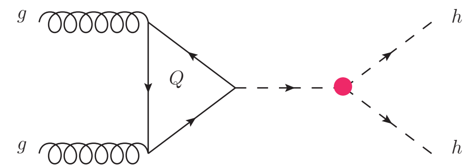
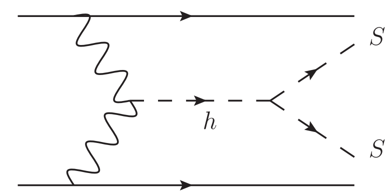
Probing Electroweak Baryogenesis at Future Colliders

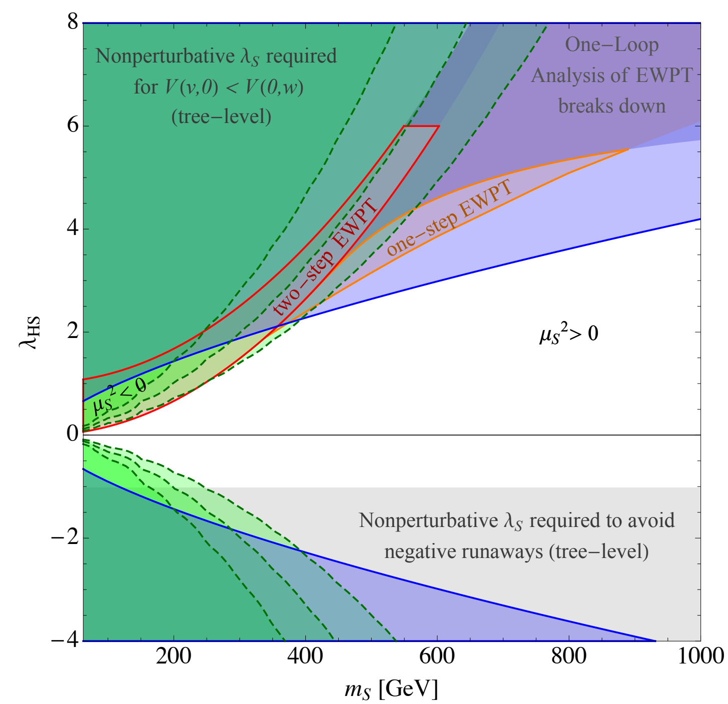




Exploring the Physics Frontier with Circular Colliders
Aspen Winter Workshop

28 January 2015

David Curtin
Maryland Center for Fundamental Physics
University of Maryland



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

Going 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.

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!

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 ~10^{-12} s old

Electroweak Baryogenesis

Higgs at High Temperatures

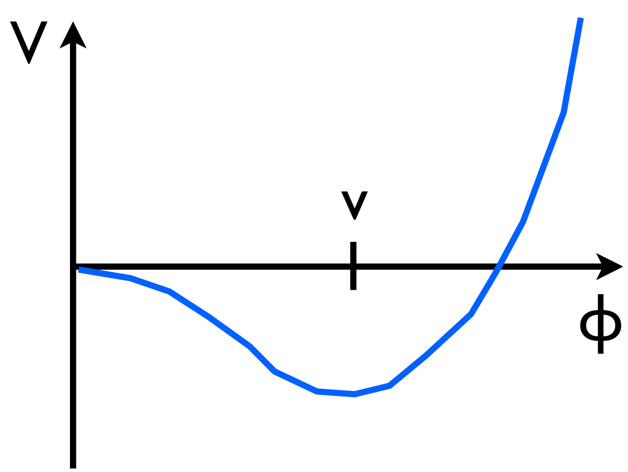
At finite temperature, the higgs potential receives new contribution from its interaction with the plasma.

Many reviews, e.g. Quiros hep-ph/9901312

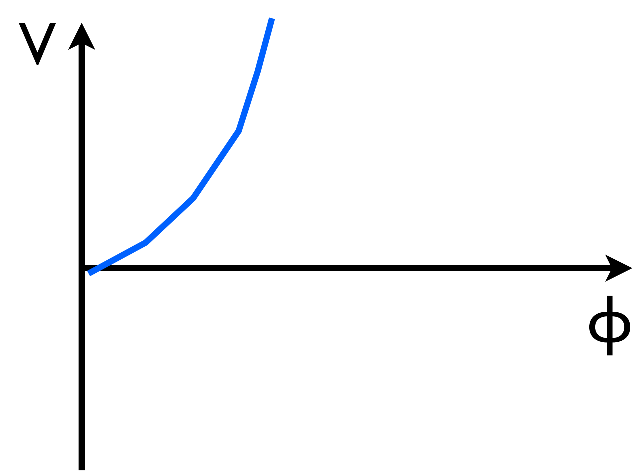
At high temperature, the higgs is stabilized at the origin.

→ The early universe was SU(2) symmetric!

T = 0

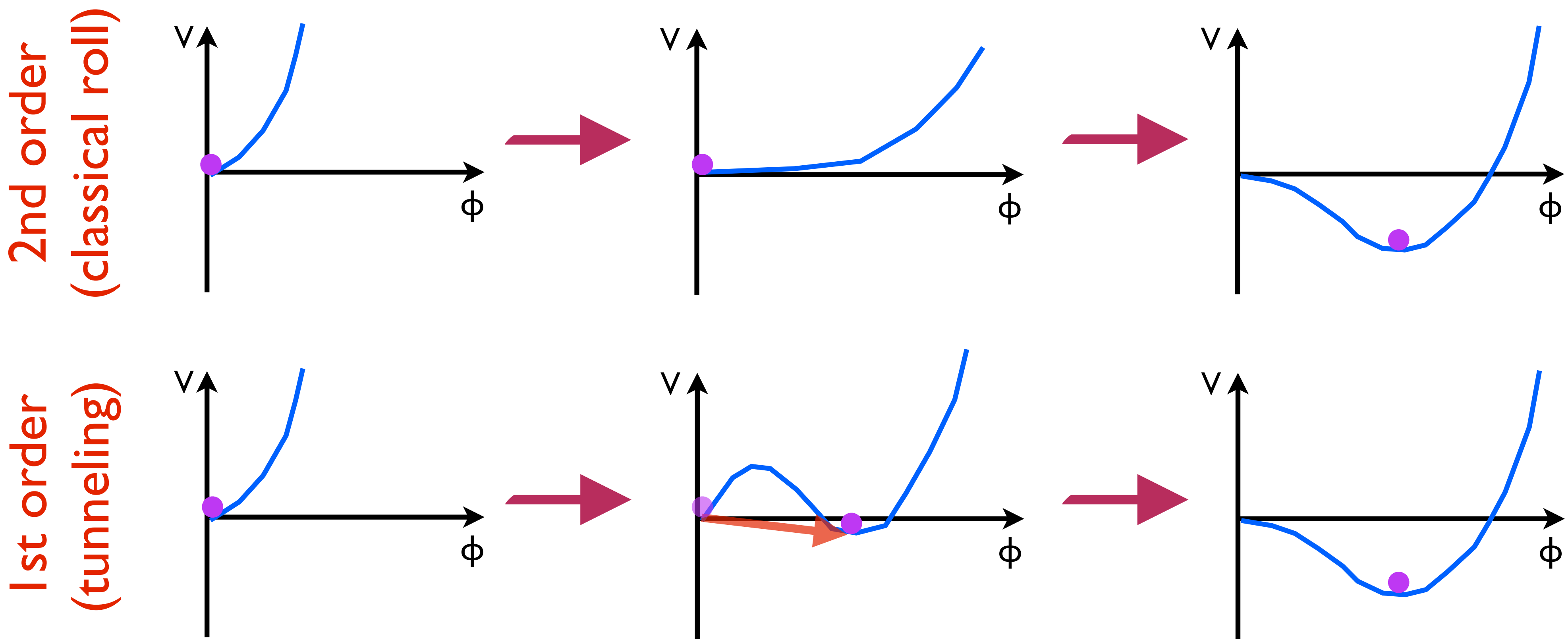


T ≫ 100 GeV



Higgs at High Temperatures

As the universe cools, the higgs undergoes a **phase transition (PT)** from zero to nonzero VEV.



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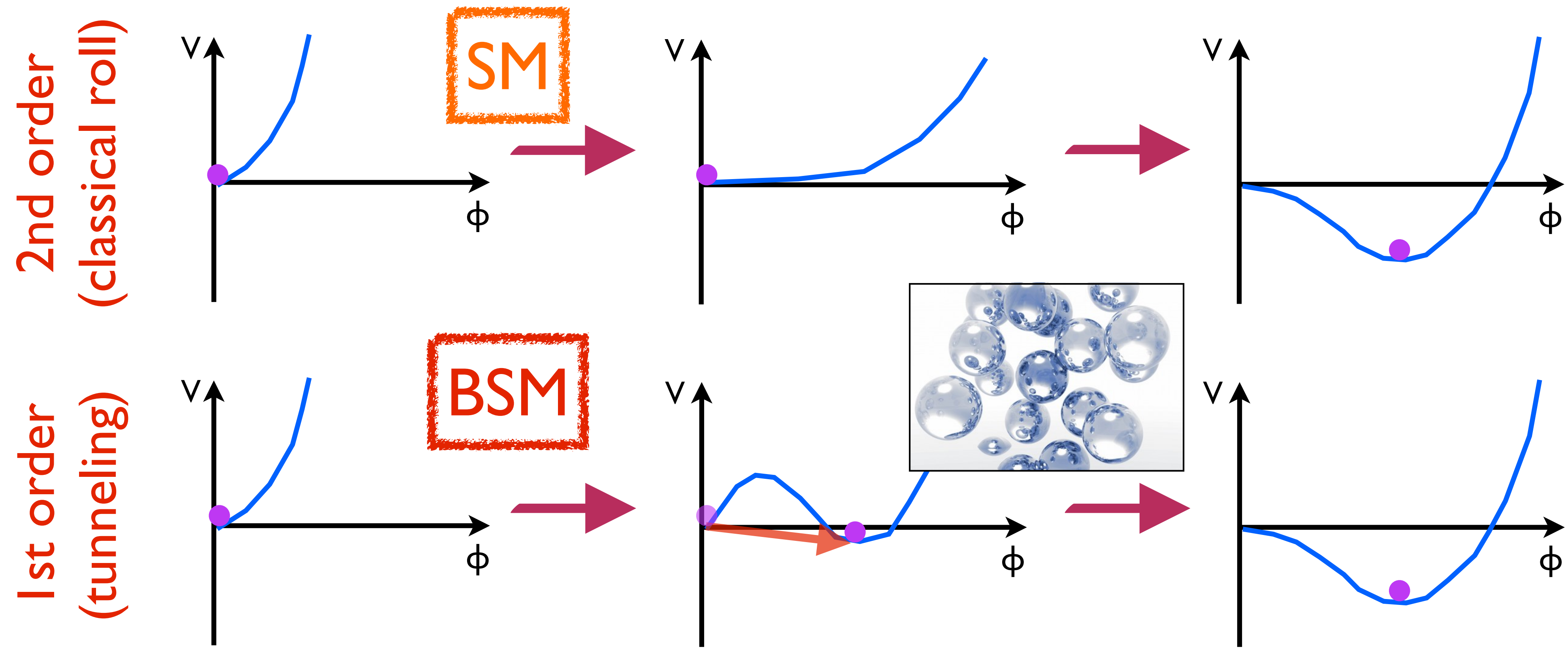


1st order phase transition gives rise to bubble nucleation!

This could create baryons...

$$\frac{n_B}{s} \sim 10^{-10}$$

Why?

To dynamically create Baryon Number Asymmetry, the three Sakharov conditions must be satisfied.

1. **B** Number Violation
2. **CP** Violation
3. **Departure from thermal equillibrium** ("**T** violation")

Most Baryogenesis mechanisms (Affleck–Dine, Leptogenesis,...) rely on very high-scale physics.

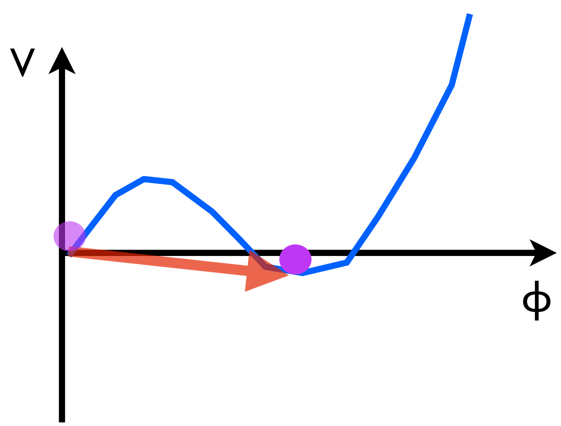
Electroweak Baryogenesis is all weak scale $\Rightarrow$ testable mechanism!

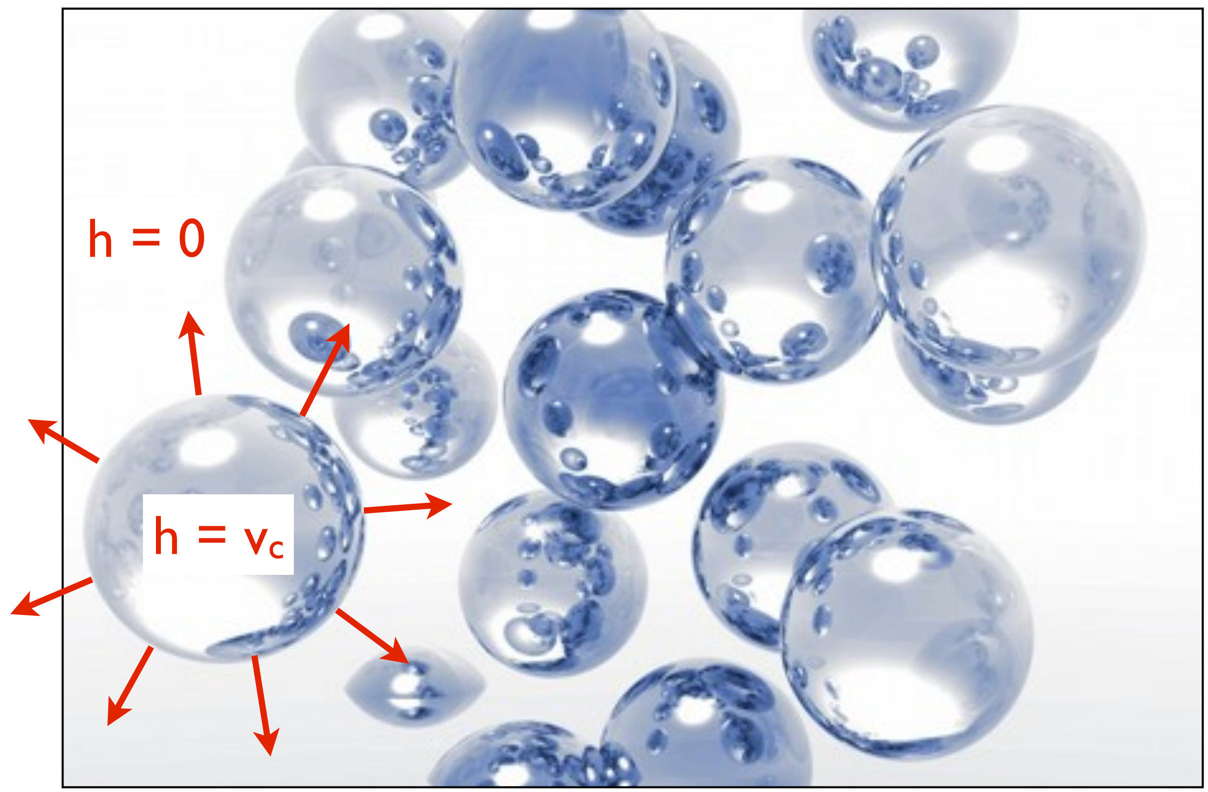
Kuzmin, Rubakov, Shaposhnikov 1985
Klinkhamer, Manton 1984
...

Electroweak Baryogenesis

say the electroweak phase transition was strongly 1st order....

At some critical temperature, bubbles of true vacuum $\mathbf{h = v_c}$ form, and grow into the false vacuum surroundings where $\mathbf{h = 0}$.





Electroweak Baryogenesis

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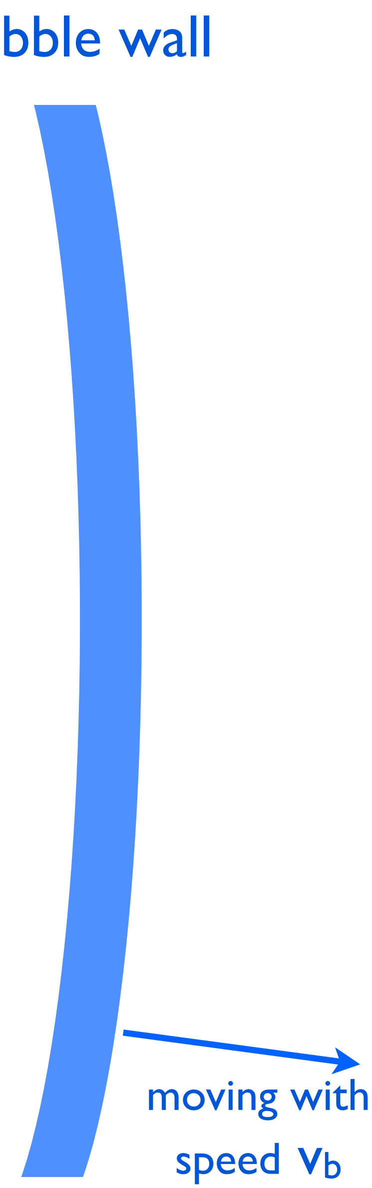
True Vacuum
$\langle h \rangle = v_c$



False Vacuum
$\langle h \rangle = 0$

$T \cong T_c \sim 100$ GeV

Electroweak Baryogenesis

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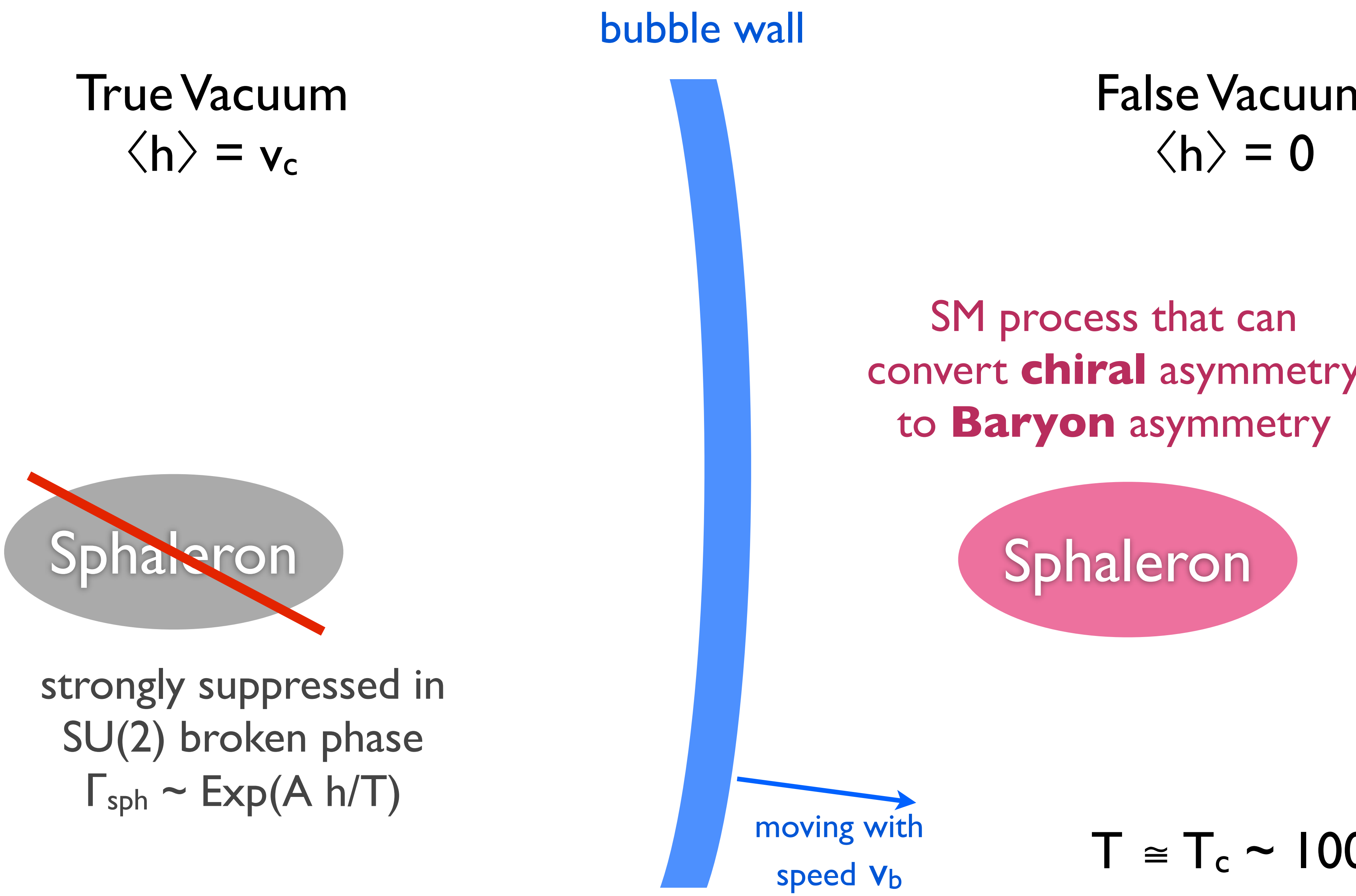

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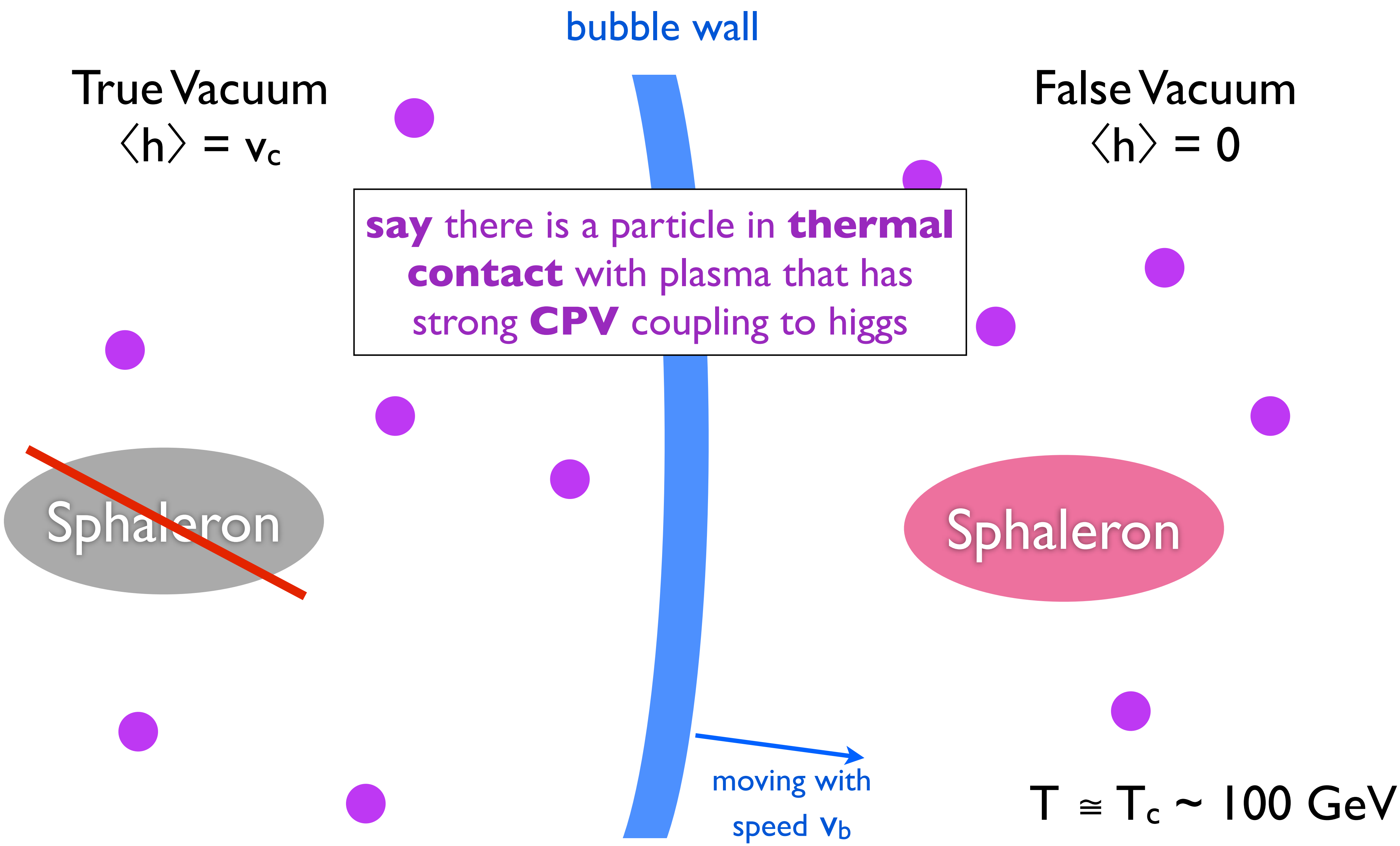

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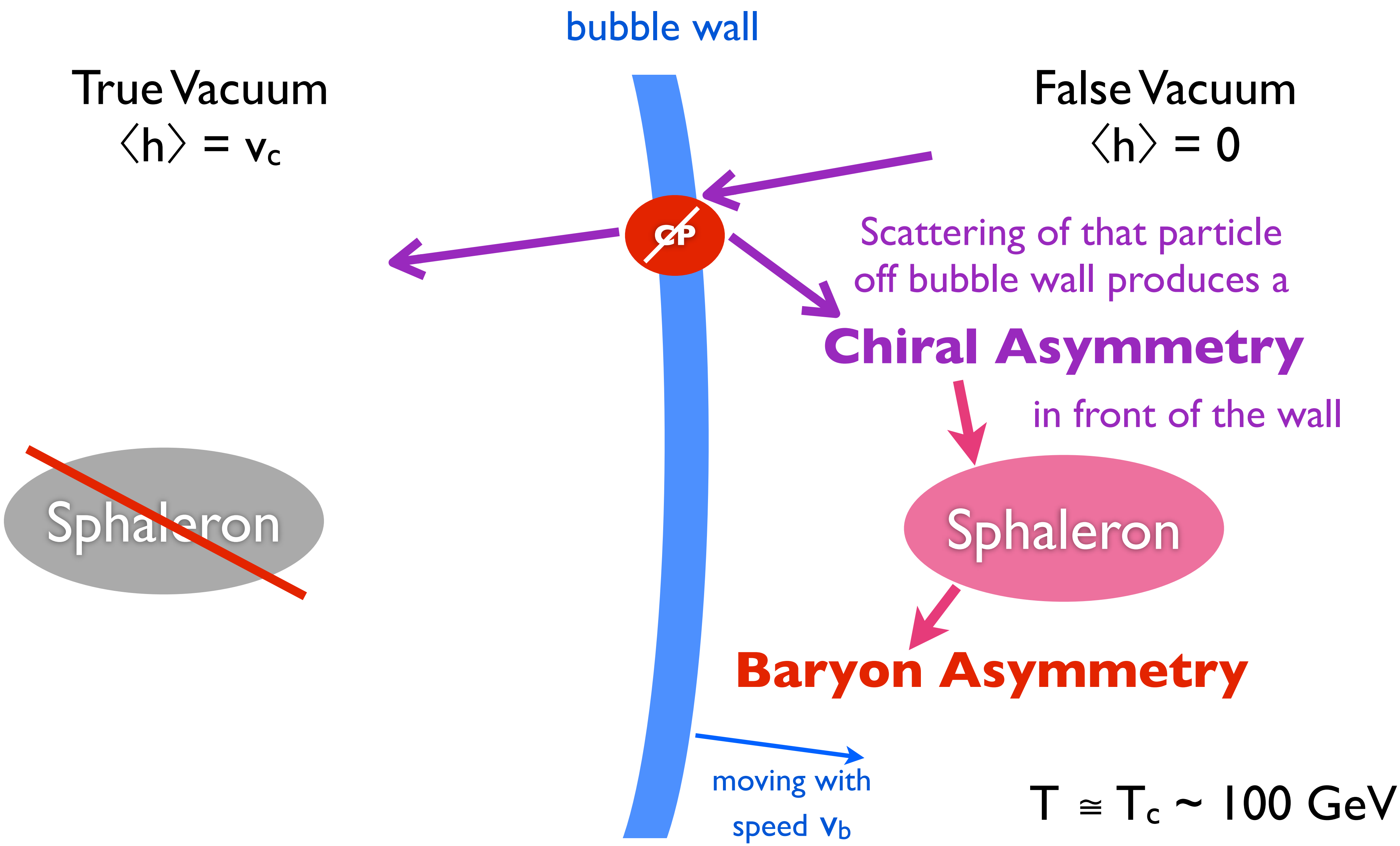

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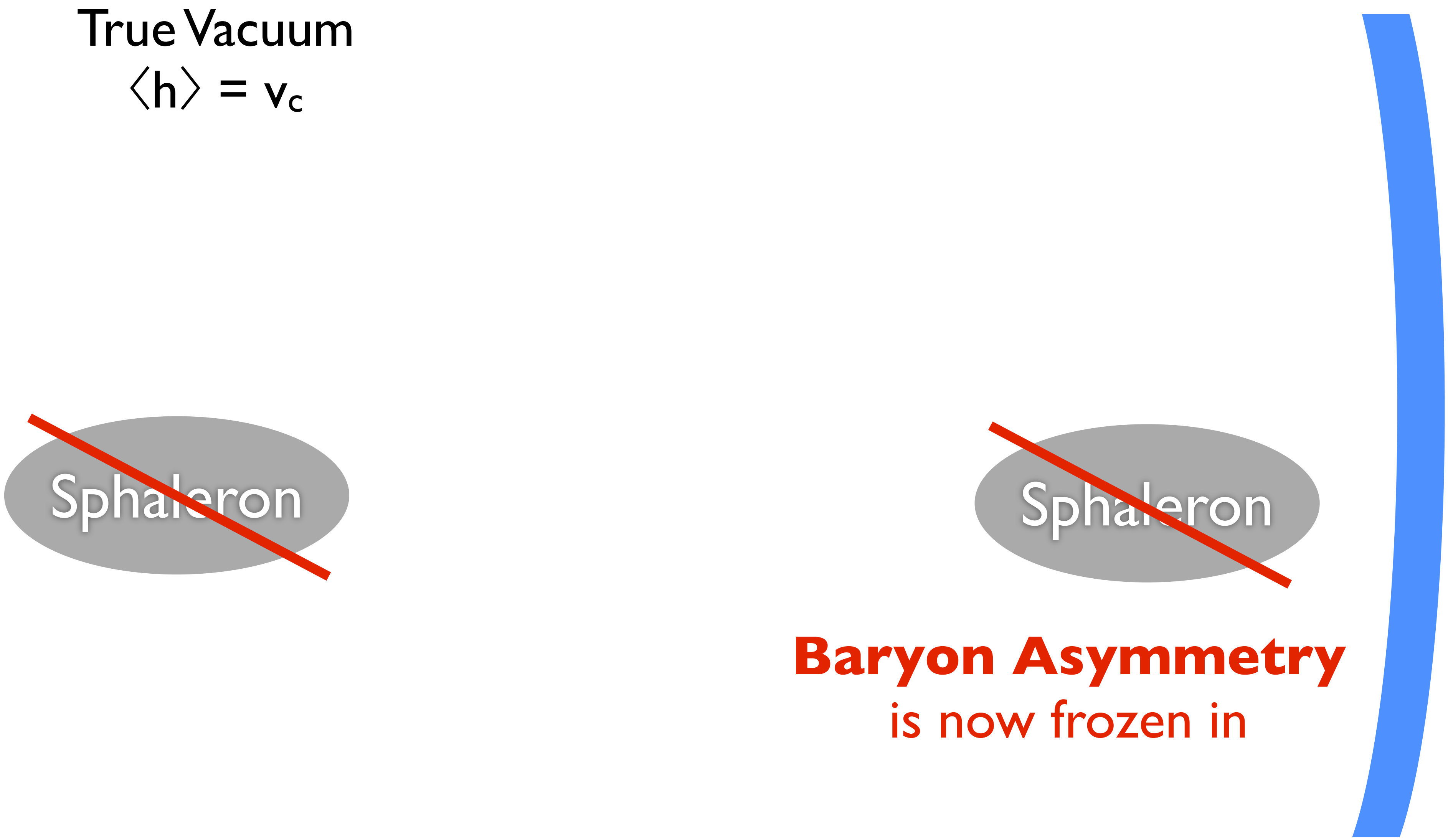
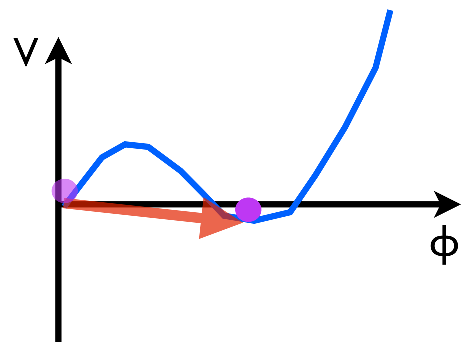


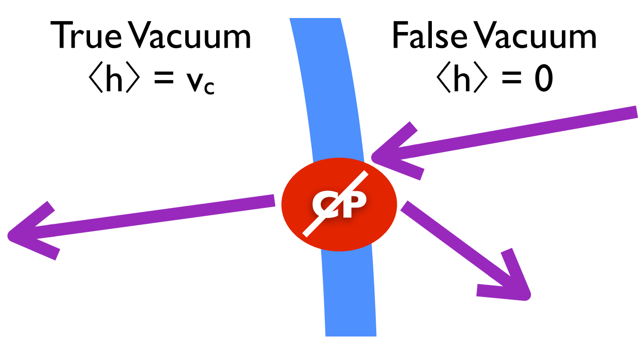
Electroweak Baryogenesis

EWBG requires two BSM ingredients:

1. Modified higgs potential to make phase transition 1st order



2. Sizable CPV coupling between higgs and another particle (BSM or SM) that is thermally active in the plasma ($M \lesssim T$)



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?

Let's factorize the two necessary conditions for EWBG

Strong phase transition

CP Violation

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also a **huge** literature...

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Try and exclude this

CP Violation

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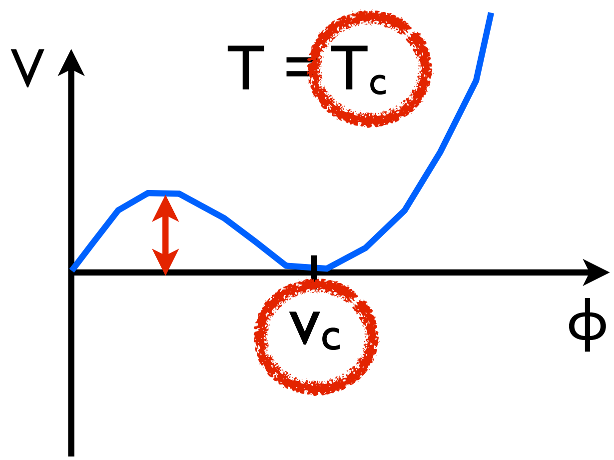
huge literature...

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.

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

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

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

No-Lose Theorem?

Central question:

can you come up with a "no-lose" theorem that **this**:

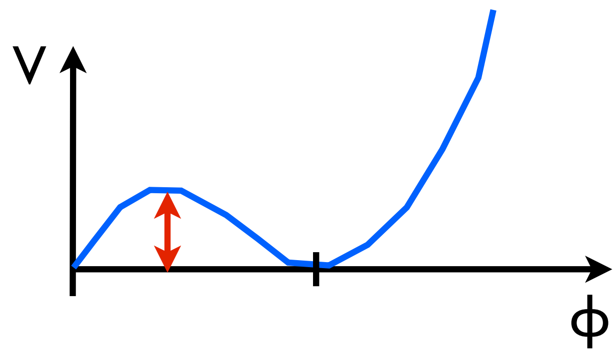
$$\frac{v_c}{T_c} > 0.6 - 1.6$$

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 $v_c/T_c \gtrsim 1$?

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

tree-level potential — loop correction — finite temperature corrections

Achieving a strong PT

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

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

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

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

Classic example: light stop scenario in MSSM.
Basically excluded from higgs coupling measurements!*

*Carena, Nardini, Quiros, Wagner 1207.6330

More generally:

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

⇛ 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, large corrections to **higgs cubic coupling**.

Promising...

Thermally driven PT

Classic example: light stop scenario in MSSM.

Cohen, Morrissey, Pierce 1203.2924,
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Exclusion or discovery
is relatively easy here!

00 GeV to be in
ing the PT.

⇛

Large direct production cross section at LHC
Large

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

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

⇛ If it is

Di LENGING!

bu tiplicity.

→Generally, large corrections to **higgs cubic coupling**.

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

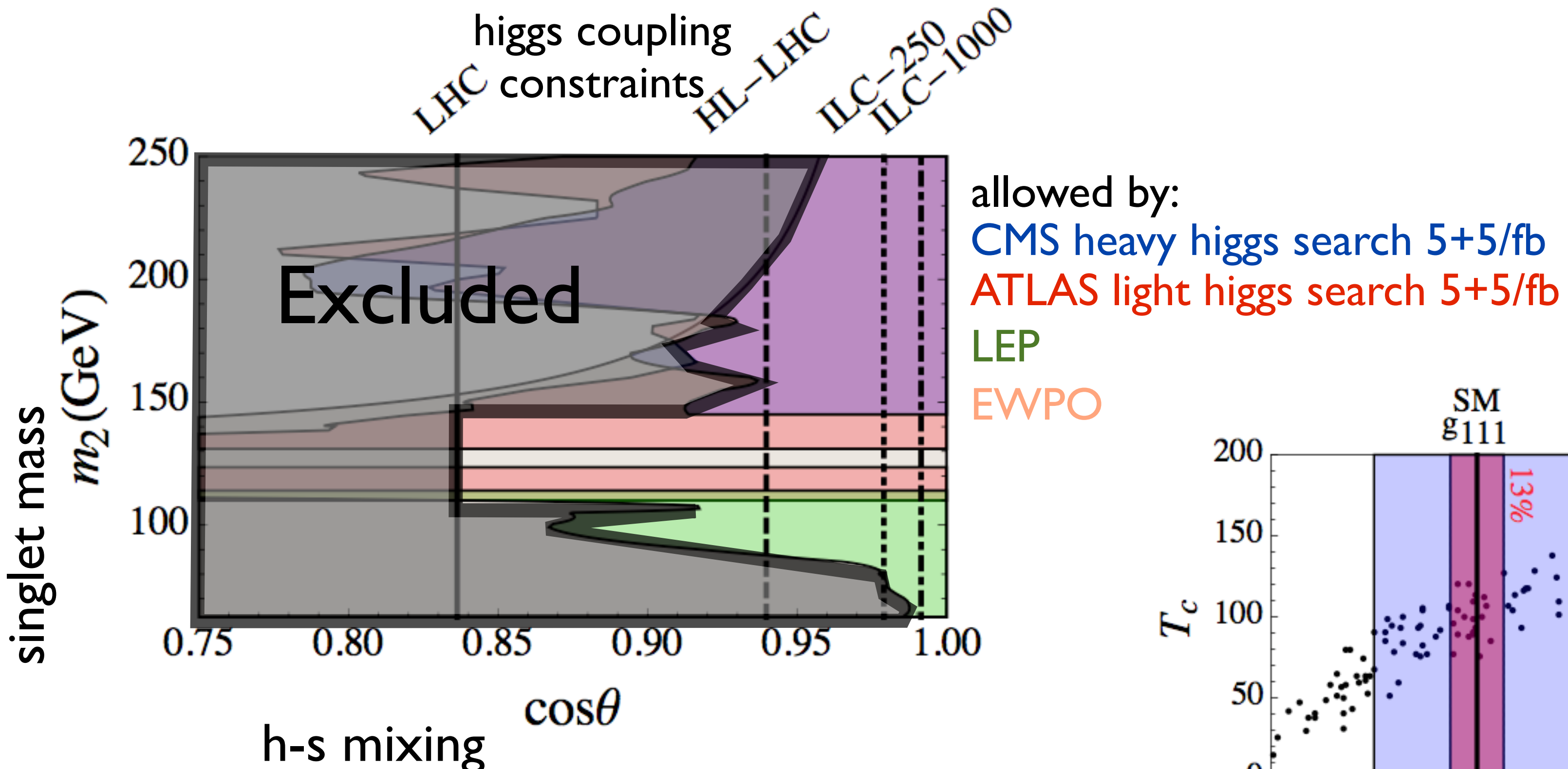
A lot of handles for discovery!

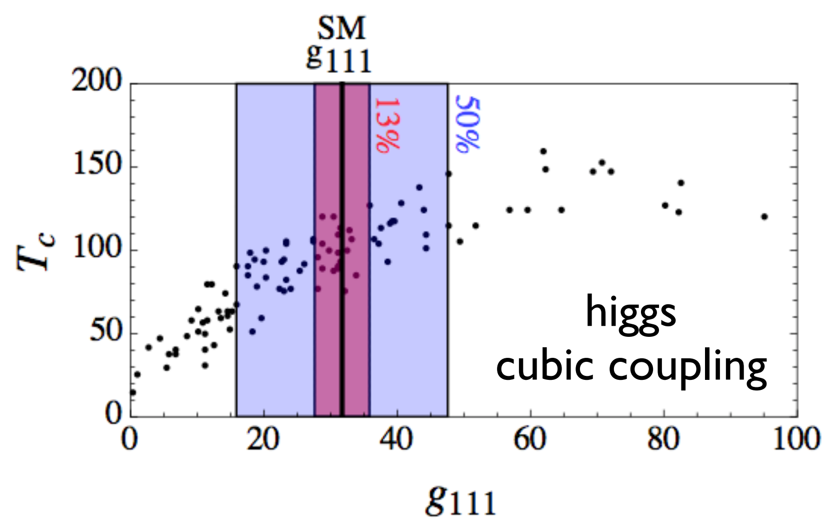
But the model still has many parameters. Can EWBG be completely excluded?

Tree and Loop-driven PT

Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342

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





Possible to get PT even with ILC constraints.

How does this correlate with higgs cubic coupling?

Tree and Loop-driven PT

Need 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

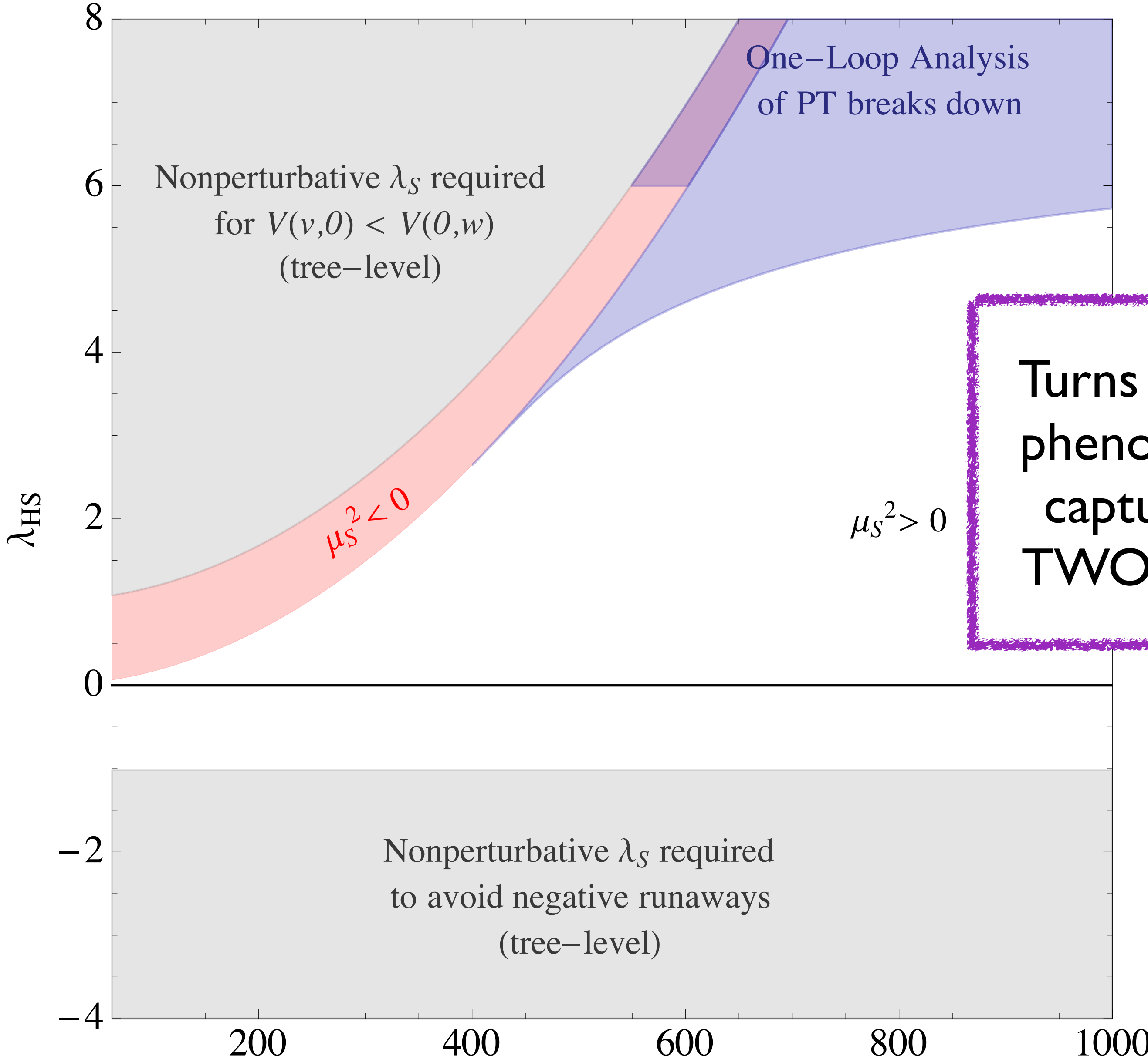
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

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

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

The (m_S, λ_{HS}) Plane

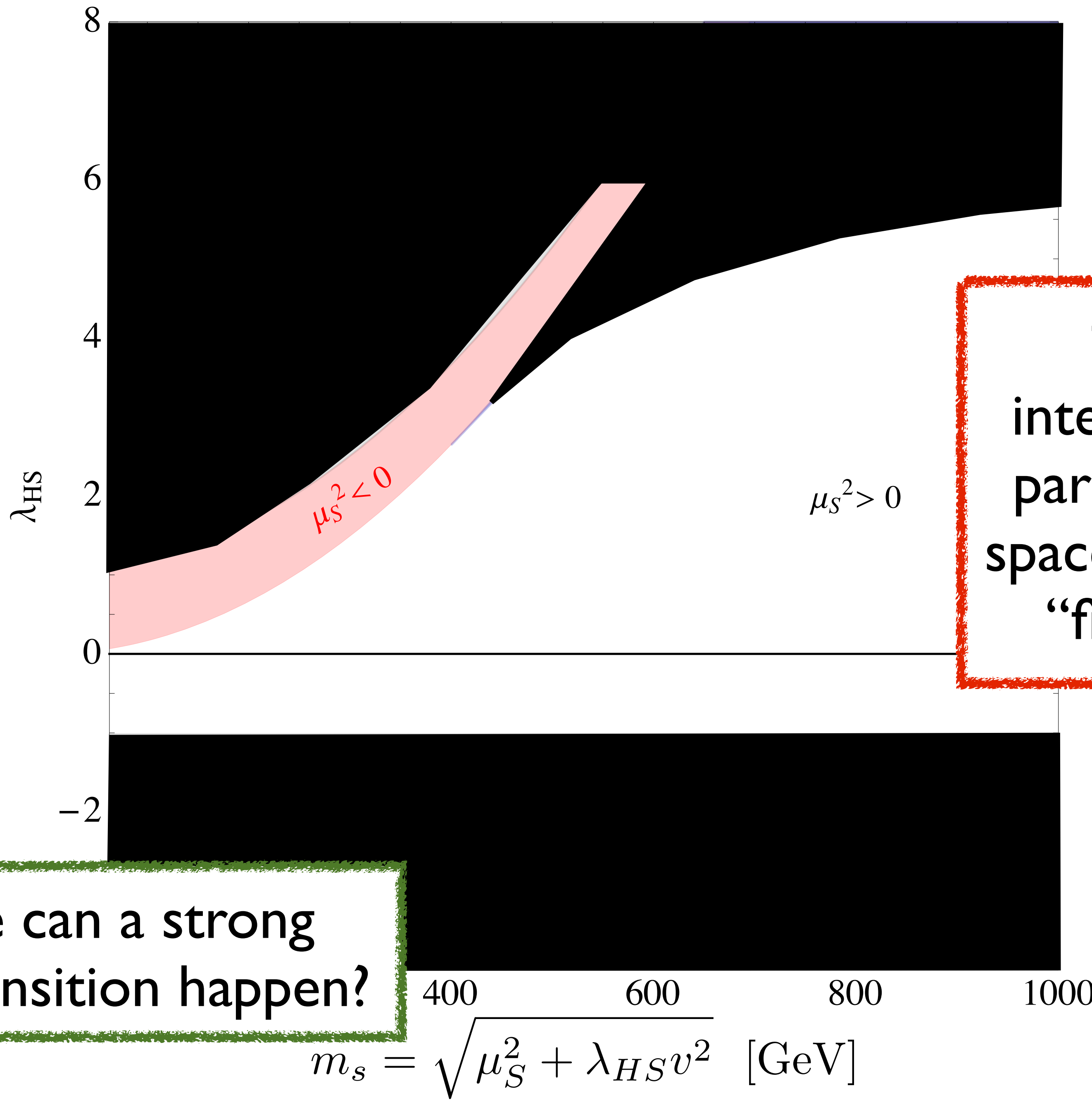
singlet-higgs coupling



Turns out ENTIRE phenomenology is captured by just TWO parameters

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

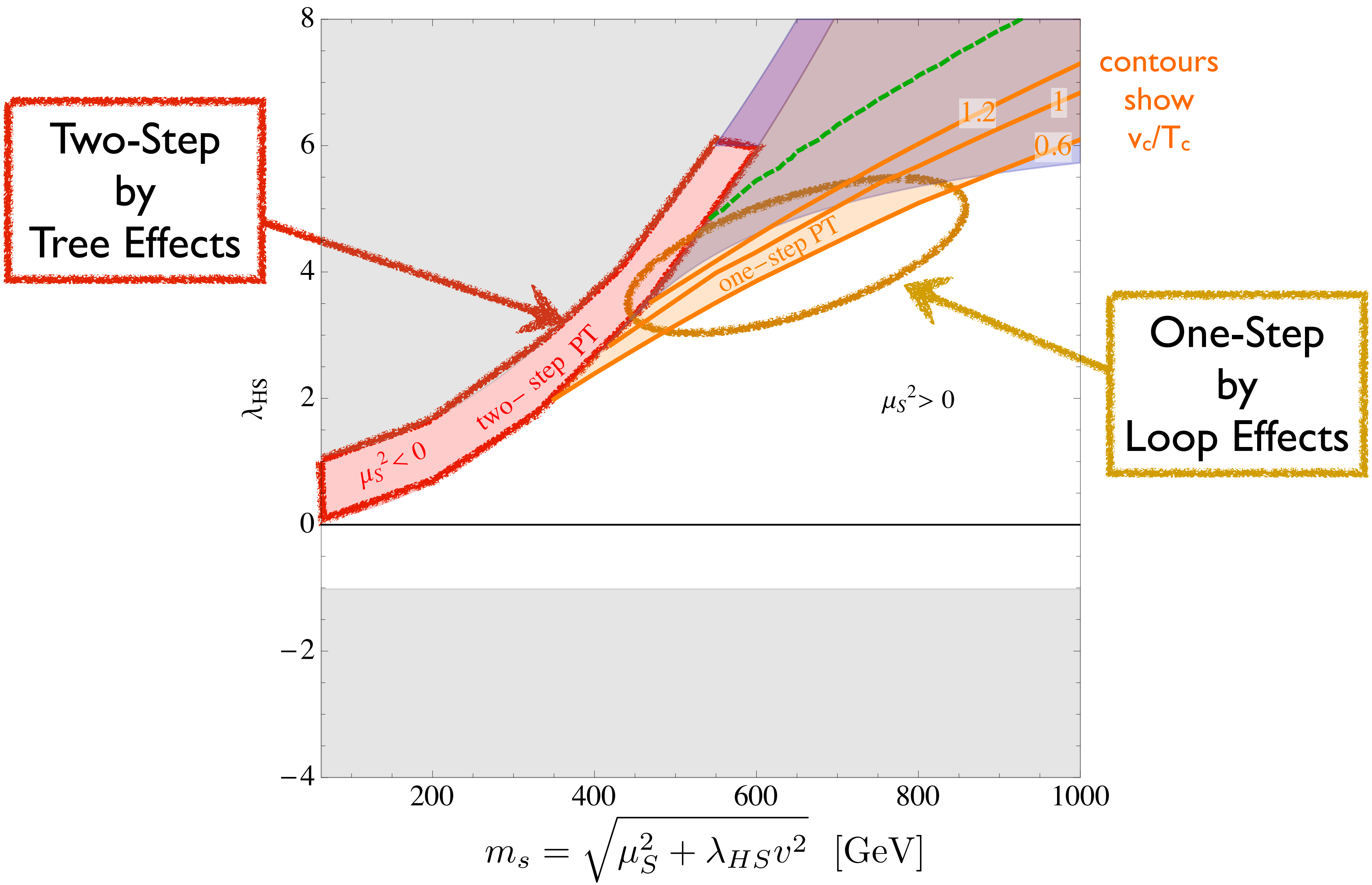
The (m_S, λ_{HS}) Plane



The interesting parameter space is very "finite".

Where can a strong phase transition happen?

Two* kinds of phase transitions

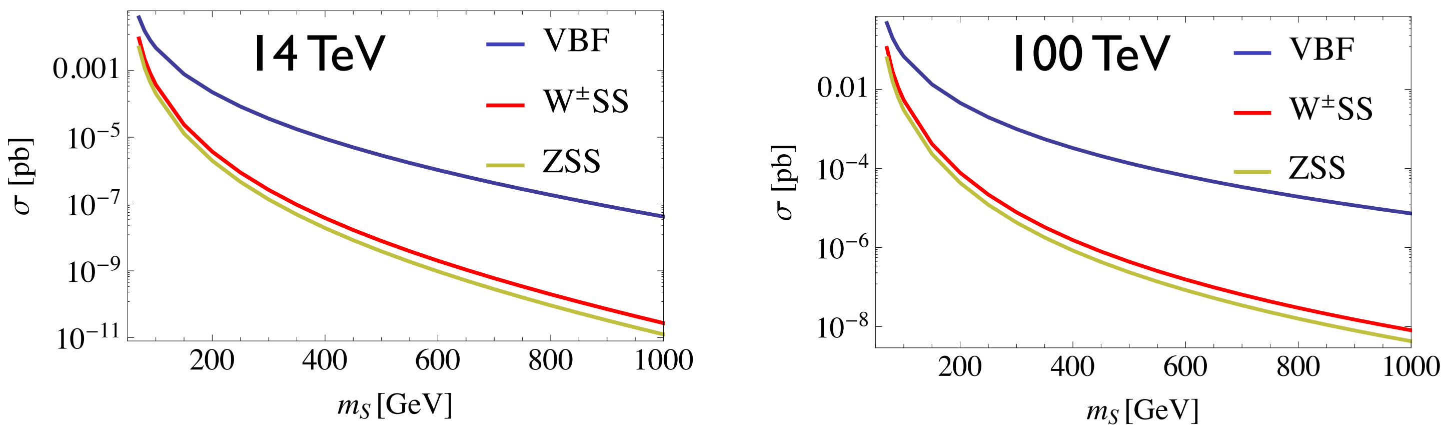


Direct Signatures of the Phase Transition

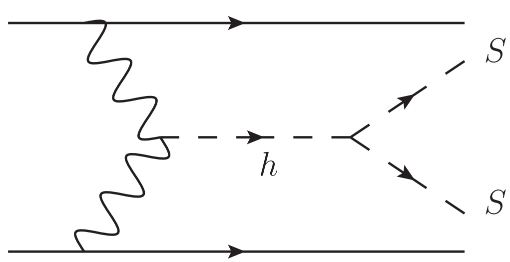
Direct Singlet Production

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 $h^* \to SS$.



Look for VBF-like dijets + MET. Irreducible BG from $jj(Z \to \nu\nu)$

Direct Singlet Production

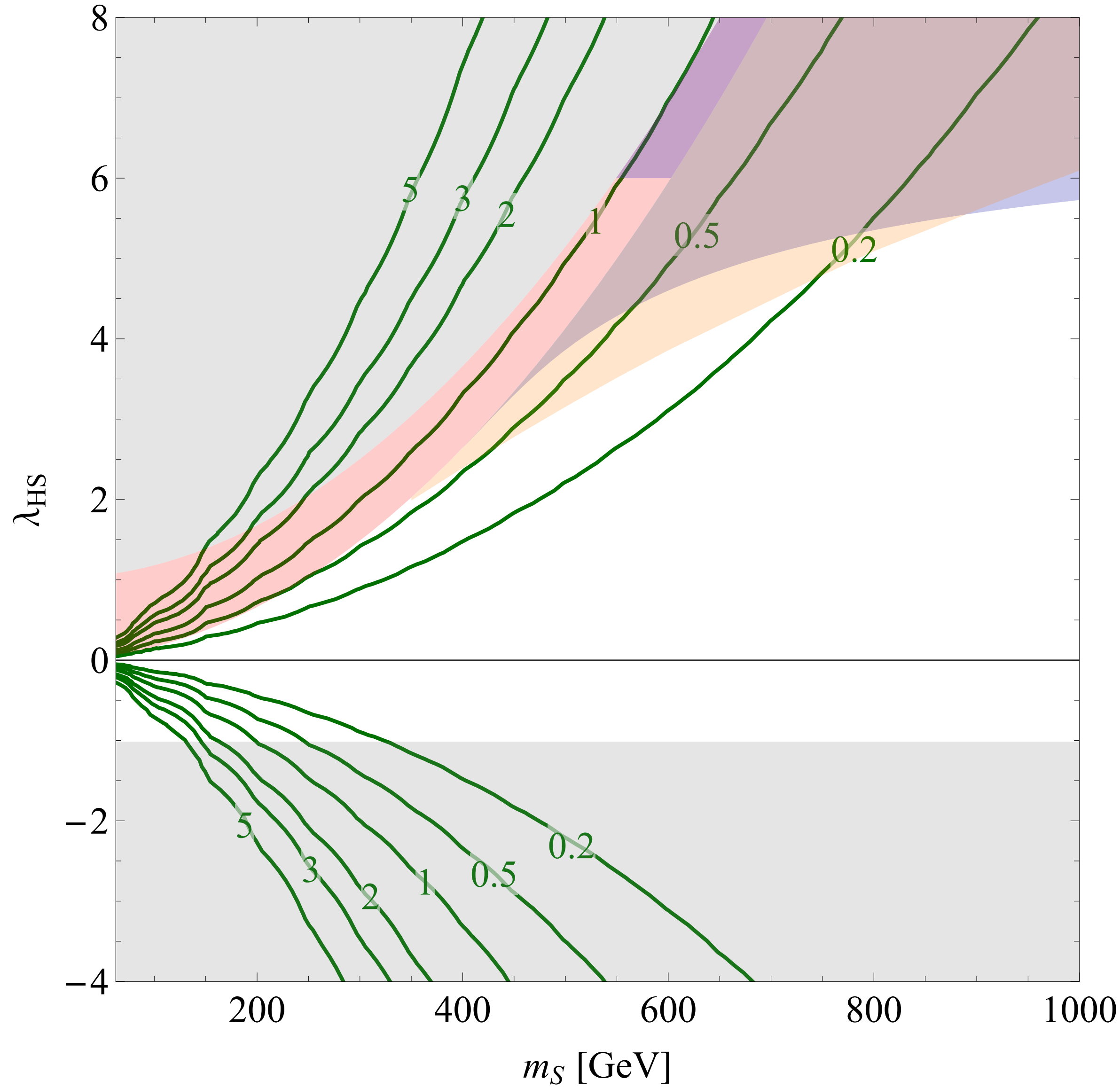
LHC, HL-LHC, TLEP, ILC have no chance of finding this...

But a 100 TeV collider with ~3000/fb could be sensitive to the two-step region!

Not so good for one-step...

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

$S/\sqrt{B}$ @ 100 TeV with 3000/fb



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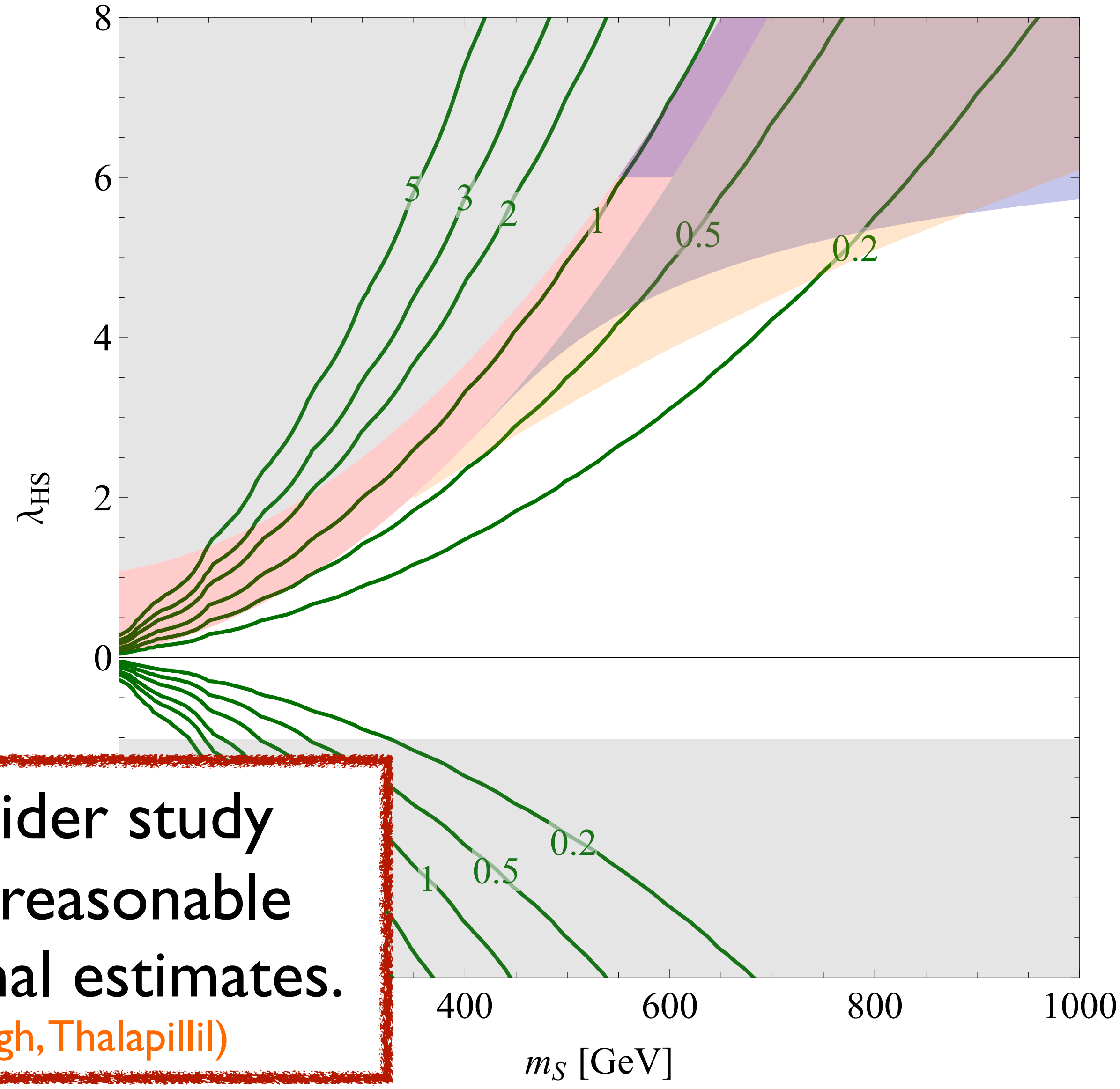


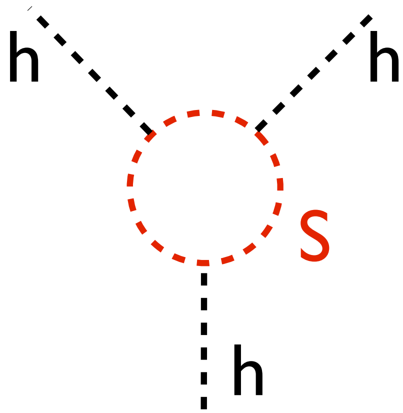
A recent dedicated collider study of the h→SS signal is in reasonable agreement with our original estimates.

1412.0258 (Craig, Lou, McCullough, Thalapillil)

Indirect Signatures of the Phase Transition

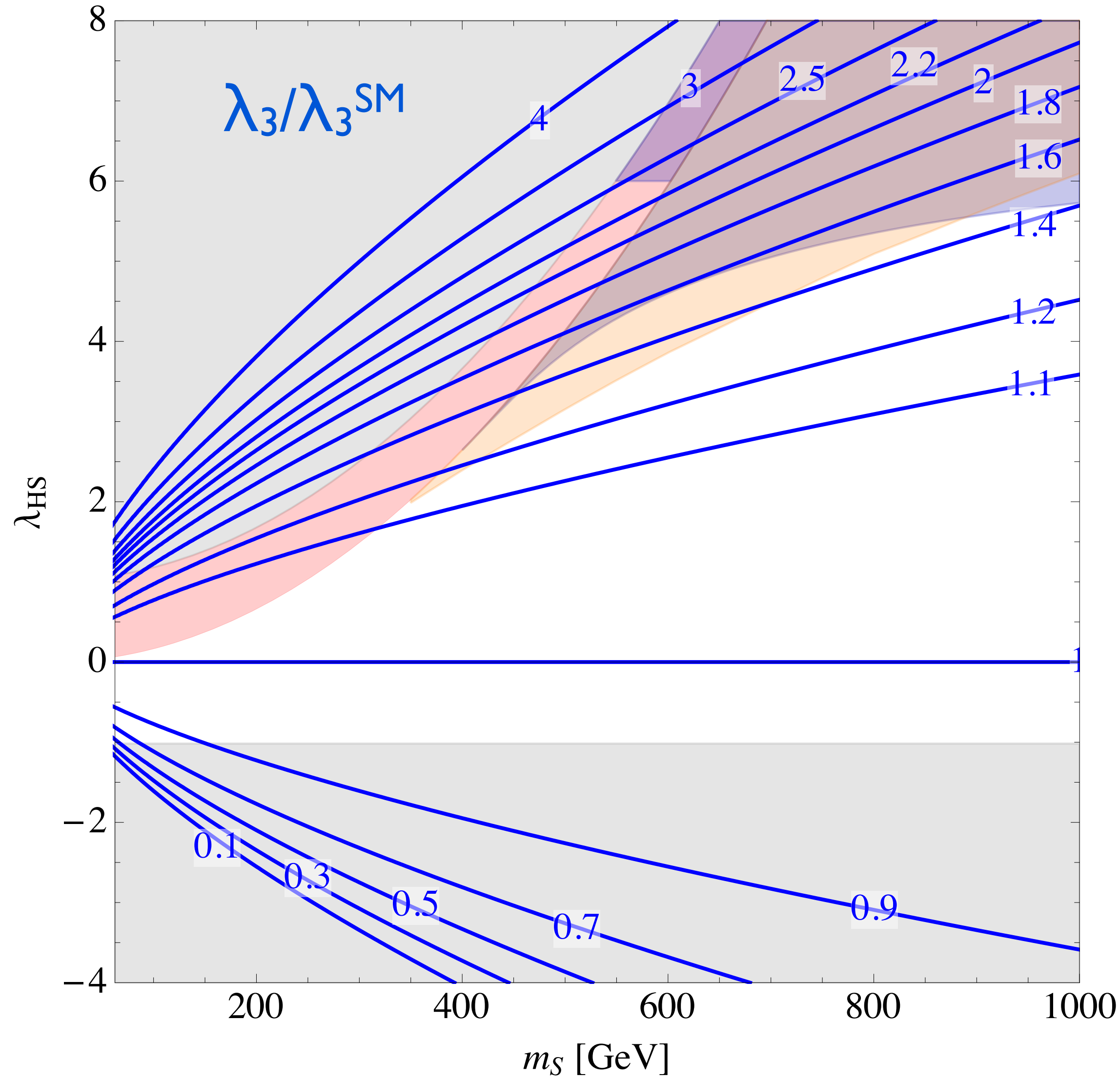
Higgs Cubic Coupling

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



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

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



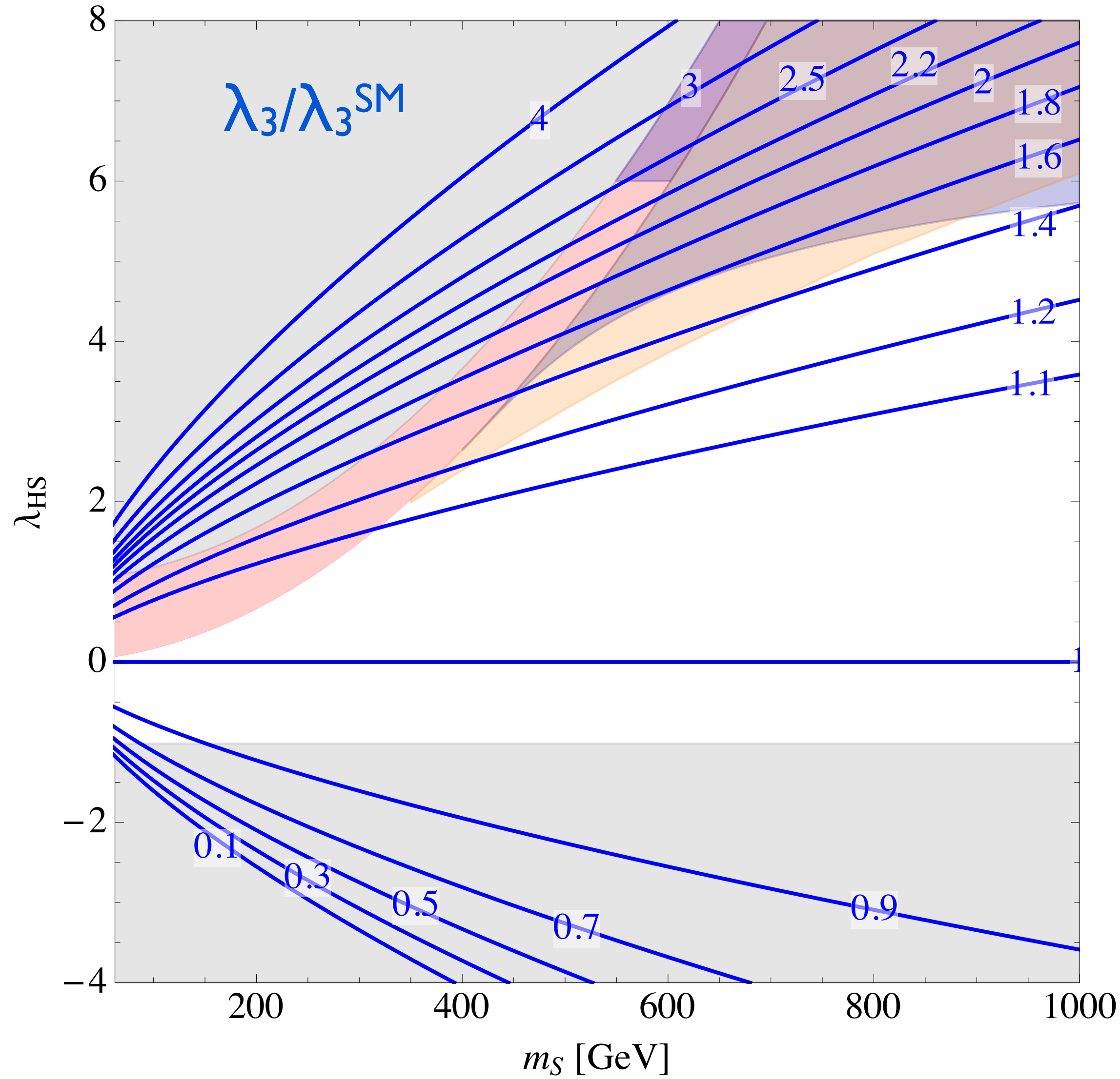
EWBG exclusion requires ~ 10% measurement of λ_3

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...



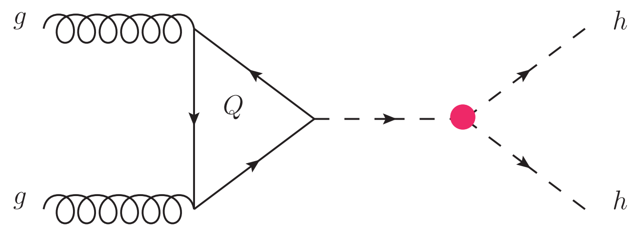
hep-ph/0407019 Grojean, Servant, Wells
0711.2511 Delaunay, Grojean, Wells

EWBG exclusion requires ~ 10% measurement of λ_3

Higgs Cubic Coupling

Precisely measuring λ_3 is **very challenging.**

Most studies concentrate on $gg \to hh$ process



Achievable precision: 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 3000/fb: 8% Yao, 1308.6302

Higgs Cubic Coupling

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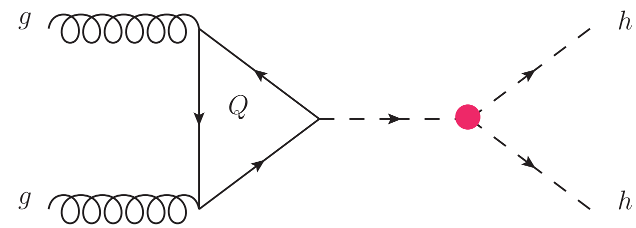

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100 TeV with 3000/fb: 8% — Yao, 1308.6302

New more sophisticated analysis including fake BG — 100 TeV with **30,000**/fb: ~ 10% — Barr, Dolan, Englert, de Lima, Spannowsky, 1412.7154

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

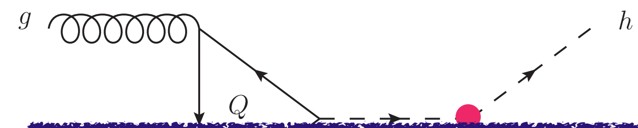
100 TeV with 30/ab could also get there.

Motivates both colliders!!

Higgs Cubic Coupling

Precisely measuring λ_3 is **very challenging.**

Most studies concentrate on gg→hh process



Achievable precision: HL-LHC: 30-50%

1 Tev ILC with 2

100 TeV with 30

New more sophisticated analysis including fake BG

100 TeV with **30**

de Lima,
2.7154

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

see upcoming analysis by Englert, Spannowsky, Thompson

extremely challenging BGs!

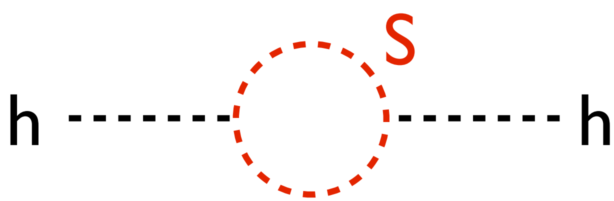
1 Tev ILC with 2500/fb almost has 10% precision.

100 TeV with 30/ab could also get there.

Motivates both colliders!!

Shift in σ_{Zh} at Lepton Colliders

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

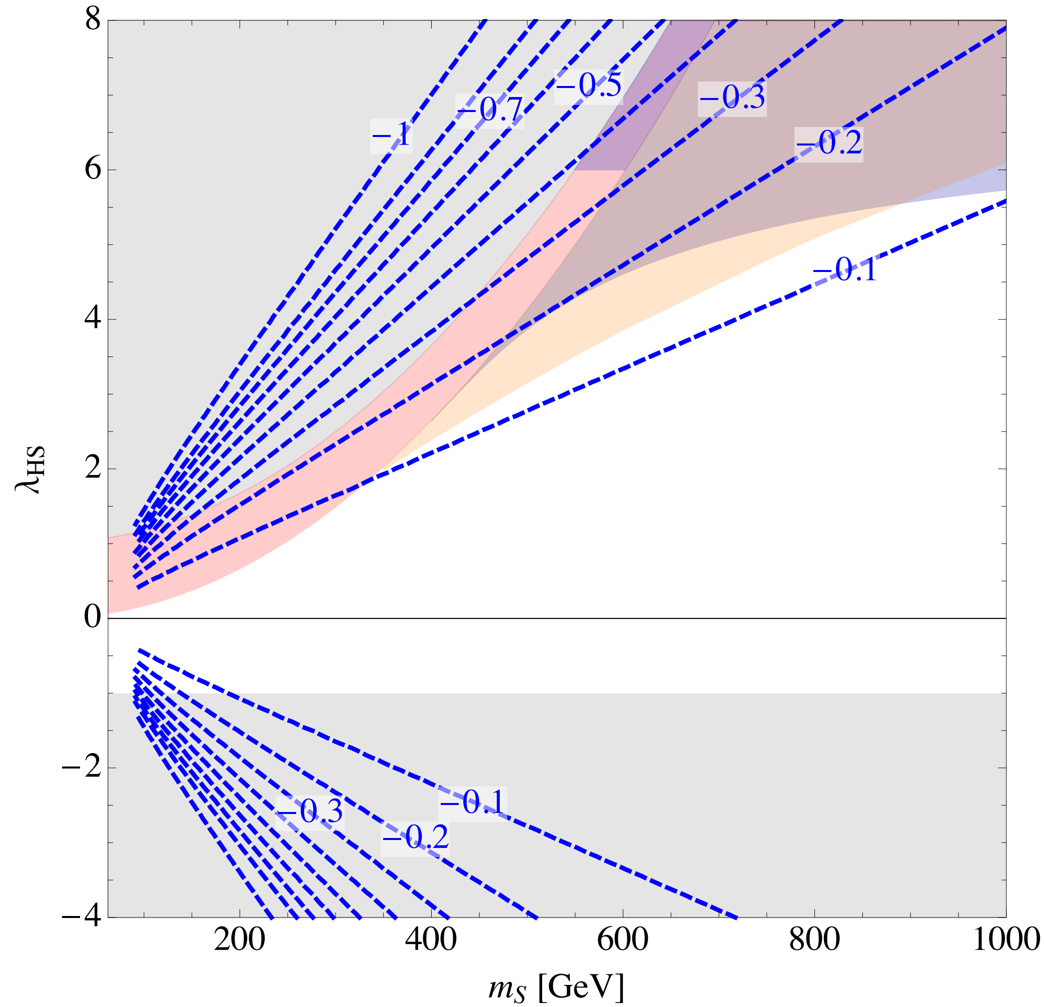


This leads to an O(0.1%) reduction in the σ_{Zh}.

TLEP 4 detectors combined: 0.2% σ_{Zh} precision

Blondel et al. 1208.0504

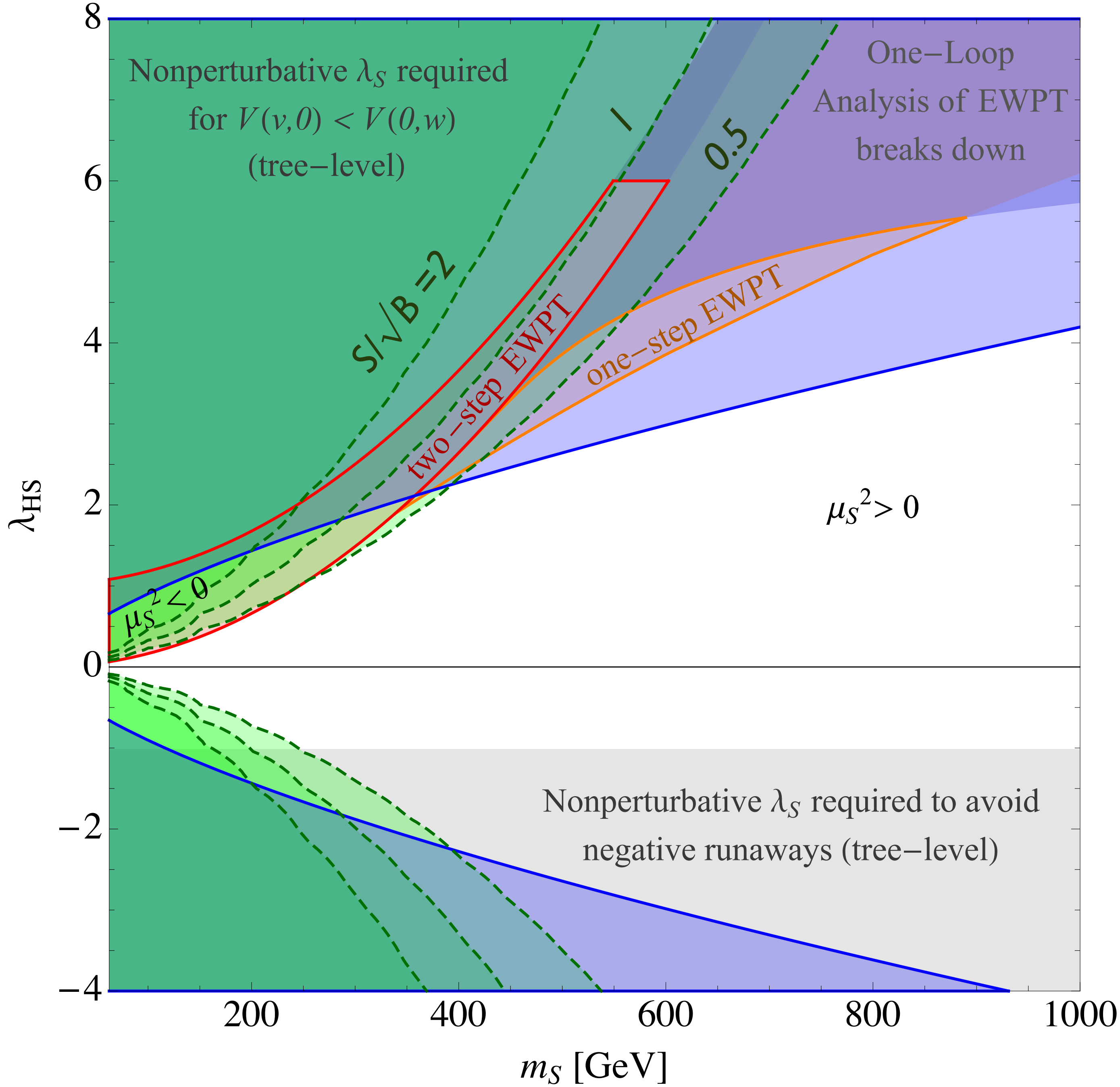
$\delta\sigma_{Zh}(\%)$



Very difficult!

So can we exclude EWBG in this model?

Yes!*



*"with some luck" (depends on future collider capabilities)

100 TeV Collider

8% Higgs triple-coupling measurement

(95%CL exclusion, ~10% is achievable with 30/ab)

Direct detection of VBF h* →SS

(S/√B ~ 1)

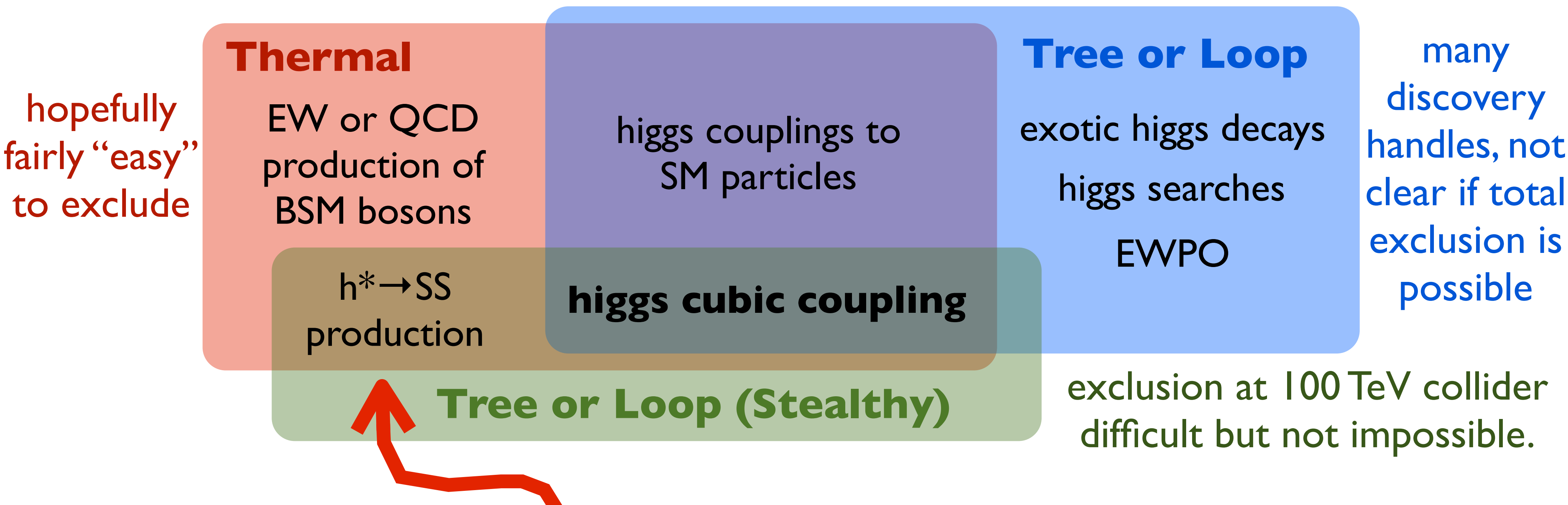
100 TeV collider is both necessary and *maybe* sufficient to detect EWBG

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 collider is also necessary for higgs precision and possibly higgs cubic.