ_S m f X_t 0

next to minimal SUSY SM (NMSSM)

Δ_s 500 GeV



e.g. $\sin\theta_W(\Lambda)$ 1/4 (Λ 37 TeV

$m_h < 350$ GeV

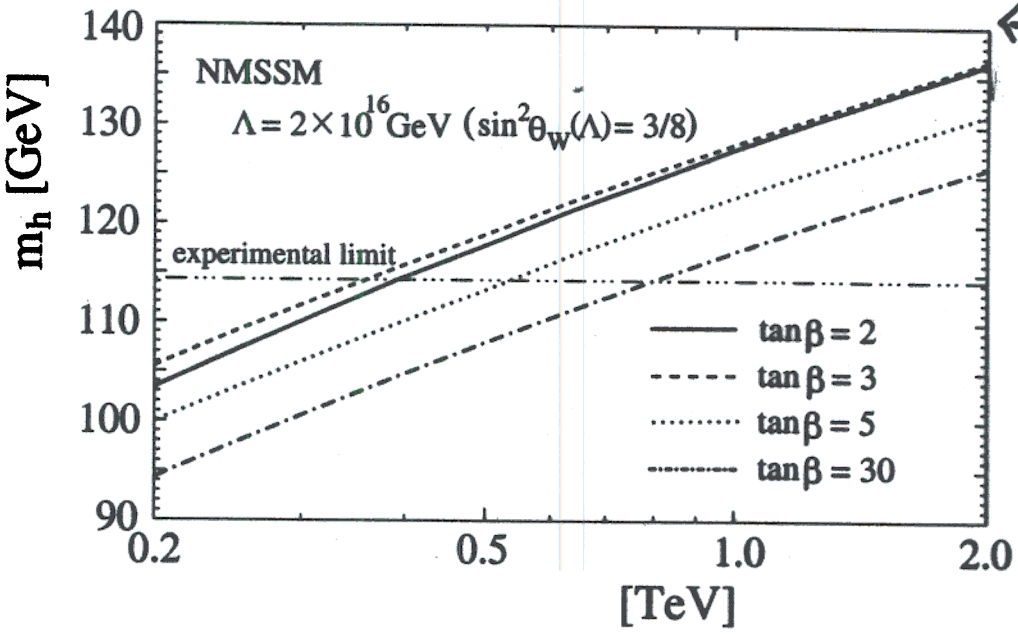
$\sin^2\theta_W(\Lambda)$ 3/8 ($\Lambda = 2$ 10^{16} GeV

$m_h <$ 20 GeV

Δ_s 500 GeV

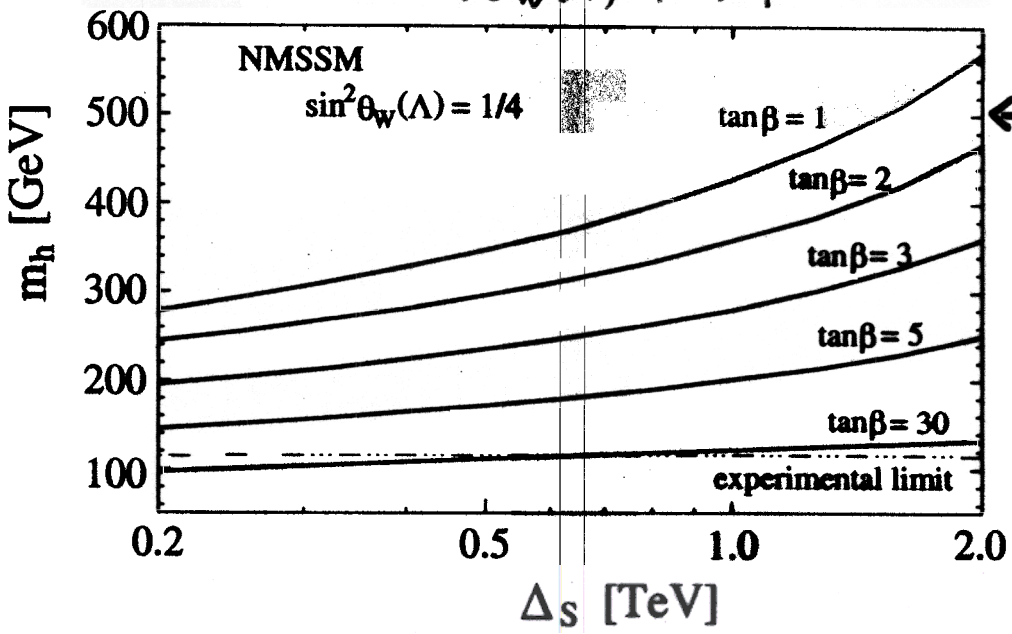
NMSSM

" $\sin^2\theta_W(\Lambda) = 3/8$ "



← 140 GeV

" $\sin^2\theta_W(\Lambda) = 1/4$ "



← 500 GeV

- m_h can be as large as 500 GeV if $\Lambda \sim 10$ TeV
- $\tan\beta \leq 1$ is consistent with experimental m_h limit.

Summary

Higgs mass limits in perturbative theories

$10^4\,\mathrm{GeV} \lesssim \Lambda < 10^{18}\,\mathrm{GeV}$ or $1/4 \lesssim \sin^2\theta_W(\Lambda) \lesssim 3/8$

Standard Model

"$\sin^2\theta_W(\Lambda)$ $3/8$" ($\Lambda \sim 10^{13}\,\mathrm{GeV}$)

$\underline{m_h < 200\,\mathrm{GeV}}$

$\sin^2\theta_W(\Lambda)$ $1/4$" ($\Lambda \sim 4\,\mathrm{TeV}$)

$\underline{m_h < 460\,\mathrm{GeV}}$

Standard Model with one extra generation

electroweak fit with $m_h = 500\,\mathrm{GeV}$ as good as the SM

→ to get $m_h = 500\,\mathrm{GeV}$

one needs $\Lambda \sim 10^3\,\mathrm{GeV}$

SUSY Models

- <u>MSSM predicts a light Higgs</u>
- non-minimal model (NMSSM)

$\underline{m_h < 500\,\mathrm{GeV}}$ $\underline{\text{if } \Lambda \simeq 10\,\mathrm{TeV}}$ ($\sin^2\theta_W(\Lambda) = 1/4$)

★ LHC (and LC) can tell us whether perturbative theories with Λ are consistent or not

(<u>if</u> $m_h \sim 300 - 500\,\mathrm{GeV}$

Λ should be very low

or the theory should be non-perturbative.)