# Implications of a 125 GeV SM-like Higgs

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# Outline

- The Standard Model. Vacuum properties.

- 2HDM. Alignment limit. Searches for other states.

- Supersymmetry. Consistent models. Fine-tuning. Arguments for various SUSY-breaking scales.

This talk will review the work of many people!

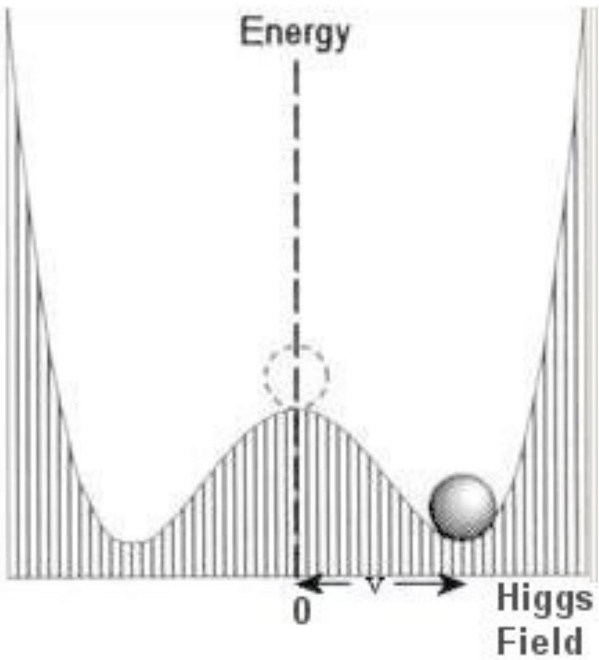
# SM Higgs Potential for Weak Fields

Potential: $$V(\phi) = -\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Minimum: $$\langle\phi^2\rangle = \frac{m^2}{\lambda}$$

Curvature at minimum
(mass of physical state): $$m_h^2 = 2\lambda\langle\phi^2\rangle$$

Quartic coupling determines physical mass




The known Z and W masses fix $<\phi>=174$ GeV,

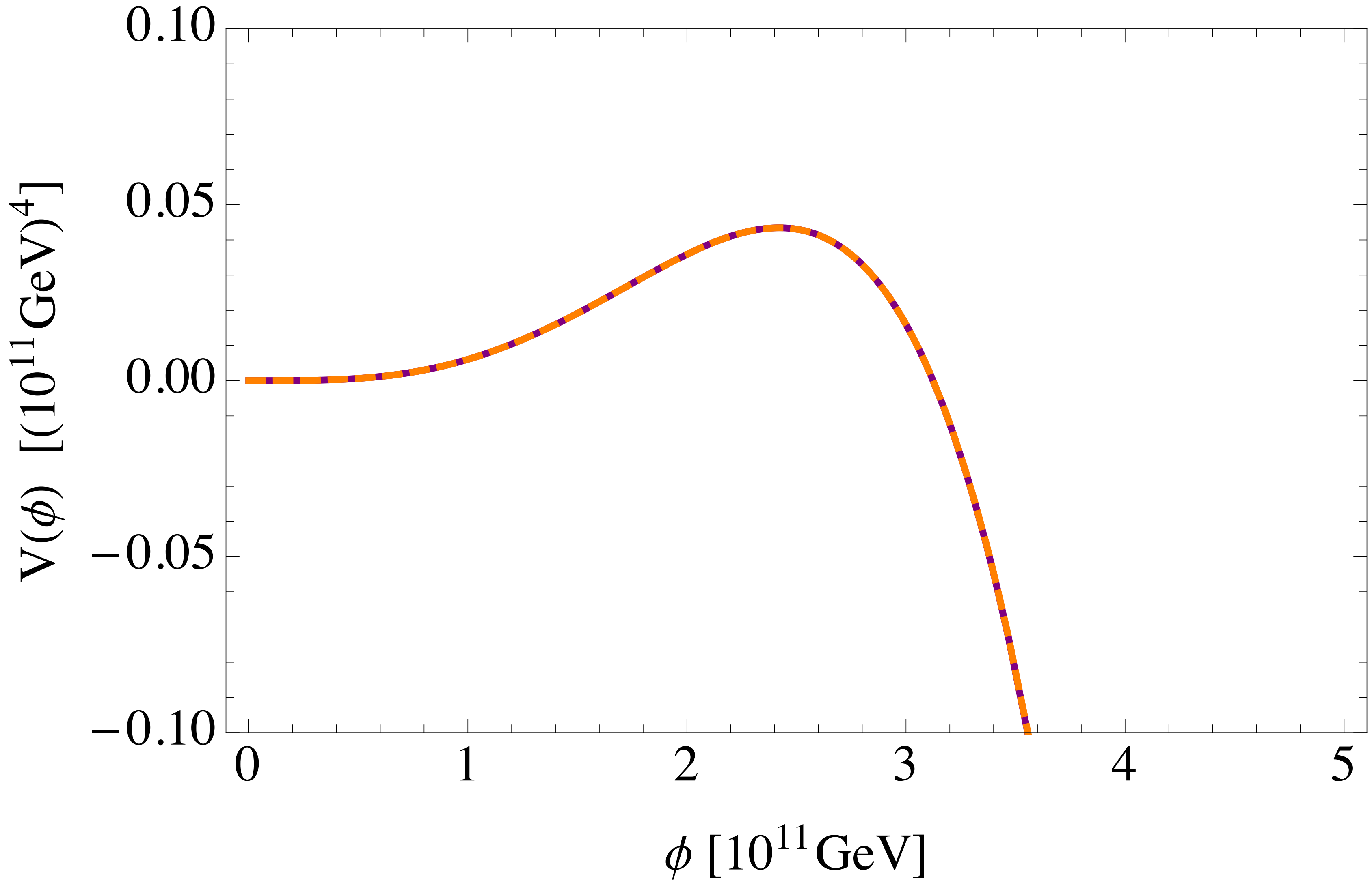
fixing one combination of m and λ.

Now the measurement $m_h=125$ GeV fixes the other.

$$\boxed{-(m^2) \approx -(89\ \mathrm{GeV})^2\,, \qquad \lambda \approx 0.26}$$

Self-coupling is weak.

# RG-improved Effective Potential at High Field Values




Adapted from
Degrassi, Di Vita, Elias-Miro,
Espinosa, Giudice, Isidori,
Strumia 2012

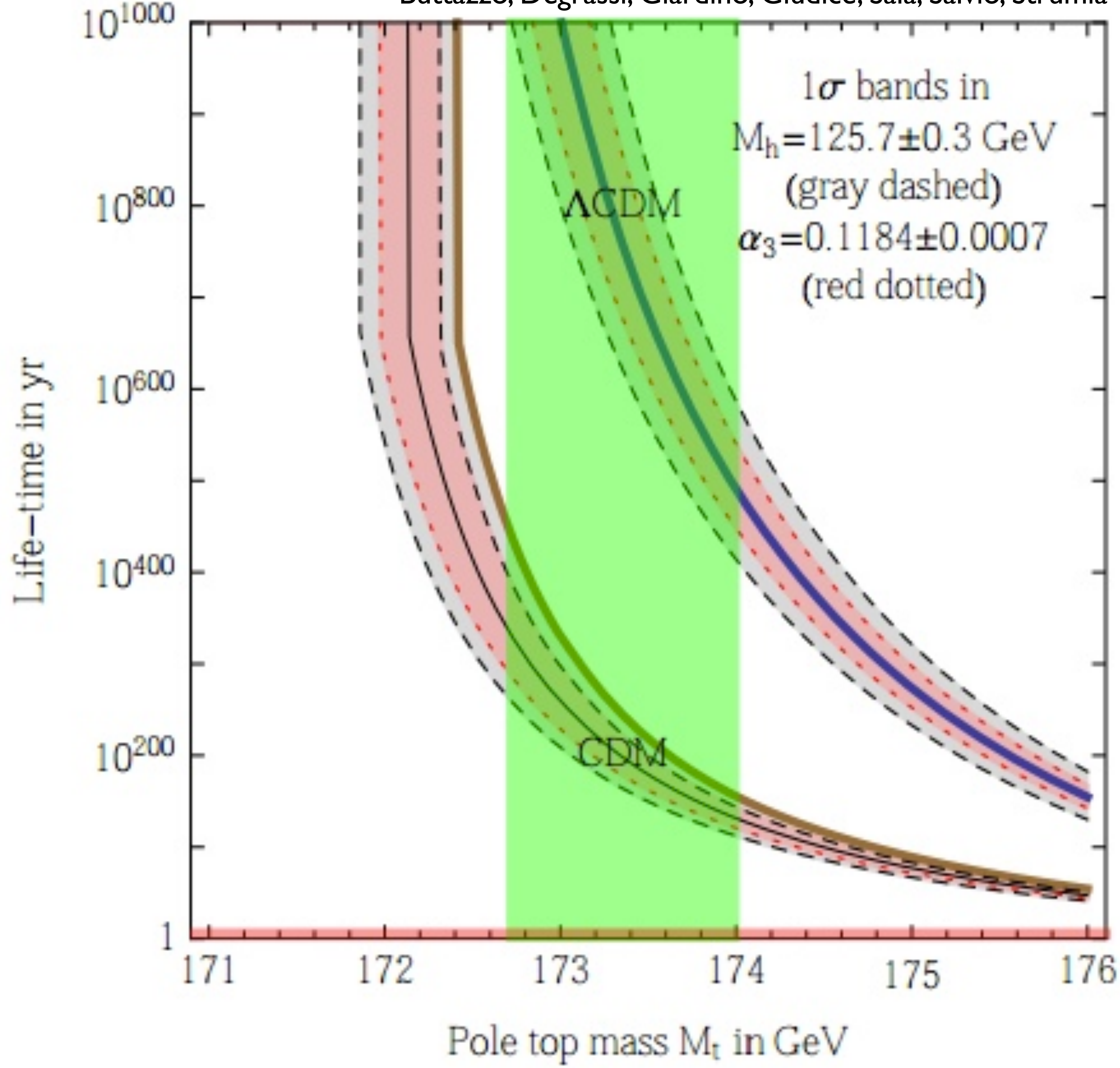
Potential turns over near $10^{11}$ GeV and is unbounded from below.
New physics must stabilize it!

2 possibilities:

(1) new physics is below the instability scale. Our vacuum probably stable.

(2) new physics is only above instability scale. Our vacuum metastable, lifetime ~ $10^{800}$ y

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia



# Beyond the SM

A common extension of the SM is to add a second Higgs doublet (2HDM).
Can arise in larger extensions: SUSY, composite models, Twin Higgs, etc.

**Two** SU(2) doublets: $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \; H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$

$\boxed{\tan\beta \equiv \langle H_u^0 \rangle / \langle H_d^0 \rangle}$

Convenient input parameter

→ Two charged states $H^{+/-}$, one neutral CP-odd mass eigenstate A

\+ Two neutral CP-even mass eigenstates h, H; mixing angle $\alpha$

4 different 2HDM conserve CP and do not contribute to FCNCs at tree level

Lightest Higgs mass is a free parameter in general 2HDMs

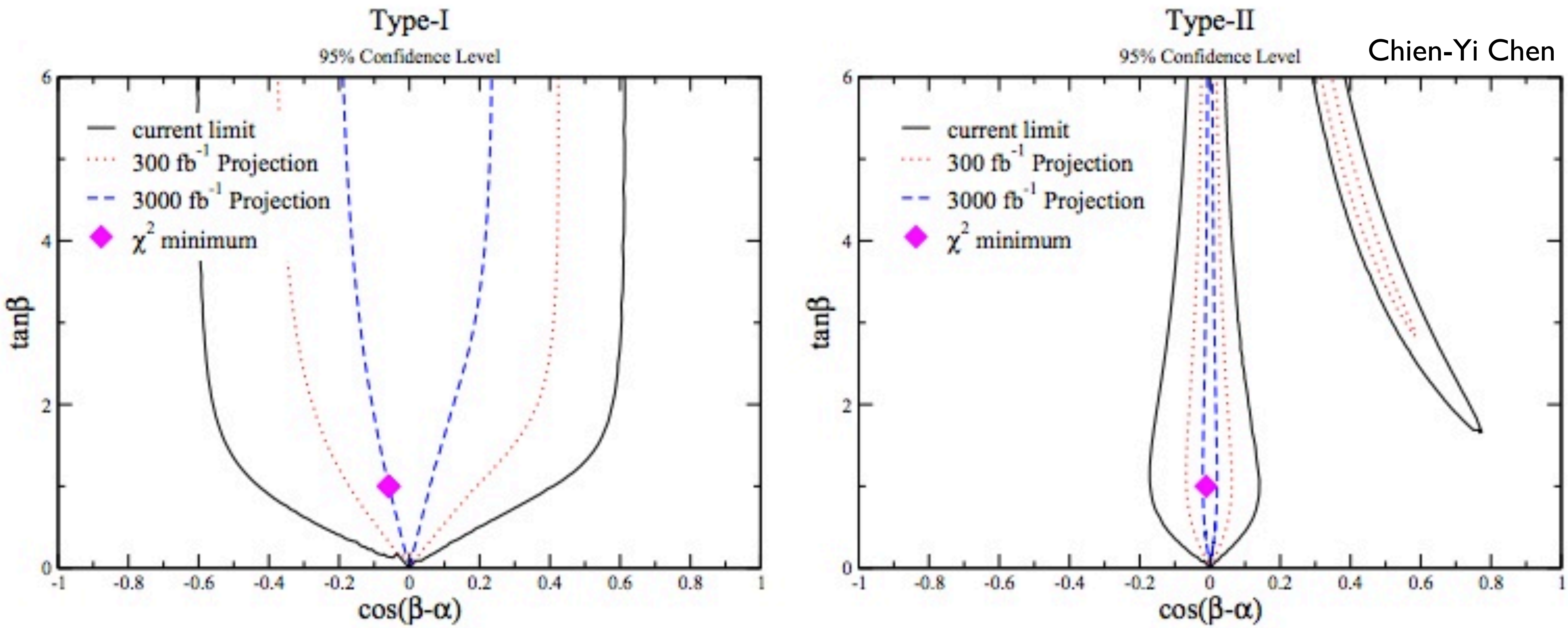
Scalar couplings to SM fermions and vector bosons controlled by $\alpha$, $\beta$

Craig, Galloway, Thomas

| $y_{2HDM}/y_{SM}$ | 2HDM 1 | 2HDM 2 | 2HDM 3 | 2HDM 4 |
|---|---|---|---|---|
| $hVV$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ | $s_{\beta-\alpha}$ |
| $hQu$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ |
| $hQd$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ |
| $hLe$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$ | $s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$ |
| $HVV$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ | $c_{\beta-\alpha}$ |
| $HQu$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ |
| $HQd$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ |
| $HLe$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$ | $c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$ |

# 2HDM Signatures

The rates for the 125 GeV Higgs are close to the SM predictions.
Suggestive of an "alignment" limit of 2HDM. $\alpha \to \beta - \pi/2$ Haber & Nir




In the MSSM (2HDM 2) with $m_A > m_h$, limit on $\beta-\alpha$ translates to a lower limit on $m_A$ ~ 300 GeV for a broad range of tan β

May have modifications of rates for h in channels that are not yet well-measured:

"In a Type I 2HDM... an enhancement of up to 80% in VBF or Vh associated production with $h \to \gamma\gamma, VV^*$ is consistent with the current 68% CL coupling fits at low tan β."

Craig, Galloway, Thomas

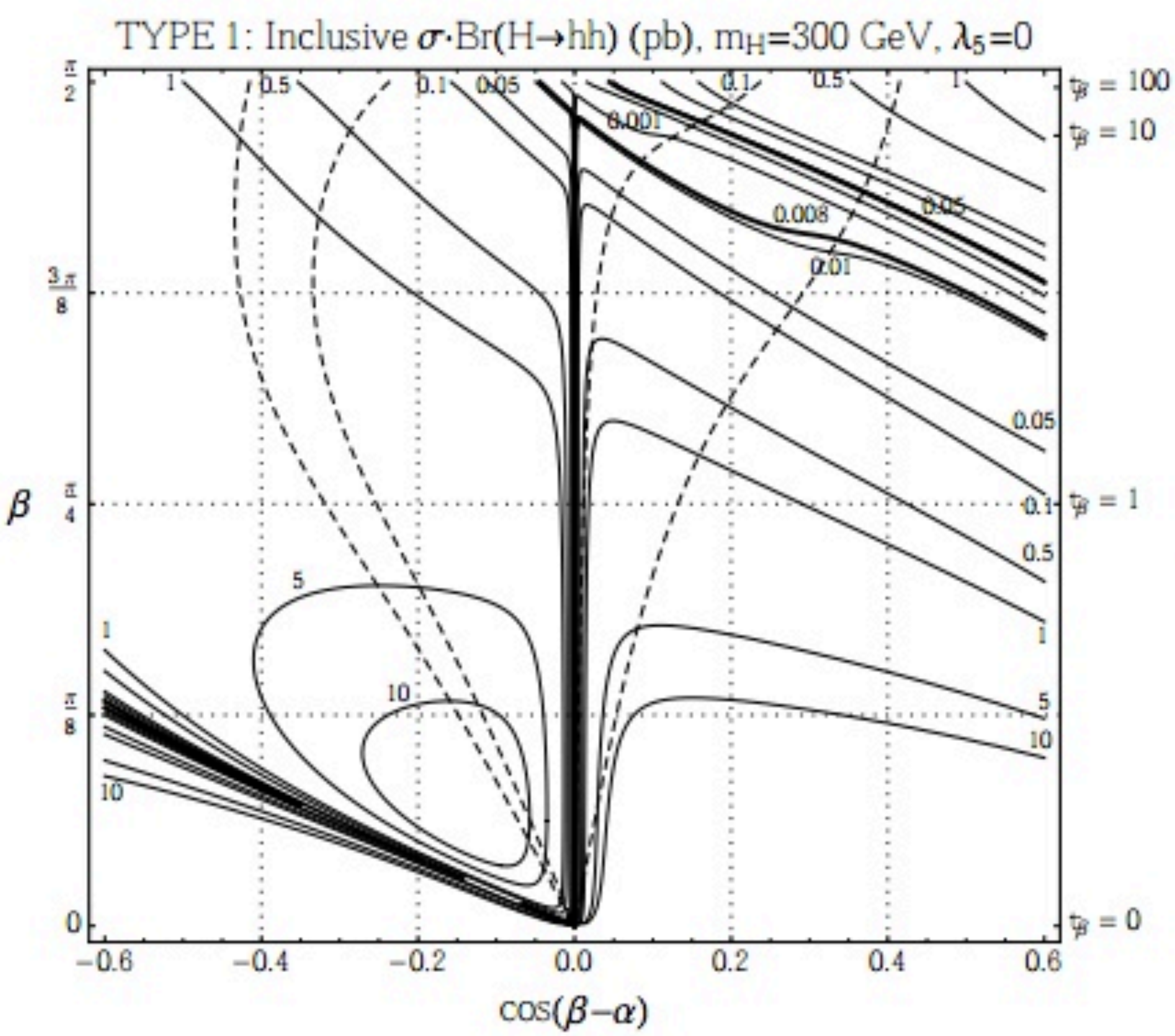
# 2HDM Signatures

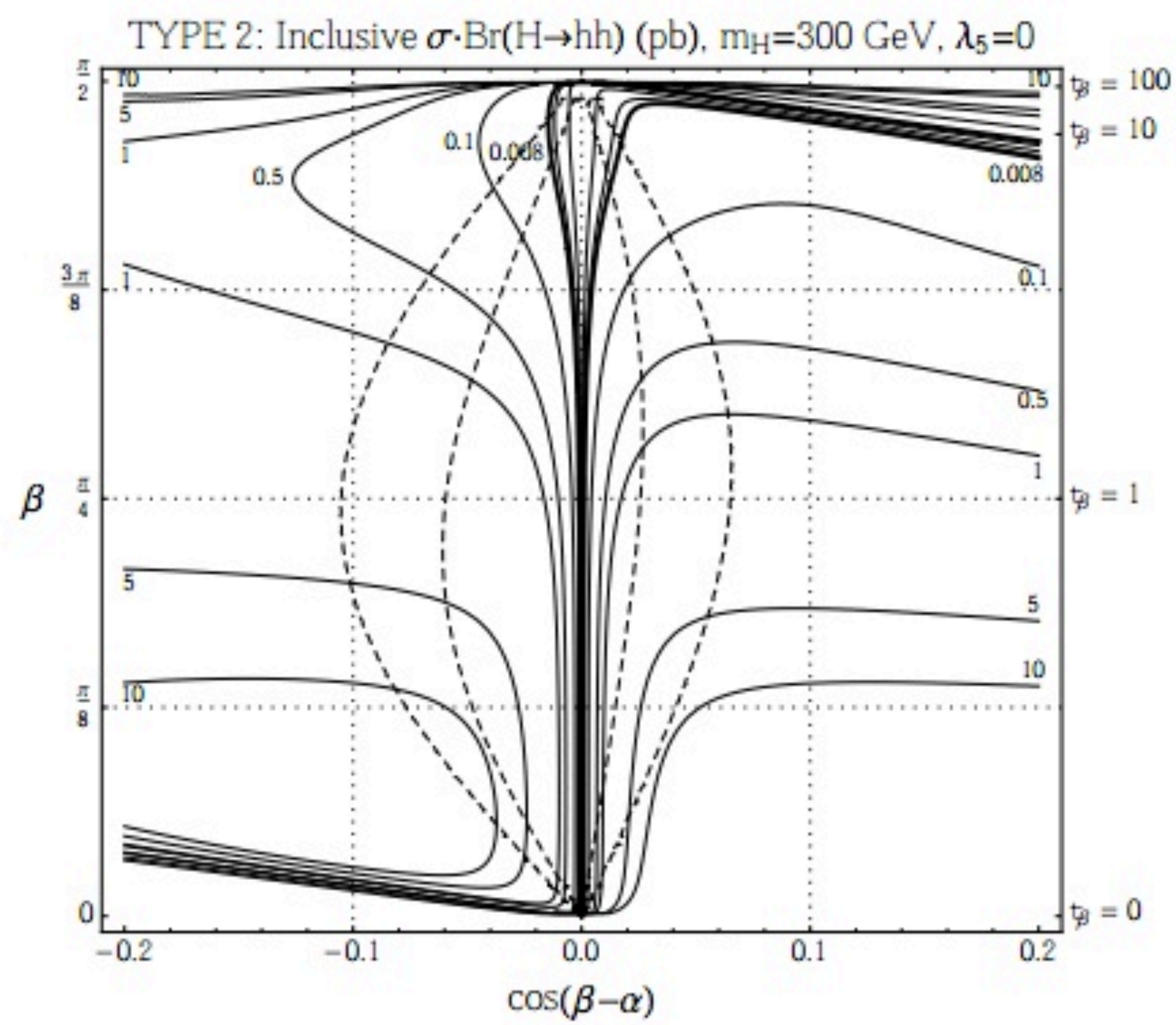
Can also search for signs of 2HDM via direct production of other scalars.

Best prospects typically for gluon fusion → A,H (alignment limit suppresses VBF, assoc prod)

Some promising final states include h (if kinematically accessible, away from perfect alignment): H(A) → hh(Zh)

Craig, Galloway, Thomas



# "Natural" Microscopic Theories

In SM & generic 2HDM, require enormous fine-tuning between bare parameters and quantum corrections to keep the electroweak scale where it is.

1 part in $10^{32}$ for new physics at $M_{planck}$

## Natural Theories:

**No fundamental scalar.** Strong dynamics/extra dimensions naturally generate a low scale by dimensional transmutation; dynamics around that scale generate electroweak symmetry breaking scale.

Models with no light Higgs DOF manifestly dead!

Higgs could be a dilaton/radion (disfavored - Falkowski, Riva, Urbano) or a more general composite pseudo-Nambu-Goldstone boson (possible; new states expected below a TeV, modified rates.)

**Fundamental scalar.** Higgs is really there, but symmetry naturally protects the mass term. Supersymmetry: generically exists a SM-like Higgs state with calculable mass.

# SUSY

In the MSSM decoupling limit, effectively have a SM-like Higgs sector at low energies, with $m_h^2 = m_Z^2 \cos^2(2\beta) < 91.2 \text{ GeV}$

Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

Radiative corrections introduce:
-- polynomial dependence on stop mixing parameter $X_t/M_s$
-- log dependence on stop masses

For large tan $\beta$, $X_t/M_s = 1$, all SUSY masses at 1 TeV: $m_h$=116 GeV.
⇒ Generically MSSM with low fine-tuning does not give heavy enough Higgs

Two possibilities:

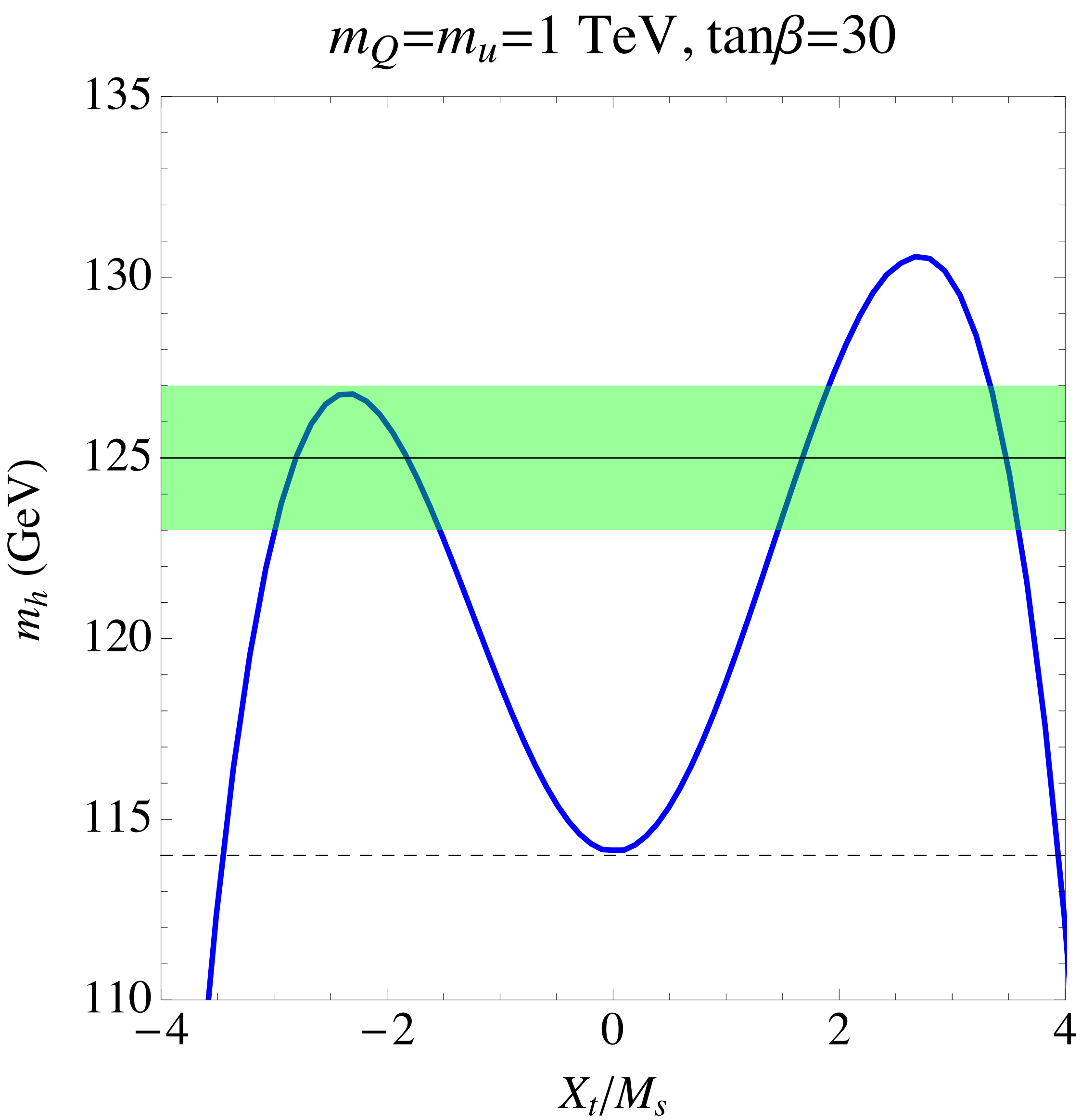
1) SUSY is light (< few TeV). Requires either:

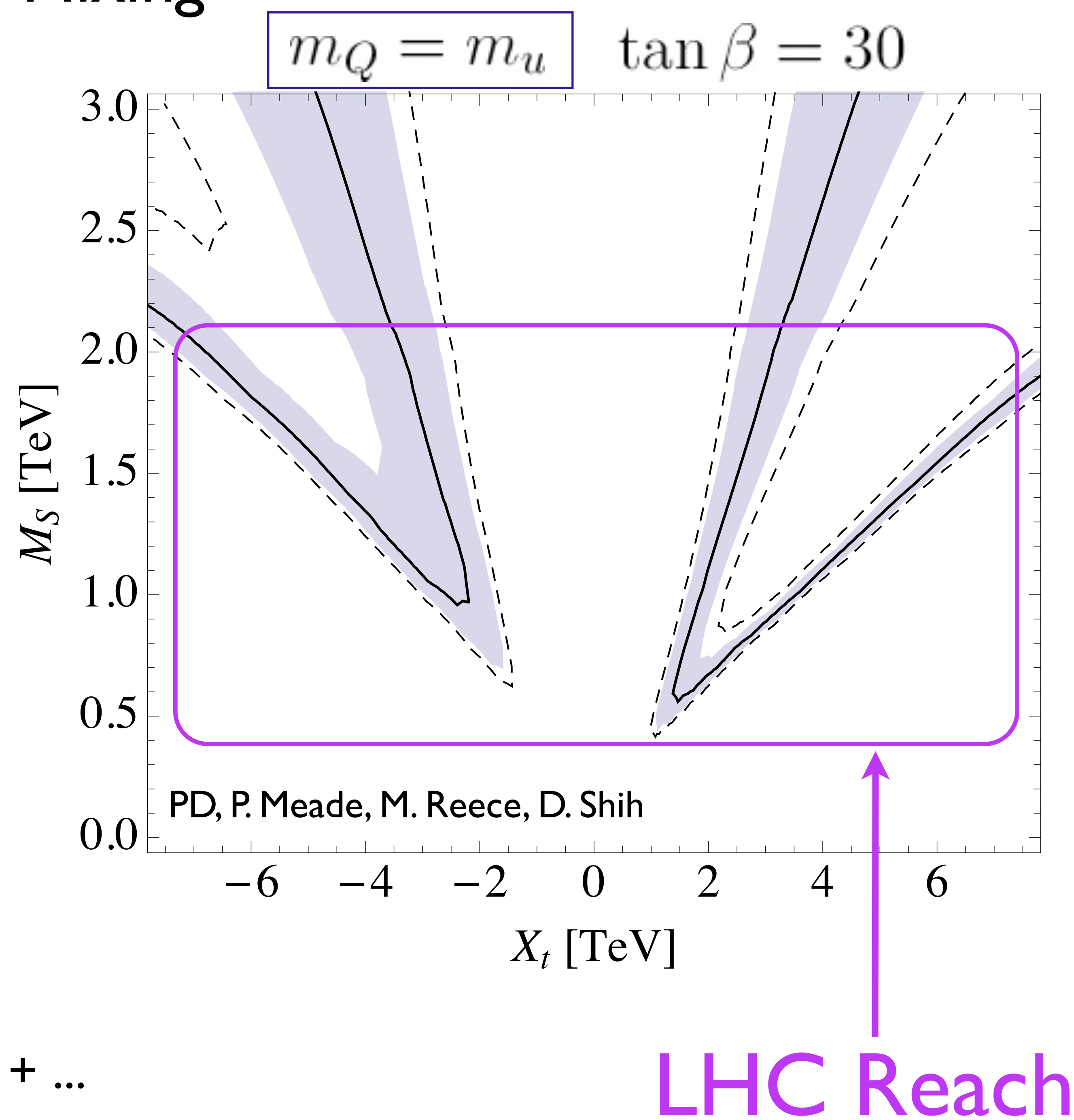
-large stop mixing (still fine-tuned, hard to make microscopic theory of ~~SUSY~~)

-beyond MSSM (possible, still typically requires rather special parameters)

2) SUSY is heavy (O(10) TeV and up). Simplest solution, but fine-tuned. How heavy?

# Stop Mixing




$$m_h^2 = m_h^{2,\text{tree}} + \frac{3}{4\pi^2}\frac{\overline{m}_t^4}{v^2}\left\{t + \boxed{\frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)}\right. \quad + \ldots$$

$$\frac{X_t}{M_S} \approx -3,\ -1.7,\ 1.5,\ \text{or}\ 3.5 \qquad |X_t| \gtrsim 1000\ \text{GeV}, \qquad M_S \gtrsim 500\ \text{GeV}$$

strongest direct-search limit on stop/sbottom is $M_{3\text{rd gen}}$ > 6-700 GeV
stronger limit if produced in gluino decays; $M_{\text{gluino}}$ > 1.2 TeV
1st/2nd gen masses may or may not be tied to 3rd gen masses; $M_{1\text{st gen}}$ > 700 GeV if gluino decoupled

# Beyond MSSM: NMSSM

Add a gauge singlet to the MSSM; solves a theoretical issue ("**μ** problem")

Creates a new quartic term for the Higgs, free parameter **λ**:

$$V(\phi) \sim -\frac{1}{2}m^2\phi^2 + \frac{1}{4}\underbrace{(g_1^2+g_2^2)\cos^2(2\beta)\phi^4}_{\text{MSSM}} + \frac{1}{2}\underbrace{\lambda^2\sin^2(2\beta)\phi^4}_{\text{NMSSM}}$$

MSSM + NMSSM

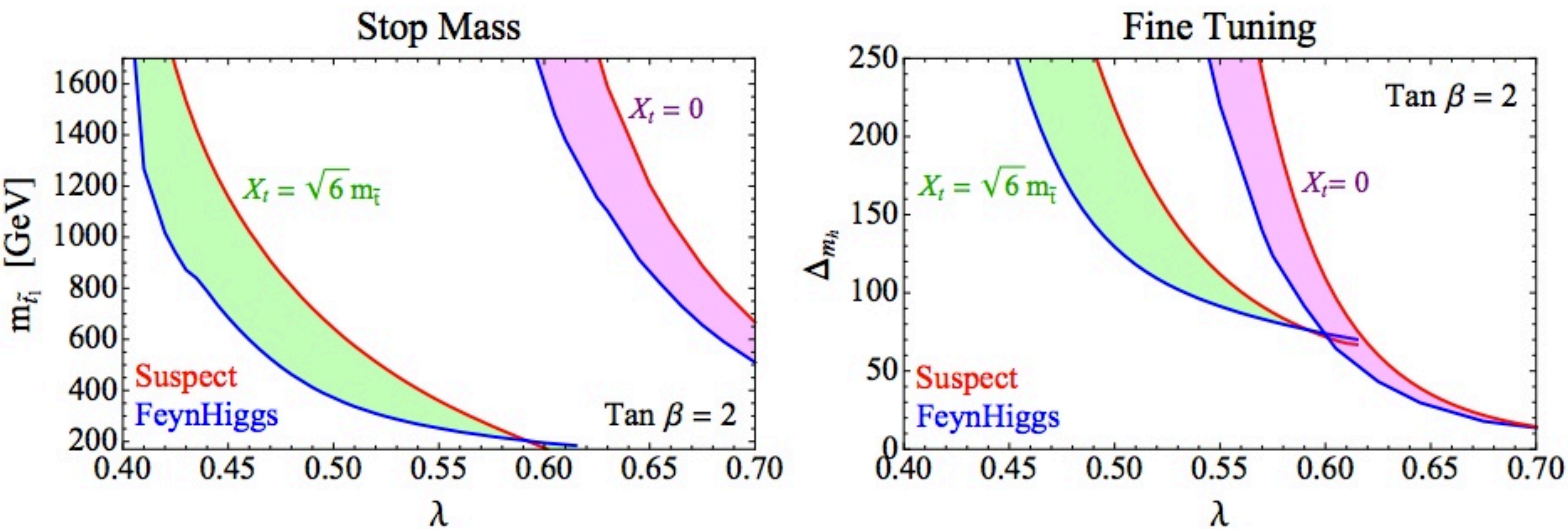
If **λ** is large and tan **β** is small, new term pushes up $m_h$ at tree level

Larger tree level mass:
⇒ stop-induced quantum corrections still needed but not as big

⇒ less fine-tuning

# NMSSM

Hall, Pinner, Ruderman 2012

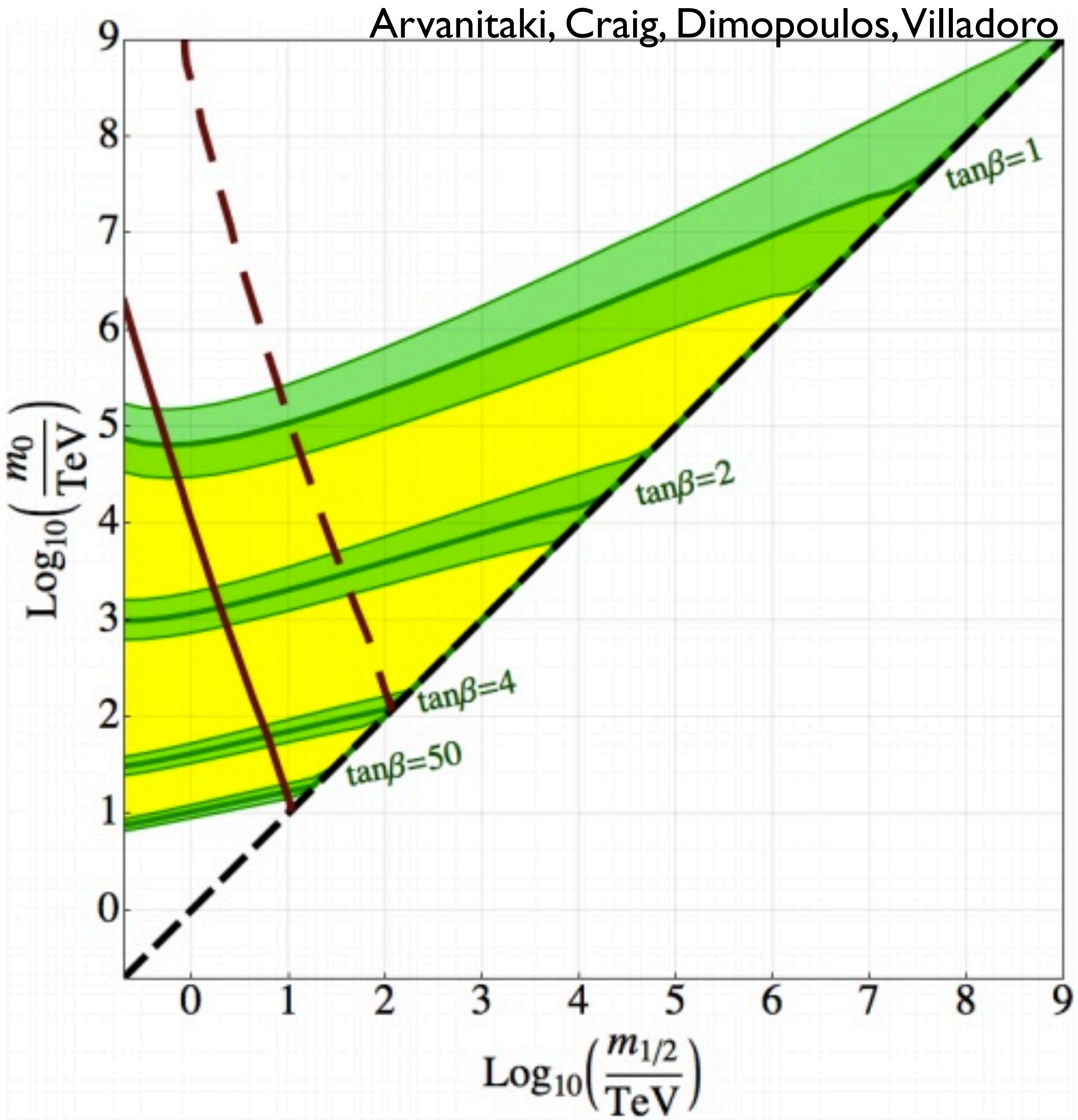



Stops can be as light at 600 GeV with no mixing! 10% tuning. (Only for corner of **λ** and tan **β** near two perturbativity boundaries-- fine tuning measure inadequate?)

In principle **λ** could go even higher and all need for stops goes away.

However, if **λ** too large (>0.7) theory becomes strongly-coupled below GUT scale (ok in principle), and most natural models have large Higgs mixing effects that alter branching ratios (increasingly constrained by data but not ruled out.)

# $m_h$ =125 GeV from heavy stops, no mixing




10 TeV for tan β > 5 (A-terms of order $m_{SUSY}$ or smaller)
100 TeV for tan β ~ 3-5
>1000 TeV for tan β < 2-3 (upper bound ~ $10^7$ TeV)

What scale is best-motivated?

# 10 TeV

fine-tuning ~ part in $10^4$. Still a huge improvement over $10^{32}$.

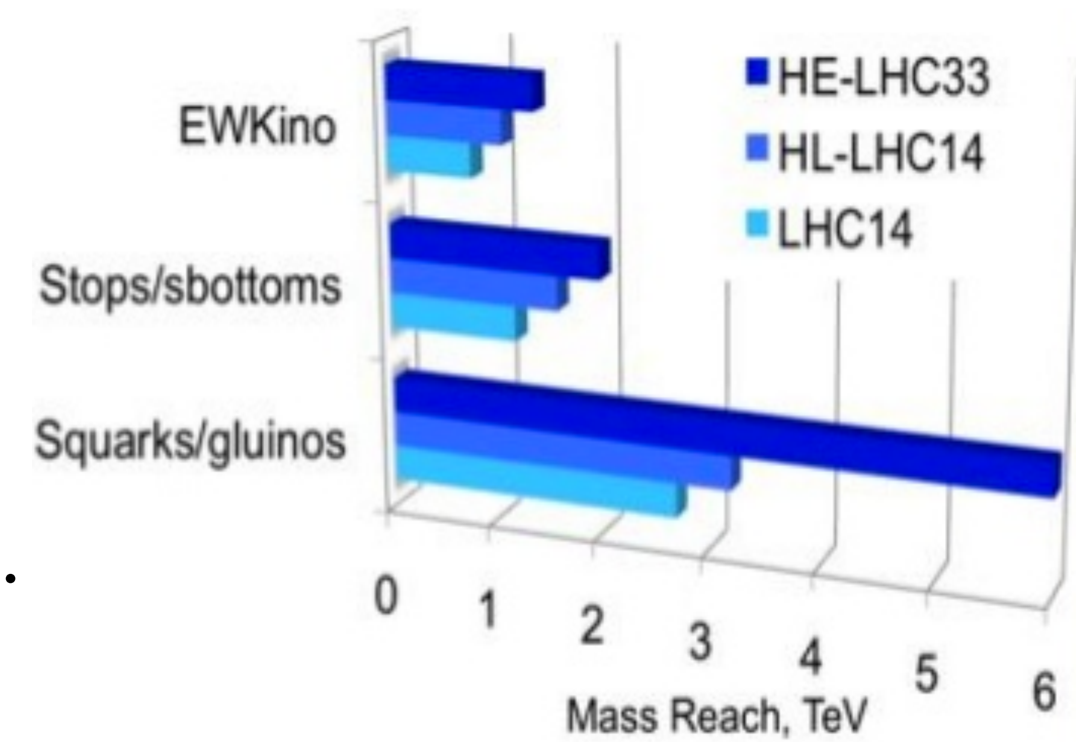
structure necessary in the soft sector to suppress FCNC, EDM
Gabbiani, Gabrielli, Masiero, Silvestrini

Any moduli need to be > 30 TeV for cosmological reasons   Banks, Kaplan, Nelson

Experimental prospects:

LHC14 with $3ab^{-1}$ will pair-produce less than 10 stop pairs if the stops are heavier than about 2.5 TeV.

100 TeV VHE-LHC may reach ~14 TeV stops.
Cohen, Howe, Wacker



# 100 TeV

Scale appears in the context of the moduli problem

May exist very weakly-interacting scalars with masses small compared to $M_p$ (e.g. string moduli). Some moduli candidates naturally have masses of order or less than the SUSY-breaking scale (e.g. saxion, inflaton). Banks, Dine, Graesser

When moduli decay in the early universe they may destroy the light elements. Reheating temperature sufficiently high for masses of order 30-100 TeV. Banks, Kaplan, Nelson

Virtue: may produce wino dark matter ($m_{wino}$~200 GeV) nonthermally. Moroi, Randall
However:
-100 TeV may not be high enough to avoid overproduction Bose, Dine, P.D.
-nonthermal wino DM in tension with indirect detection (HESS, Fermi) Fan, Reece

Might imagine avoiding LSP DM problems; e.g., RPV + axion DM.
For given $\theta_0 f_a$, preventing axion domination before T=1 eV limits $T_{Reheat}$ $(m_\phi)$

$$m=100\ \text{TeV}\ ,\ f_a=M_p/16\pi^2 \ \Rightarrow\ \theta_0 \sim 10^{-2}$$

Bose, Dine, P.D.

# $10^3$-$10^9$ TeV ("PeV-ZeV")

Tuning > part in $10^8$, $m_h$ obtained for tan $\beta$ < 2-3   Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia

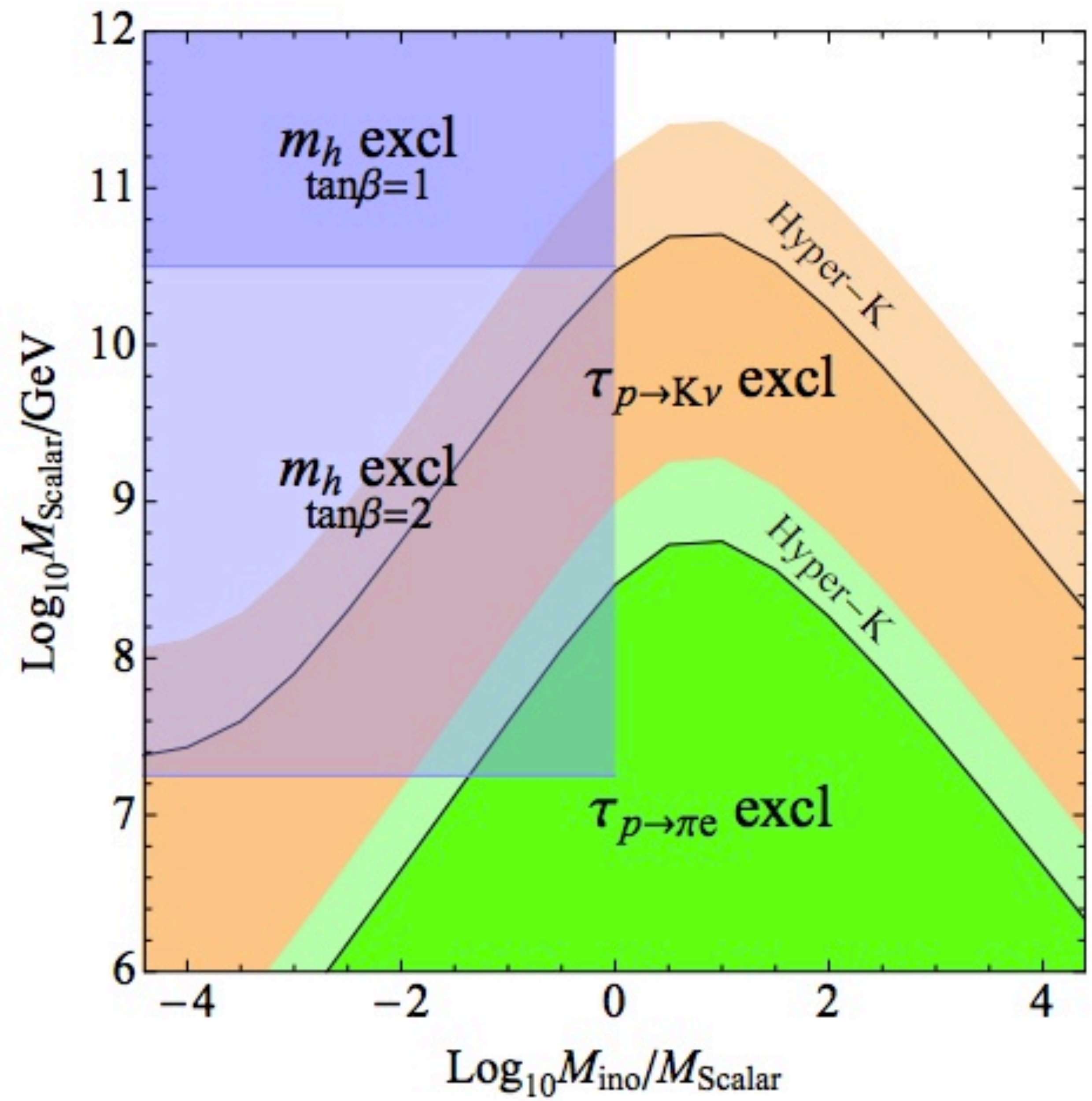
FCNCs and EDMs sufficiently decoupled at the PeV scale.   Wells; McKeen, Pospelov

$\Rightarrow$ less structure needed for PeV SUSY?

Wells, Giudice, Romanino; Arvanitaki, Craig, Dimopoulos, Villadoro
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski

But without flavor symmetry, may have proton decay from dim 5 operators
$W \sim 1/M_p$ QQQL, uude

Above ~$10^9$ GeV, protons ok; tension with Higgs mass   Dine, P.D., Shepherd




Anomaly-mediated (mini-split) spectrum can give ~3 TeV wino: thermal DM

Thermal wino in tension with absence of signals in indirect detection

Cohen, Lisanti, Pierce, Slatyer; Fan, Reece

# Summary

## A 125 GeV Higgs is exciting: theoretically nontrivial!

It may be providing us with detailed information about physics beyond the TeV scale.

If the Standard Model is good to very high scales, the Higgs is telling us something fascinating about UV physics.

If SUSY steps in to cure the hierarchy problem, the Higgs is a window into other sectors of the theory. Pointing to a higher scale for the superpartners than originally anticipated on naturalness grounds? Clues about nonminimal model structure?

After the upgrade, LHC will tell us if SUSY or anything else is around near the TeV scale. Multiple probes exist if the Higgs sector is larger than that of the SM: precision Higgs, direct searches.

Lots of work to do to understand how natural the weak scale is and why $m_h$=125 GeV!