Higgs Cubic Coupling and Electroweak Phase Transition

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Andrew Noble, MP, arXiv0711:3018 [hep-ph], in print in PRD

ElectroWeak Phase Transition

- In our world, EW gauge symmetry is broken:

$$SU(2) \times U(1)_Y \to U(1)_{\rm em}$$

- 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 to satisfy Sakharov's out-of-eq. condition!)

EWPT and Collider Data

- Direct relics from the transition in the early universe unlikely to survive (possibly gravitational waves?) [see e.g. Grojean and Servant, hep-ph/0607107]
- However, finite-T physics is described by the same Lagrangian as the 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 $\Rightarrow$ learn the order of the transition, critical temperature, etc.
- Note: standard FRW cosmology at the phase transition time is assumed
- What measurements will be necessary to address this?
- We’ll try to approach this question in a fairly model-independent way

Finite-T Effective Potential

- Assume weakly coupled physics at the TeV scale (otherwise this analysis would require lattice simulations!)
- Assume single physical higgs h participates in the transition (easy to generalize away from this assumption)
- One-loop effective potential has the form

$$V(h;T) = V_{\rm t}(h) + V_{T=0}(h) + V_T(h)$$

  - T=0 (Coleman-Weinberg) part:

$$V_{T=0}(h) = \sum_i \frac{g_i(-1)^{F_i}}{64\pi^2} M_i^4 \left(\log \frac{M_i^2}{\mu^2} + C_i \right)$$

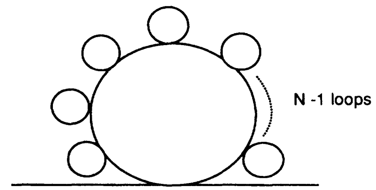
  - Finite-T part:

$$V_T(h) = \sum_i \frac{g_i(-1)^{F_i} T}{2\pi^2} \int dk k^2 \log[1 - (-1)^{F_i} \exp(-\beta\sqrt{k^2 + M_i^2})]$$

  - In a renormalizable theory $M_i^2 = M_{i,0}^2 + a_i h^2$

Effective Potential: Ring Terms

- Beyond one-loop, include "ring" contributions

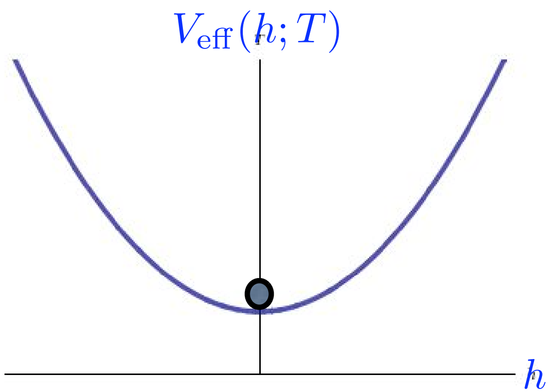


- Can be summed up to yield: [Carrington, PRD 1992]

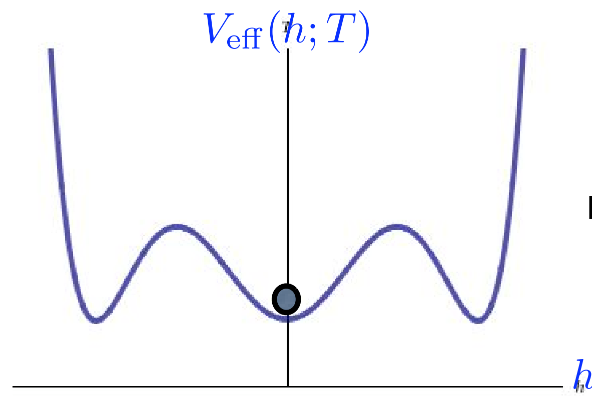
$$V_r(h,T) = \sum_b \frac{T}{12\pi}\left[M_b^3 - \left(M_b^2 + \Pi_b(0)\right)^{3/2}\right]$$

- Only bosons contribute (due to IR divergence)
- Important for the first-order EWPT since at high T, $V_r \propto T|h|^3$ which can produce the desired "dip"
- Ring terms typically controlled by the same parameters as the one-loop effective potential

First-Order Phase Transition



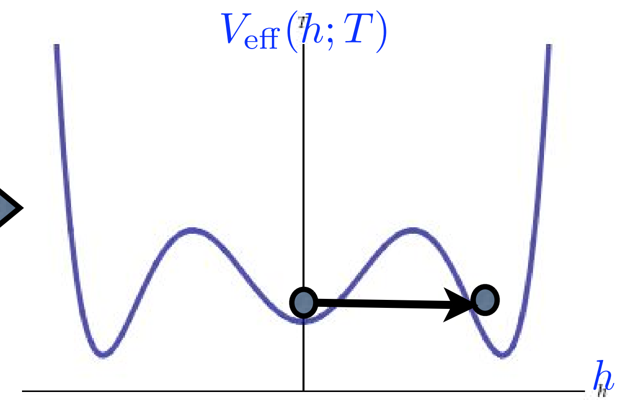
$T > T_c$



$T = T_c$

critical temperature:

$V_{\rm eff}(0) = V_{\rm eff}(v(T_c))$

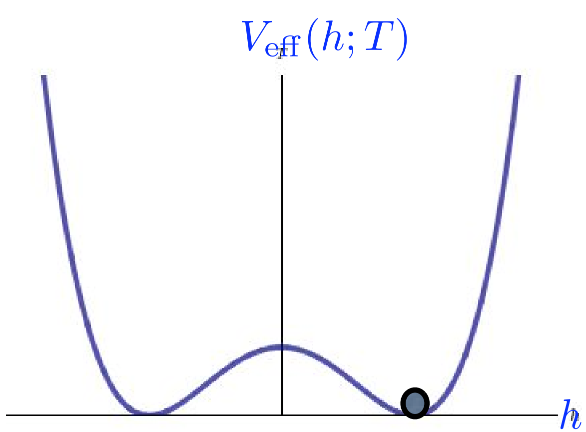


$T = T_n \sim T_c$

nucleation temperature:

$$\Gamma_n \sim H \approx \frac{T_n^2}{M_{\rm Pl}}$$

$$\Gamma_n \propto e^{-S}$$



$T = 0$

strong first-order transition:

$$\xi = \frac{v(T_c)}{T_c} \geq 1$$

Effective Potential from Colliders?

- So, to reconstruct finite-T potential, we need to know the following:
  - Higgs zero-temperature tree-level potential: vev, mass
  - Full spectrum of states (SM and BSM) with significant couplings to the Higgs and masses up to ~few 100 GeV
  - Their fermion numbers and state multiplicities
  - Their masses and couplings to the Higgs:

$$M_i^2 = M_{i,0}^2 + a_i h^2$$

- This is definitely difficult, and may be impossible: e.g.

$$V = V_{\rm SM}(H) + \frac{1}{2} M_0^2 S^2 + \zeta |H|^2 S^2 \quad \text{with} \quad m_S > \frac{m_h}{2}$$

- [still, may be possible in specific models - future work!]

EWPT and Higgs Cubic Coupling

- Idea: look for simple observables that are correlated with the order of the EWPT in a reasonably model-independent framework
- Proposal: use Higgs boson cubic self-coupling λ_3
- Heuristic explanation:
  - In the SM transition is 2nd order for $m_h > 114\ \mathrm{GeV}$
  - New physics must change the shape of V(h) at T_c
  - This changes the shape of V(h) at T=0 $\Rightarrow$ different $\lambda_3(v, m_h)$
- 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 designed to mimic the known mechanisms for getting a first-order PT

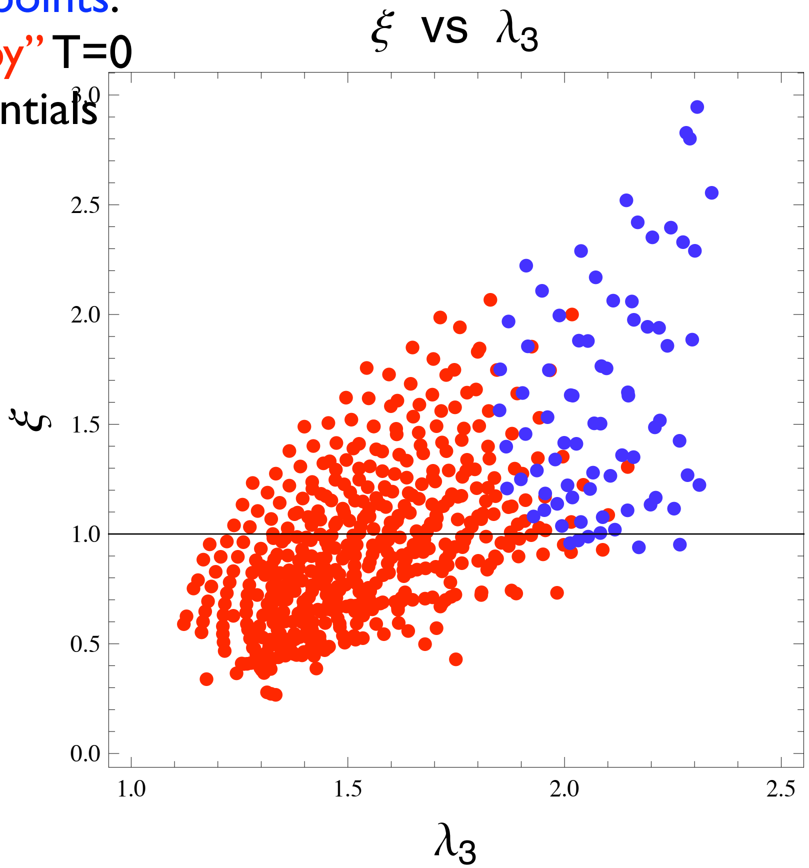
Toy Model I: "Quantum" EWPT

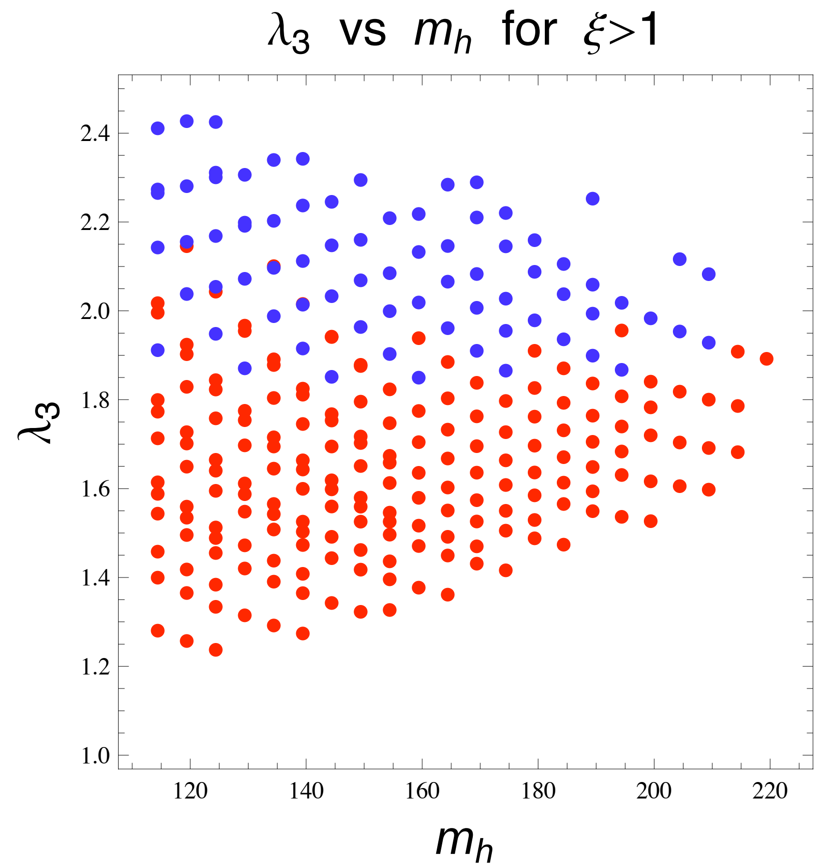
- Single Higgs doublet, SM couplings to SM states, add a real scalar field S
- Scalar potential: $V = V_{\rm SM}(H) + \frac{1}{2}M_0^2 S^2 + \zeta |H|^2 S^2$
- Assume positive M_0^2, ζ $\Rightarrow$ $\langle S \rangle = 0$
- Compute effective Higgs potential
- At high T, $V_{\rm eff}(h;T) = (\mu^2 + DT^2)h^2 + ET|h|^3 + \lambda h^4 + \dots$
- Look for minima: $\partial V_{\rm eff}/\partial h = 0$
- If $h = 0$ and $h \neq 0$ minima coexist, 1st order transition
- Scan m_h, M_0, ζ $\Rightarrow$ find points with first-order EWPT
- 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 120-GeV Higgs at a 500-GeV ILC, 1 ab-1

[Castanier, Gay, Lutz, Orloff, hep-ex/0101028]

20-30% for 160-180 GeV Higgs at SLHC

8-25% for 150-200 GeV Higgs at 200 TeV VLHC

[Baur, Rainwater, Plehn, hep-ph/0206024, 0211224]

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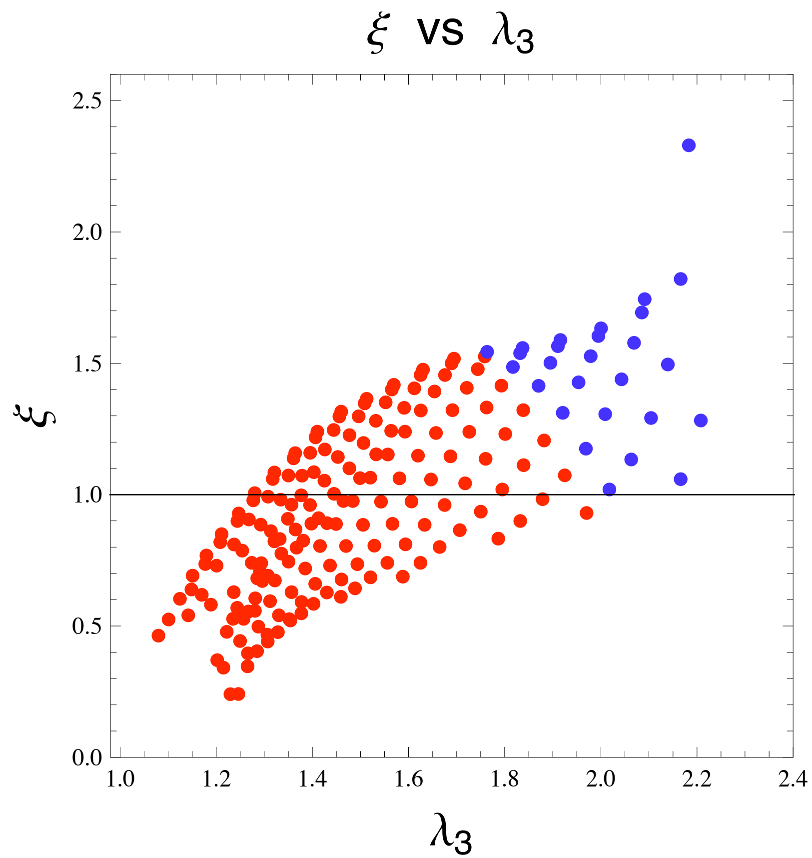

$m_h = 160$ GeV

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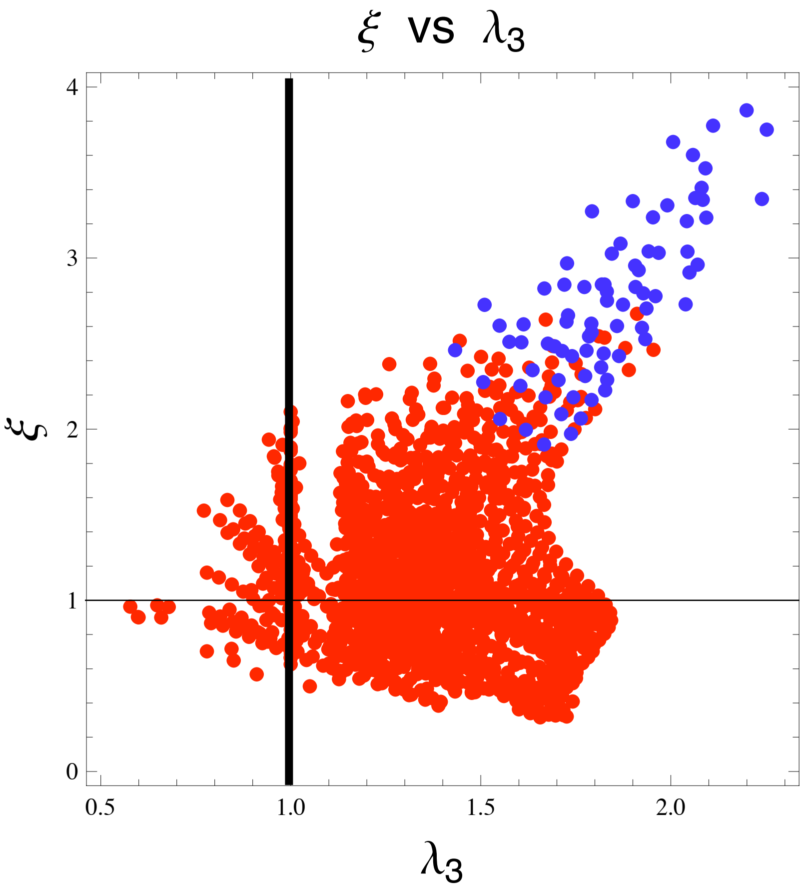
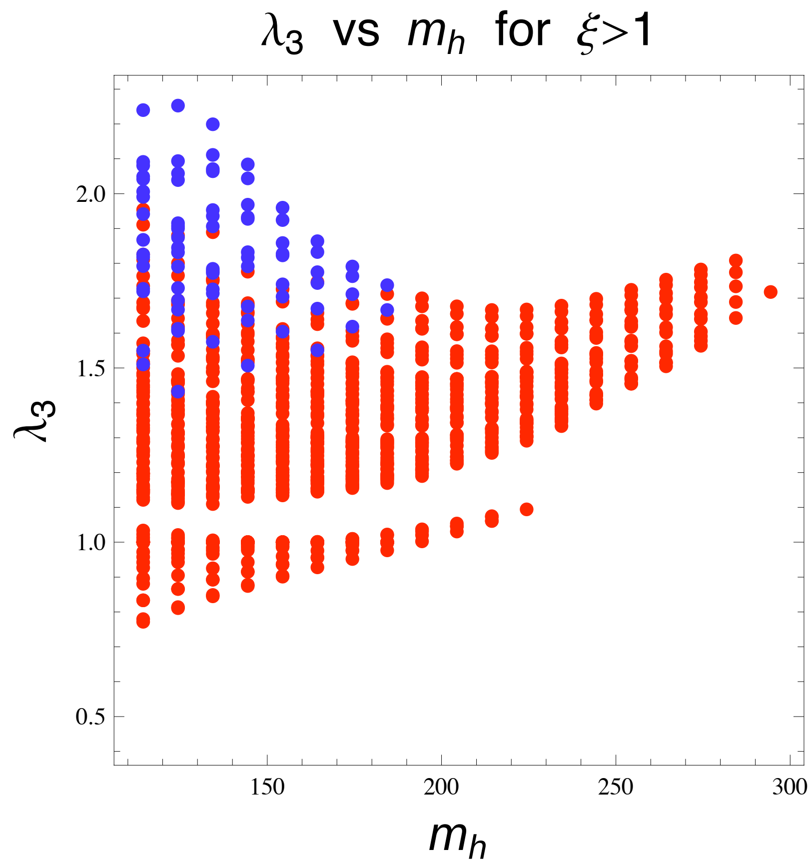
Quantum EWPT: Extensions

- Same calculations apply in a model with identical N real (or N/2 complex) scalars - simple scaling argument: $\xi \rightarrow \xi N^{1/4}$
- One-loop analysis is independent of the scalar's gauge charges - could be e.g. stops of the MSSM (in the decoupling limit - one Higgs), weak 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 $V_{\rm eff}$ (no ring terms $\Rightarrow$ no $|h|^3$)
- A more interesting case: add a scalar-fermion pair ("supermultiplet") with same coupling to the Higgs, different masses

Quantum EWPT with BF Pair





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

[But SUSY is broken by strong coupling to the SM via h!]

$$\Delta M \geq 100 \text{ GeV} \Rightarrow \frac{\delta\lambda_3}{\lambda_3} \geq 7\%$$

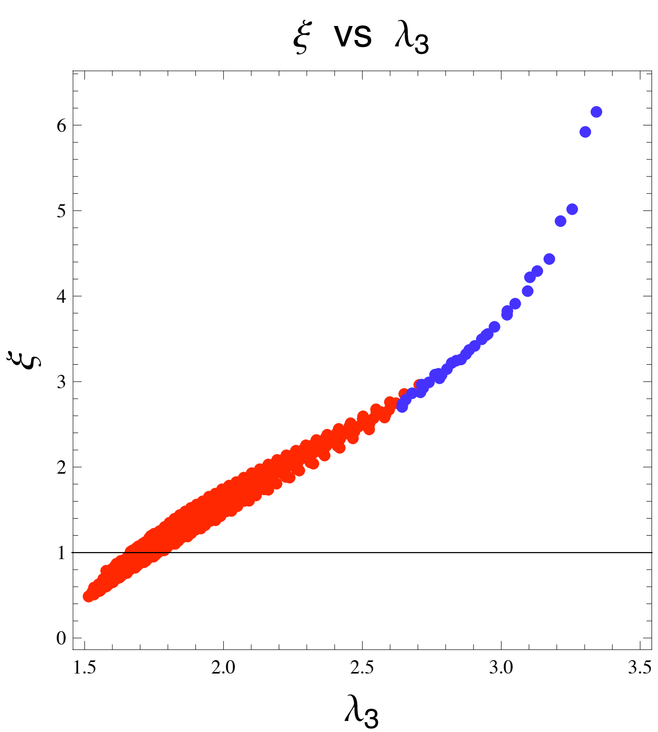
TM 2: "Non-renormalizable" EWPT

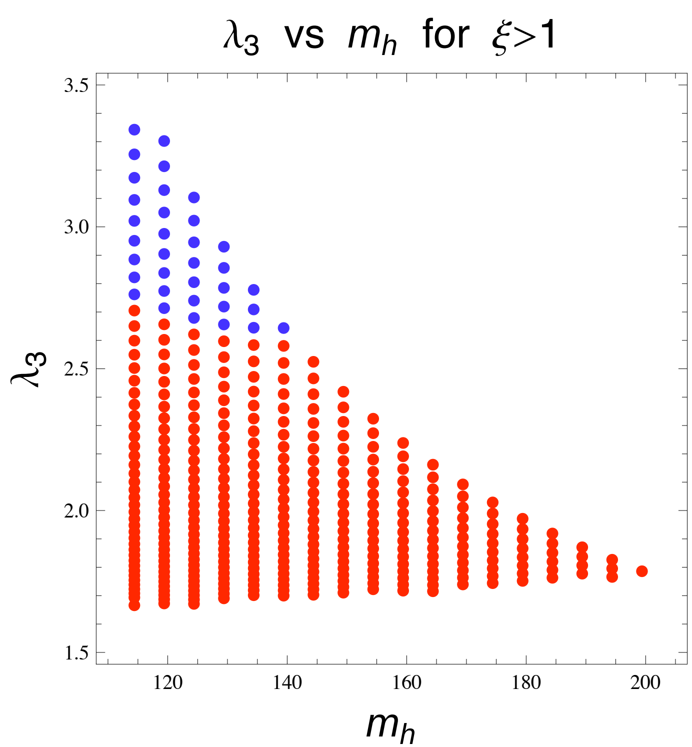
- An alternative way to get 1st-order EWPT: add a non-renormalizable operator to the SM Higgs potential

[Grojean et al, 2004]

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

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





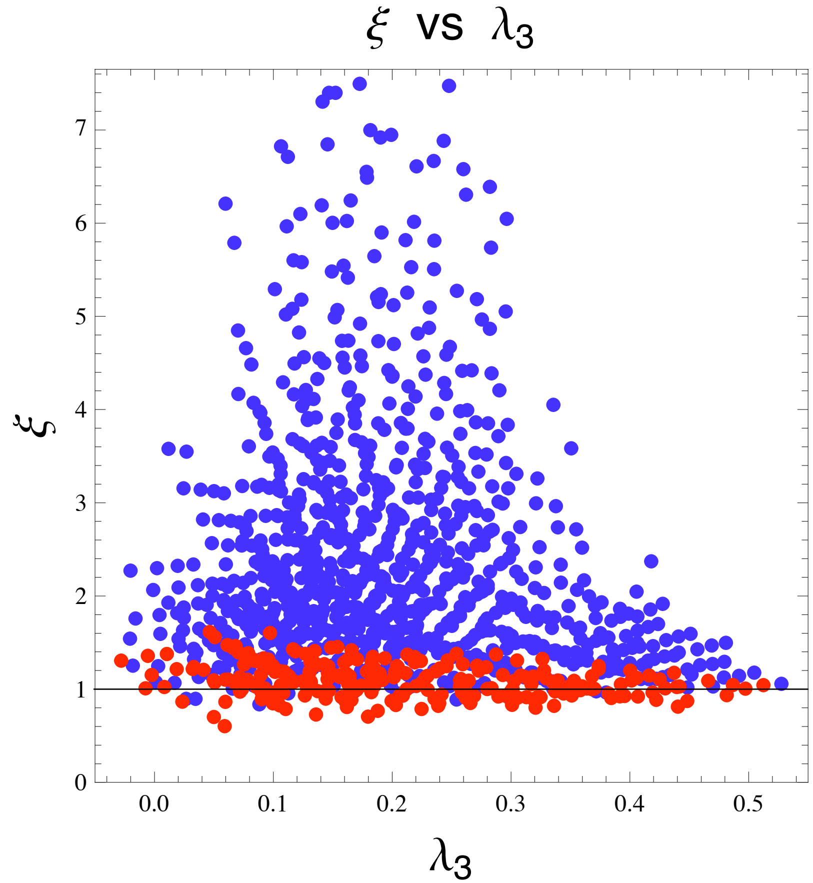
TM 3: Higgs-Singlet Mixing

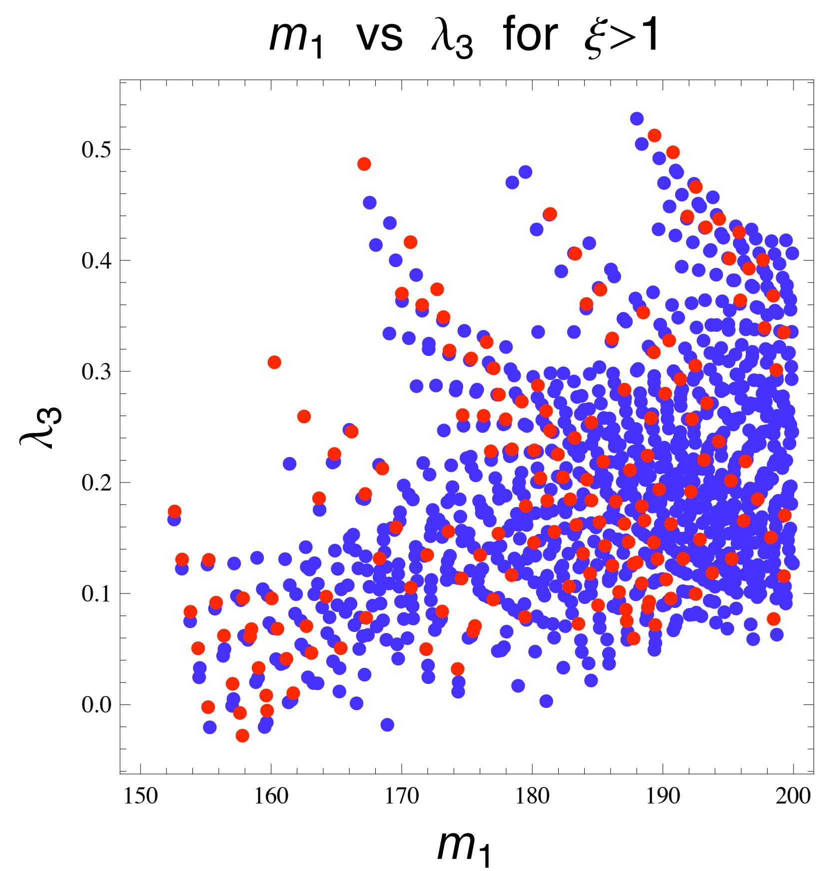
- As in TM1, add 1 real scalar, but with a more general potential:

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

- 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 $\Rightarrow$ possible strongly first-order EWPT
- Zero-T spectrum: two "higgses" (mixed H and S)
- Only H enters Yukawa couplings $\Rightarrow$ 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

Small correction to λ_3 seems only possible if there's an accidental cancellation of two large contributions

Conclusions

- Higgs boson cubic self-coupling is correlated with the order of EWPT
- Stronger 1-st order phase transition $\Leftrightarrow$ larger deviation in λ_3
- Typical deviations large enough to be seen at the ILC or the SLHC/VLHC
- Correlation seen in 3 toy models, illustrating different mechanisms for getting a first-order EWPT
- All examples (known to us) violating this conclusion involve accidental cancellations of two large corrections to λ_3
- Observing SM value would strongly disfavor first-order phase transition (and hence EW baryogenesis)
- Caution: Models with 2nd order EWPT can still produce large deviations, though!