Higgs Couplings and Electroweak Phase Transition

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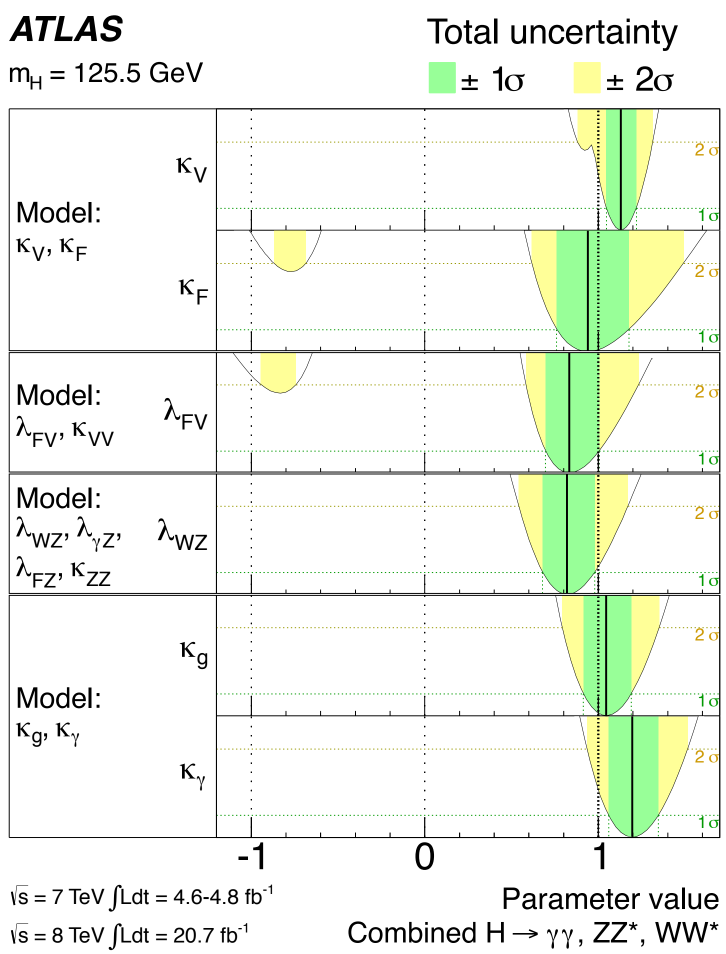
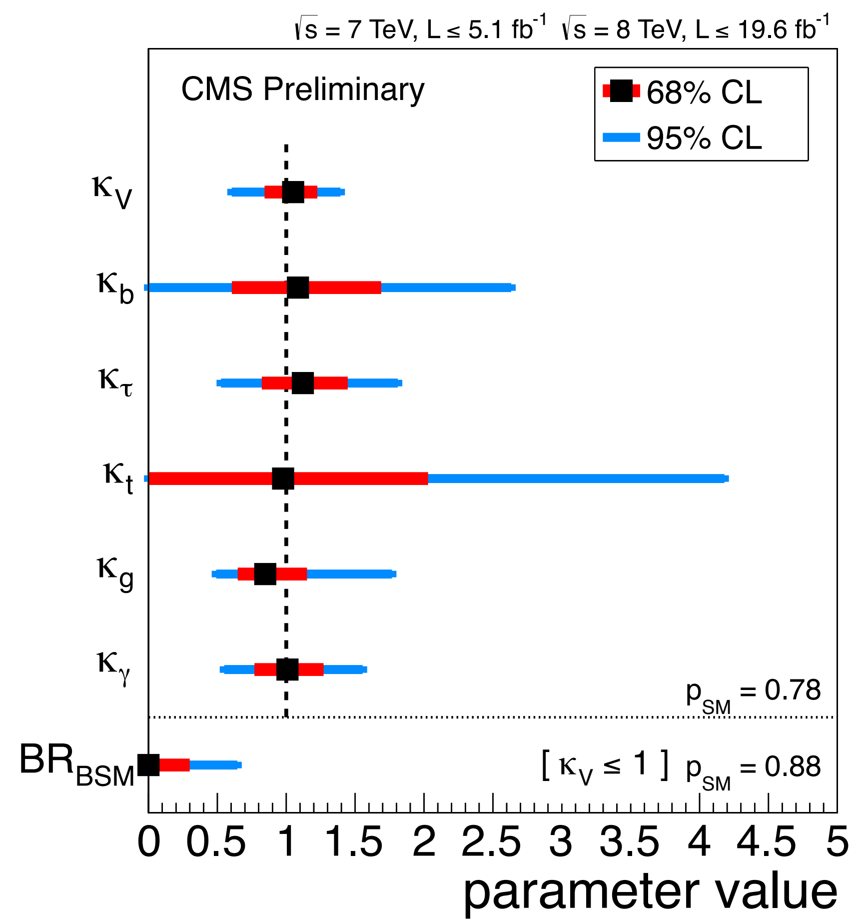
[Based on: Andrey Katz, MP, 1401.1827, JHEP]

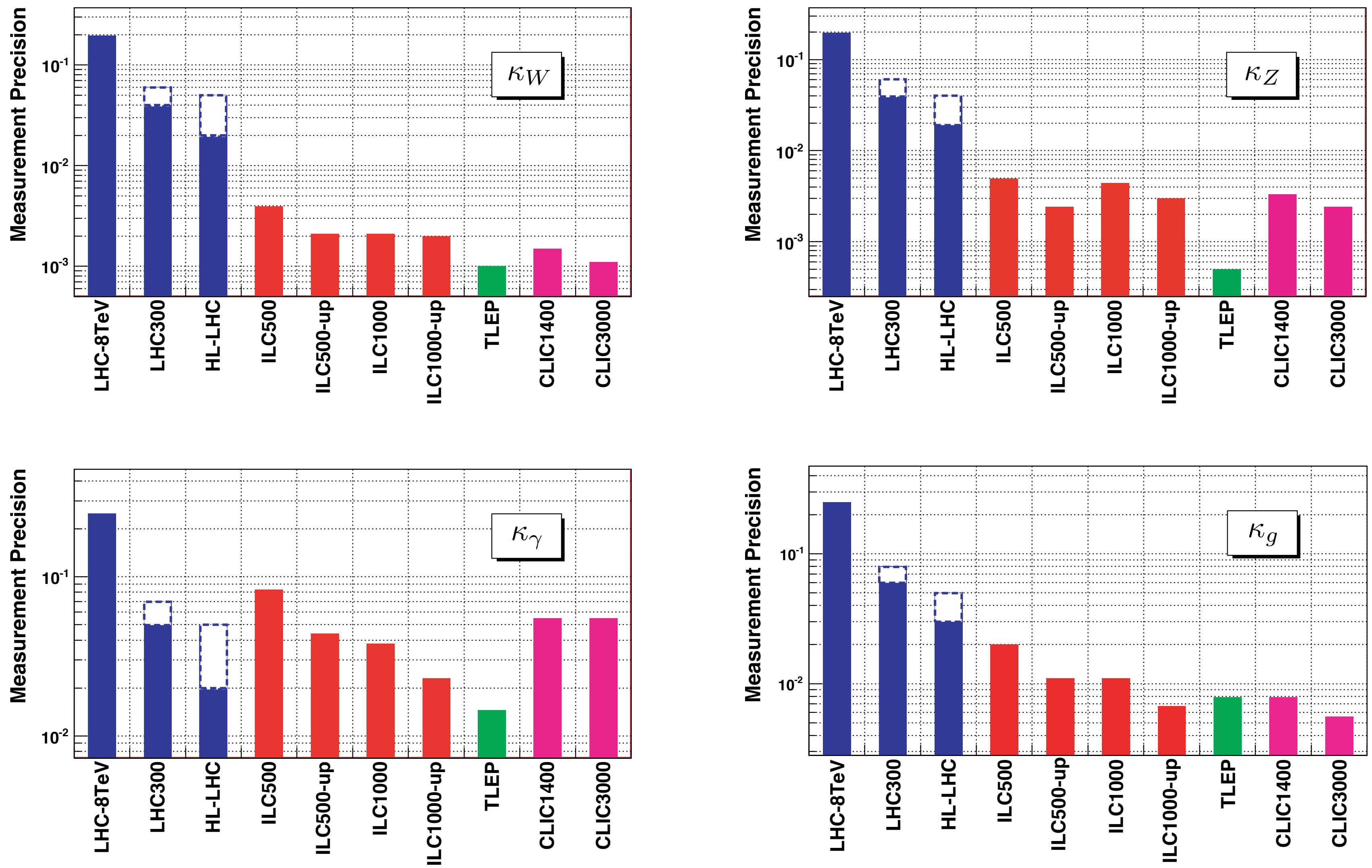
Higgs: Discovery to Precision





Current status: ~10-20% precision on some couplings (V, g, gamma)

Future: Higgs Precision Program



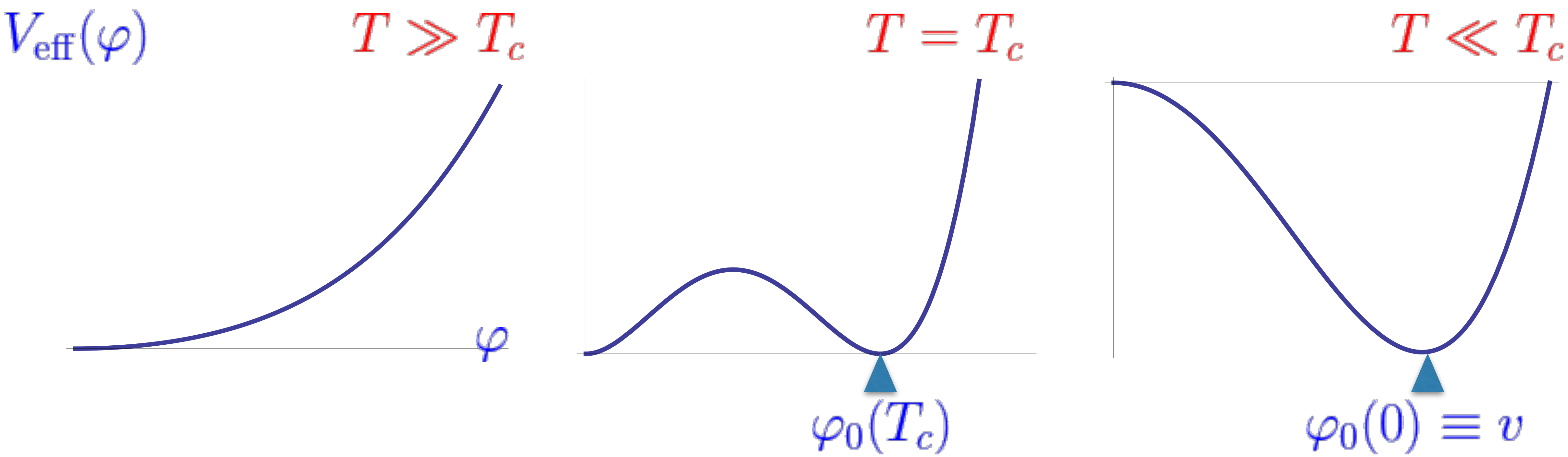
Snowmass Higgs Report

- 2-5% precision achievable at the HL-LHC
- 0.1% precision on V, 1% on g and gamma at e+e- Higgs factories
- At or almost at precision electroweak levels!

Electroweak Phase Transition

- At high temperatures (e.g. in the early Universe), electroweak symmetry is restored: $m^2_{\text{eff}} = -m^2 + cT^2 > 0$ ➡ $\langle \varphi \rangle = 0$
- Electroweak Phase Transition into the current broken-EW phase occurred about 10^{-10} sec after the Big Bang ($T \sim 100$ GeV)
- Baryon asymmetry may have been produced during this phase transition - "electroweak baryogenesis"
- A strongly first-order transition is required for successful EWBG
- In the SM, transition is second order; BSM physics at the weak scale can modify dynamics, inducing a 1st order transition

First-Order EWPT in Cartoons



- "Transition strength" ~ entropy release $\xi = \varphi_0(T_c)/T_c$
- Numerical studies: EW Baryogenesis possible if $\xi \geq 0.9$
- Otherwise, sphelaron washout of the baryon number

HC and EWPT

- No possibility of producing "plasma" with restored EW symmetry (T-RHIC?) so no direct experimental probe
- However, hard to induce large modifications of the finite-T potential without also modifying T=0 Higgs potential and couplings
- Can precise measurements of Higgs couplings conclusively probe the nature of EWPT?
- Two basic mechanisms for first-order EWPT: tree-level mixing with other scalars; and loop-induced corrections (the famous Th^3 term)
- We focused on loop-y models since they seem harder to probe*

[* a study of tree-y models is now in progress…]

HC and EWPT: Setup

- The cubic term at high-T is induced by loops of scalars, not fermions

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

- One-loop corrections to the potential at both T=0 and finite-T are well known:

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

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

- The key object is the Higgs-dependent Φ mass! But recall:

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

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

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

- 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:

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

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

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

- 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: $R_g = \frac{1}{8} \frac{\kappa v^2}{m_0^2 + \frac{\kappa v^2}{2}} \approx 25\%$

Numerical Studies

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

- Numerical code also includes SM contributions, "daisy resummations" etc.

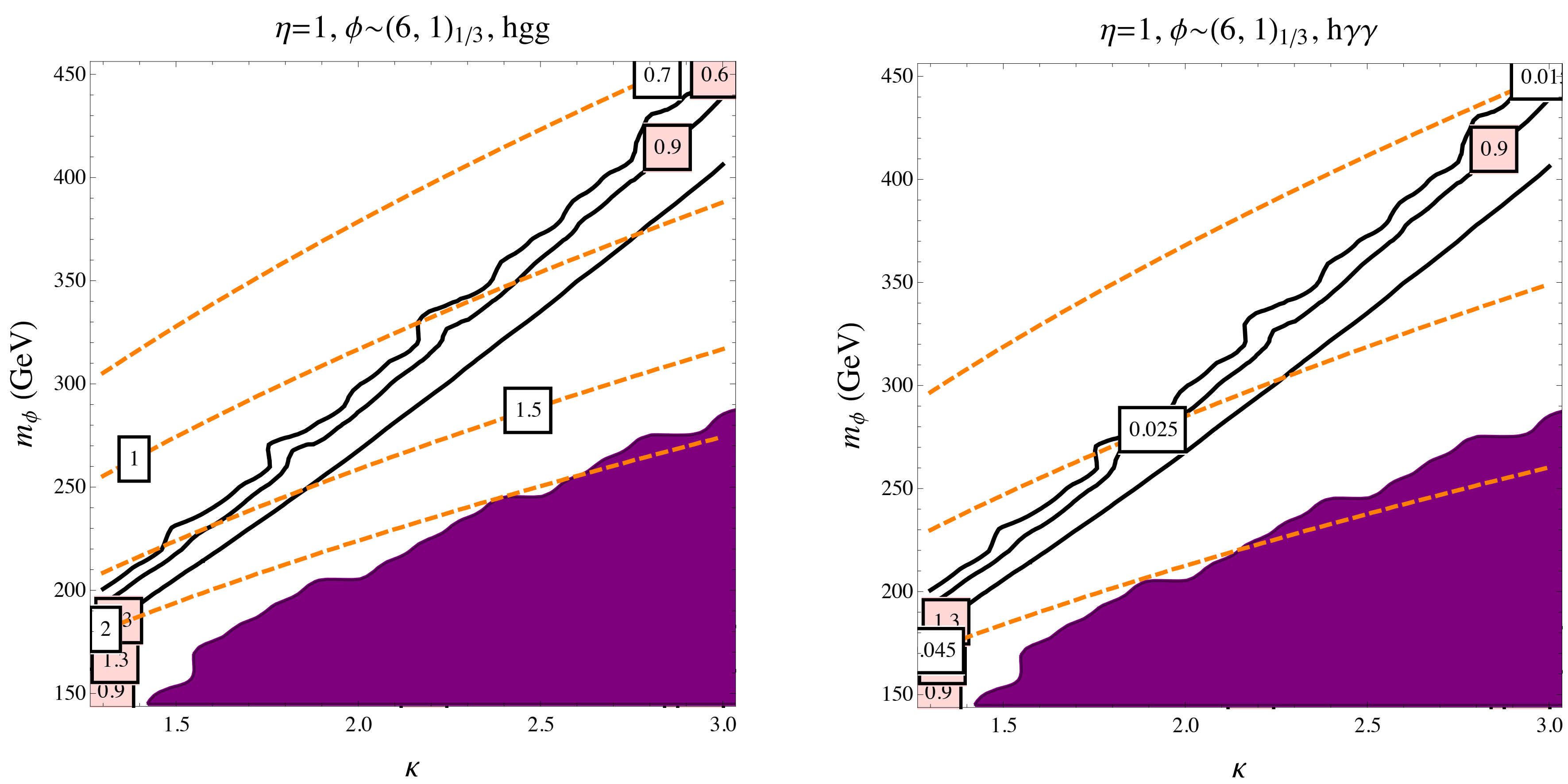
- Analyzed a few toy models, representative of the range of possibilities for quantum numbers of the Φ field

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"

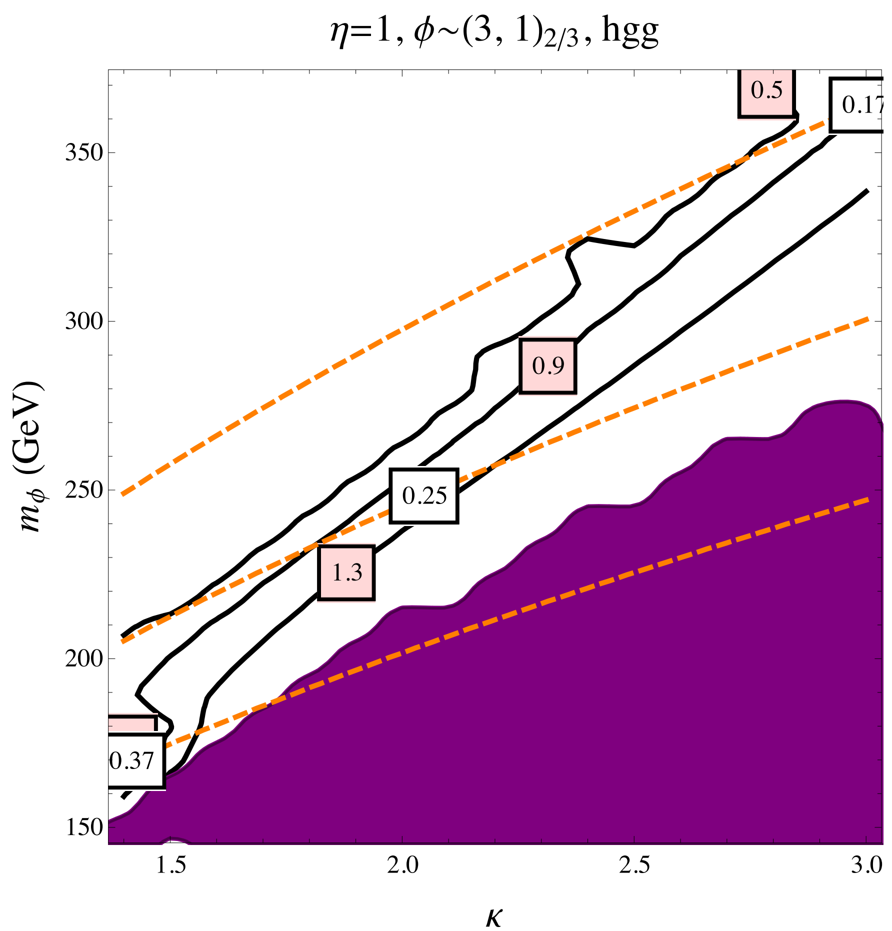


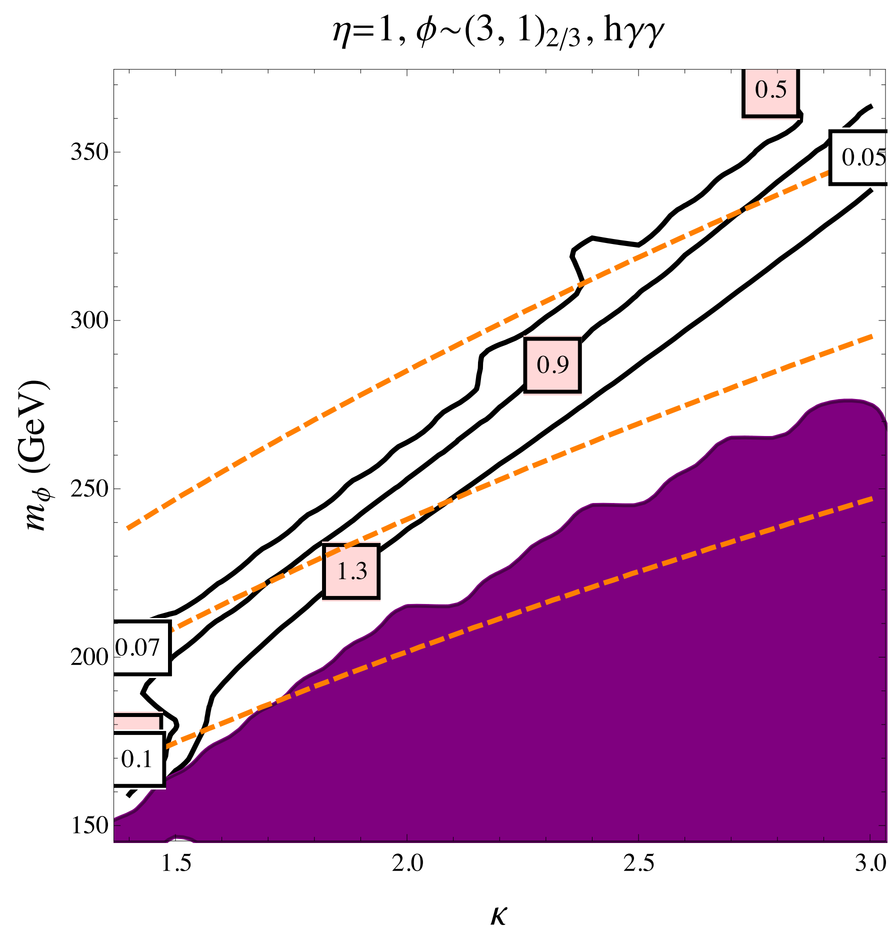
ATLAS: $R_g = 1.08 \pm 0.14,$ $R_\gamma = 1.23^{+0.16}_{-0.13}.$ → ruled out!*

[* usual caveat: SM total width assumed]

NOTE: Our sextet can decay to 4 jets → no direct search!

Results: "RH Stop"





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

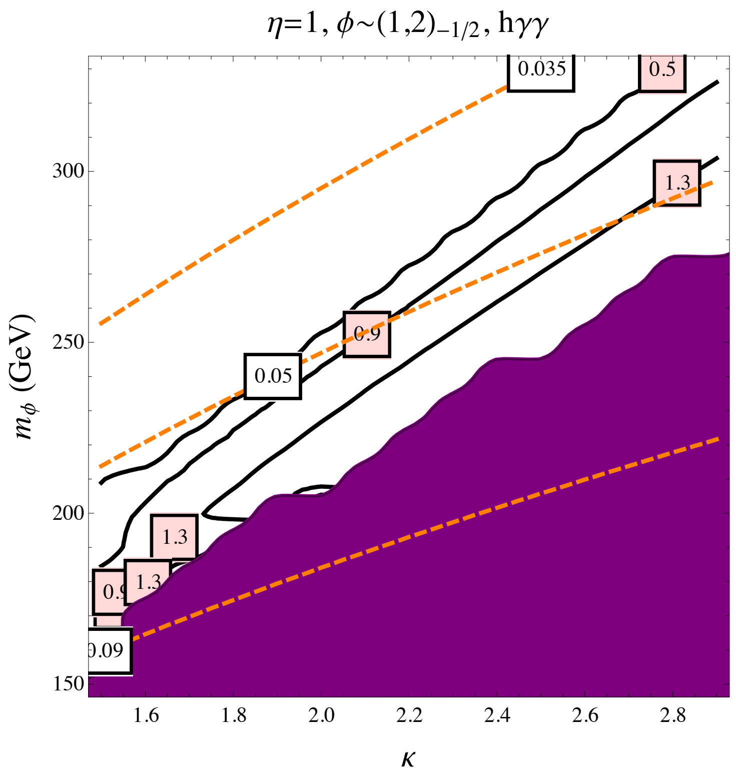
MIN deviation ~17%, probed at 3-sigma at LHC-14

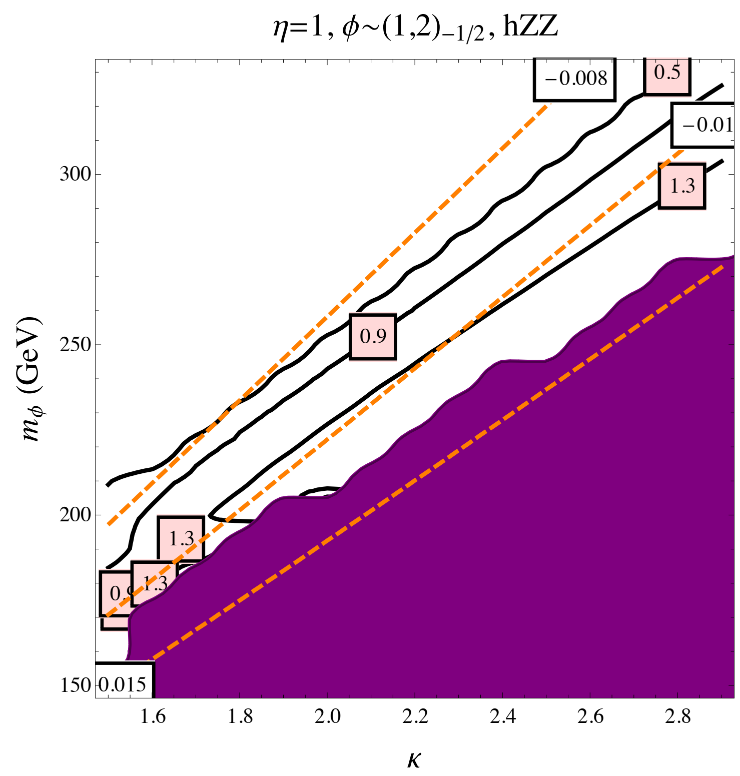
NOTE: The "RH stop" can decay to 2 jets or be "stealthy/compressed" → avoid direct searches!

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]

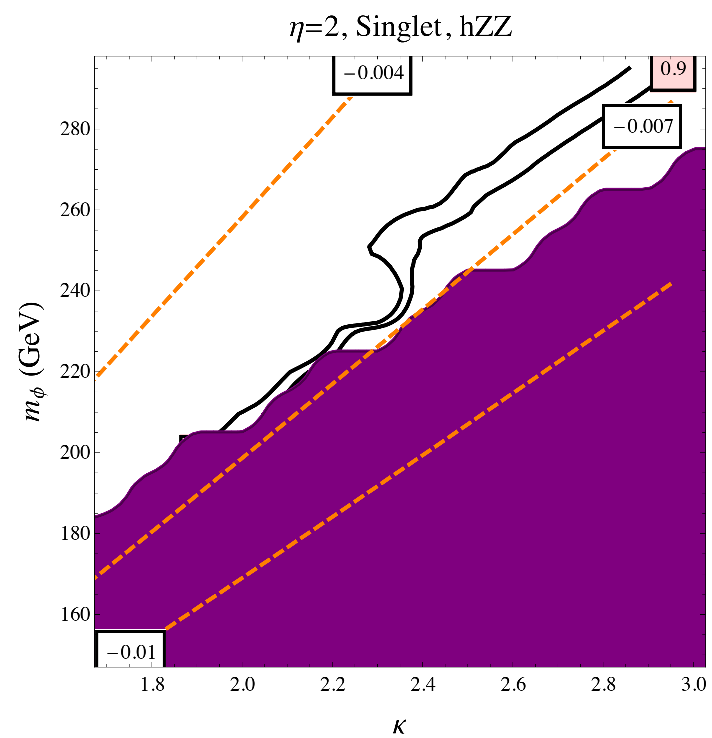
Results: "LH Stau"

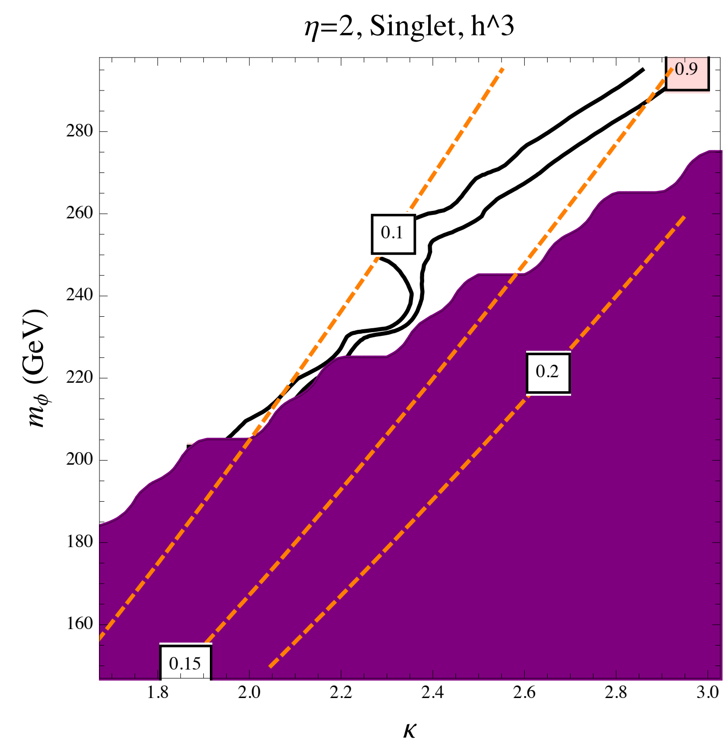




hZZ: MIN deviation 0.8%, probed at 3-sigma at ILC

Results: Singlet

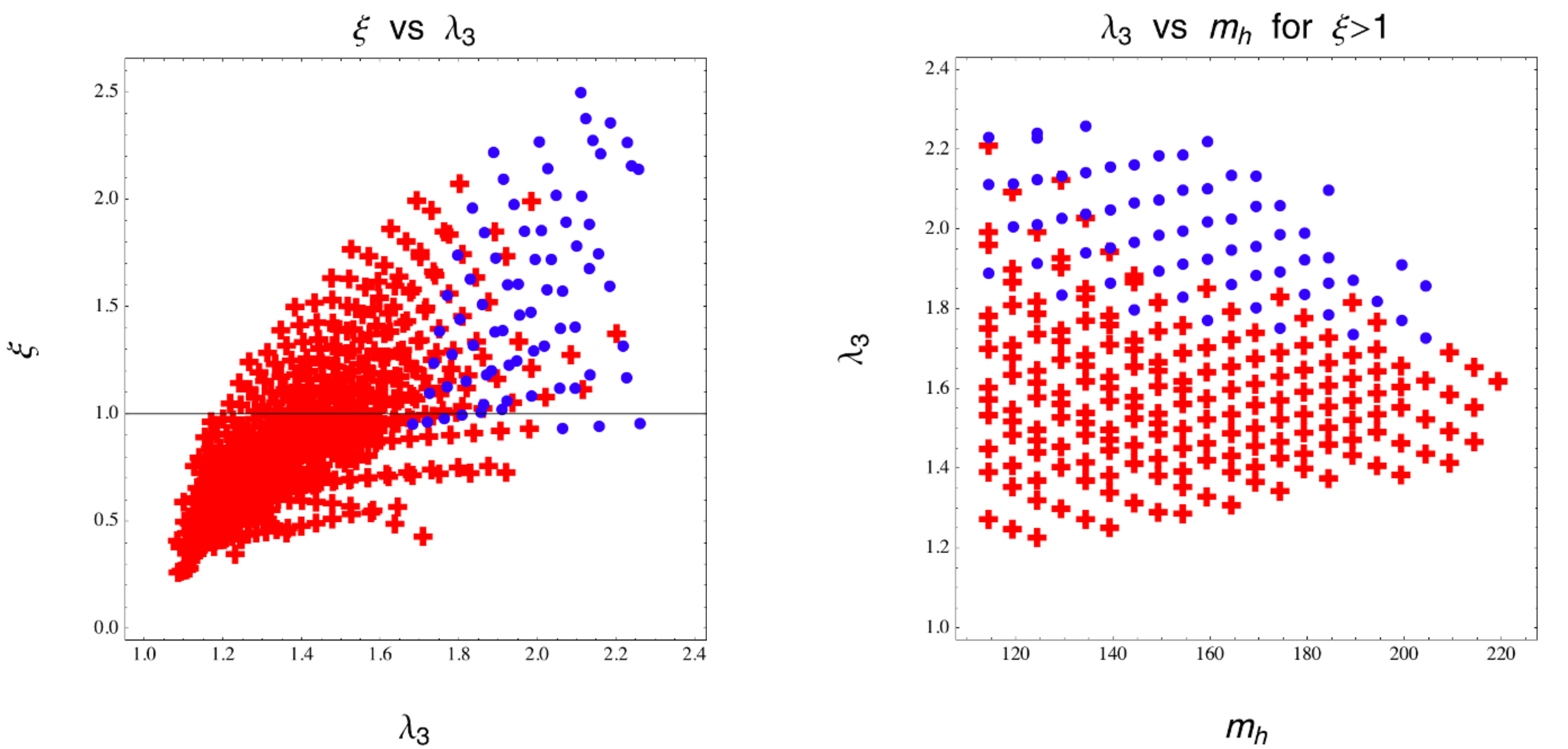




hZZ: MIN deviation 0.5%, probed at ~2-sigma at ILC, 10-sigma at "TLEP"

Higgs Self-Coupling

[Noble, MP, 0711.3018]



same correlation for Higgs self-coupling: deviations of 20% or more in a broad range of models with first-order EWPT

Measure it at the ILC-1TeV? a 100 TeV collider?

Conclusions: EWPT

- 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