Gauge Extensions of the MSSM

P.B., A Delgado, D.E. Kaplan & T. Tait

hep-ph/0309149
hep-ph/0404251

The Standard Model

The Minimal Supersymmetric Standard Model

Anagrams to
"TeSted daMn hard"
(l,o)

The Standard Model

Anagrams to
"TeSted daMn hard"
(l,o)

The Minimal Supersymmetric Standard Model

~2x as many particles

The Standard Model	The Minimal Supersymmetric Standard Model
Anagrams to "TeSted daMn hard" (l,o)	~2x as many particles ~5x as many parameters (105 total)

The Standard Model	The Minimal Supersymmetric Standard Model
Anagrams to "TeSted daMn hard" (l,o)	~2x as many particles ~5x as many parameters (105 total) Anagrams to "TeSted daMn hard" (l,o) + 21 other letters

The Standard Model

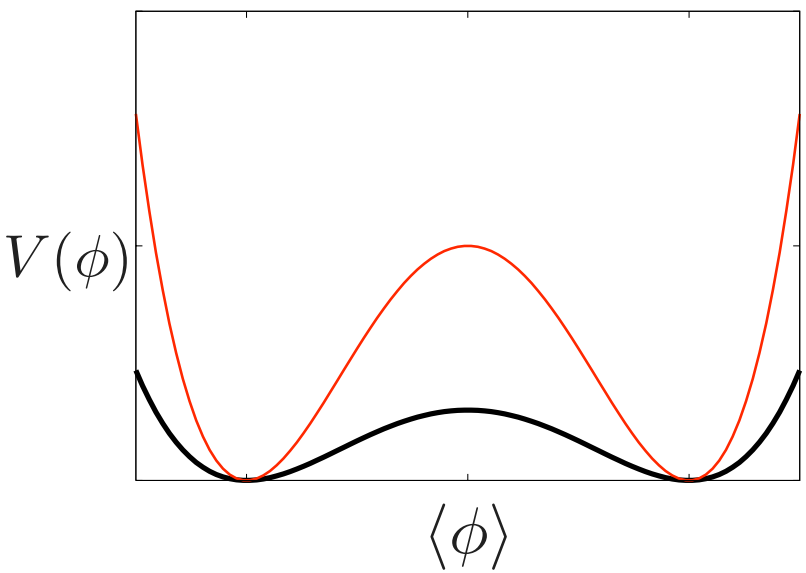
The Minimal Supersymmetric Standard Model

Also Anagrams to
"reSilient Theory-Scam aMidst Madmen"
+(plurmd)

The Standard Model

$$\lambda |H|^4$$

λ is not constrained

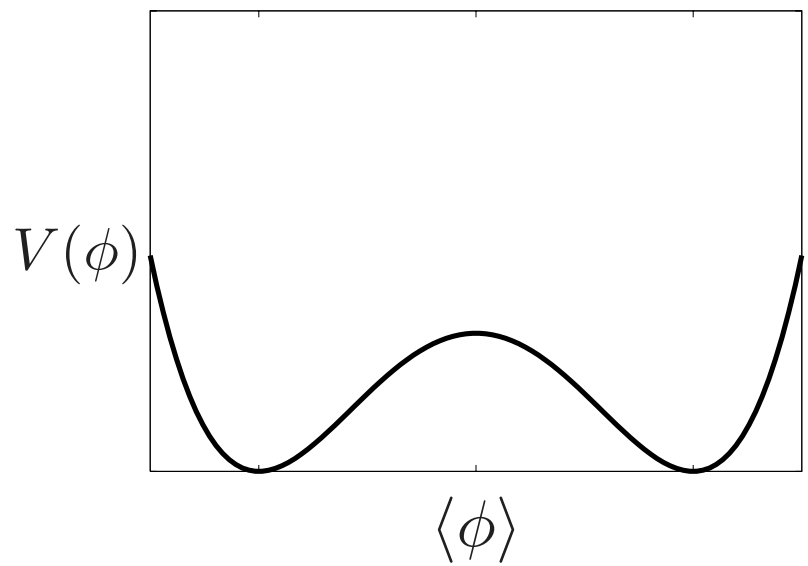


The Minimal Supersymmetric Standard Model

Well known tree-level constraint:

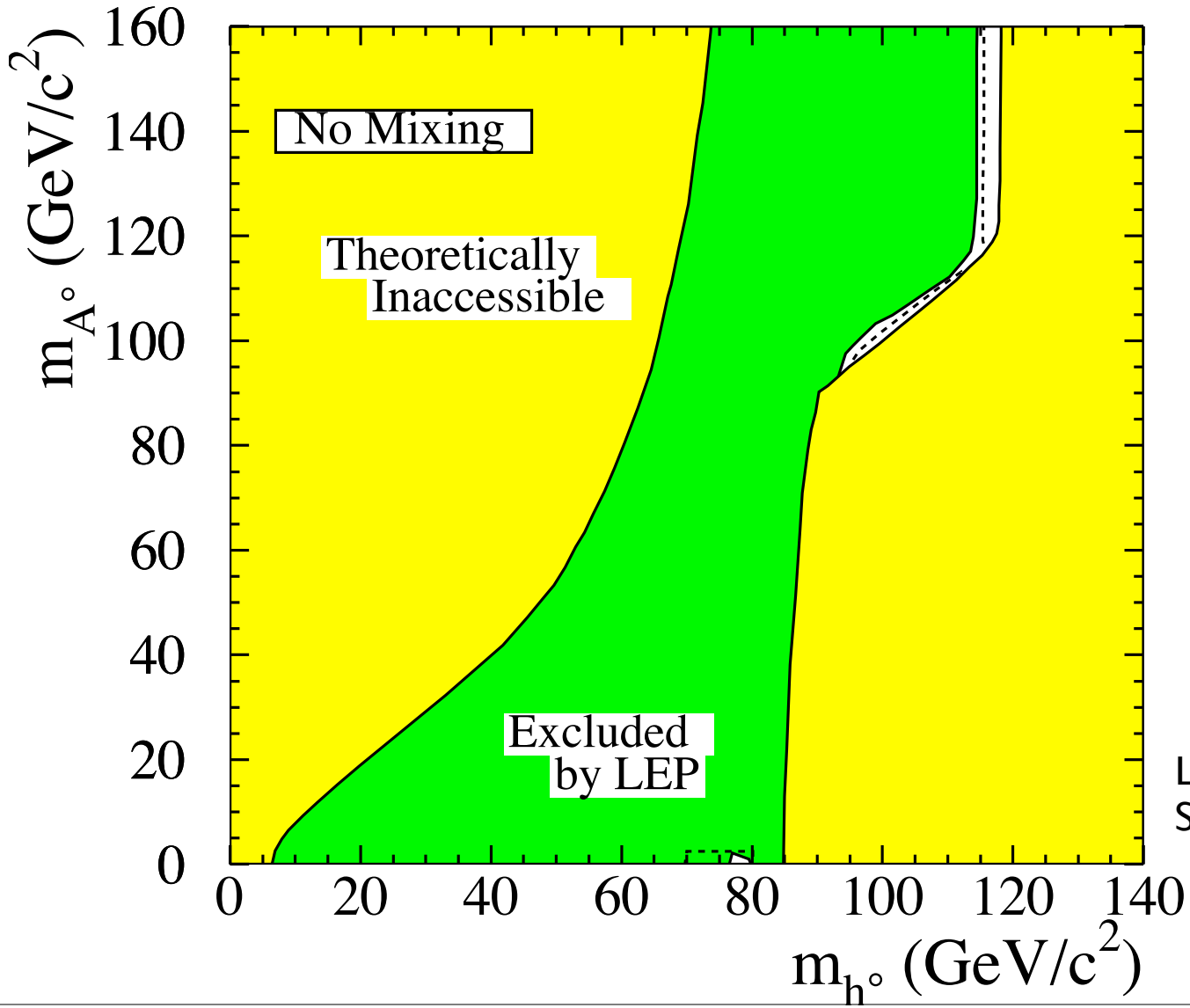
$$m_{h^0} \leq M_Z$$

$$\lambda \propto g^2$$



LEP-Bounds on the MSSM

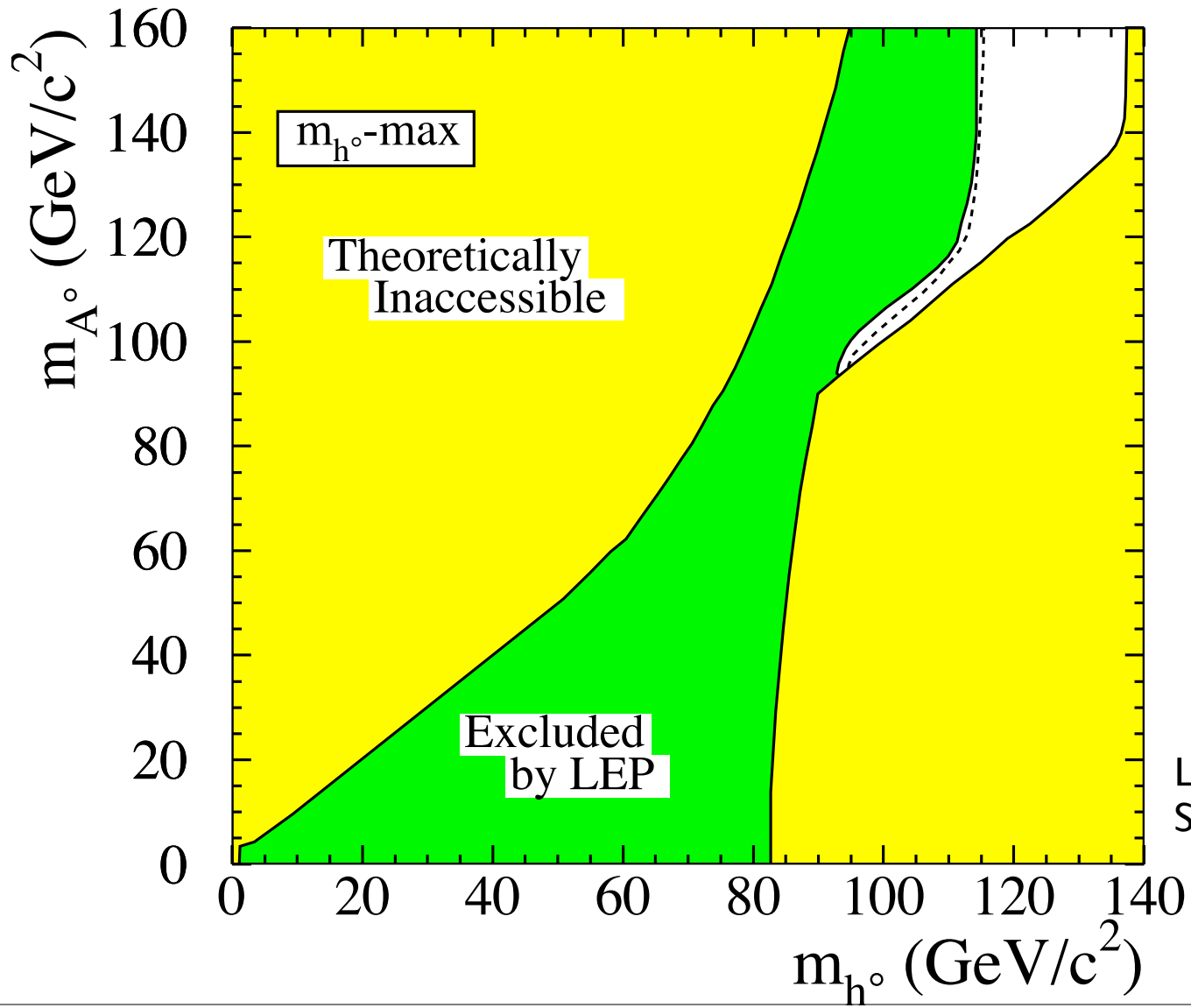
Large radiative corrections from the stop sector help the MSSM evade the direct search bounds on m_{h^0}



LEP Working Group
Summer '04

LEP-Bounds on the MSSM

More parameter space available in the Max-Mixing scenario



LEP Working Group
Summer '04

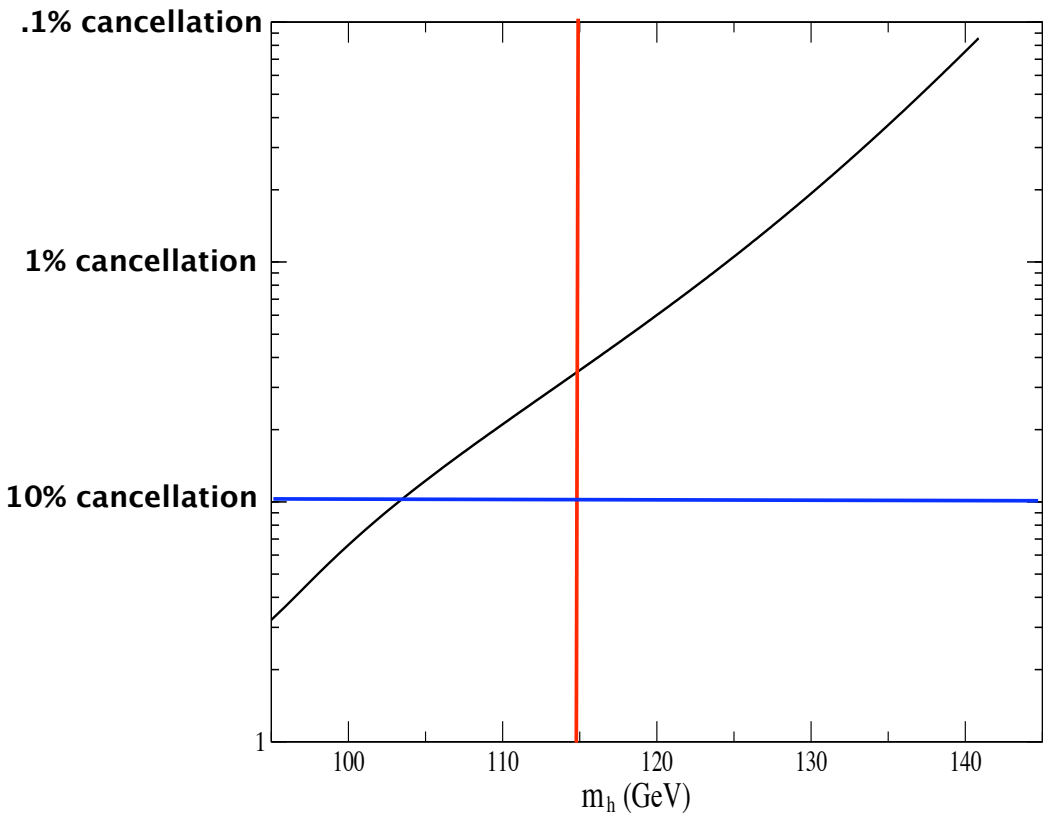
MAX-mixing?

- Two-possibilities: (Kane, Nelson, L. Wang, T. Wang)

  the Higgs sector has escaped detection...
  fine-tuned at ~.1 %, difficult to explain SUSY sector

  Max-Mixing scenario, CP-even Higgs soon...
  still fine-tuned, Max-mixing is hard to generate

- Any increase in m_{h^0} comes at a price



Dimensional Analysis

$$\lambda \propto \ln\left(\frac{m_S^2}{m_t^2}\right)$$

$$\delta m_\phi^2 \propto m_S^2$$

(Casas, Espinosa, Hidalgo)

Can we raise m_{h^0} ?

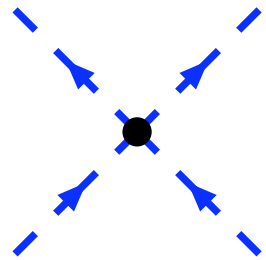
- Need a new, dimensionless, tree-level parameter

(Haber & Sher, Espinosa & Quiros, ...)

New Gauge Groups

$$g^2_{\rm new}, W^\mu_{\rm new}$$

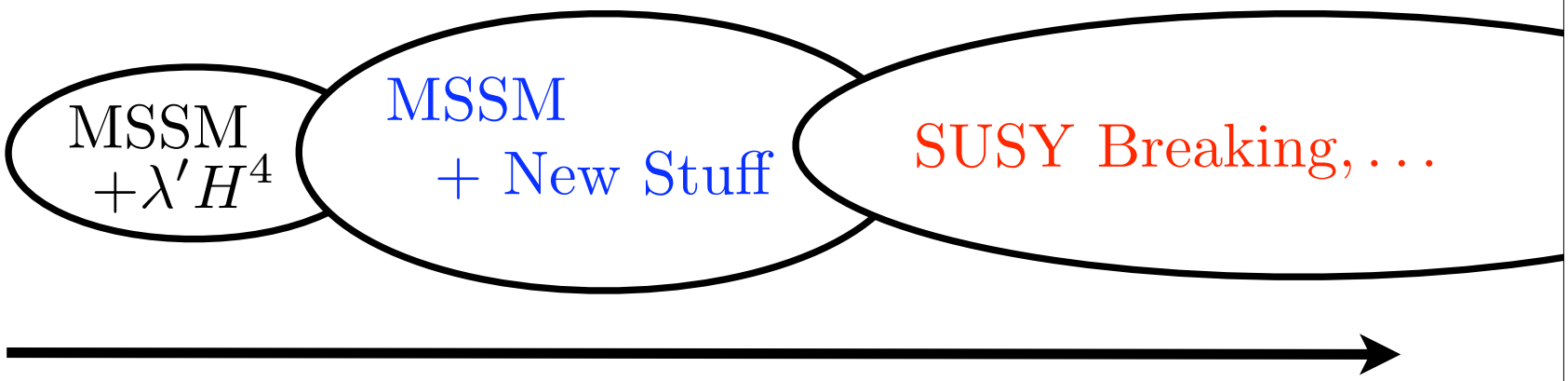
$$\propto g^2_{\rm new}$$



New Matter

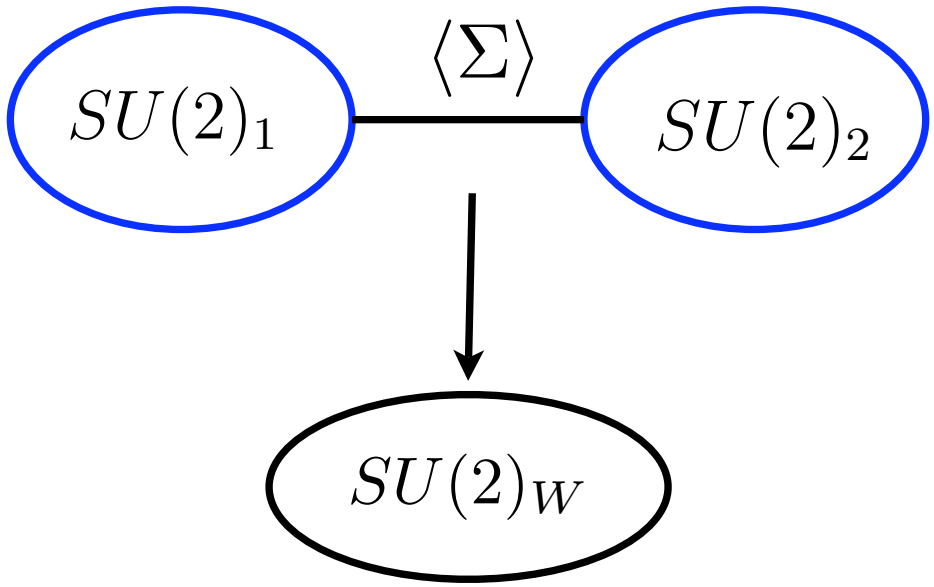
$$\lambda_S S H_u H_d$$

$$\propto \lambda_S^2$$

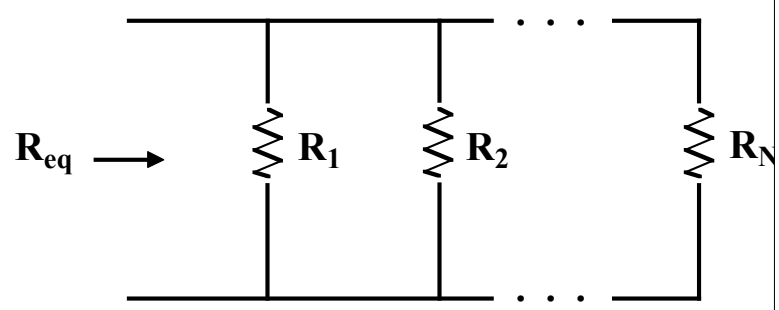


Energy Weak TeV 10-100 TeV

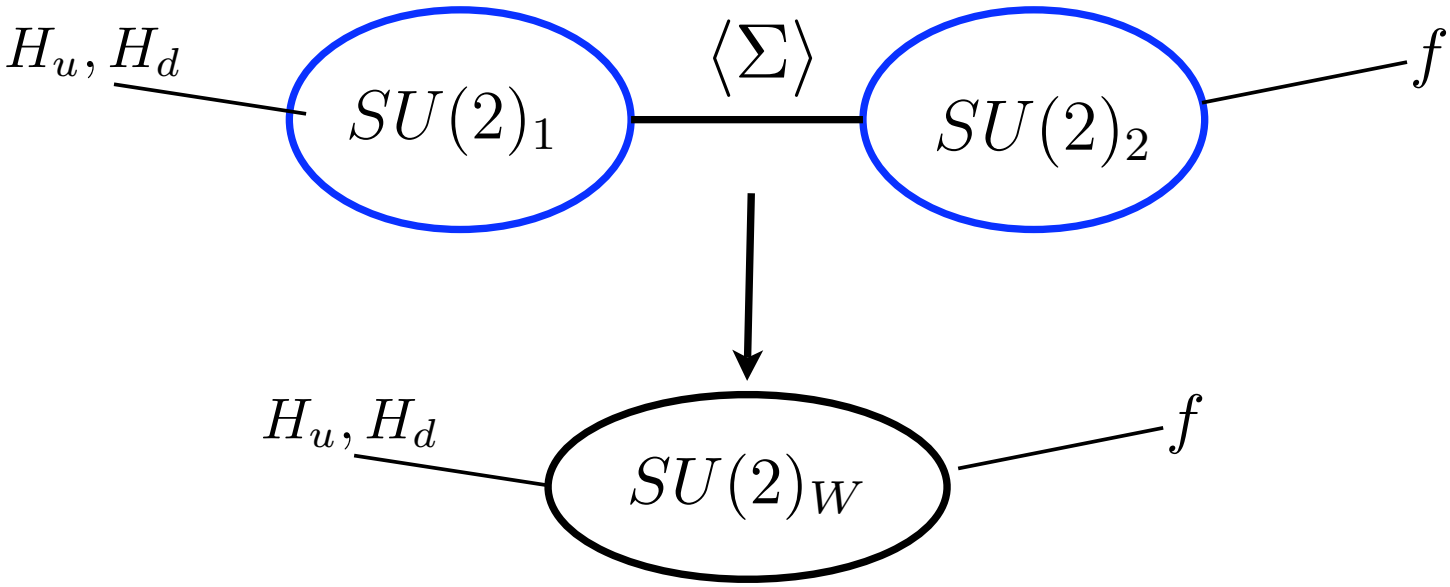
Symmetry Breaking



- $m_{W'} \sim \langle\Sigma\rangle$
- $\dfrac{1}{g^2} = \dfrac{1}{g_1^2} + \dfrac{1}{g_2^2}$



Symmetry Breaking



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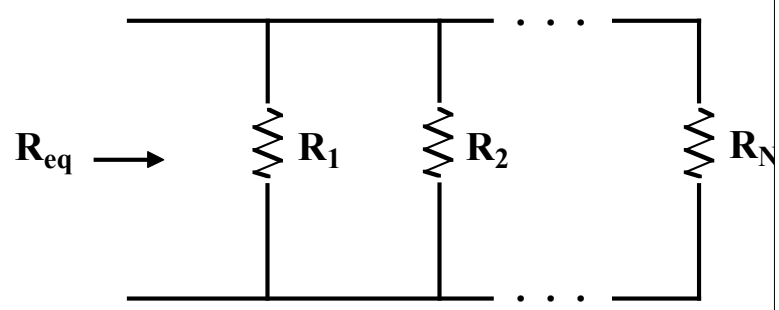
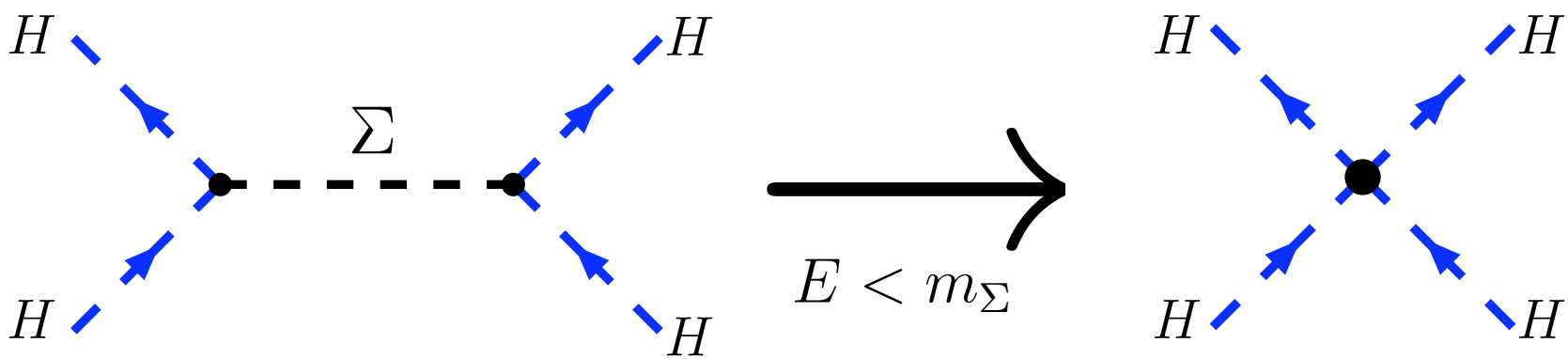


- Potentially large quartic as $g_1 \to \infty, g \to g_2$

$$W^\mu \to A_2^\mu$$

Non-decoupling D-terms

- The low-energy theory 'remembers' its origins



- $\lambda \sim \dfrac{\Delta g^2 + g'^2}{8}$ $\quad m_\Sigma^2 \ll \langle\Sigma\rangle \rightarrow \Delta g^2 \sim g^2$ no effect

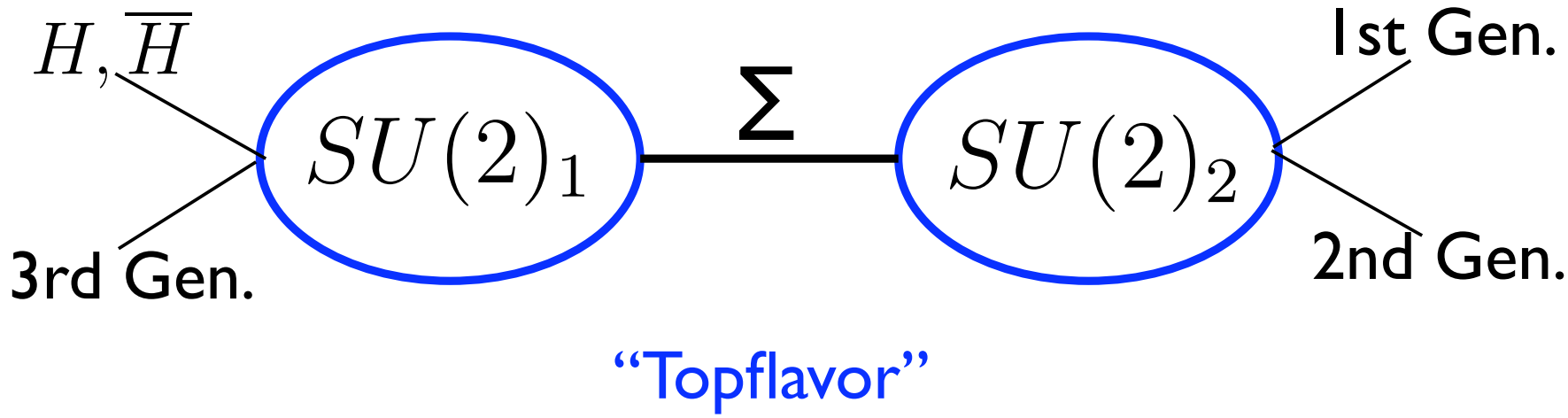
  $m_\Sigma^2 \gg \langle\Sigma\rangle \rightarrow \Delta g^2 \sim g_1^2$ big effect!

- Non-decoupling limit, must have $m_\Sigma^2 > \langle\Sigma\rangle$

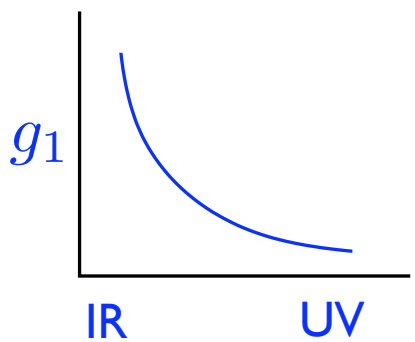
  stable ratio of scales, communicates with Higgs sector at two-loops only.

  D-flat breaking, so the Higgs sector is still light

Asymptotic Freedom

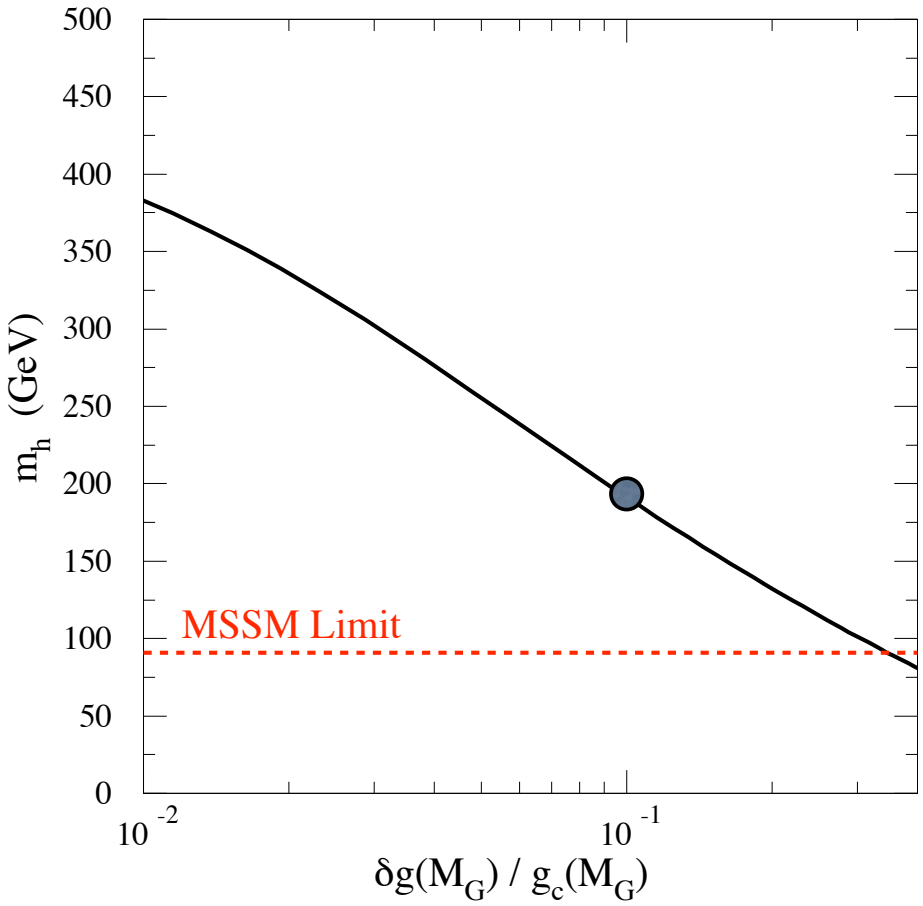


- different flavor structure to prevent non-perturbative physics before the GUT scale



- Third generation must be included with the Higgs to keep the top heavy

A New Mass Bound for SUSY



Sample Point:

- $\langle \Sigma \rangle = 2.5 \text{ TeV}, \quad m_\Sigma \sim 10 \text{ TeV}$

$$M_V = 4.5\text{TeV}$$

$$\Delta \approx 7, \quad m_{h^0} \leq 210 \text{ GeV}$$

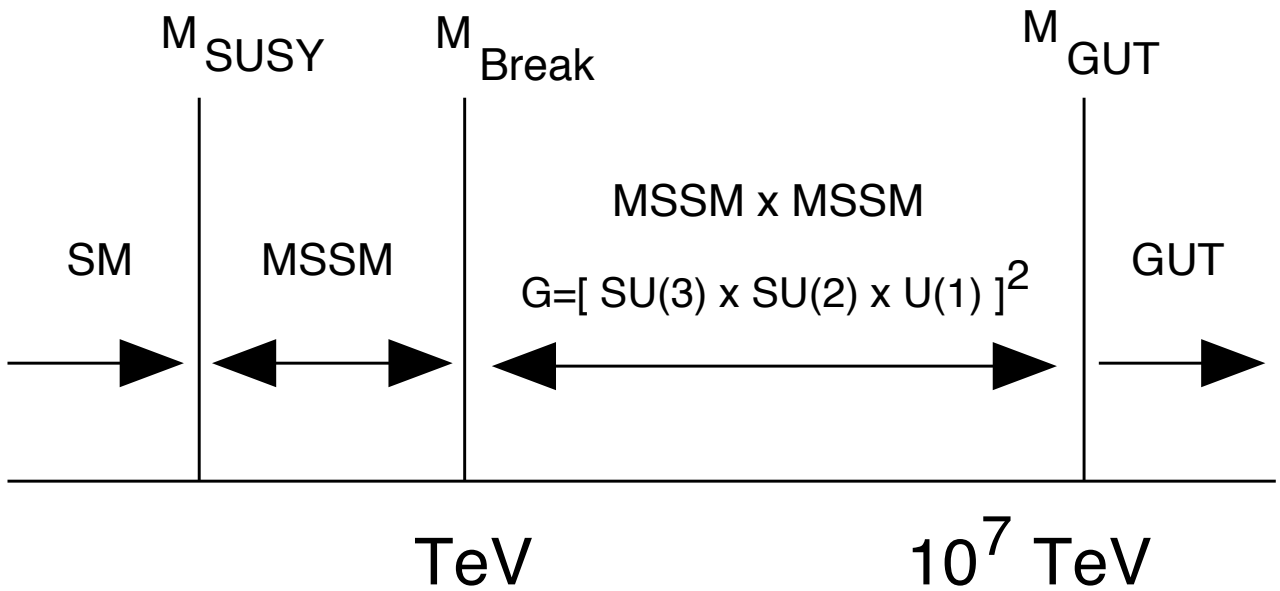
$$\boxed{m_{h^0} < \sim 350 \text{ GeV}}$$

Gauge Coupling Unification

- apparent SU(5) unification could be explained by SU(5) x SU(5)
  Breaks to SU(3) x SU(2) x SU(2) x U(1) at a high-scale, leaves behind spectator fields to give the observed coupling constants

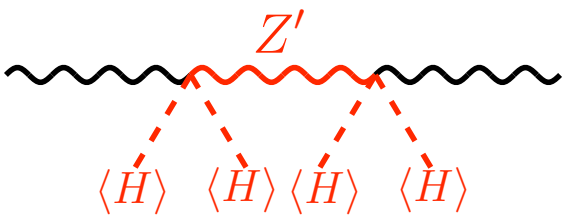
- Accelerated Unification or Product Unification models can also increase the Higgs mass (40-50 GeV at Tree-level) without requiring 'Unifons'.

Maloney, Pierce, Wacker

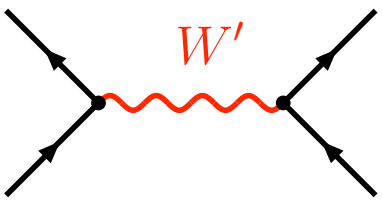


Precision Corrections

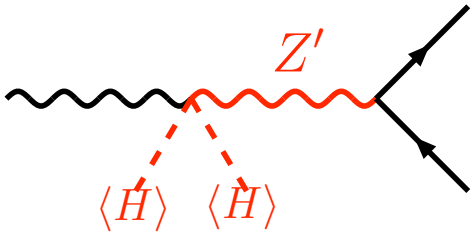
- oblique corrections to M_W, M_Z



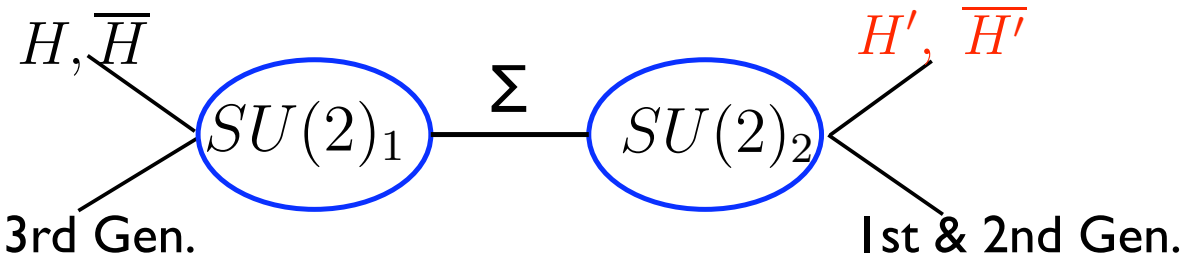
- non-oblique corrections to G_F



- f_L vertex corrections



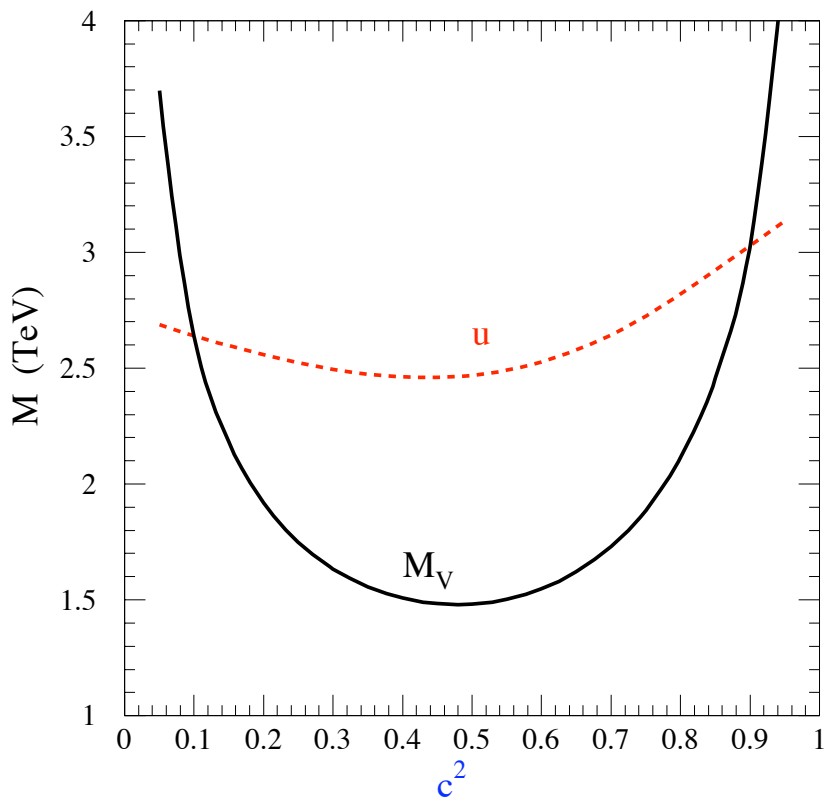
- non-universal 3rd Generation couplings!



Precision Corrections

- $\langle \Sigma \rangle = u \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad M_{W',Z'} \sim u^2 \left(g_1^2 + g_2^2 \right) \quad g_1 \equiv \frac{g}{\sin\phi} \quad g_2 \equiv \frac{g}{\cos\phi}$

Lower Bounds as a function of $\cos\phi$



Large g_2
Small g_1

Large g_1
Small g_2

Phenomenology

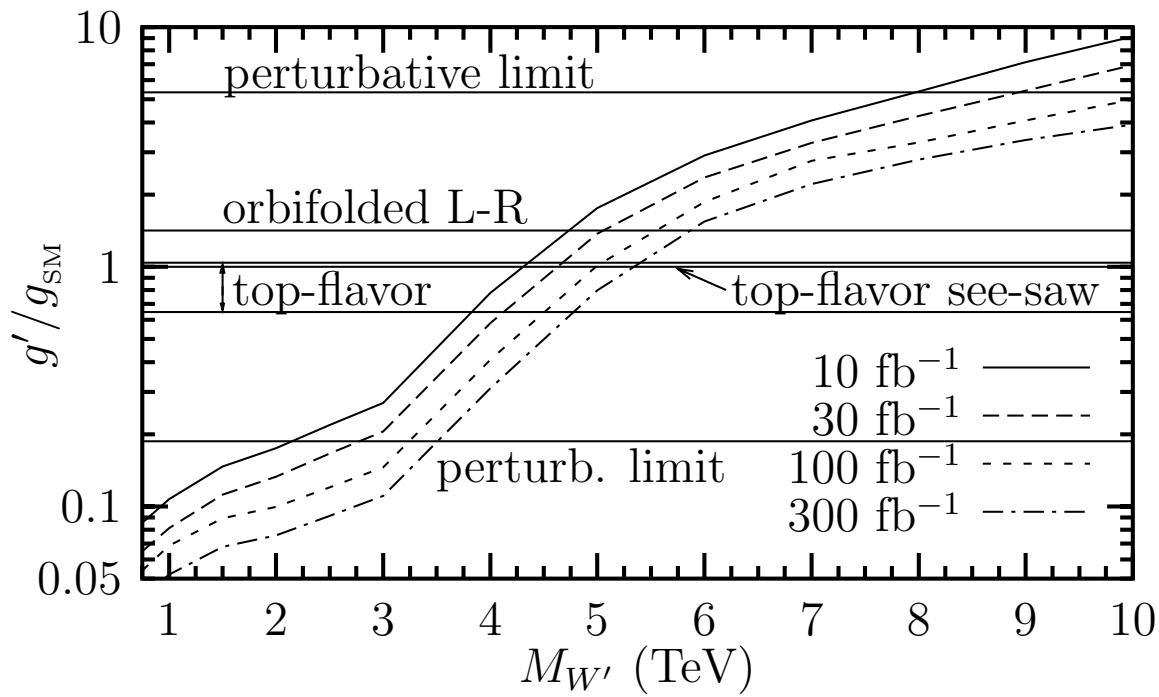
- Lightest Higgs mass which violates the MSSM bound (and LEP-II bound) for a range of Tan (β)

- Consistently altered mass sum rules (usual VVh couplings):

$$m_{H^+}^2 = m_A^2 + \Delta m_W^2 \qquad m_h^2 = \Delta' m_Z^2 \cos^2(2\beta) \qquad m_H^2 = m_A^2 + \Delta' m_Z^2 \sin^2(2\beta)$$

- WW and ZZ Higgs decay modes can dominate

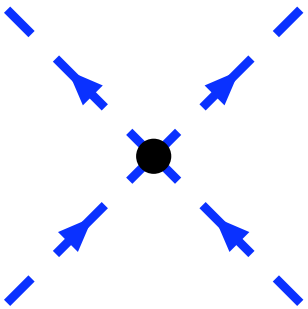
- Heavy Vector bosons which couple preferentially to the third generation



Z. Sullivan

Singlet + Gauge Extensions

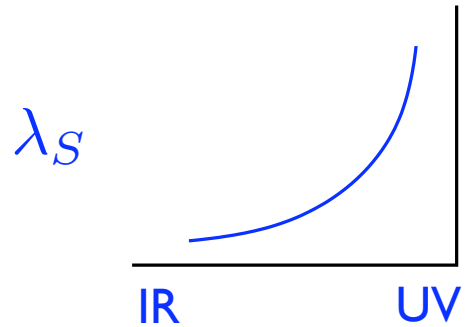
New Matter

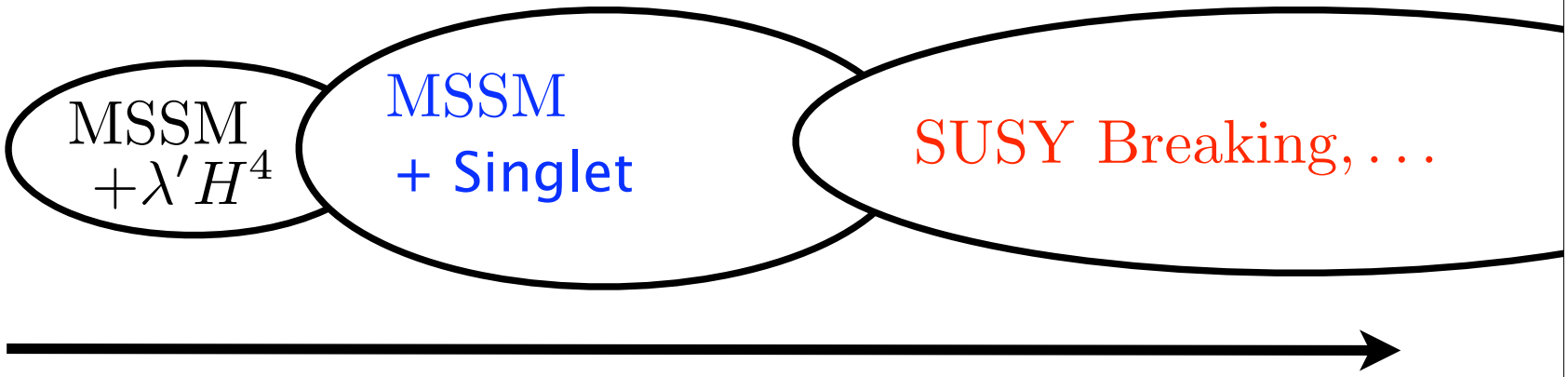


$$\lambda_S S H_u H_d$$

$$\propto \lambda_S^2$$

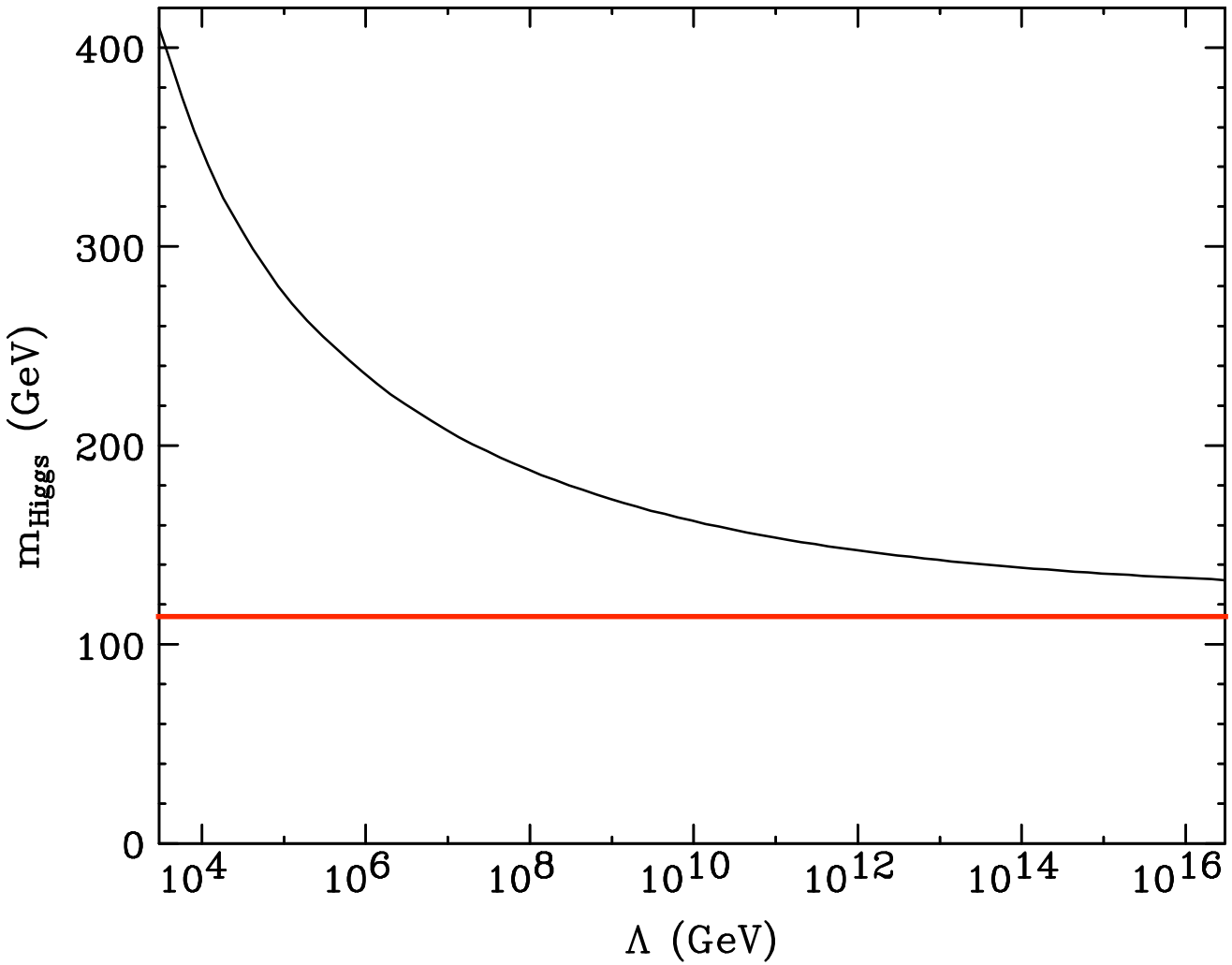
- No SM field will do
- Prefers Tan (β) ~ 1
- Bounded by perturbativity





Energy Weak TeV 10–100 TeV

Mass Bounds



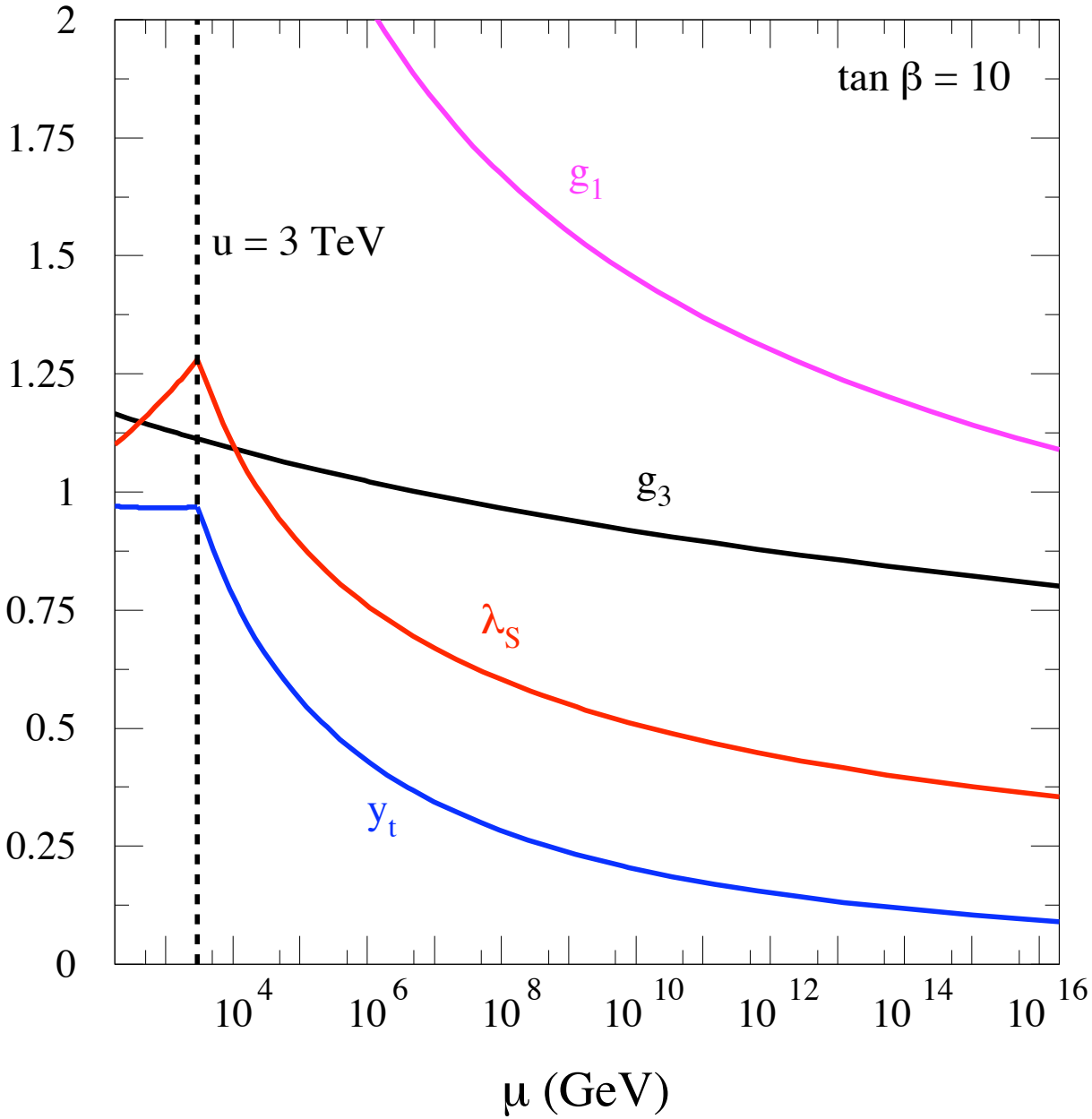
- $\lambda_S \leq 2\pi$

← 135 GeV

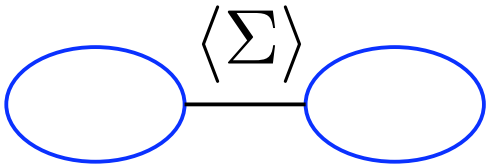
Espinosa & Quiros

Birkedal, Chacko, Nomura

Intermediate Physics



Product Groups



or

Confining Dynamics

Harnik, Kribs, Larson, Murayama
"Fat Higgs"

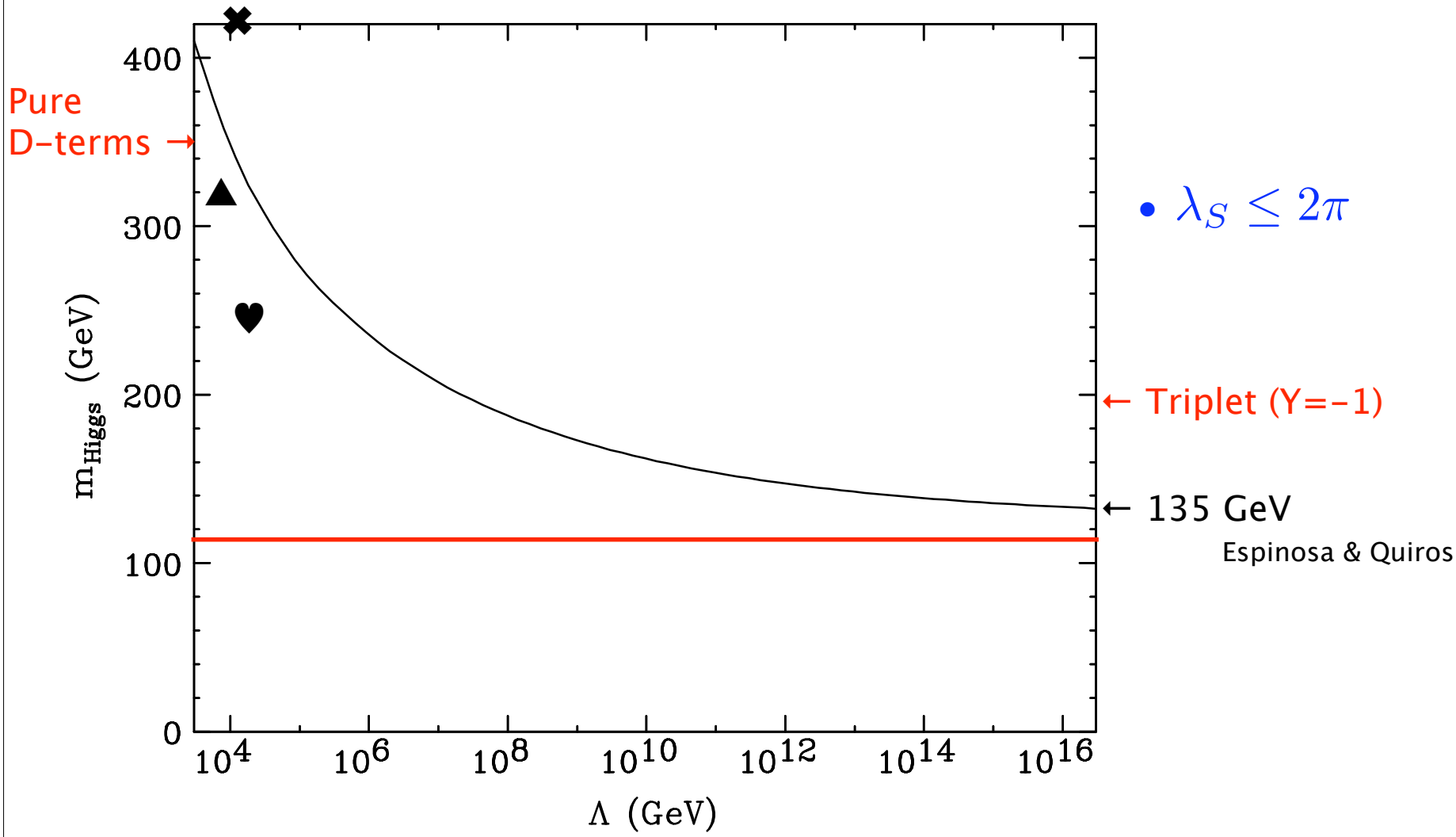
Chang, Kilic, Mahbubani

or

AdS 5-d Structure

Birkedal, Chacko, Nomura

Mass Bounds



- $\lambda_S \leq 2\pi$

✖ Harnik, Kribs, Larson, Murayama

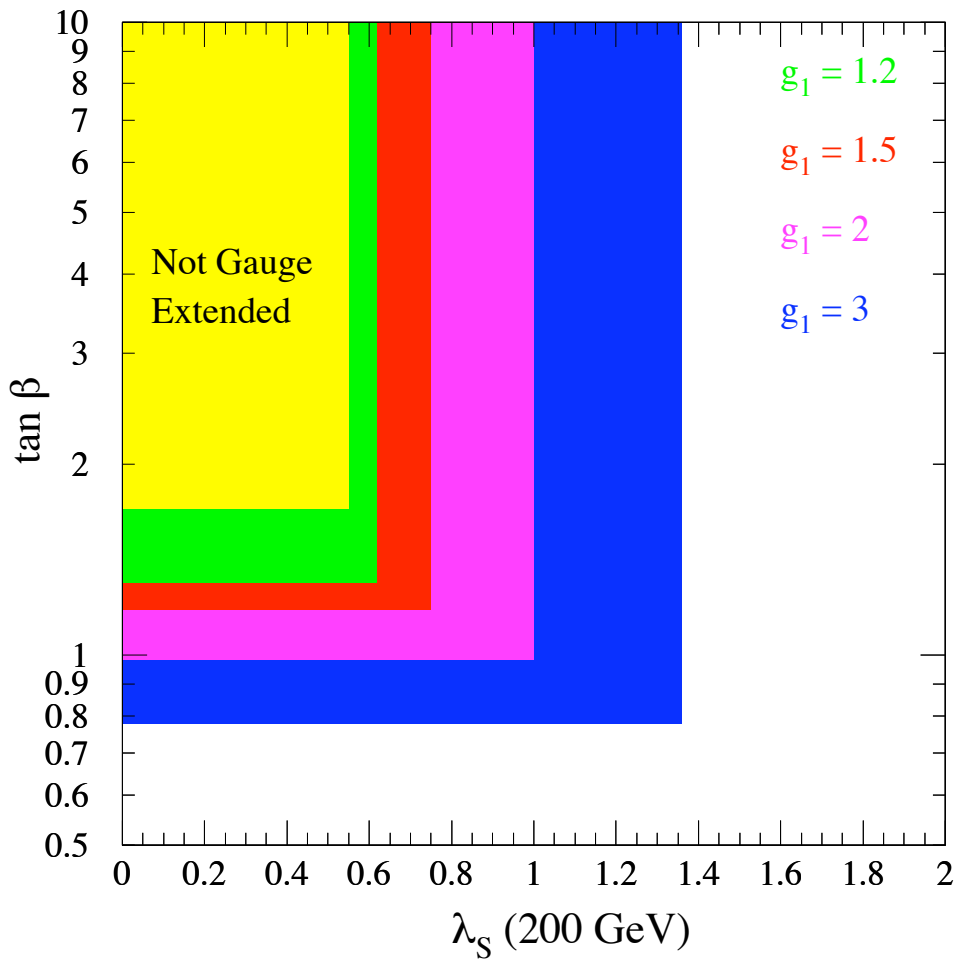
▲ Birkedal, Chacko, Nomura (AdS)

♥ P.B, Delgado, Kaplan, Tait

Phenomenology

- Higgs mass at odds with the MSSM, altered mass-sum rules, preference for low Tan (β)

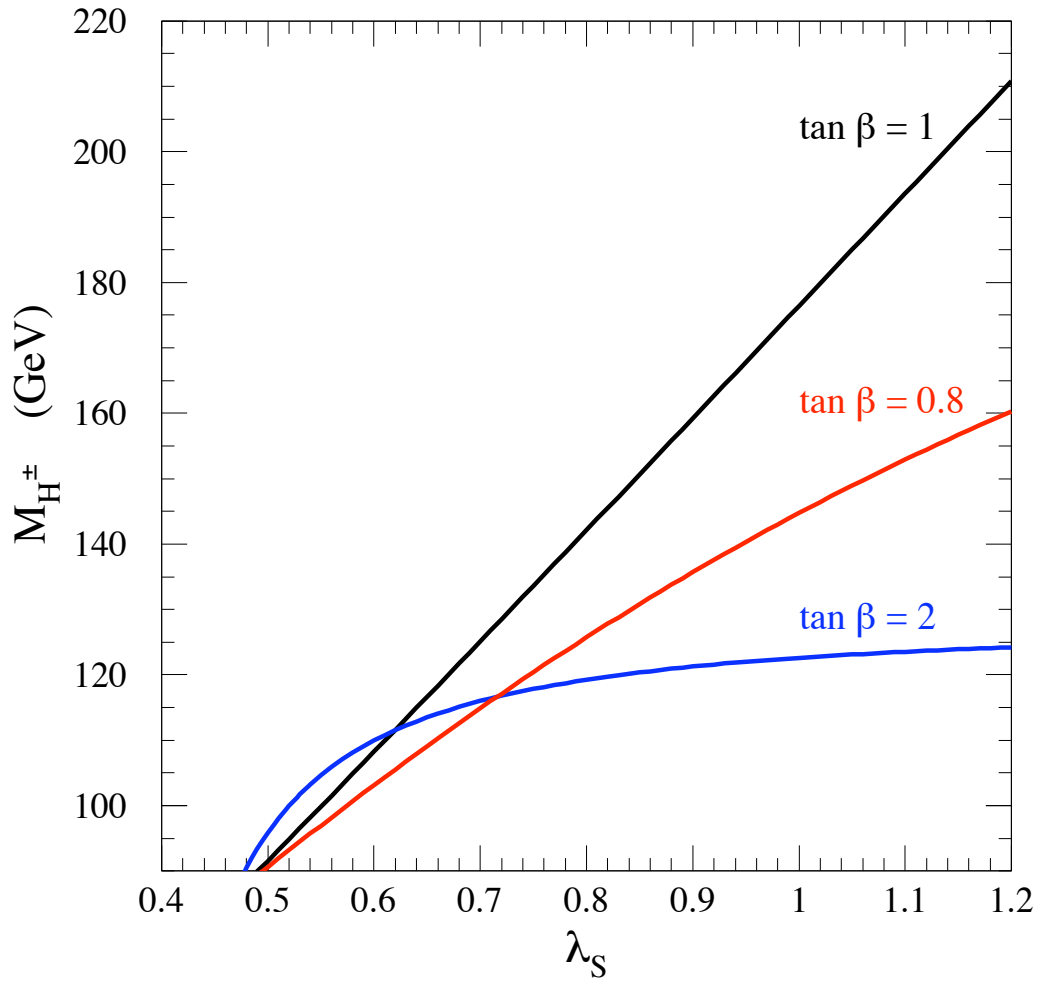
- Smaller values of Tan (β) allowed by perturbativity (enhanced top couplings!)



Light Charged Higgs

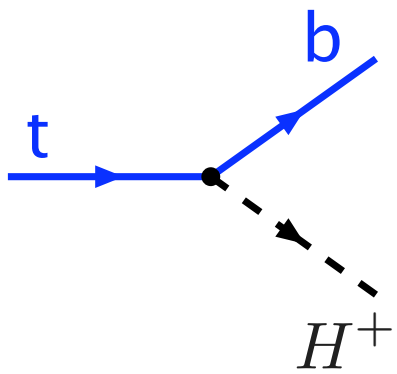
- Spectrum where the charged Higgs is the lightest state in the Higgs spectrum

$$m_{H^+}^2 = m_A^2 + \Delta m_W^2 - \lambda_S v^2$$



Light Charged Higgs

- Possibility of rare top decays



Tevatron (2 fb^{-1}) can exclude (Run II Higgs Report, Carena et al.)

$$\tan\beta < 1, \quad m_{H^+} < 120 \text{ GeV}$$

LHC (100 fb^{-1}) can exclude (CERN Top Yellow Book, Beneke et al.)

$$m_{H^+} < 160 \text{ GeV}$$

- Modifies branching ratios to jets vs. leptons compared to the usual top decay

Conclusions

- 'The MSSM'='Resilient-scam amidst theory madmen'

- Max-Mixing and %-ish fine-tuning are needed to evade LEP-II bounds on the MSSM!

- Signals of SUSY will likely include low-energy evidence of additional structure beyond the MSSM--

  massive vectors bosons
  altered mass relations in the Higgs Sector
  light, charged Higgs fields

- Will some other successes of the MSSM (radiative EWSB, simple GUT unification) be lost?

Supplemental Slides

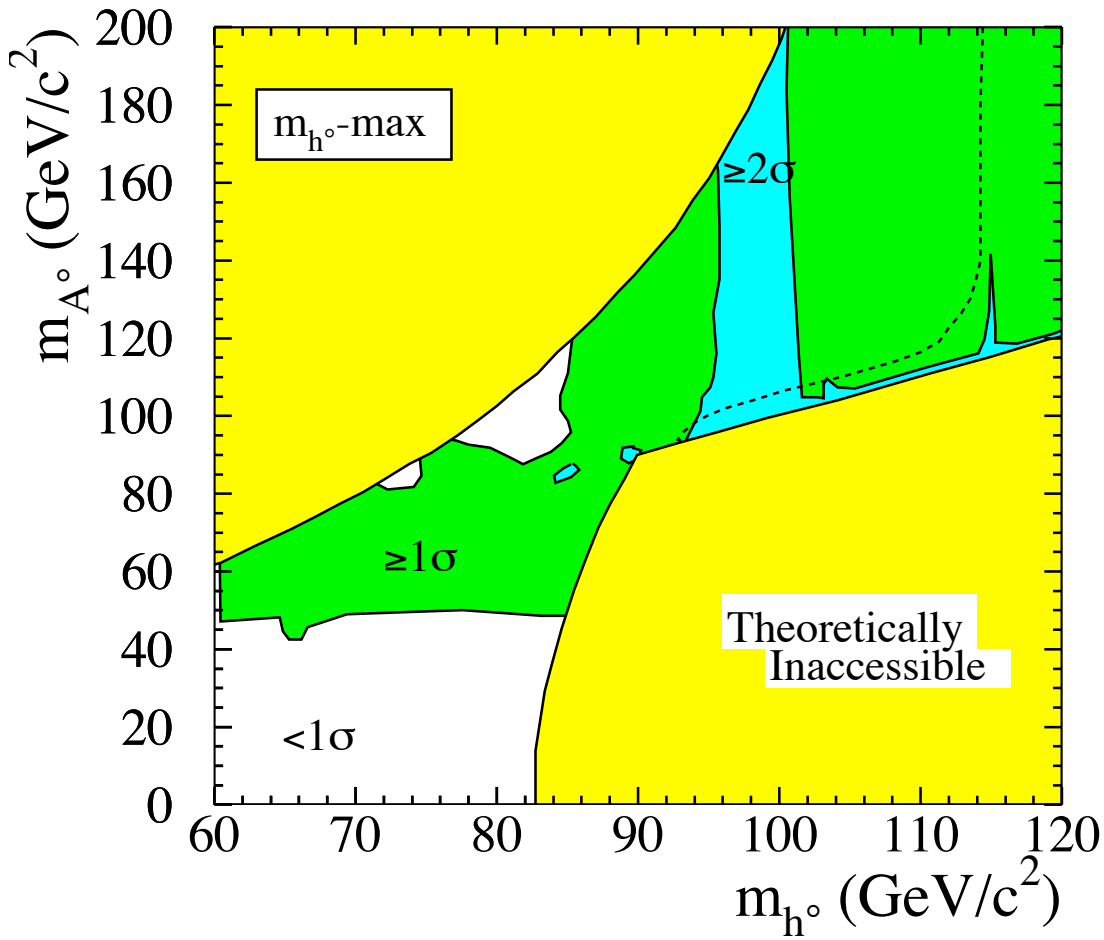
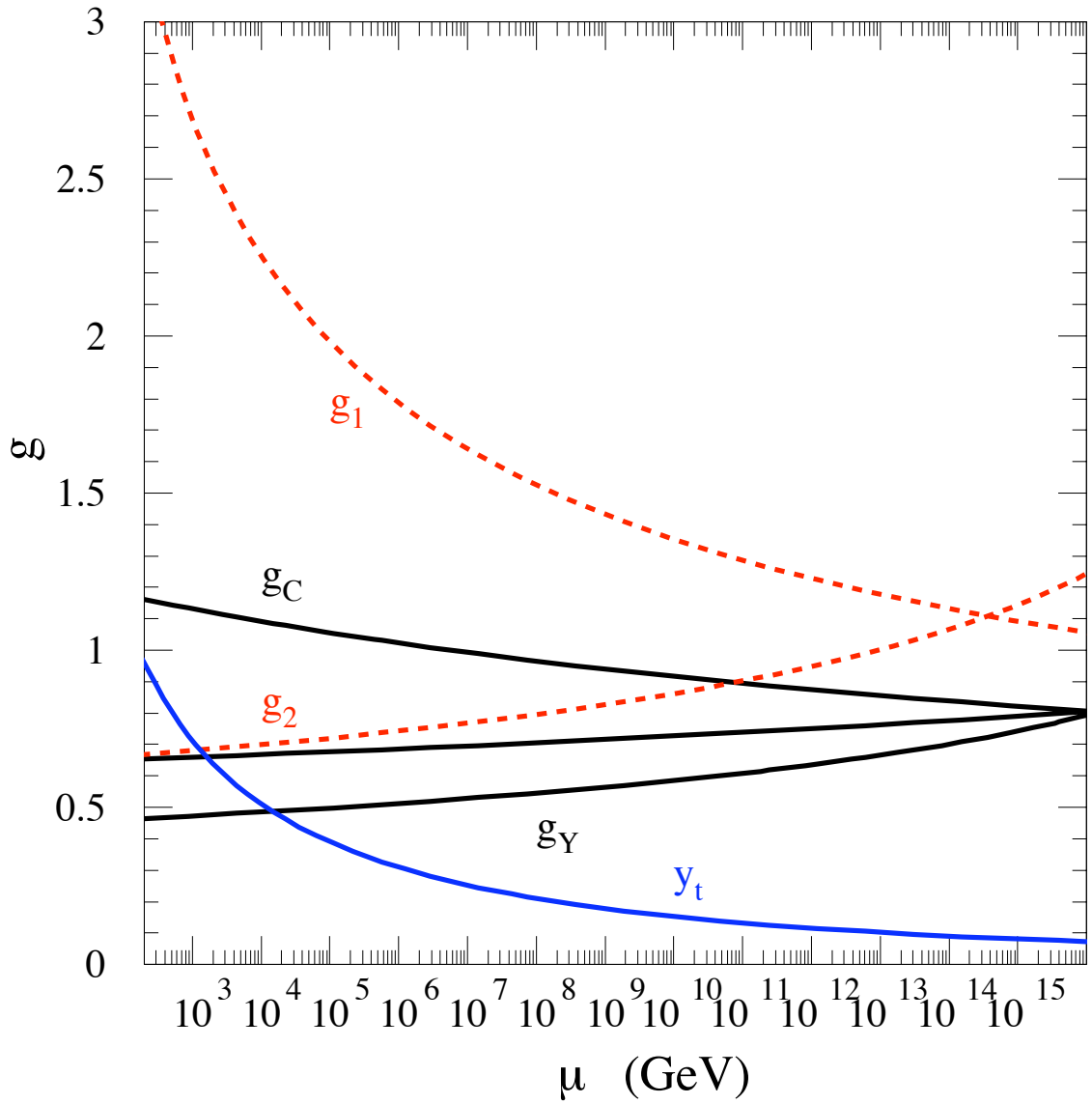
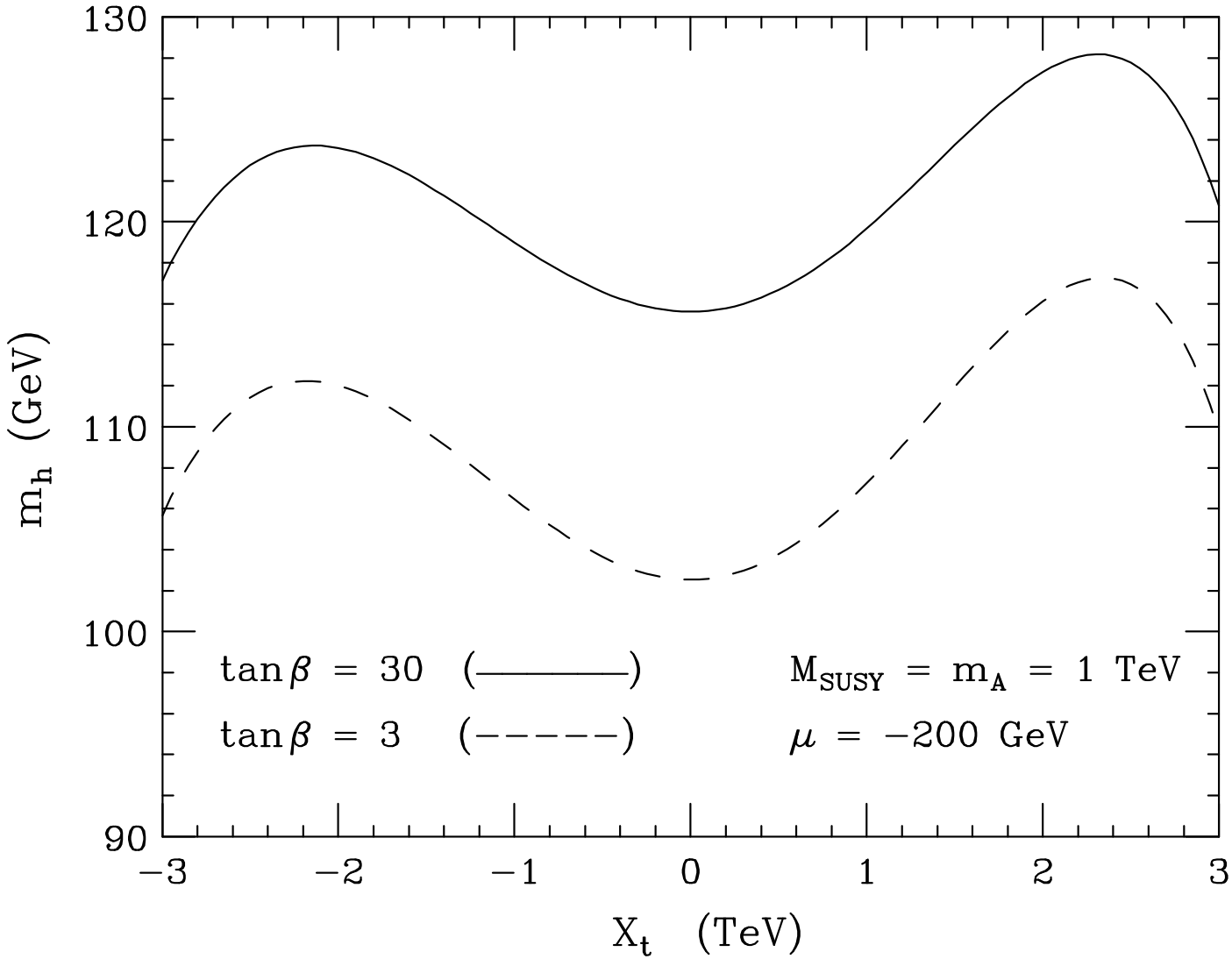


Figure 3: *Contours of the p-value* $1-CL_b$ *for the* $m_{\rm h}$*-max benchmark scenario, in the* $(m_{\rm h}, m_{\rm A})$ *projection of the MSSM parameter space. The theoretical limits are indicated. In the white regions labeled* $< 1\sigma$ *the data deviate by less than one standard deviation from the expectation based on Monte Carlo simulation with no signal. Similarly, in the dark-grey (green) regions labeled* $\geq 1\sigma$ *the deviation is between one and two standard deviations and in the light-grey (blue) regions labeled* $\geq 2\sigma$ *it is between two and three standard deviations. The dashed line represents the upper edge of the region excluded at 95% c.l. by this search (compare to Figure 4, upper left).*

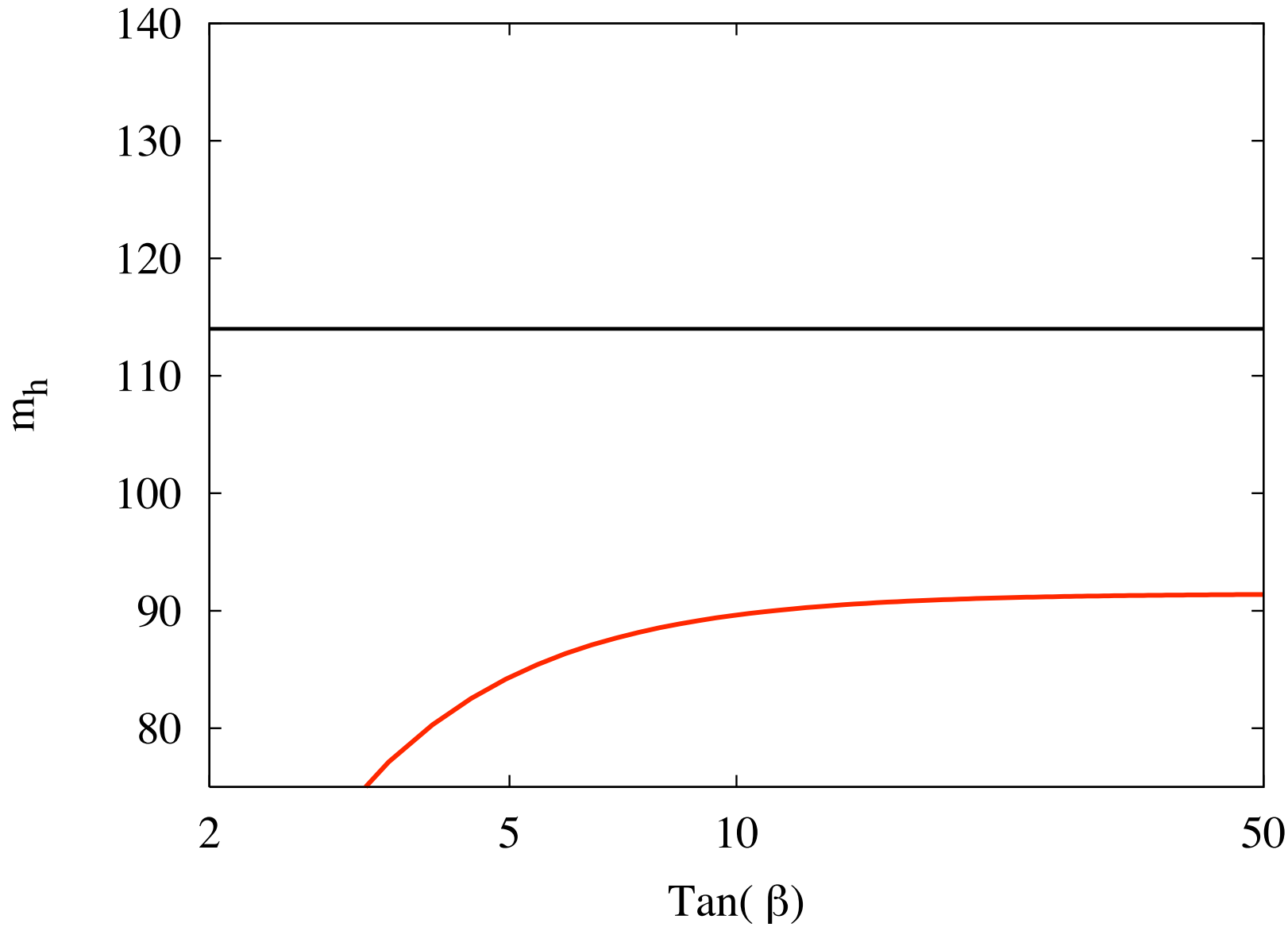
Gauge Coupling Unification



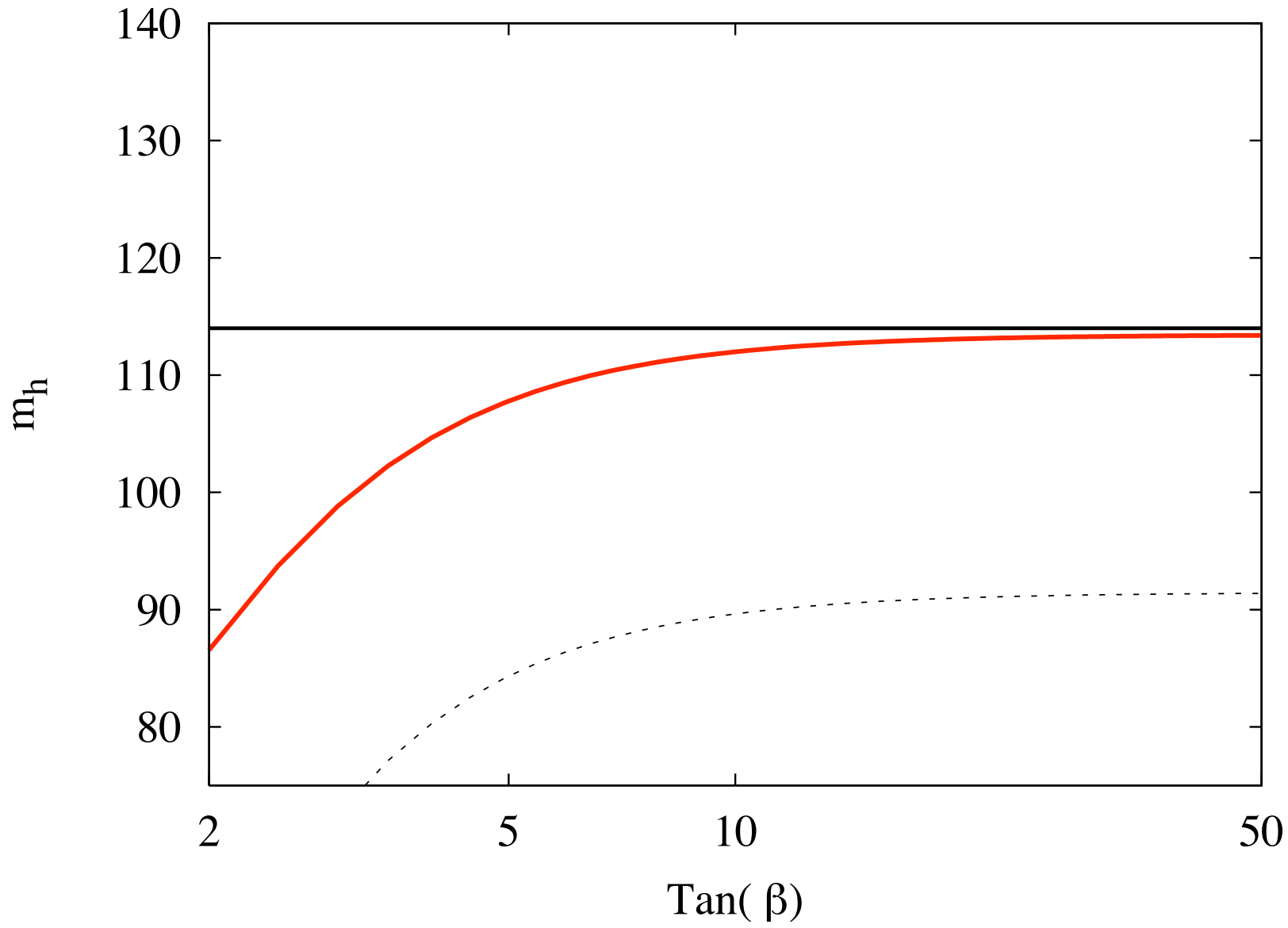
Max vs. Min mixing



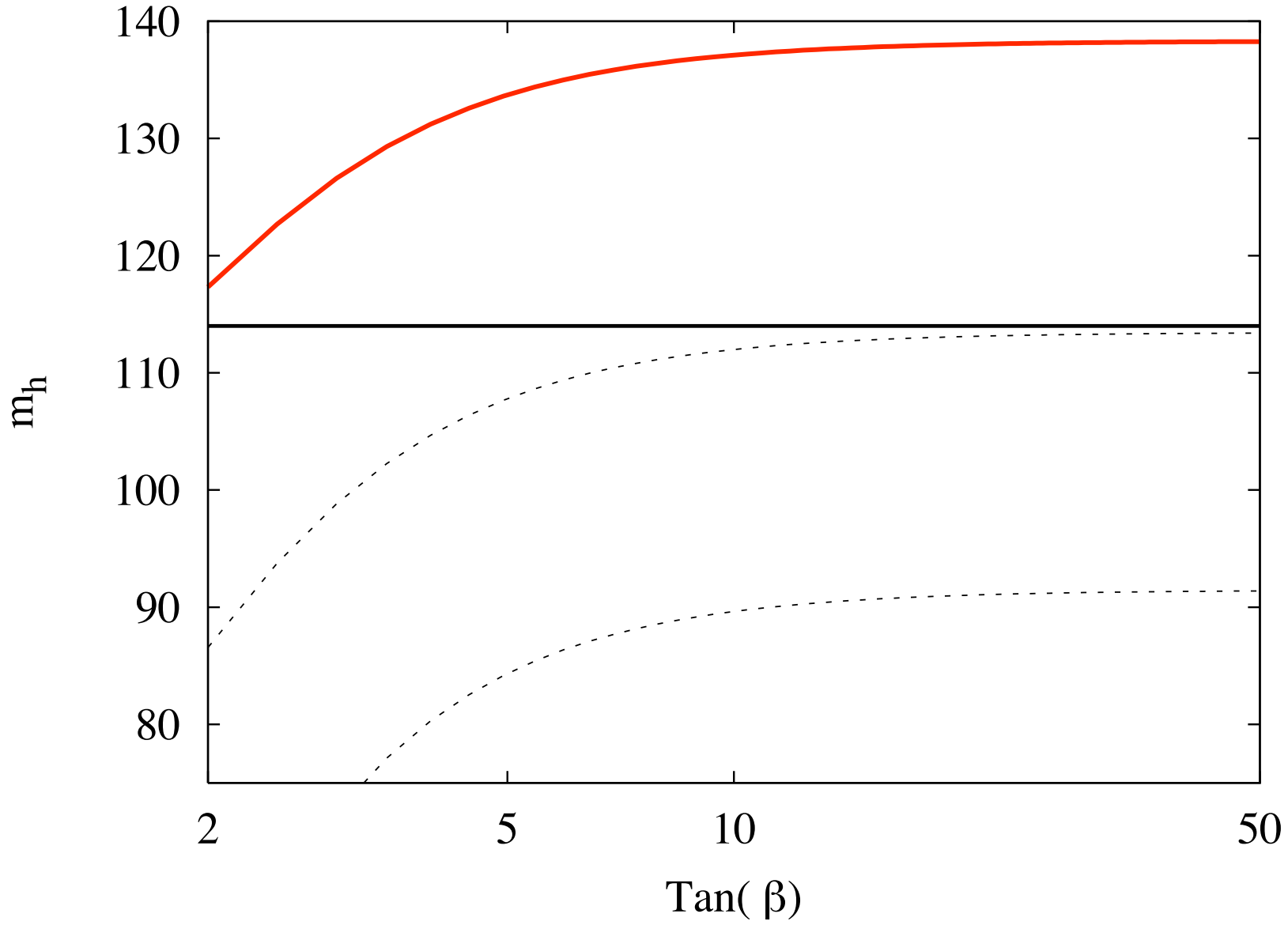
Tree-level mass



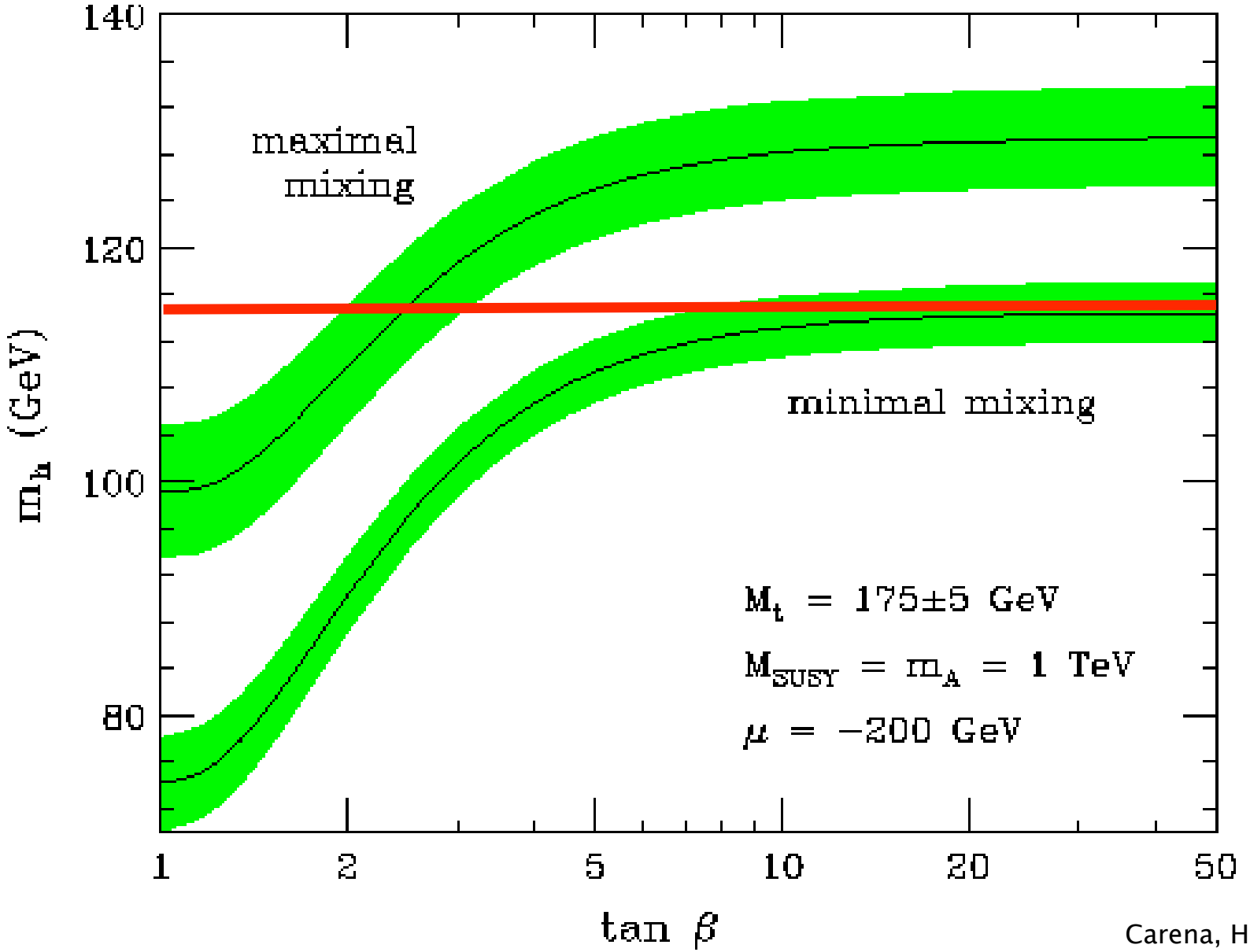
Min mixing with 500 GeV stop



Max mixing with 500 GeV stop

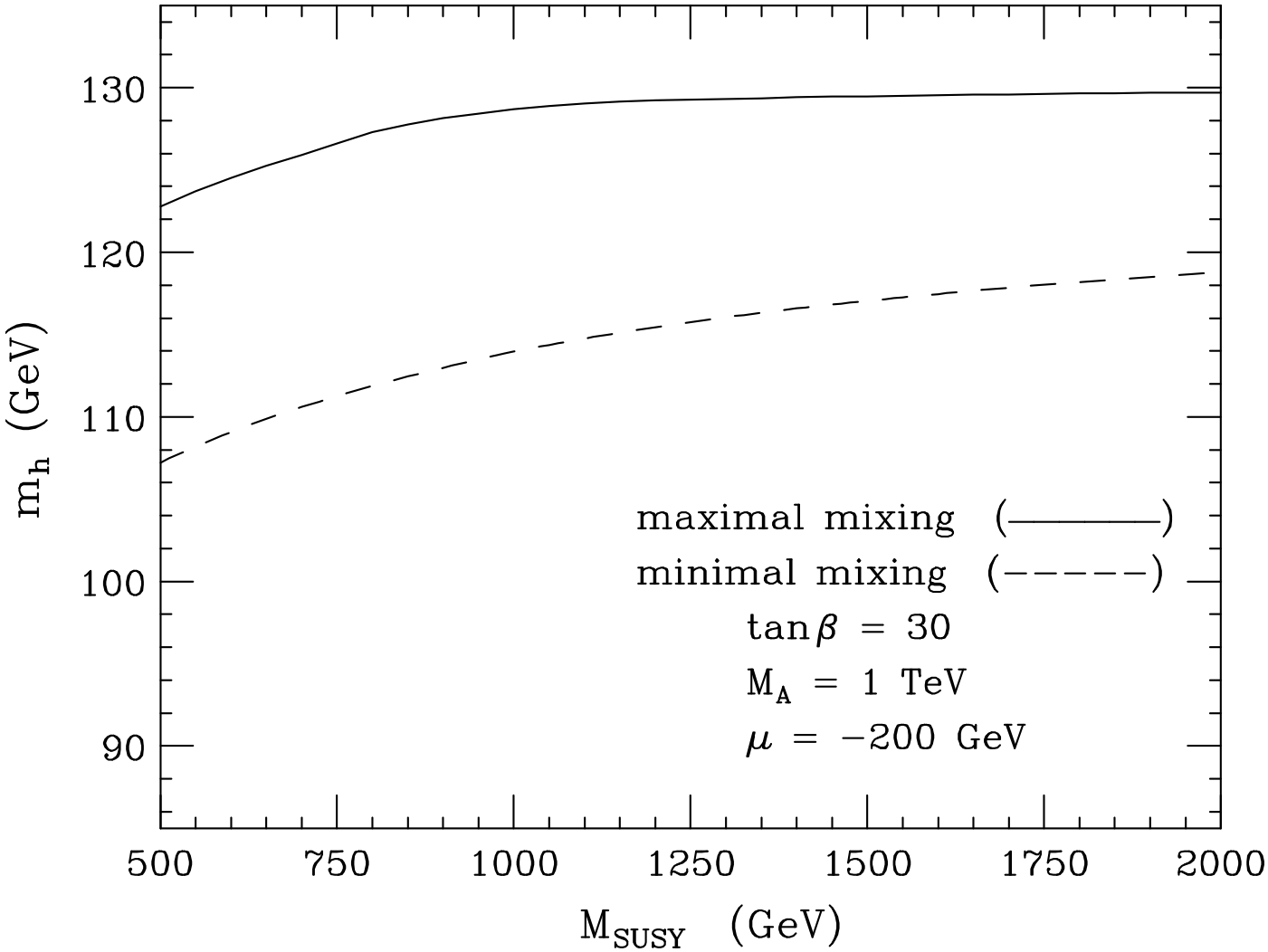


Higher order max vs min mixing



Carena, Haber

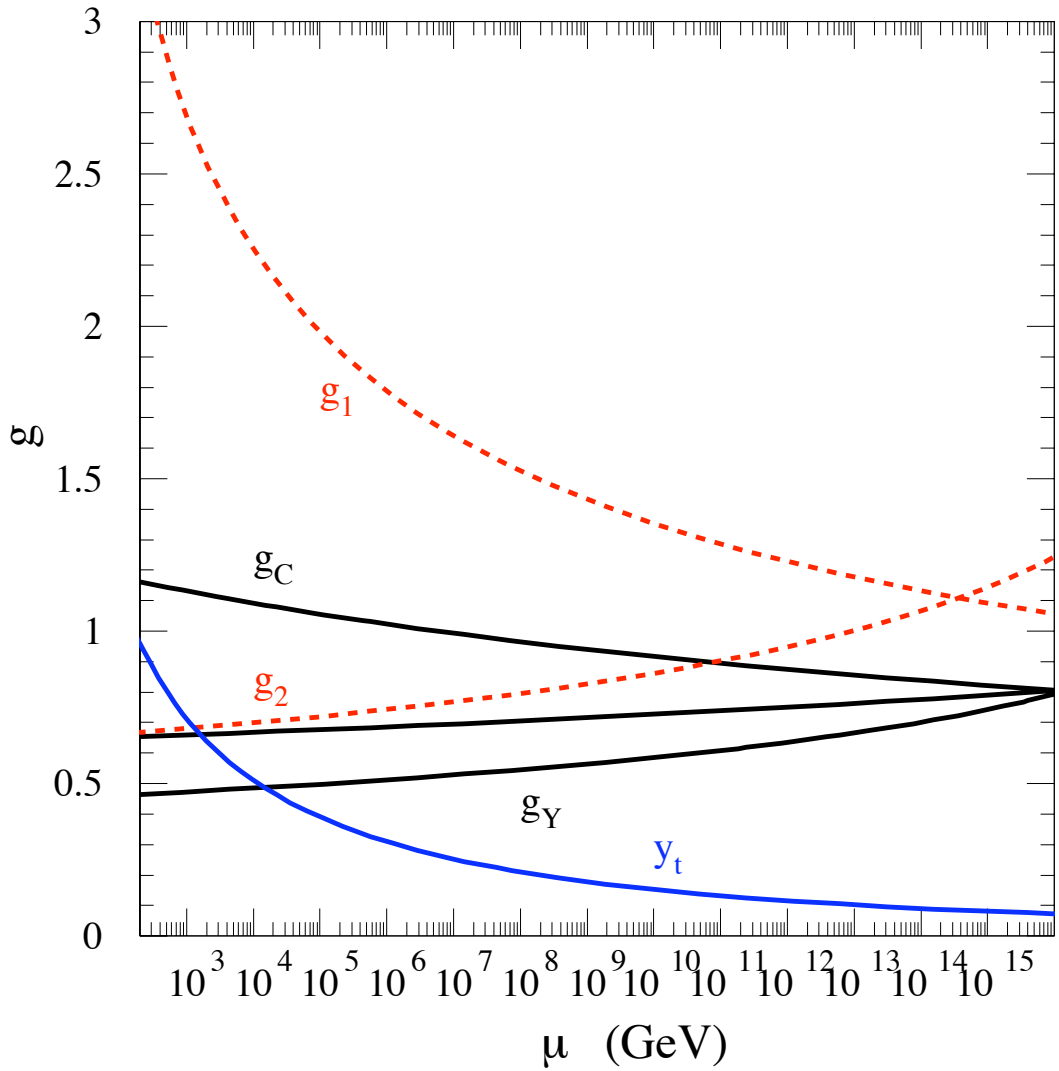
Dependence on soft masses



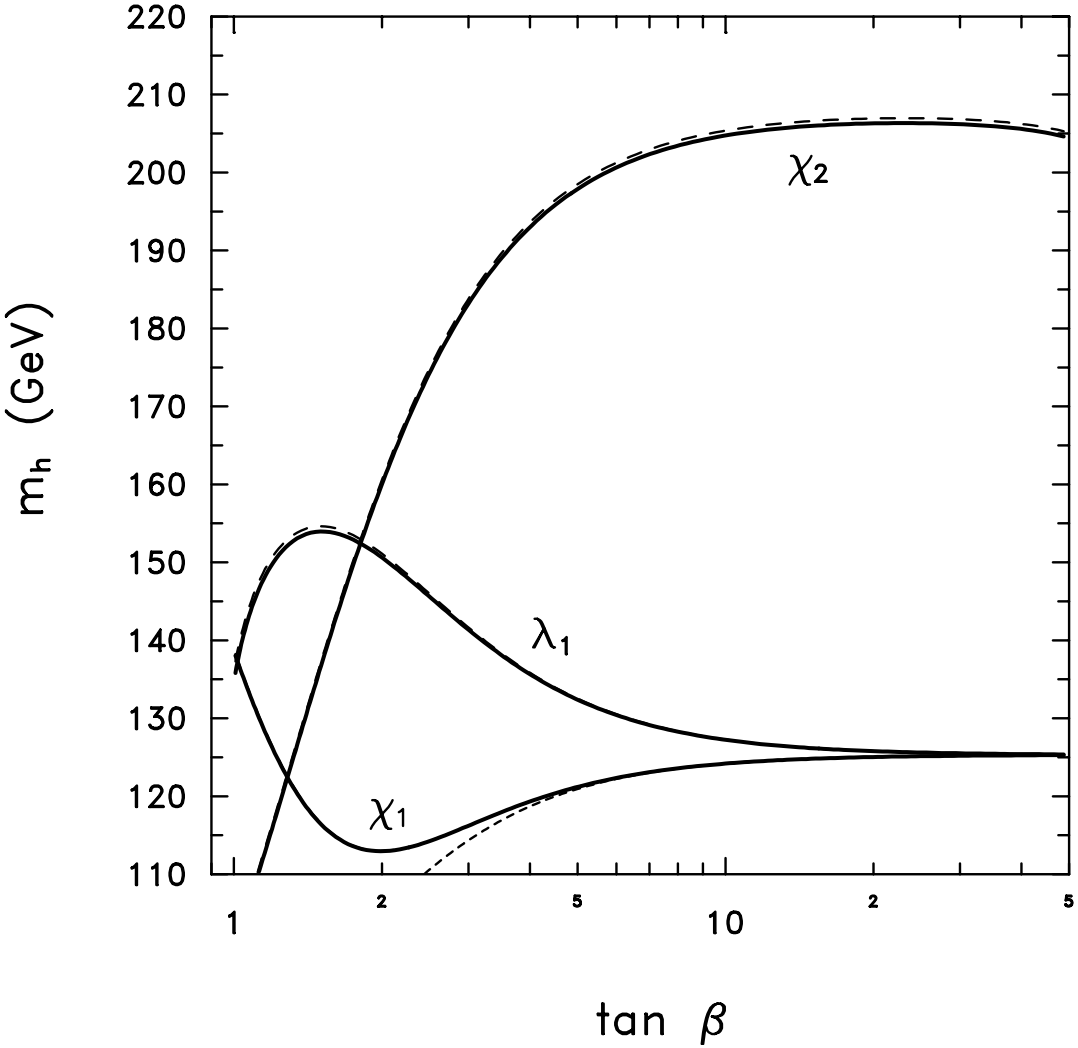
Carena, Haber (2002)

Unification

- Diagonal SU(5) Unification

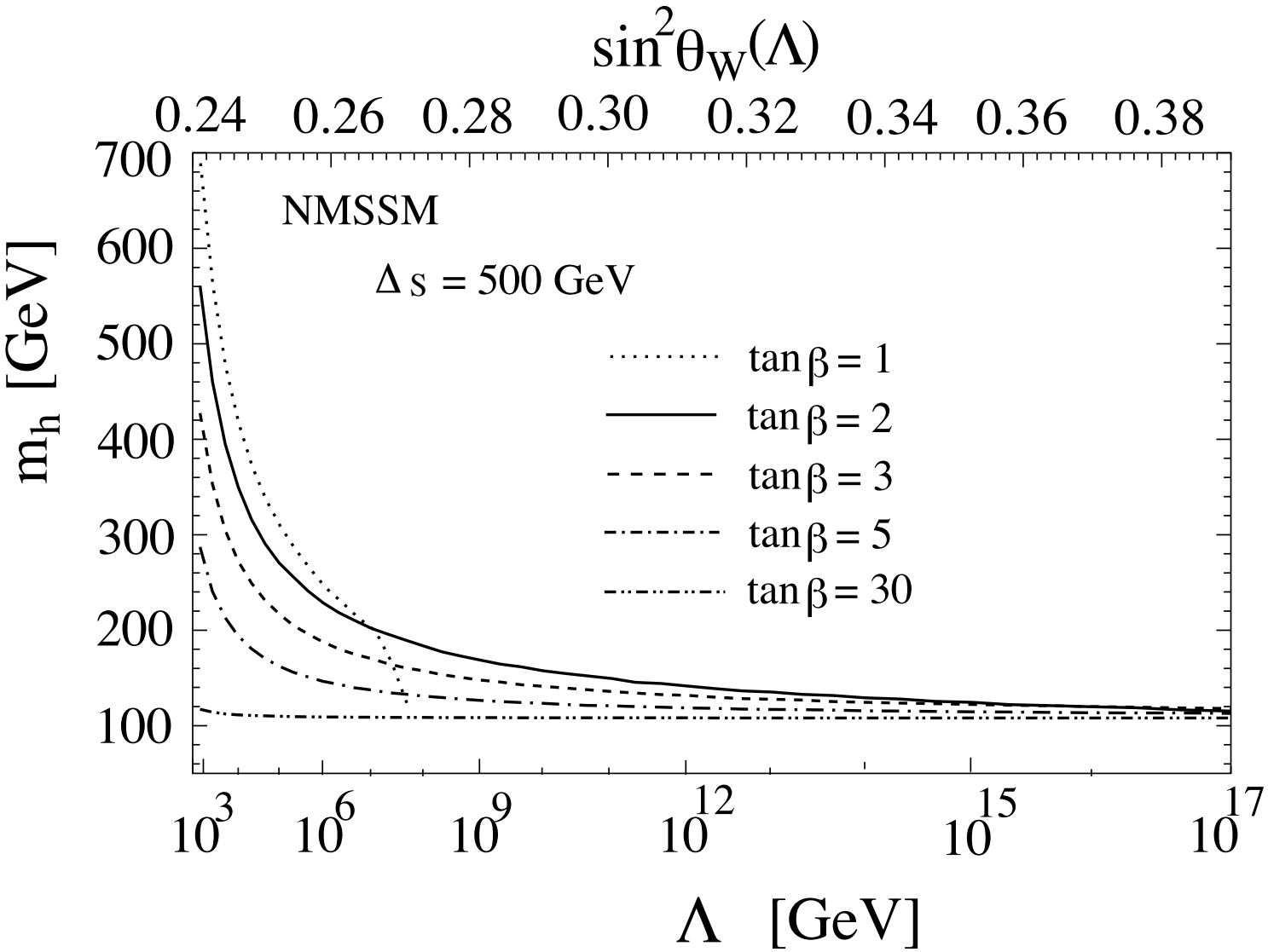


"MSSM+S" Limits



Espinosa, Quiros (1998)

"MSSM+S" Limits



Tobe, Wells 2002

Yukawas

- add an extra pair of Higgs-like doublets

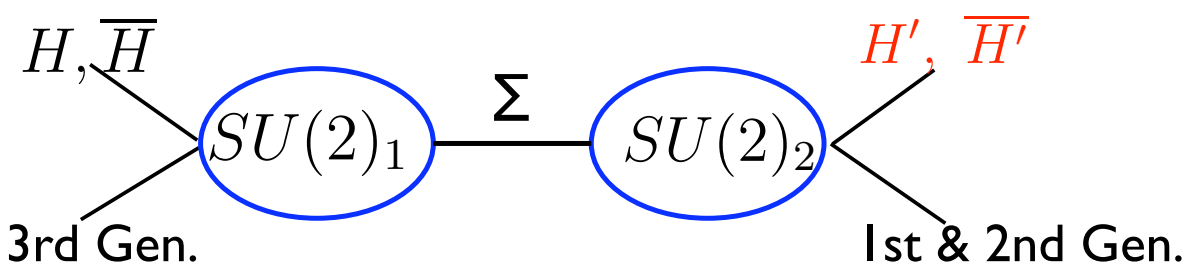
- include mixing terms in the Superpotential

$$W \supset \underbrace{\mu' H' \overline{H'}}_{\text{Large mass term}} + \underbrace{\lambda_c Q_c \overline{c} \overline{H'}}_{SU(2)_2 \text{ 'Yukawa'}} + \underbrace{\lambda_f H \Sigma \overline{H'} + \lambda_f H' \Sigma \overline{H}}_{\text{Feeding terms}}$$

- at low energies:

$$W \supset \frac{\lambda_f \lambda_c \langle \Sigma \rangle}{\mu'} Q_c \overline{c} \overline{H}$$

$SU(2)_W$ Yukawa's with natural suppression



Fine-tuning

Recall, we require $m_\Sigma \gg \langle \Sigma \rangle$

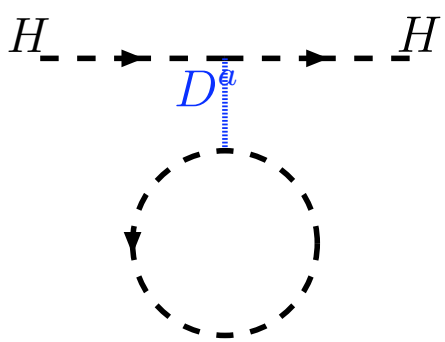
10 TeV 1 TeV

Two sources of fine-tuning:

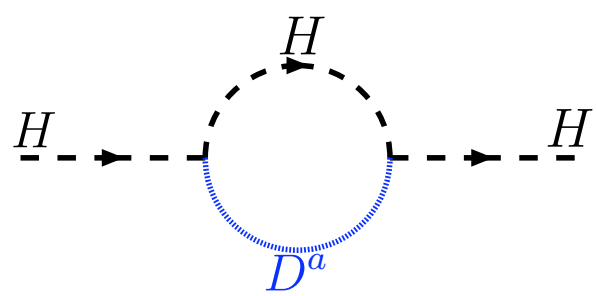
- Below $\langle \Sigma \rangle$, a hard breaking of SUSY in the gauge sector from Δ
- UV sensitive logarithmic contributions of m_Σ^2 into $m_H^2, m_{\overline{H}}^2$

only enters at two-loops!

$$\mathcal{L} \supset D^a \left(\mathrm{Tr} \left(\Sigma^\dagger \sigma^a \Sigma \right) + H^\dagger \sigma^a H - \overline{H} \sigma^a \overline{H}^\dagger \right)$$



$\propto \mathrm{Tr}\ \sigma^a = 0$



independent of m_Σ

Delta, Delta, Delta

$$\Delta = \frac{1 + \frac{2m_\Sigma^2}{u^2}\frac{1}{g_2^2}}{1 + \frac{2m_\Sigma^2}{u^2}\frac{1}{g_1^2 + g_2^2}}$$