Non-Standard SUSY Higgs Signals

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Puneet Batra and EP (**PRD 79, 035001; arXiv:0809.3453**)

M. Carena, KC Kong, EP and J. Zurita (**PRD 81, 015001; arXiv:0909.5434**)

M. Carena, EP and J. Zurita (**arXiv:1005.4887**)

Electroweak Symmetry Breaking

- Good experimental evidence for *spontaneously* broken $SU(2)_L \times U(1)_Y$ gauge symmetry

  - Symmetry unbroken in the vertices (couplings to fermions and gauge self-interactions)

  - Symmetry badly broken in the spectrum (spin-1 longitudinal polarizations, ``up-down" fermion mass splittings)

  → Evidence for a ``Higgs sector"

- But details of the mechanism for EWSB remain elusive...

  Limited knowledge from precision measurements:

  $M_W^2 \approx M_Z^2 \cos^2\theta_W$ → Bulk of EWSB due to a weak isospin doublet (either elementary or composite)

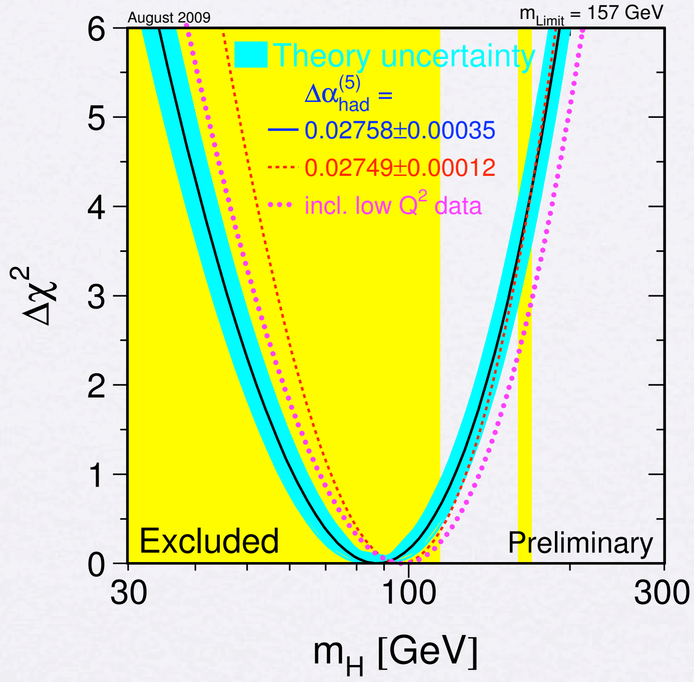
Establishing the precise mechanism one of the most important goals at the LHC

The Standard Model

- On the whole good agreement for a single SU(2) doublet with

$$114\ \text{GeV} < m_H < 186\ \text{GeV} \quad (95\%\ \text{CL})$$

(if nothing else out there)



- **New physics must be well-hidden!**

(Heavy or loop-level effects)

``SUSY” (or the MSSM)

- Two Higgs doublets, $H_u\,(Y=+\frac{1}{2})$ and $H_d\;(Y=-\frac{1}{2})$ (Type II THDM)

- At tree-level: quartic couplings related to gauge couplings (squared)

  → Light SM-like Higgs $m_h < m_Z$ (but not seen at LEP)

- Important loop-level corrections from top-stop sector, but still $m_h \lesssim 135$ GeV

``SUSY” expectation: SM-like Higgs in $b\bar{b}$ channel at the Tevatron

$\tau\bar{\tau}$ (or $\gamma\gamma$) channels at the LHC

Note that these couplings not as directly related to EWSB as hWW or hZZ

Non-standard Higgses: may require large $\tan\beta$ enhancement for production

Again: connection to EWSB somewhat remote

Beyond the MSSM

Perhaps SUSY Higgs sector non-minimal...

e.g. singlet extensions lead to larger Higgs mass

In fact: BMSSM physics can easily change MSSM expectations for Higgs physics

... even if somewhat heavy (with mass $M \gg v_{EW}$)

(may or may not be directly observed at the LHC)

Why?

Beyond the MSSM

Higgs quartic couplings in MSSM at tree level:

$$V \supset \frac{1}{2}\lambda_1(H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4(H_u H_d)(H_u^\dagger H_d^\dagger)$$

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

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g^2+g'^2), \quad \lambda_3 = \frac{1}{4}(g^2-g'^2), \quad \lambda_4 = -\frac{g^2}{2}$$

Effective field theory with heavy fields integrated out easily explains large effects

At leading order: $W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 + \cdots$ (plus a SUSY breaking operator)

See also: Brignole, Casas, Espinosa, Navarro, '03
Dine, Seiberg, Thomas, '07
Antoniadis et. al. '07 ...

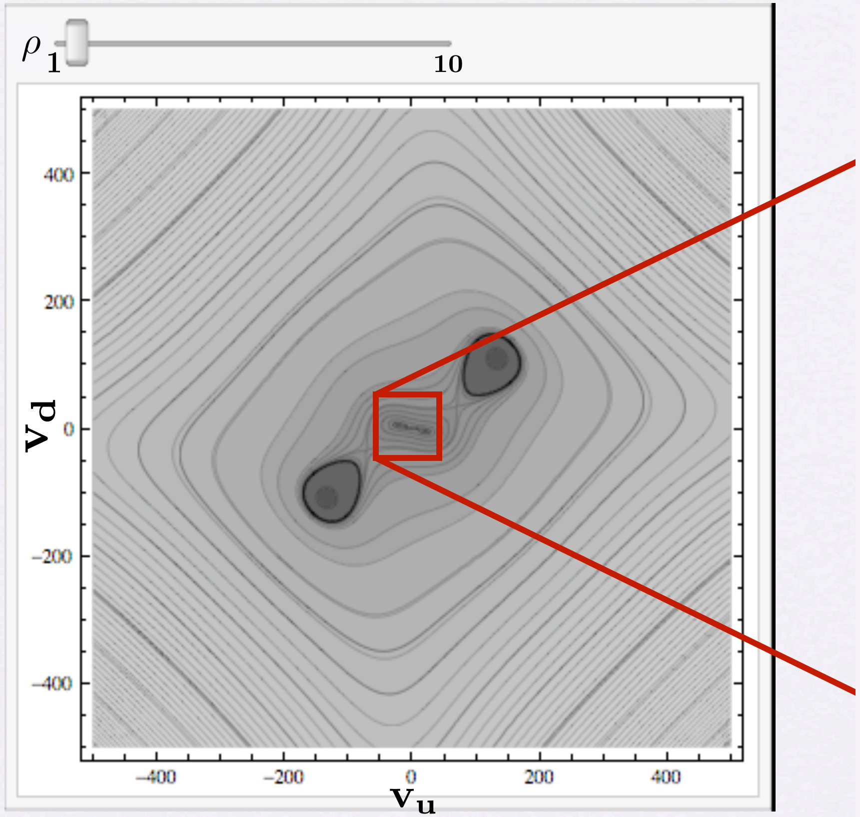
$$\lambda_5, \lambda_6, \lambda_7 = \mathcal{O}(1/M)$$

Qualitatively new effects, e.g. ``instabilities" controlled by higher-dimension operators in the scalar potential (THDM not the whole story)

Minima from Infinity

(Batra & EP, 2008)

Scaling $M \to \rho M$ with $\rho \in [1, 10]$ $\begin{cases} \text{sEWSB Minimum} \ \propto \sqrt{\rho} \\ \text{MSSM-like Minimum} \ \to \ \text{const.} \end{cases}$



A technical point...

Second order in 1/M expansion can be as important as the leading order...

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \sim g^2 + \mathcal{O}(1/M^2)$$

↑

numerically small

However, this does not mean mean the 1/M expansion breaks down...

... in the following it does not!

Thus:

- More parameters to consider 👎
- More handles to (try to) infer the UV completion 👍

(Carena, Kong, EP & Zurita, 2009)

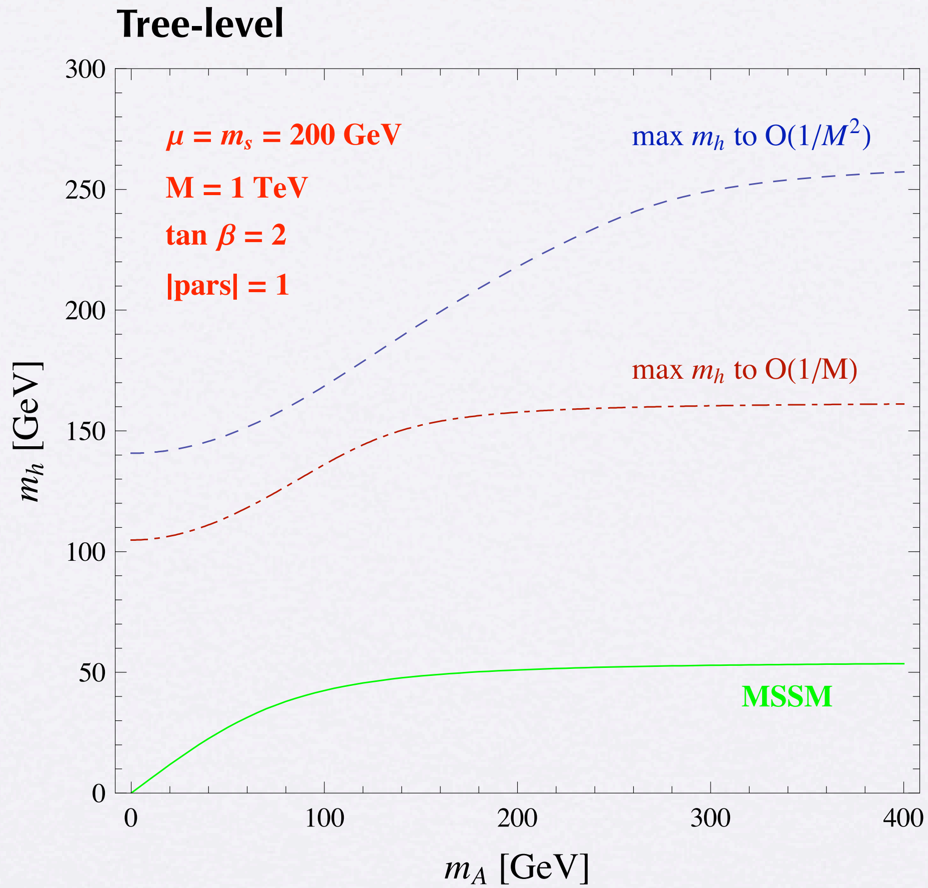
Here, treat coefficients as independent, and scan over $[-1, 1]$ → **survey collider phenomenology**

Beyond leading order (spectrum)

(Carena, Kong, EP & Zurita, 2009)

Maximize m_h assuming dimensionless parameters below 1

(But higher orders should have smaller effects)



Beyond leading order (spectrum)

(Carena, Kong, EP & Zurita, 2009)

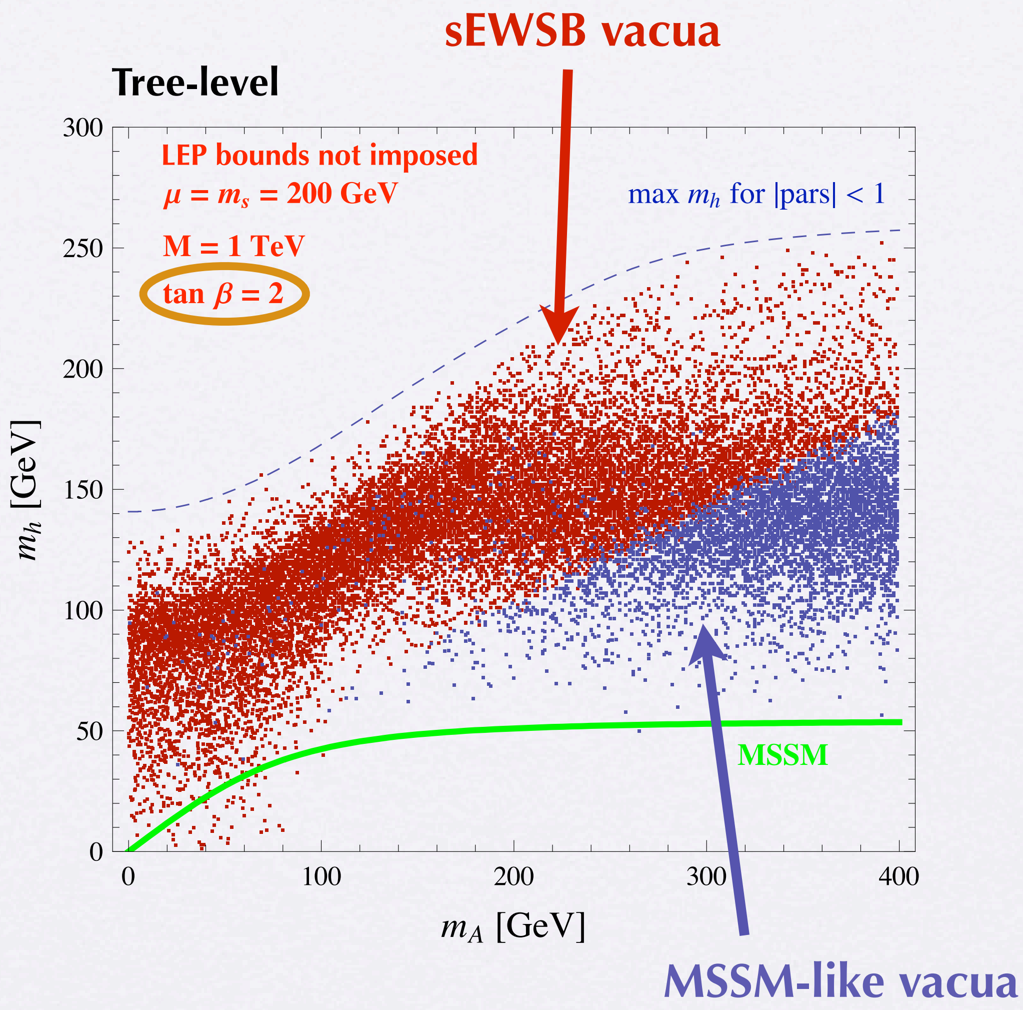
Maximize m_h assuming dimensionless parameters below 1

(But higher orders should have smaller effects)

At small $\tan\beta$:

Large fraction of sEWSB vacua

(Smaller fraction at large $\tan\beta$)



Scan: $|\omega_1|, |c_4|, |c_6|, |c_7| \in [0,1]$ and $|\alpha_1|, |\beta_i|, |\gamma_i|, |\delta_i| \in [1/3, 1]$ for $i = 4, 6, 7$ (assume all real)

Assumptions

- Heavy physics characterized by a scale $M \gtrsim 1~\mathrm{TeV}$
- SUSY breaking in MSSM *and* heavy sectors of same order, and $m_S \sim \text{few hundred GeV}$
- Main modification in Higgs sector (matter sector more constrained)

→ **Superspace language, classify higher-dimension operators at super- and Kähler potential level**

→ **SUSY breaking via spurion superfield**

Predictions for a relatively ``generic" SUSY extension, with SUSY broken at the EW scale

Constraints

- ***Robustness***: study points expected to be insensitive to higher orders in 1/M expansion

  (danger of accidental cancellations in lowest orders, rather than breakdown of EFT!)

- ***Several minima***: ensure global, no charge/color breaking, and no $\not{C}P$ (for simplicity), in EFT.

- ***EW precision constraints***: heavy physics, modified MSSM Higgs spectrum + sparticles

  Mild cancellations in e.g. Peskin-Takeuchi T parameter allowed

- Current direct collider bounds from LEP and Tevatron

  HiggsBounds + $H^\pm$ +decay-mode-independent

  (Bechtle, Brein, Heinemeyer, Weiglein & Williams, 2008)

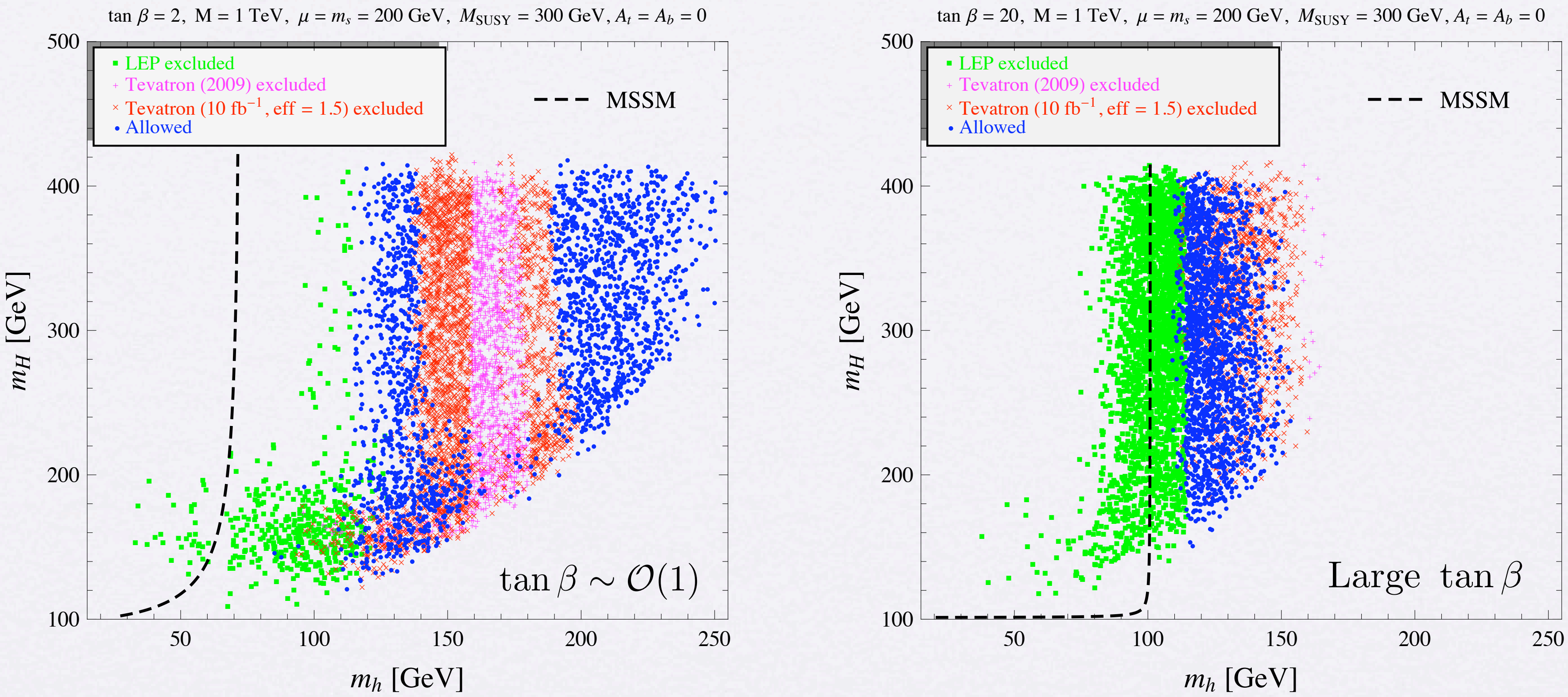
- We do not consider indirect, flavor-dependent bounds, e.g. from $b \to s\gamma$

  (depend on details of SUSY sector, model-dependent)

Selected Results...

CP-even Higgses and Current Bounds

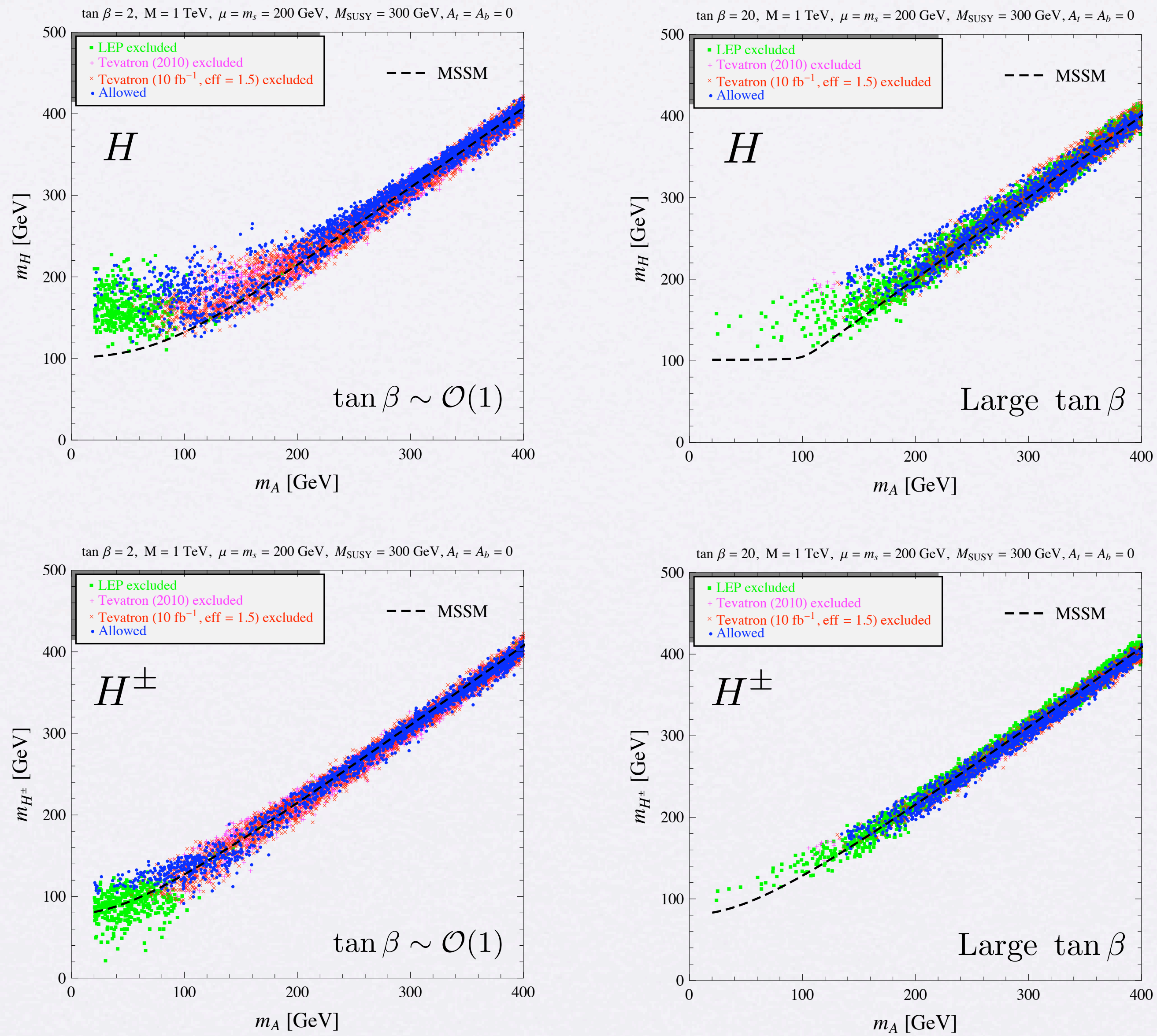
Carena, EP & Zurita, 2010



- Allowed
- Excluded by LEP
- Excluded by Tevatron
- Tevatron projection (with 10 fb^{-1} and 50% efficiency improvement)

See also Draper, Liu & Wagner (0905.4721)

Non-Standard Higgs Masses



- Corrections decrease at large m_A
- Significant mass splittings between $m_A, m_H, m_{H^\pm}$
- Multi-Higgs decay channels can open:

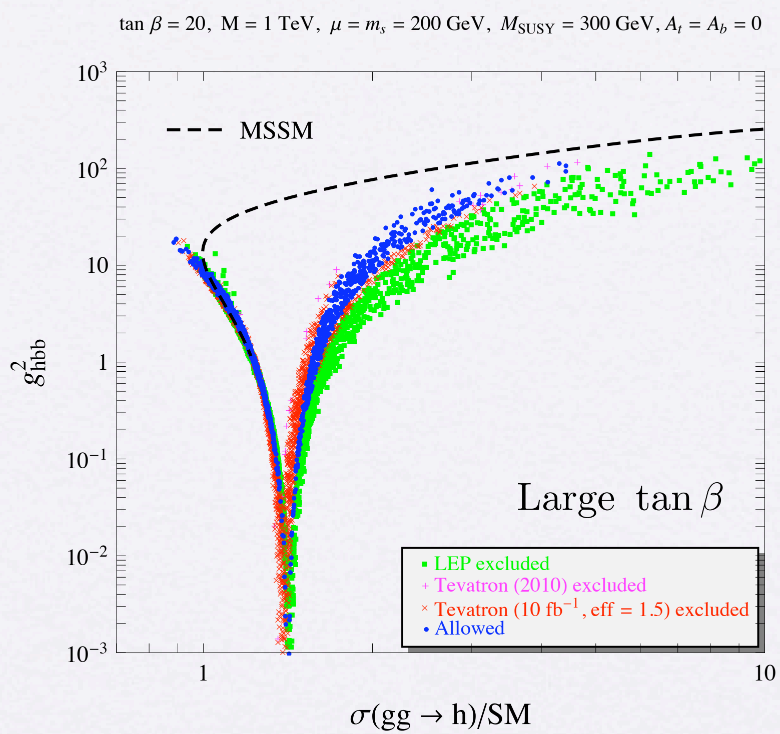
$$h/H \to AA$$
$$H^\pm \to AW^\pm$$

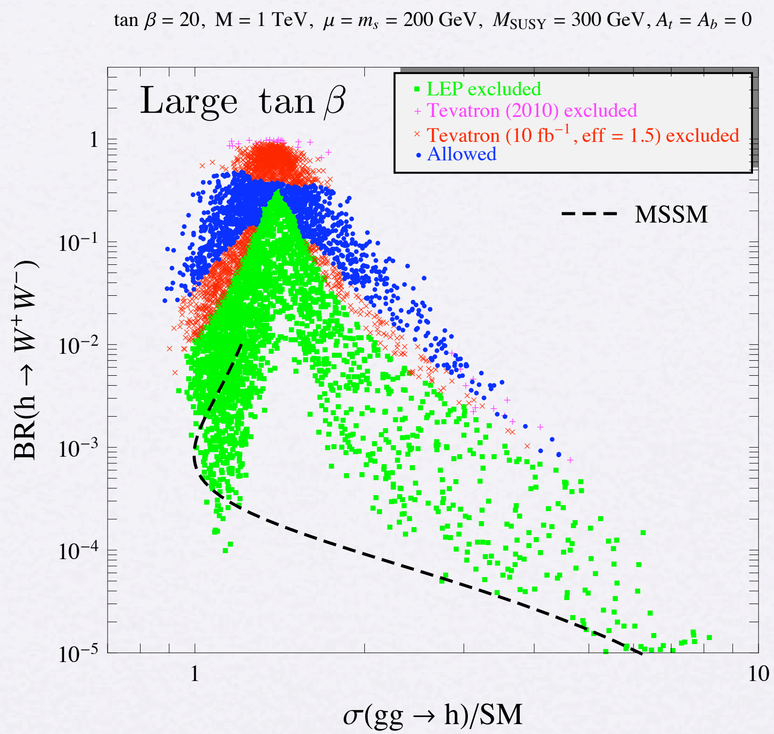
But

$$H/A \to hh$$
$$H^\pm \to hW^\pm$$

typically closed

Suppressed couplings of h to bb





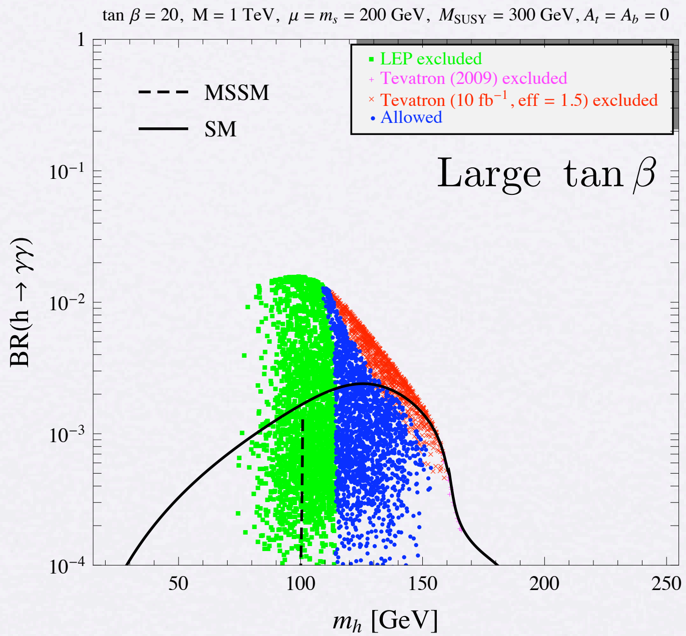
- Region associated with suppressed $b\bar{b}$ ⟶ enhanced $\mathrm{BR}(h \to W^+W^-)$
- Also at low $\tan\beta$, suppressed $b\bar{b}$ associated with enhanced gluon fusion cross-section!

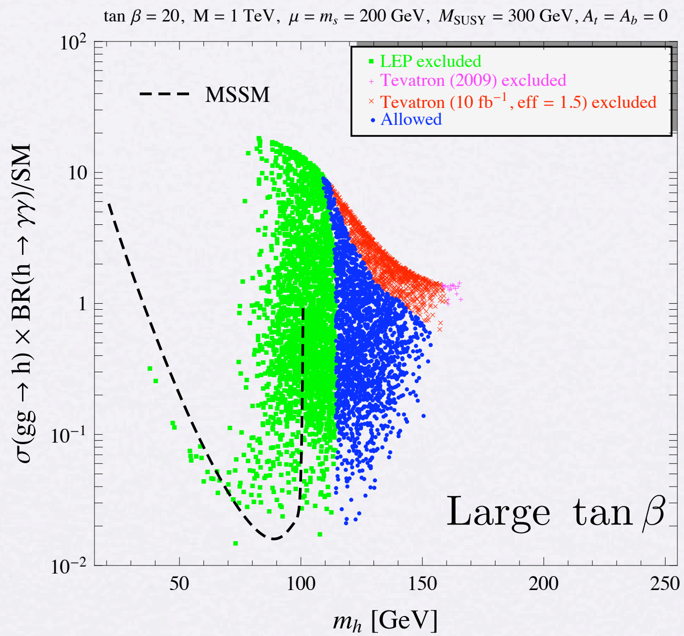
Sensitivity at Tevatron to the light CP-even Higgs

Enhancements elsewhere

Suppression of bb leads to enhancement of other channels across the board

- Decays into gg and quarks ⟶ large BR into jets
- But also enhancement into gauge bosons or taus
- As well as rare decays like $\gamma\gamma$ ...





At low tan β ⟶ similar to SM rate

An example

An ``unusual" SUSY spectrum:
(in GeV)

m_h	m_H	m_A	$m_{H^\pm}$
172	197	110	167

$\tan\beta = 2$

Main decay modes: (BRs)

$h \to b\bar{b}$	$h \to WW$
0.05	0.91

$H \to WW$	$H \to ZZ$
0.73	0.25

$H^\pm \to \tau\nu_\tau$	$H^\pm \to W^\pm A$
0.43	0.20

$A \to b\bar{b}$	$A \to \tau\bar{\tau}$
0.9	0.1

Note: here H is ``SM-like" $g^2_{hZZ}/SM = 0.2$
$g^2_{HZZ}/SM = 0.8$

h can be excluded at Tevatron (with 10 fb^{-1} and 50% efficiency improvement):

Heavy CP-even Higgs observable at LHC in 4-lepton ``gold-plated" mode:

$$\sigma(gg \to H) \times \text{BR}(H \to ZZ)/\text{SM} \approx 0.5$$

May observe both H^+ and A in top decays

Summary

Collider phenomenology can be understood from:

Suppression/enhancement in relevant channels

- Interesting suppression in $b\bar{b}$ couplings $\longrightarrow$ enhancement in easier channels
  - WW at the Tevatron potentially very interesting
  - Potentially spectacular enhancements in $\gamma\gamma$

Altered Higgs spectrum: heavier, ``unusual" mass splittings

- Both CP-even Higgses ``heavy" with significant decays into gauge bosons

  Potential to map in detail the physics of EWSB!

- Decay chains such as $h/H \to AA$ and $H^+ \to AW^+$ (e.g. with H^+ from top decays)
  - Multiple Higgs signals (no need for large $\tan\beta$ to test full 2HDM)

Conclusions

Observation of

- ``Light" superpartners (e.g. strongly interacting scalars) ⟶ It's SUSY!
- Unusual SUSY Higgs sector, e.g.
  - At least a SM-like Higgs heavier than 135 GeV ...

    ... or unexpected properties such as large enhancement in diphoton channel
  - More than one scalar with non-negligible couplings to Z's and W's, and significant decays in these channels

⟶ Clear signal for BMSSM.

This broad information can be useful to infer nature of physics ``around the corner":

- Recall that e.g. heavy singlets may be hard to see directly
- But if new physics is accessible, a rather interesting cross check would be possible

Supplementary Slides

``The SUSY 2HDM''

Carena, Kong, EP & Zurita, 2009

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

with $\omega_1, \omega_2, \ldots$ ``free'' dimensionless parameters (fixed by UV physics)

Corrections to Kähler potential:

$$\Delta K^{\rm non-cust.} = \frac{c_1}{M^2}(H_d^\dagger e^V H_d)^2 + \frac{c_2}{M^2}(H_u^\dagger e^V H_u)^2 + \frac{c_3}{M^2}(H_u^\dagger e^V H_u)(H_d^\dagger e^V H_d) + \cdots$$

$$\Delta K^{\rm Custodial} = \frac{c_4}{M^2}|H_u H_d|^2 + \left[\frac{c_6}{M^2} H_d^\dagger e^{2V} H_d + \frac{c_7}{M^2} H_u^\dagger e^{2V} H_u\right](H_u H_d) + \text{h.c.} + \cdots$$

Plus SUSY breaking via spurion $X = m_S \theta^2$

UV completions: singlets, triplets, Z's, W's can generate all of these with arbitrary coefficients

(exception: c_6 and c_7 , but main points do not depend strongly on these)

But note: different UV theories generate subsets of op's, sometimes with definite signs

→ handle to infer UV details from Higgs properties

Here, treat coefficients as independent, and scan over $[-1, 1]$ → **survey collider phenomenology**

UV Completions: Singlets

Example 1: singlets

B_μ-term

$$W = \mu H_u H_d + \frac{1}{2} M_S S^2 + \lambda_S S H_u H_d - X \left(a_1 \mu H_u H_d + \frac{1}{2} a_2 M_S S^2 + a_3 \lambda_S S H_u H_d \right)$$

$$K = H_u^\dagger e^V H_u + H_d^\dagger e^V H_d + S^\dagger S - X^\dagger X \left(b_1 H_d^\dagger H_d + b_2 H_u^\dagger H_u + b_3 S^\dagger S \right)$$

Soft masses: $m_{H_d}^2, m_{H_u}^2, m_S^2$

Integrating out the singlet:

$$M = M_S \;, \qquad \omega_1 = -\lambda_S^2 \;, \qquad \alpha_1 = a_2 - 2a_3 \;,$$

$$c_4 = |\lambda_S|^2 \;, \qquad \gamma_4 = a_2 - a_3 \;, \qquad \beta_4 = |a_2 - a_3|^2 - b_3$$

Note $c_4 > 0$, other arbitrary

UV Completions: Triplets

Example 2: triplets with $Y = \pm 1$

$$W \supset M_T T\bar{T} + \frac{1}{2}\lambda_T H_u T H_u + \frac{1}{2}\lambda_{\bar{T}} H_d \bar{T} H_d$$
$$+ X\left(a_2 M_T T\bar{T} + \frac{1}{2}a_3\lambda_T H_u T H_u + \frac{1}{2}a_4\lambda_{\bar{T}} H_d \bar{T} H_d\right)$$

$$K \supset T^\dagger e^{2V} T + \bar{T}^\dagger e^{2V}\bar{T} + XX^\dagger\left(b_3 T^\dagger T + b_4 \bar{T}^\dagger \bar{T}\right)$$

Integrating out the triplets:

$$M = M_T\,, \qquad \omega_1 = \frac{1}{4}\lambda_T\lambda_{\bar{T}}\,, \qquad \alpha_1 = a_2 - a_3 - a_4\,,$$
$$c_1 = \frac{1}{4}|\lambda_{\bar{T}}|^2\,, \qquad \gamma_1 = a_2 - a_4\,, \qquad \beta_1 = |a_2 - a_4|^2 - b_3\,,$$
$$c_2 = \frac{1}{4}|\lambda_T|^2\,, \qquad \gamma_2 = a_2 - a_3\,, \qquad \beta_2 = |a_2 - a_3|^2 - b_4\,,$$

Induce custodially violating ops.

Note $c_1, c_2 > 0$, other arbitrary

$(\Delta T < 0)$

UV Completions: Triplets

Example 2: triplets with $Y = \pm 1$

$$W \supset M_T T\bar{T} + \frac{1}{2}\lambda_T H_u T H_u + \frac{1}{2}\lambda_{\bar{T}} H_d \bar{T} H_d$$
$$+ X\left(a_2 M_T T\bar{T} + \frac{1}{2}a_3\lambda_T H_u T H_u + \frac{1}{2}a_4\lambda_{\bar{T}} H_d \bar{T} H_d\right)$$

$$K \supset T^\dagger e^{2V} T + \bar{T}^\dagger e^{2V}\bar{T} + XX^\dagger\left(b_3 T^\dagger T + b_4 \bar{T}^\dagger \bar{T}\right)$$

For triplets with $Y = 0 \longrightarrow \lambda_T H_u T H_d$

$$\left.\begin{array}{lll} M = M_T\ , & \omega_1 = -\frac{1}{4}\lambda_T^2\ , & \alpha_1 = a_2 - 2a_3\ , \\ c_3 = \frac{1}{2}|\lambda_T|^2\ , & \gamma_3 = a_2 - a_3\ , & \beta_3 = |a_2 - a_3|^2 - b_3\ , \\ c_4 = -\frac{1}{4}|\lambda_T|^2\ , & \gamma_4 = a_2 - a_3\ , & \beta_4 = |a_2 - a_3|^2 - b_3\ , \end{array}\right\}$$

Induce custodially violating ops.

Note $c_3 > 0$ $(\Delta T > 0)$,

and $c_4 < 0$!

UV Completions: Gauge Extensions

Example 3: W primes $SU(2)_1 \times SU(2)_2 \xrightarrow{\Sigma} SU(2)_D$ $\Sigma(2,2)$ $H_{u,d}(2,0)$

$$K = H_u^\dagger e^{g_1 V_1} H_u + H_d^\dagger e^{g_1 V_1} H_d + \frac{2M_{V'}^2}{(g_1^2 + g_2^2)} \mathrm{Tr}\left[e^{g_2 V_2} e^{g_1 V_1}\right]$$

Integrating out the triplets: ($\tilde{g} = g_1^2/\sqrt{g_1^2 + g_2^2}$ is the coupling of $V' = W'$)

$$K_{\text{eff}} \supset -\frac{\tilde{g}^2}{8M_{V'}^2} \left\{ \left(H_u^\dagger e^{gV} H_u + H_d^\dagger e^{gV} H_d \right)^2 - 4\,|H_u \epsilon H_d|^2 \right\}$$

Now $c_1, c_2, c_3 < 0$!

$$c_1 = -\frac{1}{4}\tilde{g}^2 \,, \qquad c_2 = -\frac{1}{4}\tilde{g}^2 \,, \qquad c_3 = -\frac{1}{4}\tilde{g}^2 \,, \qquad c_4 = \frac{1}{2}\tilde{g}^2 \,,$$

For U(1)′ case: similar, but $c_4 = 0$, and depends on Higgses U(1)′ charges

EW Precision Constraints

1. Tree-level effects due to new physics:

$$\alpha T^{\rm Tree} = -\frac{v^2}{2M^2}\sin^4\beta\left[c_2 - 2(\tan\beta)^{-2}c_3 + (\tan\beta)^{-4}c_1\right]$$

2. Effects from MSSM Higgs sector:

- Heavier SM-like Higgs
- Mass splittings among non-standard Higgses

} Loop-level contr. to S and T

3. Custodially violating mass splittings in SUSY sector

Here: require that $-0.4 < T^{\rm Tree} + T^{\rm Higgs} < 0.3$ $\quad (S \text{ is small})$

Consistent with $-0.2 < T^{\rm Total} < 0.3$ $(95\%\ C.L.)$ for $0 < T^{\rm SUSY} < 0.2$

(see e.g. Medina, Shah & Wagner, 2009)