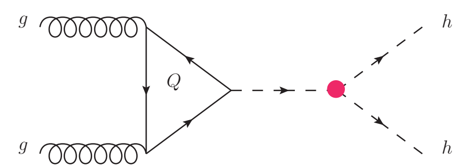
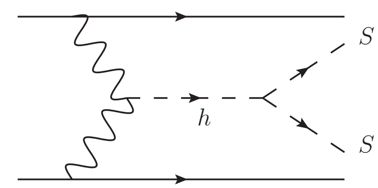
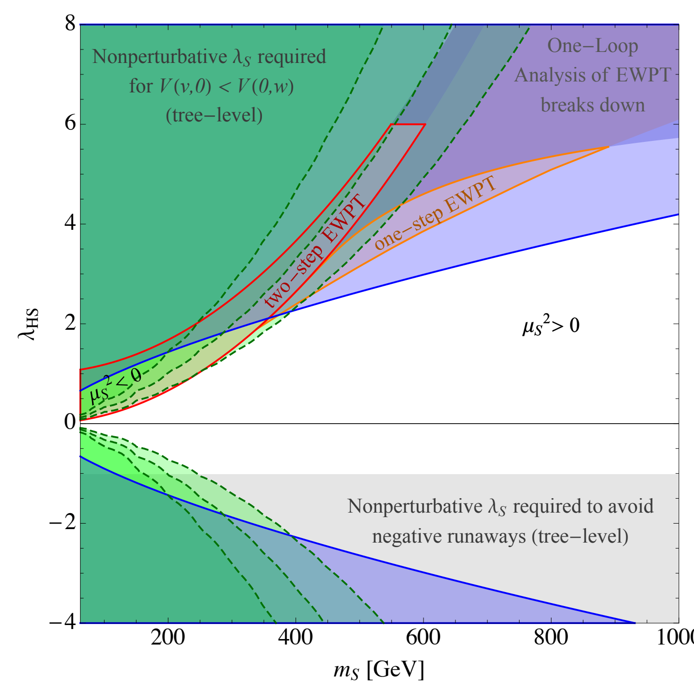
Probing Electroweak Baryogenesis at Future Colliders





Theory Seminar
University of Sydney
13 March 2015

David Curtin
Maryland Center for Fundamental Physics
University of Maryland



Partially based on 1409.0005 (DC, Patrick Meade, Tien-Tien Yu)

Also DC, Patrick Meade, Harikrishan Ramani (1511.XXXX?)

HEP in 2025 - 2045

The LHC is just about to start its first run near the initial design energy!

Even so, the time to think about the next big machine is NOW: it takes 20+ years to go from "proposal" to "first beam" at an energy-frontier collider.

Japan has plans for an e^+e^- Higgs factory in the intermediate future (2025ish). *ILC plans are technically mature, ready-to-go.*

ILC

But we have to think even further ahead. The next-next step would have to be a ~100 TeV, ~ 100 km proton-proton machine....

CERN?

CEPC-SPPC

Preliminary Conceptual Design Report: Physics and Detector

China?

HEP in 2025 - 2045

The LHC is just about to start its first run near the initial design energy!

Even so, the time to think about the next big machine is NOW: it takes 20+ ye … er.

Ja… cto…
fu… ica…

B… ur… t
st… 0 … ton
m…

FCC
hh ee he

CERN?

CEPC-SPPC

Preliminary Conceptual Design Report: Physics and Detector

China?

Why go beyond the LHC?

The LHC was *guaranteed* to find the Higgs, and it's a great machine to look for garden-variety top-partners near a TeV.

But we always knew that BSM physics can be a lot richer than that.

Why go beyond the LHC?

Hierarchy Problem

solution could rely on
uncolored top partners

Twin Higgs hep-ph/0506256, Folded SUSY hep-ph/0609152, & follow-ups....

Dark Matter

EW charged
[if we're lucky!]

Baryogenesis

Testable (?) option:
Electroweak baryogenesis

Why go beyond the LHC?

Hierarchy Problem

solution could rely on
uncolored top partners

Twin Higgs hep-ph/0506256, Folded SUSY hep-ph/0609152, & follow-ups....

Dark Matter

EW charged
[if we're lucky!]

Baryogenesis

Testable (?) option:
Electroweak baryogenesis

This is the Uncolored TeV scale

Lepton colliders can obviously offer great insight here.
Curiously, a 100 TeV pp collider might be even better!

The huge cross sections at a 100 TeV pp collider elevate the TeV scale into the intensity frontier!

Why go beyond the LHC?

Hierarchy Problem

solution could rely on
uncolored top partners

Twin Higgs hep-ph/0506256, Folded SUSY hep-ph/0609152, & follow-ups....

No lose theorem
for uncolored top partners
at future colliders:
DC, Saraswat 1509.04284

Dark Matter

EW charged
[if we're lucky!]

Baryogenesis

Testable (?) option:
Electroweak baryogenesis

No lose theorem?
make some progress here...

A 100 TeV Collider would allow us to study the electroweak phase transition in considerable detail!

Like going back in time..

.. to when the universe was just $\sim 10^{-12}$ s old

How to exclude EWBG?

Excluding EWBG

All the new physics MUST be active at the weak scale.

$\Rrightarrow$ EWBG is inherently testable!

But there are many models implementing EWBG...
Can we exclude them all?
After all, we are looking for a general *physical mechanism*!

Let's factorize the two necessary conditions for EWBG

Strong phase transition

CP Violation

Excluding EWBG

All the new physics MUST be active at the weak scale.

$\Rrightarrow$ EWBG is inherently testable!

But there are many models implementing EWBG...
Can we exclude them all?
After all, we are looking for a general *physical mechanism*!

Let's factorize the two necessary conditions for EWBG

Strong phase transition

CP Violation

Assuming strong PT, computing generated baryon asymmetry is very complicated with large theoretical uncertainties.

huge literature...

Excluding EWBG

All the new physics MUST be active at the weak scale.

$\Rrightarrow$ EWBG is inherently testable!

But there are many models implementing EWBG...
Can we exclude them all?
After all, we are looking for a general *physical mechanism*!

Let's factorize the two necessary conditions for EWBG

Strong phase transition

Relatively simple to check that the thermal potential has the the required 'energy barrier'

also a **huge** literature...

CP Violation

Assuming strong PT, computing generated baryon asymmetry is very complicated with large theoretical uncertainties.

huge literature...

Excluding EWBG

All the new physics MUST be active at the weak scale.

$\Rrightarrow$ EWBG is inherently testable!

But there are many models implementing EWBG...
Can we exclude them all?
After all, we are looking for a general *physical mechanism*!

Let's factorize the two necessary conditions for EWBG

Strong phase transition

Relatively simple to check that the thermal potential has the the required 'energy barrier'

also a **huge** literature...

Try and exclude this

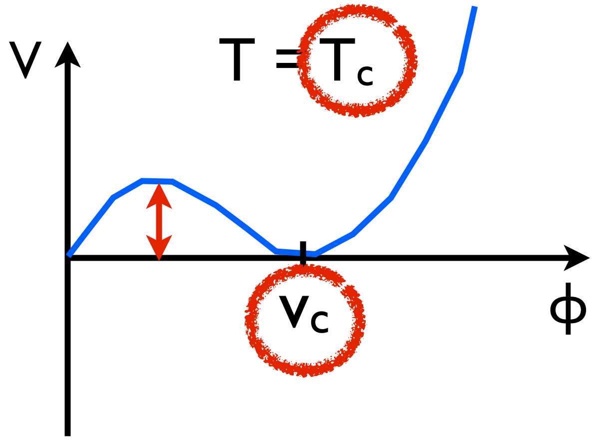
CP Violation

Assuming strong PT, computing generated baryon asymmetry is very complicated with large theoretical uncertainties.

huge literature...

How to exclude discover? a strong electroweak phase transition?

Strong Phase Transition



The phase transition has to be strong enough to suppress sphaleron washout of the generated baryon number in the broken phase.

Very simple criterion to determine if EWBG is at least *possible* with a given higgs potential.

$$\frac{v_c}{T_c} > 0.6 - 1.6$$

Normally given as ~1, this more accurate figure is from Patel, Ramsey-Musolf, 1101.4665

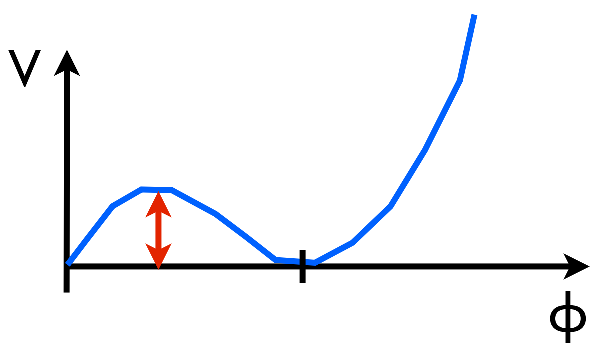
Central question:

can you come up with a **“no-lose” theorem** that large v_c/T_c **always** leads to a detectable experimental signature?

Achieving a strong PT

How can you modify the SM higgs potential to get $v_c/T_c \gtrsim 1$?

We want a ‘bump’ at some critical temperature.



~ like a cubic term for the higgs
(though there are other ways)

In the SM, the W and Z bosons ‘want’ to give you this bump via their thermal corrections to the higgs potential, but their contributions are too feeble to overcome the potential difference.

Achieving a strong PT

How can you modify the SM higgs potential to get $v_c/T_c \gtrsim 1$?

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

tree-level potential | loop correction | finite temperature corrections

Achieving a strong PT

How can you modify the SM higgs potential to get $v_c/T_c \gtrsim 1$?

$$V_{\text{eff}}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

tree-level potential — loop correction — finite temperature corrections

1. Thermal Effects
   add new BOSONS to the plasma to generate barrier (analogous to W and Z contributions)
2. Loop Effects
   add particles whose loops reduce the 'depth of the higgs potential well', so W and Z contributions can make a barrier.
3. Tree Effects
   add scalars to modify tree-level higgs potential and create a barrier
4. add non-renormalizable operators
   really a general way of parameterizing (2) and (3) ← a little subtle....

Thermally driven PT

Classic example: light stop scenario in MSSM.
Excluded from higgs coupling measurements!

Cohen, Morrissey, Pierce 1203.2924,
DC, Jaiswal, Meade 1203.2932

Katz, Perelstein, Ramsey-Musolf,
Winslow, 1509.02934

See Andrey's talk tomorrow

More generally:

The new boson has to be lighter than ~ 200 GeV to be in thermal contact with the plasma during the PT.

see e.g. Katz, Perelstein 1401.1827

⇛ If it has *any* SM gauge charge:

Large direct production cross section at LHC.

Large modifications to higgs couplings & decays

We'll find it! (or already excluded!)

⇛ If it is a SM singlet:

Direct production only through higgs portal. CHALLENGING!

but.. requires very large higgs coupling or large multiplicity.

→Generally, O(10%) corrections to **higgs cubic coupling**.

O(1%) corrections to **Zh coupling**

Very Promising!

Thermally driven PT

Classic example: light stop scenario in MSSM.

Excluded from higgs coupling measurements!

Cohen, Morrissey, Pierce 1203.2924,
DC, Jaiswal, Meade 1203.2932

Katz, Perelstein, Ramsey-Musolf,
Winslow, 1509.02934

See Andrey's talk tomorrow

Exclusion or discovery
is relatively easy here!

00 GeV to be in
ing the PT.

see e.g. Katz, Perelstein 1401.1827

⇛

Large direct production cross section at LHC

Large

Motivates precision
measurements at future lepton
colliders & 100 TeV machine.

⇛ If it is

Di LENGING!

bu tiplicity.

→Gen **pling**.

O(1%) corrections to **Zh coupling**

We'll find it!
(or already excluded!)

Very Promising!

Tree and Loop-driven PT

These do *not* require new light (~ 100 - 200 GeV) light particles.

Many models, such as the NMSSM, can realize these strong PT's...

see e.g. Kozaczuk, Profumo, Haskins, Wainwright 1407.4134

... but they have lots of baggage that has nothing to do with the PT.

Singlet Scalar Extensions of the SM are very minimal models that can produce a strong PT.

Tree and Loop-driven PT

Consider SM + single real scalar

$$V_0^{T=0}(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

In generality, this scalar mixes with the higgs after EWSB.

$\Rrightarrow$
- direct production in (heavy) higgs searches
- exotic higgs decays h→ss (if light enough)
- EWPO constraints
- higgs precision coupling measurement constraints
- modifications to higgs self-couplings
- modification to Zh coupling

future lepton collider

100 TeV pp collider

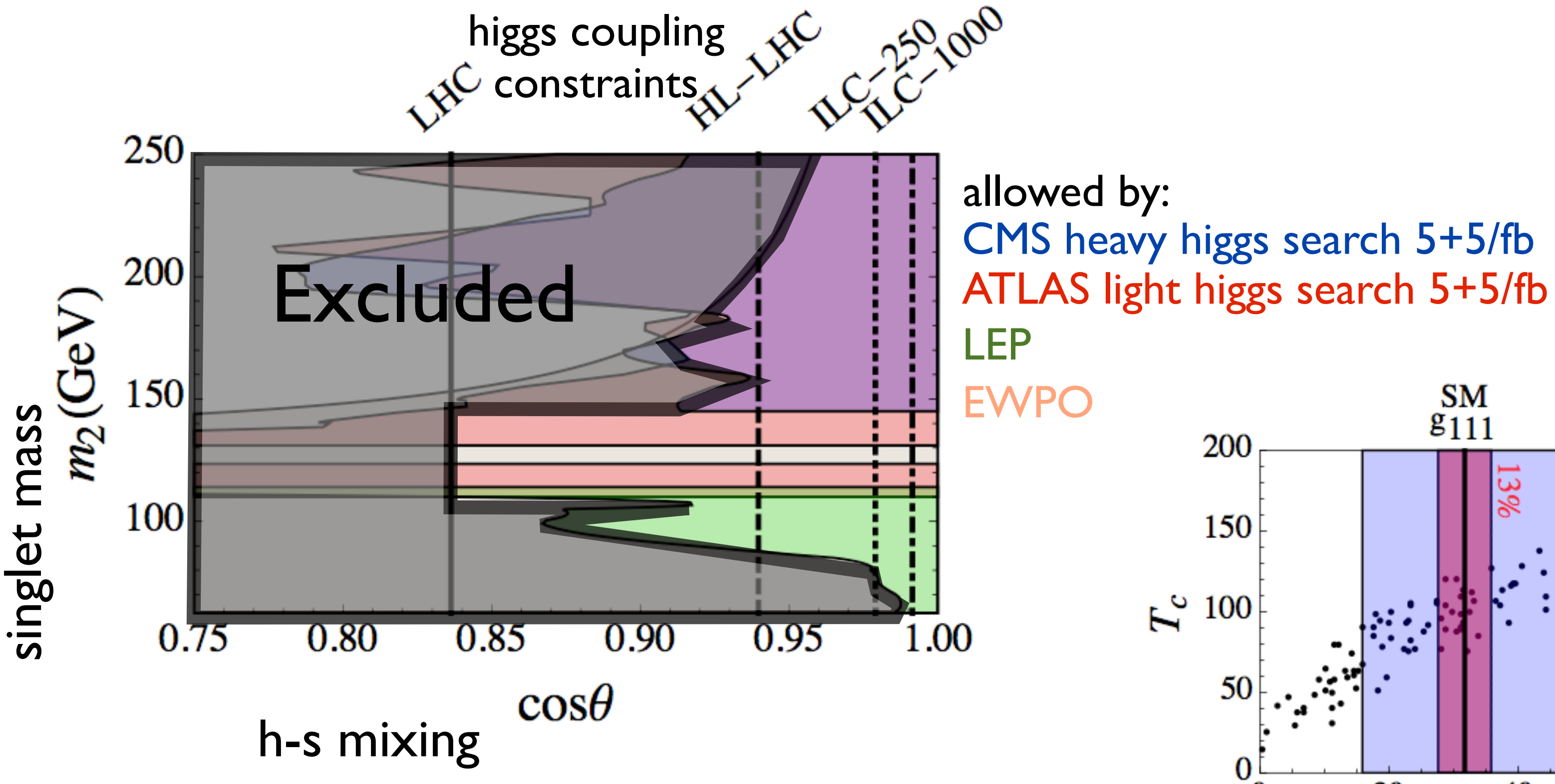
A lot of handles for discovery using all future colliders!

But the model still has many parameters. Can EWBG be completely excluded?

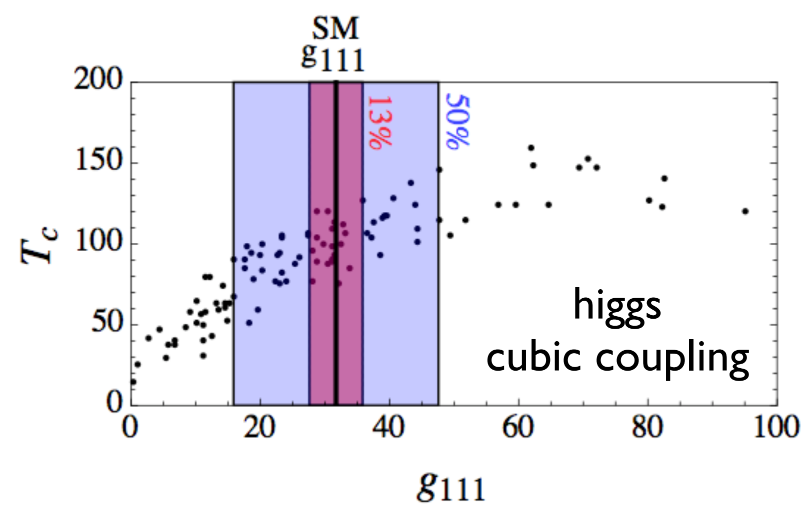
Tree and Loop-driven PT

Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342

Parameter scan limited to one-step, tree-driven transitions.



See Peter's talk earlier today



Possible to get PT even with ILC constraints.

How does this correlate with higgs cubic and Zh coupling?

Tree and Loop-driven PT

Would like a simpler model to investigate these strong phase transitions....

DC, Patrick Meade, Tien-Tien Yu 1409.0005

build a 'maximally stealthy' model to implement these mechanisms, then see how to exclude that model.

Can we **exclude** a strong PT by loop or tree effects?

A `simplified model' of stealthy electroweak baryogenesis!

Defining a Benchmark Model

We want a maximally stealthy singlet extension of the SM.

Smallest number of extra degrees of freedom to reduce all signatures. → Add just one real scalar S.

Avoid modified higgs couplings, SM-higgs-like production and EWPO → No higgs-singlet mixing. unbroken Z_2 ⇛ No singlet VEV.

Avoid exotic higgs decays → Singlet mass > $m_h/2 \cong 62$ GeV

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \boxed{\frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4}$$

This is our "Nightmare Scenario" for a strong EW phase transition.

Can the “nightmare scenario” yield EWBG without being detected?

Important Parameters

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Very simple model, only three BSM parameters: μ_S^2, λ_{HS}, λ_S

Turns out ENTIRE phenomenology is captured by just TWO parameters:

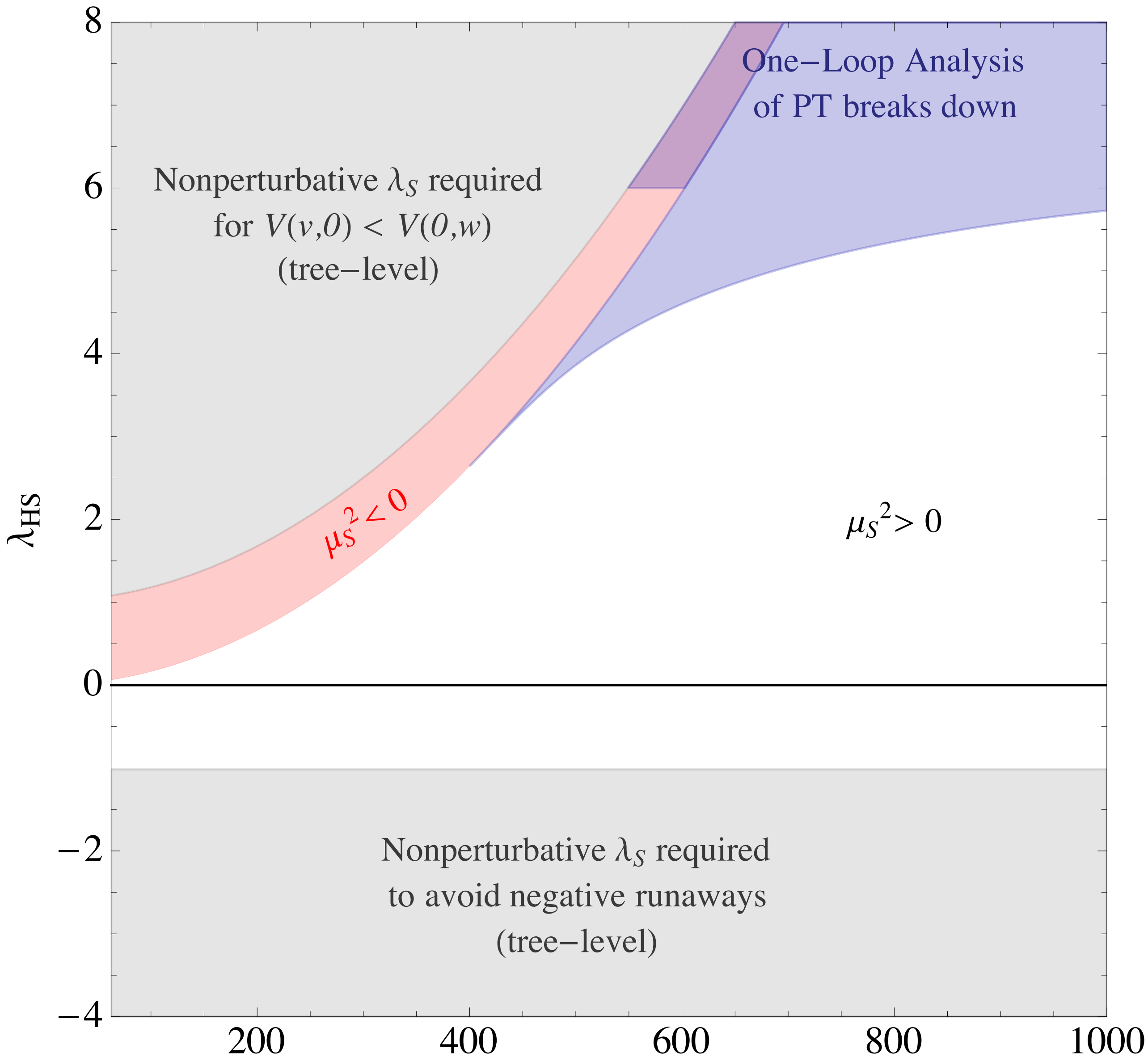
Singlet mass in our vacuum: $m_S^2 = \mu_S^2 + \lambda_{HS} v^2$

Singlet interaction with higgs: λ_{HS}

To find largest allowed parameter regions, we optimize λ_S for a strong phase transition.

The (m_S, λ_{HS}) Plane

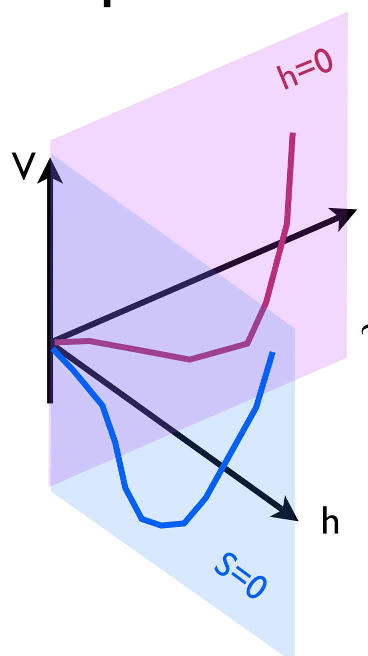
singlet-higgs coupling

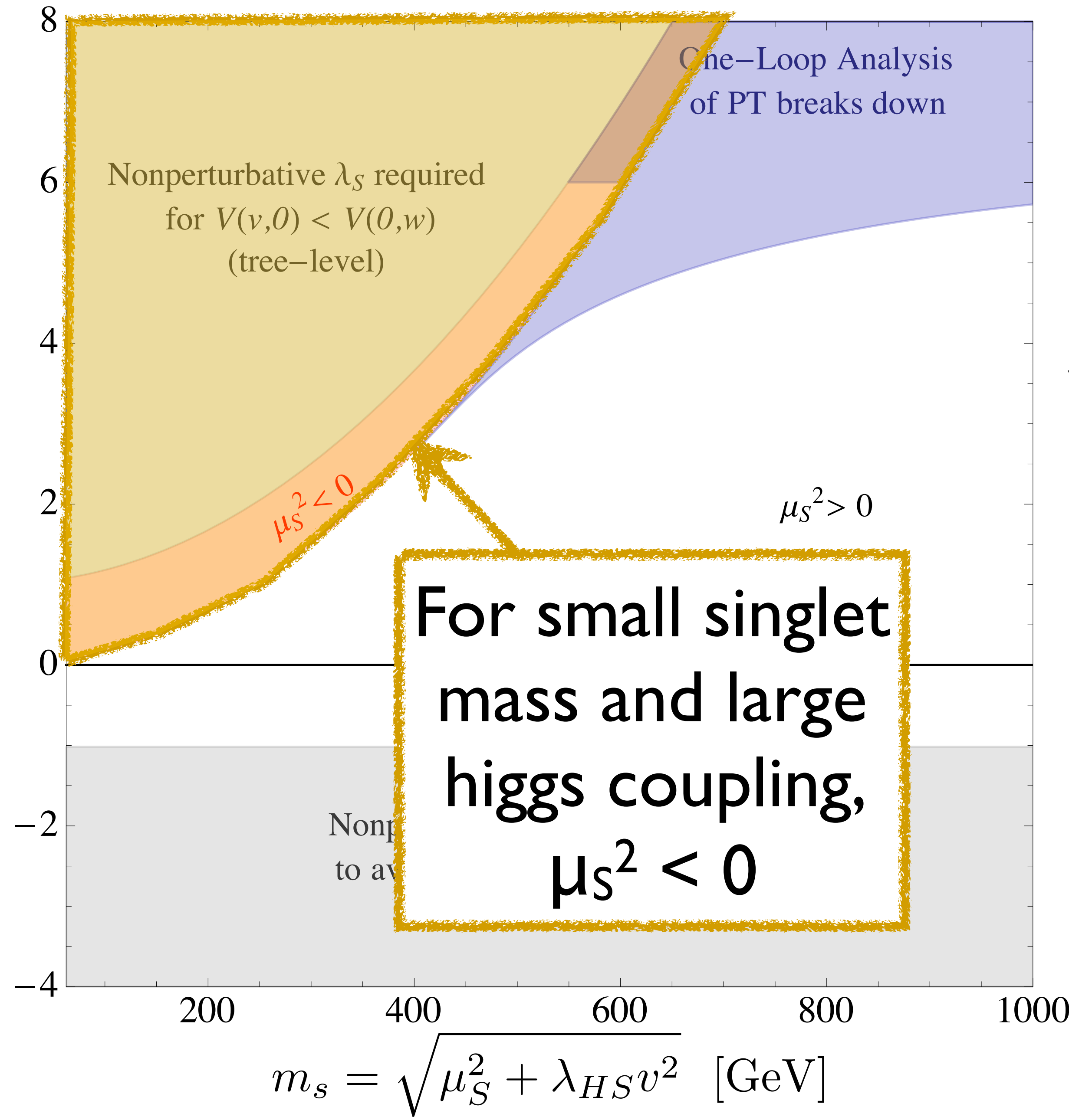


singlet mass in our vacuum $m_s = \sqrt{\mu_S^2 + \lambda_{HS} v^2}$ [GeV]

The (m_S, λ_{HS}) Plane

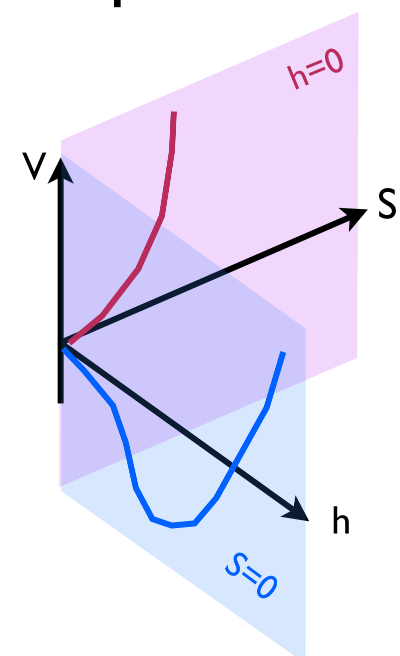
$\mu_S^2 < 0$



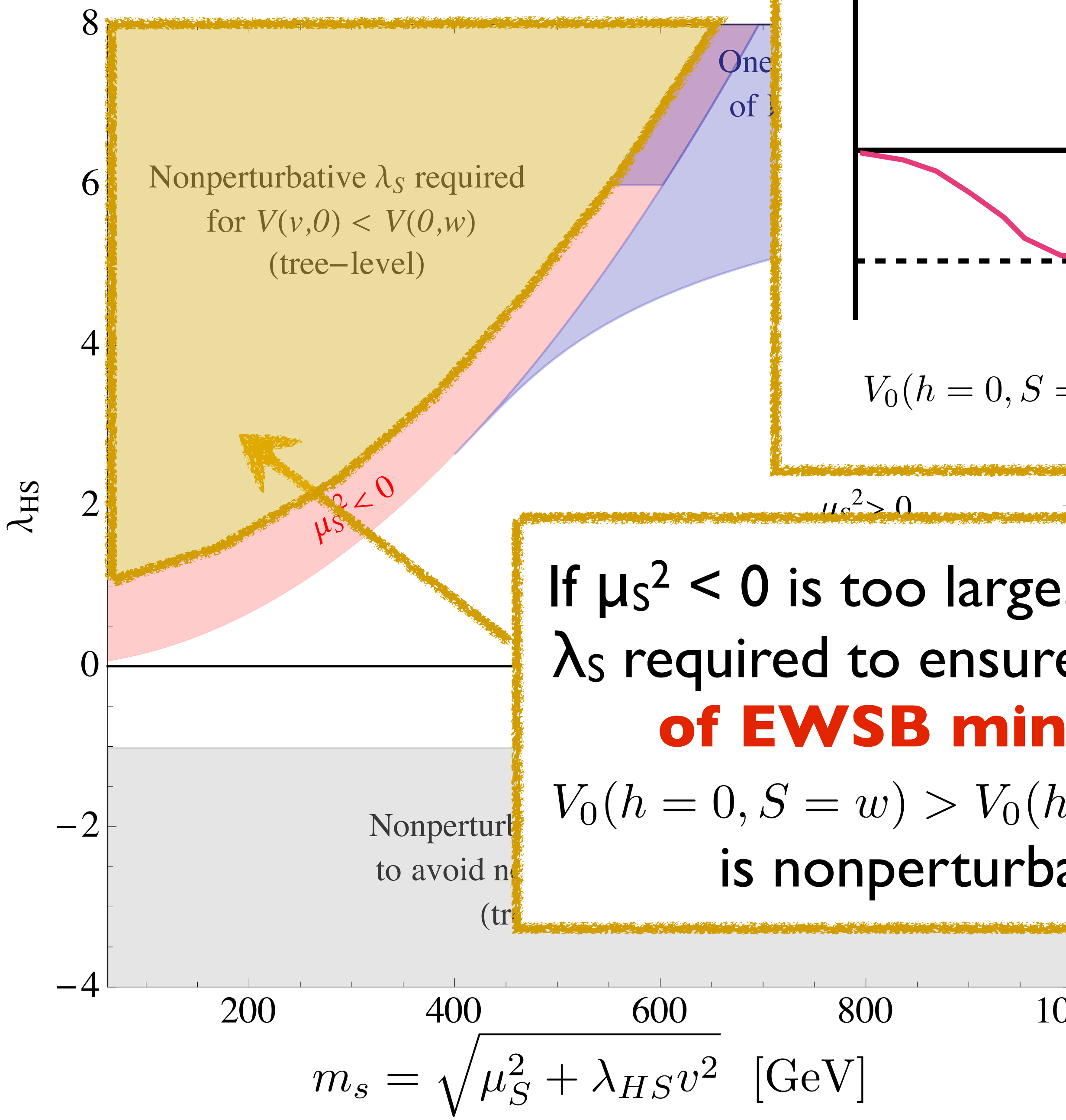


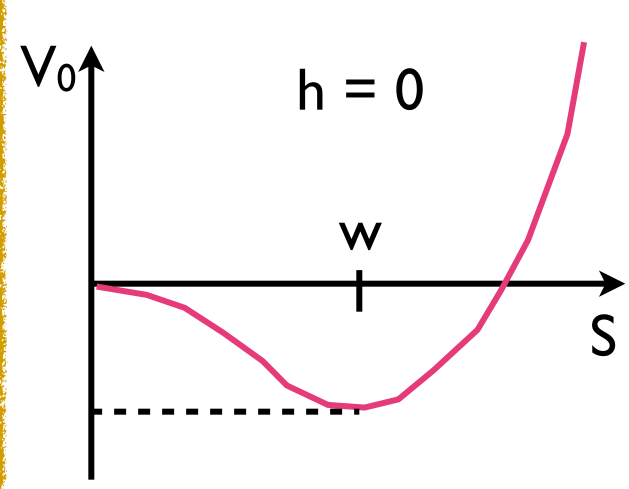
For small singlet mass and large higgs coupling, $\mu_S^2 < 0$

$\mu_S^2 > 0$



The (m_S, λ_{HS}) Plane





$$V_0(h=0, S=w) = -\frac{\mu_S^4}{4\lambda_S}$$

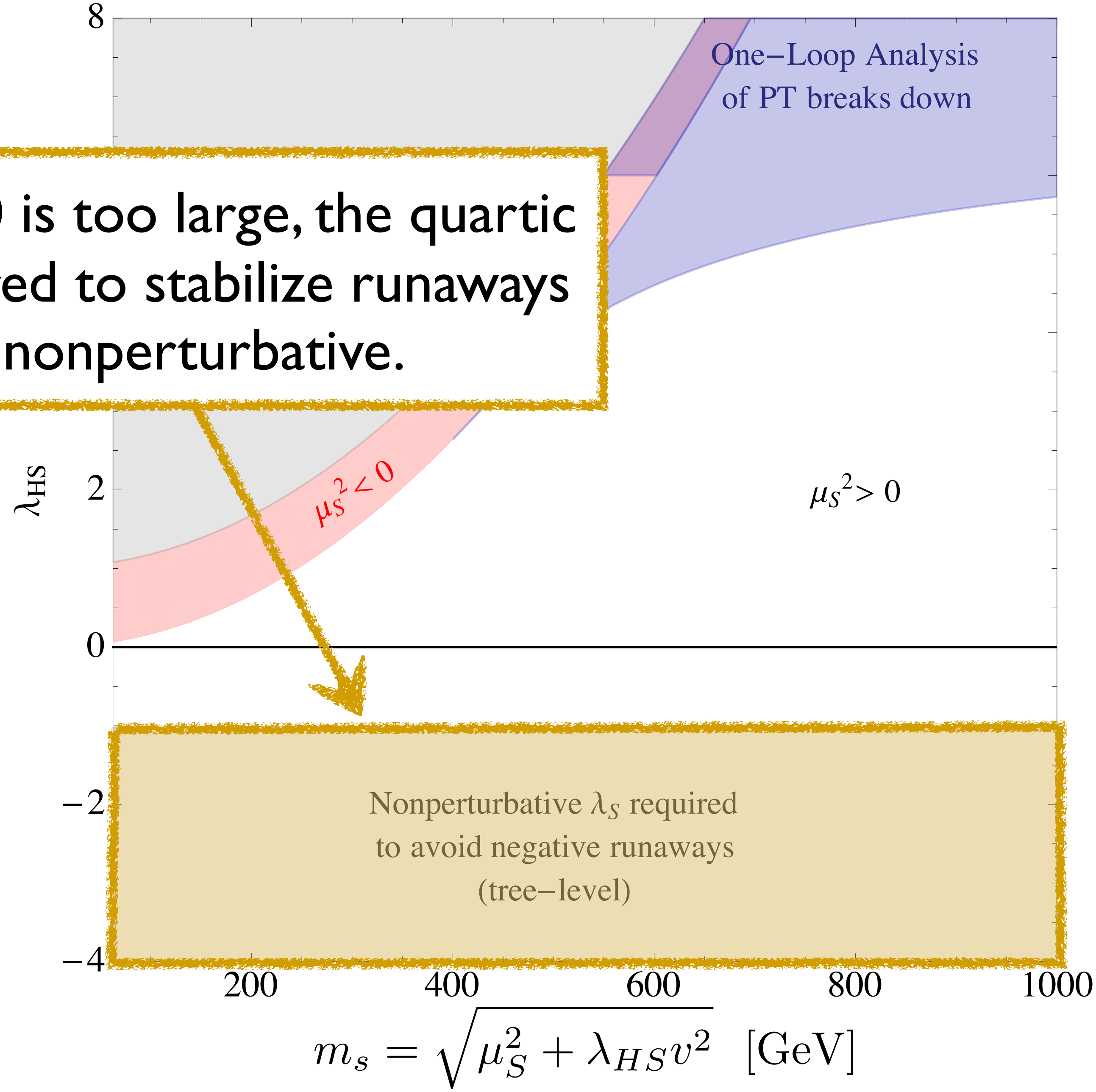
If $\mu_S^2 < 0$ is too large, the quartic λ_S required to ensure **stability of EWSB minimum**

$$V_0(h=0, S=w) > V_0(h=v, S=0)$$

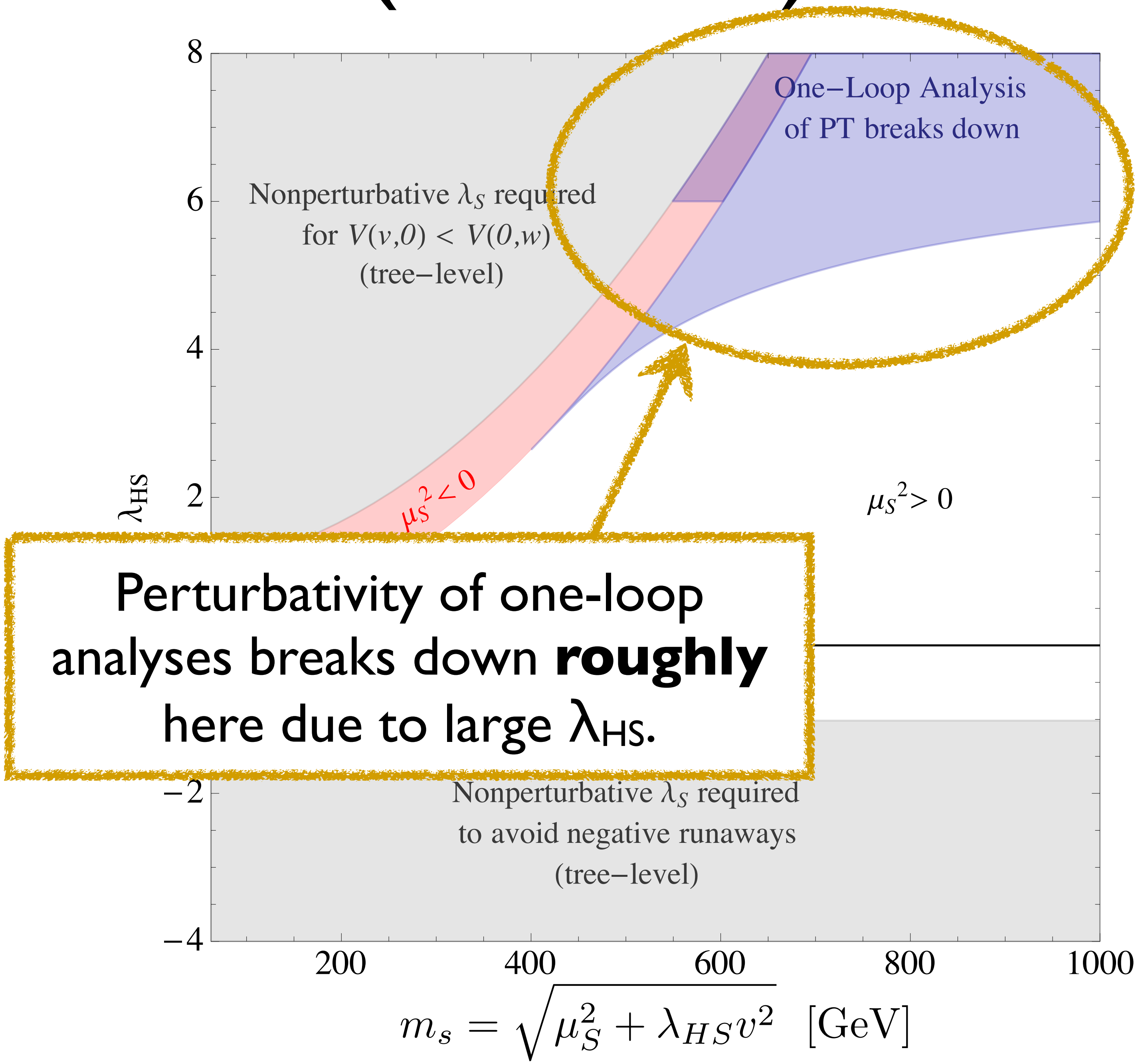
is nonperturbative.

The (m_S, λ_{HS}) Plane

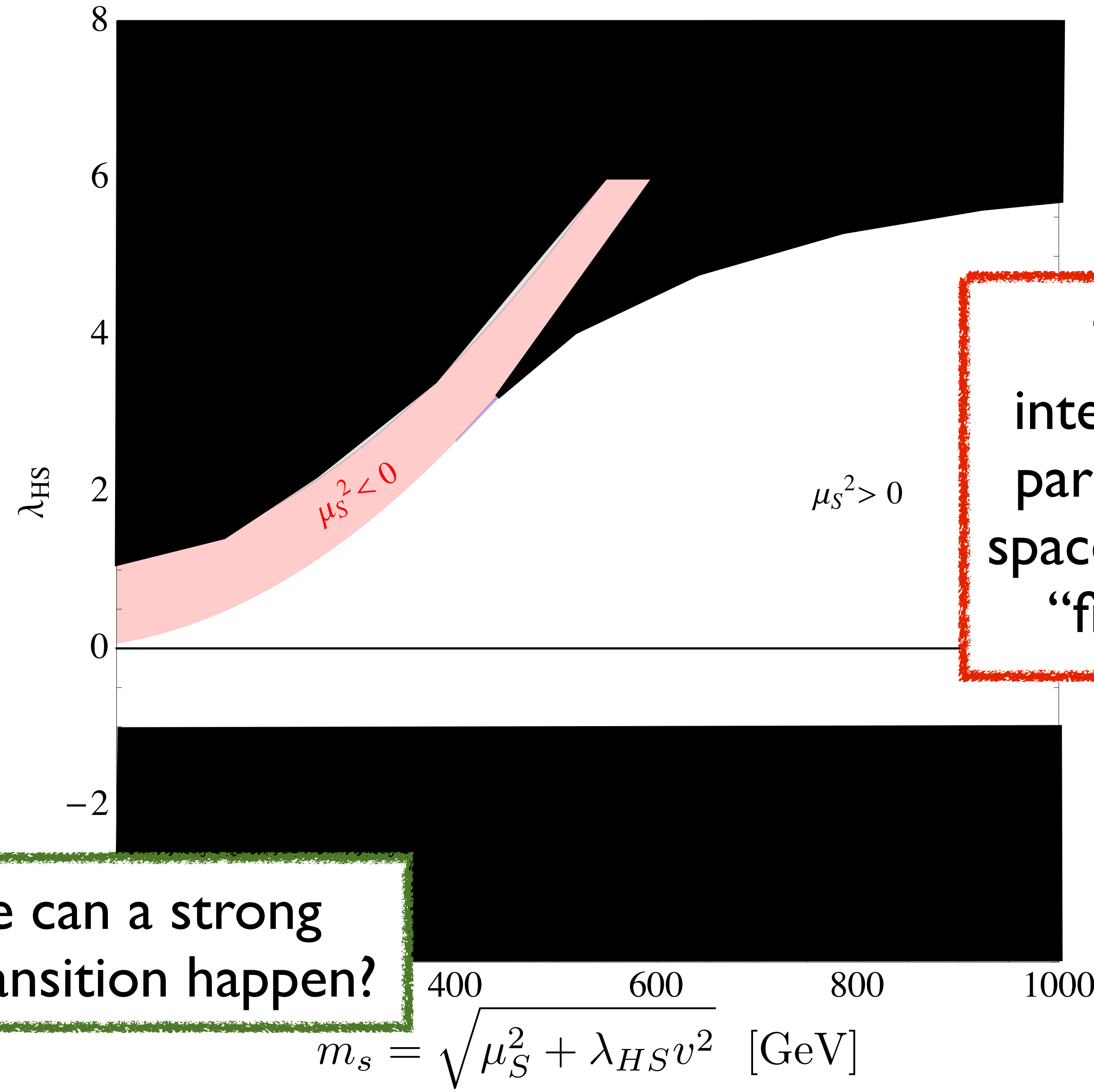
If $\lambda_{HS} < 0$ is too large, the quartic λ_S required to stabilize runaways is nonperturbative.



The (m_S, λ_{HS}) Plane



The (m_S, λ_{HS}) Plane

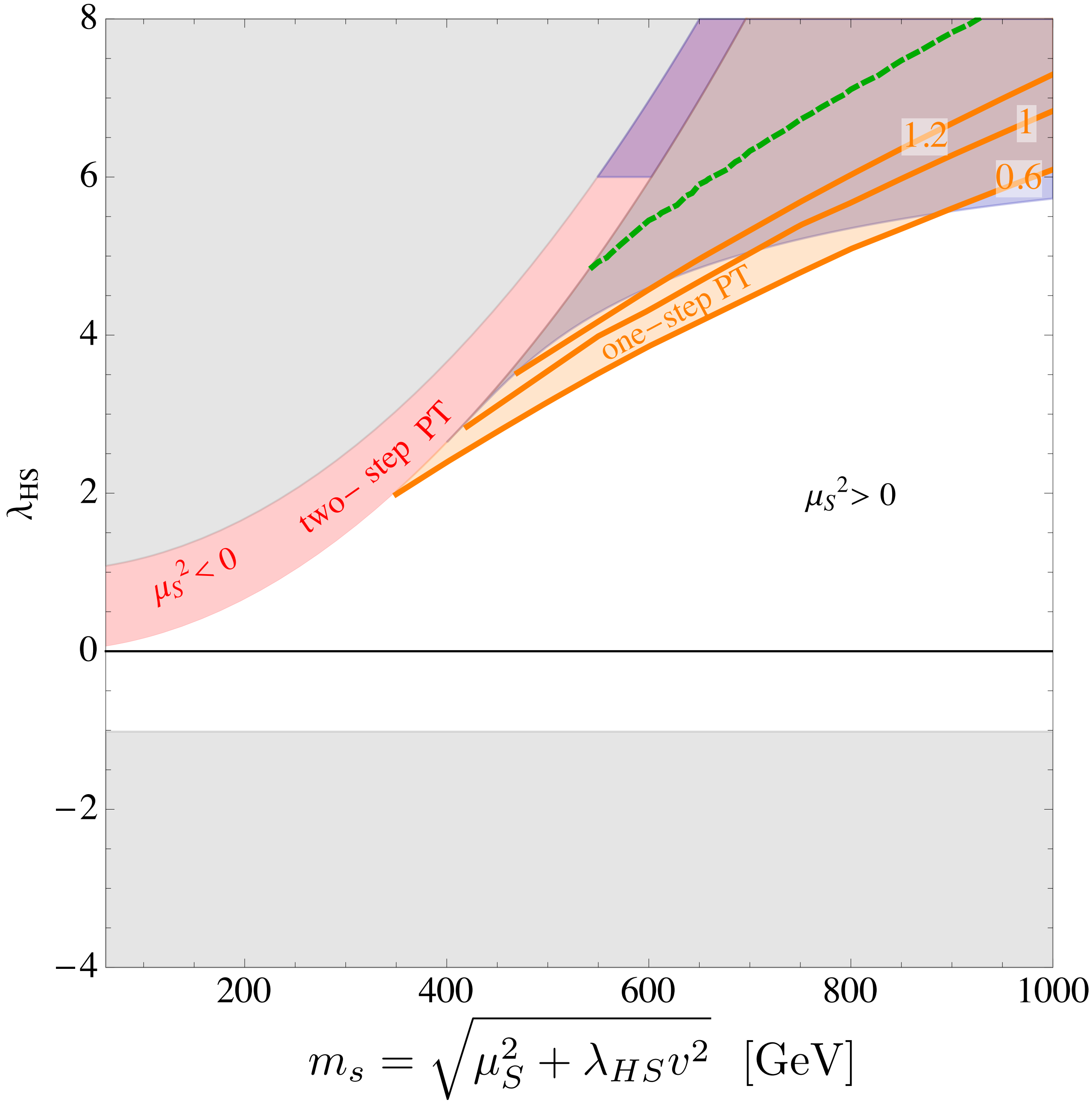


The interesting parameter space is very "finite".

Where can a strong phase transition happen?

Electroweak Phase Transition
in the Nightmare Scenario

Two* kinds of phase transitions

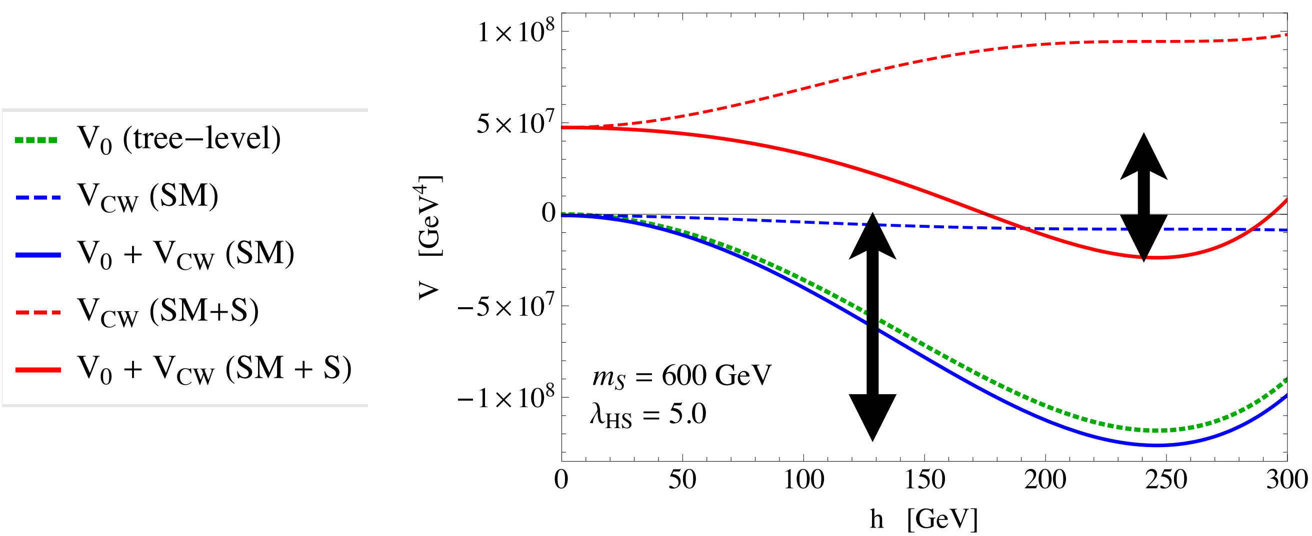


One-Step by Loop Effects

$$V_{\text{eff}}(h,T) = V_0(h) + \boxed{V_0^{CW}(h)} + V_T(h,T) + V_r(h,T)$$

Requires large λ_{HS}, which implies m_S > 400 GeV (otherwise singlet is unstable at origin)

Zero Temperature Potential



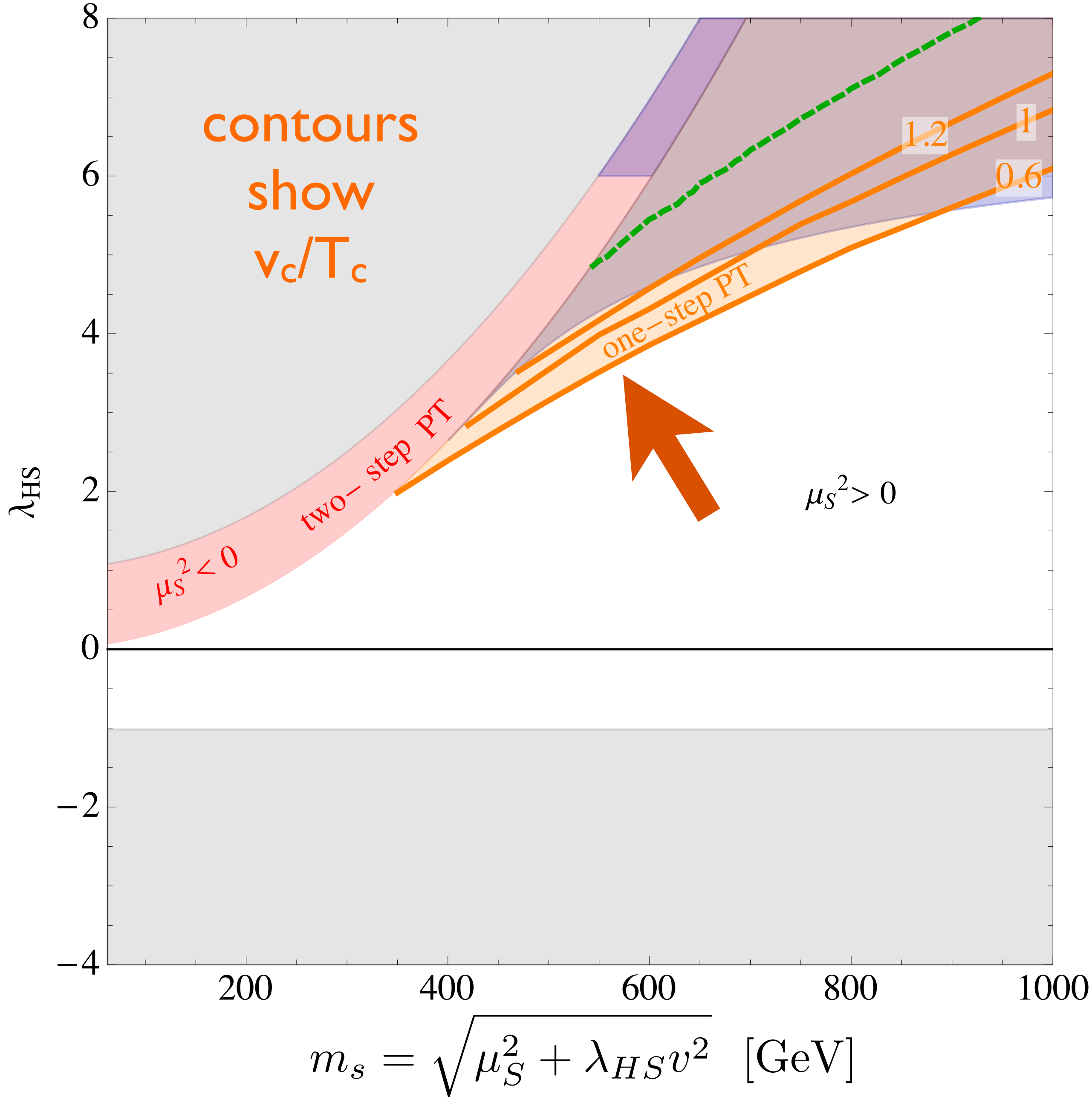
The singlet is not 'thermally active' in the plasma due to its high mass, but its large coupling generates a loop correction which reduces the potential difference between h = 0 and h = v.

SM thermal contributions can then generate a potential barrier and make the phase transition first order.

One-Step by Loop Effects

Find regions where PT is strong.

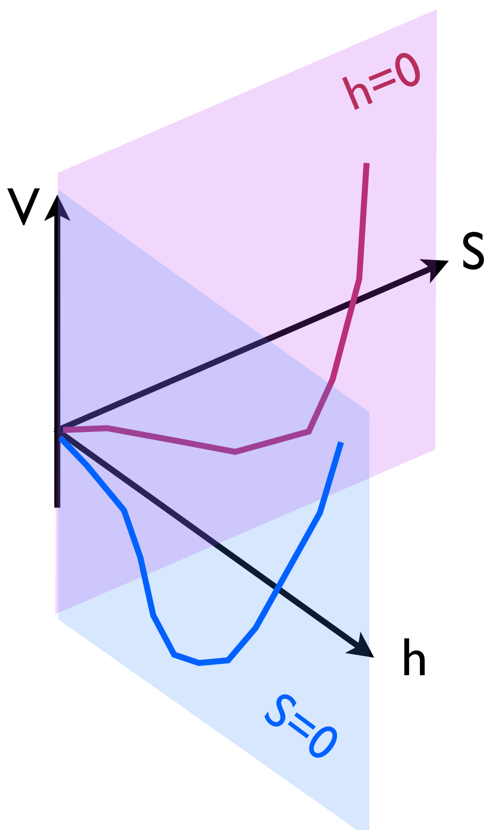
λ_S only enters via thermal mass so has no big effect. PT is maximized for λ_S = 0 (shown).

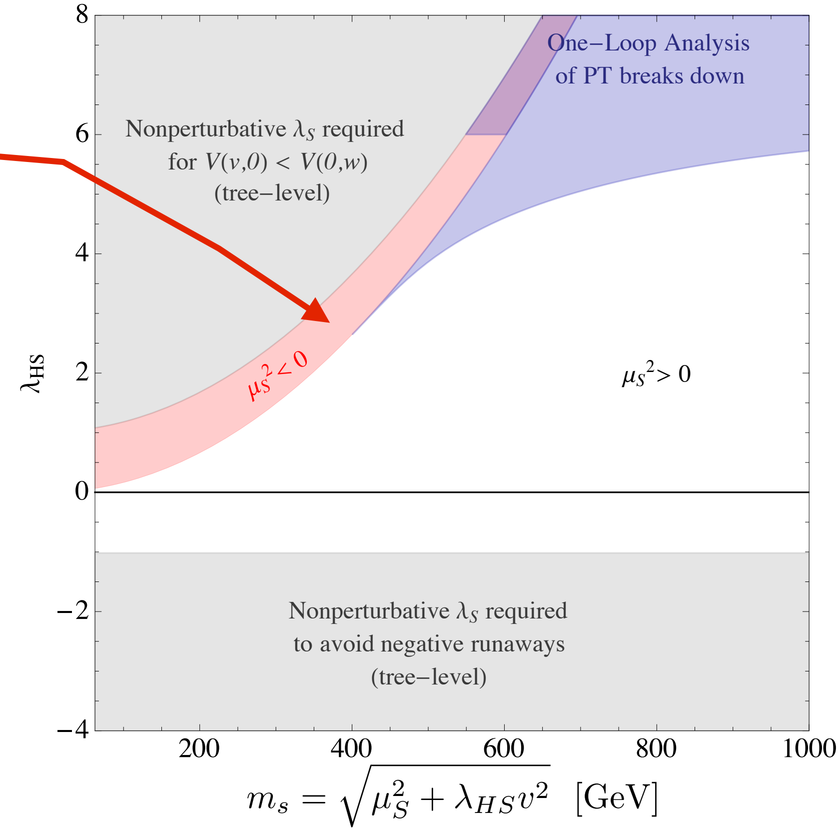


Two-Step by Tree Effects

Say you live here, with $\mu_S^2 < 0$

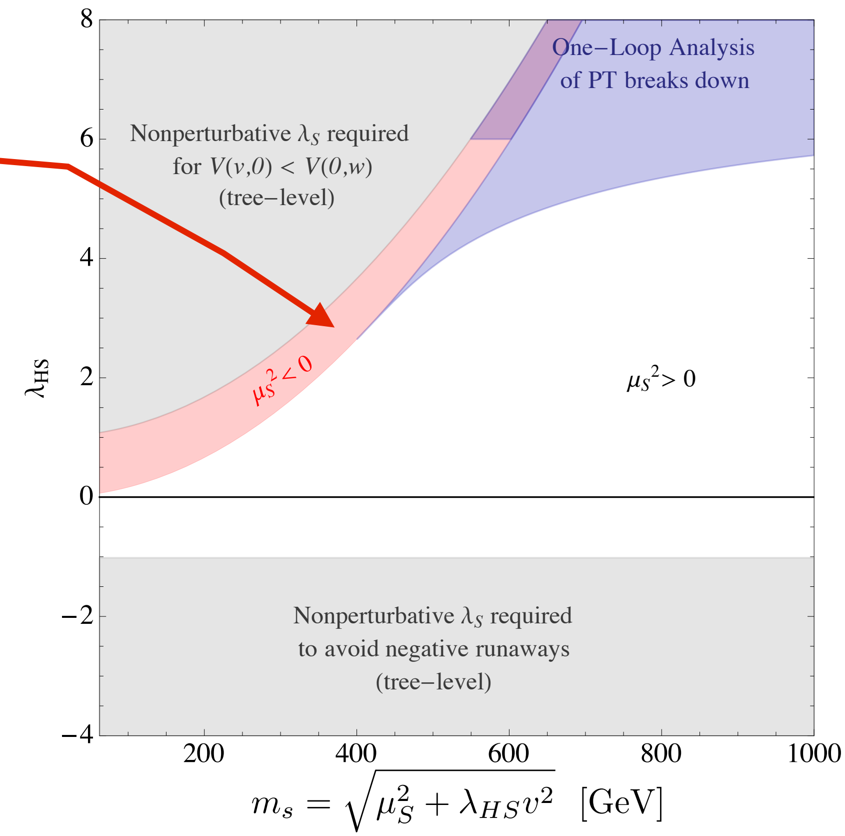
Then h and S are both unstable at the origin...



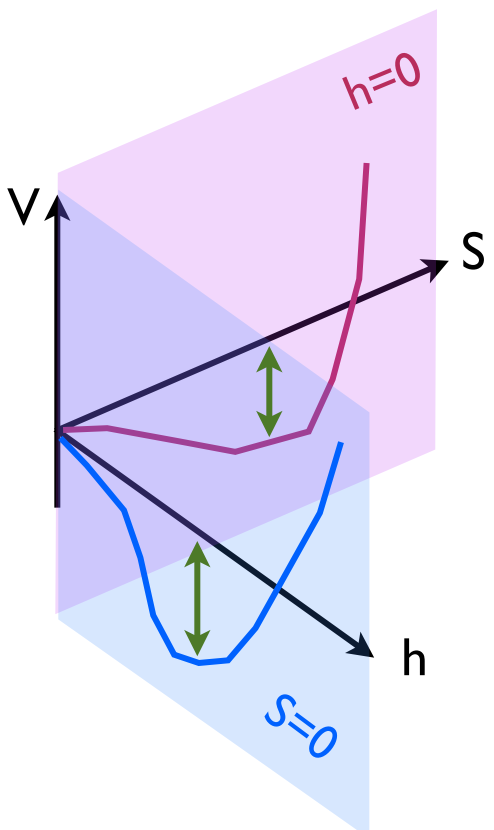


Two-Step by Tree Effects

Say you live here, with $\mu_S^2 < 0$



Then h and S are both unstable at the origin...



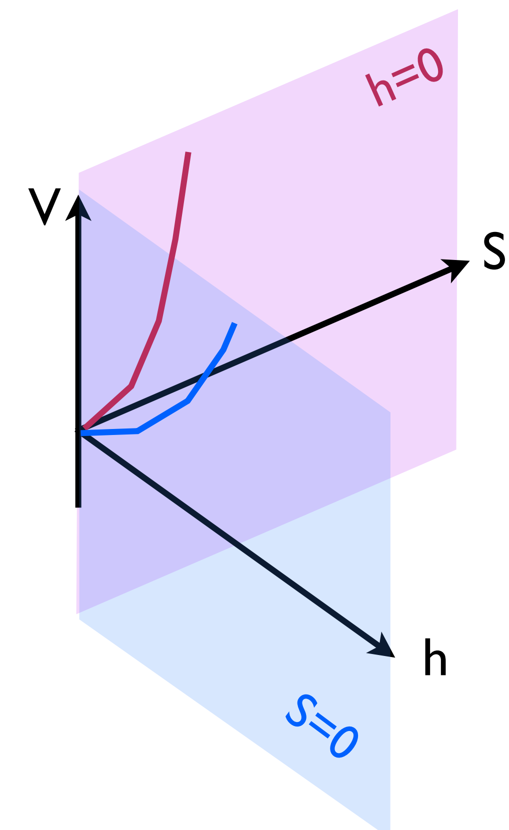
...and you can choose λ_S such that the singlet-minimum lies only a tiny bit above the EWSB minimum.

Claim: you then **always** have a strong electroweak phase transition

Two-Step by Tree Effects

$T \gg 100$ GeV

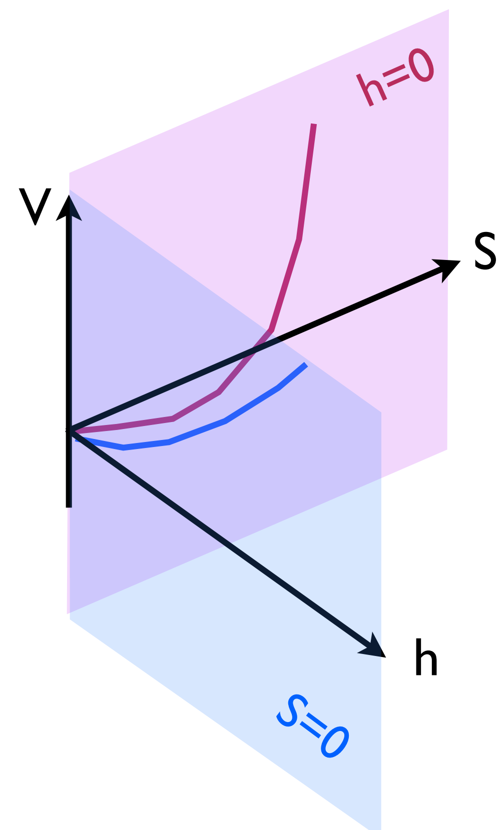
At very high temperature, both h and S are stabilized at the origin.



Two-Step by Tree Effects

$T \sim T_{c1} > 100$ GeV

As the universe cools, the singlet is destabilized FIRST, since it couples to fewer degrees of freedom in the plasma.



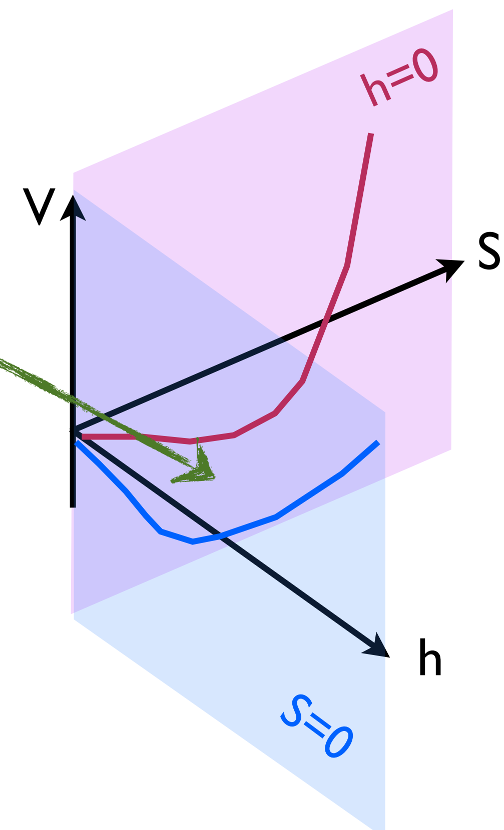
Two-Step by Tree Effects

As the universe cools some more, our EWSB local minimum appears.

It is separated from the singlet-VEV minimum by a potential barrier at tree-level.

However, the singlet-VEV minimum is still the true vacuum.

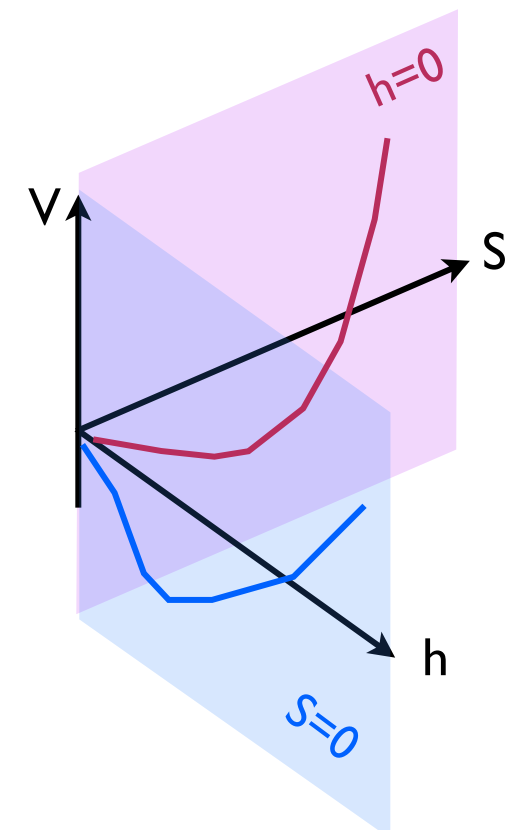
$T \gtrsim 100$ GeV



Two-Step by Tree Effects

Finally, the EWSB minimum becomes the true minimum, and the universe undergoes a 1st order PT across the potential barrier separating the two minima.

$T = T_{c2}$

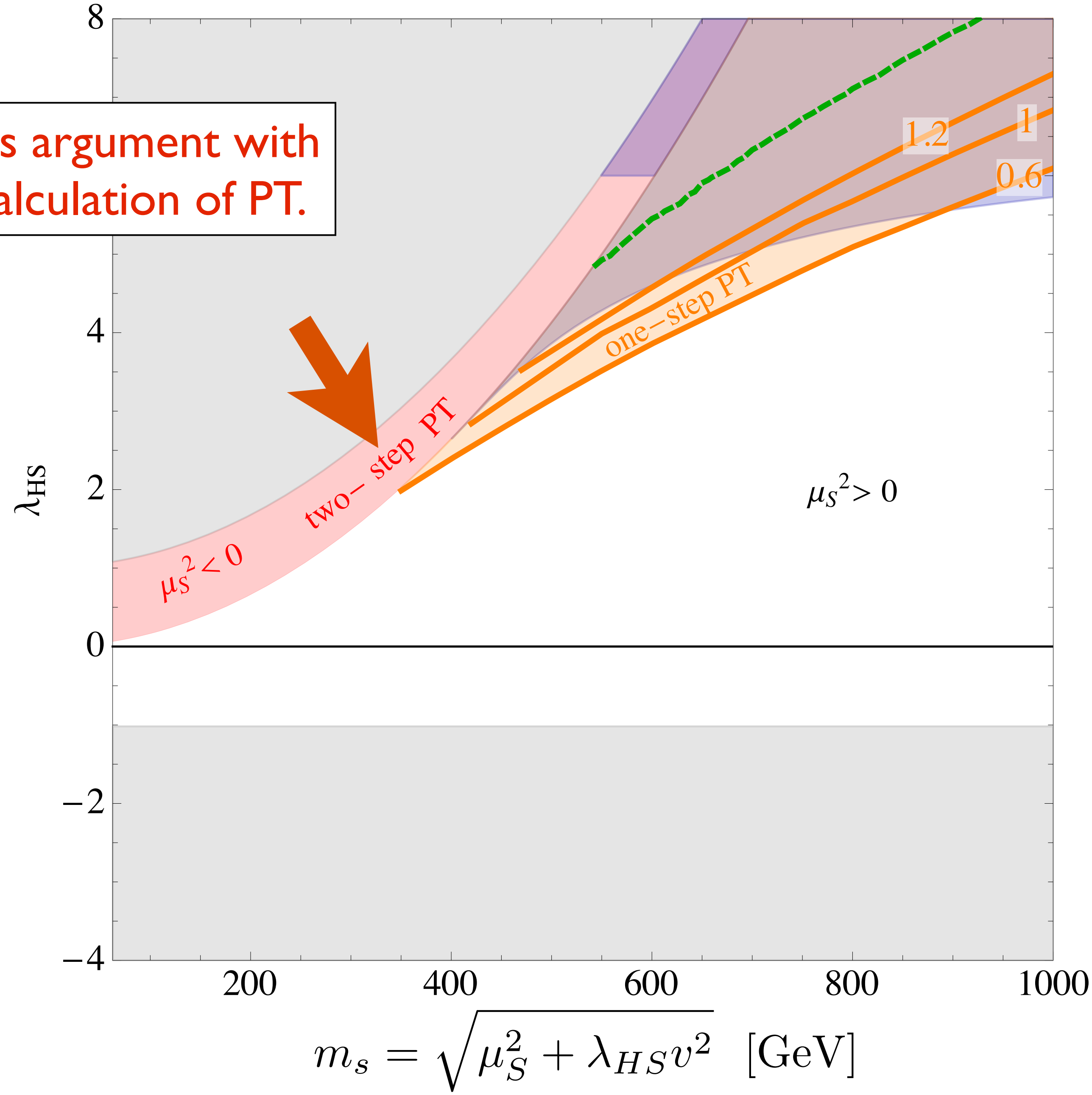


This happens at a temperature T_{c2} which is "arbitrarily" low depending on the zero-temperature potential difference (i.e. choice of λ_S)

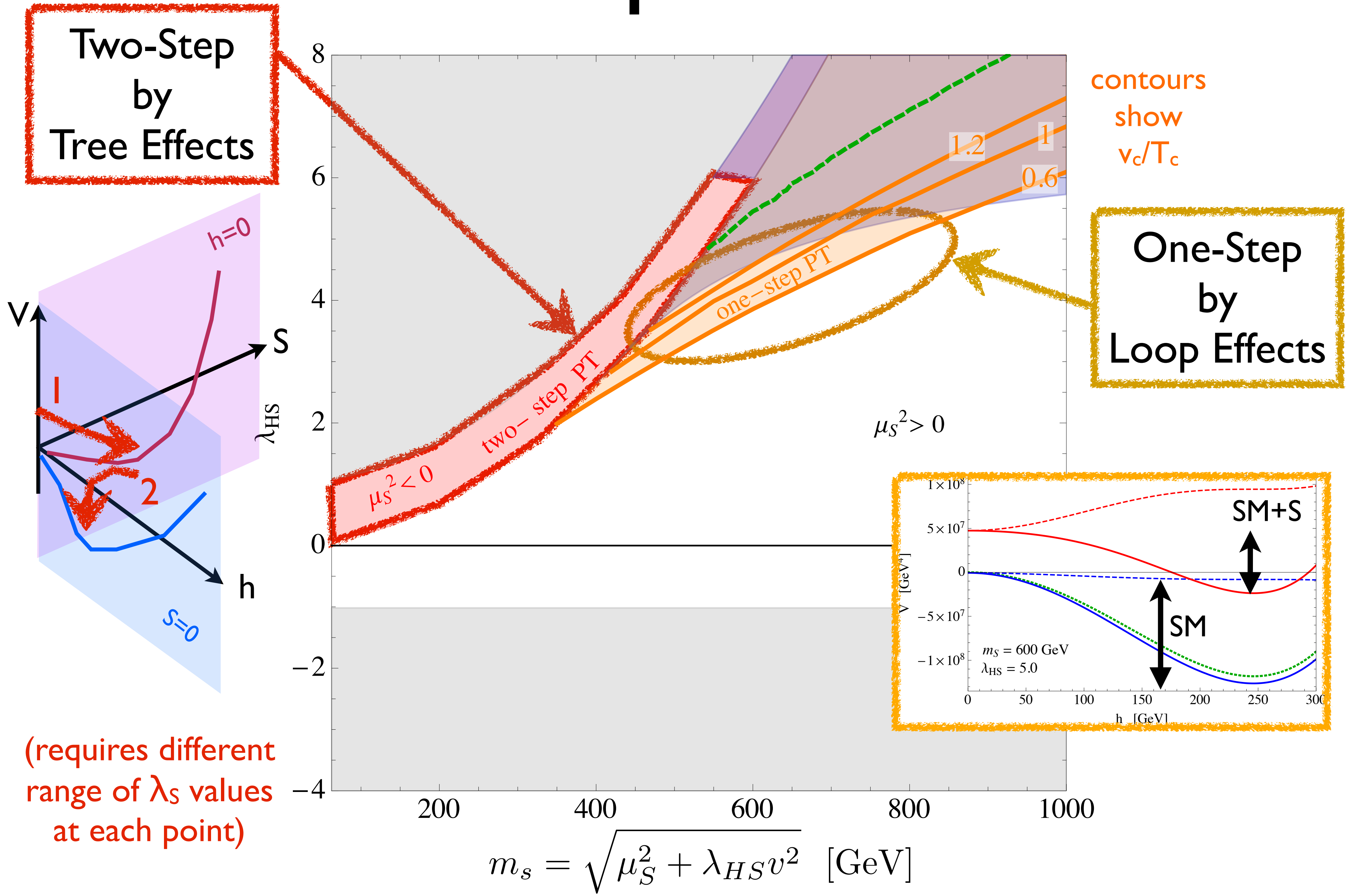
$\Rightarrow$ v_c/T_c is "arbitrarily" large $\Rightarrow$ can always have EWBG

Two-Step by Tree Effects

Verified this argument with full loop calculation of PT.



Two* kinds of phase transitions

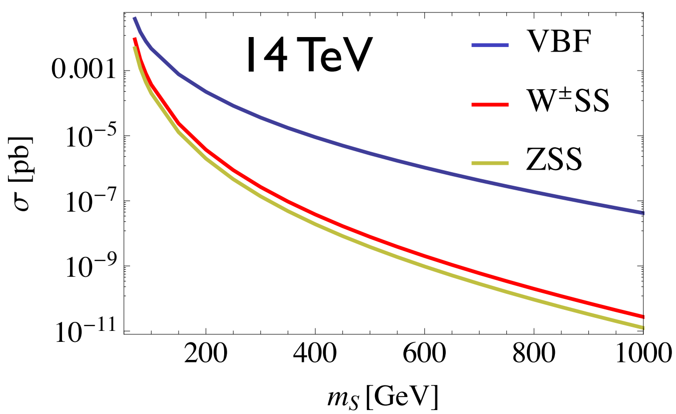


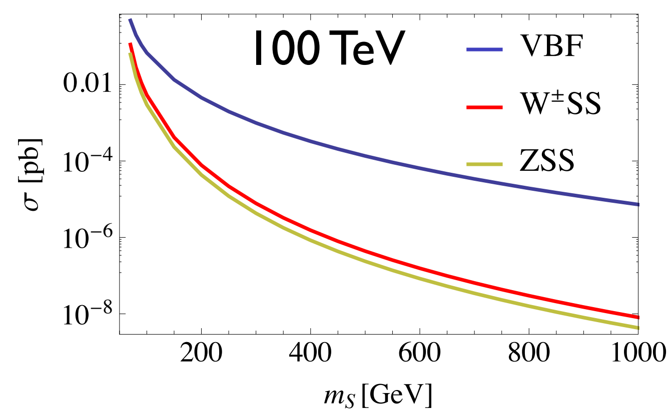
Direct Signatures of the Phase Transition

Direct Singlet Production

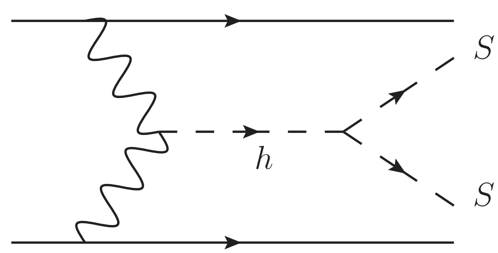
We're looking for a singlet scalar that couples to the SM via the higgs portal.

Very challenging collider signal: S is invisible, and has small production cross section via off-shell higgs.





Most promising channel:
VBF h* → SS.



Look for VBF-like dijets + MET.
Irreducible BG from jj(Z→νν)

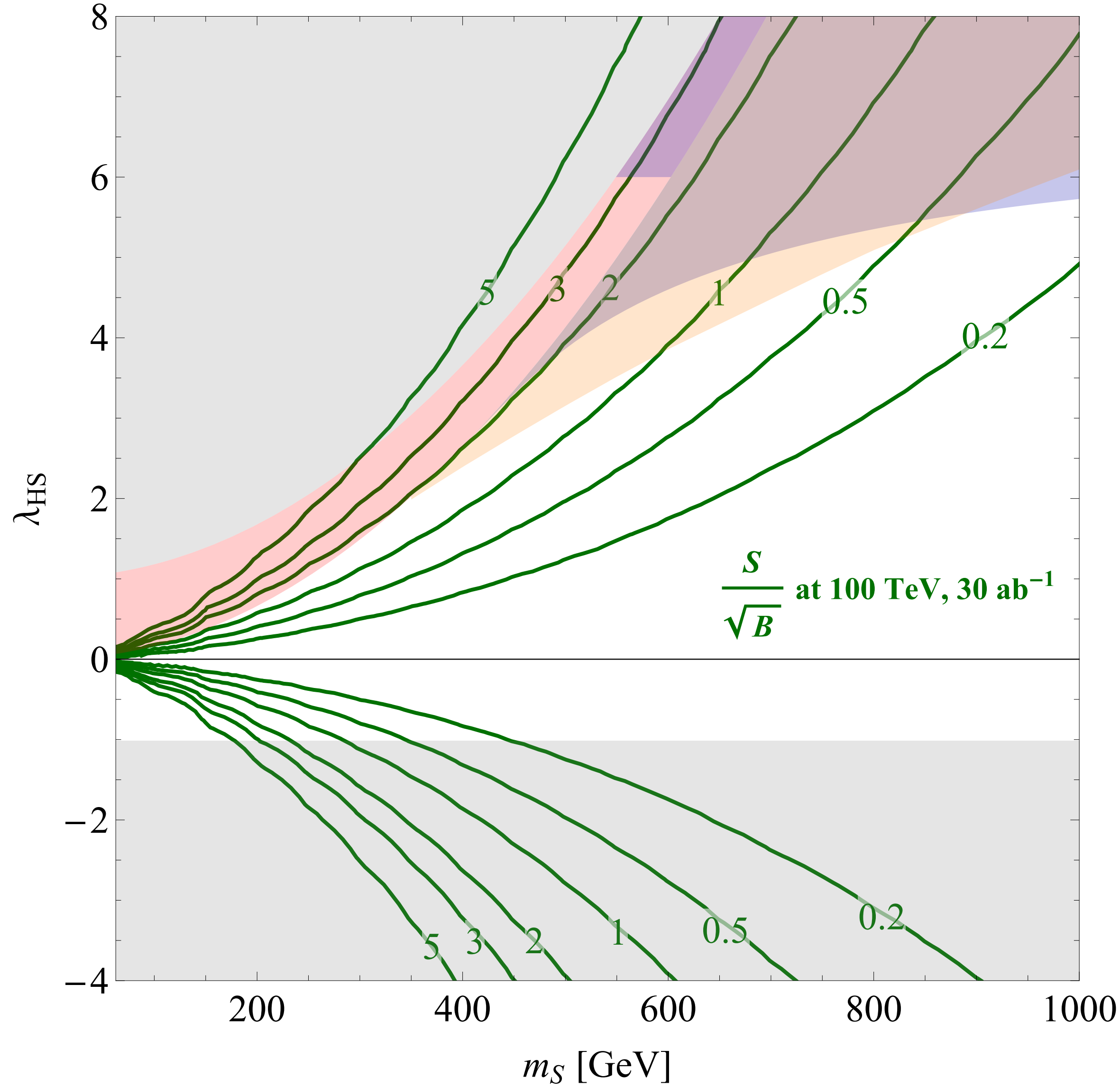
Direct Singlet Production

LHC, HL-LHC, TLEP, ILC have no chance of finding this...

But a 100 TeV collider with ~30/ab could exclude the whole two-step region.

Not as good for one-step...

(Keep in mind an actual future collider could have O(1) different capabilities...)

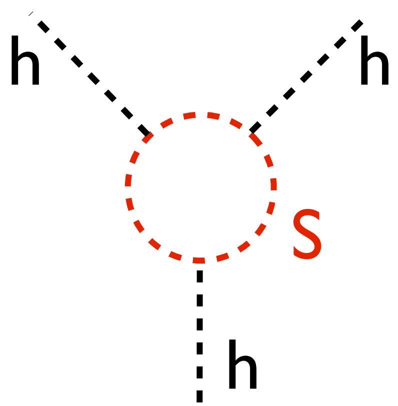


New study 1412.0258 (Craig, Lou, McCullough, Thalapillil) is in excellent agreement with our estimates.

Indirect Signatures of the Phase Transition

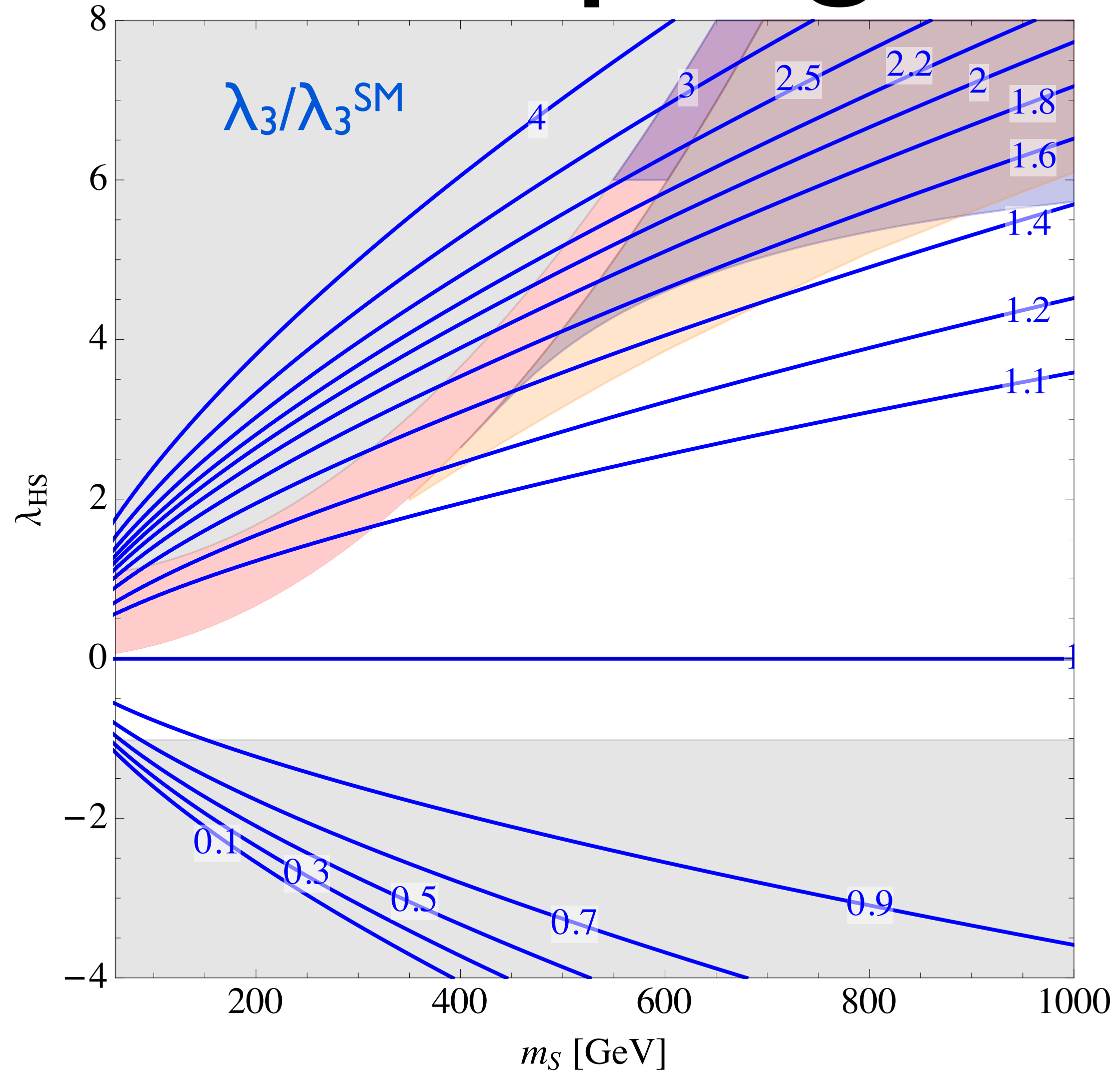
Higgs Cubic Coupling

The singlet generates a loop correction to the higgs cubic coupling.



$$\lambda_3 \equiv \frac{1}{6}\frac{d^3\left(V_0(h)+V_0^{CW}(h)\right)}{dh^3}\bigg|_{h=v}$$

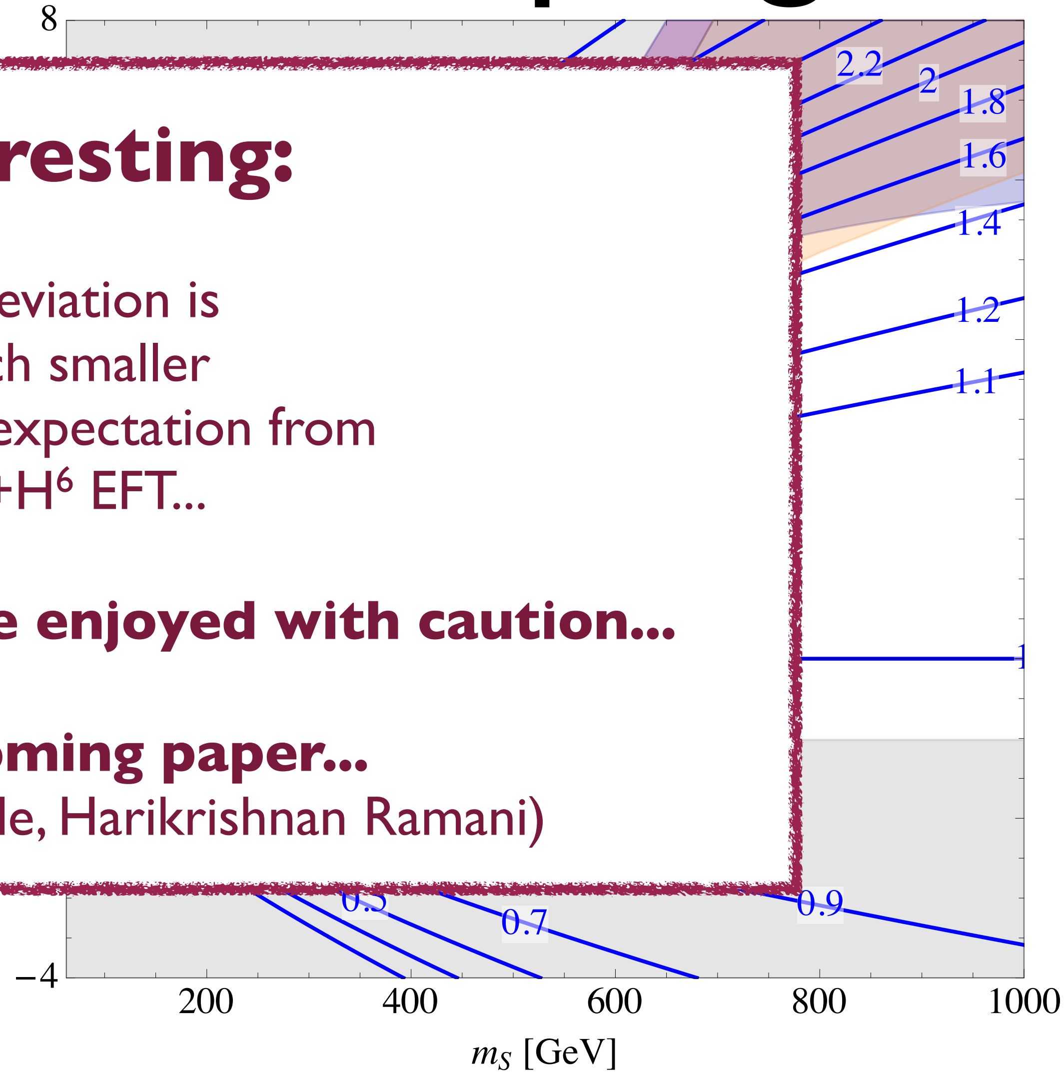
$$= \frac{m_h^2}{2v} + \boxed{\frac{\lambda_{HS}^3 v^3}{24\pi^2 m_S^2}} + \ldots$$



EWBG exclusion requires ~ 10% measurement of λ_3

(1 σ uncertainty)

Higgs Cubic Coupling



Interesting:

λ_3 deviation is
much smaller
than naive expectation from
SM+H^6 EFT...

finite-T EFT is to be enjoyed with caution...

See upcoming paper...
(DC, Patrick Meade, Harikrishnan Ramani)

hep-ph/0407019 Grojean, Servant, Wells
0711.2511 Delaunay, Grojean, Wells

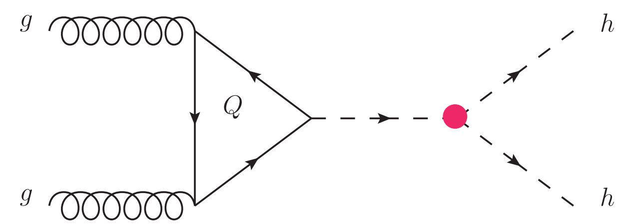
EWBG exclusion requires ~ 10% measurement of λ_3

(1 σ uncertainty)

Higgs Cubic Coupling

Precisely measuring λ_3 is **very challenging.**

Most studies concentrate on $gg \to hh$ process



Achievable precision: (1 σ uncertainties)

HL-LHC: 30-50% — ATLAS-PHYS-PUB-2013-001,

1 Tev ILC with 2500/fb: 13% — Asner, Barklow, Calancha, Fujii, Graf, et al. 1310.0763

100 TeV with 30/ab: ~ 5% — Barr, Dolan, Englert, de Lima, Spannowsky, 1412.7154

He, Ren, Yao 1506.03302

1 Tev ILC with 2500/fb almost has 10% precision.

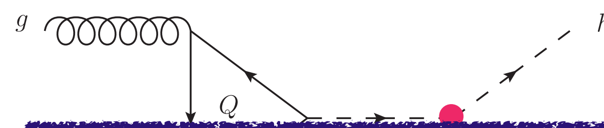
100 TeV with 30/ab surpasses 10%!

Motivates both colliders!!

Higgs Cubic Coupling

Precisely measuring λ_3 is **very challenging.**

Most studies concentrate
on gg→hh process



Achievable precision:
(1 σ uncertainties)

HL-LHC: 30-50%

1 Tev ILC with 25

100 TeV with 30/

tthh channel might yield more promising sensitivity at 100 TeV??

see upcoming analysis by Englert, Spannowsky, Thompson

extremely challenging BGs!

e Lima,
154

3302

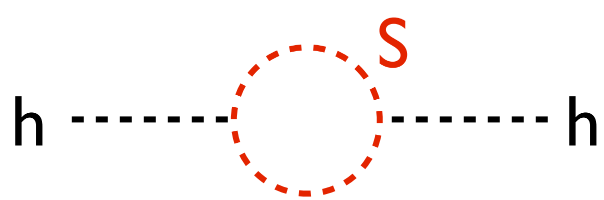
ab

1 Tev ILC with 2500/fb
almost has 10% precision.

Motivates both colliders!!

Shift in σ_{Zh} at Lepton Colliders

S-loops renormalize the higgs kinetic term, reducing all couplings slightly.



Craig, Englert, McCullough, 1305.5251

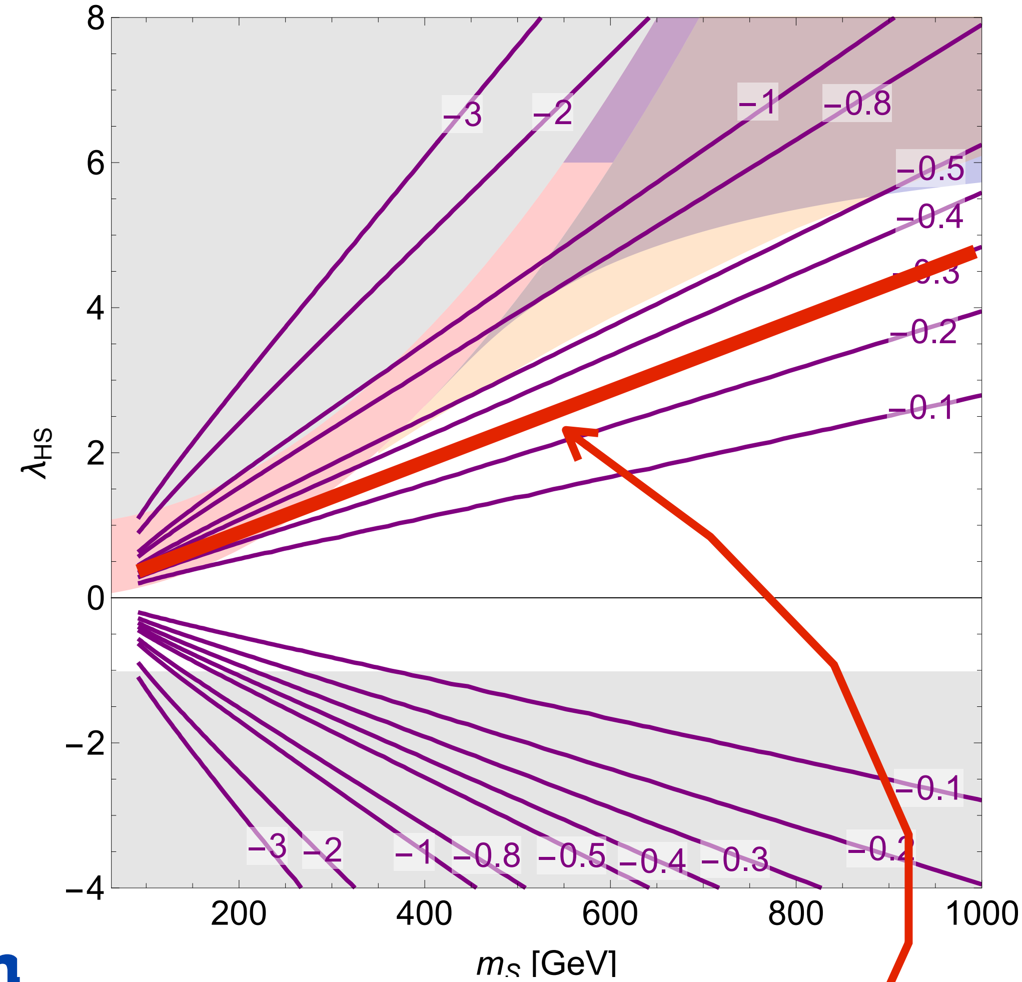
This leads to an O(0.5%) reduction in the σ_{Zh}.

ILC: 1% precision
ILCLumiUp: 0.5% precision
TLEP: 0.15% precision

Klute et al. 1301.1322

Blondel et al. 1208.0504

$\delta\sigma_{Zh}(\%)$

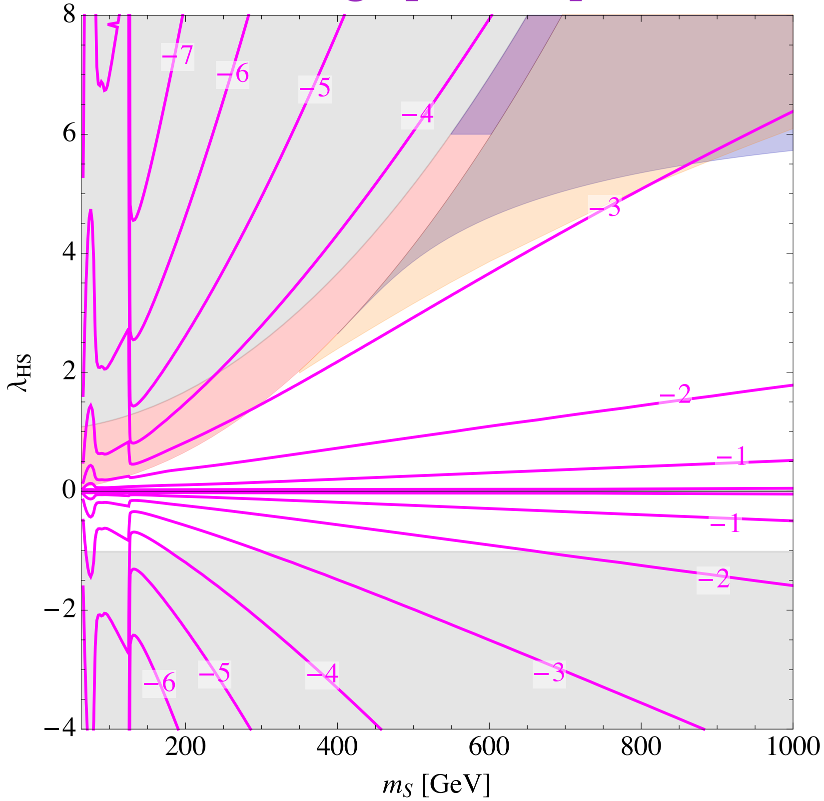


TLEP can cover much of the EWBG parameter space!

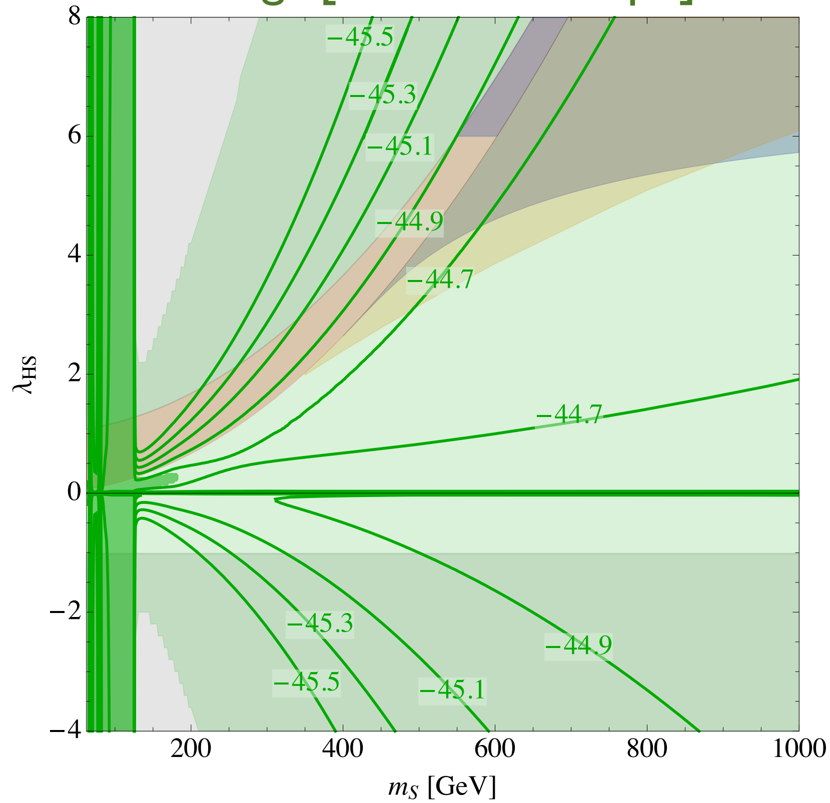
What about Dark Matter?

Singlet Scalar DM

Singlet Relic Density
$\text{Log}_{10}[\Omega/\Omega_{DM}]$



Singlet Direct Detection xsec
$\text{Log}_{10}[\Omega/\Omega_{DM} \times \sigma_S^{SI}/\text{pb}]$



Excluded by LUX
Excludable by Xenon1T

Xenon1T can exclude the singlet if it is cosmologically stable.

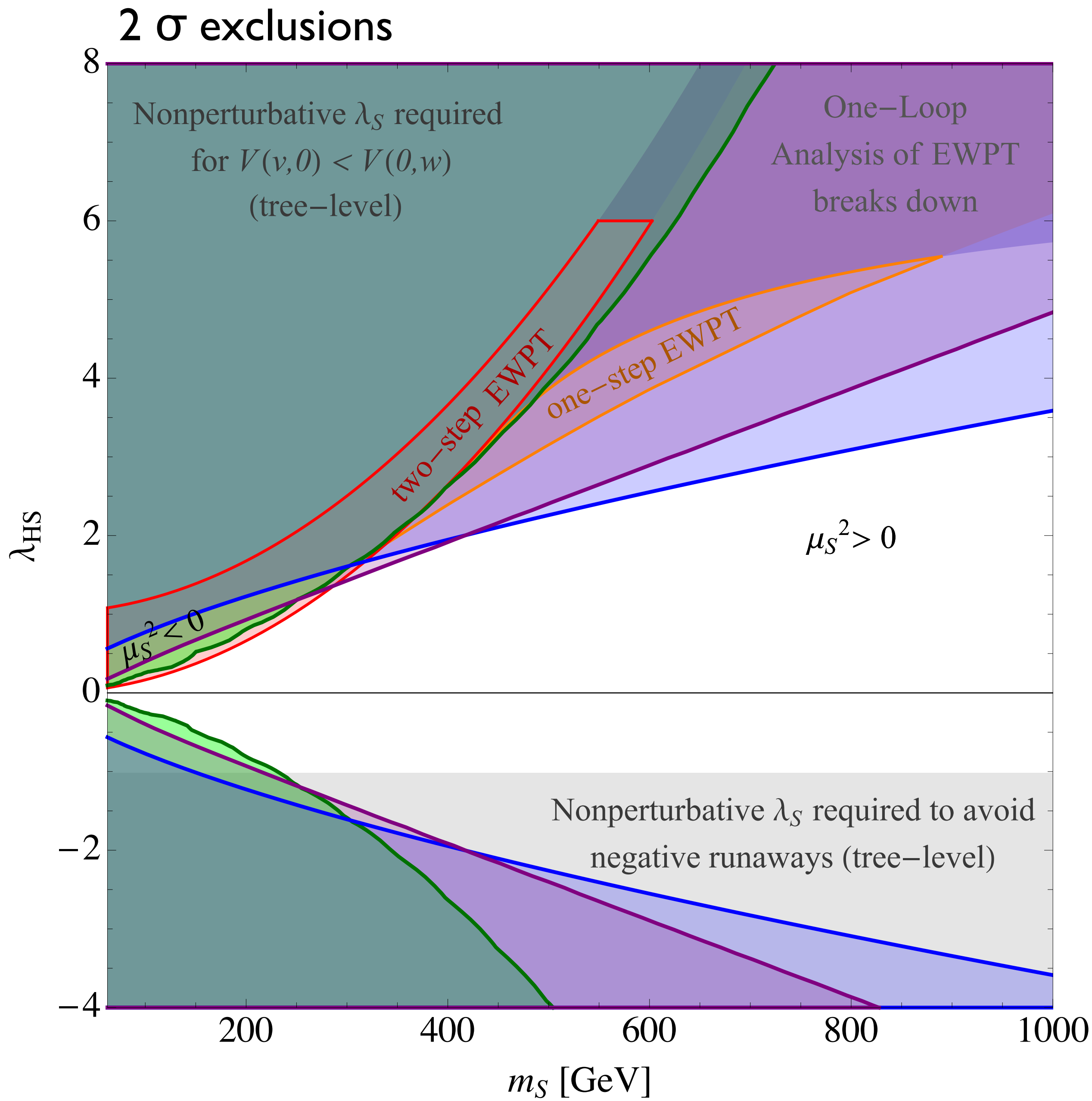
Cline, Kainulainen, Scott, Weniger 1306.4710

However, it's easy to change cosmological history of S without affecting EWBG. Not as robust an exclusion path as collider experiments!

So can we exclude EWBG in this model?

Yes!*

*(depends on future collider capabilities)



100 TeV Collider, 30/ab

triple-Higgs coupling measurement (> 10%)

Direct detection of VBF h* → SS

(S/√B > 2)

TLEP

$\delta\sigma_{Zh}$ measurement (> 0.3%)

100 TeV collider could cover *entire* parameter space.

TLEP can cover *almost all* of parameter space.

Potential complimentarily!

What’s next?

Making our findings more robust & general

EFT approach?

hep-ph/0407019 Grojean, Servant, Wells
0711.2511 Delaunay, Grojean, Wells

Finite-T makes EFT tricky!
Predictions of SM+H^6 EFT for e.g. h^3 coupling are violated by unmixed SM+S model.

Strong PT → sizable couplings, spectrum varies along Higgs potential.

How can we model-independently extract PT information using only IR information from **our vacuum**?

Many poorly understood effects feed into thermal Higgs potential.

For strong PTs, common approximations in thermal resummations break down even in the full theory.

These approximations are also incompatible with EFT matching.

We have implemented iterative numerical approaches for a more reliable calculation, which resumms the most important 2loop thermal effects while keeping field and mass dependence outside of the high-T approximation.

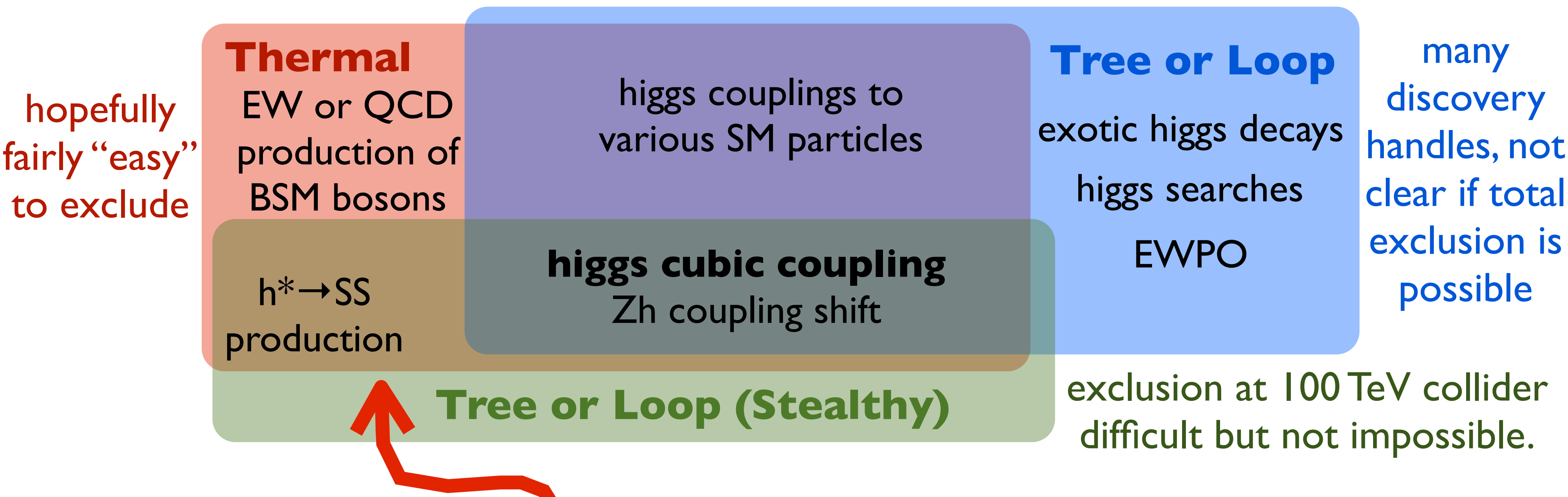
DC, Patrick Meade, Harikrishan Ramani [soon]

Conclusions

Conclusions

- Future colliders give us access to the Uncolored TeV scale. Might allow us, for the first time, to meaningfully probe the electroweak phase transition in a general sense, so we can test whether electroweak baryogenesis is possible.

- We investigate the *entire parameter space* of a maximally stealthy "nightmare scenario" for EWBG (SM + unmixed real singlet) to investigate possibility of no-lose theorem for excluding a strong phase transition (PT).



- A 100 TeV collider is necessary and maybe sufficient (**30/ab**!?) for excluding strong PT. Lepton colliders are also necessary for higgs precision, Zh shift, and possibly higgs cubic.