Simplified DM Models with Z'

A story with a dark Higgs

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1605.09382, 1610.03063 and 1705.01105

Overview

1. Introduction

2. A Model with Z' and a Dark Higgs

3. Dark Sector Mass Generation

4. Dark ISR Enhances Annihilation

5. Summary

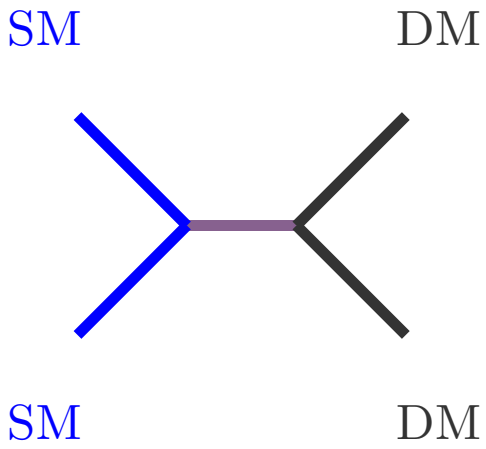
Introduction

Simplified Models and Unitarity

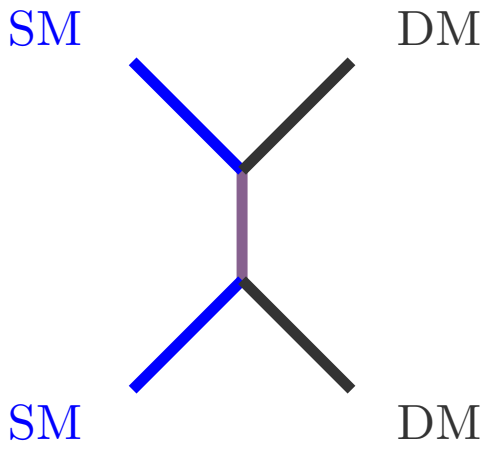
Simplified models suggested for the LHC Run 2 search 1507.00966

- a handful of new particles and interactions
- can be seen as a limit of various UV complete models

s-channel



t-channel



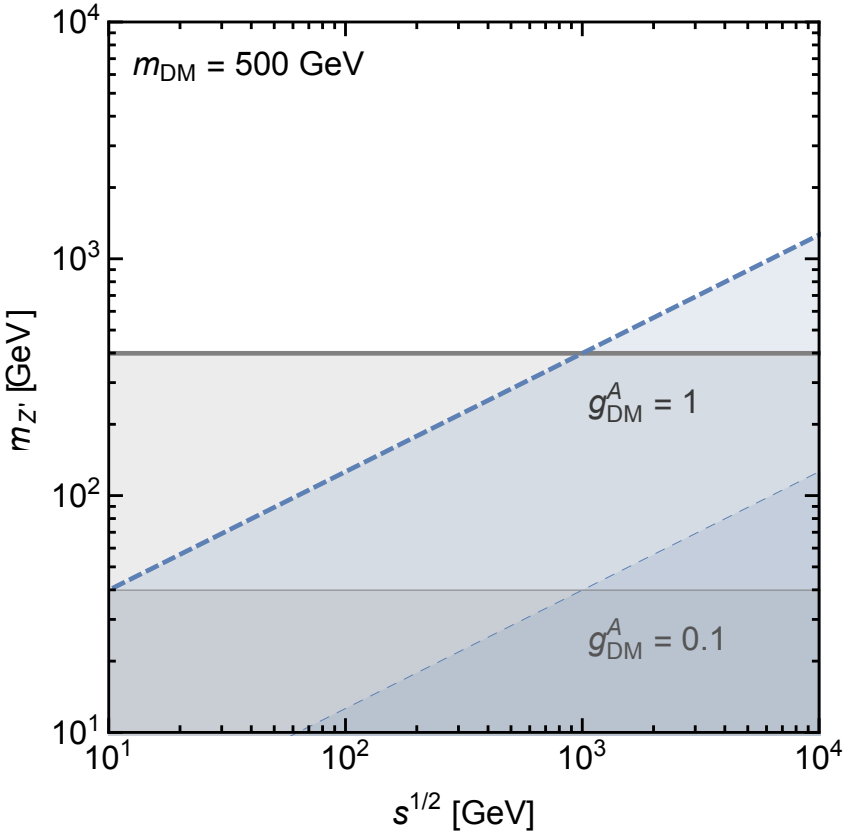
Each simplified model features one type of mediator.

Unitarity issues if SM or dark gauge symmetry broken 1503.07874

A Simple Example

eg: a spin-1 mediator Kahlhoefer et. al. 1510.02110, 1606.07609

$$\Delta\mathcal{L} \sim Z'^{\mu}\,\bar{f}\left[g_f^V\gamma_\mu + g_f^A\gamma_\mu\gamma^5\right]f + Z'^{\mu}\,\bar{\chi}\left[g_\chi^V\gamma_\mu + g_\chi^A\gamma_\mu\gamma^5\right]\chi$$



- Axial vector couplings break unitarity
  - DM self-scattering
  - DM annihilation
- Z' mass breaks $U(1)'$
- Extra scalar needed for AV to restore unitarity and also generate mass

Recap: Z' and a dark Higgs

Axial vector mediator implies the existence of a dark Higgs field.

- A simplified model with only a DM candidate and an axial vector mediator is oversimplified.
- This leads to a dual-mediator model: both spin-1 and spin-0 mediators.
- The presence of both a spin-1 and spin-0 mediator leads to interesting new phenomenology, not captured by a single mediator scenario.

A Model with Z' and a Dark Higgs

Maj. DM with Z' mediator in a Hidden Sector Scenario

- $U(1)_\chi$ with Majorana DM χ, Z' & complex scalar S
- let $Q'(S) = 1$, Yukawa interaction sets $Q'(\chi) = -\frac{1}{2}$

$$-\frac{1}{4} g_\chi \bar{\chi} \gamma_5 \gamma_\mu \chi Z'^\mu - \frac{1}{2} y_\chi \bar{\chi}_L^C \chi_L S$$

- Hidden sector scenario

$$-\lambda_{HS}(S^\dagger S)(H^\dagger H) - \frac{1}{2} \sin\epsilon Z'_{\mu\nu} B^{\mu\nu}$$

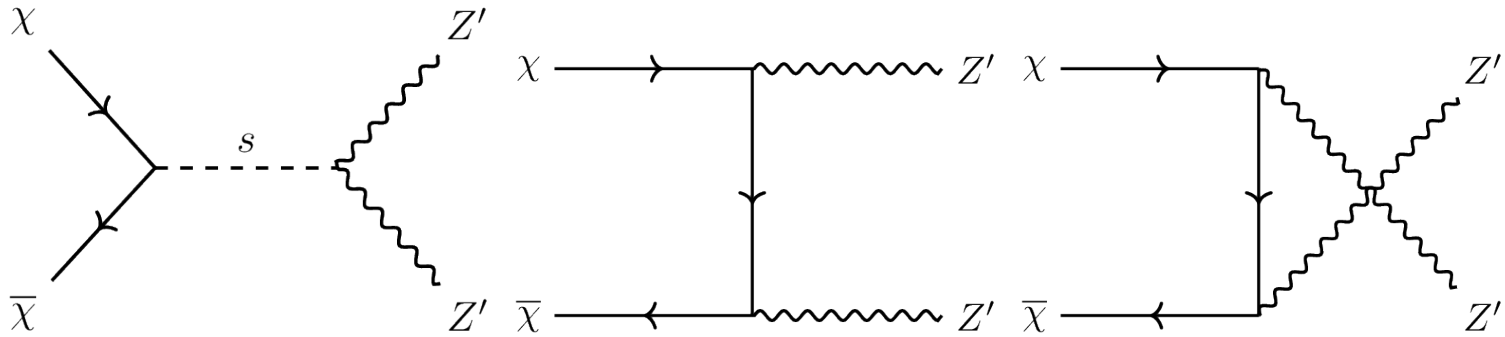
small mixing allows decay of S and Z'

  - Dark-visible sector couplings can be small, to satisfy collider and direct detection constraints
  - Large indirect detection signals possible

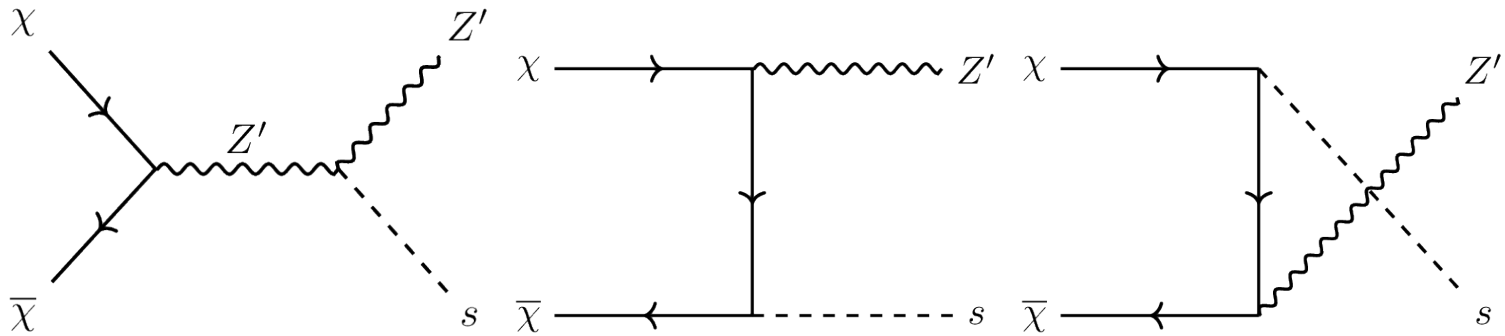
What is New for the Dual-Mediator Model?

- A new contribution to $\chi\chi \to Z'Z'$

  prevents unphysical high energy behavior



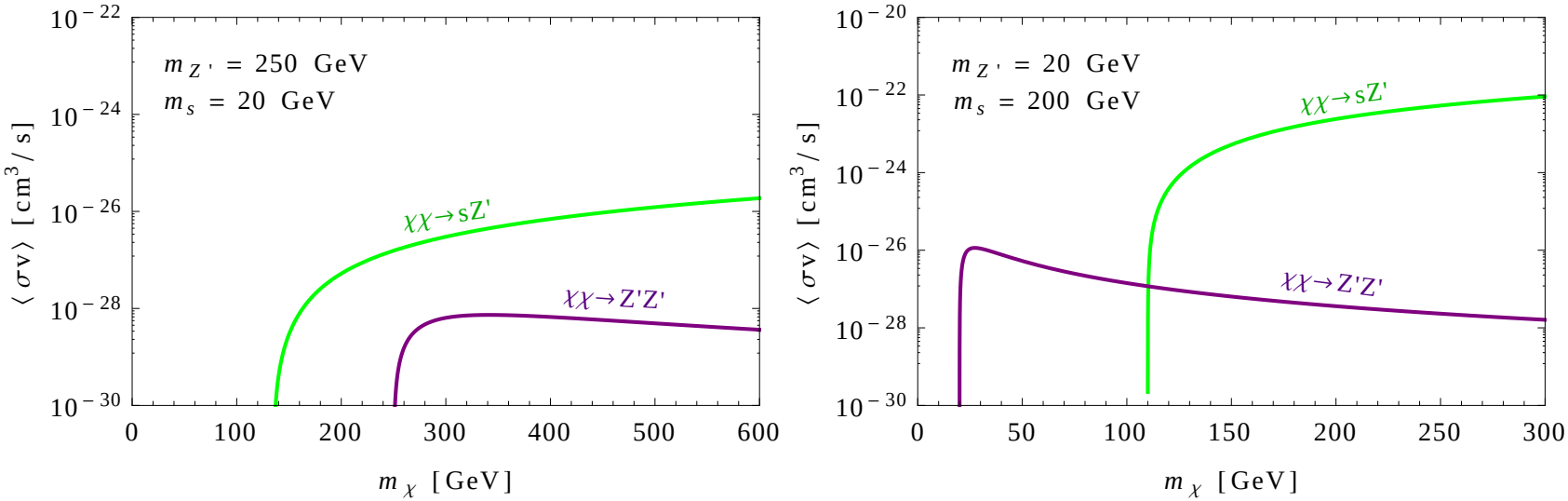
- A brand new channel of interests: dark Higgstrahlung



Bell, Cai and Leane, 1605.09382

Comparison of the Cross Sections

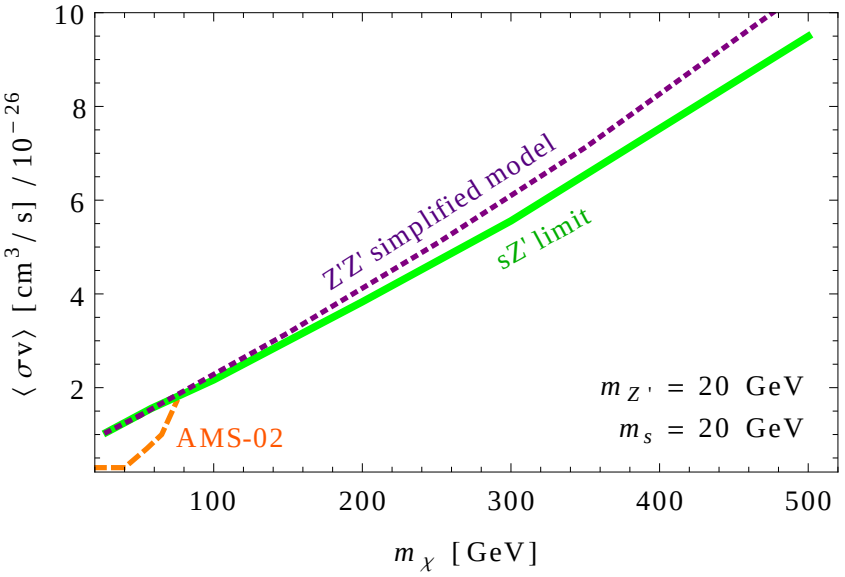
Parameters: m_s, $m_{Z'}$, m_χ, g_χ. With $m_s < 2m'_Z$: $Z', s \Rightarrow$ SM

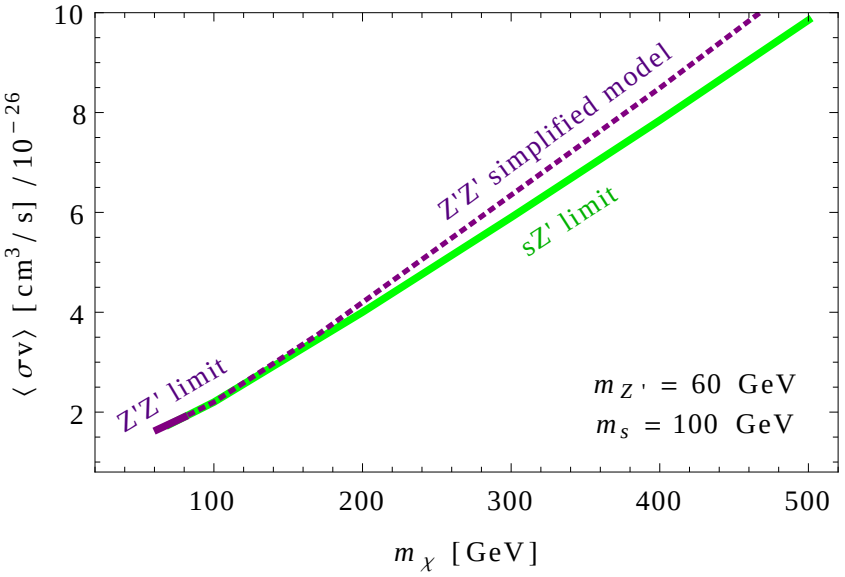


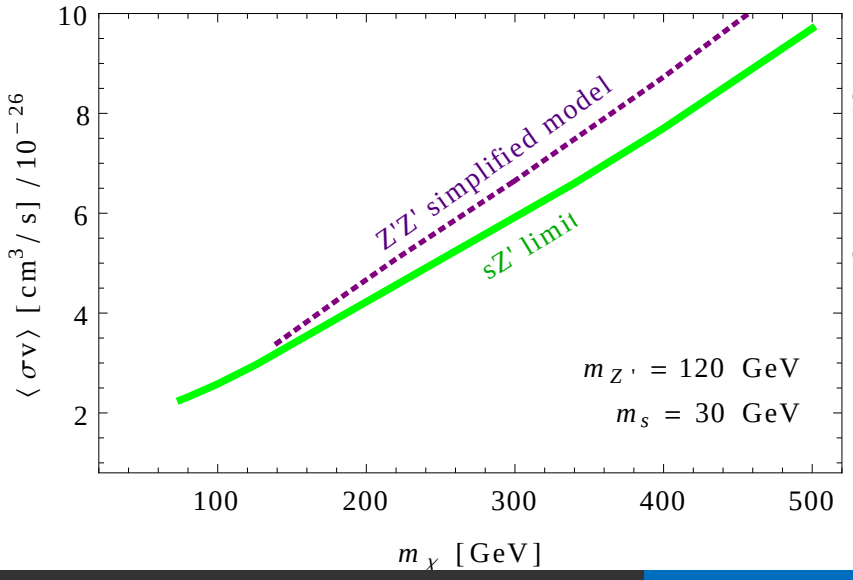
- Both cross sections scale as g_χ^4, $g_\chi = 0.1$
- Large cross section for $\chi\chi \to sZ'$
  enhanced by $Z'_L \sim \frac{m_\chi^2}{m_{Z'}^4}$
- With $m_s + m_{Z'} < 2m_\chi < 2m'_Z$, sZ' is the only channel
- Inaccurate limits if only $Z'Z'$ considered

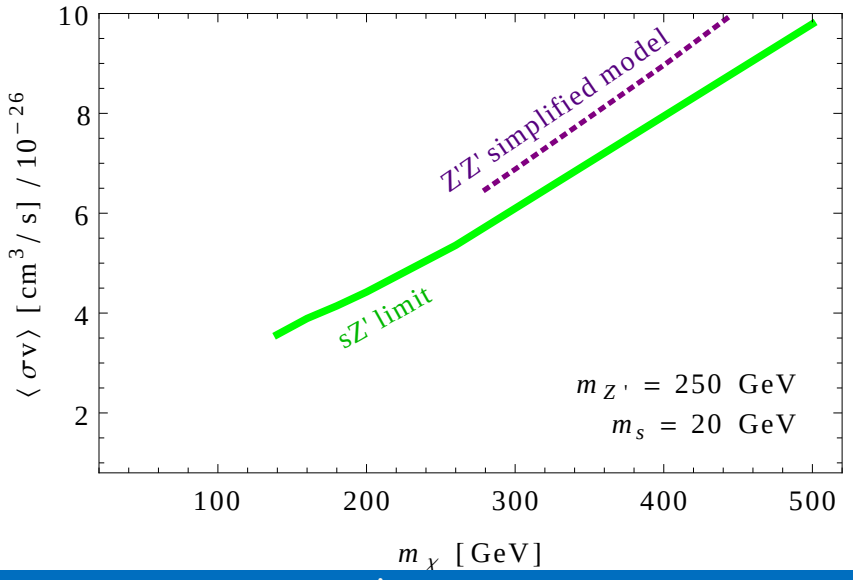
Results for ID

Fermi-LAT and AMS-02









Dark Sector Mass Generation

Fermionic Dark Matter

Majorana DM

- only axial-vector couplings to a Z' allowed
- dark Higgs mechanism gives mass to both Z' and DM.

Dirac DM

Both vector and axial-vector couplings to Z' allowed

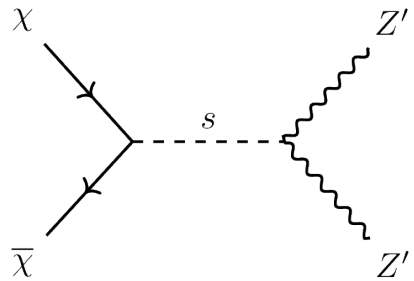
- If Z' has pure vector couplings
  - Z' mass: either dark Higgs or Stueckelberg mechanism
  - DM mass: bare mass or dark Higgs mechanism
  - mass mechanisms not necessarily connected
- If Z' has non-zero axial coupling
  - Dark Higgs gives mass to both Z' and DM (like Majorana)

Dark Sector Mass Generation: Dirac DM

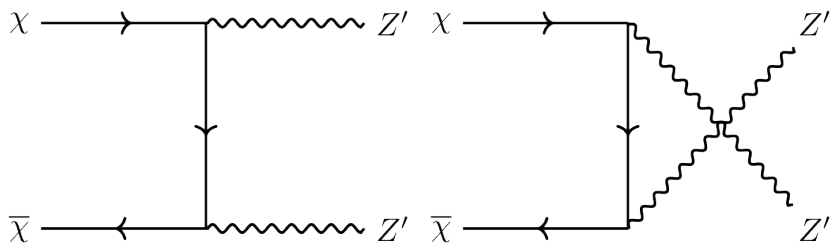
	m_χ	$m_{Z'}$	$\chi - Z'$ coup.	Ann.	Z' pol.
I	Bare mass	Stueckelberg	Vector	$Z'Z'$	Z'_T
II	Dark Higgs	Dark Higgs	Axial$\neq 0$	$Z'Z'$ & sZ'	Z'_T & Z'_L
III	Dark Higgs	Stueckelberg	Vector	$Z'Z'$ & sZ'	Z'_T
IV	Bare mass	Dark Higgs	Vector	$Z'Z'$ & sZ'	Z'_T

Bell, Cai & Leane 1610.03063

$\chi\chi \to Z'Z'$

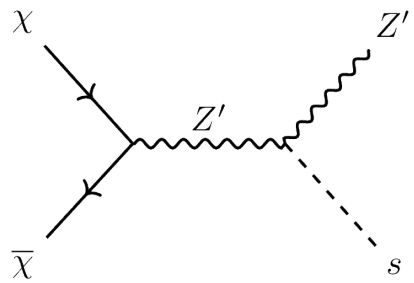


Case II only

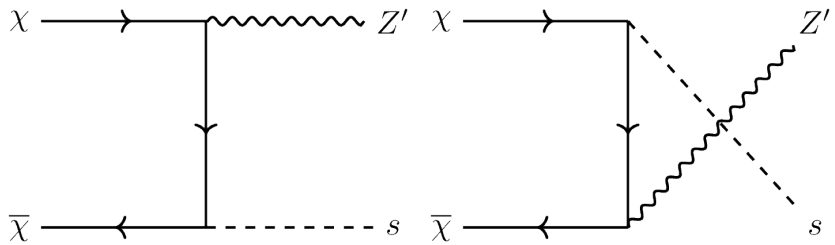


All Cases

$\chi\chi \to sZ'$



Case II, IV

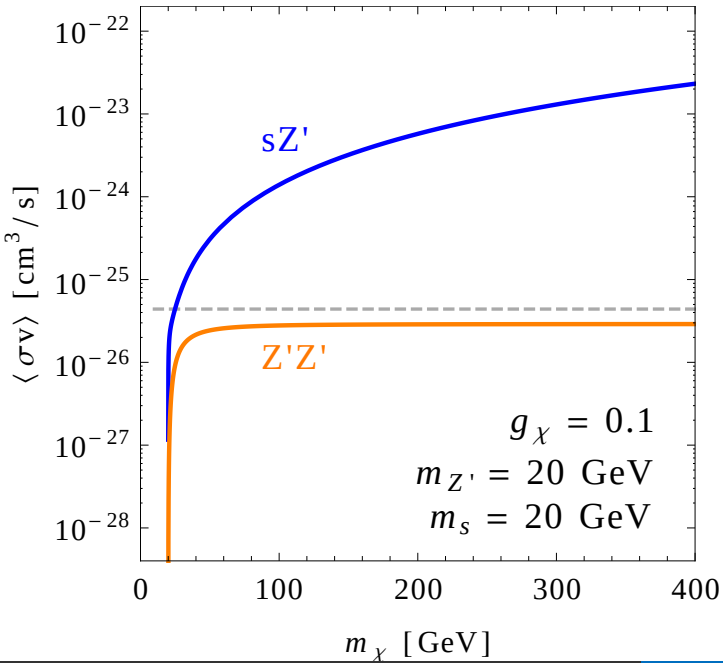


Case II, III

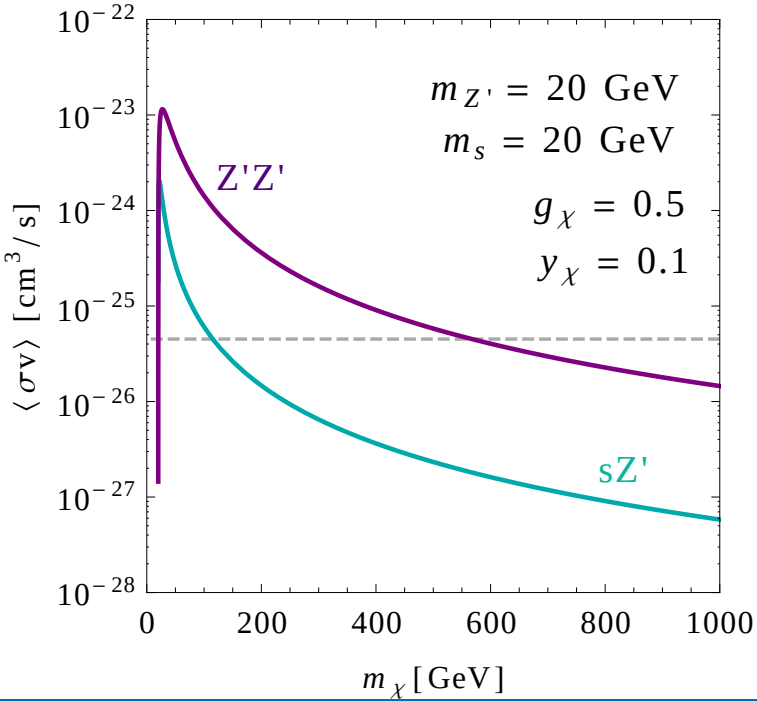
Case II & III: a quick comparison

- Case II: Z' and DM mass from dark Higgs
  - sZ' dominates over $Z'Z'$ when kinematically allowed
  - Cross sections enhanced by longitudinal Z'
- Case III: DM mass from dark Higgs, Z' from Stu. mechanism
  - y_χ and g_χ not related: relative strength freely arranged

Case II

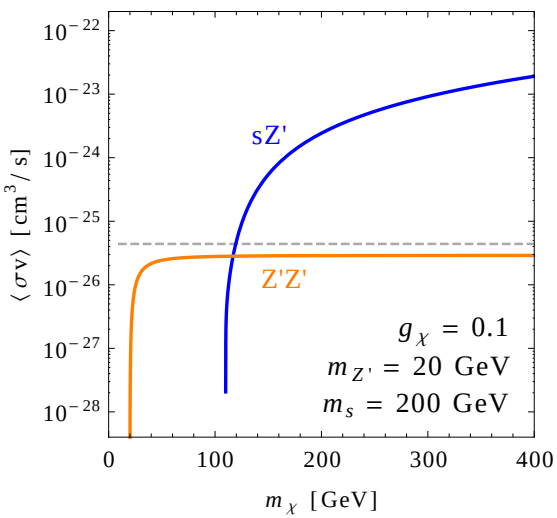


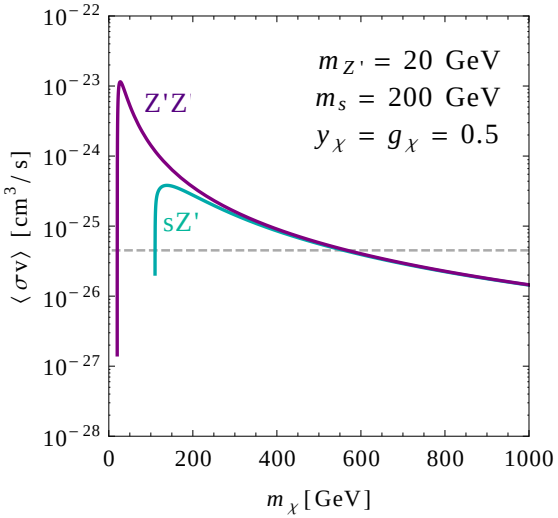
Case III

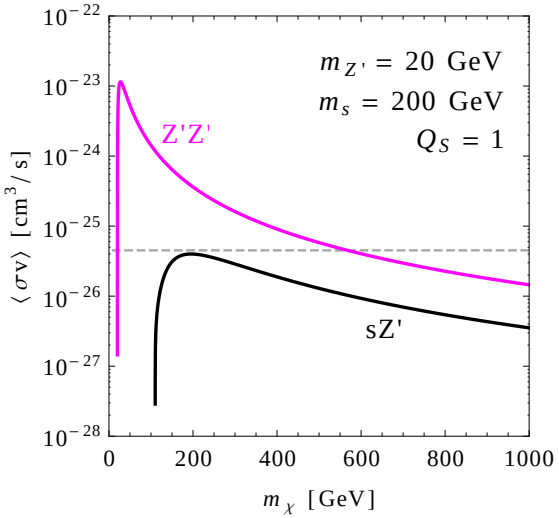


Polarization of Z'

Enhancement from longitudinal Z' only for axial couplings







Case II Case III Case IV

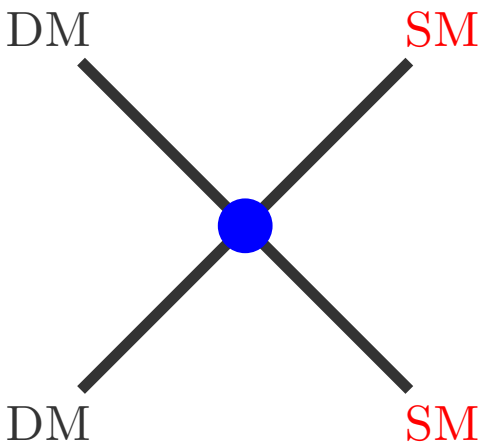
Dark ISR Enhances Annihilation

DM Annihilation: $\chi\bar{\chi} \to f\bar{f}$

$$(\bar{\chi}\Gamma_\chi \chi)\,(\bar{f}\Gamma_f f)$$

Annihilation rates often suppressed

- p-wave suppressed: $\sim v^2$
  $A \otimes V$, $S \otimes S$, $S \otimes P$
- helicity suppressed: $\sim m_f^2/m_\chi^2$
  $A \otimes A$

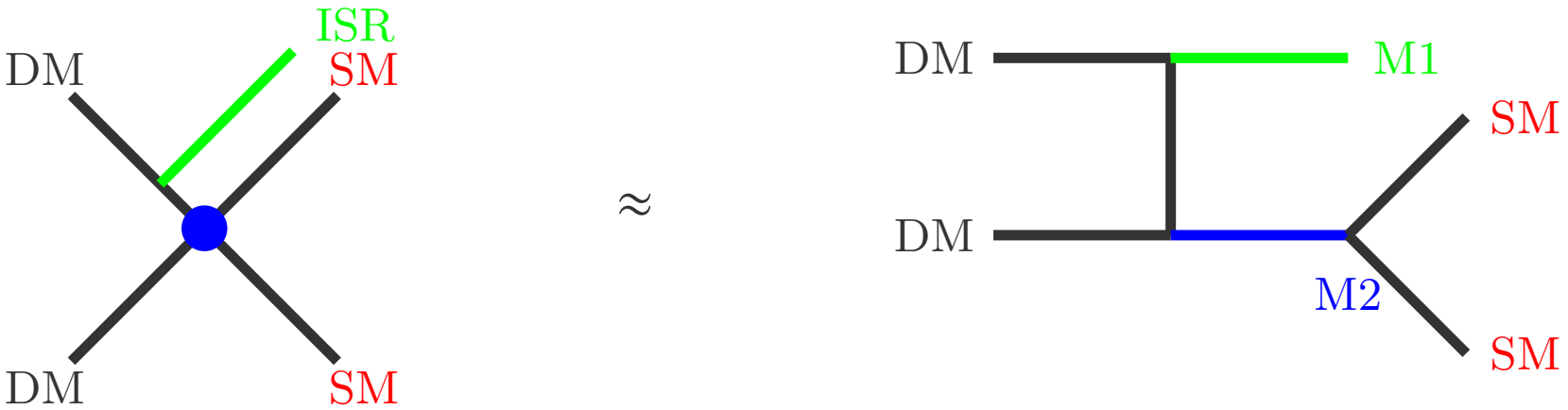


Possible treatment

- Final state radiation
- Internal Bremsstrahlung
- Initial state radiation

Dark ISR: A simple equivalence

only true for $\left(\bar{\chi}\Gamma_\chi\chi\right)\left(\bar{f}\Gamma_f f\right)$

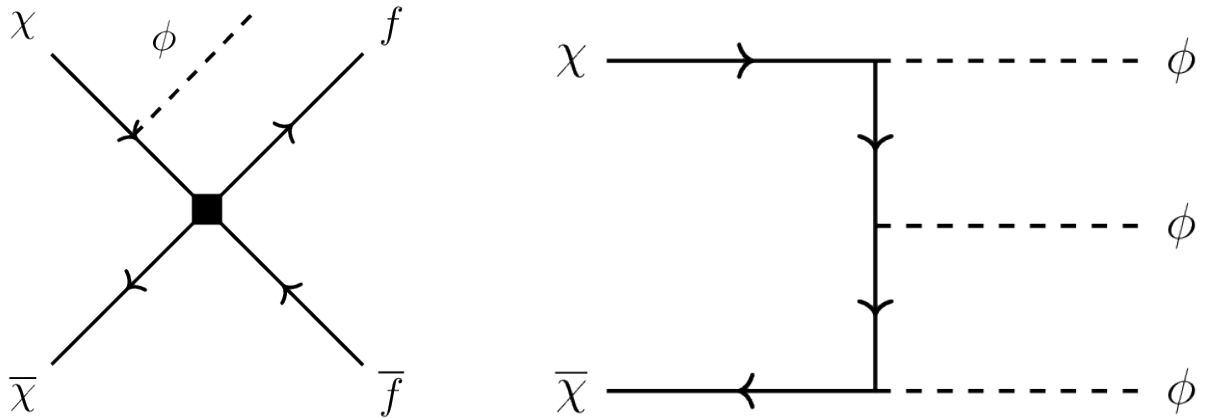


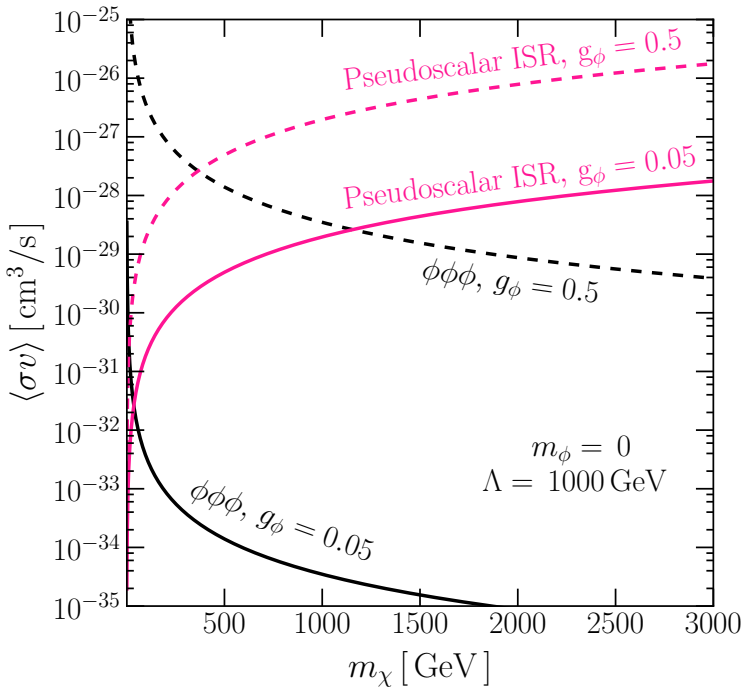
$\Gamma_{M_1}\otimes\Gamma_{M_2}$	$S\otimes S$	$S\otimes P$	$P\otimes P$	$V\otimes V$	$V\otimes A$	$A\otimes A$	$S\otimes V$	$S\otimes A$	$P\otimes V$	$P\otimes A$
$\overline{\chi}\chi\to M_1 M_2$	v^2	1	v^2	1	1	1	1	v^2	1	v^2

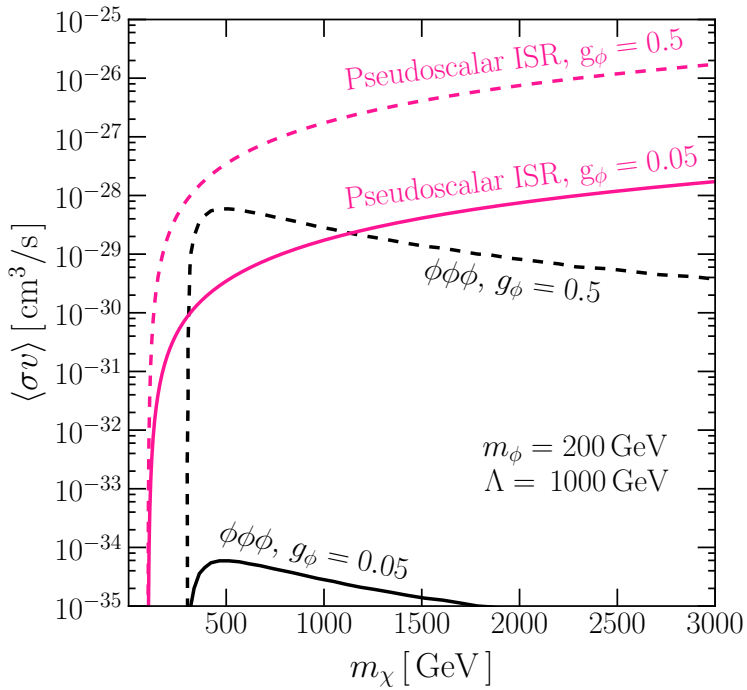
- p-wave suppressed: $\sim v^2$
  $A\otimes V$: V or A , $S\otimes S$: V or P, $S\otimes P$: V or P
- helicity suppressed: $\sim m_f^2/m_\chi^2$
  $A\otimes A$: V or A

Example: $S \otimes S$ with pseudoscalar

$$\Delta L \sim i g_\phi \bar{\chi} \gamma_5 \chi \phi$$







Summary

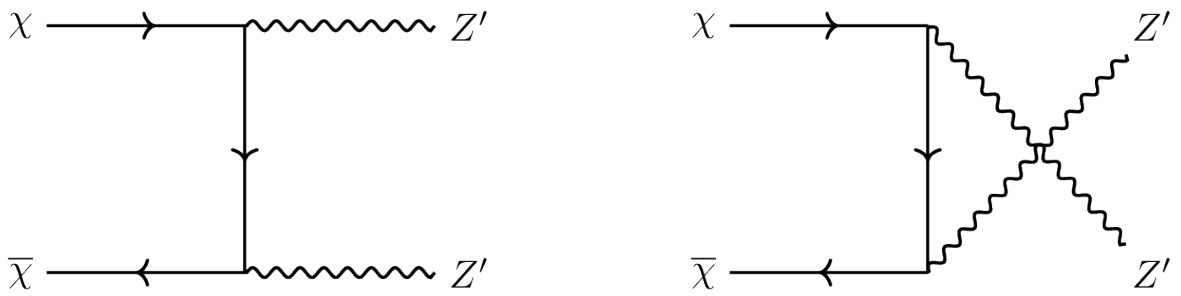
Summary

- Single mediator Simplified Models may not be self consistent
  - Two mediators can be required by gauge invariance
  - Phenomenology not captured by single-mediator model
- Axial vector Z' requires dark Higgs to unitarize Z'_L
  - New, dominant, s-wave annihilation channel $\chi\chi \to sZ'$
- Dark sector mass generation mechanisms should not be ignored
  - Choice of mass generation mechanism dictates the allowed coupling structure and annihilation processes
- Dark ISR is pretty useful to lift suppressed annihilation cross sections

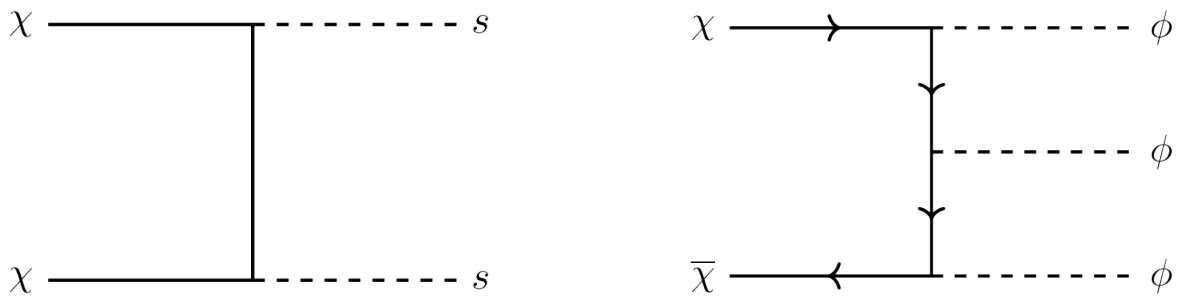
Backup

Dark Matter Annihilation

Simplified model with vector mediator:*s*-wave



Simplified model with scalar mediator



p-wave

s-wave yet PS suppr.

Basic Constraints

Mediation parameters: ϵ, λ_{HS}

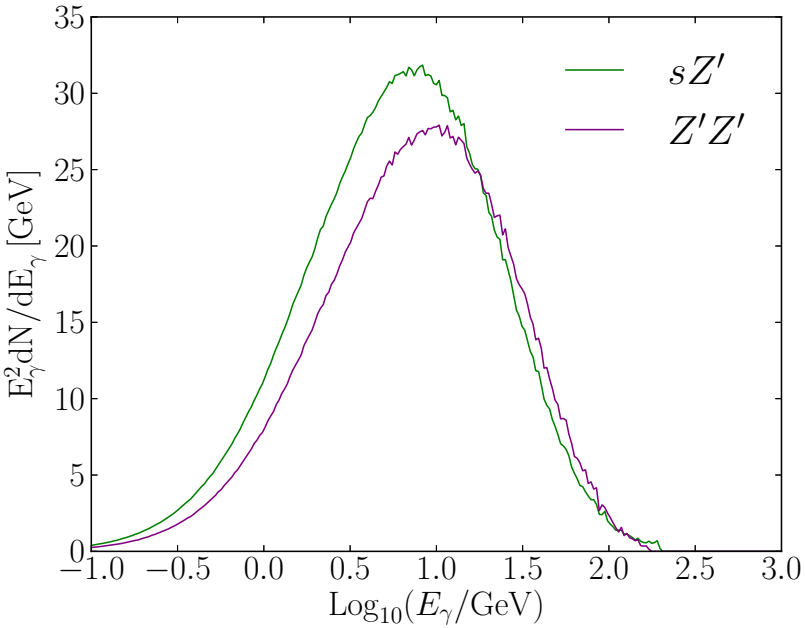
- ✓ small value consistent with non-observation of DD
- ✓ BBN requires $\tau < 1$ s, fairly easy to satisfy

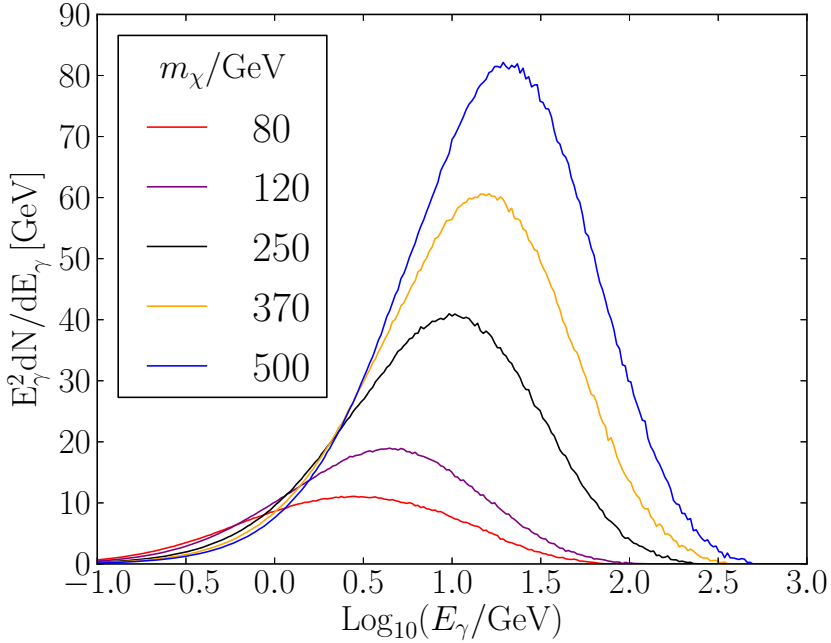
Cosmic Microwave Background

- ✓ constraints on annihilation cross section weaker than AMS-02 and dSphs

Gamma Spectra

Spectra per annihilation generated with PYTHIA





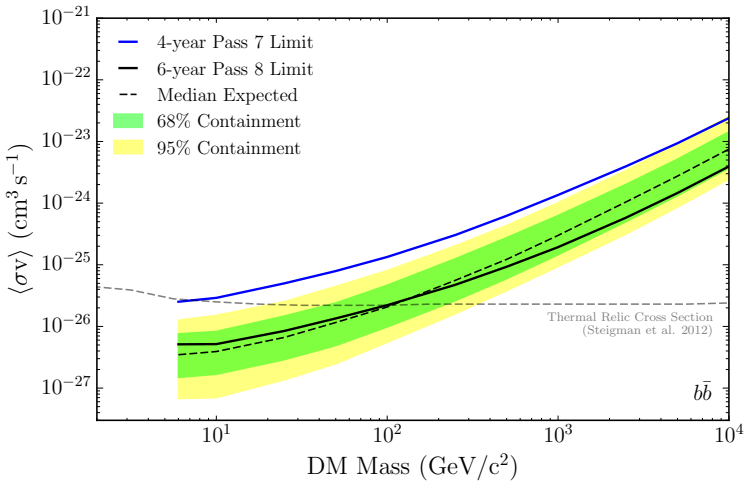
$$m_{Z'} = 60 \text{ GeV}$$
$$m_s = 100 \text{ GeV}$$
$$m_\chi = 200 \text{ GeV}$$

$$\chi\chi \to sZ'$$
$$m_{Z'} = 120 \text{ GeV}$$
$$m_s = 30 \text{ GeV}$$

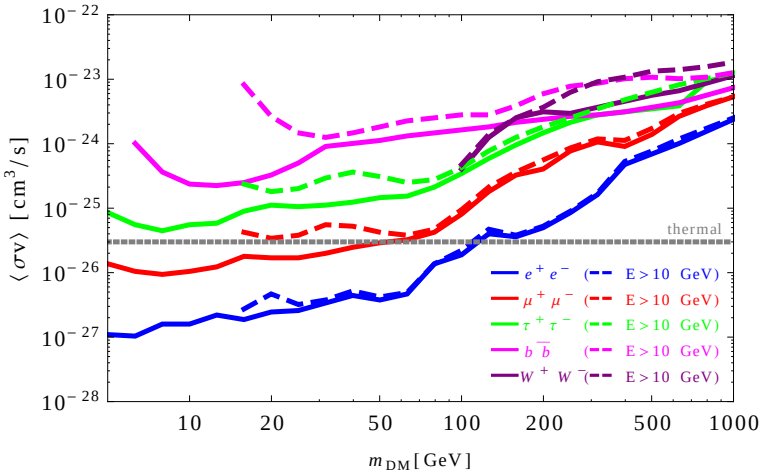
Limits from Indirect Detection

- From Fermi-LAT dwarf spheriodal results
  - No results for s and Z'
  - s and Z' with different masses
  - Likelihood functions of 15 dSphs used to derive limits
  - J-factor as nuisance parameter
  - Limits reproduced within 10%
- From AMS-02
  - Consider $e^{\pm}$ final states as they are the strongest
  - Cascade decay via s negligible
  - Only competitive for low m_χ
  - Crude estimate with cross section of Z' rescaled with $Br_{e^{\pm}}$

Fermi-LAT 1503.02641

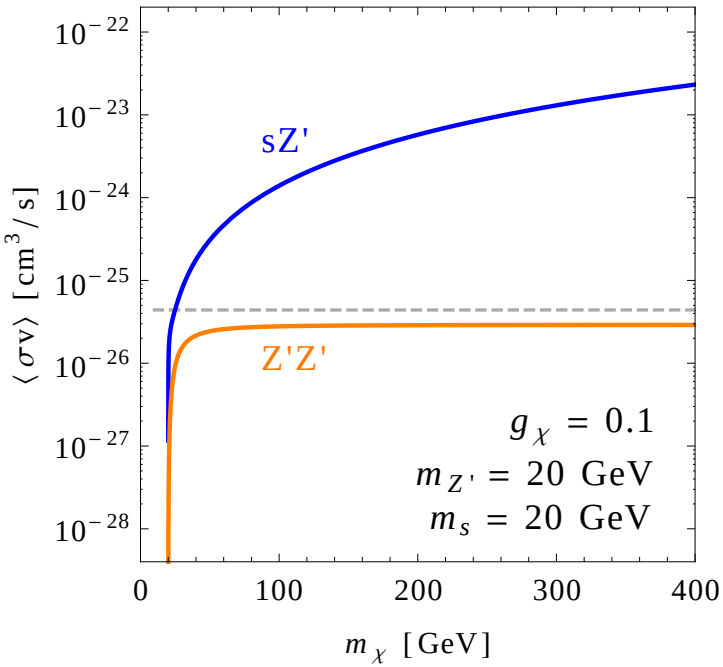


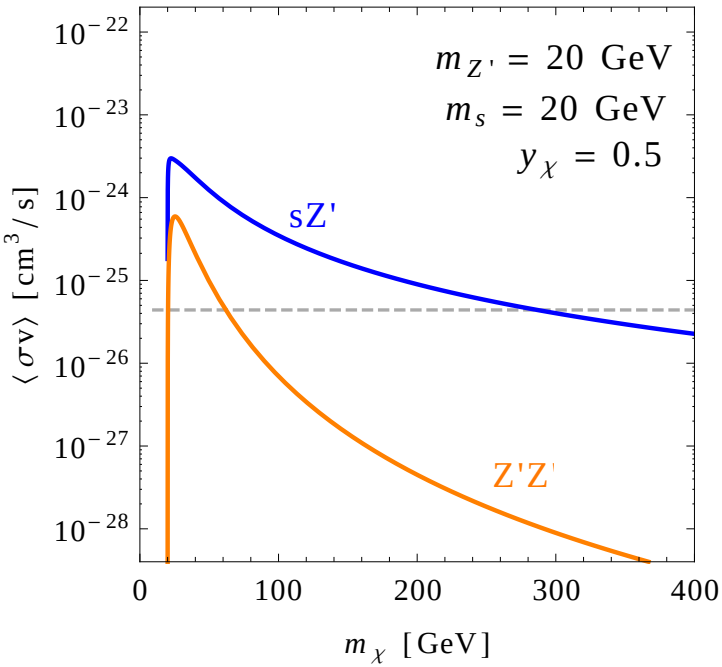
Ibarra et. al. 1309.2570



Case II: Z' and DM mass from dark Higgs

- Couplings related: $\frac{y_\chi}{g_\chi} = \frac{\sqrt{2} m_\chi}{m_{Z'}}$
- $Q'_S = Q'_{\chi_L} - Q'_{\chi_R} \equiv 2Q'_A$ while Q'_V unconstrained
- sZ' dominates over $Z'Z'$ when kinematically allowed
- Cross sections enhanced by longitudinal Z'
  (for $Z'Z'$ this only occur when Q'_V , Q'_A both nonzero)



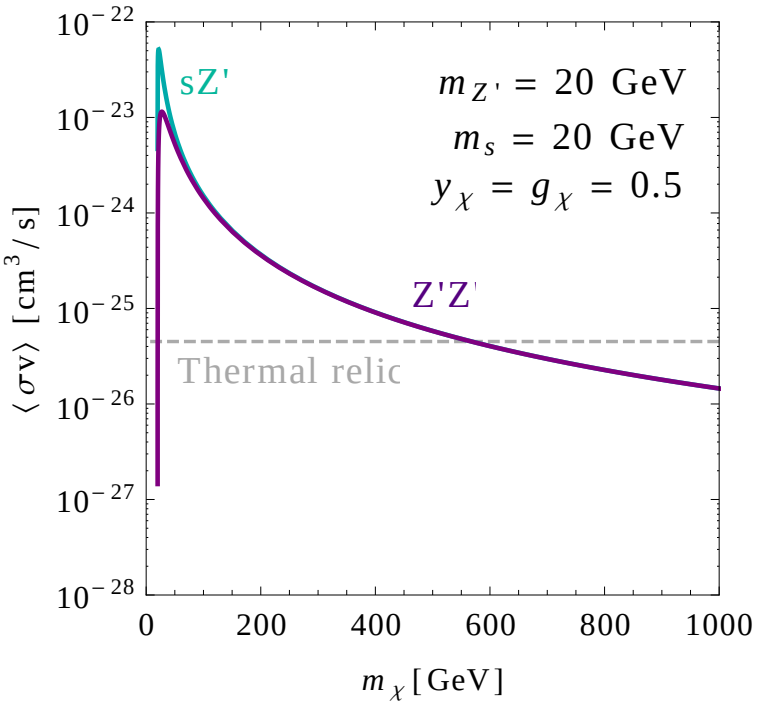


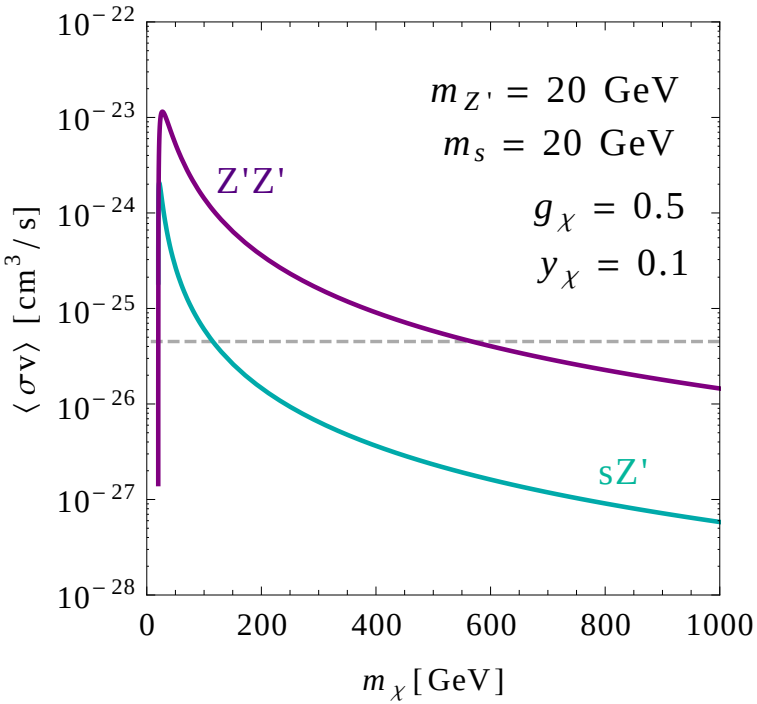
$$Q'_V = Q'_A = Q'_S/2 = 1$$

Case III

DM mass from dark Higgs and Z' mass from Stueckelberg mechanism

- y_χ and g_χ are not related: relative strength of the two ann. cross sections can be freely arranged
- Only transverse polarized Z'





Case IV: Bare DM Mass & Z' Mass from Dark Higgs

- $U(1)_\chi$ charge of Z' and S unrelated
  relative strength of the two ann. cross sections can be freely arranged
- Only transverse polarized Z'