Singlet-Assisted Electroweak Phase Transitions: The Search for Precision at the LHC and Lepton Colliders

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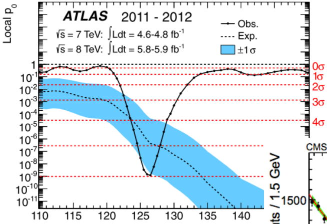
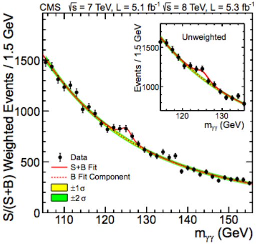
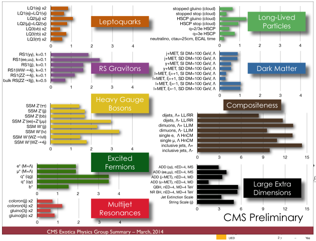
Outline

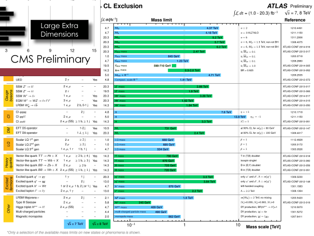
- Higgs Portals: Collider Physics $\Leftrightarrow$ Cosmology
- The xSM: a Minimally Extended Scalar Sector
- What we learn from colliders and precision EW observables
- What we learn from 1st order phase transitions

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



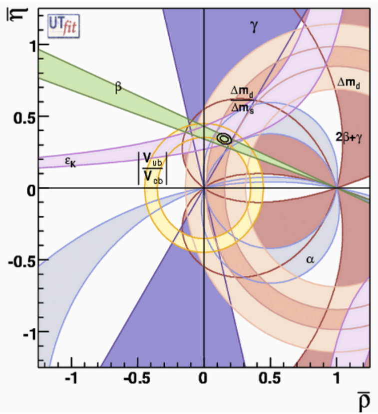


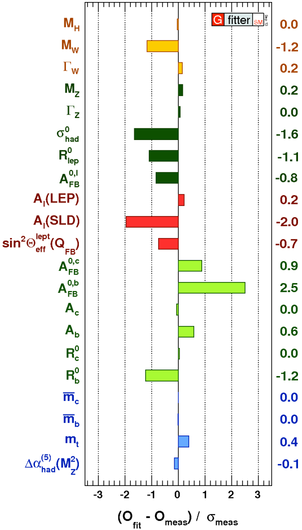




... but it's still not clear what NP is out there

Situation is similarly unclear when considering global fits to Flavor and EW precision observables

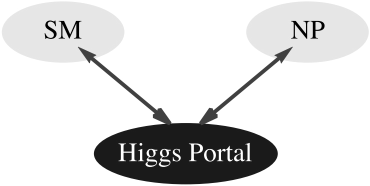




- Yet the search continues...
  DM, BAU, origin of ν masses, etc.
- Can cosmology guide/motivate collider searches?
  ⇒ Higgs portals

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

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



- *Many* scenarios fit into this picture...
- Start with minimal extensions: real, gauge singlet scalar $\Rightarrow$ xSM
- Renormalizable potential

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

- 7 free parameters

Coefficient	Corresp. Term	Mass Dimension	$\mathbb{Z}_2$ symmetric
a_1	$(H^\dagger H)\,S/2$	1	No
a_2	$(H^\dagger H)\,S^2/2$	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
  $\Rightarrow$ min conditions allow us to trade in 2 parameters

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

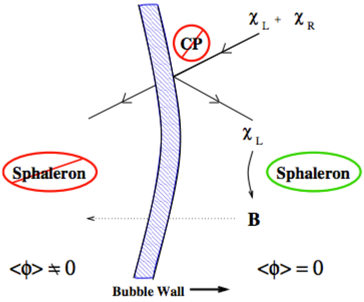
$$b_2 = -b_3 x_0 - b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0} - \frac{a_2 v_0^2}{2}$$

  $\Rightarrow$ Better to get rid of mass^2 parameters
  $\Rightarrow$ Now 6 free parameters

- Applications include inducing a strong 1st order EWPT
  $\Rightarrow$ Requirement for successful EWBG

EWBG basics:

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



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

Cubic terms in $V(\phi, T)$ play a large role $\dfrac{\phi(T_c)}{T_c} = \dfrac{2E}{\lambda}$

$$V(\phi, T)^{SM} = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$

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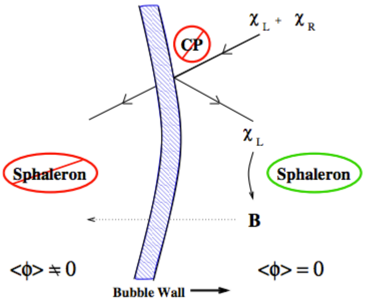
  $\Rightarrow$ Gauge dependent!



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- Z_2-breaking Higgs portal and self-interactions generate tree level cubic terms

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

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

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

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

- Raises barrier between phases
- Lowers T_c

$$\cos\alpha_c\frac{\phi_c}{T_c} = -\cos\alpha_c\frac{e}{2T_c\bar{\lambda}} \gtrsim 1$$

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

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

$$m_{hh} = 2\lambda v_0^2$$
$$m_{ss} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$
$$m_{hs} = \left(\frac{a_1}{2} + a_2 x_0\right) v_0$$

- 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

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

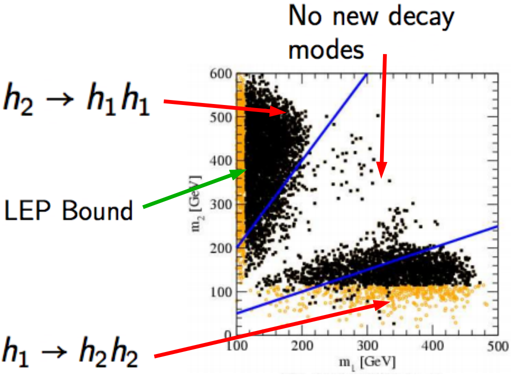
- For $m_2 < m_1 \leq 2m_2$,

$$\frac{\sigma BR}{\sigma^{SM} BR^{SM}} = f(\theta)$$

$\Rightarrow$ A precision game

- What do we know from current LHC?

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



Profumo et. al. JHEP 0708 (2007) 010

Note: we take h_2 as the observed light scalar

$$\Rightarrow m_2 \equiv m_h \simeq 125 \; GeV$$

- *Do 1st order PTs prefer certain masses and angles?*

SM Higgs searches

- All Higgs interactions are rescaled by mixing

$$h \to h_1 \cos\theta - h_2 \sin\theta \qquad \Longrightarrow \qquad \begin{array}{c} g = -\sin\theta g^{SM} \\ \theta^{SM} \equiv -\pi/2 \end{array}$$

- Mass is fixed $\Rightarrow$ only modification of σBR is universal rescaling

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

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

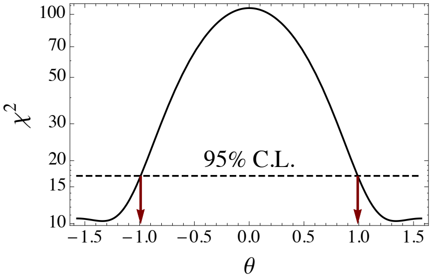
- Global χ^2 fit to current CMS and ATLAS data

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

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 upgrade promises precise measurements of Higgs properties

  ⇒ How much sensitivity can we expect from HL-LHC

  ⇒ Future lepton colliders (ILC)?

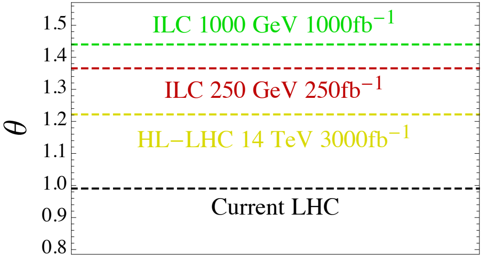
- Both CMS and ATLAS give projections for $\Delta\mu_i^{obs}$ based on current syst. uncertainties by scaling signal and background events

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

- Projected uncertainties for ILC stages
$\Rightarrow$ ILC Higgs White Paper arXiv:1310.0763

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

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

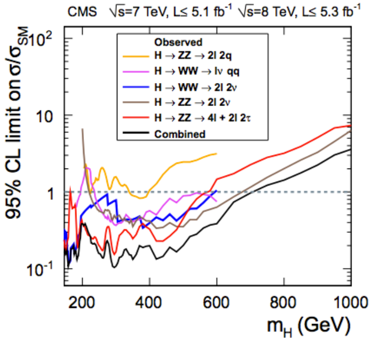


As $\theta \to \pi/2$, heavy scalar decouples from SM

- Presence of heavy scalar state, h_1, can be probed by heavy Higgs searches

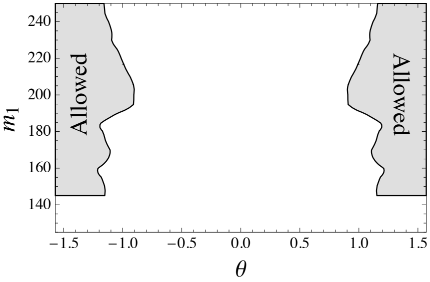
CMS-HIG-12-034

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



- h_1 couples to SM as $\Rightarrow g = \cos\theta g^{SM}$

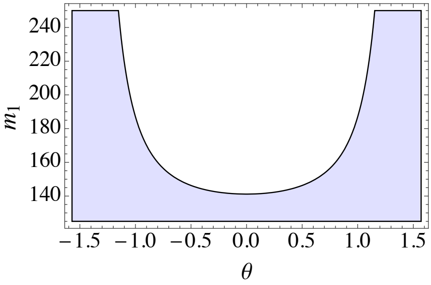
- For $m_1 \leq 2m_h$, signal rates are still mass independent but constraint has large mass dependence



- Heavy scalar mass and mixing are constrained by oblique parameters

- Effects are simple to calculate

$$\Delta\mathcal{O}_i = \cos^2\theta\, \mathcal{O}_i^{SM}(m_1) + (\sin^2\theta - 1)\mathcal{O}_i^{SM}(m_h)$$



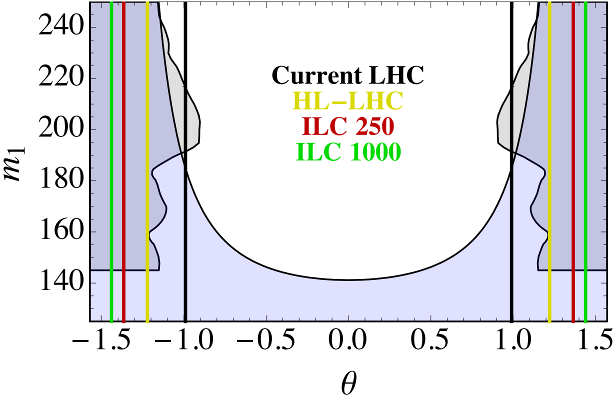
- Fit to current best-fit values given by Gfitter group

Eur. Phys. J. C72 (2012) 2205

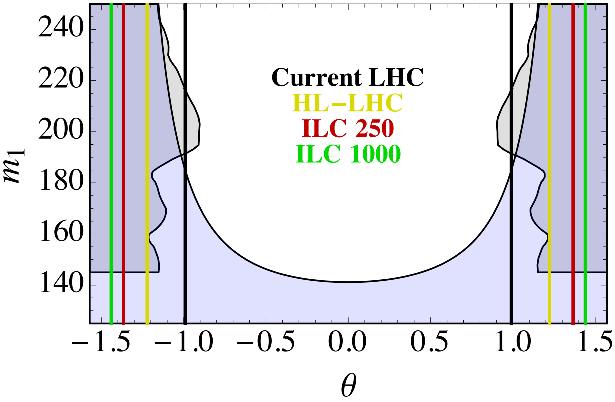
$$\Delta\chi^2 = \sum_{i,j} \left(\Delta\mathcal{O}_i - \Delta\mathcal{O}_i^0\right)_i \left(\sigma^2\right)^{-1}_{ij} \left(\Delta\mathcal{O}_j - \Delta\mathcal{O}_j^0\right)$$

Current situation:

- $m_h < m_1 < 145$ GeV ⇒ SM Higgs searches
- $145 \text{ GeV} < m_1 \lesssim 190$ GeV ⇒ Heavy Higgs searches
- $190 \text{ GeV} < m_1 < 2m_h$ ⇒ Electroweak precision
- $m_h < m_1 < 2m_h$ GeV ⇒ HL-LHC, ILC



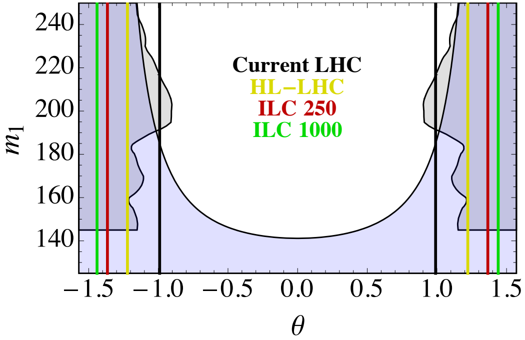
Which regions prefer strong 1st order phase transitions?



- Mass matrix elements connect collider parameters to potential parameters

$$m_1^2 = 2\lambda v_0^2 + b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0} - m_h^2$$

$$\sin\theta = \pm\sqrt{\frac{1+\sqrt{1-\xi^2}}{2}} \qquad \xi \equiv \frac{(a_1 + 2a_2 x_0)\, v_0}{m_1^2 - m_h^2} \leq 1$$



Basic potential constraints:

- Vacuum stability ⇒ potential must be bounded from below

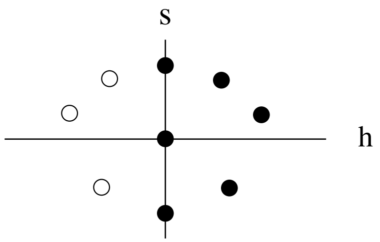
$$\lambda \geq 0, \qquad b_4 \geq 0, \qquad a_2 > -2\sqrt{\lambda b_4}$$

- Viable EWSB ⇒ Requires two conditions be met
  - Determinant of mass matrix is positive

$$b_3 x_0 + 2 b_4 x_0^2 - \frac{a_1 v_0^2}{4 x_0} - \frac{(a_1 + 2 a_2 x_0)^2}{8\lambda} > 0$$

  - EW min is the absolute min

- Vacuum structure can be mapped out analytically
- Empty points are related by $h \to -h$ symmetry



$$\frac{dV}{dh} = h\left(-\mu^2 + \lambda h^2 + \frac{a_1}{2}s + \frac{a_2}{2}s^2\right) = 0$$
$$\frac{dV}{ds} = \frac{a_1}{4}h^2 + s\left(\frac{a_2}{2}h^2 + b_2 + b_3 s + b_4 s^2\right) = 0$$

Numerically impose EW min as absolute min on point-by-point basis

*Written by C. Wainwright

Strategy:

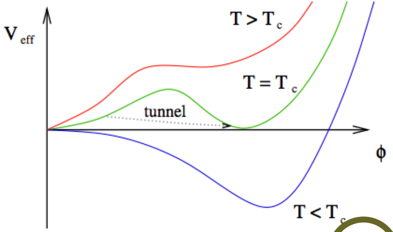
- MC scan over finite ranges of model space

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

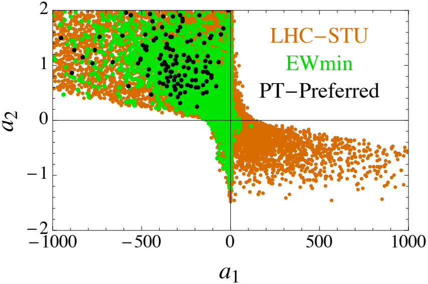
- Impose all collider and theory constraints
- Single-step or multi-step? We'll take both!

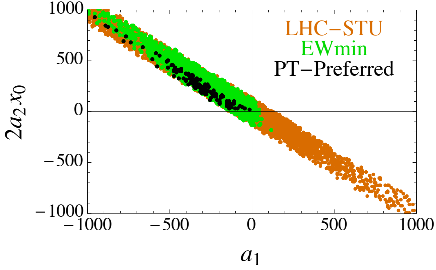
Use CosmoTransitions* to evaluate

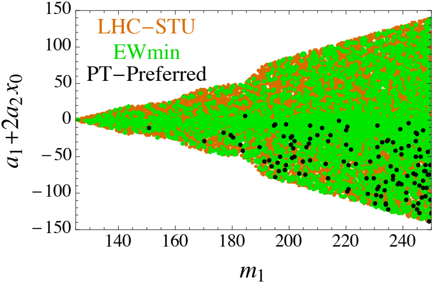
- 1st or 2nd order?
- $T_c, v(T_c), x(T_c) \Rightarrow \phi(T_c), \tan\alpha_c$
- $S_3, T_N \Rightarrow S_3/T_N \sim 140$ at least one critical bubble of EW phase nucleates



Scan Results







$$-\cos\alpha_c \frac{e}{2T_c\bar{\lambda}} \gtrsim 1$$

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

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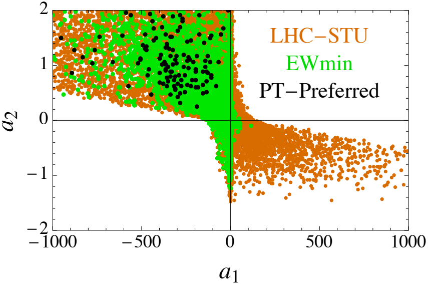
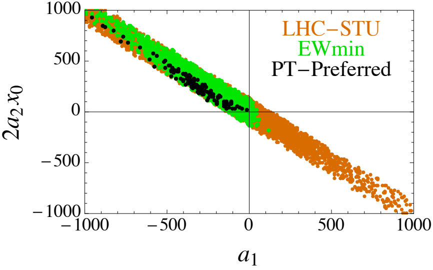
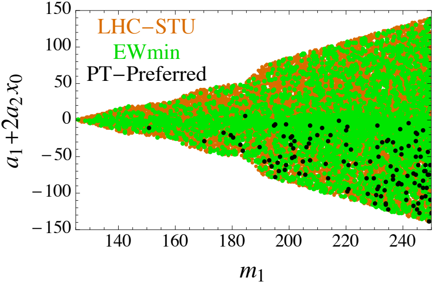




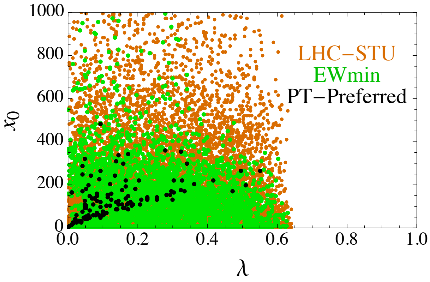


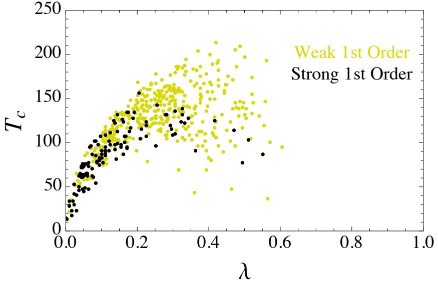
$$\sin\theta = \pm\sqrt{\frac{1+\sqrt{1-\xi^2}}{2}}$$

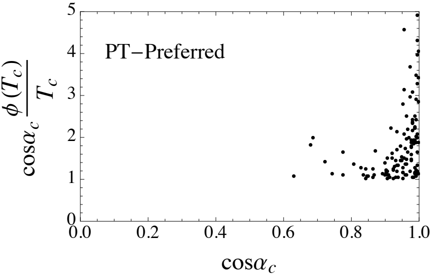
$$\xi \equiv \frac{(a_1 + 2a_2x_0)\,v_0}{m_1^2 - m_h^2} \leq 1$$

$\Rightarrow$ Small masses ($m_1 \sim m_h$) require large tuning to get PT

Scan Results







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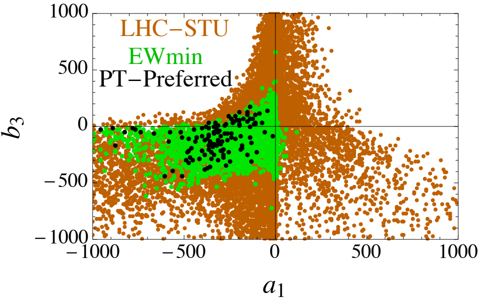
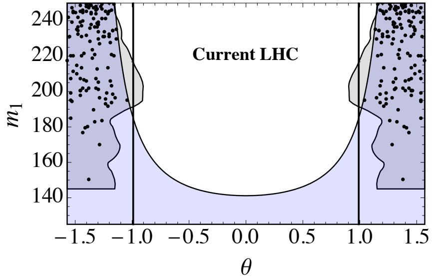


Self-interactions do play a role!

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



A stronger correlation between LHC and PT by turning them off?

Summary

- Higgs portals have the potential to connect SM to otherwise-secluded sectors and also link collider physics and cosmology
- The xSM is a minimal set-up which exemplifies many of the salient features of Higgs portal scenarios and has the added bonus of inducing strong 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
- PTs can motivate some general trends in Higgs portal couplings but these don't necessarily translate to well-defined, preferred regions for mixing angles and masses