Supersymmetric EWSB

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Based on work with Puneet Batra (**PRD 79, 035001; arXiv:0809.3453**)

Also work in progress with M. Carena, KC Kong and J. Zurita

Of course, it's SUSY

But even if it's SUSY, why should it be the MSSM?

After all, the SM does not look particularly minimal...

In fact, the prediction of a light SM-like Higgs results in some tension with LEP bounds

Beyond the MSSM?

- This may suggest a more complicated Higgs sector than the MSSM

  ... and indeed has motivated detailed studies of a number of extensions

- MSSM is ``special" in that EWSB *requires* SUSY breaking effects

  Maybe good/appealing: radiative EWSB induced at a ``low scale"

  $(m^2_{H_u}(\mu) < 0 \text{ for } \mu \ll M_G, \text{ due to top Yukawa})$

- Tension with LEP bounds seems to require somewhat large ~~SUSY~~

  If EWSB due to ~~SUSY~~, should we expect scales to be the same? Tuned cancellations suggest so.

Here: point out that if the EWS is broken in the SUSY limit, picture changes

Bottom-line: significant changes in

- Vacuum structure
- Higgs phenomenology

sEWSB defined

sEWSB = Supersymmetric Electroweak Symmetry Breaking

Vacua with broken EW symmetry, even in SUSY limit

sEWSB: an example

sEWSB already occurs in simple extensions of the MSSM, e.g. adding a singlet:

$$W = \mu H_u H_d + \lambda S H_u H_d + \frac{1}{2}\mu_S S^2 + \frac{1}{3}\kappa S^3$$

Note:
- no attempt at solving μ-problem (follow ``MSSM philosophy")
- Singlet has SUSY mass, μ_S
- No need to write term linear in S

F-flatness:

sEWSB

$$\langle S \rangle = -\mu/\lambda \quad \& \quad \begin{cases} \langle H_u \rangle = \langle H_d \rangle = 0 \quad \text{or} \\ \langle H_u H_d \rangle = -\left(\frac{\mu\mu_S}{\lambda^2}\right)\left(1 - \frac{\kappa\mu}{\lambda\mu_S}\right) \end{cases}$$

sEWSB more generally: EFT

sEWSB vacua arise easily in extensions of the MSSM Higgs sector (by singlets, triplets...)

- Characterize MSSM-like vacua versus sEWSB vacua?
- Which is the true vacuum?
- Are these phenomenologically viable?
- Related: charge or color breaking minima... but I will concentrate here on viable scenarios (assumption on soft breaking terms)

It proves convenient to study sEWSB in the limit that the BMSSM physics is slightly above the weak scale (say, around 1 TeV or so)

- Obtain effective Lagrangian for MSSM degrees of freedom

{ If heavy mass mostly from ~~SUSY~~: see e.g. Batra, Delgado, Kaplan and Tait and talk by A. Medina

{ Heavy threshold *nearly* supersymmetric... this talk

(soft parameters can be a couple hundred GeV)

sEWSB more generally: EFT

EFT approach:

- allows model-independent study
- leads to simplifications (reduced number of degrees of freedom)
- useful if MSSM d.o.f. are more readily accessible experimentally

For a nearly SUSY threshold:

- can use superspace formalism
- can include SUSY breaking via a spurion X

Low-energy superpotential takes the form see also Dine, Seiberg and Thomas (2007)

$$W = \mu H_u H_d + \frac{\omega_1}{2\mu_S}(H_u H_d)^2 + \frac{\omega_2}{3\mu_S^3}(H_u H_d)^3 + \cdots$$

(e.g. in singlet theory: $\omega_1 = -\lambda^2, \omega_2 = -\lambda^3\kappa, \ldots$)

Associated soft SUSY-breaking terms: $W_X \supset \frac{\omega_1}{2\mu_S} X (H_u H_d)^2 + \cdots$

(ω_i-coefficients contain information about UV completion)

The SUSY limit

Consider SUSY limit, with only leading order operator

$$W = \mu H_u H_d + \frac{\omega_1}{2\mu_S}(H_u H_d)^2$$

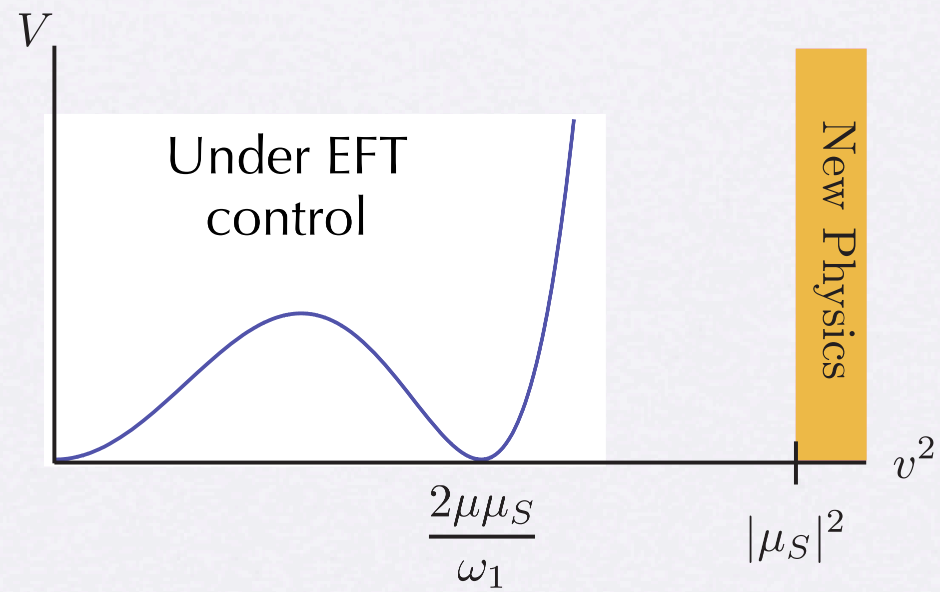
F-flatness: $\langle H_u \rangle = \langle H_d \rangle = 0$ or $\langle H_u H_d \rangle = \frac{\mu \mu_S}{\omega_1}$

→ reproduces singlet result to leading order in μ/μ_S

Rest of ω_i -operators give corrections suppressed by $\frac{\langle H \rangle^2}{\mu_S^2} \sim \frac{\mu}{\mu_S}$

$\longrightarrow$ Provided $\mu \ll \mu_S$ these theories have (at least) two minima, one with

$$\langle H_u H_d \rangle \sim \frac{\mu \mu_S}{\omega_1} \qquad \text{(sEWSB vacuum)}$$



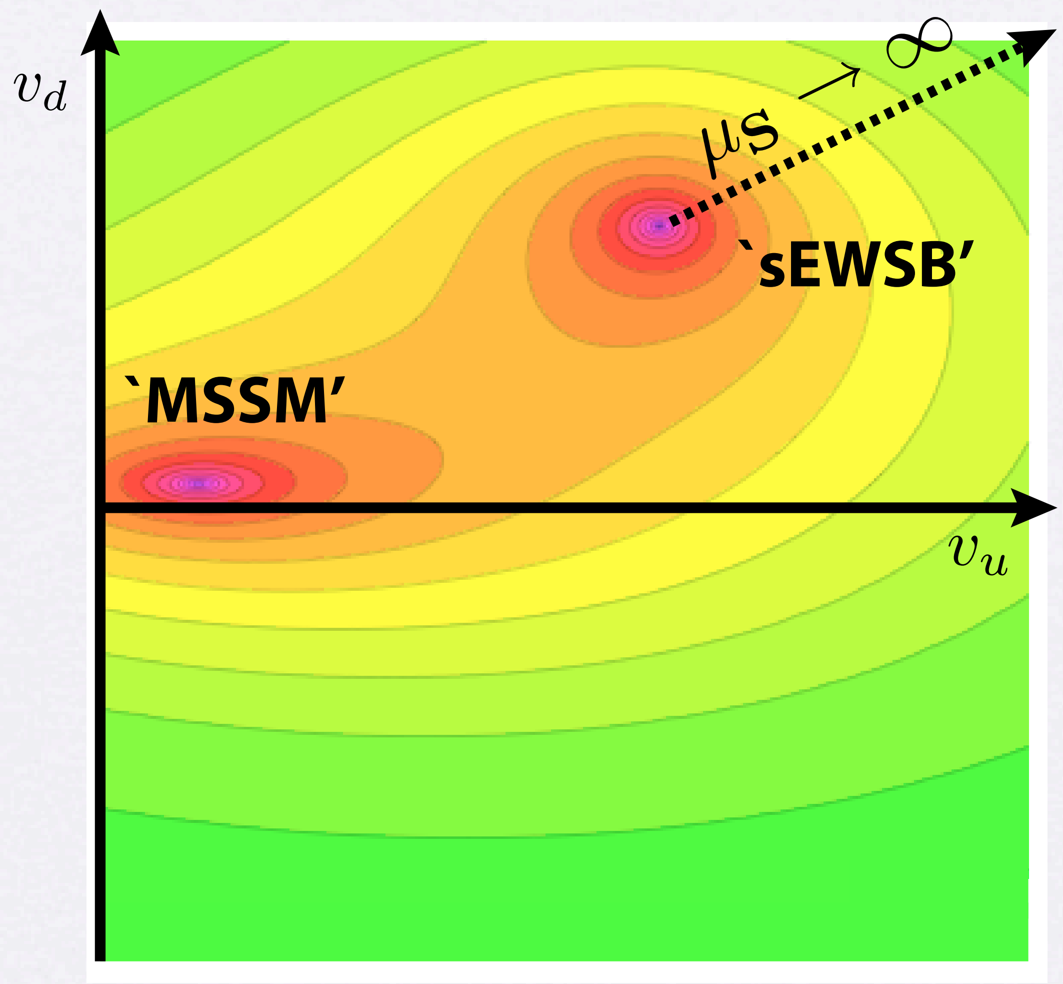
Characterization of New Vacua

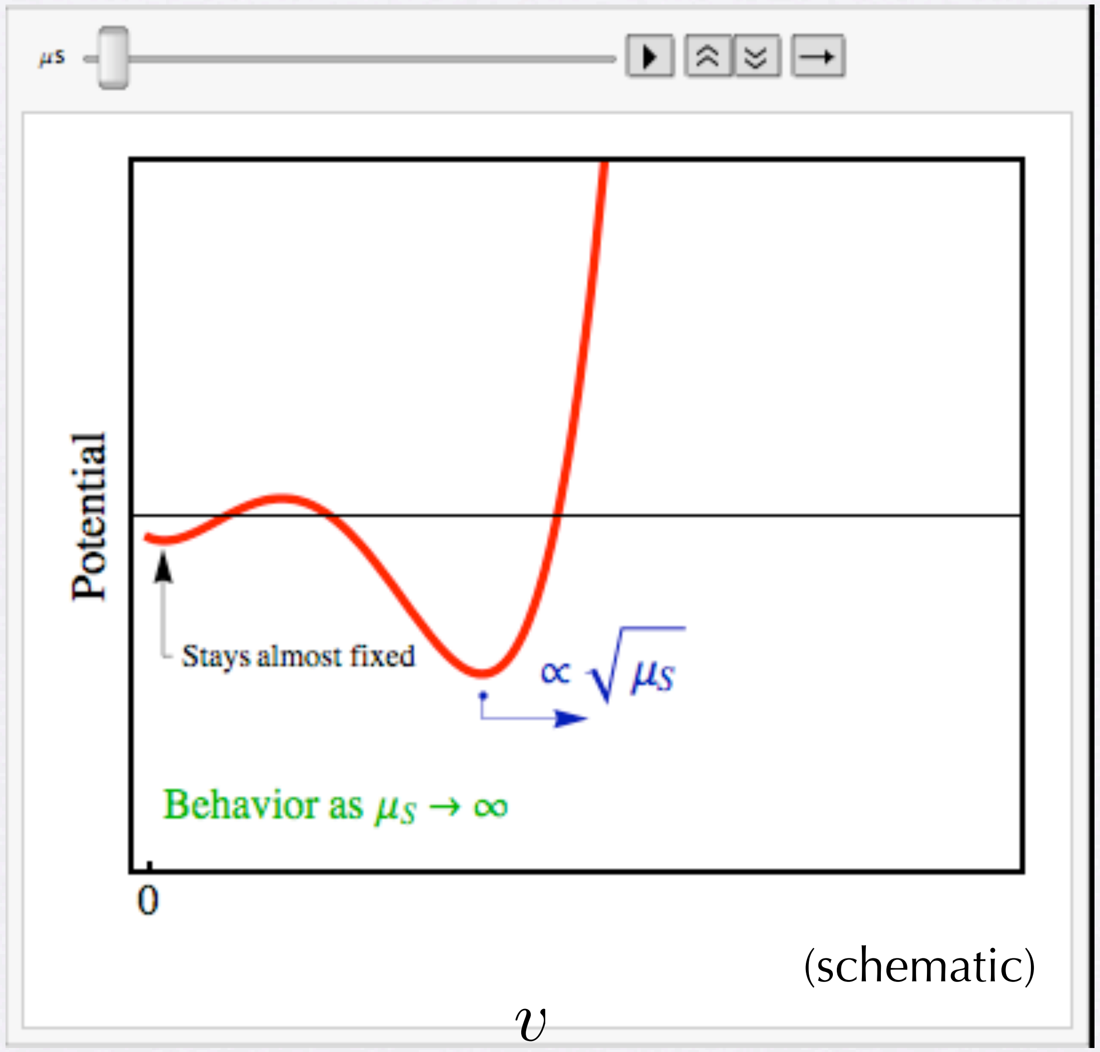
- Existence of sEWSB vacuum depends crucially on the scale μ_S :

$$v \propto \sqrt{\mu_S} \quad \text{as} \quad \mu_S \to \infty \qquad \text{(other parameters fixed)}$$

(However, notice that the EFT becomes more and more reliable in this limit!)

- The MSSM-like vacuum completely decouples from UV physics in this limit.





sEWSB Spectrum in the SUSY Limit

- At leading order, D-flatness implies $\tan\beta = 1$
- Super-Higgs mechanism: vector multiplet ``eats" complete chiral multiplet

  e.g. the Z-multiplet eats $H = (H_u^0 - H_d^0)/\sqrt{2}$

  → contains true Goldstone mode

- Orthogonal ``super-radial" mode $v + H_{\rm SM} = (H_u^0 + H_d^0)/\sqrt{2}$

  → contains SM-like Higgs (unitarization of WW scattering)

- Go to ``unitary gauge" (set $H = 0$ & $H^\pm = 0$ in superpotential)

$$W = \mu H_u H_d + \frac{\omega_1}{2\mu_S}(H_u H_d)^2$$

$$\to \frac{1}{2}(2\mu)h^2 + \cdots$$

Mass	Scalars	Fermions	Vectors
0	—	1 majorana	A_μ
m_W	$H^\pm$	2 Dirac	$W_\mu^\pm$
m_Z	H	1 Dirac	Z_μ
$2\lvert\mu\rvert$	$H_{\rm SM}$, A	1 majorana	—

unrelated to gauge couplings! ← $2\lvert\mu\rvert$

Mass of super-radial mode

$$2|\mu| > M_Z \;\; \rightarrow \;\; H_{\rm SM} = H^0$$

Inverted scalar hierarchy

Away from the SUSY limit

We are interested in vacua with $v \propto \sqrt{\mu_S}$ $\longrightarrow$ criterion useful even with ~~SUSY~~

$\longrightarrow$ In extreme limit, ~~SUSY~~ small so EWSB in SUSY limit

At leading order in $1/\mu_S$ expansion, only one additional soft term:

$$V_{\rm SB} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + \left[b\, H_u H_d - \xi \left(\frac{\omega_1 \mu}{2\mu_s} \right) (H_u H_d)^2 + h.c. \right]$$

- Parametrize by dimensionless ξ
- Assume soft parameters of order μ [take $\xi \sim \mathcal{O}(1)$]

Away from the SUSY limit

Due to $v^2 \sim \mu\mu_S$ and $\mu \ll \mu_S$ $\longrightarrow$ too light charginos?

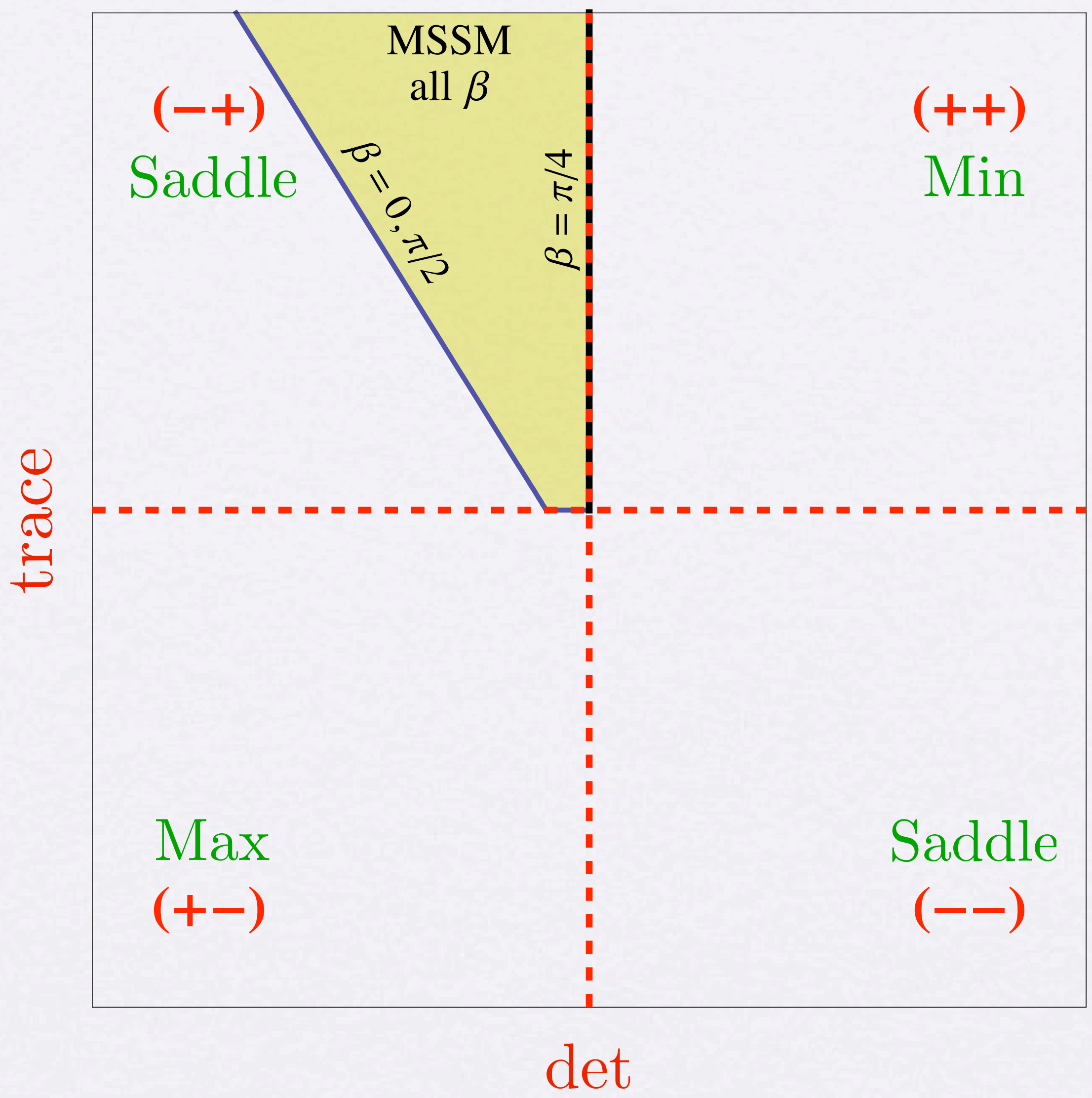
SUSY breaking has several important effects:

- lift masses of $\chi^\pm, \chi^0$ and $H^\pm$ beyond direct LEP limits
- Introduces MSSM-like vacua (minimum at origin slightly displaced)
- Breaks vacuum degeneracy (determines true minimum)

  e.g. for very small SUSY breaking

$$m_{H_u}^2 + m_{H_d}^2 + 2b < 0 \rightarrow \text{ sEWSB vacuum is global}$$

Behavior at the Origin



Eigenvalues determined by:

$$\begin{aligned} \text{det} &= (m_{H_u}^2 + \mu^2)(m_{H_d}^2 + \mu^2) - b^2 \,, \\ \text{trace} &= m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 \end{aligned}$$

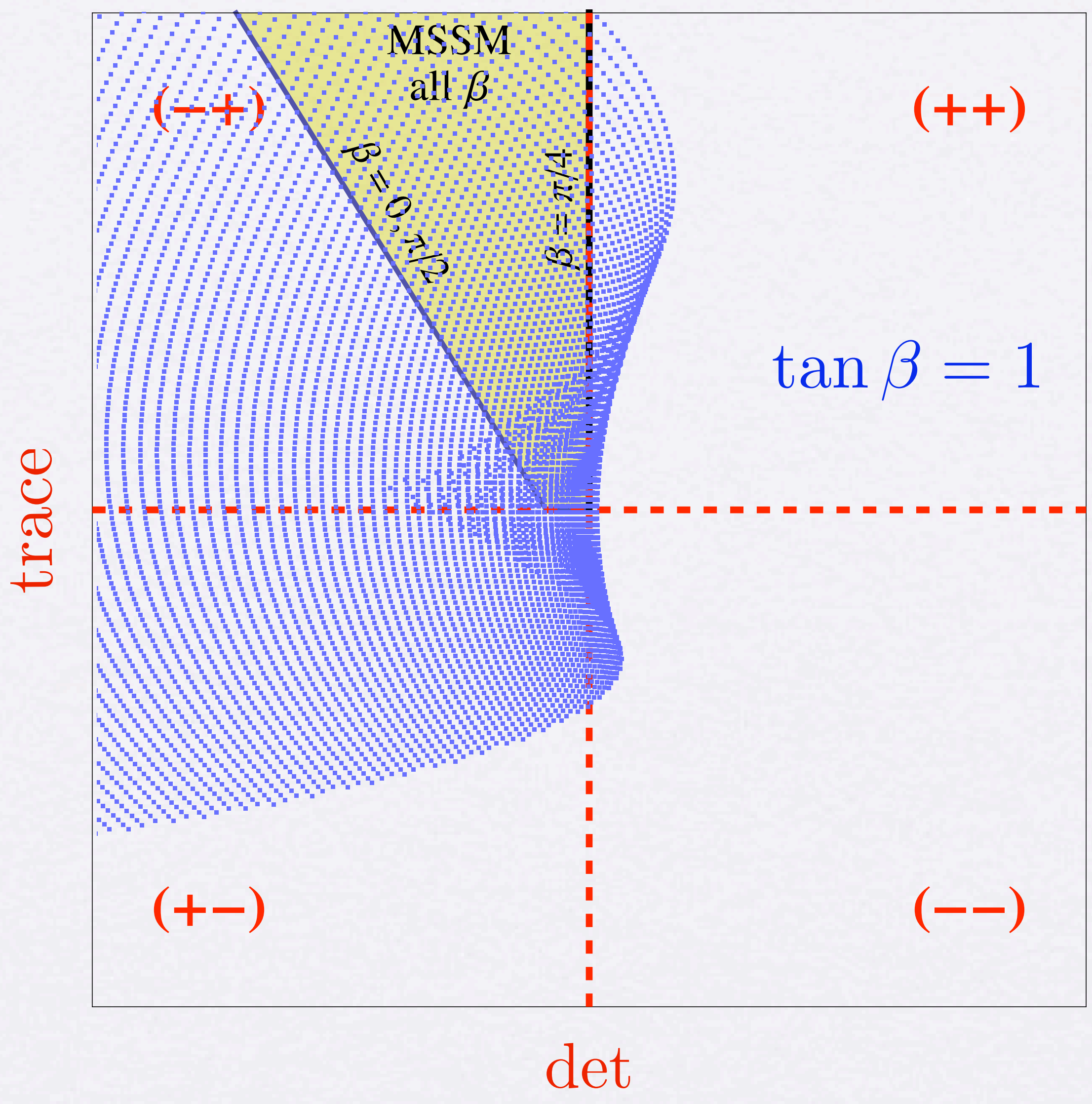
In MSSM, trace > 0 due to stability cond.:

$$m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 - 2|b| > 0$$

MSSM EWSB region given by:

$$\begin{aligned} \text{trace} &= -m_Z^2 - \frac{2\sec^2 2\beta}{m_Z^2}\,\text{det} \\ \text{trace} &> 0 \end{aligned}$$

Behavior at the Origin



Higher-dimension operators can lead to

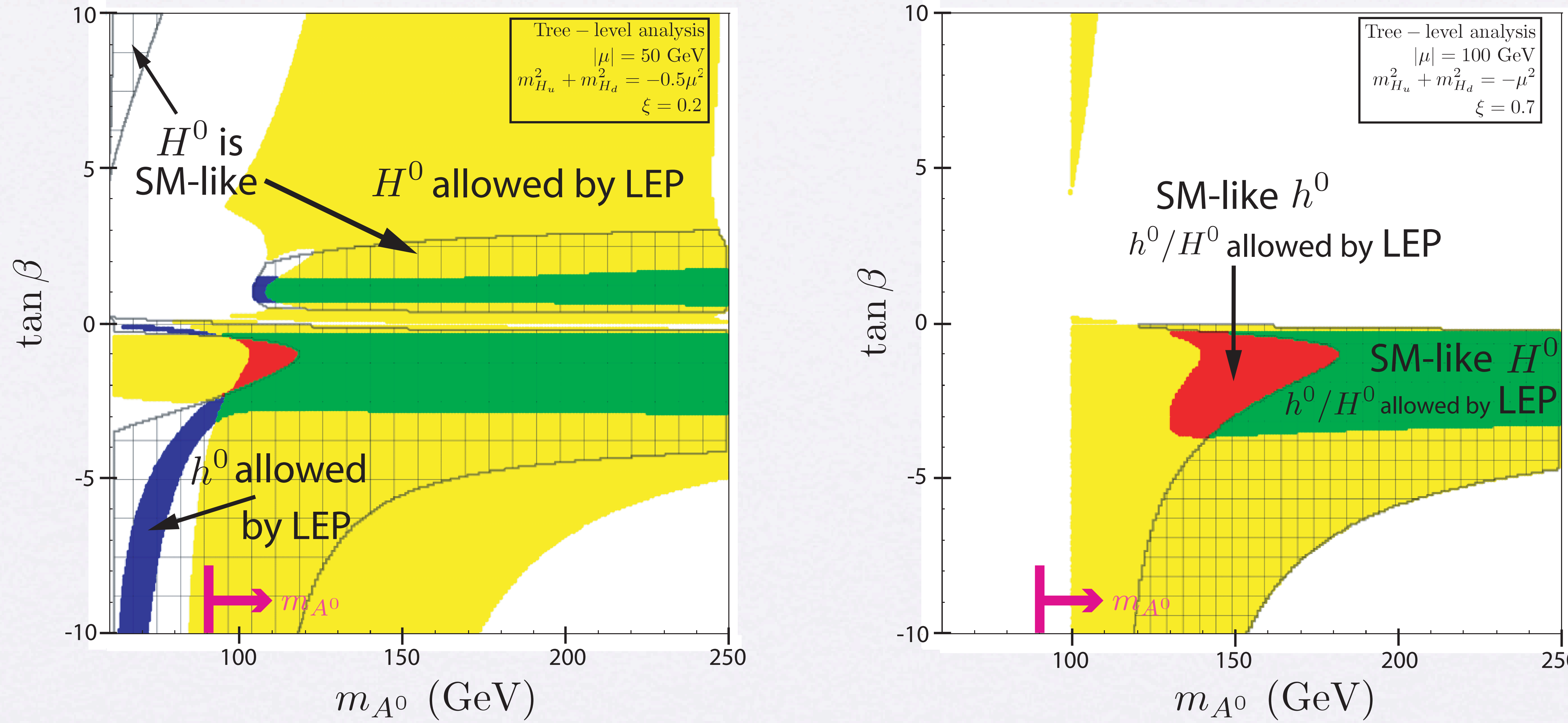
- Stable origin, but EWSB (barrier)
- Violation of MSSM stability cond.
- Multiple non-trivial minima
  - MSSM + other types
  - Only other types

Not only is allowed region much larger...

... physics can be qualitatively different!

Constraints due to LEP: examples

Tree-level only!



- Yellow: H^0 allowed by LEP
- Green: LEP allowed, H^0 is SM-like
- Blue: h^0 allowed by LEP
- Red: LEP allowed, h^0 is SM-like

hatched = Inverted hierarchy (H^0 is SM-like)

Spectrum: sample points

Point 1

μ	ω	μ/μ_s	b/μ^2	m_u^2/μ^2	$m_{H_d}^2/\mu^2$	ξ	M_1/μ	M_2/μ
-60	1	0.11	-2.2	-1.7	-0.60	0.20	1.5	1.7

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g^2_{H^0ZZ}/g^2_{h_{SM}ZZ}$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
0.47	-1.3	120	150	0.98	100	120	110	90

Point 2

μ	ω	μ/μ_s	b/μ^2	m_u^2/μ^2	$m_{H_d}^2/\mu^2$	ξ	M_1/μ	M_2/μ
-150	2	0.14	-1.1	-0.99	-0.51	0.20	0.36	0.57

ρ	$\tan\beta$	m_{h^0}	m_{H^0}	$g^2_{H^0ZZ}/g^2_{h_{SM}ZZ}$	m_{A^0}	m_{H^+}	m_{χ^+}	m_{χ^0}
.20	-1.3	190	210	0.77	185	190	105	60

Beyond leading order

Carena, Kong, EP & Zurita

Quartic interactions of 2HDM can be written as

$$V \supset \frac{1}{2}\lambda_1(H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u H_d)(H_u^\dagger H_d^\dagger)$$
$$+ \left\{\frac{1}{2}\lambda_5(H_u H_d)^2 + \left[\lambda_6(H_d^\dagger H_d) + \lambda_7(H_u^\dagger H_u)\right](H_u H_d) + \text{h.c.}\right\}$$

(but note that sEWSB cannot be captured by 2HDM: higher-dim. ops. essential!)

At $\mathcal{O}(1/\mu_S)$: $\lambda_5, \lambda_6, \lambda_7 \neq 0$

At $\mathcal{O}(1/\mu_S^2)$: all $\lambda_i{}'s$ get corrections

But at tree-level in MSSM: $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \propto g^2$ (small)

Since superpartners need not be heavy (LEP bounds are easily satisfied at tree-level), loop corrections need not be too large

Note this leads to some degree of sequestering between the Higgs sector and the rest.

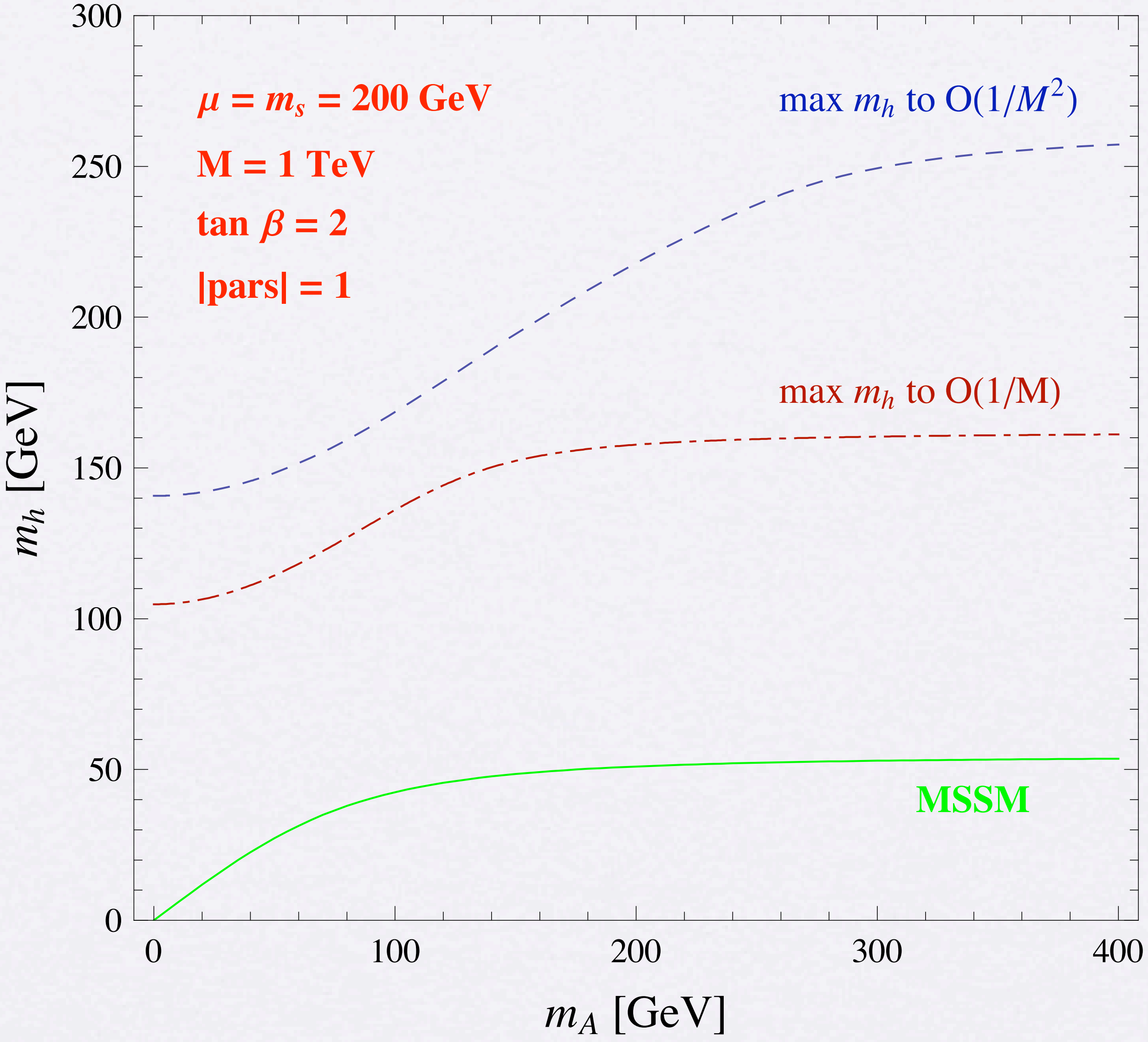
Beyond leading order

Second order terms can have a relevant impact

e.g. on lightest Higgs mass

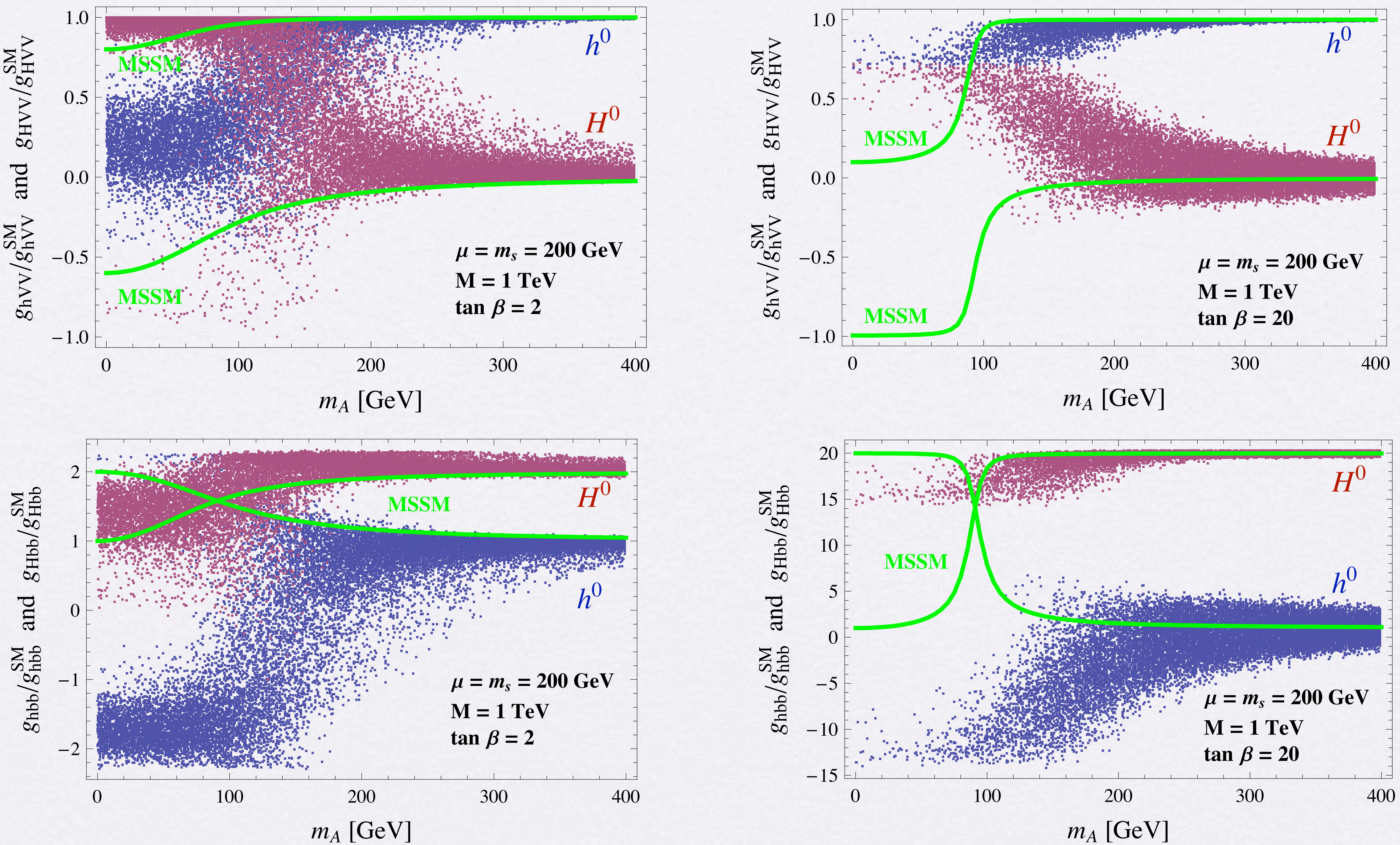
But higher orders should have smaller effects

Note: $\mu_S \to M$



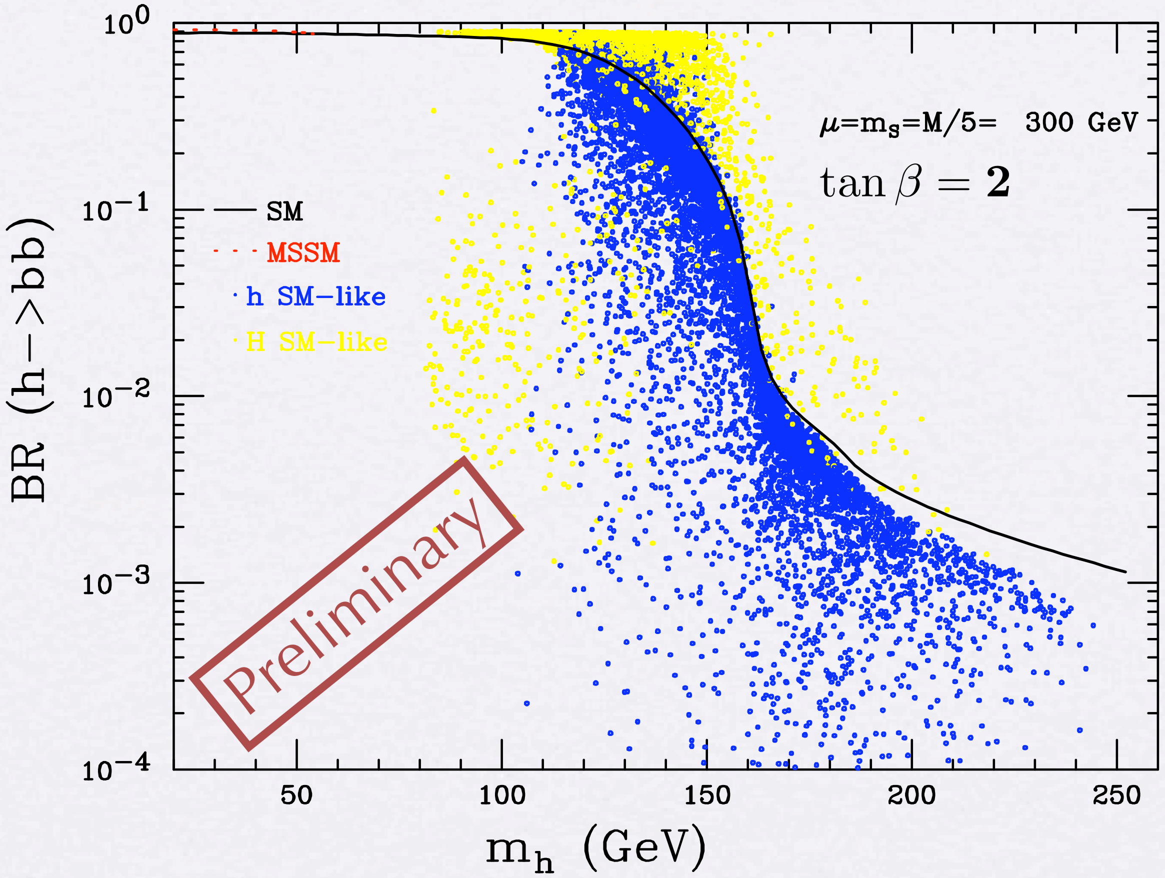
Couplings to second order

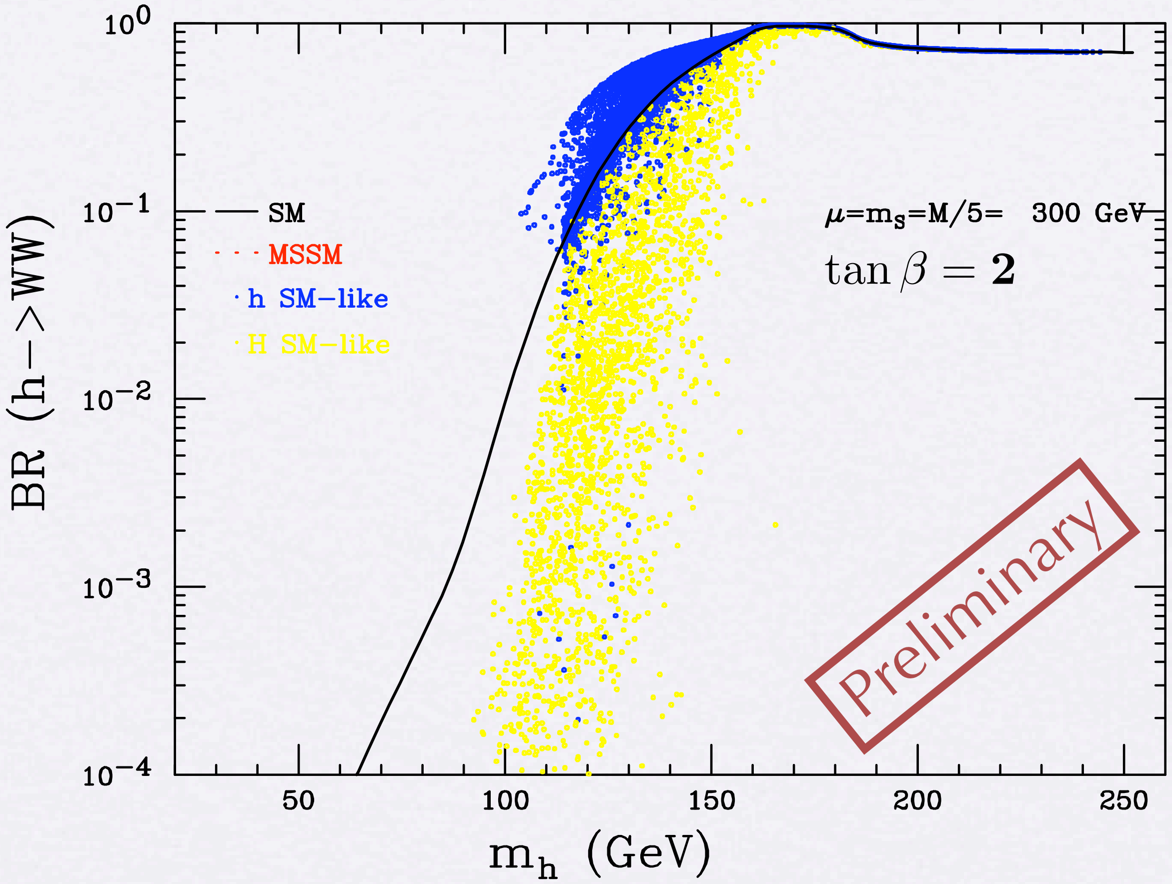
LEP bounds not imposed yet!



Can have: • suppressed decays into $b\bar{b}$

• enhanced decays into WW





Conclusions

- sEWSB is ``generic'' in extensions of the MSSM
- Such vacua can be fundamentally different from the familiar MSSM vacuum
- EFT approach: effects of higher-dimension operators crucial, yet under theoretical control
- Constraints on MSSM parameter space relaxed
  - Higgs mass decoupled from gauge couplings
  - Motivation for considering order one $\tan\beta$ region
  - ``Unusual'' Higgs spectrum. Also expect light charginos and neutralinos
  - Expect ``unusual'' SUSY Higgs phenomenology