Higgs Couplings and Electroweak Phase Transition

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Based on:
Andrew Noble, MP, 0711.3018, PRD
Andrey Katz, MP, 1401.1827, JHEP

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) $m_{\rm eff}^2 = -m^2 + cT^2 > 0 \Rightarrow \langle \varphi \rangle = 0$
- Early universe: electroweak phase transition at $T \sim 100\ {\rm GeV}$
- How much can we learn about the dynamics of this transition? First-order ("boiling") or second-order ("quasi-adiabatic") transition? Cross-over?
- 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]
- No possibility of producing "plasma" with restored EW symmetry (T-RHIC?) so no direct experimental probe
- 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 colliders ⇒ learn the order of the transition, critical temperature, etc.
- What measurements will be necessary to address this?

Finite-T Effective Potential

- Assume weakly coupled physics at the TeV scale (beware: finite-T may still 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

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

Higgs-dependent Mass

- T=0 (Coleman-Weinberg) part:

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

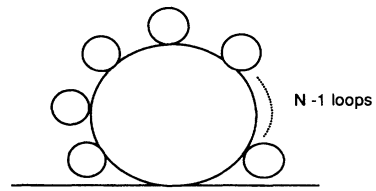
- Finite-T part:

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

- 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



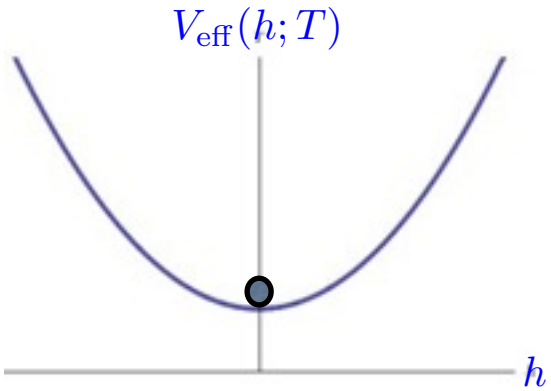
- Can be summed up to yield: [Carrington, PRD 1992]

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

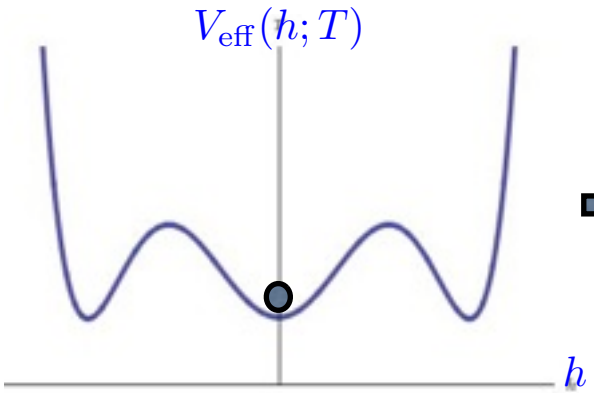
Higgs-dependent Mass

- 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 controlled by the same parameters as the one-loop effective potential

First-Order Phase Transition



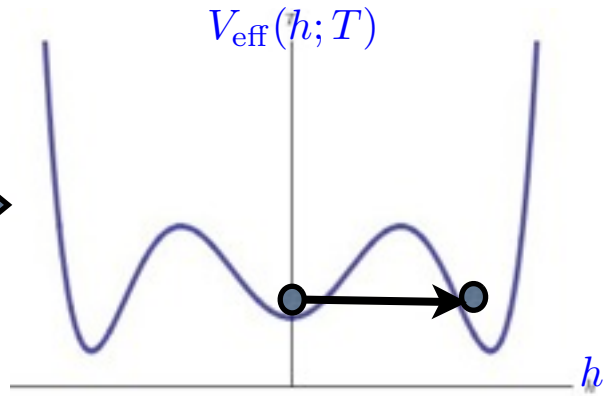
$T > T_c$



$T = T_c$

critical temperature:

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

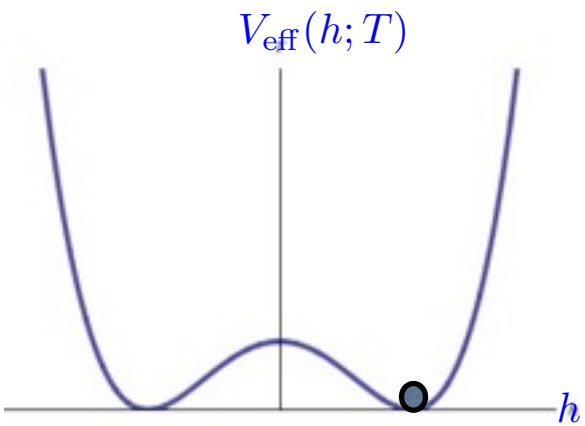


$T = T_n \sim T_c$

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:

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

- One possibility is to directly discover all new states, measure their masses and couplings
- This is difficult: e.g. $V = V_{\rm SM}(H) + \frac{1}{2} M_0^2 S^2 + \zeta |H|^2 S^2$

  with $m_S > \frac{m_h}{2}$

[see D. Curtin's talk]

2007: EWPT and Higgs Cubic

- 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 cross over for a 125 GeV Higgs
  - New physics must change the shape of V(h) at T_c
  - This changes the shape of V(h) at T=0 ⇨ 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

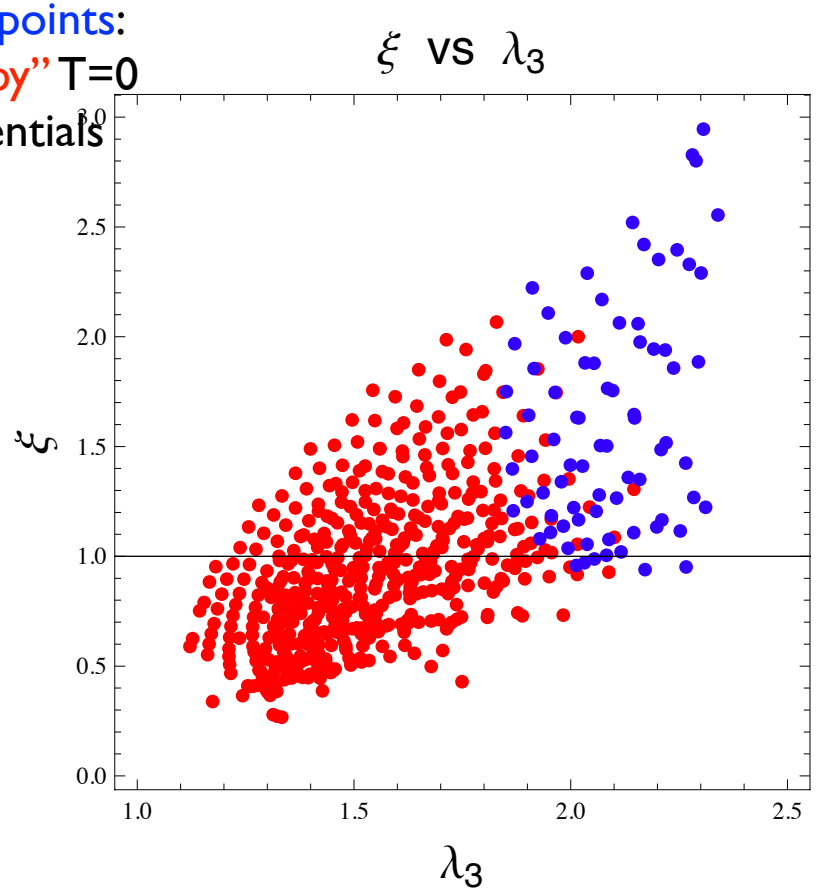
Toy Model 1: "Quantum" EWPT

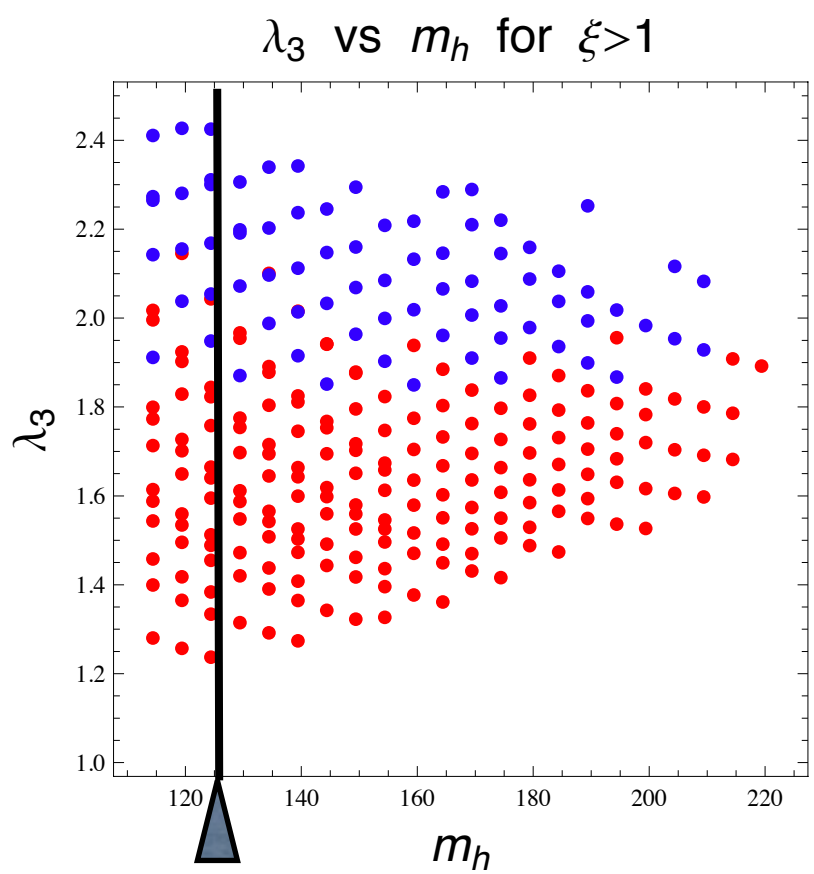
- Single Higgs doublet, SM couplings to SM states, add a real scalar field S
- Scalar potential: $V = V_{\rm SM}(H) + \frac{1}{2} M_0^2 S^2 + \zeta |H|^2 S^2$
- Assume positive M_0^2, ζ ⇨ $\langle S \rangle = 0$
- Compute effective Higgs potential
- At high T, $V_{\rm eff}(h;T) = (\mu^2 + DT^2)h^2 +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





~20% minimal deviation

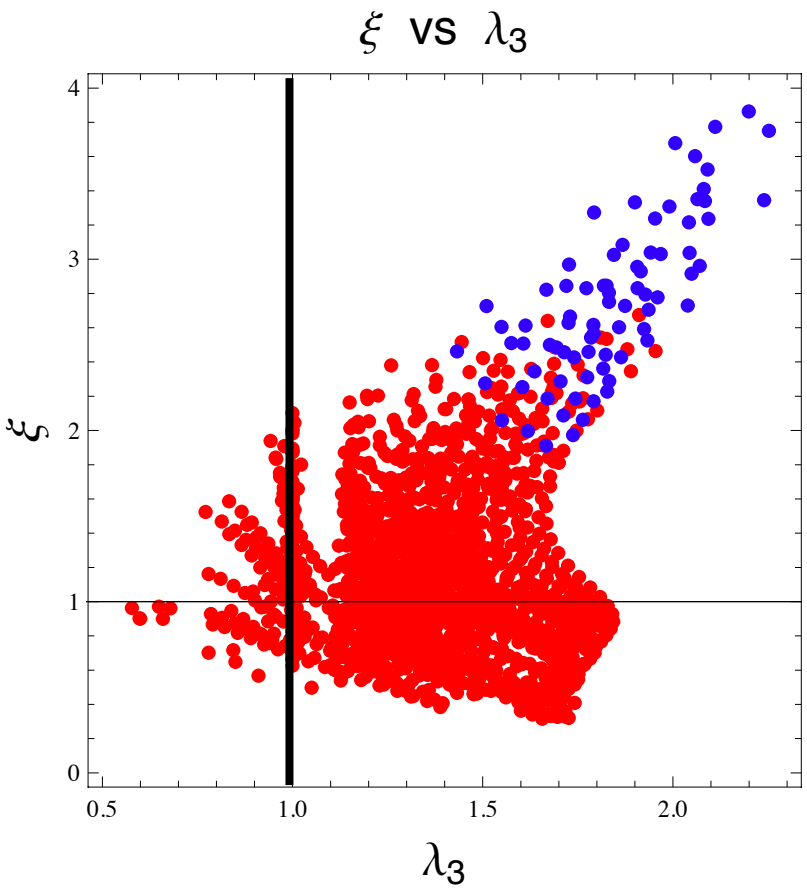
Exp. prospects: 27% for H-20 scenario at ILC [1506.05992]

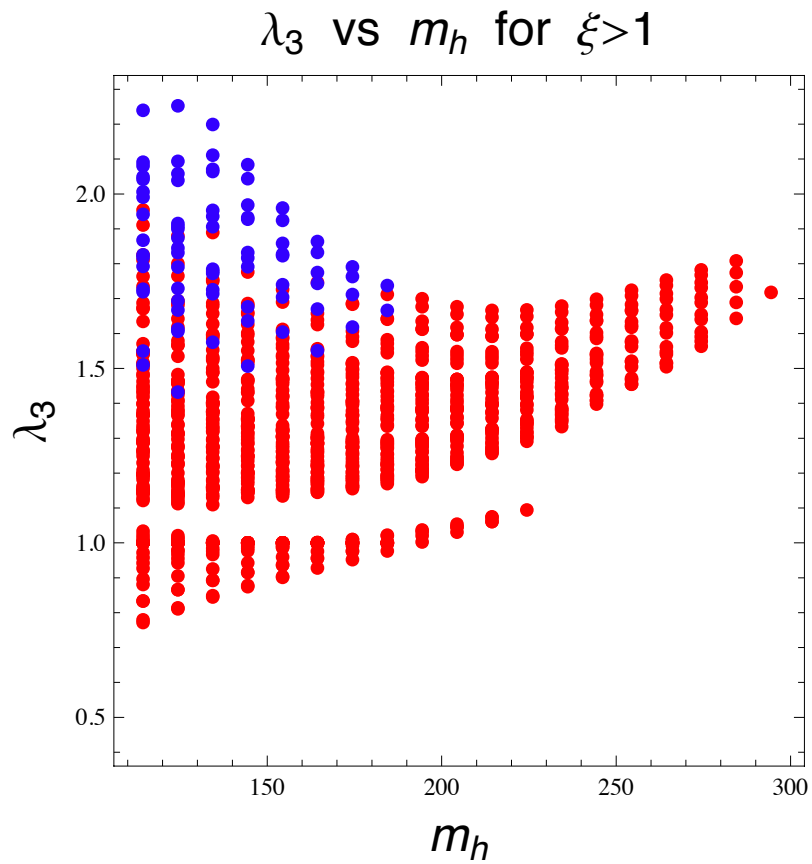
??? at a 100 TeV pp collider

Quantum EWPT: Extensions

- Same calculations apply in a model with identical N real (or N/2 complex) scalars - simple scaling argument: $\xi \to \xi N^{1/4}$
- 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 ⇨ 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!]

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

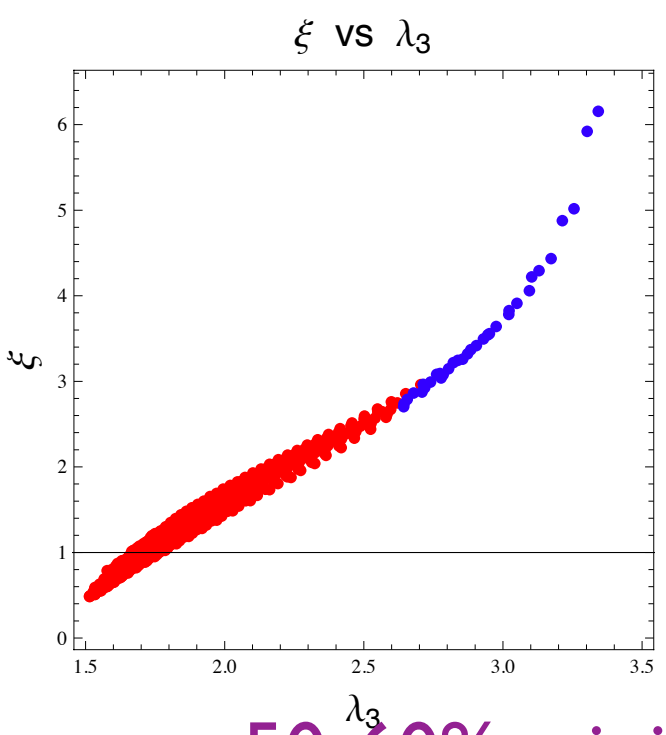
TM 2: "Non-renormalizable" EWPT

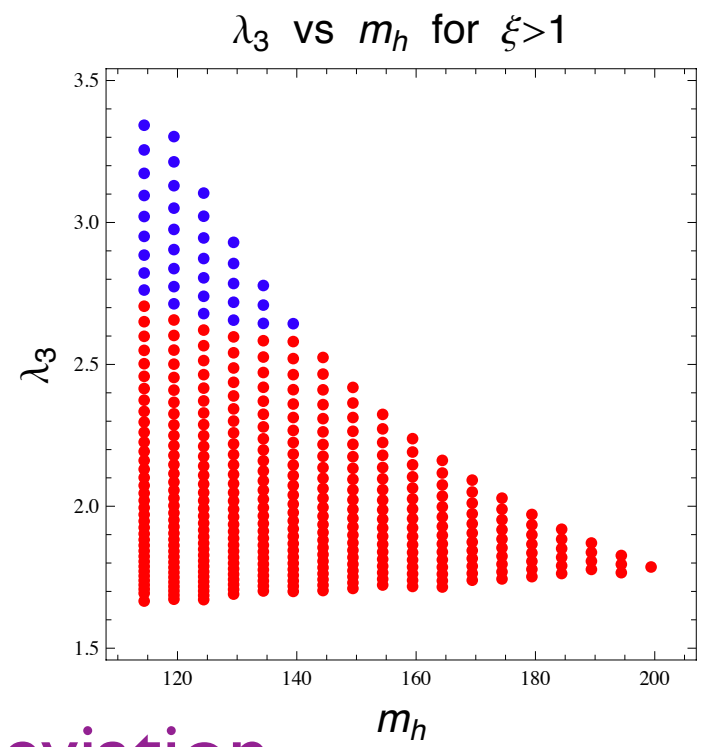
- An alternative way to get 1st-order EWPT: add a non-renormalizable operator to the SM Higgs potential

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

[Grojean et al, 2004]

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





50-60% minimal deviation

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 typically O(100%) away from the SM value

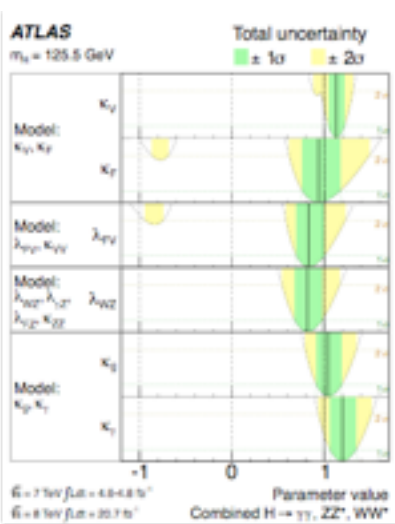
[see talks later today for "modern" analyses]

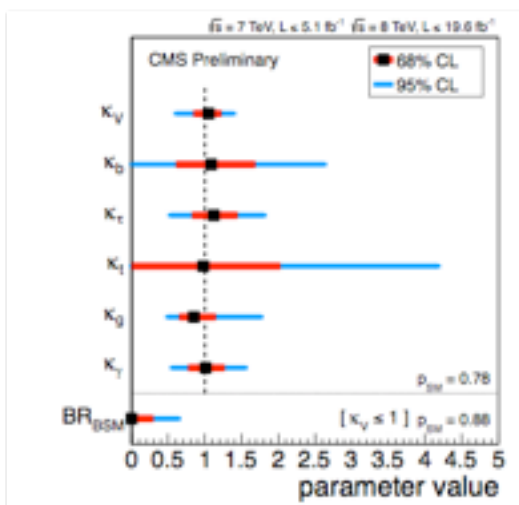
Conclusions: 2007 paper

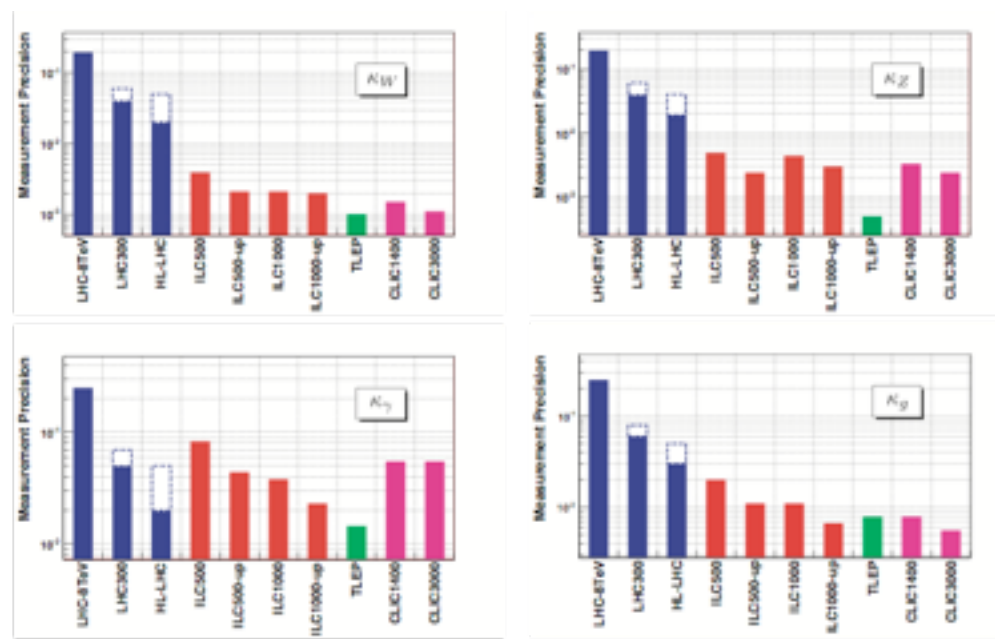
- Higgs boson cubic self-coupling is correlated with the order of EWPT
- Stronger 1-st order phase transition ⇔ larger deviation in λ_3
- Typical deviations large enough to be seen at the ILC or the SLHC/VLHC
- Correlation seen in 3 toy models, illustrating different mechanisms for getting a first-order 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!

2014: EWPT and Higgs-VB Couplings

- Measuring Higgs cubic provides direct information about the Higgs potential (admittedly at T=0)
- ...but experimentally it's a difficult measurement
- In contrast, couplings to vector bosons (γ, g, Z) are already measured at ~10-20% level, will improve to ~a few % with more LHC data, and <1% if e+e- Higgs factory is built
- Are these correlated with the order of EWPT?







HC and EWPT: Setup

- Focus on the "quantum" PT scenario: The cubic term at high-T is induced by loops of scalars

- Add a single complex scalar Φ , with $V_\Phi = m_0^2|\Phi|^2 + \kappa|\Phi|^2|H|^2 + \eta|\Phi|^4.$

- Effective potential controlled by the H-dependent mass of Φ :

$$V_1(\varphi) = \frac{g_i(-1)^{F_i}}{64\pi^2}\left[m_i^4(\varphi)\log\frac{m_i^2(\varphi)}{m_i^2(v)} - \frac{3}{2}m_i^4(\varphi) + 2m_i^2(\varphi)m_i^2(v)\right];$$

$$V_T(\varphi;T) = \frac{g_i T^4(-1)^{F_i}}{2\pi^2}\int_0^\infty dx\, x^2 \log\left[1-(-1)^{F_i}\exp\left(\sqrt{x^2+\frac{m_i^2(\varphi)}{T^2}}\right)\right],$$

- But the same H-dependent mass controls Φ loop contributions to HVV:

$$\mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v}C_\gamma h F_{\mu\nu}F^{\mu\nu}, \quad \mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v}C_g h G_{\mu\nu}G^{\mu\nu}$$

$$C_\gamma = 1 + \frac{3}{8}\sum_f^{Dirac\ fermions} N_{c,f}Q_f^2\frac{\partial\ln m_f^2(v)}{\partial\ln v} + \frac{3}{32}\sum_s^{scalars} N_{c,s}Q_s^2\frac{\partial\ln m_s^2(v)}{\partial\ln v}$$

$$C_g = 1 + \sum_f^{Dirac\ fermions} C(r_f)\frac{\partial\ln m_f^2(v)}{\partial\ln v} + \frac{1}{4}\sum_s^{scalars} C(r_s)\frac{\partial\ln m_s^2(v)}{\partial\ln v},$$

- Expect direct correlation between the size of the cubic coupling induced at finite-T and non-SM contributions to hgg and $h\gamma\gamma$ (unless Φ is color and EM-neutral)

Analytic Example

- A special case can be studied analytically*: $m_0 = 0$

- High-temperature expansion of the thermal potential:

$$V_{\rm eff}(\varphi;T) = V_0(\varphi) + V_T(\varphi;T) \approx \frac{1}{2}\left(-\mu^2 + \frac{g_\Phi \kappa T^2}{24}\right)\varphi^2 - \frac{g_\Phi \kappa^{3/2} T}{24\sqrt{2}\pi}\varphi^3 + \frac{\lambda}{4}\varphi^4$$

- Location of the broken-symmetry minimum at finite T: $\frac{\partial V_{\rm eff}}{\partial \varphi} = 0 \Rightarrow \varphi_0(T)$

- Critical temperature: $V_{\rm eff}(0,T_c) = V_{\rm eff}(\varphi_0(T_c),T_c)$

- Solve together: $T_c^2 = \frac{24\mu^2}{g_\Phi \kappa\left(1 - \frac{g_\Phi \kappa^2}{24\pi^2\lambda}\right)}, \quad \varphi_+(T_c) = \frac{g_\Phi \kappa^{3/2} T_c}{12\sqrt{2}\pi\lambda}.$

- Strongly 1-st order if $\kappa > 3.6\, g_\Phi^{-2/3}$

- Gluon-Higgs coupling (assume fundamental Φ): $R_g = \frac{1}{8}\frac{\kappa v^2}{m_0^2 + \frac{\kappa v^2}{2}} \approx 25\%$

Numerical Studies

- In general, no analytic solution for critical T and order parameter - solve numerically

- Numerical code includes one-loop Φ and SM contributions at finite-T and T=0 (CW), daisy terms

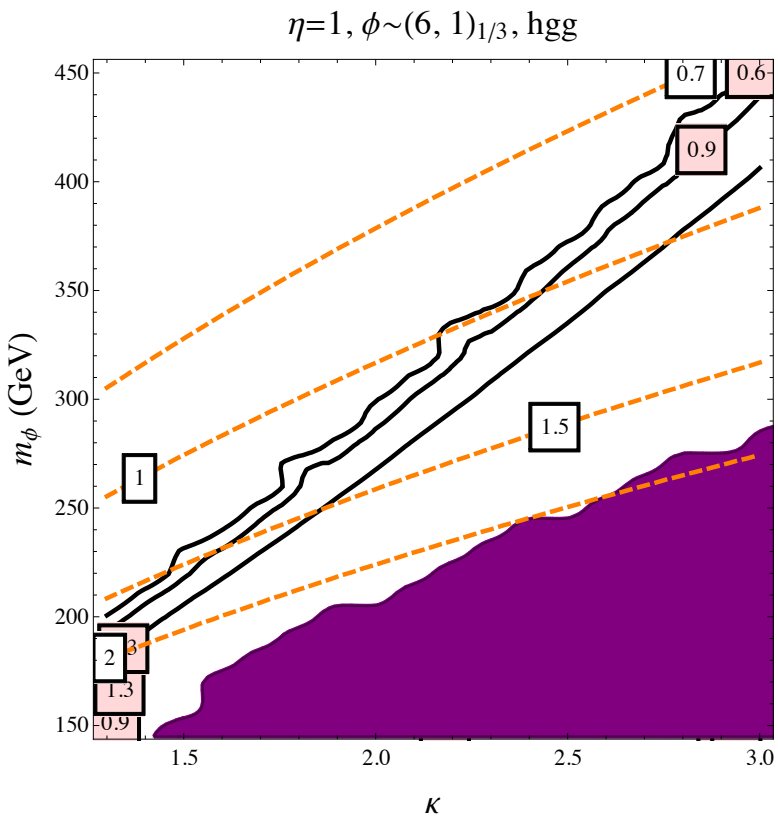
- Analyzed a few toy models, representative of the range of possibilities for Φ

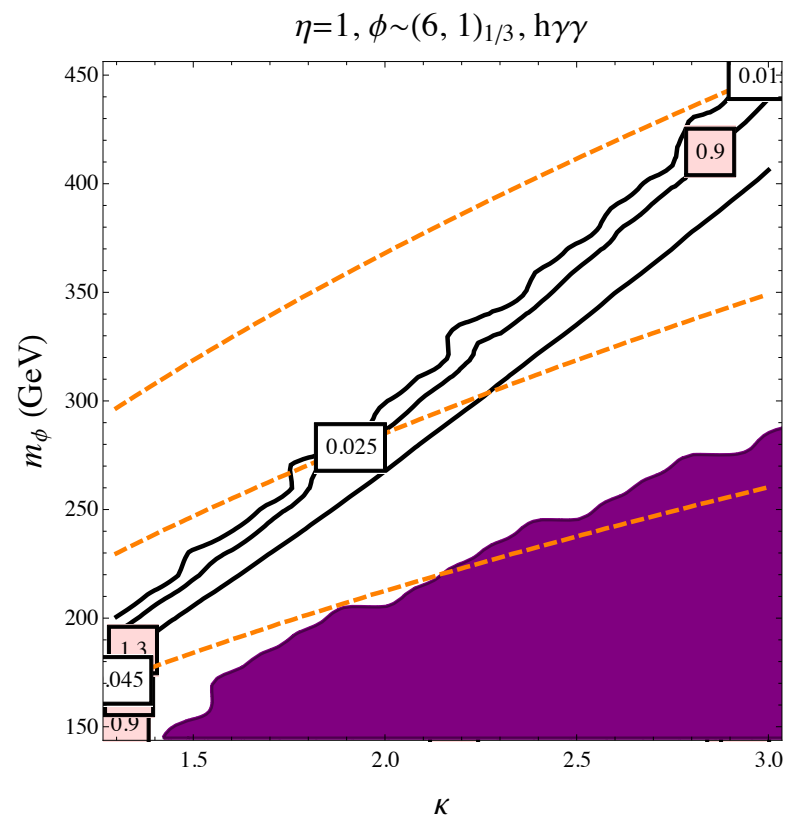
Model	$(SU(3), SU(2))_{U(1)}$	g_Φ	C_3	C_2	$\frac{\Pi_W}{g^2T^2}$	$\frac{\Pi_B}{g'^2T^2}$	$\frac{\Delta\Pi_h}{\kappa T^2}$
"RH stop"	$(\bar{3}, 1)_{-2/3}$	6	4/3	0	11/6	107/54	1/4
Exotic triplet	$(3, 1)_{-4/3}$	6	4/3	0	11/6	131/54	1/4
Exotic sextet	$(\bar{6}, 1)_{8/3}$	12	10/3	0	11/6	227/54	1/2
"LH stau"	$(1, 2)_{-1/2}$	4	0	3/4	2	23/12	1/6
"RH stau"	$(1, 1)_1$	2	0	0	11/6	13/6	1/12
Singlet	$(1, 1)_0$	2	0	0	11/6	11/6	1/12

Table 1. Benchmark models studied in this paper.

[* we treat κ as a free parameter, unlike SUSY]

Results: "Sextet"

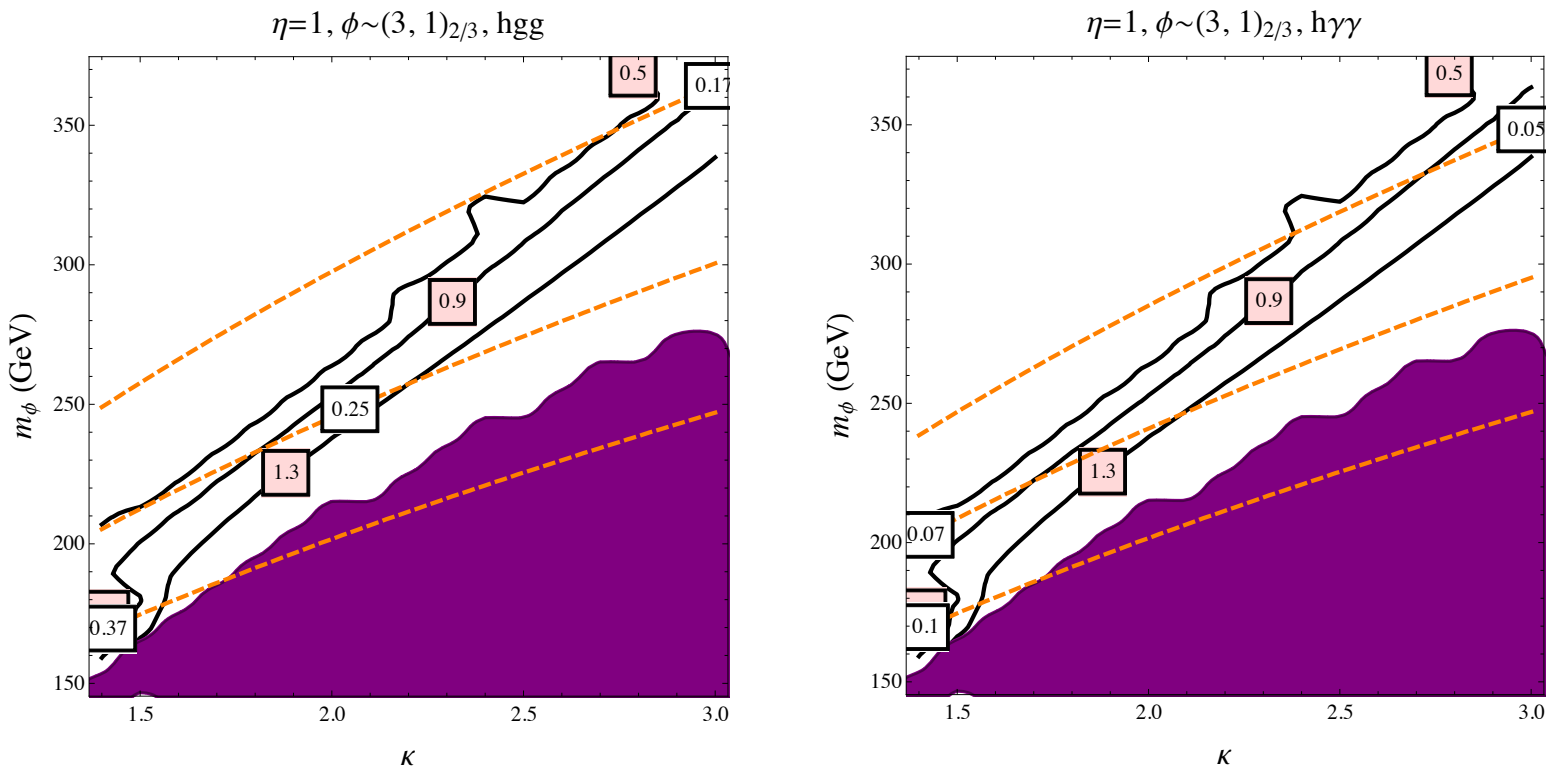




ATLAS: $R_g = 1.08 \pm 0.14,$ $R_\gamma = 1.23^{+0.16}_{-0.13}.$ → ruled out!*

[* usual caveat: SM total width assumed]

Results: "RH Stop"



NOT ruled out if $\kappa > \kappa_{\rm MSSM}$!

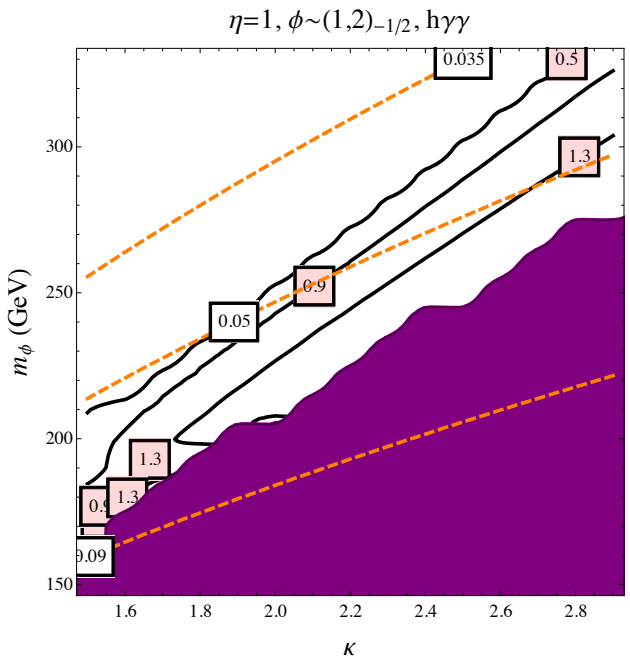
MIN deviation ~17%, probed at 3-sigma at LHC-14

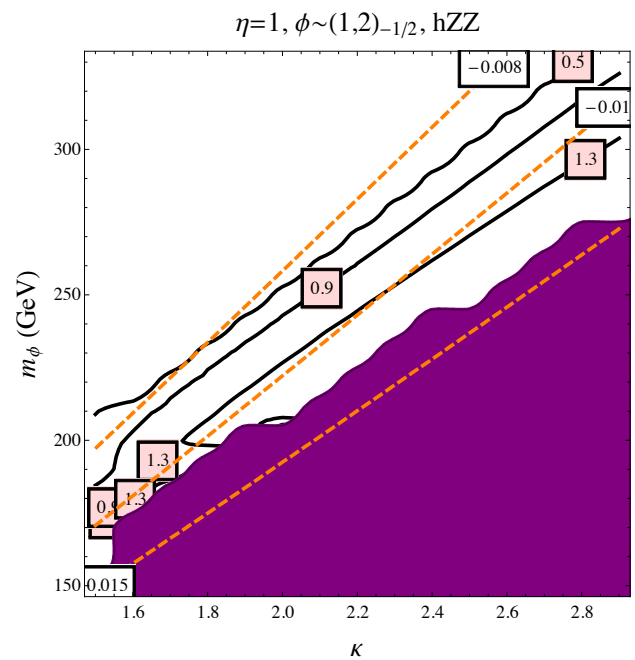
NOTE: The "RH stop" can decay to 2 jets or be "stealthy/ compressed" ➡ avoid direct searches!

Higgs and a Singlet

- Φ does not need to have SM gauge interactions to drive a first-order EWPT
- Obviously this scenario would not produce any deviation in hgg or $h\gamma\gamma$
- However, it does predict a (small) deviation in hZZ coupling [Craig, Englert, McCullough, 1305.5251]
- Consider $m_\Phi \gg v$, integrate it out ➡ a dim-6 operator: $\frac{\kappa^2}{16\pi^2}\frac{1}{m_\Phi^2}\left(\partial_\mu |H|^2\right)^2$
- After Higgs gets a vev: $\frac{\kappa^2}{16\pi^2}\frac{v^2}{m_\Phi^2}\left(\partial_\mu h\right)^2$
- Canonically normalized Higgs ➡ shift in hZZ coupling
- Effect is small, but hZZ coupling can be determined very precisely from Higgsstrahlung cross section: ~0.25% ILC, ~0.05% "TLEP" [Snowmass Higgs report]

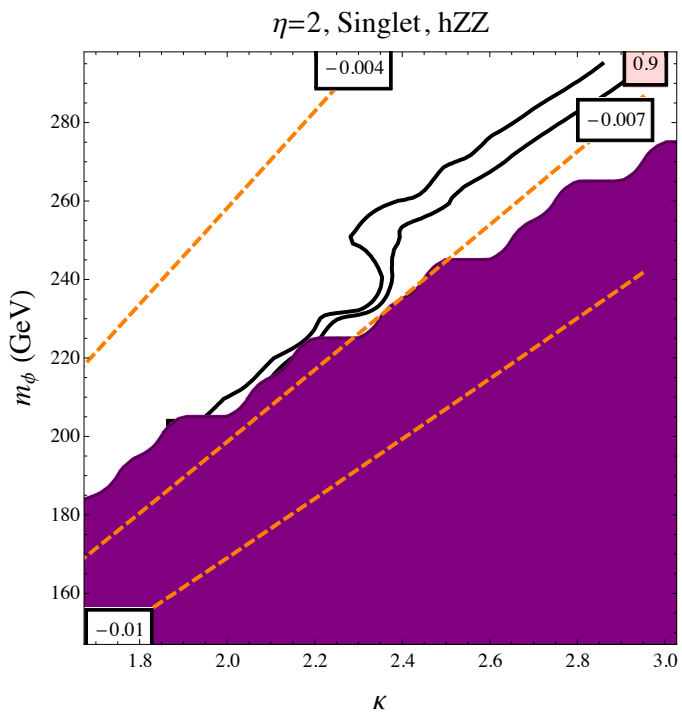
Results: "LH Stau"





hZZ: MIN deviation 0.8%, probed at 3-sigma at ILC

Results: Singlet



hZZ: MIN deviation 0.5%, probed at ~2-sigma at ILC, 10-sigma at "TLEP"

Conclusions: 2014 paper

- Strongly first-order EWPT, and with it Electroweak Baryogenesis, remains a viable possibility in a general BSM context
- We focused on the models where first-order EWPT is induced by loops of a BSM scalar, with various SM quantum numbers
- In the case of colored scalar, LHC-14 measurement of hgg will be able to conclusively probe the full parameter space with a 1-st order EWPT
- For non-colored scalars, e+e- Higgs factories will be necessary
- Higgs factory may be able to conclusively probe the full parameter space with 1-st order EWPT in all models, even if induced by a SM-singlet scalar