Title: The Higgs Self-Coupling as a Probe of the Electroweak Phase Transition

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Abstract: We argue that, within a broad class of extensions of the Standard Model, there is a tight corellation between the dynamics of the electroweak phase transition and the cubic self-coupling of the Higgs boson: Models which exhibit a strong first-order electroweak phase transition predict a large deviation of the Higgs self-coupling from the Standard Model prediction, as long as no accidental cancellations occur. Order-one deviations are typical. This shift would be observable at the Large Hadron Collider if the proposed luminosity or energy upgrades are realized, as well as at a future electron-positron collider such as the proposed International Linear Collider. These measurements would provide a laboratory test of the dynamics of the electroweak phase transition.

The Higgs Cubic and The Viability of Electroweak Baryogenesis

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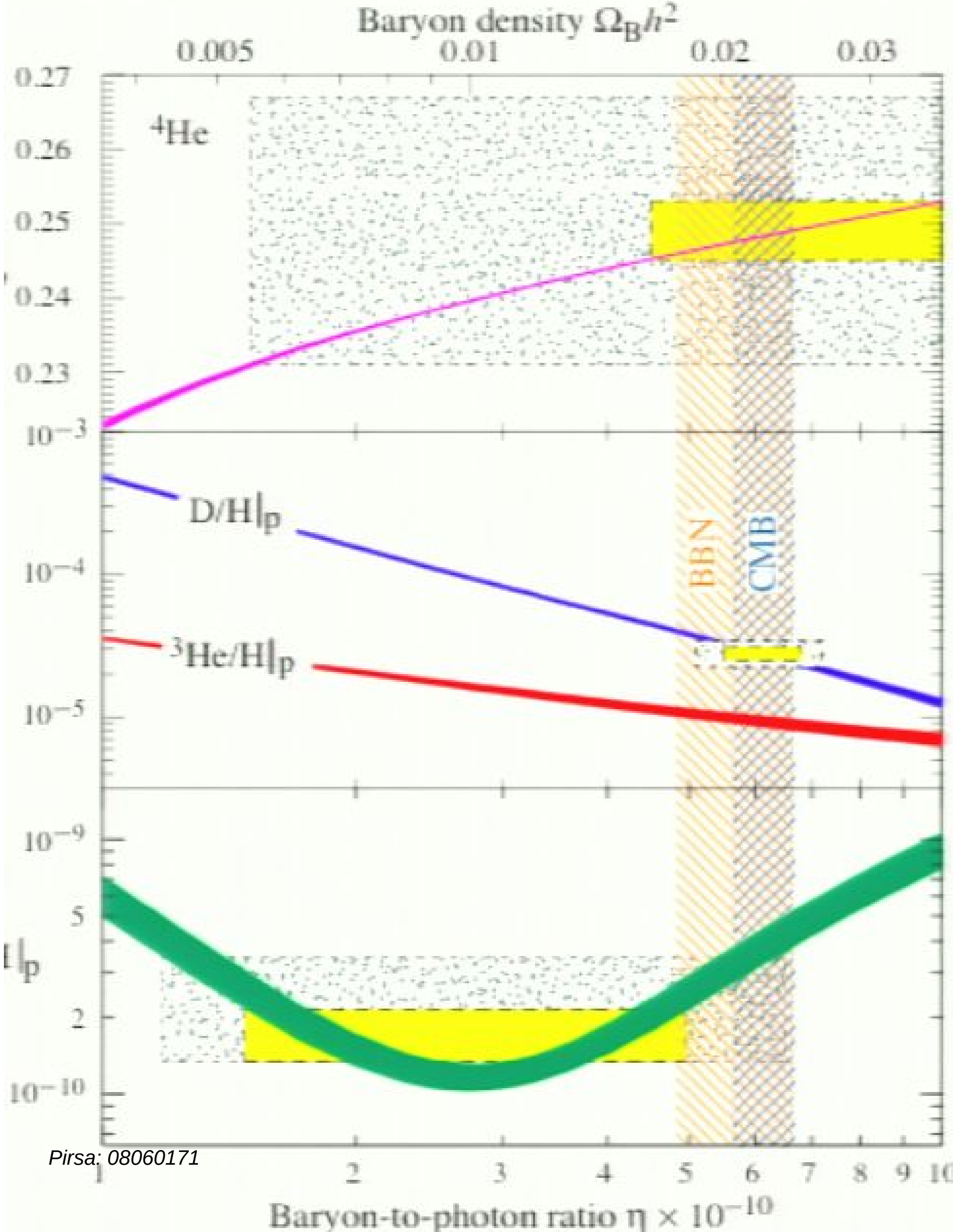
with Maxim Perelstein
hep-ph/0711.3018

Cornell University
Laboratory for Elementary-Particle Physics

After sifting through the astrophysical evidence . . .

A Precise Target

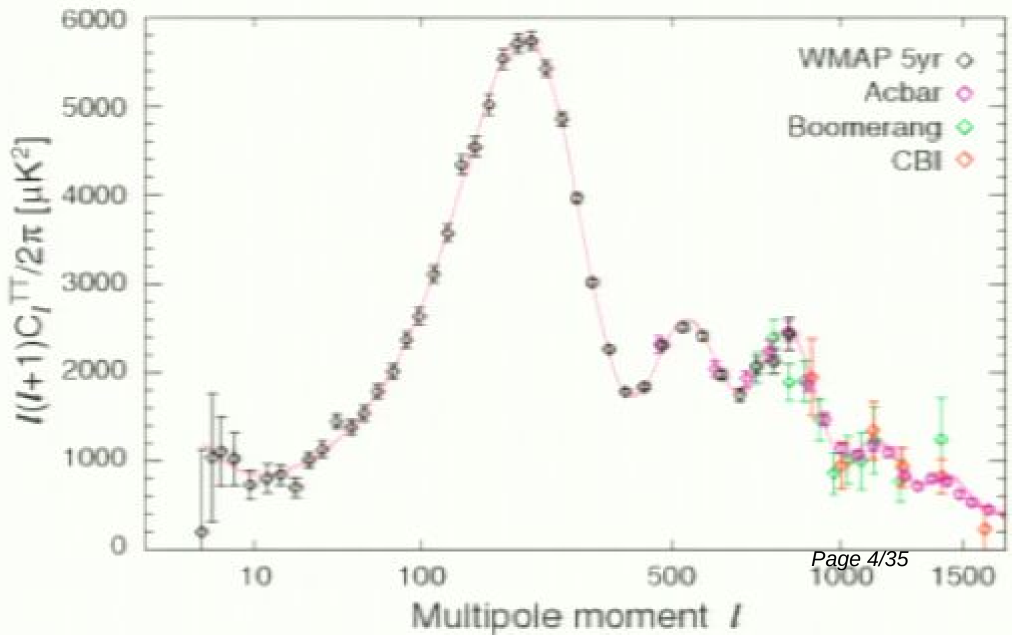


$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

$$= (273.9 \times 10^{-10})\Omega_B h^2$$

$$5.9 < \eta \times 10^{10} < 6.4$$

(Simha and Steigman 2008)



Many Creative Ideas

- Planck Scale Baryogenesis
- GUT Baryogenesis
- Leptogenesis
- Affleck-Dine Baryogenesis
- Electroweak Baryogenesis (EWBG)

Many nice reviews: Cohen, Kaplan, Nelson 1993
Trodden 1998, Riotto and Trodden 1999
Dine and Kusenko 2003

Sakharov's Criteria

Nobel Peace Prize 1975

A successful mechanism for Baryogenesis must include:

- Violation of B.
- Violation of C and CP.
- Nonequilibrium dynamics.

Nonequilibrium Dynamics

One possibility: A First Order Phase Transition (FOPT) in the breaking of the electroweak symmetry,

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

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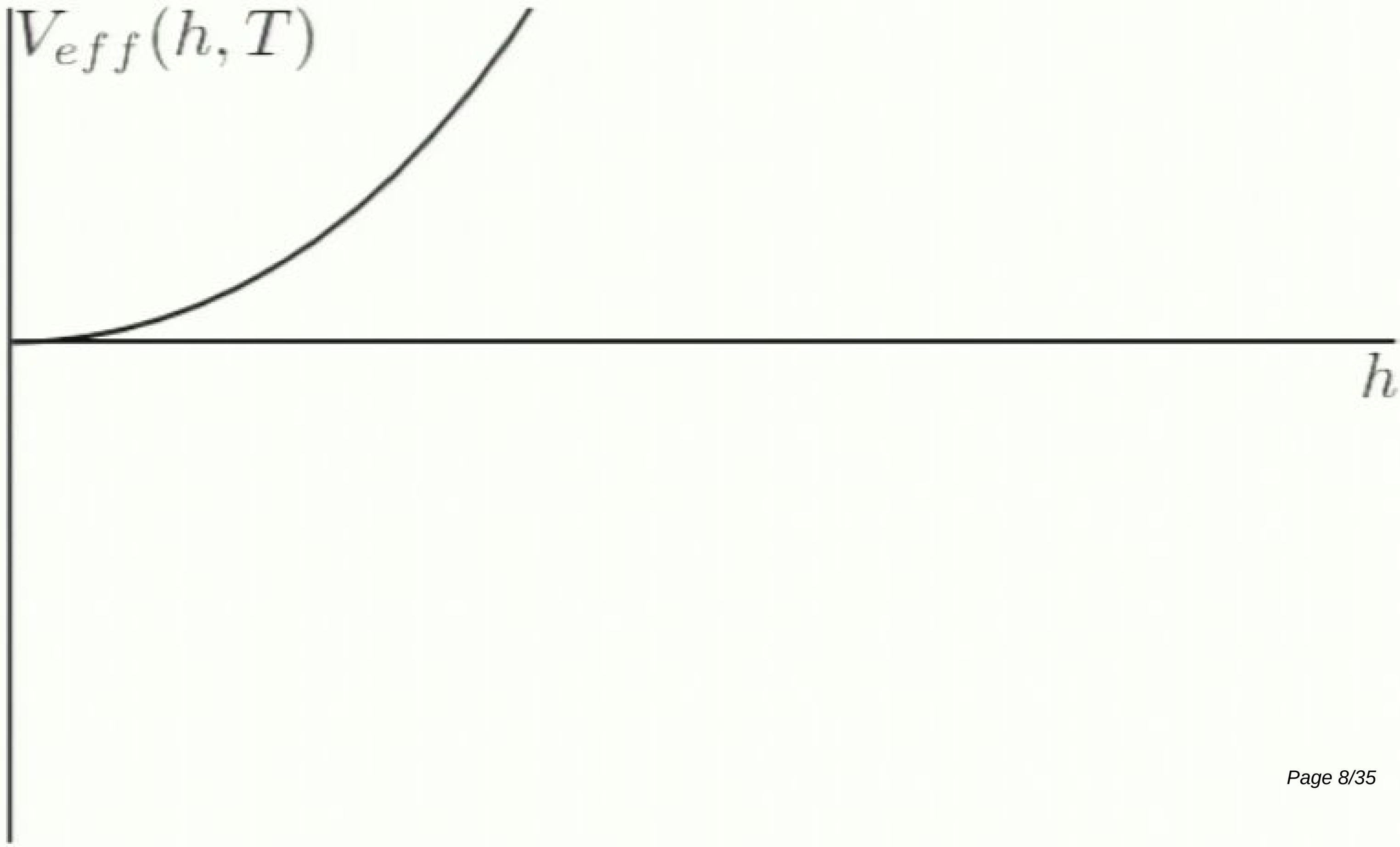
Second Order Transition:



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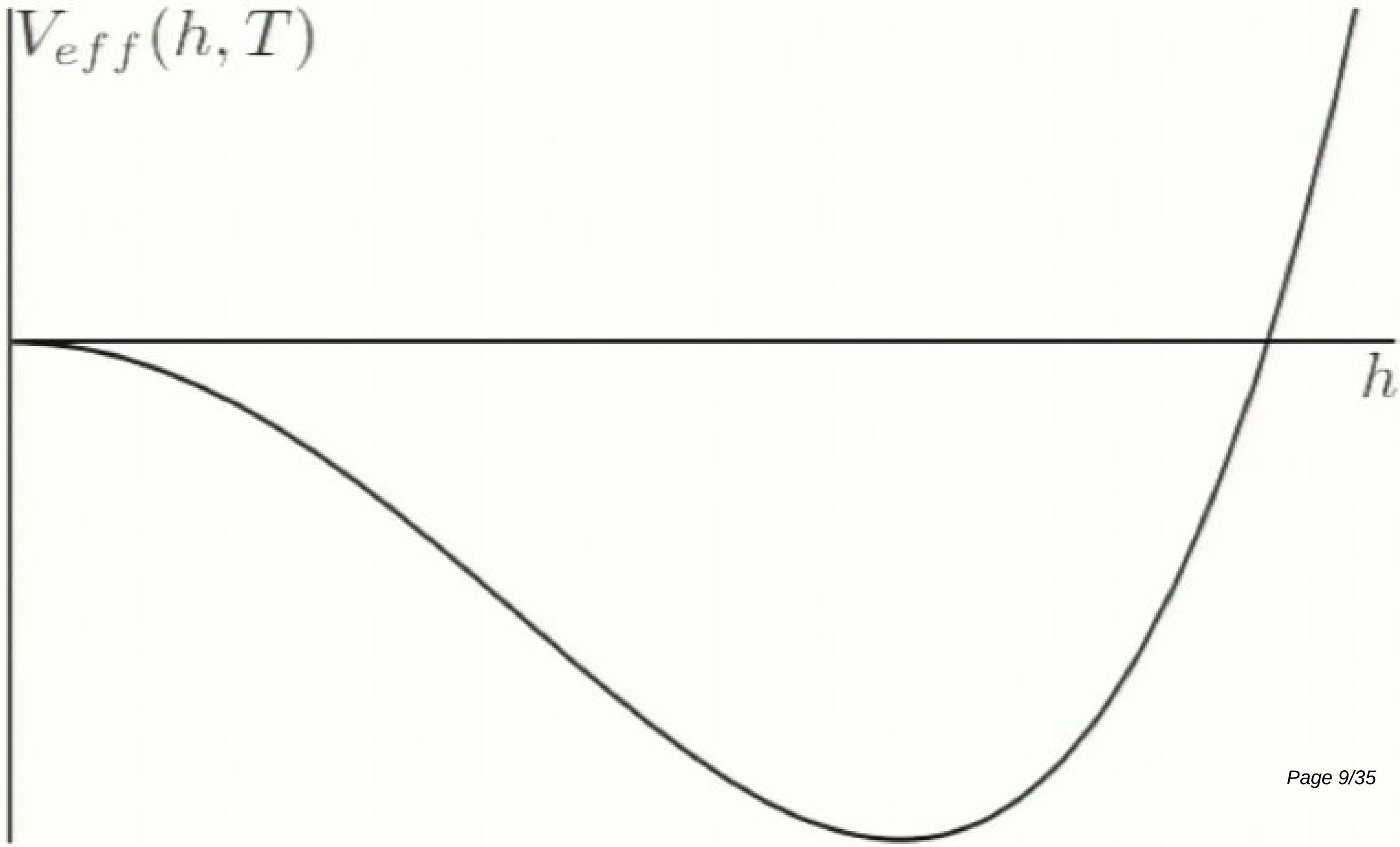

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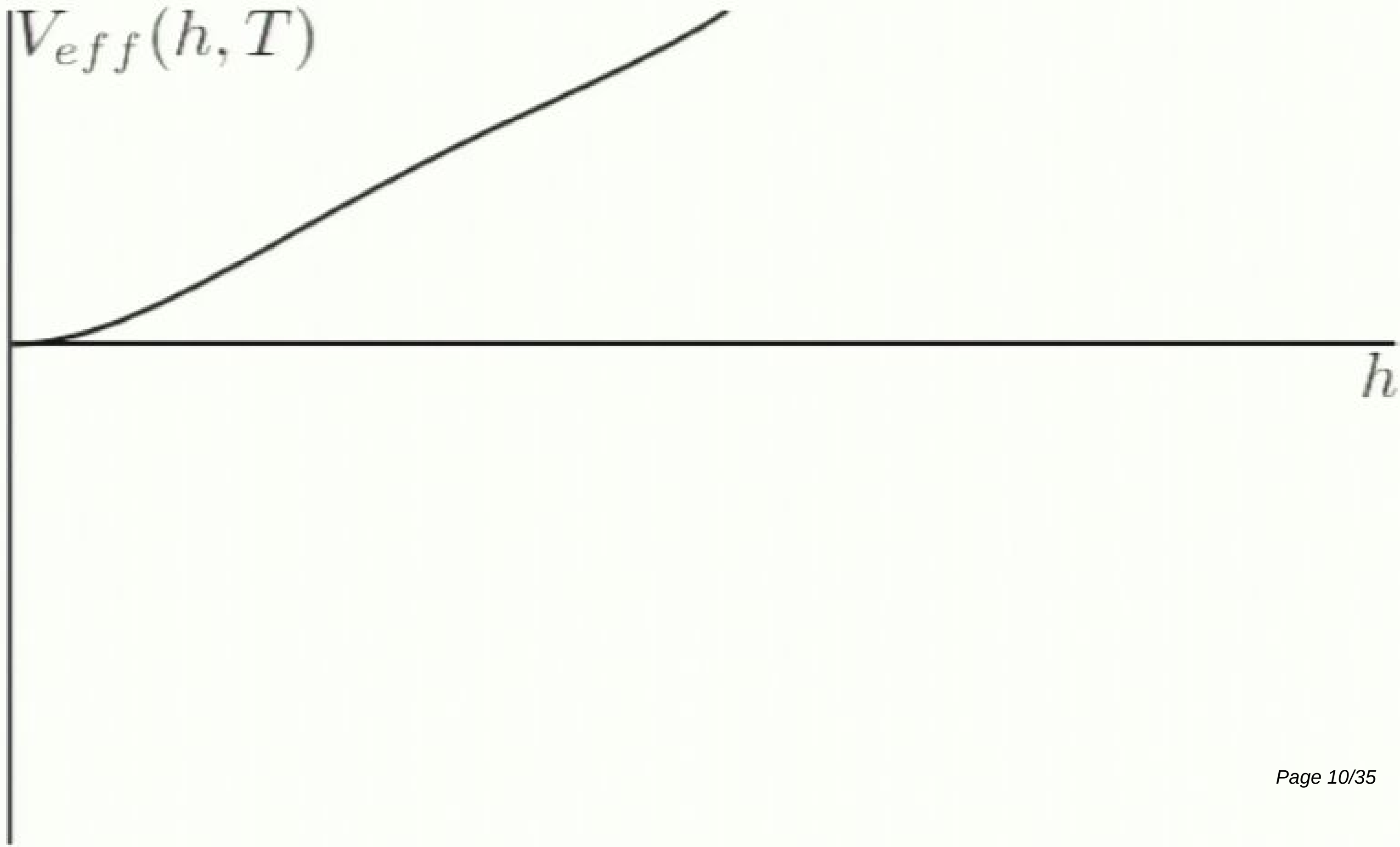

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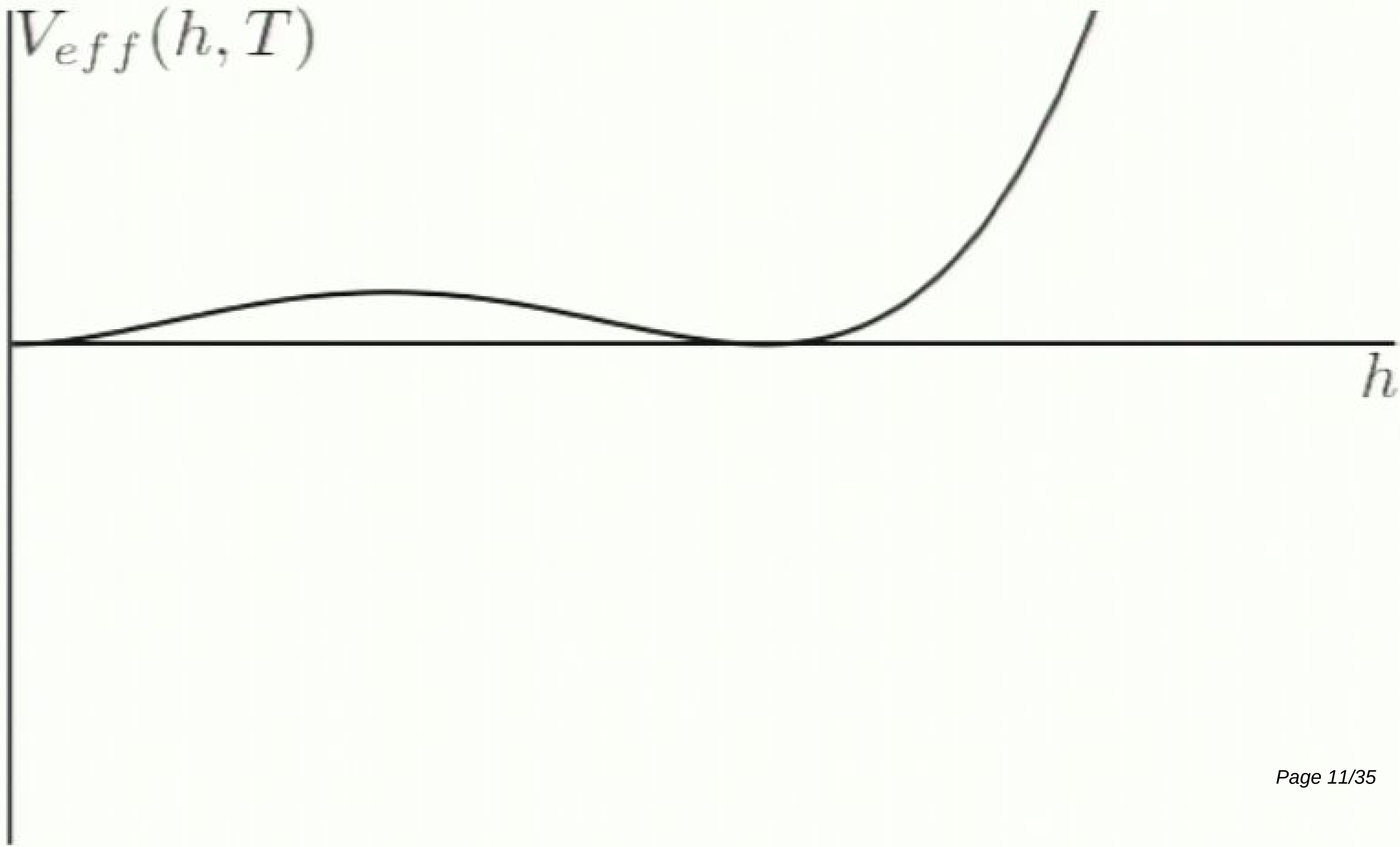

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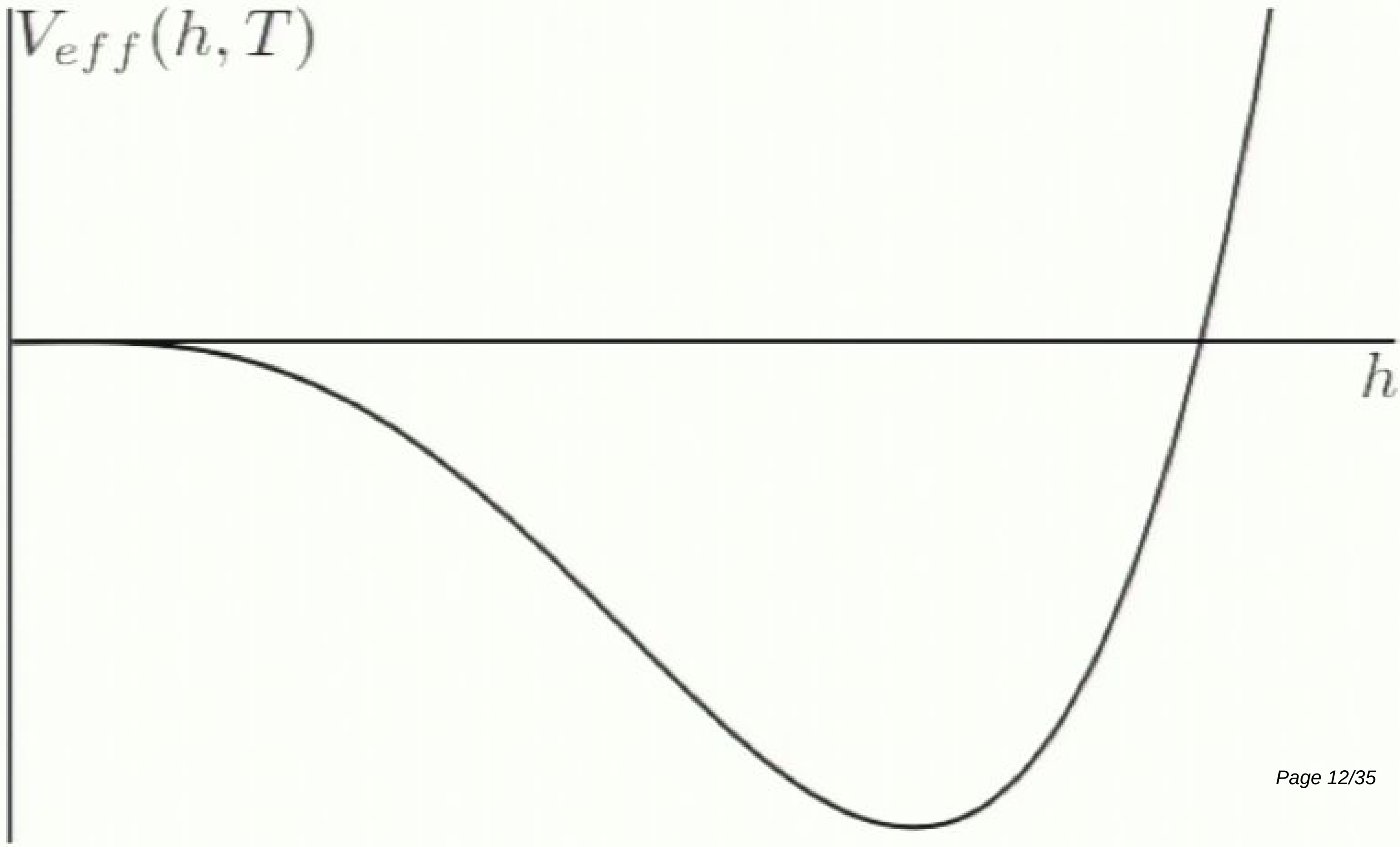
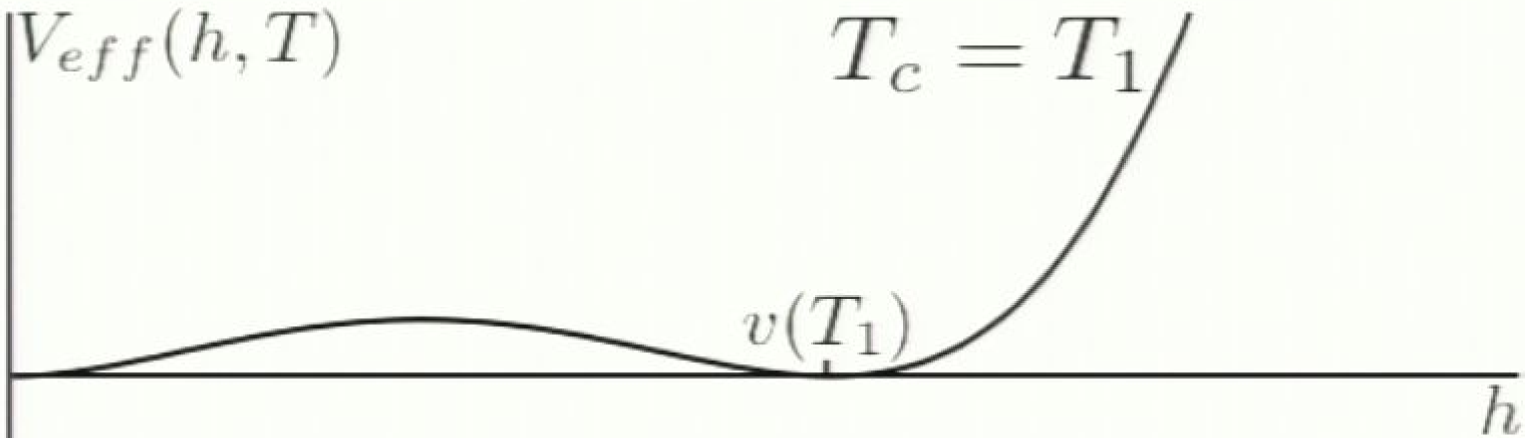


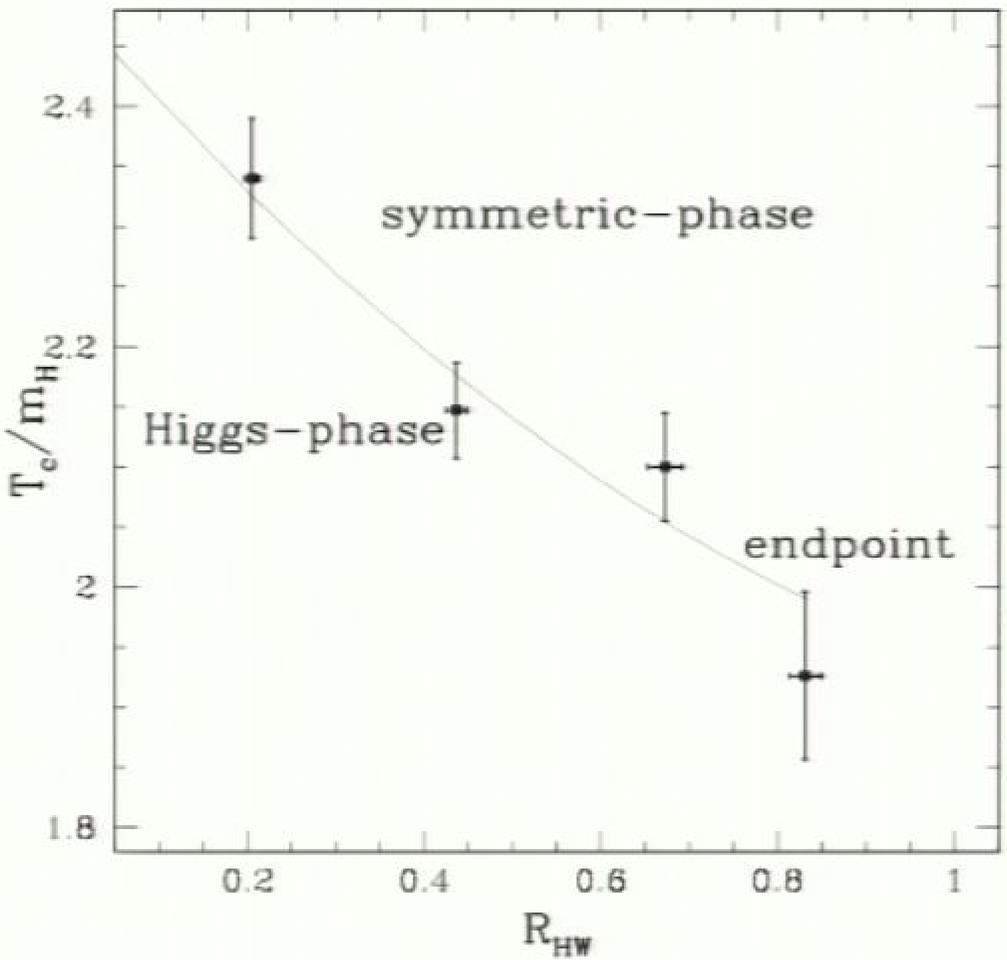
A "Strong FOPT"



$$E_{sp}(T_1) \sim \frac{2m_w(T_1)}{\alpha_w} = \frac{4\pi}{g} v(T_1) \gg T$$

$$\Rightarrow \boxed{\xi \equiv \frac{v(T_1)}{T_1} \gtrsim 1}$$

SM Higgs Phase Diagram



(Csikor, Fodor, Heitker 1999)

The transition is second order (a cross over) for $m_h > 114\text{GeV}.$

FOPT Phenomenology

- Realistic mechanisms of electroweak symmetry breaking modify the ad hoc SM higgs potential. The enlarged parameter space may allow for a strong FOPT.
- A precision measurement of the full TeV Lagrangian (masses, couplings, mixings, etc.) would allow us to calculate the order of the phase transition.
- Lacking that, how much can we determine from the least data?

  -Astrophysics: Gravitational relics of a FOPT may be accessible to LISA. (Grojean and Servant, 2006)

  -Collider Physics: Search for simple observables correlated to the order of the phase transition.

The Higgs Cubic Coupling

$$\lambda_3 \equiv \frac{1}{6} \frac{d^3 V_{\rm eff}}{dh^3}\bigg|_{h=v}$$

$$\left(\text{e.g.} \quad \lambda_{3,SM}^{tree} = \frac{m_h^2}{2v}\right)$$

Our claim:

The higgs cubic provides a model-independent collider probe of the viability of EWBG. Models possessing a strong FOPT exhibit large (typically 20-100%) deviations of the Higgs cubic coupling from its SM value.

Previous Studies

- Low-cutoff models:
  Grojean, Servant, Wells, 2005

- Two-Higgs doublet models:
  Ham, Oh, 2005
  Kanemura, Okada, Senaha, 2005

Our Claim: The correlation of a strong FOPT with large deviations in the Higgs cubic coupling is *generic* for a large class of BSM physics models.

Our Evidence

We demonstrate the correlation between ξ and λ_3 by analyzing a series of toy models that can be matched onto a broad range of realistic BSM Higgs scenarios with weakly coupled physics at the TeV scale.

- Toy Model I:
  Loop Modified, Unmixed Higgs.

- Toy Model II:
  Tree-Level Modified, Unmixed Higgs.

- Toy Model III:
  Tree-Level Modified, Mixed Higgs.

I: Loop Modified, Unmixed h

Add a single BSM real scalar field

$$\Delta V_{SM} = \frac{1}{2} M_{0,S}^2 S^2 + a|H|^2 S^2 + \frac{b_4}{4} S^4$$

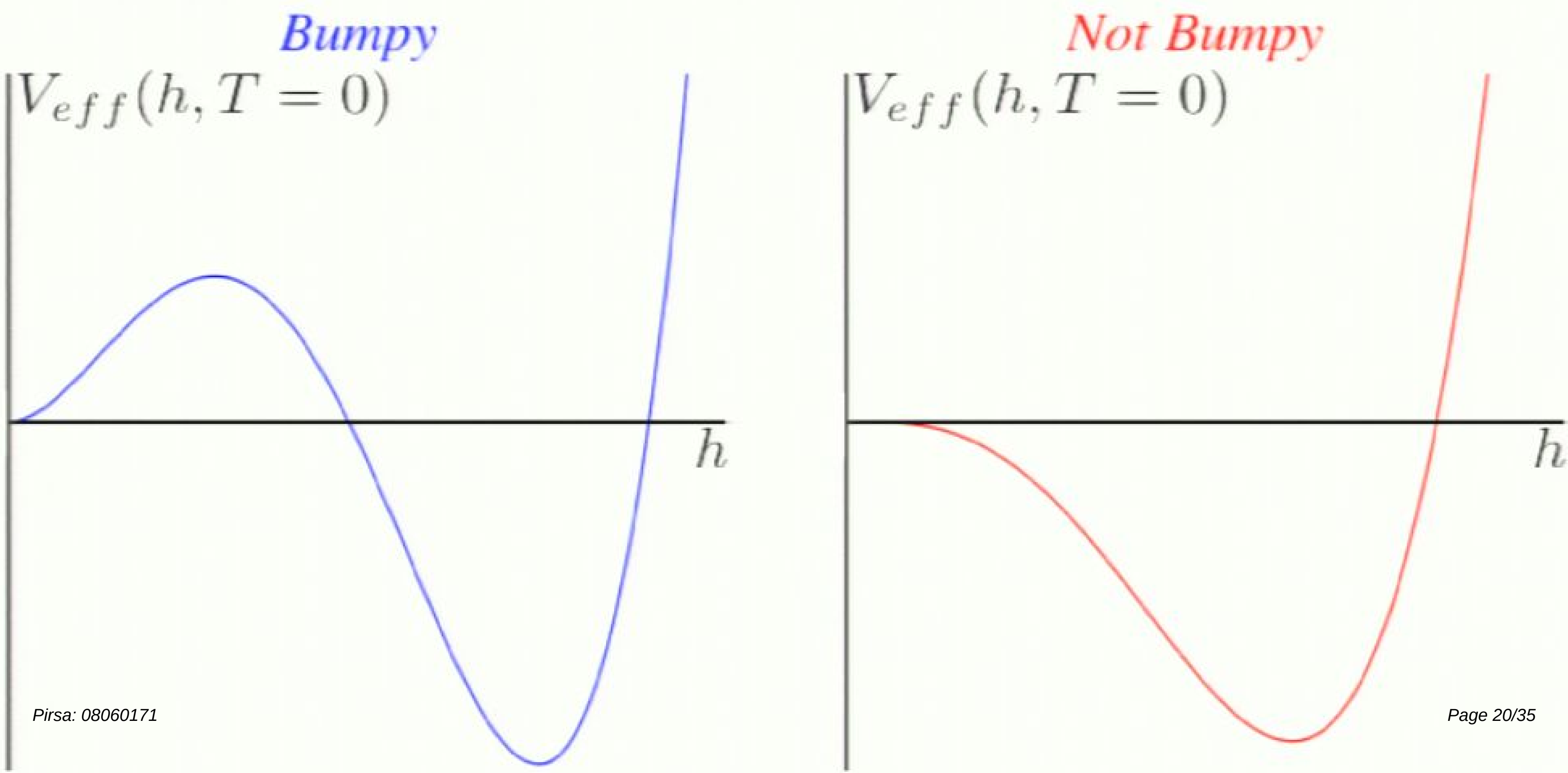
$$\Downarrow$$

$$\Delta V_{eff}(h, T=0) = \frac{1}{64\pi^2} m_S^4(h) \log \frac{m_S^2(h)}{m_S^2(v)} + \cdots$$

- $M_{0,S}^2 > 0$ ensures $\langle S \rangle = 0$.
- Most general interaction after imposing a symmetry $S \to -S$ to prevent mixing.

'Bumpy' Higgs Potentials

BSM couplings may induce a 'bump' in the zero temperature potential. This bump generally persists at finite temperature, allowing for a strong EWPT.



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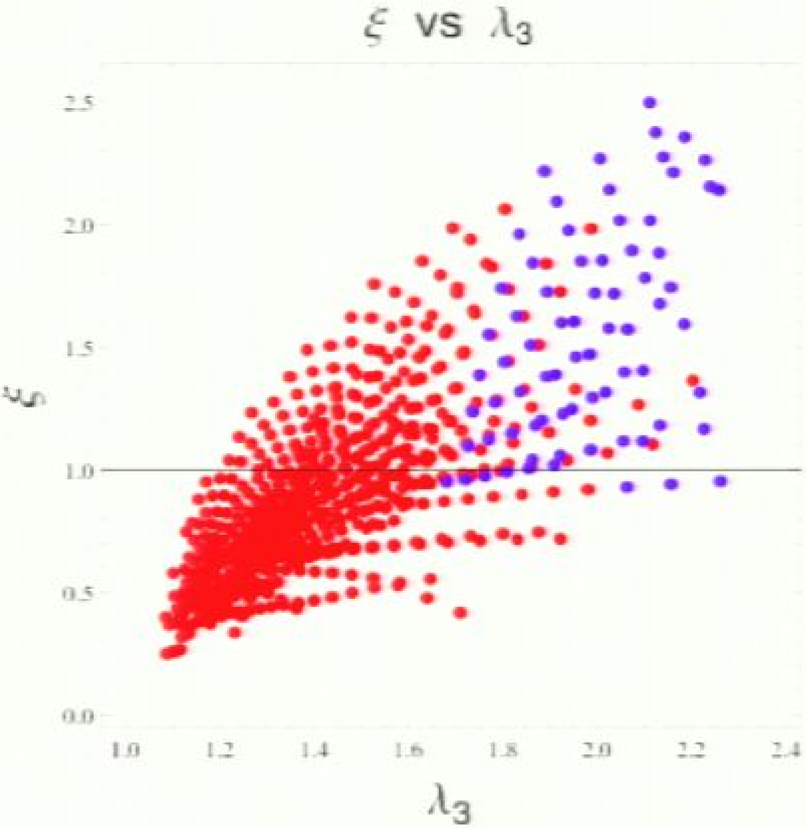

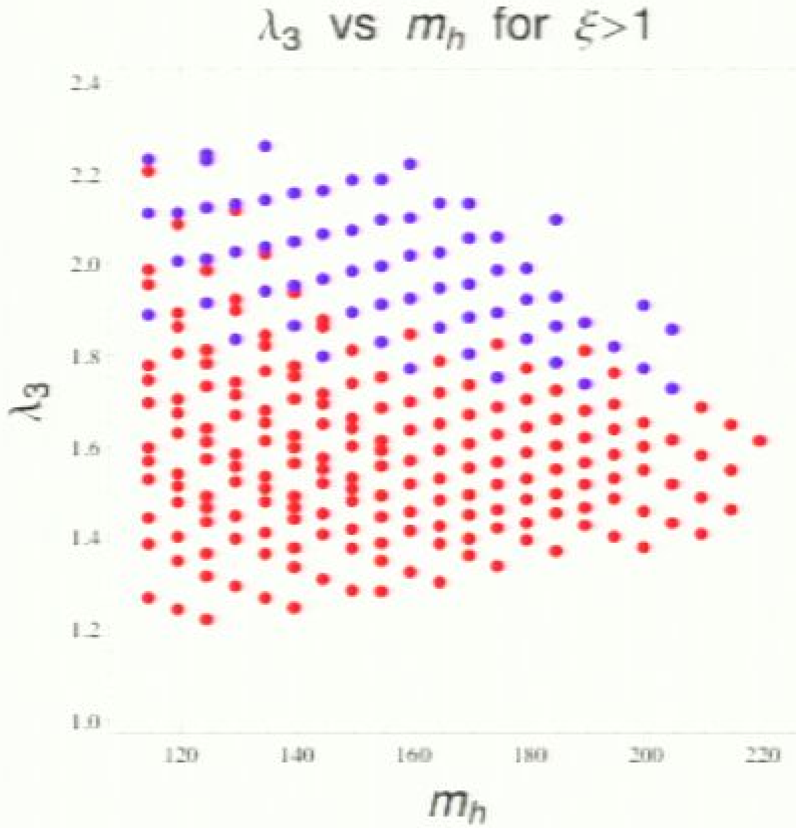

Blue = Bumpy at T=0

pt. Prospects:

-30% for 160-180GeV Higgs at the SLHC (Djouadi, et. al., 2007)

% for a <140GeV Higgs at a 500GeV ILC (Baur, et. al., 2002)

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Multiple BSM scalars.

- The same conclusions apply to models with N real (or N/2 complex) identical scalars by a simple scaling argument.

- We checked that the pattern continues to hold for 2 non-identical scalars. A conjecture that it holds for N independent scalars seems reasonable.

- The one-loop analysis is independent of the scalars' gauge charges. They could be stops in the MSSM decoupling limit (one unmixed Higgs), a weak triplet in Little Higgs models, etc.

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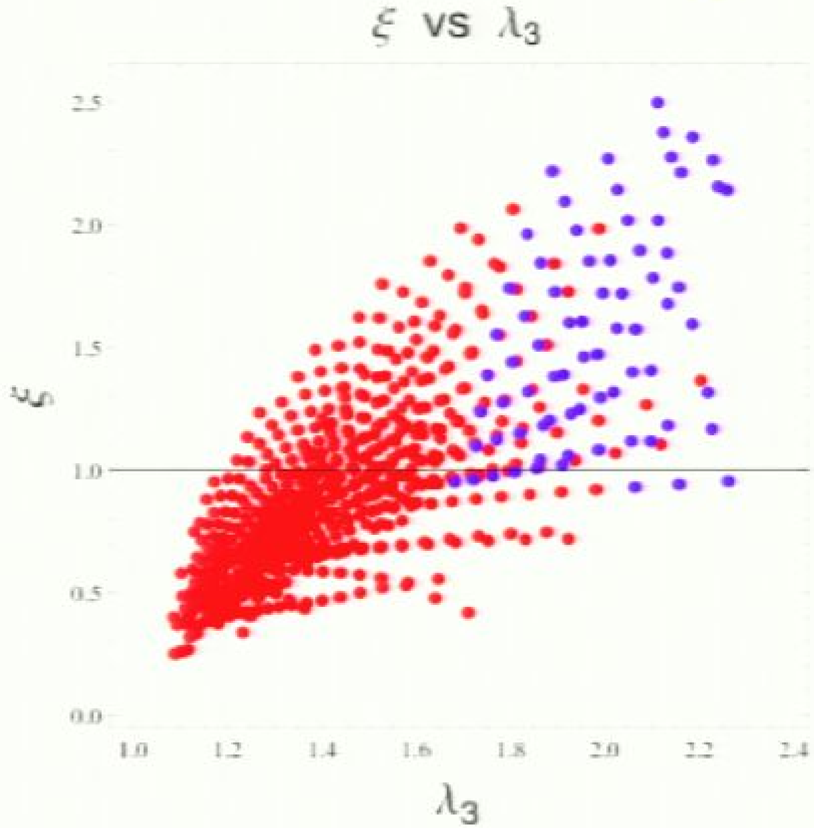

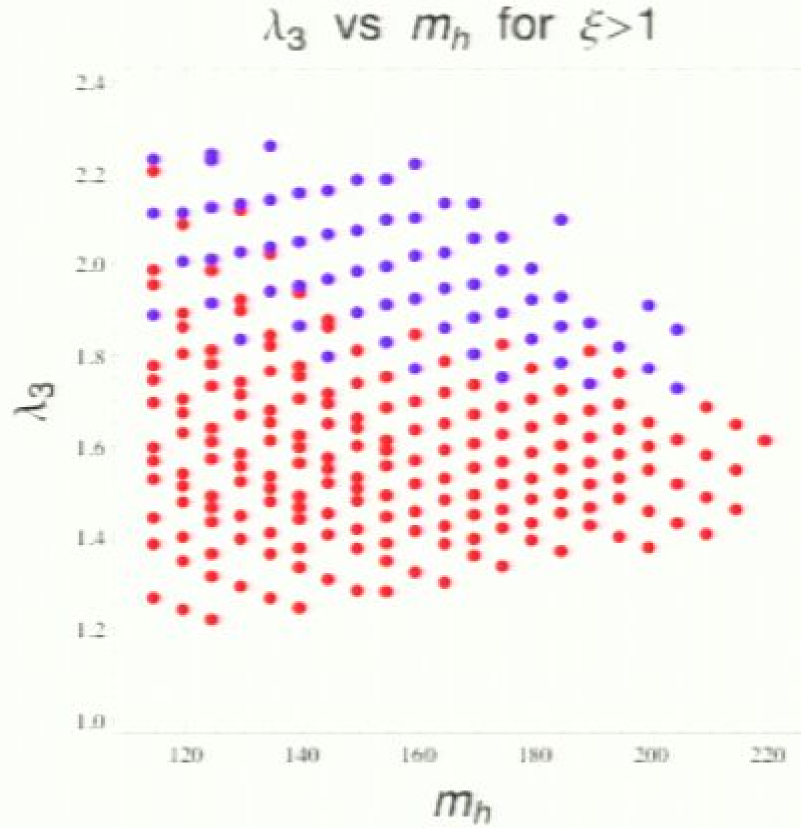

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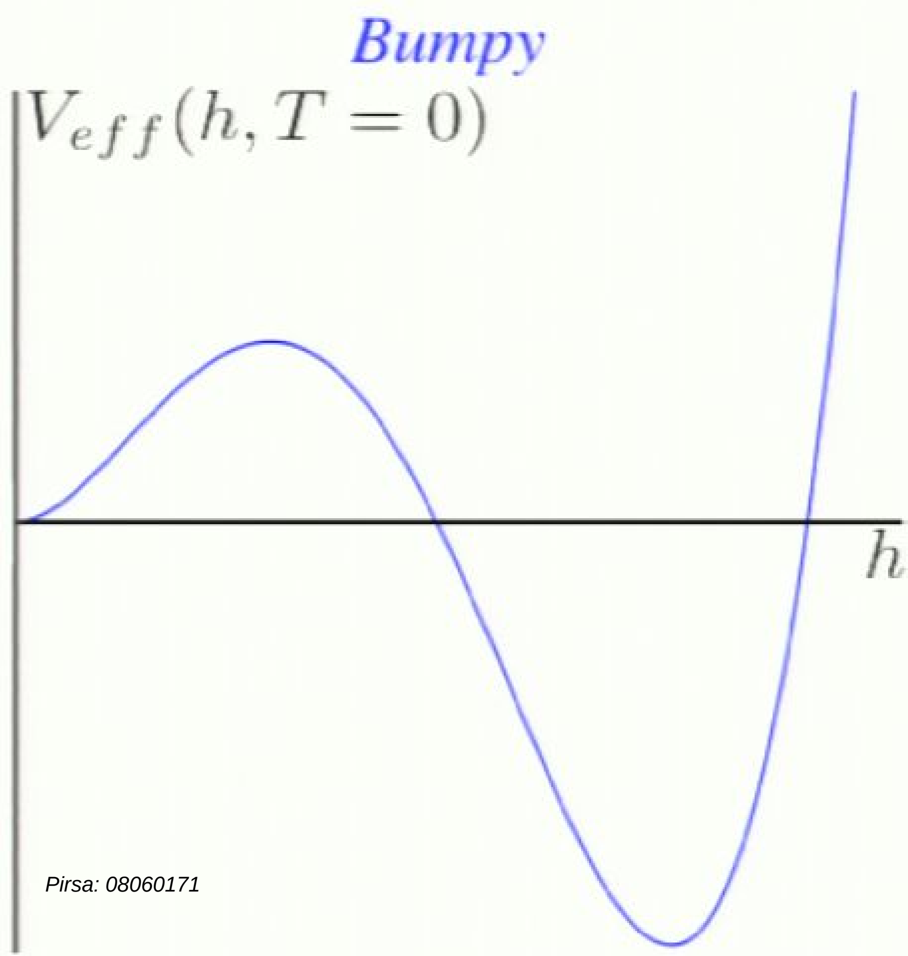

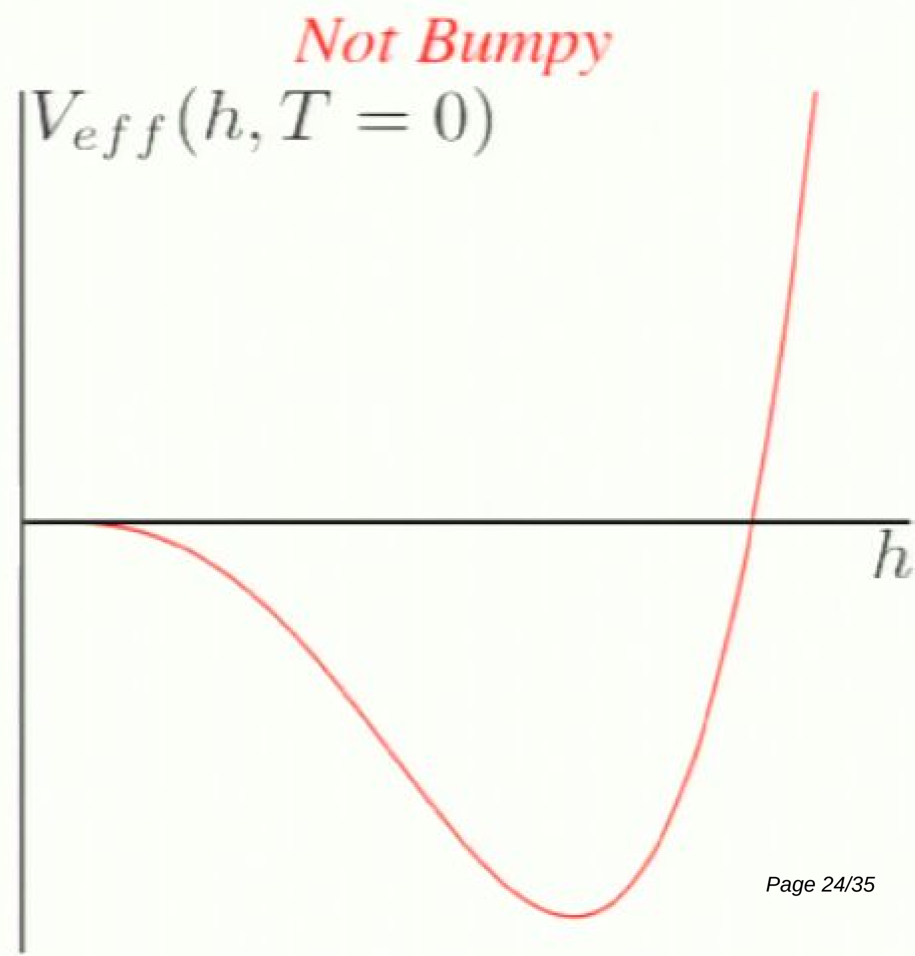

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I: Loop Modified, Unmixed h

Add a BSM boson-fermion pair (a la SUSY).
We choose a Dirac fermion and four identical real scalars.

$$V_{SM} = \sum_i \left(\frac{1}{2}M_{0,S}^2 S_i^2 + a|H|^2 S_i^2\right) + \left(M_{0,\Psi} + \frac{a}{M_{0,\Psi}}|H|^2\right)\Psi^\dagger\Psi$$

$$\Downarrow$$

$$\Delta V_{eff}(h, T=0) = \sum_i \frac{n_i}{64\pi^2} m_i^4(h) \log \frac{m_i^2(h)}{m_i^2(v)} + \cdots$$

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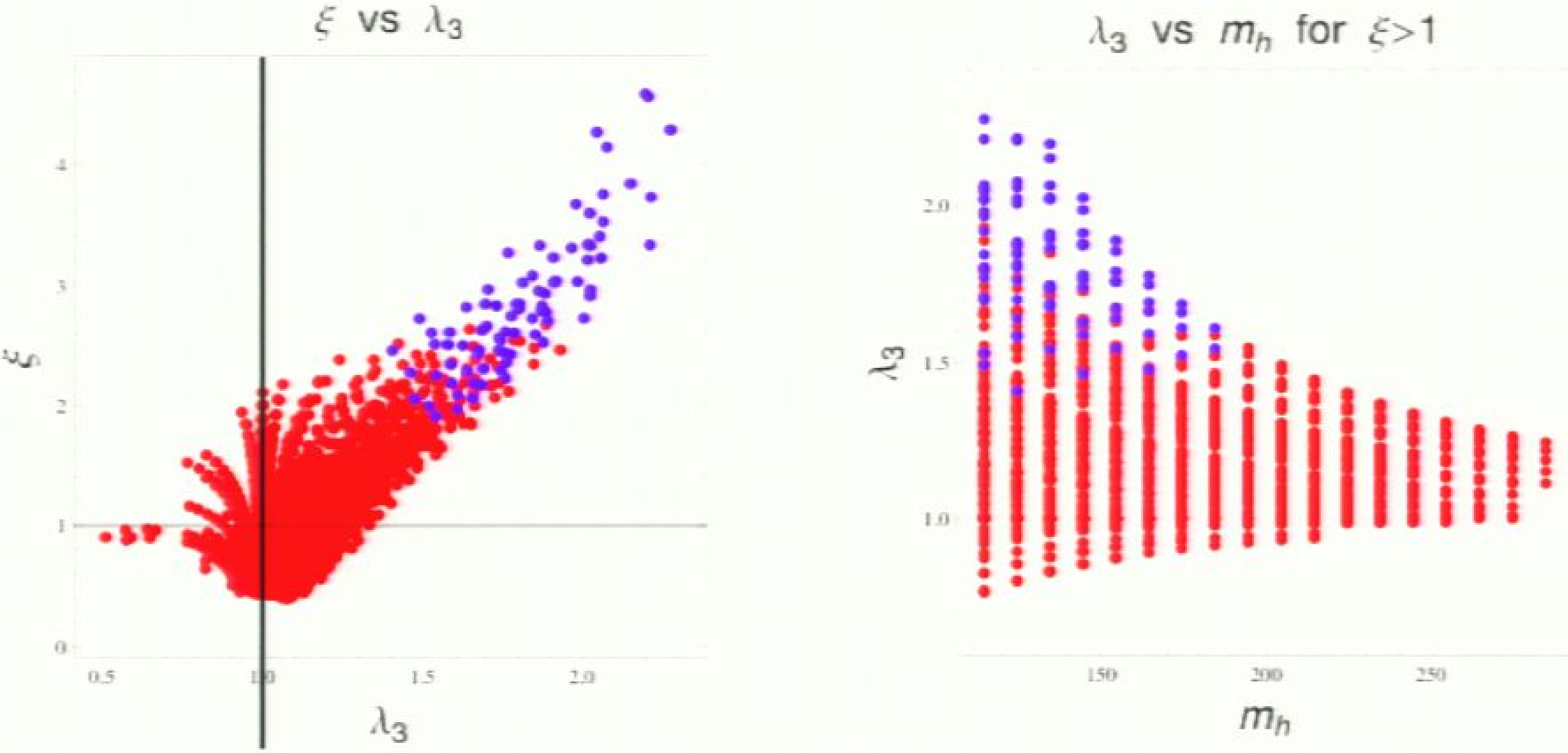

Blue = Bumpy at T=0

Accidental cancellations violate our claim!

But $M_{0,S} = M_{0,\Psi}$ requires substantial fine-tuning, since SUSY is broken by large couplings to the SM via h.

II: Tree-Level, Unmixed h

Consider the SM Higgs sector as an EFT and add the leading correction.

(Grojean, Servant, Wells, 2007)

$$\Delta V_{SM} = \frac{1}{\Lambda^2}|H|^6$$

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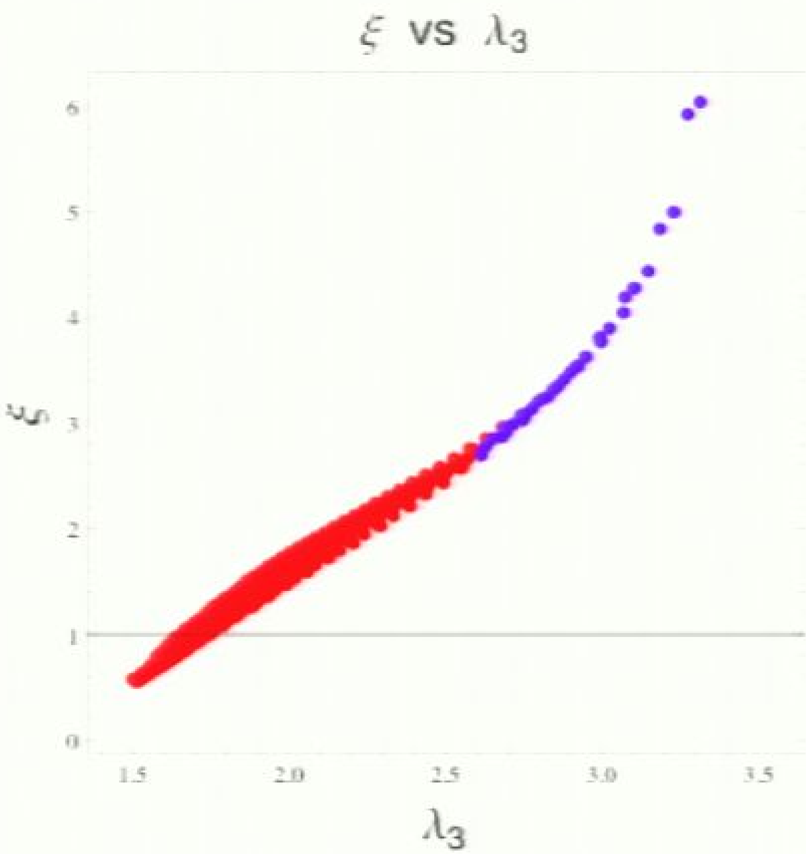

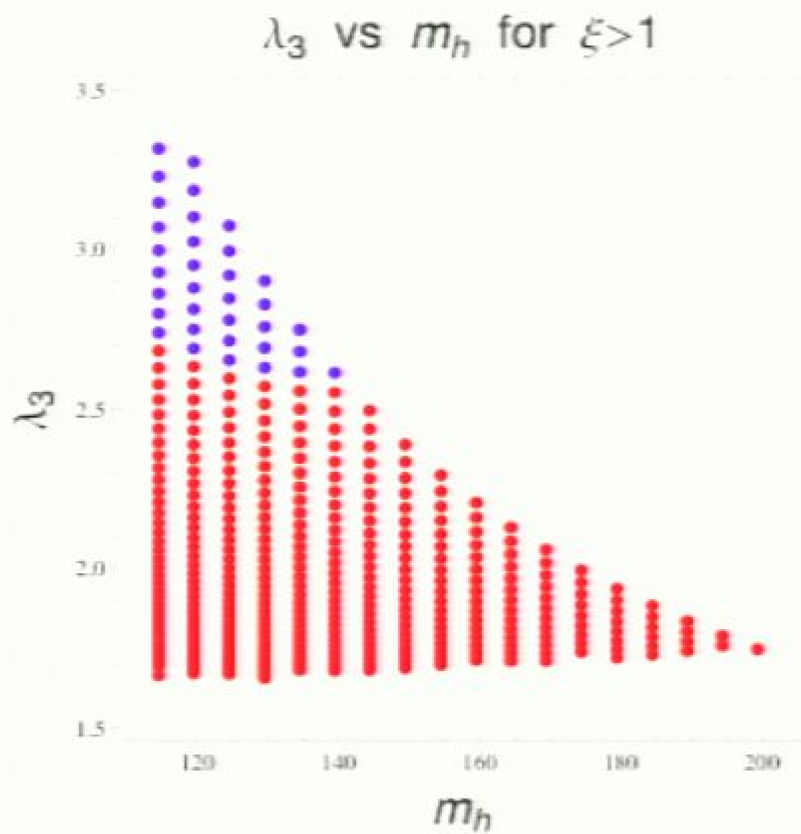

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$$\frac{\lambda_3^{\rm GSW}}{\lambda_3^{\rm SM}} = 1 + \frac{2v^4}{m_h^2\Lambda^2}$$

III: Tree-Level, Mixed h

Consider the most general, renormalizable potential with one additional scalar (as in the NMSSM or nMSSM).

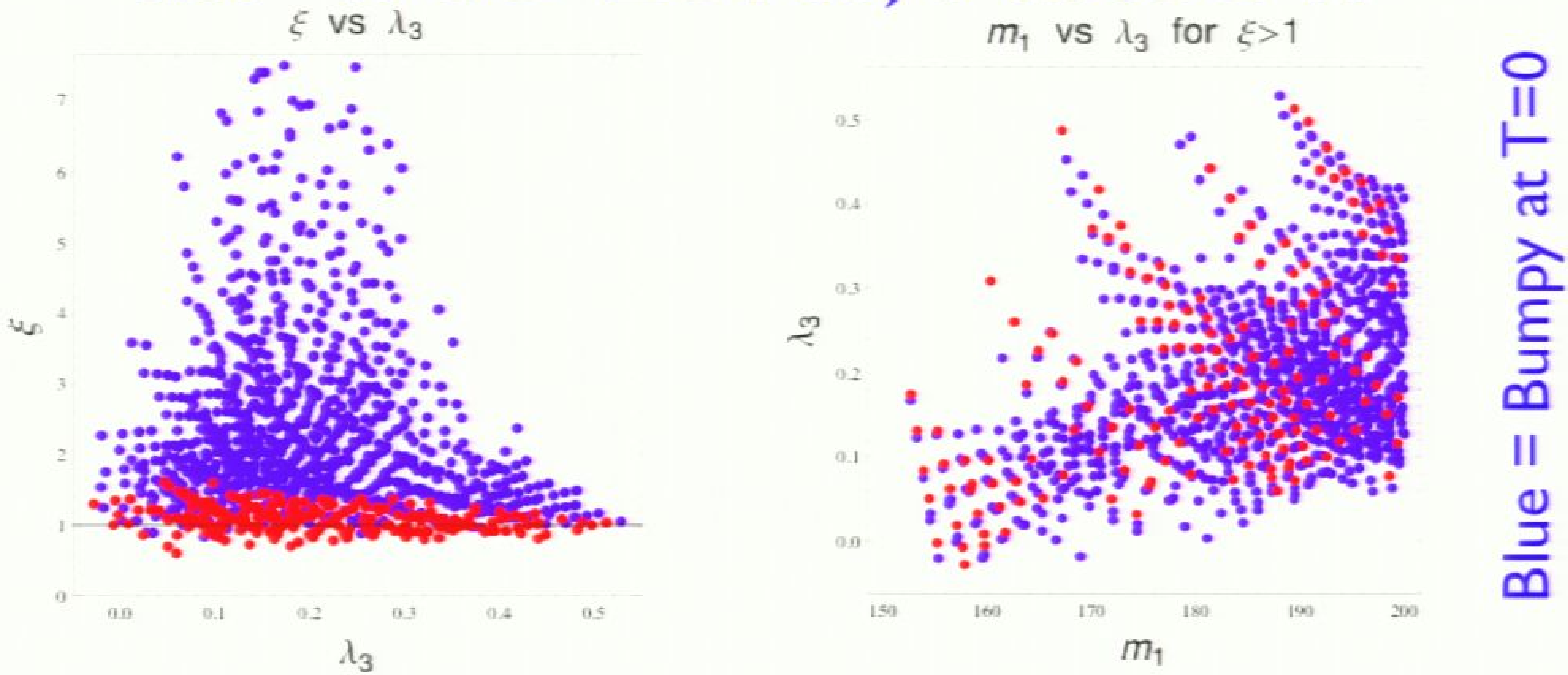
$$\Delta V_{SM} = \frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

Mass eigenstates: $h_1 = \sin\theta \; s + \cos\theta \; h$

$h_2 = \cos\theta \; s - \sin\theta \; h$

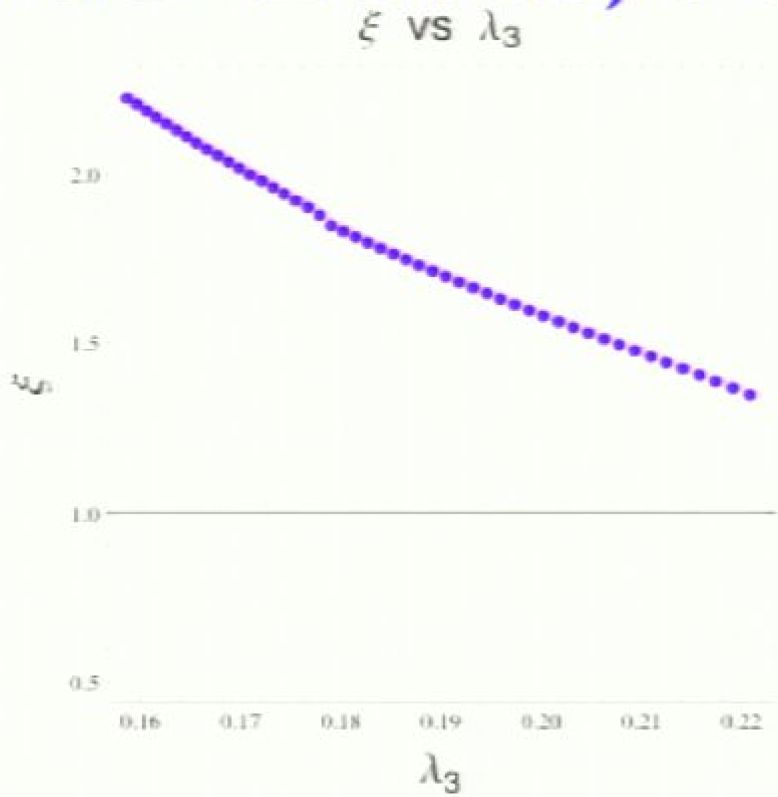
- Generically, H and S both acquire vevs, so the order parameter for the phase transition is a linear combination of two classical fields.
- h_1 is the most doublet-like, so we consider its λ_3.

III: Tree-Level, Mixed h



- This partial scan of the 6-dimensional parameter space is roughly consistent with EW precision constraints.
- Both suppression and enhancement of λ_3 is possible.
- Small λ_3 corrections only occur due to accidental cancellations of two large contributions.

III: Tree-Level, Mixed h



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- All parameters are fixed except for the mixing coefficient a_1.
- If the Higgs is mixed, deviations from the SM Higgs production x-section and braching ratios would be observed well before λ_3 is measured. Nevertheless, the correlation between ξ and λ_3 persists.

Conclusions

- Barring the possibility of accidental cancellations, there must be a large deviation in λ_3 from its SM value to achieve a strong first order EWPT and make EWBG viable.
- Typical deviations are large enough to be probed at the SLHC and ILC.
- Future work: For specific models, could the order of the EW phase transition be determined from a small number of quantities measured to an accessible level of precision?

(cf. David Morrissey's talk on constraining the window for EWBG in the MSSM.)