Dark matter and collider phenomenology of an SU(2) triplet and singlet scalar extended standard model

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Based on work done in collaboration with N. Bell[1] , M. Dolan[1], M. Ramsey-Musolf[2,3,4], and R. Volkas[1]

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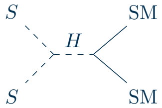
- Models with new scalars expand the scalar potential parameter space.
- This may lead to a first-order electroweak phase transition, as required for electroweak baryogenesis.
- If these new scalars are also stable, they will contribute to the dark matter density.
- Is there a relatively simple scalar extension that could explain both the DM density and BAU?

Minimal Scalar Extensions - Singlets

Adding a real singlet scalar S is the simplest possible scalar extension.

- Relic density determined by the Higgs coupling, as it is the only coupling to the SM particles.



$$\Longrightarrow \quad \langle \sigma_A v \rangle \propto \lambda_{HS}^2$$

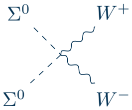
- This coupling also determines the direct detection cross section.

$$\Longrightarrow \quad \sigma_{\mathrm{SI}} \propto \lambda_{HS}^2$$

- Severe DM constraints are inconsistent with requirements for a SFO EWPT.

Adding a real SU(2) triplet scalar Σ is the next simplest extension.

- Annihilation rate dominated by gauge couplings.



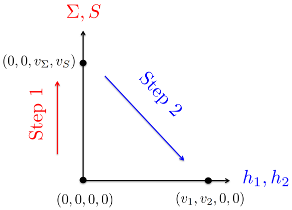
$$\implies \langle \sigma_A v \rangle \propto g^4$$

- This large annihilation rate requires the new scalars to have a very large mass ($m_\Sigma \gtrsim 2$ TeV).
- Similar result for inert doublet DM ($m_{H_2} \gtrsim 500$ GeV).
- When the coupling to the SM Higgs is non-zero, as required for interesting EWPT, these masses need to be even larger.
- Minimal scalar multiplet DM is inconsistent with parameter space required for an interesting EWPT.

Minimal scalar extensions cannot provide a DM candidate while also contributing significantly to the EWPT. Need additional particles.

- Multiple gauge singlet scalars.
- Multiplet SU(2) multiplet scalars, e.g., multiple inert Higgs doublets.
- 2HDM+singlet
- Triplet+Singlet Model

- We examine a model where the SM is extended by a real scalar singlet S and a real scalar triplet $\Sigma \sim (1, 3, 0)$.
- Motivated by a similar model, with two Higgs doublets, that was examined in the context of EWBG (arXiv:1508.05404).



We must impose a $\mathbb{Z}_2$ symmetry in order to ensure one of the new particles is stable.

- We will charge both the singlet and triplet under a single $\mathbb{Z}_2$ symmetry.
- Similar models have been examined in arXiv:1311.1077 and arXiv:2009.01262
- The $\mathbb{Z}_2$ symmetry ensures that there is a stable particle.
- This symmetry also prevents the new scalars from mixing with the SM Higgs.
- However, the singlet and triplet can mix with each other.

Scalar Mixing

- The $\mathbb{Z}_2$ symmetry permits a $\lambda_{H\Sigma S} H^\dagger \Sigma H S$ term.
- After EWSB this will give rise to mixing between Σ^0 and S
- We rotate to the mass basis

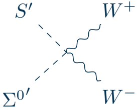
$$\begin{pmatrix} \Sigma^{0\prime} \\ S' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Sigma^0 \\ S \end{pmatrix}.$$

- The heavier scalar will decay into the lighter one and an (off-shell) SM Higgs.
- The lightest scalar will be stable and contribute to the DM density.
- If $m_{\Sigma^{0\prime}} < m_{S'}$, encounter same issue as in minimal triplet scalar DM, annihilation rate is large $\implies$ need large masses.

Equilibrium processes in the Singlet-Triplet Model

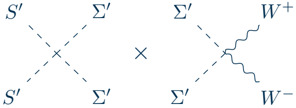
Consider $m_{S'} < m_{\Sigma^{0\prime}}$, S' is the DM. There are three significant processes that could keep the S' in thermal equilibrium.

(a) Equilibrium through weak gauge boson couplings.



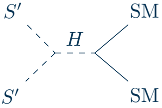
$$\implies \langle \sigma_A v \rangle \propto g^4 \sin^2 \theta$$

(b) Equilibrium through coupling to Σ.



$$\implies n_{S'}^{-1} \propto \lambda_{\Sigma S'}^2 g^4$$

(c) Equilibrium through coupling to SM Higgs.

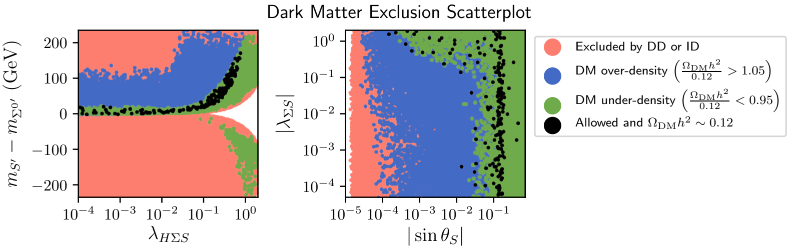


$$\implies \langle \sigma_A v \rangle \propto \lambda_{HS'}^2$$

$$\lambda_{HS'} = \lambda_{HS} \cos^2 \theta - \lambda_{H\Sigma S} \cos \theta \sin \theta + \lambda_{H\Sigma} \sin^2 \theta$$

- We use `micrOMEGAS` to evaluate relic density and DD cross sections.
- Apply constraints from XENON1T.
- Apply Fermi-LAT limits arising from loop induced $S'S' \to \gamma\gamma$ annihilation.
- Also include constraints from oblique parameters.

- Perform a random scan of the parameter space.



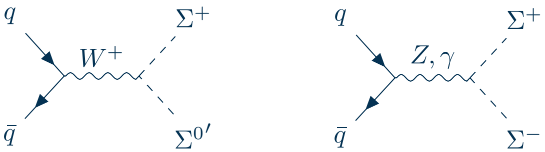
From the scatter-plot, we conclude that either:

(a) $|\sin\theta| \sim 0.1$ and $\Delta m > 0$.

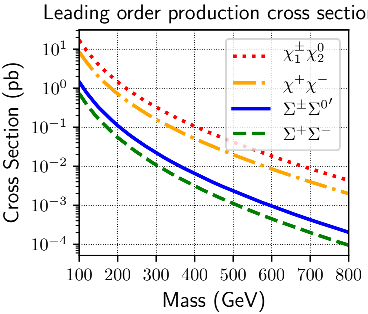
(b) $\lambda_{\Sigma S} > 0.1$ and $0 < \Delta m < 30$ GeV.

- No dedicated collider searches exist for this model.
- However, this model is somewhat analogous to SUSY models with a stable neutralino,
  - $\Sigma^{\pm} \Longleftrightarrow \chi_1^{\pm}\,, \quad \Sigma^{0\prime} \Longleftrightarrow \chi_2^0\,, \quad S' \Longleftrightarrow \chi_1^0$
- This model can be constrained using SUSY searches.
- Search strategy depends significantly on "neutralino" mass difference $\Delta m = m_{S'} - m_{\Sigma^{0\prime}}$.

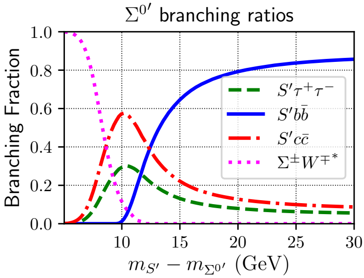
- The scalars are mainly pair produced via charged and neutral current Drell-Yan processes.

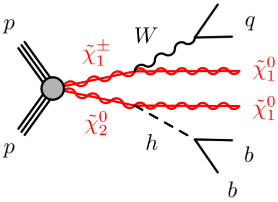


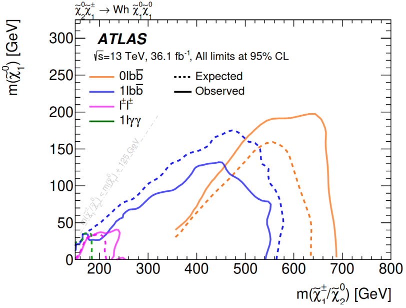
- The production cross section is about 10× smaller than for $\chi^{\pm}$, χ^{0}



- The $\Sigma^{\pm}$ will decay almost exclusively into $S'W^{\pm(*)}$.
  - Directly analogous to $\chi_1^{\pm} \to \chi_1^0 W^{\pm(*)}$.
- The $\Sigma^{0\prime}$ will generally decay into $S'h^{(*)}$.
  - For large Δm, there exist analogous neutralino searches using $\chi_2^0 \to \chi_1^0 h$
  - However, for low Δm, these searches use $\chi_2^0 \to \chi_1^0 Z^{(*)}$.
- If $m_{\Sigma^{0\prime}} > m_{\Sigma^{\pm}}$, the $\Sigma^{0\prime}$ can also decay into $\Sigma^{\pm} W^{\mp(*)}$
  - No direct chargino analogue.

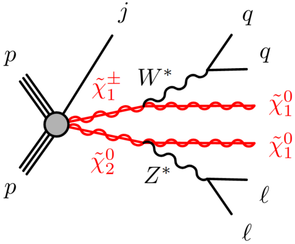


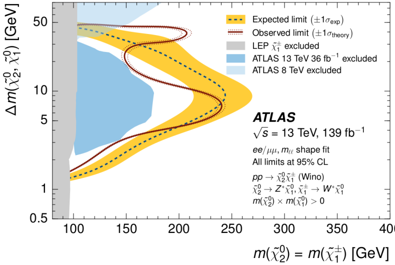




[Image credit: ATLAS Collaboration, arXiv:1812.09432]

- The large Δm decay processes have directly analogue SUSY searches.
- Constraints well approximated by directly taking the 95% CL on the chargino production cross sections.
- Doing so, we find that current SUSY searches do not constrain our model.



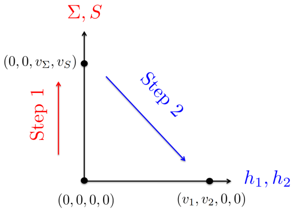


[Image credit: ATLAS Collaboration, arXiv:1911.12606]

- Charginos and neutralinos are notoriously difficult to search for when they only have a small mass difference.
- Existing Searches are not directly applicable due to presence of $Z^* \to \ell\ell$ decays.
- However, perhaps $h^* \to \tau\tau \to \ell\ell\nu\nu\nu\nu$ decays can yield signal events?
- Expect that maybe just about constrain up to $m_{S'} \sim 70$ GeV.

Summary

- A Singlet+Triplet extension is capable of explaining the DM density.
- Scalars can be light and have sizeable couplings to SM Higgs $\Longrightarrow$ potential for novel EWPT.
- Currently relatively unconstrained at colliders.
  - Similar to chargino-neutralino searches, with a factor of $\sim 10\times$ less data.
- Future work
  - How does DM and Collider phenomenology change in Singlet+Triplet+2HDM?
  - This model can generate a baryon asymmetry (arXiv:1508.05404).
  - Can this model simultaneously yield the correct DM density and baryon asymmetry?



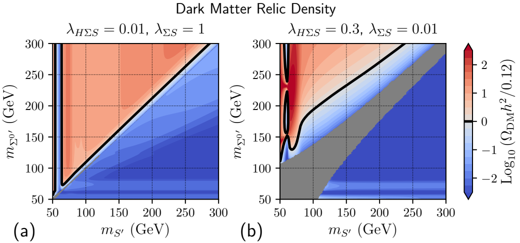
Appendix

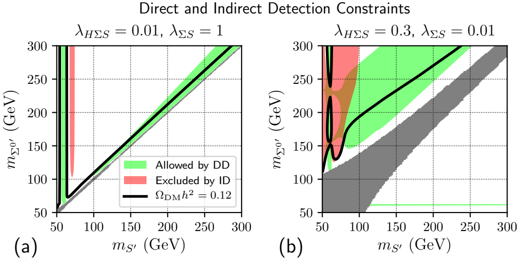
$$
\begin{aligned}
V_{\Sigma x\mathrm{SM}} \;=\; & -\; \mu_H^2 H^\dagger H \;-\; \frac{1}{2}\mu_\Sigma^2 \mathrm{Tr}(\Sigma^2) \;-\; \frac{1}{2}\mu_S^2 S^2 \\
& +\; \lambda_H (H^\dagger H)^2 \;+\; \frac{1}{4}\lambda_\Sigma \mathrm{Tr}(\Sigma^2)^2 \;+\; \frac{1}{4}\lambda_S S^4 \\
& +\; \frac{1}{\sqrt{2}} a_{H\Sigma} H^\dagger \Sigma H \;+\; a_{HS} H^\dagger H S \;+\; \frac{1}{2} a_{\Sigma S} \mathrm{Tr}(\Sigma^2) S \;+\; \frac{1}{3} a_S S^3 \\
& +\; \frac{1}{2}\lambda_{H\Sigma} \mathrm{Tr}(\Sigma^2) H^\dagger H \;+\; \frac{1}{2}\lambda_{HS} H^\dagger H S^2 \;+\; \frac{1}{4}\lambda_{\Sigma S} \mathrm{Tr}(\Sigma^2) S^2 \\
& +\; \frac{1}{\sqrt{2}}\lambda_{H\Sigma S} H^\dagger \Sigma H S \;+\; bS\,,
\end{aligned}
$$

$$
V_{\Sigma x\mathrm{SM}} \supset \frac{1}{2} \begin{pmatrix} \Sigma^0 & S \end{pmatrix} \begin{pmatrix} -\mu_\Sigma^2 + \frac{1}{2} v_H^2 \lambda_{H\Sigma} & -\frac{1}{4} v_H^2 \lambda_{H\Sigma S} \\ -\frac{1}{4} v_H^2 \lambda_{H\Sigma S} & -\mu_S^2 + \frac{1}{2} v_H^2 \lambda_{HS} \end{pmatrix} \begin{pmatrix} \Sigma^0 \\ S \end{pmatrix}.
$$

(a) Equilibrium through weak gauge boson couplings.

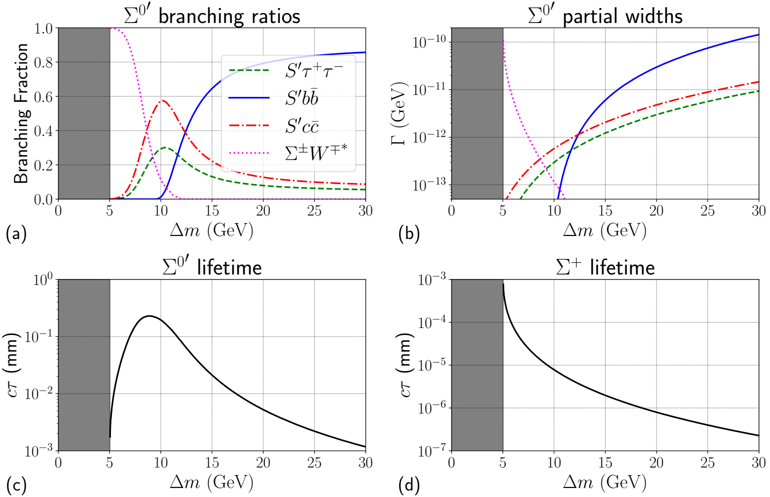
(b) Equilibrium through coupling to Σ.



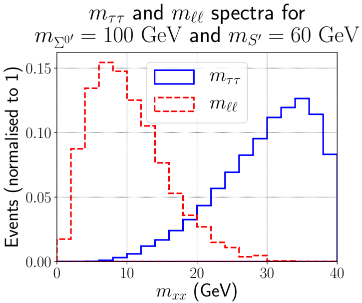


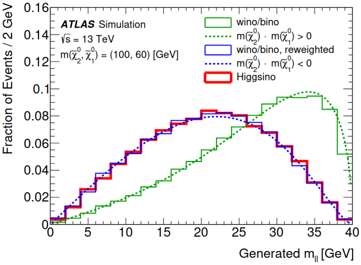
Singlet+Triplet Model – Decays

Σ decays with $m_{\Sigma^\pm} = 150$ GeV and $\lambda_{H\Sigma S} = 0.05$



Singlet+Triplet Model – $m_{\ell\ell}$ Spectrum





[Image credit: ATLAS Collaboration, arXiv:1911.12606]