Impact of Mass Generation for Simplified Dark Matter Models

Rebecca K. Leane

ATLAS Astroparticle Forum Meeting
November 2nd, 2016

Based on 1610.03063
with Nicole Bell and Yi Cai

THE UNIVERSITY OF MELBOURNE

CoEPP

Introduction

- Particle nature of DM remains unknown. Ideally, want to interpret experimental results in a model independent manner as possible.
- Simplified models reasonably achieve this aim: while they may not capture the full phenomenology of UV complete theories, they are designed for use in appropriate limiting cases.
- Standard benchmarks include spin-0 or spin-1 mediators in isolation.
- However, this can lead to unphysical scenarios, such that the reported phenomenology may not map to any viable model.
- To avoid this, important to consider minimal ingredients of gauge invariant models, ensuring valid interpretation of experimental data.

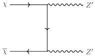
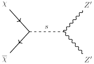
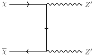
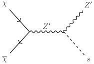
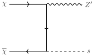
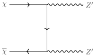
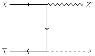
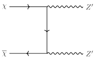
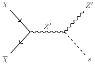
Mass Generation for Spin-1 Models

- Mass generation is not typically specified for simplified DM models.
- Any massive spin-1 mediator requires a mass generation mechanism.
- This can be achieved without introducing new fields, but requires that:
  - Mediator obtains mass via the Stueckelberg mechanism, and
  - DM is Dirac, with pure vector couplings.

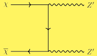
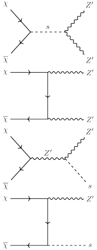
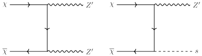
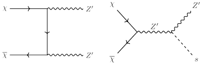
Mass Generation for Spin-1 Models

- Mass generation is not typically specified for simplified DM models.
- Any massive spin-1 mediator requires a mass generation mechanism.
- This can be achieved without introducing new fields, but requires that:
  - Mediator obtains mass via the Stueckelberg mechanism, and
  - DM is Dirac, with pure vector couplings.
- This is a very specific scenario. No reason to assume it is what is realized by nature.
- Well motivated to consider a variety of scenarios where different dark sector fields acquire their mass by various methods: the Stueckelberg mechanism, a dark Higgs mechanism, or where allowed, a bare mass term.

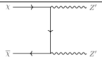
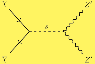
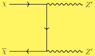
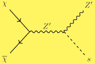
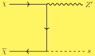
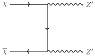
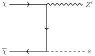
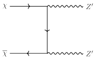
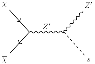
Impact of Specifying Mass Generation

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.	   	Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector	 	Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector	 	Z'_T

Scenario I

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector		Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector		Z'_T

Scenario II

Scenario	**χ mass**	**Z' mass**	**Required $\chi - Z'$ coupling type**	**Annihilation processes**	**Z' pol**
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.	   	Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector	 	Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector	 	Z'_T

Scenario II

In this scenario, the dark Higgs field, $S = w + s + ia$, provides a mass generation mechanism for the dark sector fields Z' and χ.

After symmetry breaking, the interaction terms of interest are

$$\mathcal{L} \supset g_\chi^2 w Z'^\mu Z'_\mu s + g_f \sum_f Z'_\mu \overline{f} \Gamma_f^\mu f - \sin\theta \frac{m_f}{v} s \overline{f} f$$
$$- g_\chi Q_V Z'_\mu \overline{\chi} \gamma^\mu \chi - g_\chi Q_A Z'_\mu \overline{\chi} \gamma^\mu \gamma_5 \chi - \frac{y_\chi}{\sqrt{2}} s \overline{\chi} \chi,$$

where the masses and couplings are related as

$$y_\chi / g_\chi = \sqrt{2} m_\chi / m_{Z'}.$$

Scenario II

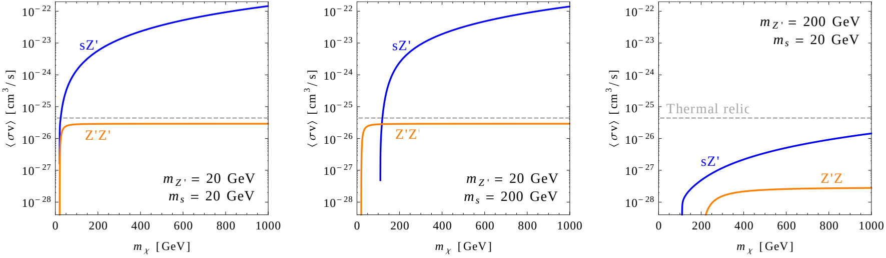
- The axial coupling is not merely possible in this case, but in fact required to be non-zero by gauge invariance.
- The reason is simple: the dark Higgs field, S, must clearly carry $U(1)_\chi$ charge to break that symmetry. Then, the Yukawa term,

$$\mathcal{L}_{\mathrm{Yukawa}} = -\left(y_\chi \overline{\chi}_R \chi_L S + h.c.\right),$$

  is possible only if the DM is chiral, i.e. χ_L and χ_R have different $U(1)_\chi$ charges.
- Depending on specific values, the vector coupling may or may not be present.

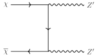
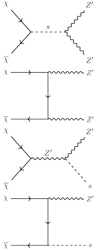
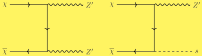
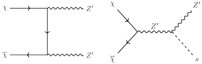
Scenario II

Two-mediator annihilation mode dominates when kinematically allowed.



This scenario requires $2Q_A = Q_S = 1$, and we have chosen $Q_V = 1/2$. The gauge coupling has been set to $g_\chi = 0.1$.

Scenario III

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector		Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector		Z'_T

Scenario III

In this scenario, the dark Higgs field, $\phi = w + s$, provides a mass generation mechanism for χ, and Stueckelberg provides Z' mass.

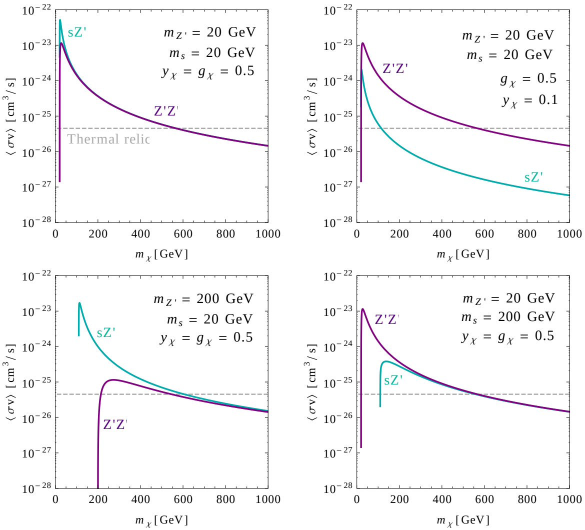
After symmetry breaking, the interaction terms of interest are

$$\mathcal{L} \supset g_f \sum_f Z'_\mu \overline{f} \Gamma^\mu_f f - \sin\theta \frac{m_f}{v} s \overline{f} f$$

$$- g_\chi Q_V Z'_\mu \overline{\chi} \gamma^\mu \chi - \frac{y_\chi}{\sqrt{2}} s \overline{\chi} \chi.$$

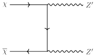
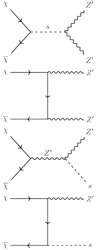
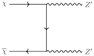
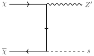
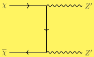
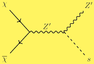
- Couplings g_χ and y_χ are now independent
- Vectorlike charge Q_V can be chosen freely
- Only real scalar needed to give fermions mass, unlike other scenarios
- Here the dark $U(1)_\chi$ remains unbroken, and instead the dark Higgs must break some other symmetry under which the DM is charged

Scenario III



Here $Q_V = 1$.

Scenario IV

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector	 	Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector	 	Z'_T

Scenario IV

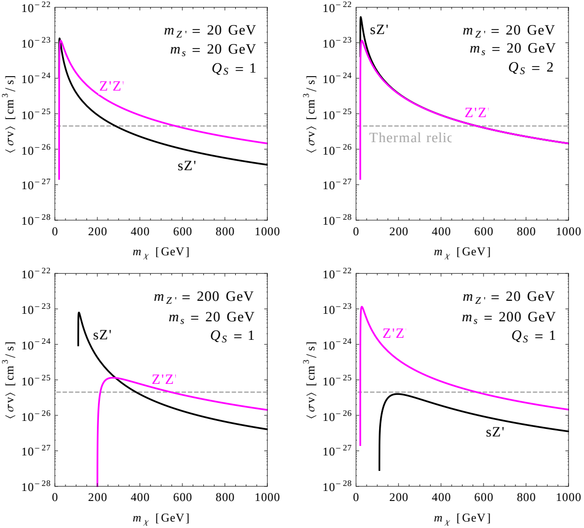
In this scenario, the dark Higgs field, $S = w + s + ia$, provides a mass generation mechanism for Z', and DM has a bare mass term.

After symmetry breaking, the interaction terms of interest are

$$\mathcal{L} \supset g_f \sum_f Z'_\mu \overline{f} \Gamma^\mu_f f - \sin\theta \frac{m_f}{v} s \overline{f} f + g_\chi^2 Q_S^2 w Z'^\mu Z'_\mu s - g_\chi Q_V Z'_\mu \overline{\chi} \gamma^\mu \chi,$$

- Vectorlike charge Q_V can be chosen freely
- Dark Higgs charge Q_S can be chosen freely

Scenario IV



Here $Q_V = 1$, $g_\chi = 0.5$.

Summary

As we can realistically expect to cover much of the WIMP parameter space in near future, it is important to have well-formulated models which span a comprehensive spectrum of interaction types.

Mass generation tells us:

- If dark Higgs interacts with both Z' and DM, non-zero axial-vector coupling is required
- All other combinations of mass generation mechanisms require pure vector DM-Z' couplings
- Relic density is set differently in each case
- Annihilation processes and indirect detection limits different
  - Interplay of s-wave sZ' and $Z'Z'$ final states
  - V-A interference boosts rate if both V and A couplings present

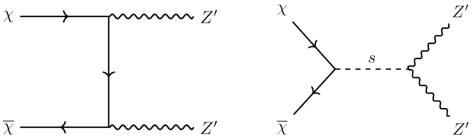
These results are not captured by the single-mediator setup.

Additional slides

Self consistency of Spin-1 Models

The presence of an axial-vector coupling is significant, as it implies that

1. The DM mass must arise after symmetry breaking, as the $U(1)_\chi$ gauge symmetry prevents a bare mass term for χ, and
2. A $U(1)_\chi$ symmetry breaking mechanism is required to give the Z' mass, in order to unitarize the longitudinal component of the Z'.



A single dark Higgs field is an economical solution to these issues.

(See 1510.02110 Kahlhoefer et al)

Charge assignments

Yukawa term is

$$\mathcal{L}_{\text{Yukawa}} = -\left(y_\chi \overline{\chi}_R \chi_L S + h.c.\right),$$

and so the charges of the dark sector field must be chosen to satisfy

$$Q_{\chi_R} - Q_{\chi_L} = Q_S \ .$$

Set the dark Higgs charge to $Q_S = 1$. The χ charges therefore satisfy

$$Q_A \equiv \frac{1}{2}(Q_{\chi_R} - Q_{\chi_L}) = \frac{1}{2},$$
$$Q_V \equiv \frac{1}{2}(Q_{\chi_R} + Q_{\chi_L}) = \frac{1}{2} + Q_{\chi_L}.$$

These charges determine the vector and axial-vector couplings of the Z' to the χ. Q_A is completely determined, while there is freedom to adjust Q_V by choosing $Q_{\chi_{L,R}}$ appropriately.

Scenario I: Full Lagrangian

In all scenarios, the gauge group is: $SM \otimes U(1)_\chi$, and so the the covariant derivative is $D_\mu = D_\mu^{SM} + iQg_\chi Z'_\mu$, where Q denotes the $U(1)_\chi$ charge.

Bare DM Mass, Z' Mass from Stueckelberg

This is the most minimal spin-1 setup, and no additional fields are introduced, as Z' obtains mass via Stueckelberg and DM is vectorlike so a bare mass term is allowed. The lagrangian is

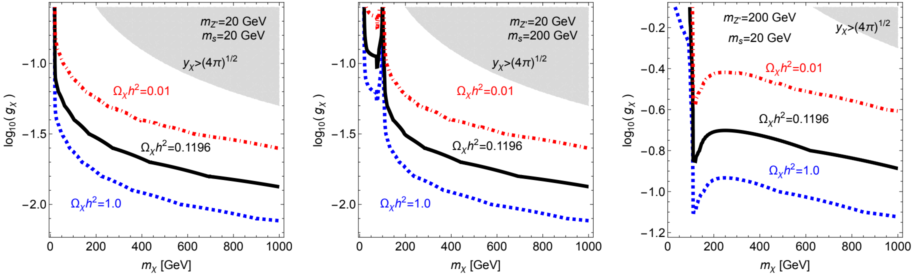
$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\chi}(\partial_\mu + ig_\chi Q_V Z'_\mu)\gamma^\mu\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu}$$
$$- m_\chi \overline{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu.$$

Scenario II: Full Lagrangian

In this scenario, the vev of the dark Higgs field provides a mass generation mechanism for the dark sector fields Z' and χ. Before electroweak and $U(1)_\chi$ symmetry breaking, the most general Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\overline{\chi}_L \not{D} \chi_L + i\overline{\chi}_R \not{D} \chi_R - (y_\chi \overline{\chi}_R \chi_L S + h.c.) - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} \\ + (D^\mu S)^\dagger (D_\mu S) - \mu_s^2 S^\dagger S - \lambda_s (S^\dagger S)^2 - \lambda_{hs} (S^\dagger S)(H^\dagger H).$$

Scenario II: Relic Density



Scenario III: Full Lagrangian

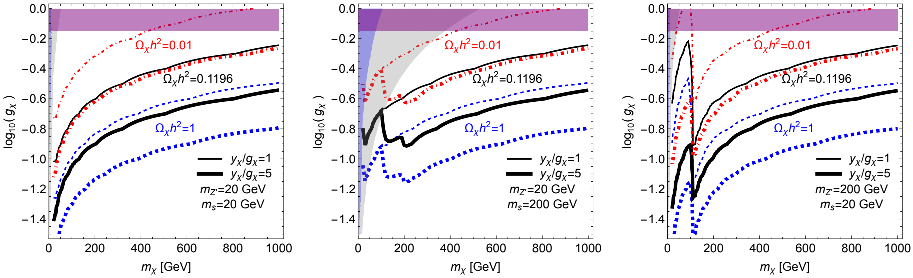
DM Mass from Dark Higgs, Z' Mass from Stueckelberg

The most minimal Lagrangian for this scenario is

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{SM} \quad &+ \quad i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{y_\chi}{\sqrt{2}}\overline{\chi}\chi\phi - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu} \\ &+ \quad \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_s^2\phi^2 - \frac{1}{4}\lambda_s\phi^4 - \frac{1}{2}\lambda_{hs}\phi^2(H^\dagger H),\end{aligned}$$

with the real scalar $\phi = w + s$, where w is the vev of ϕ and s is the dark Higgs.

Scenario III: Relic density



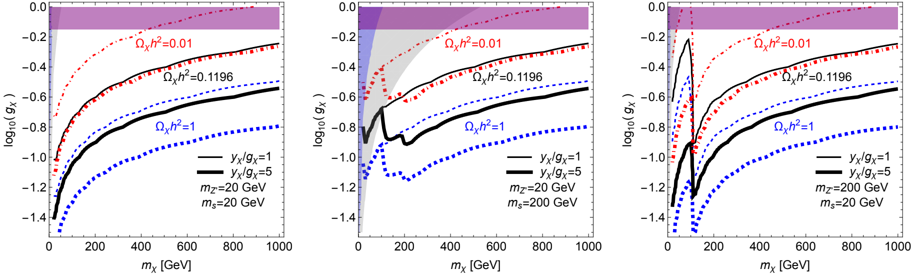
Scenario IV: Full Lagrangian

Bare DM Mass, Z' Mass from Dark Higgs

The most minimal gauge invariant Lagrangian is

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi \\
&+ \left[(\partial^\mu + ig_\chi Q_S Z'^\mu)S\right]^\dagger \left[(\partial_\mu + ig_\chi Q_S Z'_\mu)S\right] - \mu_s^2 S^\dagger S \\
&- \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H).
\end{aligned}$$

Scenario IV: Relic Density



Indirect Detection Constraints