Singlet-Assisted Electroweak Phase Transitions in the Wake of the Higgs

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In Collaboration with:

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
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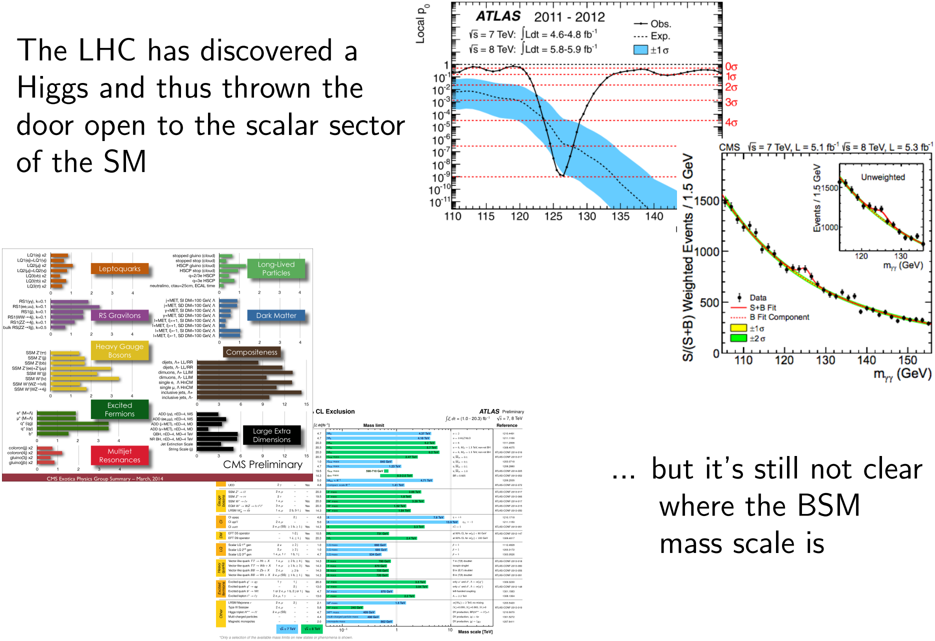
Outline

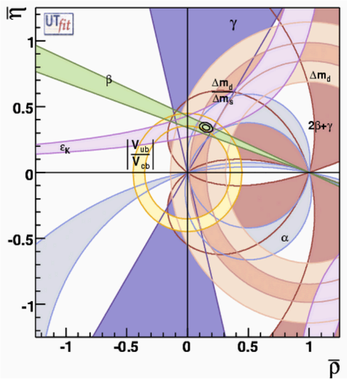
- Higgs Portals: Collider Physics ⇔ Cosmology
- The xSM: a Minimally Extended Scalar Sector
- What we learn from colliders and precision EW observables
- What we learn from 1st order phase transitions

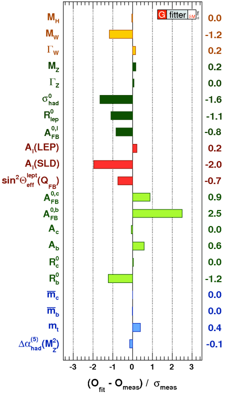
The LHC has discovered a Higgs and thus thrown the door open to the scalar sector of the SM



... but it's still not clear where the BSM mass scale is

Situation is similarly unclear when considering CKMology and EWPO





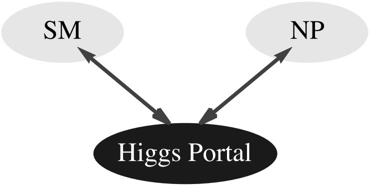
- Large BSM mass scale with funny couplings
- Hidden sectors (SM singlets)
- ...

- H.S. are less constrained, may have weak scale masses
- Typically still couple to SM through portals
  ⇒ Interesting collider signatures
- Tend to be motivated by real cosmological problems...
  ⇒ DM, BAU, origin of ν masses, etc.

To what extent can cosmology guide/motivate collider searches for new states?
⇒ Portal-dependent

Dim=2 gauge-invariant operator is naturally sensitive to NP
⇒ Hard to keep NP secluded

$$\Delta\mathscr{L} \supset \frac{g_{NP}}{\Lambda_{NP}^{D-2}}\mathcal{O}_{NP}|H|^2$$


SM

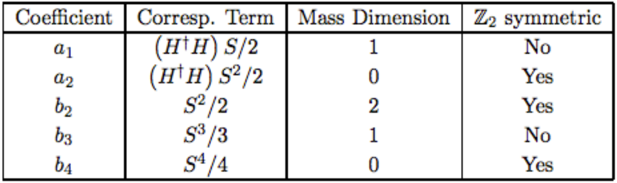
NP

Higgs Portal

- *Many* scenarios fit into this picture...
- Start with minimal extension: real, gauge singlet scalar $\Rightarrow$ xSM (0611014, 0705.2425, 0706.4311, 0912.4722, 0910.3167, ...)
- General framework for studying Cosmology⇔Collider pheno with singlets

$$V(H,S) = V_{SM}(H) + \underbrace{\left(\frac{a_1}{2}S + \frac{a_2}{2}S^2\right)|H|^2}_{\textit{Higgs Portal}} + \overbrace{\frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4}^{\textit{Secluded Self-Interactions}}$$

- 7 free parameters



Coefficient	Corresp. Term	Mass Dimension	$\mathbb{Z}_2$ symmetric
a_1	$\left(H^\dagger H\right) S/2$	1	No
a_2	$\left(H^\dagger H\right) S^2/2$	0	Yes
b_2	$S^2/2$	2	Yes
b_3	$S^3/3$	1	No
b_4	$S^4/4$	0	Yes

- In general, both take on vevs
  ⇒ min conditions allow us to trade in 2 parameters

$$\mu^2 = \lambda v_0^2 + \left(a_1 + a_2 x_0\right)\frac{x_0}{2}$$

$$b_2 = -b_3 x_0 - b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0} - \frac{a_2 v_0^2}{2}$$

  ⇒ Better to get rid of mass^2 parameters
  ⇒ Now 6 free parameters

- Higgs portal induces mixing between $SU_L(2)$-aligned field and singlet

$$Mass^2 = \begin{pmatrix} m_{hh} & m_{hs} \\ m_{hs} & m_{ss} \end{pmatrix}$$

$$m_{hh} = 2\lambda v_0^2$$

$$m_{ss} = b_3 x_0 + 2 b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

$$m_{hs} = \left(\frac{a_1}{2} + a_2 x_0\right) v_0$$

- Diagonalization requires introduction of a single mixing angle θ

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

s inherits its decay modes entirely from mixing

$$m_{1,2}^2 = \frac{1}{2}\left(m_{hh} + m_{ss} \pm \left|m_{hh} - m_{ss}\right| \sqrt{1 + y^2}\right) \qquad y \equiv \frac{m_{hs}}{m_{hh} - m_{ss}}$$

- Mixing angle is most easily defined in terms of mass eigenvalues

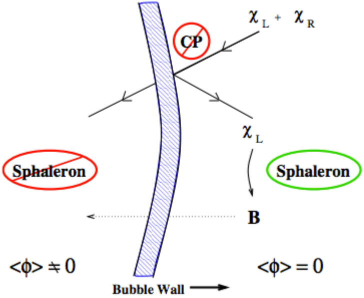
$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)\, v_0}{(m_1^2 - m_2^2)} \quad \Longrightarrow \quad -1 \leq \frac{(a_1 + 2a_2 x_0)\, v_0}{(m_1^2 - m_2^2)} \leq 1$$

Cosmological Applications:

- Dark Matter (0910.3167, 1210.4196, 1306.4710)
  - Impose $\mathbb{Z}_2$ symmetry $\Rightarrow a_1, b_3 \rightarrow 0$
  - Also require $x_0 \rightarrow 0 \Rightarrow$ Mixing induces instability

Cosmological Applications:

- Strongly 1st-order EWPT (0705.2425)



Morrissey et. al. New J.Phys. 14 (2012) 125003

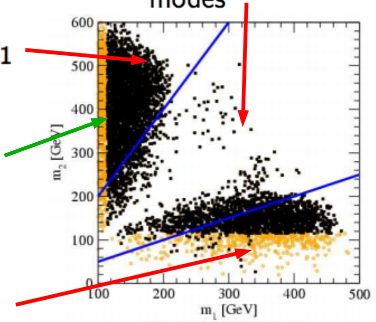
- 1st-order EWPT proceed through bubble nucleation
- Crucial that sphalerons are quenched in EW phase to avoid washout
- Sufficient quenching $\Rightarrow \dfrac{\phi(T_c)}{T_c} \gtrsim 1$

$\mathbb{Z}_2$-breaking required $\Rightarrow$ Higgs portal provides

$$\left(\frac{a_1}{2}S + \frac{a_2}{2}S^2\right)|H|^2$$

- Raises height of barrier
- Lowers critical temperature

- Require $SU_L(2)$-like scalar to satisfy $m_1 = 125$ GeV
- Phenomenology depends on m_2



No new decay modes

$h_2 \to h_1 h_1$

LEP Bound

$h_1 \to h_2 h_2$

Profumo et. al. JHEP 0708 (2007) 010

- $m_2 < m_1/2 \Rightarrow$ BSM Higgs decays
- $m_2 > 2m_1 \Rightarrow$ Resonant di-Higgs production
- $m_1/2 < m_2 < 2m_1 \Rightarrow$ Precision measurements

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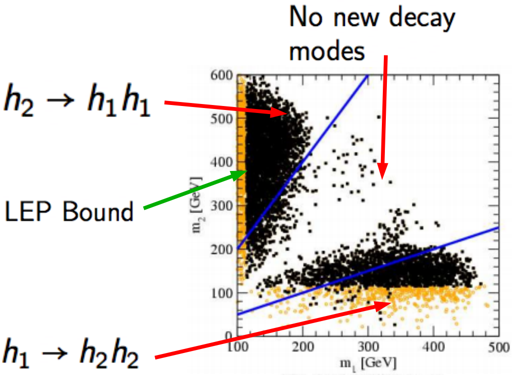

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- For $m_1/2 < m_2 < 2m_1$, $\dfrac{\sigma BR}{\sigma^{SM} BR^{SM}} = f(\theta)$

- What do we know from current LHC?

- What do we learn from HL-LHC and ILC?

SM Higgs Searches

- All Higgs interactions are rescaled by mixing

$$h \to h_1 \cos\theta - h_2 \sin\theta \qquad \Longrightarrow \qquad \begin{array}{c} g = \cos\theta g^{SM} \\ \theta^{SM} \equiv 0 \end{array}$$

- Mass is fixed ⇒ only modification of σBR is universal rescaling

$$\mu_{XX} = \frac{\sigma BR}{\sigma^{SM} BR^{SM}} = \left(\sum_i p_i^{SM} (\sigma_i/\sigma_i^{SM})\right) \frac{\Gamma_h^{SM}}{\Gamma_h} \frac{\Gamma(h \to XX)}{\Gamma^{SM}(h \to XX)}$$

$$= \left(\cos^2\theta\right)\left(\frac{1}{\cos^2\theta}\right)\left(\cos^2\theta\right) = \cos^2\theta$$

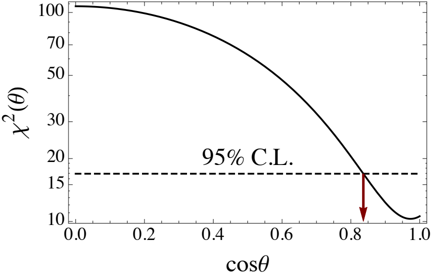
- Global χ^2 fit to current CMS and ATLAS data

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

ATLAS-CONF-2014-009, Phys.Rev. D89 (2014) 012003,

CMS-HIG-13-004, CERN-PH-EP-2014-001, HIG-13-001, JHEP 1401

(2014) 096, CMS-HIG-13-002, CERN-PH-EP-2013-220



- LHC → HL-LHC upgrades gain precision but also suffer from pileup
  ⇒ More data doesn't always mean more sensitivity

- ILC uncertainties will be dominated stat.
  ⇒ Sensitivity continually improves with more data

- How much sensitivity can we expect to gain?

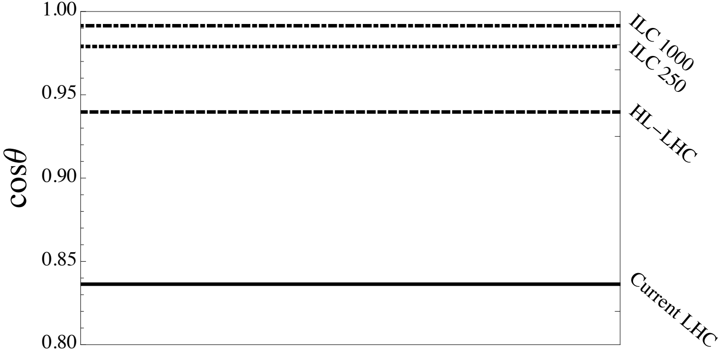
- CMS and ATLAS give projections for $\Delta\mu_i^{obs}$ based on current syst. and thy uncertainties by scaling signal and background events

  CMS-NOTE-13-002, ATL-PHYS-PUB-2013-014

- Projected uncertainties for ILC stages
  ⇒ ILC Higgs White Paper arXiv:1310.0763

- Naive χ^2 method: Assume the result of each measurement is SM ⇒ Take $\Delta\mu_i^{obs}$ as input

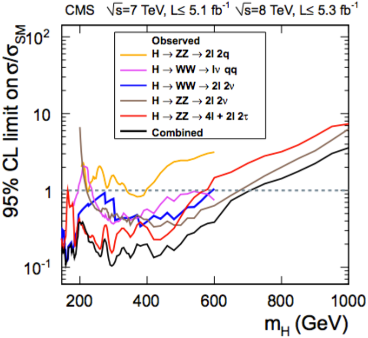
$$\chi^2 = \sum_i \frac{(1 - \sin^2\theta)^2}{(\Delta\mu_i^{obs})^2}$$



- Presence of heavy scalar state, h_2, can be probed by heavy Higgs searches

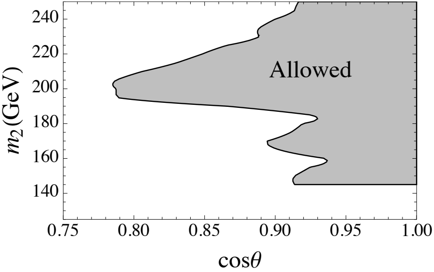
CMS-HIG-12-034

- For $m \geq 2M_w, 2M_Z$, $h_1 \to VV$ dominates



- h_2 couples to SM as $\Rightarrow g = \sin\theta g^{SM}$

- For $m_2 \leq 2m_h$, signal rates are still mass independent but constraint has large mass dependence



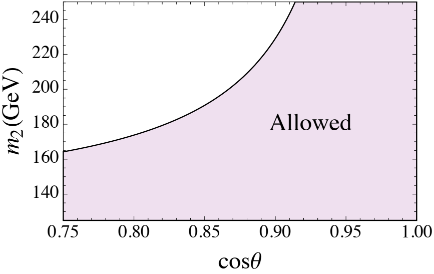
- m_2 and $\cos\theta$ further constrained by S,T,U
- Effects are simple to calculate

$$\begin{aligned}\Delta\mathcal{O} &= \cos^2\theta\mathcal{O}^{SM}(m_1)+\sin^2\theta\mathcal{O}^{SM}(m_2)-\mathcal{O}^{SM}(m_1)\\ &= \left(1-\cos^2\theta\right)\left(\mathcal{O}^{SM}(m_2)-\mathcal{O}^{SM}(m_1)\right)\end{aligned}$$

- Small m_2, θ preferred
- Fit to current best-fit values given by Gfitter group

Eur. Phys. J. C72 (2012) 2205

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

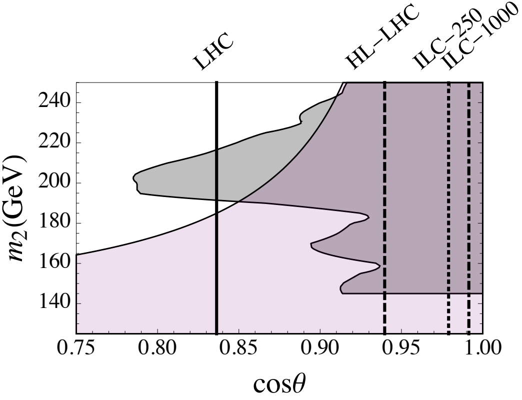


Current situation:

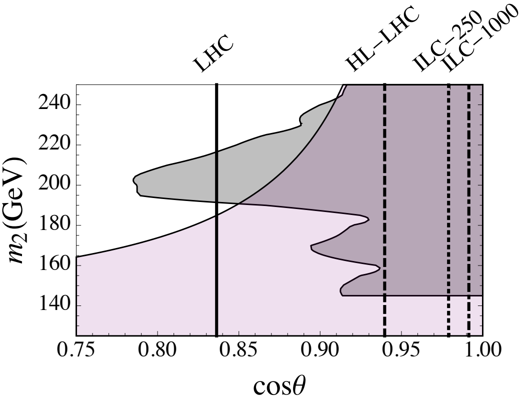
- $m_h < m_2 < 145$ GeV ⇒ SM Higgs searches
- $145\ \mathrm{GeV} < m_2 \lesssim 190$ GeV ⇒ Heavy Higgs searches
- $190\ \mathrm{GeV} < m_2 < 2m_h$ ⇒ Electroweak precision

Future situation:

- $m_h < m_2 < 2m_h$ GeV ⇒ HL-LHC, ILC



Question: Which regions prefer strongly 1st-order EWPT?



Before going to finite-T, impose basic potential constraints:

- Vacuum stability

$$\lambda \geq 0, \qquad b_4 \geq 0, \qquad a_2 > -2\sqrt{\lambda b_4}$$

- Viable EWSB: $det(M^2) > 0$ and EW min is absolute min

Standard Analysis of EWPT

- Step 1: Derive finite T potential
  - Coleman-Weinberg
  - $T \neq 0$ 1-loop corrections
  - Ring-sum corrections
- Sufficient quenching $\Rightarrow \dfrac{\Delta\phi(T_c)}{T_c} \gtrsim 1$

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  $\Rightarrow$ Gauge dependent!

Gauge independence restored in high-T limit

- Take only gauge-invariant $m^2 T^2$ thermal corrections
- Neglect thermally-generated cubic terms

Behaviour of $V(\phi, T)$ is better understood in polar coordinates
$\Rightarrow v(T)/\sqrt{2} = \phi(T)\cos\alpha(T),\ x(T) = \phi(T)\sin\alpha(T)$

$$V(\phi, \alpha, T)^{xSM} \overset{\text{High T}}{\Longrightarrow} \bar{D}(T^2 - T_0^2)\phi^2 + e\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

Cubic term remain in high-T limit due to tree-level Z_2-breaking Higgs portal and self-interactions

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

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

- Quenching only occurs along $SU_L(2)$ direction

$$\cos\alpha(T_c)\frac{\Delta\phi(T_c)}{T_c} = -\cos\alpha(T_c)\frac{e}{2T_c\bar{\lambda}} \gtrsim 1 \;\Rightarrow\; \text{Gauge Indep.}$$

  - Raises barrier between phases
  - Lowers T_c

- Supercooling into a metastable phase may prevent EWPT. Require tunnelling solution to ensure transition occurs
  $\Rightarrow$ CosmoTransitions (C. Wainwright, arXiv:1109.4189)

- Tunnelling solution is a bubble with free energy S_3
  $\Rightarrow S_3/T_N \simeq 140$ signals onset of nucleation

- Impose this as extra constraint on xSM parameters

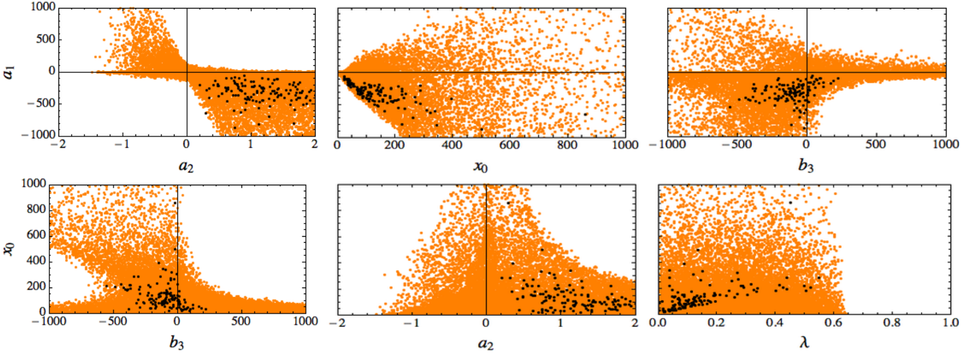
Strategy:

- MC scan over finite ranges of model space

$$\lambda, b_4 \in [0,1], \quad a_2 \in [-2\sqrt{\lambda b_4}, 2],$$
$$a_1, b_3 \in [-1,1]\ TeV, \quad x_0 \in [0,1]\ TeV$$

- Impose all collider and theory constraints
- Remain democratic about multi-step PTs
  ⇒ As long as EWPT occurs
- 3 separate scans: imposing current LHC, HL-LHC, and ILC-1000 bounds on $\cos\theta$

Orange Points: Satisfy Collider Bounds
Black Points: Satisfy EWPT



Collider level: a_1 and a_2 prefer to have opposite sign

$\Rightarrow$ Bound on $\sin 2\theta$ forces cancellation

$$\left| \frac{(a_1 + 2a_2 x_0)\, v_0}{(m_1^2 - m_2^2)} \right| \leq 1$$

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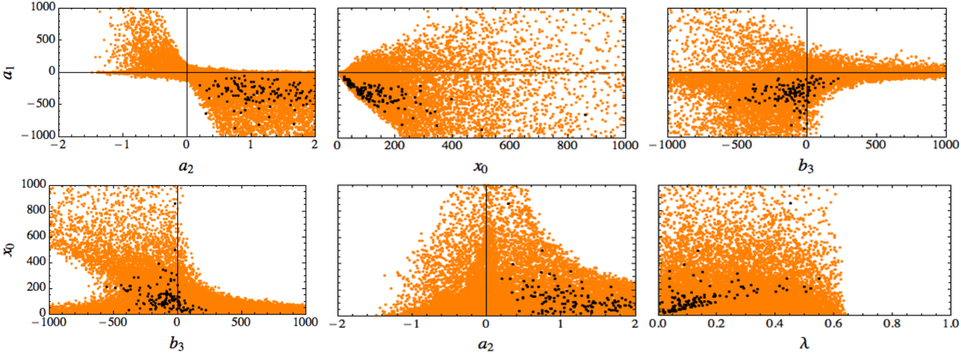

EWPT level: Prefers large, -ve a_1
$\Rightarrow$ Bound on $\sin 2\theta$ forces $a_2 > 0$

$$\left|\frac{(a_1 + 2a_2 x_0)\, v_0}{(m_1^2 - m_2^2)}\right| \leq 1$$

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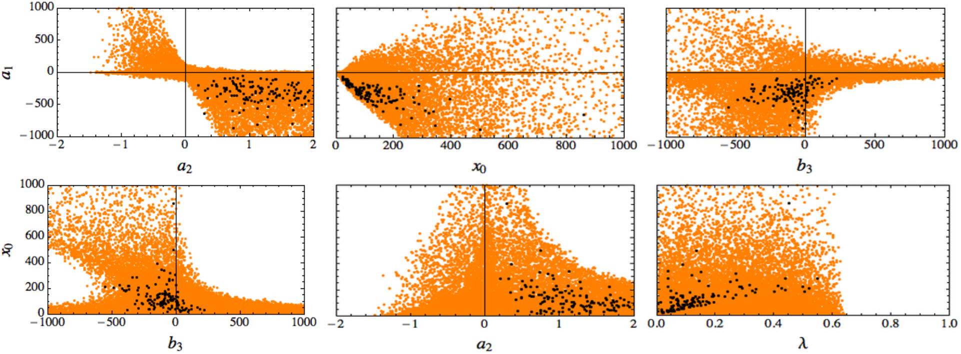

Same mechanism controls a_1 vs x_0
and x_0 vs a_2

$$\left|\frac{(a_1 + 2a_2 x_0)\,v_0}{(m_1^2 - m_2^2)}\right| \leq 1$$

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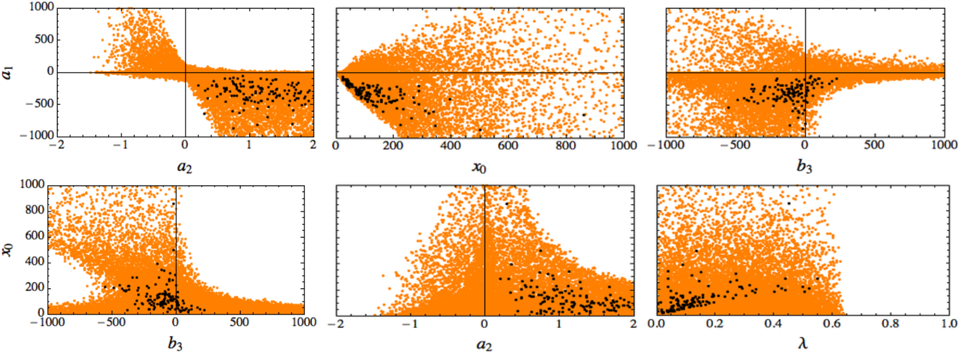

Choice of m_2 range limits λ and controls x_0 vs b_3

$$m_2 < 2m_1$$
$$\Rightarrow b_3 + 2b_4 x_0 < \frac{1}{x_0}\left(5m_1^2 - 2\lambda v_0^2 - \frac{a_2}{2} v_0^2\right)$$

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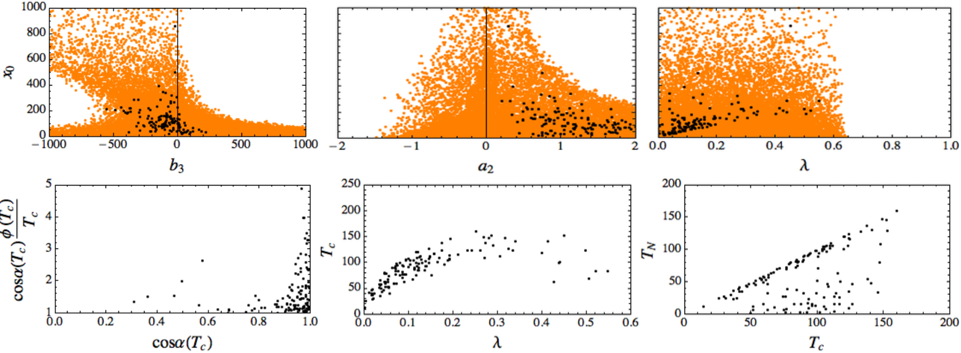

The effect of b_3 in raising barrier is suppressed by $SU_L(2)$ projection

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

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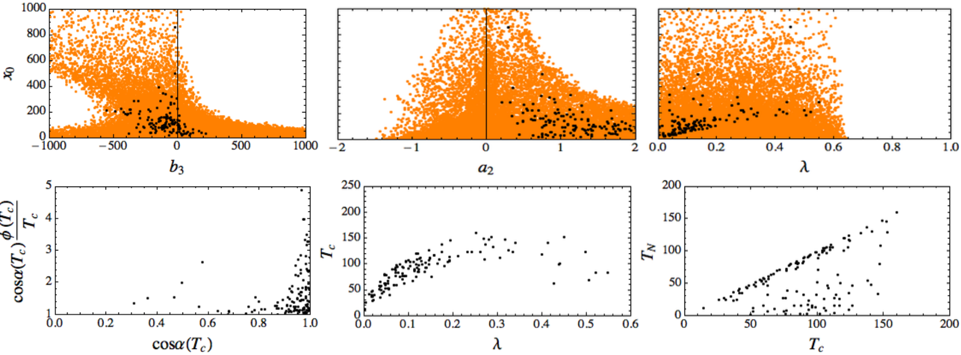

Same mechanism suppresses effect of a_2, b_4 in T_c
$\Rightarrow$ EWPT is enhanced by choosing small λ with m_1 fixed

$$\lambda\cos^4\alpha + \frac{a_2}{2}\cos^2\alpha\sin^2\alpha + \frac{b_4}{4}\sin^4\alpha$$

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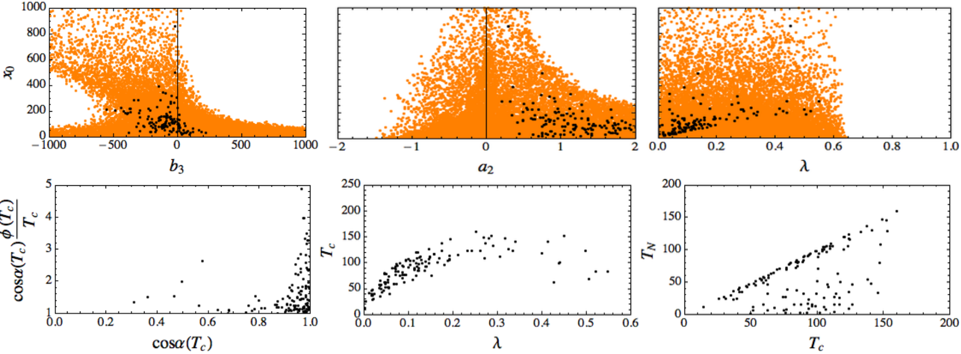
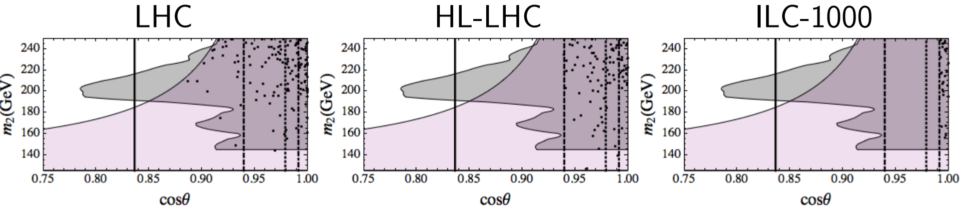


Supercooling occurs and can enhance EWPT by T_c/T_N

$T_N \gtrsim 5$ GeV ⇒ Safe from BBN



LHC

HL-LHC

ILC-1000

What do we learn about collider phenomenology?

$$\cos\theta = \sqrt{\frac{1}{2}\left(1+\sqrt{1-\sin^2 2\theta}\right)} \qquad \sin 2\theta = \frac{(a_1+2a_2x_0)v_0}{(m_1^2-m_2^2)}$$

EWPT prefers small mixing angles and large mass splitting

⇒ More than half of (LHC) points lie in

$$m_2 > 225 \text{ GeV} \qquad \cos\theta > 0.975$$

Results motivate

- Precision measurements of Higgs couplings ($\cos\theta$)
- Heavy Higgs searches near di-Higgs threshold

Summary

- Higgs portals have the potential to connect SM to otherwise-secluded sectors and also link collider physics and cosmology in interesting ways
- The xSM is a minimal set-up which exemplifies many of the salient features of more complex scenarios, including the possibility of inducing a strongly 1st-order EWPT at tree-level
- In the mass regime where no scalar-to-scalar decay modes arise, future LHC and linear collider programs hold promise for significantly improving constraints on the mixing angle
- The requirement of a strongly 1st-order EWPT provides specific motivation from baryogenesis for future precision measurements of Higgs couplings and heavy Higgs searches near the di-Higgs threshold, where singlet-like scalars may be probed directly