Singlet Assisted Electroweak Phase Transitions and Precision Higgs Studies

Peter Winslow

Based on:

S. Profumo, M. Ramsey-Musolf, C. Wainwright, P. Winslow

arXiv:1510.XXXX
A. Kotwal, J. M. No, M. Ramsey-Musolf, P. Winslow
Outline

Singlets: Collider Physics ↔ Cosmology

The xSM: a Minimally Extended Scalar Sector

1st Order Phase Transitions: Electroweak Baryogenesis in the xSM

NextGen Colliders: A motivation from Cosmology
LHC has thrown open the door to the scalar sector of the SM!

… but where’s all the NP?
No obvious hints from CKM-ology or EWPO either…

Options:
→ Heavy NP
→ Weakly coupled NP
→ Clever NP (compressed spectra, etc.)
→ Hidden Sectors / Singlets
Singlets:

- Less constrained (possibly still weak scale)
- Typically still couple to SM via portals  
  → Interesting collider signatures
- Also motivated by real cosmological problems

\[ \Delta \mathcal{L} \supset \mathcal{O}_{NP} |H|^2 \]

SM\hspace{2cm}NP

Higgs Portal
Singlets:

- Less constrained (possibly still weak scale)

- Typically still couple to SM via portals
  → Interesting collider signatures

- Also motivated by real cosmological problems
  → Matter/Antimatter Asymmetry

- Higgs portals can modify character of EWPT
  → Strongly 1st order EWPT
  → Highly motivated by EWBG

Requirement of a SFOEWPT identifies a preferred parameter space
→ *Cosmological motivation for collider searches*
The $x$SM: a useful toy model

$$V_{xSM}(H, S) = V_{SM}(H) + \left( \frac{a_1}{2} S + \frac{a_2}{2} S^2 \right) |H|^2 + \begin{array}{l}
\frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4
\end{array}$$

**Higgs Portal**

$$H = \left( \frac{1}{\sqrt{2}} \left( v_0 + h + iG^0 \right) \right), \; S = x_0 + s$$

**Higgs Mixing**

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- Set $m_{h_1} = 125$ GeV

- $h_1$ ($h_2$) couplings to SM rescaled by $\cos \theta$ ($\sin \theta$)

- Singlet inherits SM couplings entirely from mixing
  - searches for heavy scalars
  - EW precision observables

$$\sin 2\theta = \frac{(a_1 + 2a_2x_0)v_0}{(m_1^2 - m_2^2)}$$
Strong 1\textsuperscript{st} order EWPTs in the xSM

Connecting to EWPT requires finite temperature effective potential

\[ V_{\text{eff}}(\phi, T) = V_0(\phi) + V_{CW}(\phi) + V_T^{\neq 0}(\phi, T) + V^{\text{Ring-sum}}(\phi, T) \]
Strong 1st order EWPTs in the xSM

Connecting to EWPT requires finite temperature effective potential

\[ V_{eff}(\phi, T) = V_0(\phi) + V_{CW}(\phi) + V^{T \neq 0}(\phi, T) + V^{\text{Ring-sum}}(\phi, T) \]

\[ \rightarrow \text{Gauge dependent!!} \quad \text{JHEP 1107 (2011) 029} \]

\[ \rightarrow \text{Independence restored at high temperature} \]

\[ V_{eff}(\phi, \alpha, T)^{xSM} \xrightarrow{\text{High } T} \bar{D}(T^2 - T_0^2)\phi^2 + e\phi^3 + \frac{\bar{\lambda}}{4}\phi^4 \]

\[ v(T)/\sqrt{2} = \phi(T) \cos \alpha(T), \ x(T) = \phi(T) \sin \alpha(T) \]

**Condition for SFOEWPT**

\[ \cos \alpha(T_c) \frac{\Delta \phi(T_c)}{T_c} \gtrsim 1 \]

\[ \implies - \cos \alpha(T_c) \frac{e}{2T_c \bar{\lambda}} \gtrsim 1 \]

**SFOEWPT driven by tree-level parameters**

\[ \rightarrow \text{Classical transition} \]

\[ e = \left( \frac{a_1}{2} \cos^2 \alpha + \frac{b_3}{3} \sin^2 \alpha \right) \sin \alpha \]

\[ \bar{\lambda} = \lambda \cos^4 \alpha + \frac{a_2}{2} \cos^2 \alpha \sin^2 \alpha + \frac{b_4}{4} \sin^4 \alpha \]
Strong 1\textsuperscript{st} order EWPTs in the xSM

General requirements for SFOEWPT:

- Large $\cos \alpha(T_c)$

- Large, negative $a_1$  \implies \text{Raises barrier}

- $\overline{\lambda}$ linearly related to $T_C$  \implies \lambda \text{ correlated with } T_C$

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cos \alpha(T_c) \frac{\Delta \phi(T_c)}{T_c} \gtrsim 1
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Condition for SFOEWPT

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$$\implies - \cos \alpha(T_c) \frac{e}{2T_c \bar{\lambda}} \gtrsim 1$$

True value is slightly higher in xSM

PRD 90 (2014) 1, 015015

SFOEWPT driven by tree-level parameters \rightarrow Classical transition

$$e = \left( \frac{a_1}{2} \cos^2 \alpha + \frac{b_3}{3} \sin^2 \alpha \right) \sin \alpha$$

$$\bar{\lambda} = \lambda \cos^4 \alpha + \frac{a_2}{2} \cos^2 \alpha \sin^2 \alpha + \frac{b_4}{4} \sin^4 \alpha$$
Possible collider signatures

\[ m_2 < 2 m_1 \rightarrow \text{BSM Higgs-like decay modes} \]

\[ m_1/2 < m_2 < 2 m_1 \rightarrow \text{Precision measurements} \]

\[ m_2 > 2 m_1 \rightarrow \text{Resonant di-Higgs(-like) production} \]
Phenomenology depends largely on mass

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Motivates precision measurements at future colliders
Phenomenology depends largely on mass

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\[ m_2 < 2 m_1 \rightarrow \text{BSM Higgs-like decay modes} \]

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What do we *know* from current LHC?

What can we *learn* from future colliders?

Motivates precision measurements at future colliders

In progress…

Also, see Chien-Yi’s Talk!
Indirect Searches: Higgs-like coupling measurements

Fit to current data

$$\chi^2(\theta) = \sum_i \left( \frac{\mu_i^{obs} - \cos^2 \theta}{\Delta \mu_i^{obs}} \right)^2$$

Sensitivity from projected uncertainties

$$\chi^2(\theta) = \sum_i \left( \frac{1 - \cos^2 \theta}{\Delta \mu_i^{proj}} \right)^2$$

**LHC:**
All 7-8 TeV data available

**HL-LHC:**
$$\sqrt{s} = 14 \text{ TeV}, 3 \text{ ab}^{-1}$$
ATL-PHYS-PUB-2013-014, CMS-NOTE-13-002

**ILC-1:**
$$\sqrt{s} = 250 \text{ GeV}, 250 \text{ fb}^{-1}$$

**ILC-3:**
$$\sqrt{s} = 1 \text{ TeV}, 1 \text{ ab}^{-1}$$

**TLEP:**
$$\sqrt{s} = 240 \text{ GeV}, 1 \text{ ab}^{-1}$$
arXiv:1305.6498
Indirect Searches: Oblique Parameters

Effects are simple to calculate

\[ \Delta \mathcal{O} = \cos^2 \theta \mathcal{O}_{SM}^S(m_1) + \sin^2 \theta \mathcal{O}_{SM}^T(m_2) - \mathcal{O}_{SM}^S(m_1) \]
\[ = (1 - \cos^2 \theta) (\mathcal{O}_{SM}^T(m_2) - \mathcal{O}_{SM}^S(m_1)) \]

\[ \mathcal{O} = S, T, U \]

Perform full fit to current best-fit values from Gfitter

\[ \Delta \chi^2 = \sum_{i,j} (\Delta \mathcal{O}_i - \Delta \mathcal{O}_i^0) \left( \sigma^2 \right)_{ij}^{-1} (\Delta \mathcal{O}_j - \Delta \mathcal{O}_j^0) \]

Direct searches: Null results from SM-like Higgs searches

All $h_2$-SM interactions rescaled by $\sin\theta$

$$\mu_{XX} = \frac{\sigma(m_2) \cdot \text{BR}(m_2)}{\sigma^{SM}(m_2) \cdot \text{BR}^{SM}(m_2)} = 1 - \cos^2\theta$$

LEP Searches

Direct searches: Null results from SM-like Higgs searches

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Higgs Discovery

LEP Searches


LHC Searches

→ ATLAS-CMS Combination

Direct searches: Null results from SM-like Higgs searches

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**Higgs Discovery**

**LEP Searches**


**LHC Searches**

→ ATLAS-CMS Combination


**Dedicated heavy SM-like Higgs search**

→ CMS

Eur. J. Phys. 73, 2469 (2013)
Lepton Colliders

\[ \sqrt{s} > 2 \, m_{h_1} \]

Direct Production

\[ \sqrt{s} < 2 \, m_{h_1} \]

Indirect Production

Model-dependent...

Noble, Perelstein
PRD 78 063518 (2008)

Direct

\[ p_s < \]

\[ m_{h_1} \]

Indirect

\[ p_s > \]

\[ m_{h_1} \]

PRD 90 (2014) 1, 015001

Hadron Colliders

Direct Production

\[ g \, g \, \text{fusion} : \]

\[ t \]

\[ t \]

\[ h^0 \]

Indirect Production

\[ q \]

\[ \mathbb{W}, \mathbb{Z} \]

\[ h^0 \]

\[ q \]

\[ \mathbb{W}, \mathbb{Z} \]

\[ h^0 \]
Projected sensitivity to Higgs-like tri-linear self-coupling

TLEP & CEPC: Direct (Indirect)

HL-LHC: $\bar{b}b\gamma\gamma$, with $\bar{b}bW^+W^-$, $\bar{b}b\tau^+\tau^-$

$\lambda_{h_1 h_1 h_1}/\lambda_{h_1 h_1 h_1}^{SM}$

arXiv:1305.6498

Projected sensitivity to Higgs-like tri-linear self-coupling

ILC: $e^+ e^- \rightarrow Zhh$

with $e^+ e^- \rightarrow \nu \bar{\nu} hh$

1 TeV with 2.5/ab

VHE-LHC or SPPC (100 TeV pp collider)

100 TeV with 3/ab

ILC Higgs White Paper

$\lambda_{h_1 h_1 h_1}/\lambda_{SM}^{h_1 h_1 h_1}$

Projected sensitivity to Higgs-like tri-linear self-coupling

Revised to 100 TeV with 3/ab (30/ab): (~40%) ~10%

JHEP 1502, 016 (2015)

ILC: $e^+ e^- \rightarrow Z h h$
with $e^+ e^- \rightarrow \nu \bar{\nu} h h$

1 TeV with 2.5/ab

VHE-LHC or SPPC (100 TeV pp collider)

100 TeV with 3/ab

ILC Higgs White Paper


Projected sensitivity to Higgs-like tri-linear self-coupling
Phenomenological Implications

Perform MC scans over xSM space

\[ a_1/\text{TeV}, b_3/\text{TeV} \in [-1, 1], \quad x_0/\text{TeV} \in [0, 1], \quad b_4, \, \lambda \in [0, 1] \]

Require: \textit{Current Collider Constraints} \quad SFOEWPT \quad Sufficient Tunnelling

- High precision Higgs-like coupling measurements
- Searches for SM-like Higgs’ near di-Higgs threshold

SFOEWPT-viable space is biased towards small mixing and large mass splitting.

Motivates:

- High precision Higgs-like coupling measurements
- Searches for SM-like Higgs’ near di-Higgs threshold
Phenomenological Implications

Deviations for which $\lambda_{h_1 h_1 h_1} < \lambda_{h_1 h_1 h_1}^{SM}$ correspond to strong quenching of sphalerons!

Precision measurements of tri-linear Higgs self-coupling will be powerful probes of SFOEWPT-viable space!
For higher singlet-like masses, $h_2 \to h_1 h_1$ opens up
→ Resonantly enhanced di-Higgs production becomes possible

What are discovery prospects for models which feature SFOEWPT?

Assume in the resonance region
→ don’t account for box graphs

\[
\lambda_{211} = \sin \theta f(\lambda, x_0, a_1, b_3, b_4)
\]

Goal: Determine benchmark points, based on largest $\sigma$ BR, which feature a SFOEWPT
→ Concentrate on $ggF$

\[
\sigma_{LO}(pp(gg) \to h_2) = \sin^2 \theta \sigma_{ggF}^{ggF} m_2^2 \frac{d\mathcal{L}}{dm_2^2}
\]
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**What are discovery prospects for models which feature SFOEWPT?**

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\[ \sigma_{LO}(pp(gg) \rightarrow h_2) = \sin^2 \theta \ \sigma_0^{ggF} m_2^2 \ \frac{d\mathcal{L}}{dm_2^2} \]

Higgs XSWG at 100 TeV
For higher singlet-like masses, $h_2 \rightarrow h_1 h_1$ opens up
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$$BR(h_2 \rightarrow h_1 h_1) = \left(1 + \frac{8\pi \sin^2 \theta \ m_2 \Gamma_{h_1}^{SM}(m_2)}{\lambda_{211}^2 \sqrt{1 - \frac{4m_1^2}{m_2^2}}} \right)^{-1}$$
- Simulate events with MG5 + Pythia8
- Choose final states based on BG suppression
  → bbyy, 4τ, ττyy have smaller σ’s but cleaner signatures
  → 100 TeV collider may yield substantial # of events
- For each final state:
  - Combine distributions
  - Use BDT algorithm to separate signal from BG
- Simulate events with MG5 + Pythia8
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<th>Wb (GeV)</th>
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Conclusions

xSM: a simple framework linking EWPT dynamics to mixing phenomenology, allowing
- EWPT-preferred parameter space to act as a guide for collider searches
- Precision collider measurements to act as a powerful probe of the EWPT

In both cases, SFOEWPT motivates next gen. colliders for the purposes of
- High precision Higgs coupling measurements
- Direct searches for singlet-like scalars

Should future experiments find evidence for
- Non-zero Higgs mixing
- Existence of a singlet-like scalar
- Deviations in $\lambda_{h_1 h_1 h_1}^{SM}$

our work will aid in narrowing down SFOEWPT-viable parameter space

Thank you!
Orange Points: Satisfy Collider Bounds

Black Points: Satisfy EWPT

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