Constraining phase diagrams with ScannerS: A complex singlet with dark matter

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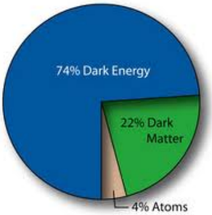
Outline

Motivation

- Besides the success of SM, **SM does not explain**, for instances,
  - the existence of dark matter



  - the measured baryon asymetry of the universe

- **Why complex singlet to test Scanners program?**
  - it's the simplest extension to SM but
  - can provide a viable dark matter candidate
  - can achieve electroweak baryogenesis through a strong first-order phase transition during the era of EWSB
  - it has some structure to test ScannerS

Complex scalar singlet extension of SM

- Add a complex scalar field $\mathbb{S} = S + i\,A$ to the scalar sector of the SM
- The most general renormalizable potential with $\mathbb{Z}_2$ ($\mathbb{S} \to -\mathbb{S}$) and $U(1)$ ($\mathbb{S} \to e^{i\alpha}\mathbb{S}$) symmetries (Barger *et al.*, arXiv:0811.0393)

$$V_{cxSM} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)$$

- Depending on the potential parameters we can have
  - particle spectra with or without DM candidates and
  - scalar particles that may mixture with SM Higgs boson.

Classification of indepedent models and their phases

- Expand around

$$\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \mathbb{S}\rangle = \frac{1}{\sqrt{2}}(v_S + i v_A), \quad (v = 246)$$

- Imposing local minimum conditions with EWSB we obtain the following classification for different models and phases:

Model	Phase	VEV's at minimum
$U(1)$ symmetry $(a_1 = b_1 = 0)$	1 Higgs + 2 degenerate DM 2 mixed Higgs + 1 Goldstone	$\langle \mathbb{S} = 0\rangle$ $\langle A = 0\rangle$
$\mathbb{Z}_2 \times \mathbb{Z}'_2$ $(a_1 = 0)$	1 Higgs + 2 DM 2 mixed Higgs + 1 DM	$\langle \mathbb{S} = 0\rangle$ $\langle A = 0\rangle$
$\mathbb{Z}'_2$ $(a_1 \in \mathbb{R})$	2 mixed Higgs + 1 DM 3 mixed	$\langle A = 0\rangle$ $\langle \mathbb{S} \neq 0\rangle$

Example: $\mathbb{Z}_2'$ model

- Symmetric phase: 2 mixed Higgs + 1 DM

$$\text{higgs with} 125 \text{ GeV} \rightarrow \begin{pmatrix} H_1 \\ H_2 \\ A' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- Broken phase: 3 mixed higgs

$$\text{higgs with} 125 \text{ GeV} \rightarrow \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \begin{pmatrix} M_{1h} & M_{1S} & M_{1A} \\ M_{2h} & M_{2S} & M_{2A} \\ M_{3h} & M_{3S} & M_{3A} \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

$$\text{with} \quad M^T M = \mathbb{1}$$

Theoretical constraints

- Stability conditions on λ_i (**routine CheckStability in ScannerS**): the scalar potential is bounded from below only if

$$\lambda > 0 \quad \wedge \quad d_2 > 0 \quad \wedge \quad (\delta_2^2 > \lambda\, d_2 \; if \; \delta_2 < 0)$$

- Global minimum (**routine CheckGlobal in ScannerS**): closed expressions for stationary points that can be below the local minimum we selected
- Imposing tree level unitarity in $2 \to 2$ high energy scattering
  - SM: $m_H \lesssim 700$ GeV
  - CxSM: (making $d_2 = \delta_2 = 0$ we reproduce SM)

$$|\lambda| \leq 16\pi, |d_2| \leq 16\pi, |\delta_2| \leq 16\pi, \left| \frac{3}{2}\lambda + d_2 \pm \sqrt{(3/2\lambda + d_2)^2 + d_2^2} \leq 16\pi \right|$$

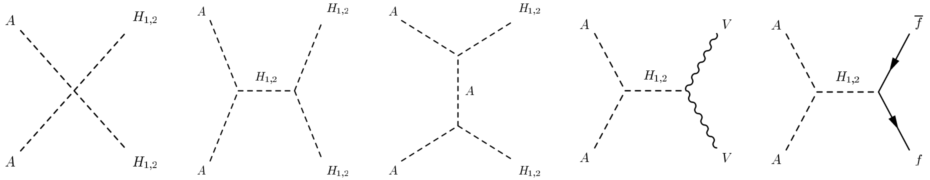
  - This is done automatically with generic routine in ScannerS.
- Electroweak Precision Observables: we calculate the variation of the S, T and U and check whether they fall into the 95% ellipsoid.

Experimental constraints: Dark Matter Relic Density

- Dark Matter Relic Density from WMAP

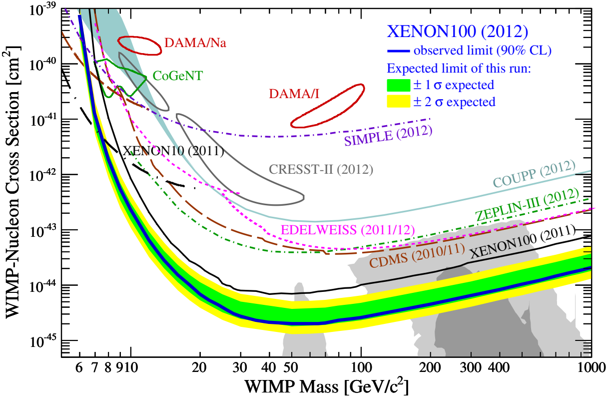
$$\Omega_{cdm}h^2 = 0.112 \pm 0.006 \quad \text{(h is the Hubble constant)}$$

- Thermal relic density: $\Omega_A h^2 \sim 1/\langle\sigma_{ann} v_{rel}\rangle$
- Annihilation processes that contribute to the thermally averaged cross section (2Higgs+1DM phase), mediated by the two Higgs eigenstates (fig from Barger et al. [arXiv:0811.0393])



- The relic density for DM candidate is calculated with micrOMEGAS and is excluded if it is above the limit for relic density $\Omega h^2 > 0.112$ (we can have another DM contributor)

Result on spin-independent WIMP-nucleon scattering from XENON100 (arXiv:1207.5988)



- We exclude a point in parameter space if, for a given DM mass, the scaled cross section $\sigma_{scaled} > \sigma_{XENON100}$

$$\sigma_{scaled} = \sigma_A \frac{\Omega_A h^2}{0.112}$$

Experimental constraints: Collider searches for the SM Higgs boson

- Predicted signal strength μ for each search channel

$$\mu_i = \frac{\sigma_{New}(H_i) \times Br_{New}(H_i \to X_{SM})}{\sigma_{SM}(h_{SM}) \times Br_{SM}(h_{SM} \to X_{SM})} = M_{ih}^2 \frac{Br_{New}(H_i \to X_{SM})}{Br_{SM}(h_{SM} \to X_{SM})}$$

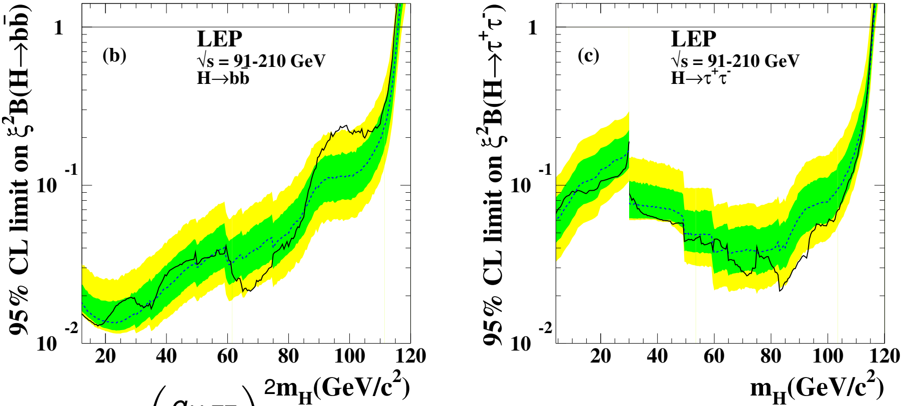
where $M_{ih} = (cos\phi, \sin\phi)$ or (M_{1h}, M_{2h}, M_{3h}) and

$$\frac{Br_{New}(H_i \to X_{SM})}{Br_{SM}(h_{SM} \to X_{SM})} = \frac{M_{ih}^2 \Gamma(h_{SM} \to X_{SM})}{M_{ih}^2 \Gamma(h_{SM} \to X_{SM}) + \Gamma(H_i \to newscalars)}$$

- For example, the decay width for a process $H_i \to H_j H_j$ (if $M_{H_i} > 2M_{H_j}$)

$$\Gamma(H_i \to H_j H_j) = \frac{g_{ijj}^2}{32\pi m_i}\sqrt{1 - \frac{4m_j^2}{m_i^2}}$$

Experimental constraints: Collider searches

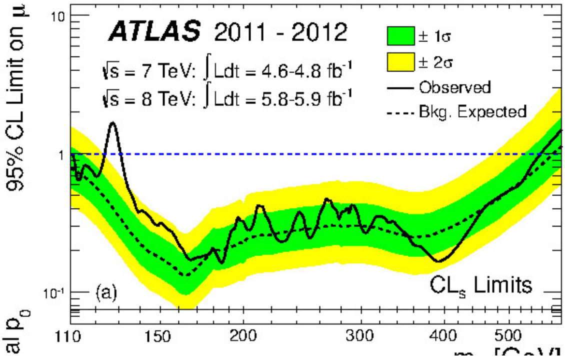


$$\chi^2 = \left(\frac{g_{H_iZZ}}{g^{SM}_{HZZ}}\right)^2 \times Br_{New}(H_i \to SM) = \mu_i \times Br_{SM}(h_{SM} \to SM)$$

We applied limits from $b\bar{b}$ and $\tau^+\tau^-$ channel.

Experimental constraints: Collider searches

Combined 95% CL exclusion limits on LHC signal normalized to SM prediction μ_i as a function of mH (arXiv:1207.7214)

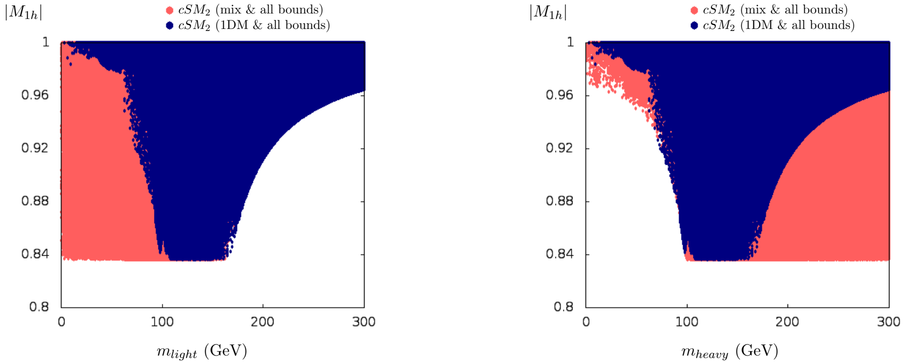


- For $m_h = 125$ GeV we exclude points outside the range $\mu_i = 1.1 \pm 0.4$
- For the other scalar particle we apply the 95% CL combined ATLAS upper limits on μ_i as a function of m_i

Scan over the phase space

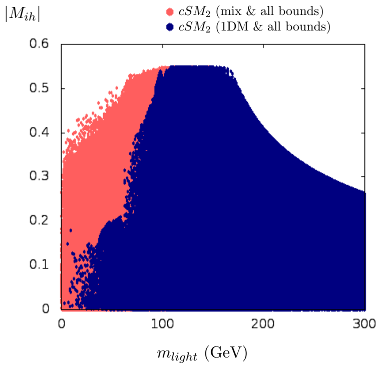
- Scan with 10^6 points uniformly generated in phase space
- $m_h = 125$ GeV
- Other scalar masses: $0 < m < 300(500)$ GeV in standard (wide) run
- $v = 246$ GeV
- Other vev's: $0 < v_S, v_A < 500$ (1000) GeV in standard (wide) run

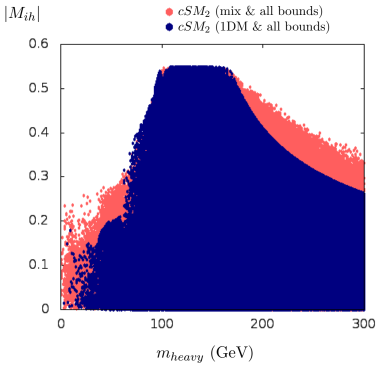
Phase Diagram for Model 2 cSM_2



- We can say if we are observing the lighter or the heavier scalar given a measurement of M_{1h} and the mass of a new scalar in a region exclusively of the "mix" phase (in pink), excluding the DM phase.
- $M_{1h} \approx \sqrt{\mu}$ if 125 GeV is not allowed to decay to any of the other scalars ($M_{1h} \gtrsim 0.84$ 1σ LHC bound for $\sqrt{\mu}$)

Phase Diagram for Model 2 cSM_2





- We can say if we are observing the lighter or the heavier scalar given a measurement on LHC of M_{ih} and the mass of a new scalar in a region exclusively of the "mix" phase (in pink), excluding the DM phase.
- From experimental bounds: $|M_{ih}| \lesssim 0.55$.

Conclusions

- We applied ScannerS to the complex singlet model using
  - theoretical constraints,
  - updated LHC and LEP data,
  - dark matter data.
- By measuring physical particle masses and mixing angles we found that
  - identification of the phase that is realized in Nature is possible in some cases,
  - we can exclude the dark matter phase with a simultaneous measurement of the mass of a non-dark matter scalar together with its mixing angle
  - we can say whether the new scalar is the lightest or the heaviest.

BACKUP SLIDES

Example: 2 mixed Higgs + 1 DM phase

- Minimum conditions:

$$\begin{aligned} m^2 &= -\frac{\lambda}{2}v^2 - \frac{\delta_2}{2}v_S^2 \\ b_2 &= -b_1 - 2\sqrt{2}\frac{a_1}{v_S} - \frac{d_2}{2}v_S^2 - \frac{\delta_2}{2}v^2 \end{aligned} \quad (1)$$

- At the minimum the mass matrix (second derivative) is

$$\begin{pmatrix} m_h^2 & m_{h,S}^2 & m_{h,A}^2 \\ m_{h,S}^2 & m_S^2 & m_{S,A}^2 \\ m_{h,A}^2 & m_{S,A}^2 & m_A^2 \end{pmatrix} =$$

$$= \begin{pmatrix} \lambda v^2/2 & \delta_2 v\, v_S/2 & 0 \\ \delta_2 v\, v_S/2 & d_2 v_S^2/2 - \sqrt{2}a1/v_S & 0 \\ 0 & 0 & -b_1 - \sqrt{2}a_1 v_S \end{pmatrix}$$

Electroweak Precision Observables

- The effects of new physics on EWPO appear only through vacuum polarisation and can be parametrized by three gauge self-energy parameters S, T, U (Peskin & Takeuchi)
- The constraints on the S, T and U parameters are derived from a fit to the electroweak precision data (Gfitter collaboration):

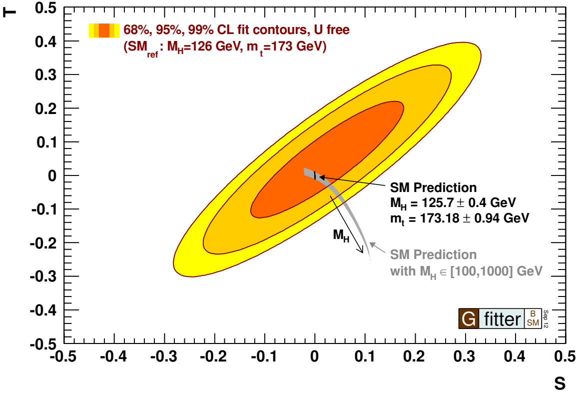
$$S = 0.02 \pm 0.11,\ T = 0.05 \pm 0.12,\ U = 0.07 \pm 0.12$$

with the correlation matrix

$$\rho = \begin{pmatrix} 1 & 0.879 & -0.469 \\ 0.879 & 1 & -0.716 \\ -0.469 & -0.716 & 1 \end{pmatrix}$$

Electroweak Precision Observables

- We calculate the variation of the S, T and U and check whether they fall into the 95% ellipse.



Decay Widths Expressions

- Decay width for a process of the type $H_i \to H_j H_j$ (if kinematically allowed)

$$\Gamma(H_i \to H_j H_j) = \frac{g_{ijj}^2}{32\pi m_i}\sqrt{1 - \frac{4m_j^2}{m_i^2}}$$

- Decay width for a process of the type $H_i \to H_j H_k$ (if kinematically allowed)

$$\Gamma(H_i \to H_j H_j) = \frac{g_{ijk}^2}{16\pi m_i}\sqrt{1 - \frac{(m_j + m_k)^2}{m_i^2}}\sqrt{1 - \frac{(m_j - m_k)^2}{m_i^2}}$$

Scan over the phase space

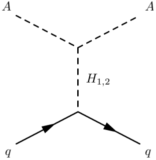
- 10^6 points uniformely generated in phase space
- Parameter ranges

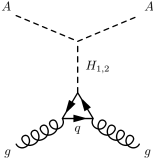
	standard run		wide run	
coupling	min	max	min	max
m^2 (GeV^2)	-10^6	10^6	-2×10^6	2×10^6
λ	0	4	0	50
δ_2	-4	4	-50	50
b_2 (GeV^2)	-10^6	10^6	-2×10^6	2×10^6
d_2	0	4	0	50
b_1 (GeV^2)	-10^6	10^6	-2×10^6	2×10^6
a_1 (GeV^2)	-10^6	10^6	-10^8	10^8

- $m_h = 125$ GeV, other scalar masses: $0 < m < 300(500)$ GeV in standard (wide) run
- $v = 246$ GeV, $0 < v_S, v_A < 500$ (1000) GeV in standard (wide) run

Experimental constraints: Dark Matter Direct Detection

- Scattering cross section of the DM candidate with a proton target (Barger *et al.*, arXiv:1005.3328)





$$\sigma_{SI} = \frac{m_p^4}{2\pi v^2} \frac{1}{(m_p + m_A)^2} \left(\frac{M_{1h}^2 g_{AAH_1}}{M_{H_1}^2} + \frac{M_{2h}^2 g_{AAH_2}}{M_{H_2}^2} \right) \left(f_{pu} + f_{pd} + f_{ps} + \frac{2}{27} 3 f_G \right)^2$$

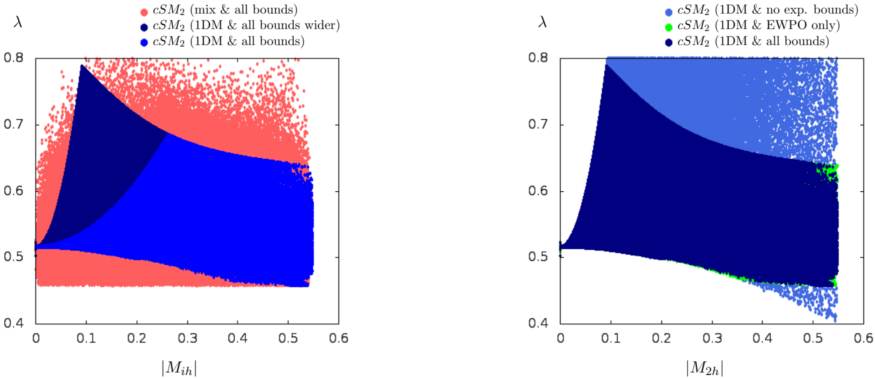
  - f_{pi} are the proton matrix elements

$$f_{pu} = 0.020, f_{pd} = 0.026, f_{ps} = 0.118, f_G = 0.836$$

  - $M_{jh} = (cos\phi, \sin\phi)$ or (M_{1h}, M_{2h}, M_{3h})

- We have done some checks with micrOmegas

Phase Diagram for Model 2 cSM_2



- For small values of $|M_{ih}|$ we can identify two pink regions exclusively of the "mix phase" above and below $\lambda_{SM} \gtrsim 0.5$
- EWPO constraints are responsible for the upper right boundary
- Theoretical constraints are responsible for the bottom boundary