Probing Electroweak Baryogenesis at Future Colliders

Theory Seminar
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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.*

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

CEPC-SPPC
Preliminary Conceptual Design Report: Physics and Detector

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

**HEP in 2025 - 2045**

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Even so, the time to think about the next big machine is NOW: it takes 20+ years for an “accelerator” or “first beam” to be a part of a particle collider.

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

China? China?

**CEPC-SPPC**

Preliminary Conceptual Design Report: Physics and Detector
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

**Dark Matter**
EW charged [if we’re lucky!]

**Baryogenesis**
Testable (?) option: Electroweak baryogenesis

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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?

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solution could rely on uncolored top partners


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Baryogenesis
Testable (?) option: Electroweak baryogenesis

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

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.

⇒ 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

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

**huge** literature...
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Relatively simple to check that the thermal potential has the required ‘energy barrier’

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also a **huge** literature... **huge** literature...
Excluding EWBG

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Also a **huge** literature...
How to exclude 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.

\[
\frac{v_c}{T_c} > 0.6 - 1.6
\]

Central question:

can you come up with a “no-lose” theorem that large \( \frac{v_c}{T_c} \) always leads to a detectable experimental signature?

Normally given as \( \sim 1 \), this more accurate figure is from Patel, Ramsey-Musolf, 1101.4665
Achieving a strong PT

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

We want a ‘bump’ at some critical temperature.

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 \( v_c/T_c \gtrapprox 1 \)?

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

tree-level loop finite temperature
potential correction corrections
Achieving a strong PT

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

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

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!

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

⇒ 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

See Andrey's talk tomorrow

See e.g. Katz, Perelstein 1401.1827

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

Very Promising!

Cohen, Morrissey, Pierce 1203.2924, DC, Jaiswal, Meade 1203.2932
Katz, Perelstein, Ramsey-Musolf, Winslow, 1509.02934
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O(1%) corrections to Zh coupling.

Exclusion or discovery is relatively easy here!

Large direct production cross section at LHC.

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

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Exclusion or discovery is relatively easy here!
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

\[ V_{0}^{T=0}(H, S) = - \mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4. \]

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

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

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

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

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 $Z_2 \Rightarrow$ No singlet VEV.

Avoid exotic higgs decays

Singlet mass $> m_h/2 \approx 62$ 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?
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: \( \mu_S^2, \lambda_{HS}, \lambda_S \)

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: \( \lambda_{HS} \)

To find largest allowed parameter regions, we optimize \( \lambda_S \) for a strong phase transition.
The \((m_S, \lambda_{HS})\) Plane

Nonperturbative \(\lambda_S\) required for \(V(\nu,0) < V(0,w)\) (tree–level)

One–Loop Analysis of PT breaks down

Nonperturbative \(\lambda_S\) required to avoid negative runaways (tree–level)

Singlet mass in our vacuum

\[ m_S = \sqrt{\mu_S^2 + \lambda_{HS}v^2} \quad \text{[GeV]} \]
Nonperturbative $\lambda_S$ required for $V(v,0) < V(0,w)$ (tree-level) to avoid negative runaways.

One-Loop Analysis of PT breaks down for $\mu_{S}^{2} < 0$.

For small singlet mass and large higgs coupling, $\mu_{S}^{2} < 0$.

The $(m_{S}, \lambda_{HS})$ Plane

$$m_{S} = \sqrt{\mu_{S}^{2} + \lambda_{HS}v^{2}} \ [\text{GeV}]$$
The $(m_S, \lambda_{HS})$ Plane

Nonperturbative $\lambda_S$ required for $V(v,0) < V(0,w)$ (tree-level)

One-Loop Analysis

PT breaks down

$\mu_S^2 < 0$

Nonperturbative $\lambda_S$ required to avoid negative runaways

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

If $\mu_S^2 < 0$ is too large, the quartic $\lambda_S$ required to ensure **stability of EWSB minimum** $V_0(h = 0, S = w) > V_0(h = v, S = 0)$ is nonperturbative.

$m_s = \sqrt{\mu_S^2 + \lambda_{HS}v^2}$ [GeV]
If $\lambda_{HS} < 0$ is too large, the quartic $\lambda_S$ required to stabilize runaways is nonperturbative.
The \((m_S, \lambda_{HS})\) Plane

Perturbativity of one-loop analyses breaks down \textbf{roughly} here due to large \(\lambda_{HS}\).

Nonperturbative \(\lambda_S\) required for \(V(v,0) < V(0,w)\) (tree-level)

\(\mu_s^2 < 0\)

Nonperturbative \(\lambda_S\) required to avoid negative runaways (tree-level)

\[
m_s = \sqrt{\mu_S^2 + \lambda_{HS}v^2} \quad [\text{GeV}]\]
The (m_S, \lambda_{HS}) Plane

The interesting parameter space is very “finite”.

Where can a strong phase transition happen?

\[ m_s = \sqrt{\mu_S^2 + \lambda_{HS}v^2} \text{ [GeV]} \]
Electroweak Phase Transition in the Nightmare Scenario
Two* kinds of phase transitions

\[ m_s = \sqrt{\mu_s^2 + \lambda_{HS} v^2} \text{ [GeV]} \]
One-Step by Loop Effects

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

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

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 \( h = v \).

**Zero Temperature Potential**

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.

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

$\mu_S^2 > 0$

$$m_s = \sqrt{\mu_S^2 + \lambda_{HS} v^2} \ [\text{GeV}]$$
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 $\lambda_S$ 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

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

$T \gg 100 \text{ GeV}$
As the universe cools, the singlet is destabilized FIRST, since it couples to fewer degrees of freedom in the plasma.

\[ T \sim T_{cl} > 100 \text{ GeV} \]
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.
Two-Step by Tree Effects

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

This happens at a temperature $T_{c2}$ which is “arbitrarily” low depending on the zero-temperature potential difference (i.e. choice of $\lambda_S$)

$\Rightarrow v_c/T_c$ is “arbitrarily” large $\Rightarrow$ can always have EWBG
Two-Step by Tree Effects

Verified this argument with full loop calculation of PT.

\[ m_s = \sqrt{\mu_s^2 + \lambda_{HS} v^2} \text{ [GeV]} \]
Two* kinds of phase transitions

Two-Step by Tree Effects

One-Step by Loop Effects

\[ \mu_s^2 < 0 \]
\[ \mu_s^2 > 0 \]

(requires different range of \( \lambda_S \) values at each point)

\[ m_s = \sqrt{\mu_S^2 + \lambda_{HS}v^2} \text{ [GeV]} \]

contours show \( v_c/T_c \)

SM+S

SM
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 $h^* \rightarrow SS$.

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

\[ \lambda_3 = \frac{1}{6} \left. \frac{d^3 (V_0(h) + V_{0}^{CW}(h))}{dh^3} \right|_{h=v} \]

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

EWBG exclusion requires ~ 10% measurement of \( \lambda_3 \)

(1 \( \sigma \) uncertainty)
Interesting:

$\lambda_3$ 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)

EWBG exclusion requires ~ 10% measurement of $\lambda_3$
(1 $\sigma$ uncertainty)
Higgs Cubic Coupling

Precisely measuring $\lambda_3$ is very challenging.

Most studies concentrate on $gg \to hh$ process

Achievable precision:

- HL-LHC: 30-50% (1 $\sigma$ uncertainties)
- 1 TeV ILC with 2500/fb: 13%
- 100 TeV with 30/ab: $\sim$ 5%

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

100 TeV with 30/ab surpasses 10%!

Motivates both colliders!!
Higgs Cubic Coupling

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Achievable precision:  
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- 1 Tev ILC with 2500/fb
  - 100 TeV with 30/fb
  - 1 Tev ILC with 2500/fb almost has 10% precision.

Motivates both colliders!!

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

see upcoming analysis by Englert, Spannowsky, Thompson

extremely challenging BGs!
Shift in $\sigma_{Zh}$ at Lepton Colliders

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

This leads to an $\mathcal{O}(0.5\%)$ reduction in the $\sigma_{Zh}$.

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

TLEP can cover much of the EWBG parameter space!

Klute et al. 1301.1322
Blondel et al. 1208.0504
What about Dark Matter?
Singlet Scalar DM

Xenon1T can exclude the singlet if it is cosmologically stable. 

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

Cline, Kainulainen, Scott, Weniger 1306.4710
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 $h^* \rightarrow SS$
($S/\sqrt{B} > 2$)

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!

Nonperturbative $\lambda_s$ required for $V(\nu,0) < V(0,w)$ (tree–level)

One–Loop Analysis of EWPT breaks down

Two-step EWPT
One-step EWPT

$\mu_s^2 > 0$

Nonperturbative $\lambda_s$ required to avoid negative runaways (tree–level)

$\mu_s^2 < 0$

$2 \sigma$ exclusions

$\sigma$ excluded

$\sigma$ not excluded

$m_s$ [GeV]
What’s next?
Making our findings more robust & general

**EFT approach?**

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 $\rightarrow$ 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.