Golden SUSY, Boiling Plasma, and Big Colliders

M. Perelstein, Cornell University

IPMU LHC Workshop talk, 12/18/07

Outline

- Part I: Supersymmetric Golden Region and its Collider Signature (with Christian Spethmann, hep-ph/0702038, JHEP0704:070,2007)
    - Naturalness in the MSSM $\Rightarrow$ Golden Region
    - Smoking-gun LHC signature of the Golden Region
- Part II: Higgs Cubic Coupling as a Probe of the Electroweak Phase Transition (with Andrew Noble, hep-ph/0711.3018)
    - Higgs effective potential and dynamics of EW phase transition
    - Mechanisms for first-order EWPT
    - Higgs cubic coupling in models with 1st order EWPT

Motivation: MSSM and Naturalness

- In the SM: $V(H) = -\mu^2|H|^2 + \lambda|H|^4$ $\mu, \lambda \to v, m_h$
- So, m_h is theoretically a free parameter
- In the MSSM, potential is more complicated (2 doublets), but the values of some of the coupling constants are constrained by supersymmetry (related to gauge couplings!)
- Consequence: at tree level, there is a firm upper bound on the mass of the lightest of the two CP-even Higgs bosons:

$$m(h^0) < M_Z$$

- Experimentally, $m(h^0) > 114\ \mathrm{GeV}$
- Either the MSSM is wrong, or loop corrections to $m(h^0)$ are large (25%)

Higgs and Stops

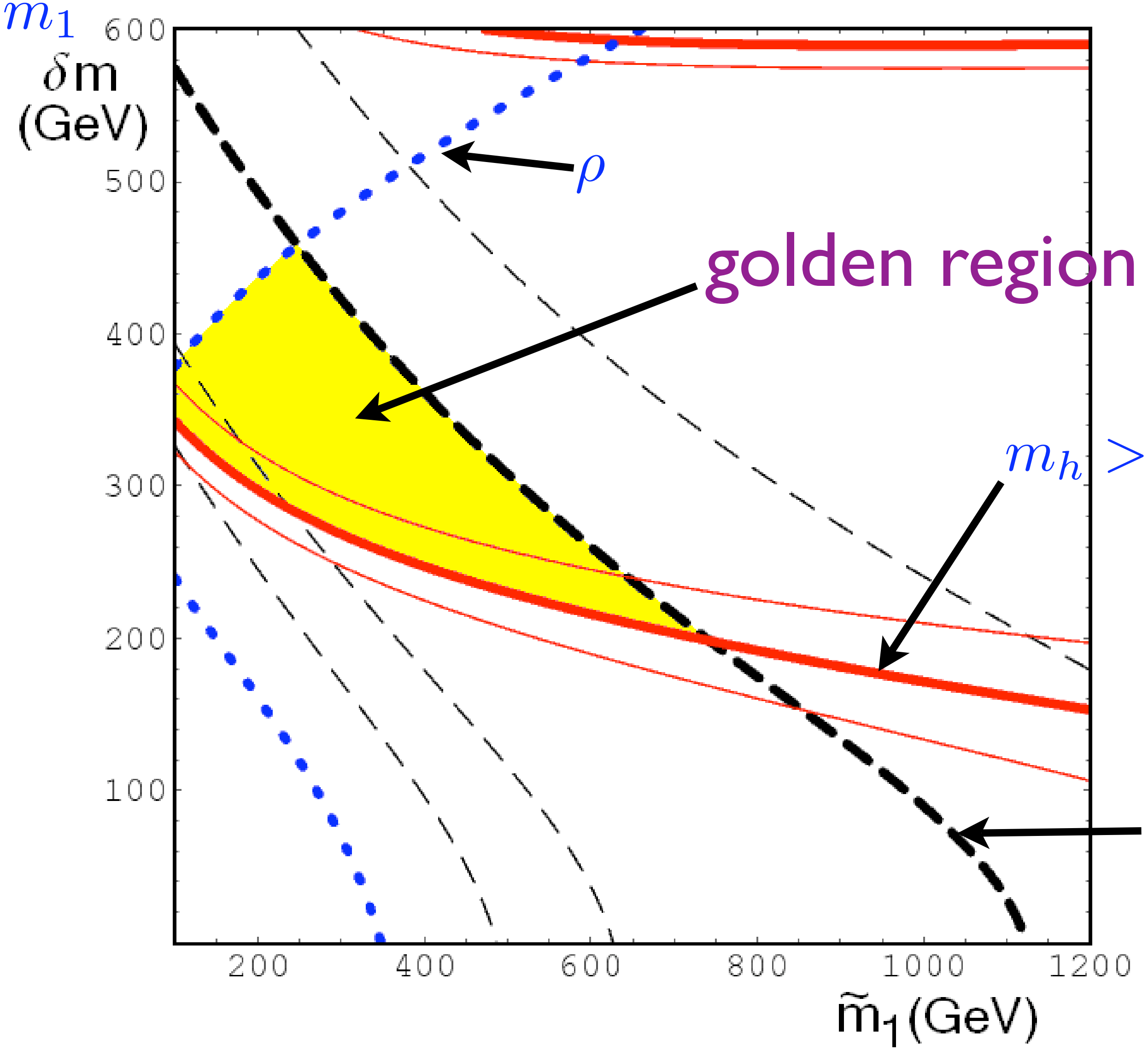
- In the SM, the strongest coupling of the Higgs is the top Yukawa, $\lambda h\bar{t}t, \quad \lambda = 1.0$
- The same is (almost always) true in the MSSM: the Higgs's biggest coupling is to top quark and its superpartners, two scalar "supertops" or stops, $\tilde{t}_L, \quad \tilde{t}_R$
- Stop mass eigenstates $\tilde{t}_1, \quad \tilde{t}_2$ are mixtures of $\tilde{t}_L, \quad \tilde{t}_R$
- Three parameters: 2 stop eigenmasses $m_1, \quad m_2$ + 1 mixing angle θ_t
- One-loop correction to the Higgs mass is a function of these parameters: $\Delta m_h^{1-\text{loop}} = F(m_1, m_2, \theta_t)$
- LEP-2 lower bound on m_h selects a specific region in the parameter space (m_1, m_2, θ_t) ⇨ direct info about stops!

Higgs and Stops, Cont'd

- Loop corrections to the Higgs potential from top and stop loops can also change the Higgs vev, not just its mass!
- Higgs vev is known ⇨ this change needs to be cancelled by other contributions
- If the top/stop loop correction to the vev is BIG, this cancellation needs to be precise ⇨ classic example of fine-tuning!
- So: need top/stop loops to change Higgs mass by a lot while not changing the Higgs vev by a lot ⇨ difficult!
- Negative spin: this only happens in a small region of parameter space, the MSSM sucks...
- Positive spin: this tells us what the right version of the MSSM is! (or at least determines 3 parameters out of 120...)

The Golden Region in the MSSM

$\delta m = m_2 - m_1$

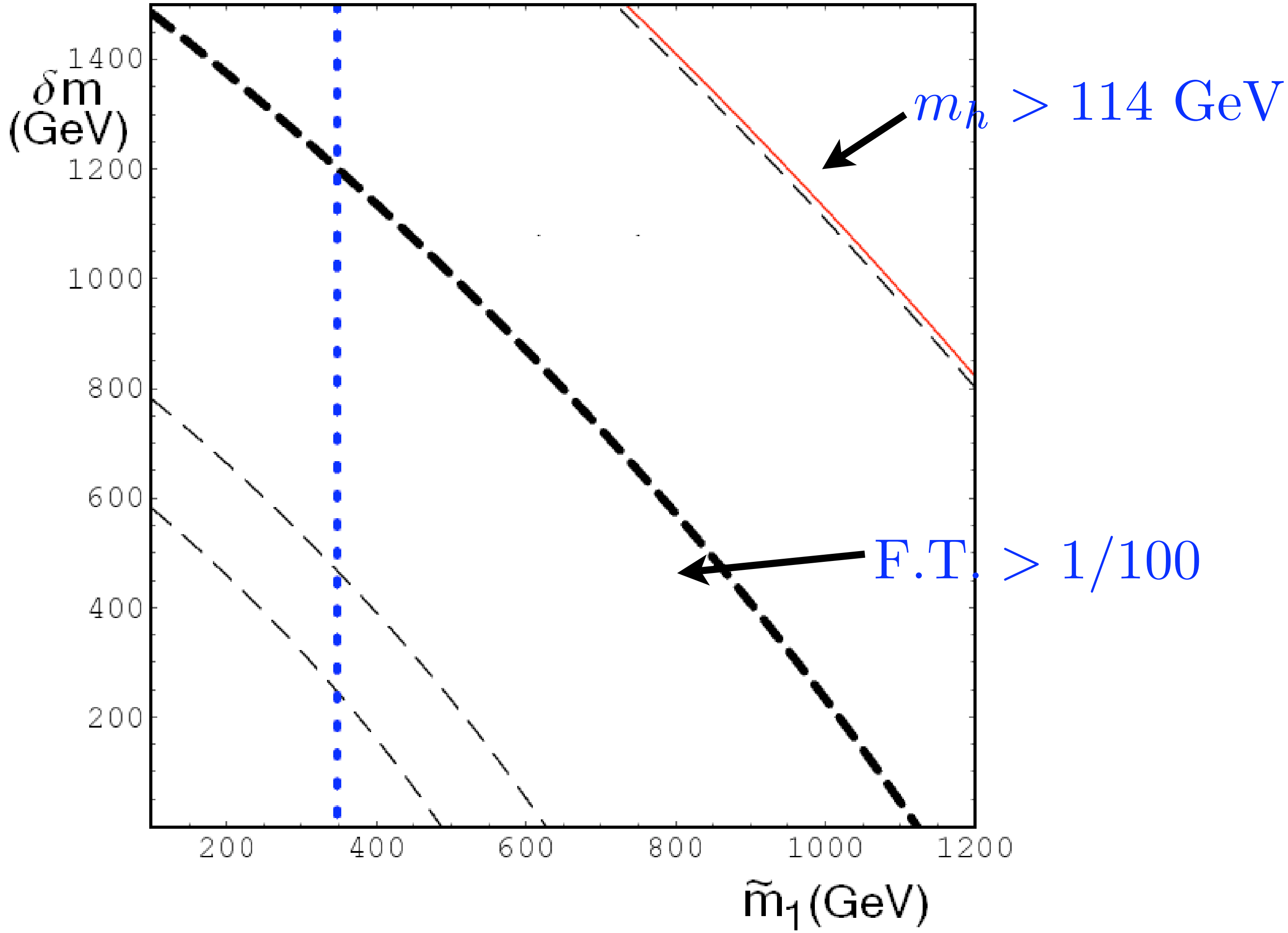


ρ

$m_h > 114$ GeV

F.T. $> 1/100$

$\theta_t = \pi/4, \quad \tan\beta = 10$



$\theta_t = 0, \tan\beta = 10$

No golden region without stop mixing!

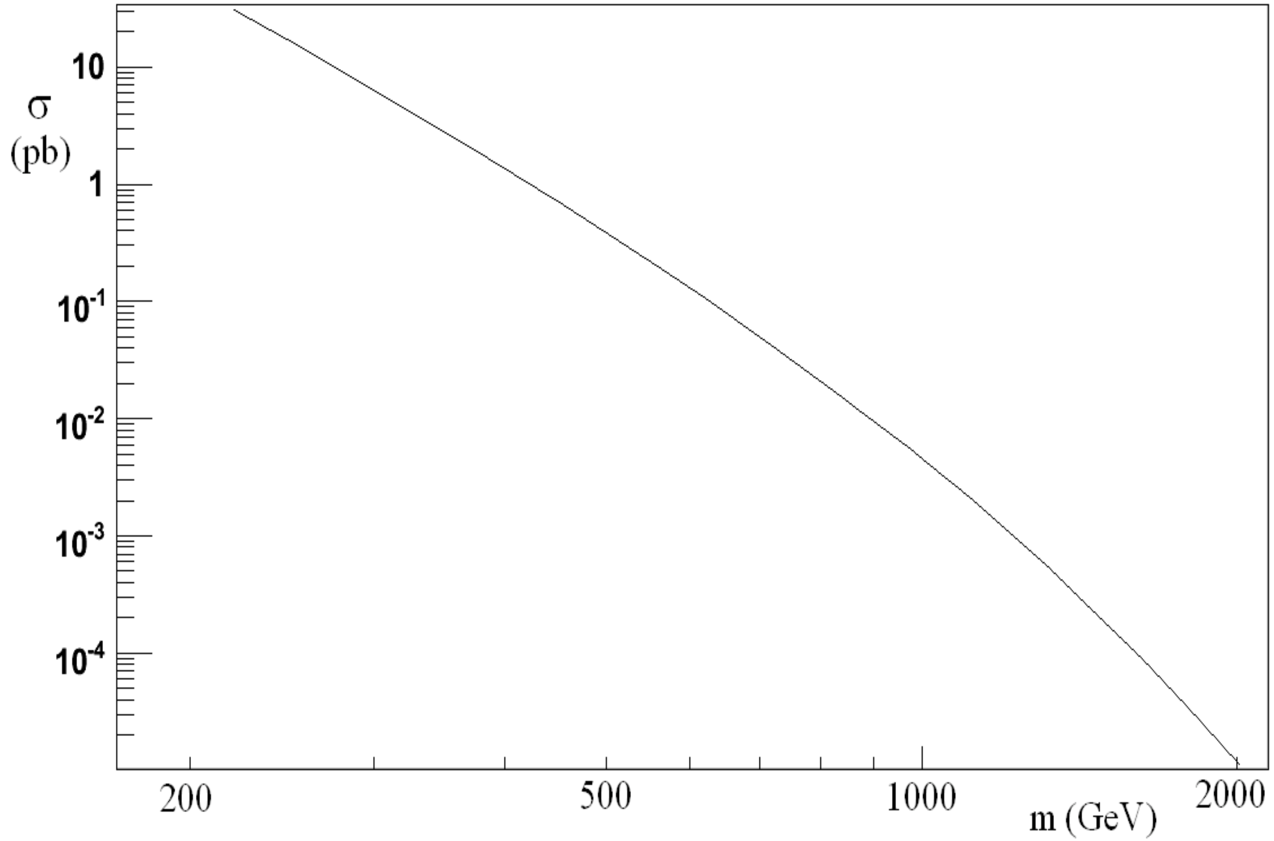
Golden Region in the MSSM

- So, the golden region has the following properties:
  - Lighter stop between 200 and 700 GeV
  - Two stops split by 300-400 GeV
  - Big (near-maximal) mixing angle in the stop sector
- Can this hypothesis be tested at the LHC?
- Both stops will be within reach, but direct measurement of the three parameters involved in the stop sector is very difficult
- However there is a simple test: the decay mode $\tilde{t}_2 \to \tilde{t}_1 + Z$ has a big branching ratio in the golden region ⇨ look for this decay!

Benchmark Point

- To estimate whether this mode will be observable, we choose a benchmark point in the center of the golden region: $m_1 = 400 \text{ GeV}, m_2 = 700 \text{ GeV}, \theta_t = \pi/4$
- Non-stop parameters also fixed, although their precise values are unimportant: $\tan\beta = 10, \mu = 250 \text{ GeV}, \ldots$
- At this point, Br($\tilde{t}_2 \to \tilde{t}_1 + Z$) = 31%; the rest made up by other decay modes: $\chi_0 + t, \chi^+ + b, W^+ + \tilde{b}$
- This branching is very robust (20-40% throughout the golden region, incl. scanning non-stop parameters)
- Unlike every other benchmark point used in MSSM collider studies, this one is (partially) directly motivated by data!
- Note: WIMP relic density wrong, but it is possible to choose non-top-sector parameters to get it right

Stops at the LHC



$$\sigma(\tilde{t}_2\tilde{t}_2^*) = 5 \text{ fb} \quad \text{for } m_2 = 700 \text{ GeV}$$

$$50 \ \tilde{t}_2 \text{ pairs/year @ } 10 \text{ fb}^{-1}\text{/yr}$$

NOT start-up physics!

Signature

- The interesting decay $\tilde{t}_2 \to \tilde{t}_1 + Z$ is followed by stop and Z decays; the detector signature depends on those decays
- Assume leptonic (e or mu) Z decays - clean, QCD background rejection
- Stop decay pattern very model dependent, but all decays involve a b quark and the LSP (missing energy)
- To retain robustness, focus on an inclusive signature:

$$\tilde{t}_1 \to b + \chi_0 + X$$

- Second $\tilde{t}_2$ decay (pair-produced!): $\tilde{t}_2 \to b + \chi_0 + X$ where X may or may not include a Z
- So: look for $Z(\ell^+\ell^-) + 2j_b + \text{ MET}$

Backgrounds

$$Z(\ell^+\ell^-) + 2j_b + \text{ MET}$$

- Physical SM backgrounds:

$$jjZZ, \text{ with } Z_1 \to \ell^+\ell^-, \quad Z_2 \to \nu\bar{nu}$$

$$t\bar{t}Z, \text{ with } Z \to \ell^+\ell^- \text{ and leptonic top(s)}$$

$$t\bar{t}, \text{ with 2 leptonic tops and } \sqrt{s(\ell^+\ell^-)} \approx M_Z \text{ accidentally}$$

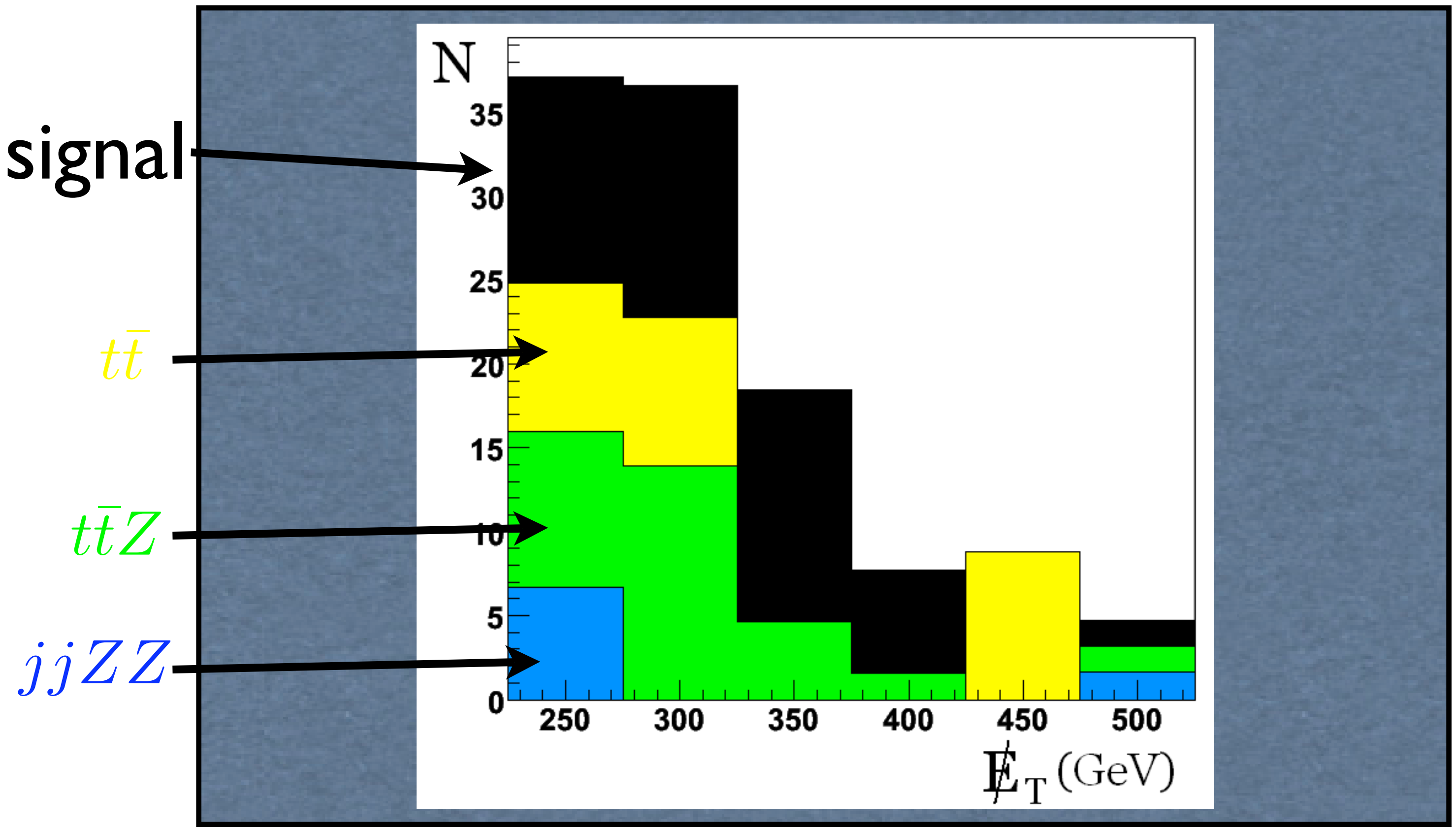
- Instrumental backgrounds

$$jjZ, \text{ with MET due to jet mismeasurement}$$

- Strategy: simulate statistically significant samples of these processes using MadGraph+Pythia, use PGS (”pretty good simulator”, by J. Conway) as a toy detector simulation, off-line cuts and statistical analysis in ROOT

	signal: $\tilde{t}_2\tilde{t}_2^*$	$jjZZ$	$t\bar{t}Z$	$t\bar{t}$	jjZ
$\sigma_{\rm prod}$(pb)	0.051	0.888	0.616	552	824
total simulated	9964	159672	119395	3745930	1397940
1. leptonic Z(s)	1.4	4.5	2.6	0.04	2.1
2(a). $p_t(j_1) > 125$ GeV	89	67	55	21	41
2(b). $p_t(j_2) > 50$ GeV	94	93	92	76	84
3. b-tag	64	8	44	57	5
4. $\gamma(Z) > 2.0$	89	66	69	26	68
5. $\not{E}_T > 225$ GeV	48	2.2	4.4	1.7	< 0.9 (95% c.l.) 0 (ext.)
$N_{\rm exp}(100\ fb^{-1})$	16.4	2.8	10.8	8.8	< 177 (95% c.l.) 0 (ext.)

Table 4: Summary of the analysis of observability of the supersymmetric golden region signature (24). First row: Production cross section for the signal and background processes at the LHC. Second row: Number of Monte Carlo events used in the analysis. Rows 3–8: Cut efficiencies, in%. Last row: The expected number of events for an integrated luminosity of 100 fb^{-1}.



Observability

- Assuming statistical uncertainties dominate, 3-sigma observation requires 75 fb-1, 5-sigma discovery requires 210 fb-1
- Did not try to estimate systematics (no expertise...)
- Note: ttbar contribution to the background (~50%) can be shoulder-subtracted ⇨ probably statistics-dominated
- Alternative sets of rectangular cuts tried (e.g. 2 b-tags), not much improvement
- Fancier analysis methods (e.g. neural nets, decision trees) may give substantial improvement?

Confusability

- If an excess of events in the $Z(\ell^+\ell^-) + 2j_b + \text{ MET}$ channel is observed, can one conclude that it's due to . $\tilde{t}_2 \to \tilde{t}_1 + Z$?
- Not really: even within the MSSM there are alternative explanations, e.g. $\tilde{t} \to t\chi_2^0, \quad \chi_2^0 \to Z\chi_1^0$
- Expect no preference for b-tagged events if Zs come from neutralino/chargino decays...
- Spin correlation observables: scalar > Z + scalar vs. fermion > Z + fermion (detailed study is needed)
- Look at the whole picture: spectrum, etc.
- This would be a great problem to have!!!

Conclusions

- In the MSSM, data (esp. Higgs mass bound) and naturalness give us a hint about some of the model parameters (stop sector)
- The preferred "golden" region has a distinct spectrum: two stops split by 300-400 GeV, large mixing
- The decay $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ has a substantial branching fraction throughout the golden region, independently of the other 117 parameters (except weird corners)
- A detector signature of this decay is $Z(\ell^+\ell^-) + 2j_b + \text{ MET}$
- Evidence for this can be observed with ~100 fb-1 of data at the LHC

Part II: ElectroWeak Phase Transition

- In our world, EW gauge symmetry is broken: $SU(2) \times U(1)_Y \to U(1)_{\text{em}}$
- At high temperature, symmetry is restored (in most models)
- Early universe: electroweak phase transition at $T \sim 100 \text{ GeV}$
- How much can we learn about the dynamics of this transition? First-order ("boiling") or second-order ("quasi-adiabatic") transition?
- Has implications for electroweak baryogenesis (1st order required!)
- Direct relics from the transition in the early universe unlikely to survive (possibly gravitational waves?)

EWPT and Collider Data

- However, finite-T physics is described by the same Lagrangian as T=0 physics we will study at colliders
- Only weak-scale states are relevant for the EW phase transition ("decoupling")
- Determine the TeV Lagrangian at the LHC, ILC ⇨ learn the order of the transition, critical temperature, etc.
- Specifically, need to know (assuming weakly-coupled physics at TeV)
  - Higgs mass(es)
  - Higgs couplings to all SM and BSM states
  - "Bare" masses of all SM and BSM states (without EWSB)

$$m^2 = m_0^2 + ah^2$$

EWPT and Collider Data

- Example: If no weak-scale BSM physics, transition is 2nd order
- With BSM, getting this information is difficult!!! (and may be impossible, e.g. if some BSM states are gauge-singlets with $m_s > m_h/2$)
- Idea: look for simple observables that are correlated with the order of the EWPT in a reasonably model-independent framework
- Proposal: Higgs boson cubic self-coupling λ_3 is one such observable
- Models with 1st order phase transition exhibit large (typically 20-100%) deviations of λ_3 from its SM value
- Evidence: analysis of a series of toy models

Toy Model 1: "Quantum" EWPT

- Single Higgs doublet, SM couplings to SM states, add a real scalar field S
- Scalar potential: $V = V_{\rm SM}(H) + \frac{1}{2}M_0^2 S^2 + \zeta |H|^2 S^2$
- Assume positive M_0^2, ζ ⇒ $\langle S \rangle = 0$
- Compute one-loop effective Higgs potential, including zero-T (Coleman-Weinberg) and finite-T
- Include "ring" contributions important at high T
- At high T, $V_{\rm eff}(h;T) = (\mu^2 + DT^2)h^2 + ET|h|^3 + \lambda h^4 + \ldots$
- Look for minima: $\partial V_{\rm eff}/\partial h = 0$
- If $h = 0$ and $h \neq 0$ minima coexist, 1st order transition

Quantum EWPT, cont'd

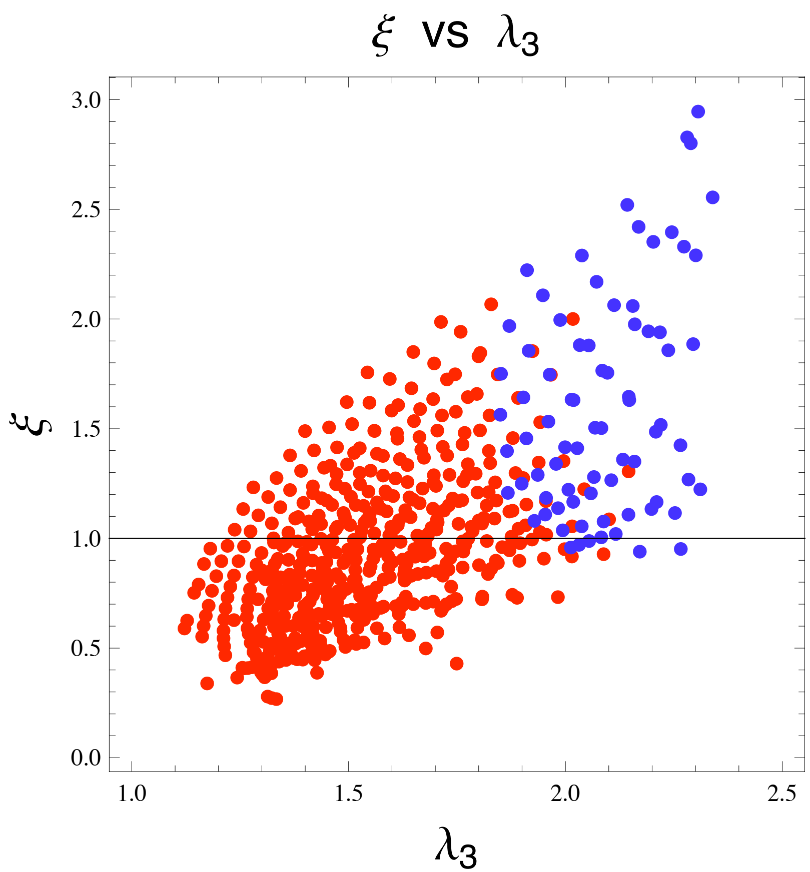
- Scan m_h, M_0, ζ ⇨ find points with first-order EWPT
- Transition occurs at "critical" temperature T_c when the zero and non-zero minima are degenerate
- Measure of "strength" of the first-order transition (roughly quantifies the amount of entropy production):

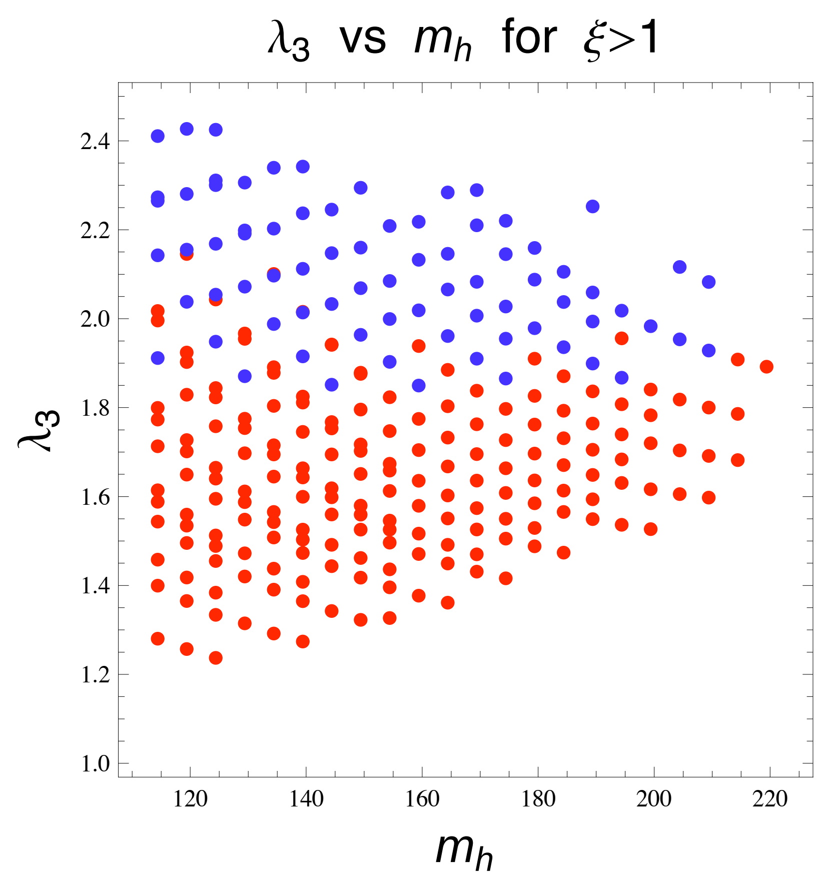
$$\xi = \frac{v_t(T_c)}{T_c}$$

- Numerical studies: $\xi > 1$ required for EW baryogenesis
- Physical Higgs boson cubic self-coupling:

$$\lambda_3 = \frac{d^3 V_{\rm eff}(v; T=0)}{dh^3}$$

Quantum EWPT: Results





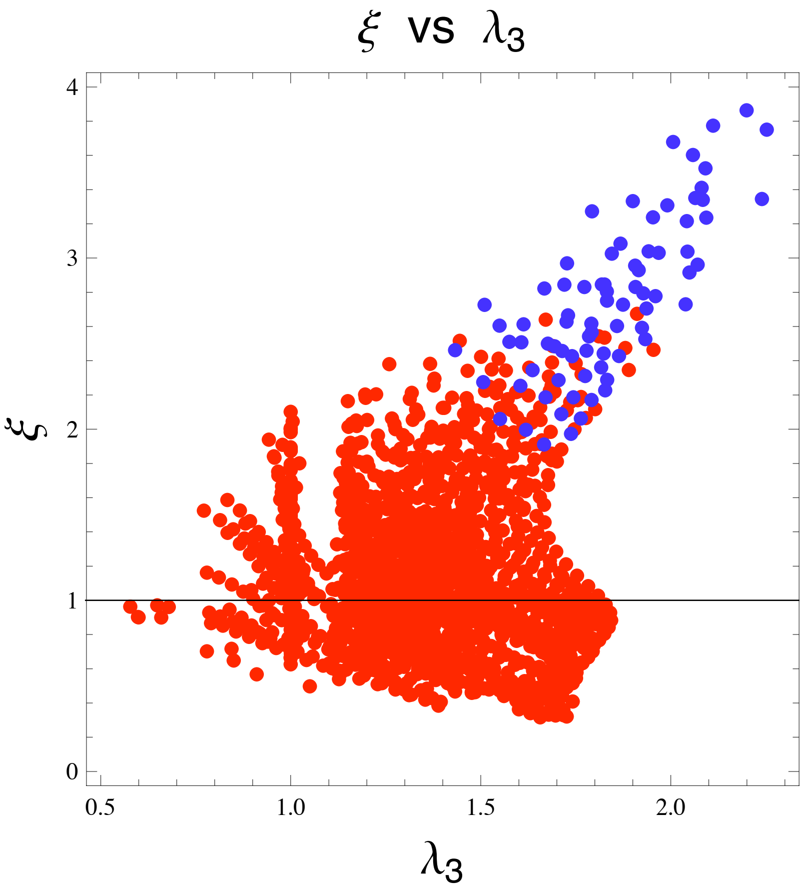
Blue points: "bumpy" T=0 potentials

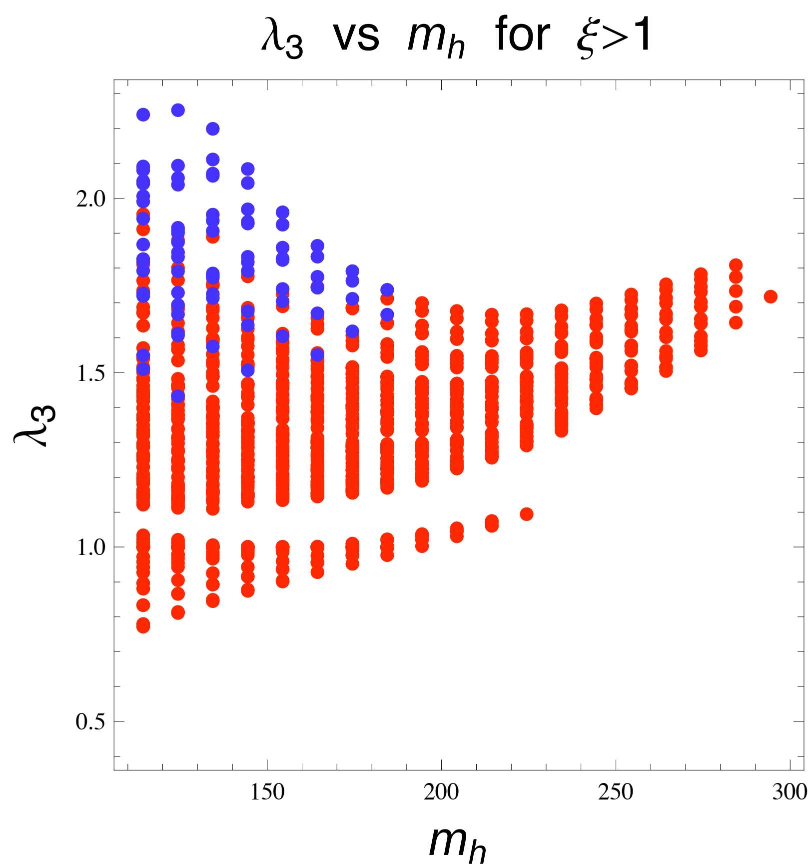
Exp. prospects: 23% for a 140-GeV Higgs at a 500-GeV ILC (Snowmass 01), similar for a 180-GeV Higgs at a 200-TeV VLHC (Baur, Plehn, Rainwater)

Quantum EWPT: Extensions

- Same conclusions apply in a model with identical N real (or N/2 complex) scalars - simple scaling argument!
- One-loop analysis is independent of the scalar's gauge charges - could be stops, triplets, etc.
- Same picture in a model with 2 independent (non-identical) scalars (N ind. scalars is a reasonable conjecture)
- If scalar replaced with a fermion, no points with first-order EWPT found, due to the different structure of the fermion contribution to $V_{\rm eff}$
- A more interesting case: add a scalar-fermion pair ("supermultiplet") with same coupling to the Higgs, different masses

Quantum EWPT with BF Pair





Blue points: "bumpy" T=0 potentials

Accidental Cancellation between B and F contributions at T=0 can result in near-SM value of λ_3

TM 2: "Non-renormalizable" EWPT

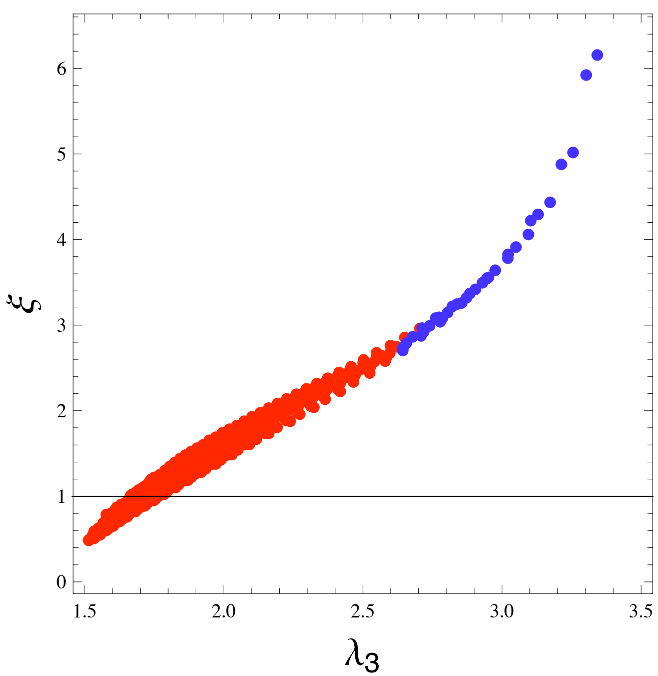
- An alternative way to get 1st-order EWPT: add a non-renormalizable operator to the SM Higgs potential

[Grojean et al, 2004]

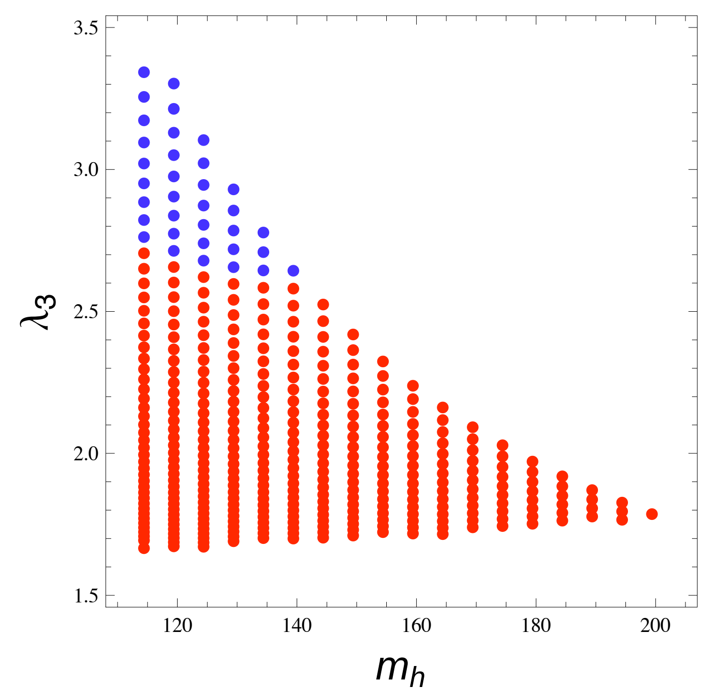
$$V = \mu^2|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6$$

- Reasonable EFT if $v \ll \Lambda$ ⇒ $|\lambda| \ll 1$
- First-order transition can occur for $\mu^2 > 0, \lambda < 0$

ξ vs λ_3



λ_3 vs m_h for ξ>1



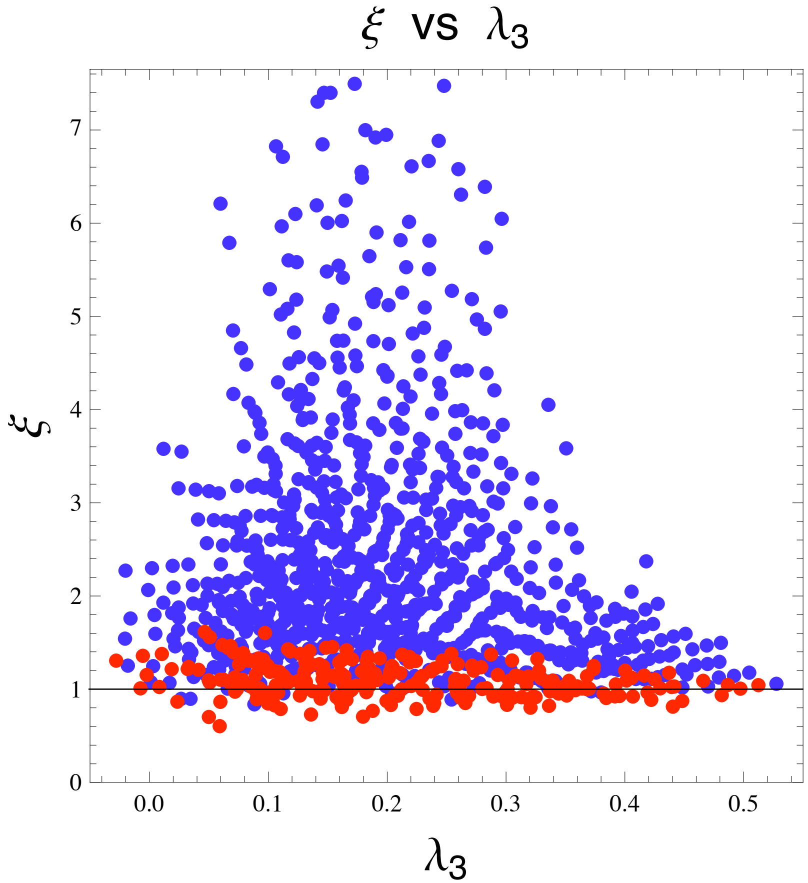
TM 3: Higgs-Singlet Mixing

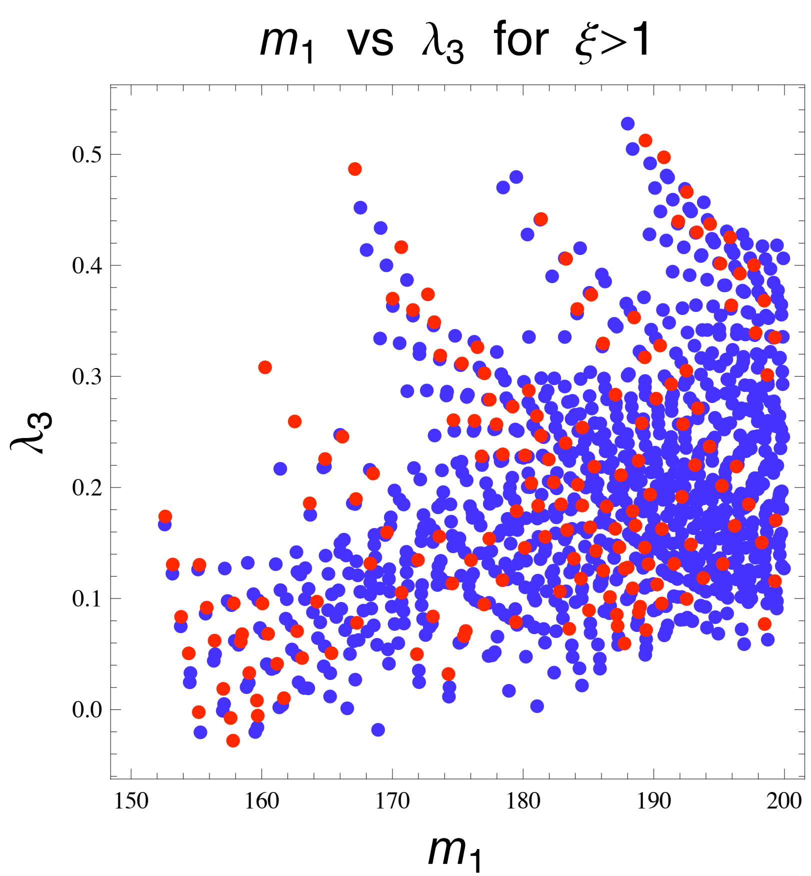
- As in TM1, add 1 real scalar, but with a more general potential:

$$V(H,S) = \mu^2|H|^2 + \lambda|H|^4 + \frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

- Generically, both H and S get vevs at zero temperature
- EWPT involves both H and S changing, order parameter is a linear combination of H and S
- Effective potential for order parameter contains tree-level cubic terms from ⇨ possible strongly first-order EWPT
- Zero-T spectrum: two "higgses" (mixed H and S)
- Only H enters Yukawa couplings ⇨ non-SM Yukawas!
- Cubic self-coupling of the "H-like" higgs = λ_3

Higgs-Singlet Mixing: Results





Partial scan of the 6-dim parameter space

Both suppression and enhancement of λ_3 is possible

Conclusions

- Higgs boson cubic self-coupling is correlated with the order of EWPT: models with 1st order EWPT generically predict large deviations of this coupling from SM
- Typical deviations large enough to be seen at the ILC or the VLHC
- Correlation seen in 3 classes of models, independent of details
- All examples (known to us) violating this conclusion involve accidental cancellations of two large corrections to λ_3 (e.g. BF pair)