Dark Forces in the Sky:
Signals from Z' and the Dark Higgs

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Outline

o **Introduction**
  Dark matter models, unitarity, and gauge invariance

o **The Z' and the Dark Higgs**
  A two mediator scenario motivated by gauge invariance

o **Dark sector mass generation & implications**
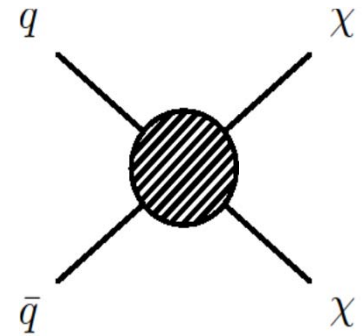 *Higgs, Stueckelberg, bare mass*

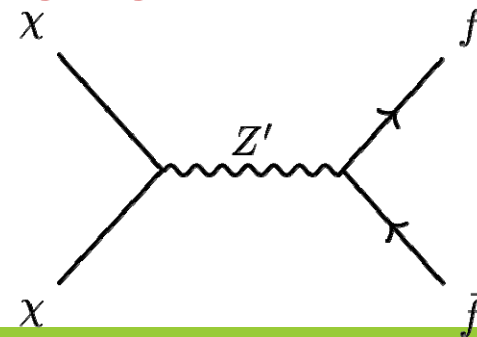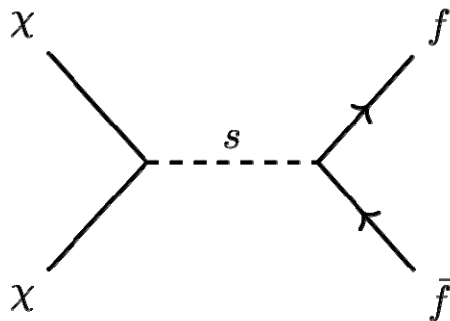o **Conclusions**

Dark matter and unitarity

- Non-renormalizble EFT operators such as

$$\frac{1}{\Lambda_{\text{eff}}^2}\left(\bar{\chi}\,\Gamma_\chi \chi\right)\!\left(\bar{f}\,\Gamma_f f\right)$$

  violate perturbative unitarity at high energy, as $\sigma \sim E^2/\Lambda^4$
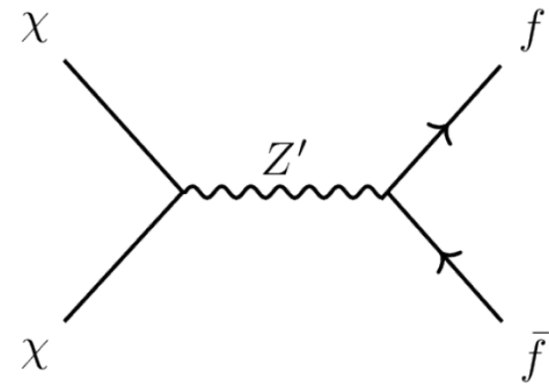
- But unitarity issues go beyond using EFTs outside their region of validity.

- Simplified Models have unitarity issues too if they break either Standard Model or dark-sector gauge invariance

Unitarity and Simplified Models

Consider a model where DM couples to SM fermions via a spin-1 mediator, *Z'*

Assume Z' is the gauge boson of a new U(1) symmetry)

Axial vector couplings → unitarity is violated at high energy

See,e.g. Kahlhoefer et al, arXiv:1510.02110, arXiv:1606.07609

Problem is that the Z' mass breaks U(1) gauge-invariance.
Need a Higgs mechanism to provide mass and restore unitarity.

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 too simple!

→ Motivates a two-mediator model (spin-1 & 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.

Majorana DM χ, axial vector Z' & dark Higgs S

$$\mathcal{L}_{dark} = \frac{i}{2}\, \bar{\chi}\partial^\mu\gamma_\mu\chi - \frac{1}{4}g_\chi\, \bar{\chi}\gamma_5\gamma_\mu\chi Z'^\mu - \frac{1}{2}y_\chi(\bar{\chi}_L^C\chi_L S + h.c)$$

$$+ (D^\mu S)^\dagger(D_\mu S) - \mu_s^2 S^\dagger S - \lambda_S(S^\dagger S)^2$$

- VEV of S leads to masses for χ and Z'
- U(1) charges of χ and S are related: $Q'(S) = 2Q'(\chi)$
- couplings and masses related: $\dfrac{y_\chi}{g_\chi} = \dfrac{\sqrt{2}m_\chi}{\text{m}'_Z}$

$$\mathcal{L}_{SM-dark\ mixing} = -\lambda_{HS}(S^\dagger S)(H^\dagger H) - \frac{1}{2}sin\epsilon\, Z'^{\mu\nu}B_{\mu\nu}$$

- Small SM – dark-sector mixing allows decay of S, Z' mediators
- Can satisfy collider & direct detection constraints while allowing large indirect detection signals
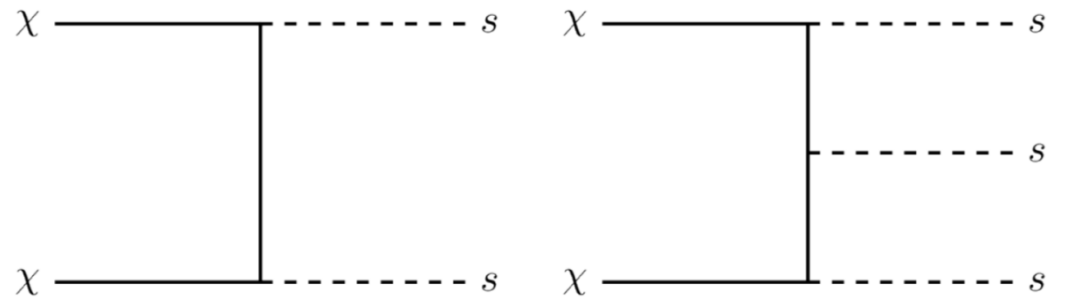
Annihilation to individual mediators

Simplified Model
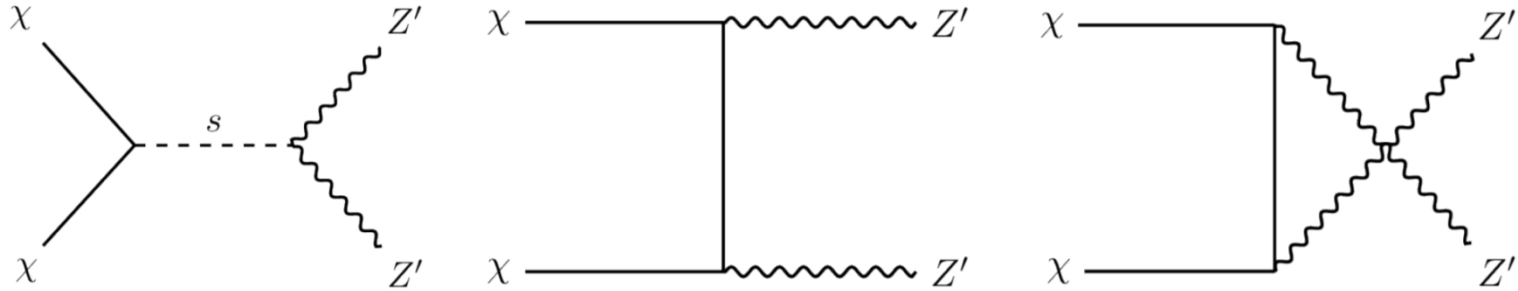with vector mediator
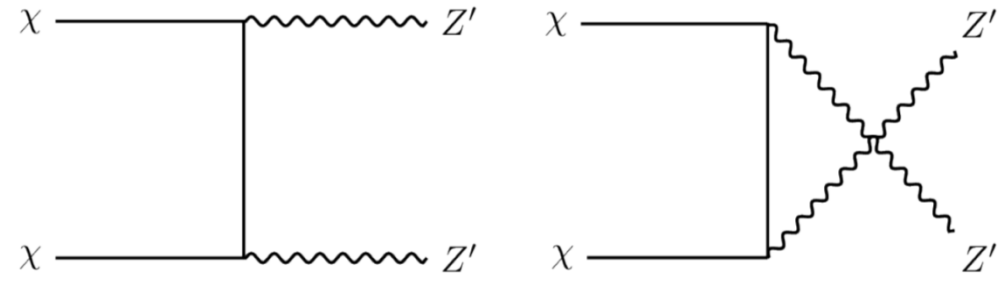
s-wave
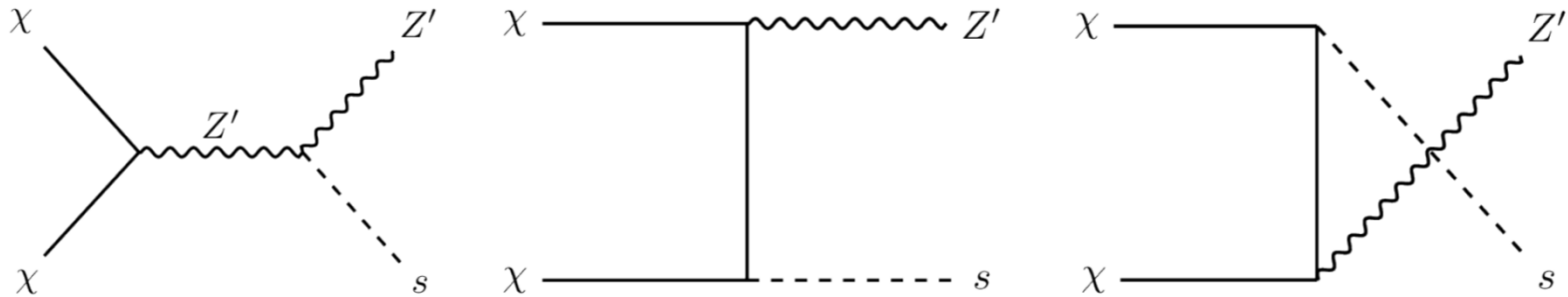
Simplified Model
with scalar mediator

p-wave

s-wave,
phase space
suppressed

Including both mediators

New contribution to $\chi\chi \to Z'Z'$ (prevents unphysical high energy behaviour)

New s-wave annihilation process $\chi\chi \to sZ'$

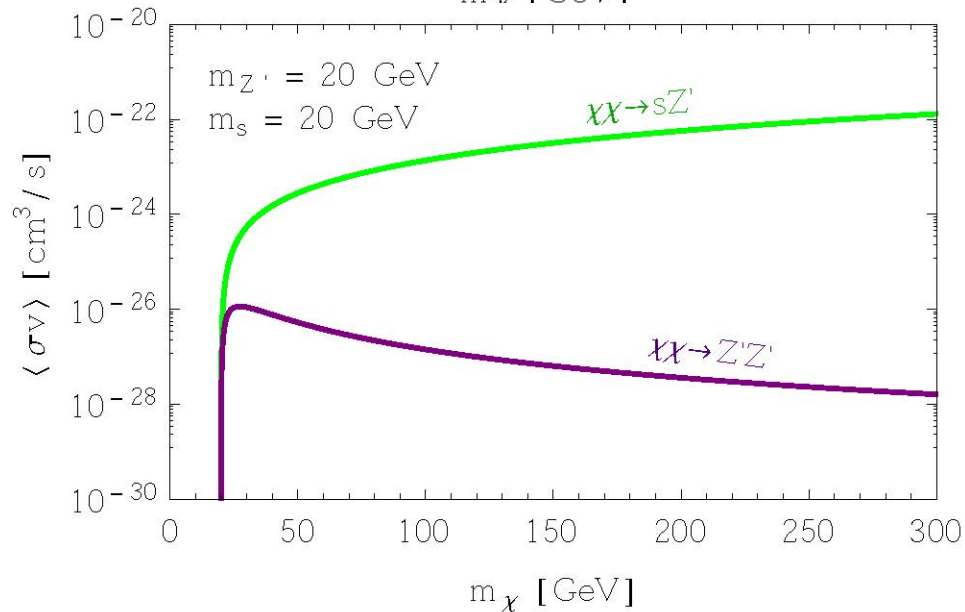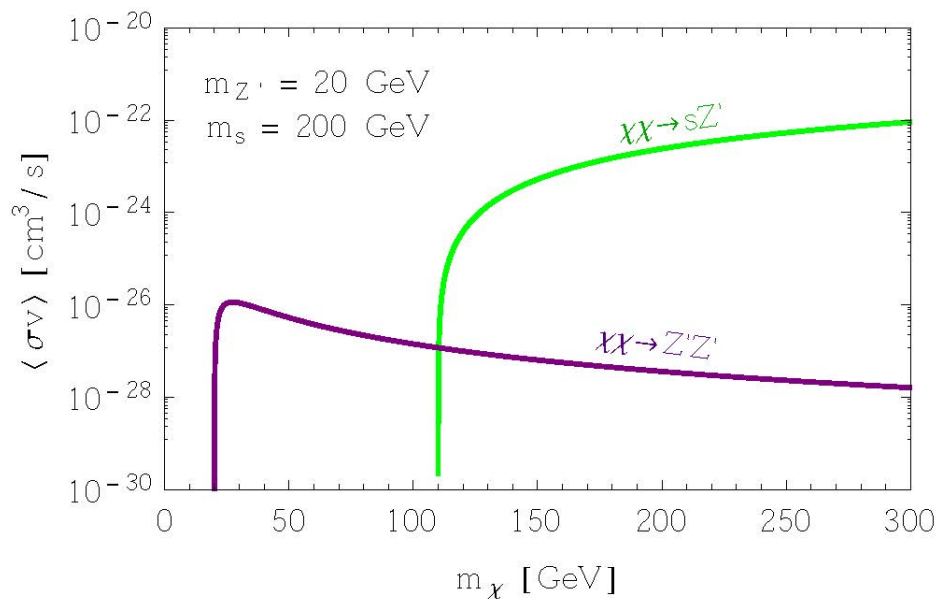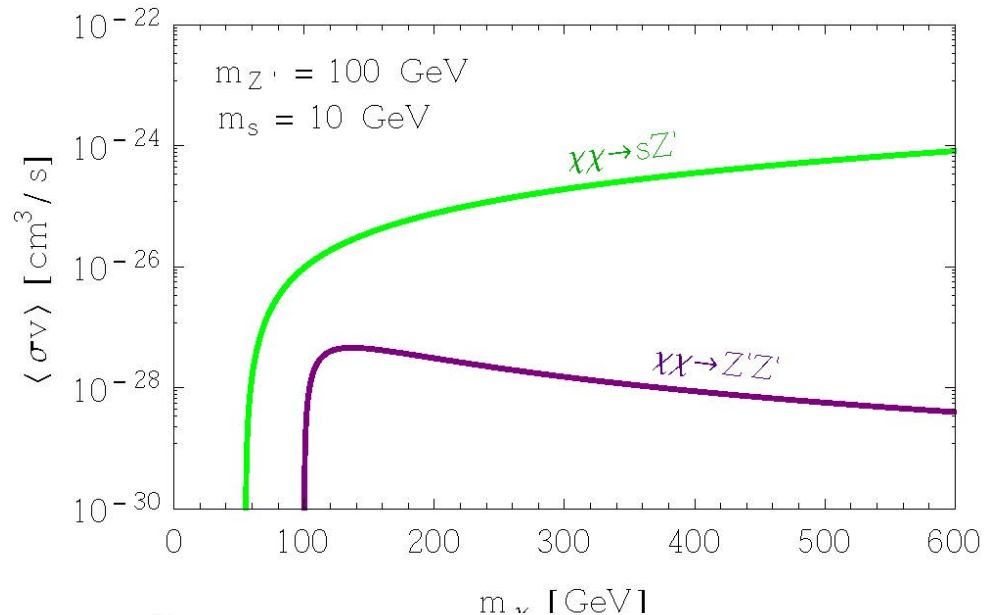Bell, Cai & Leane, arXiv:1605.09382

S-wave annihilations to both sZ' and Z'Z'

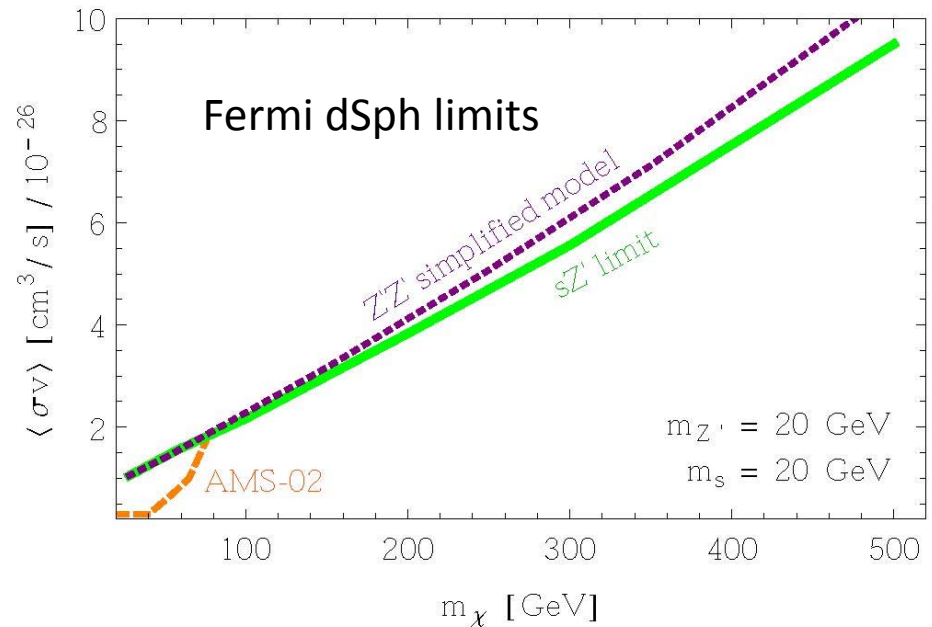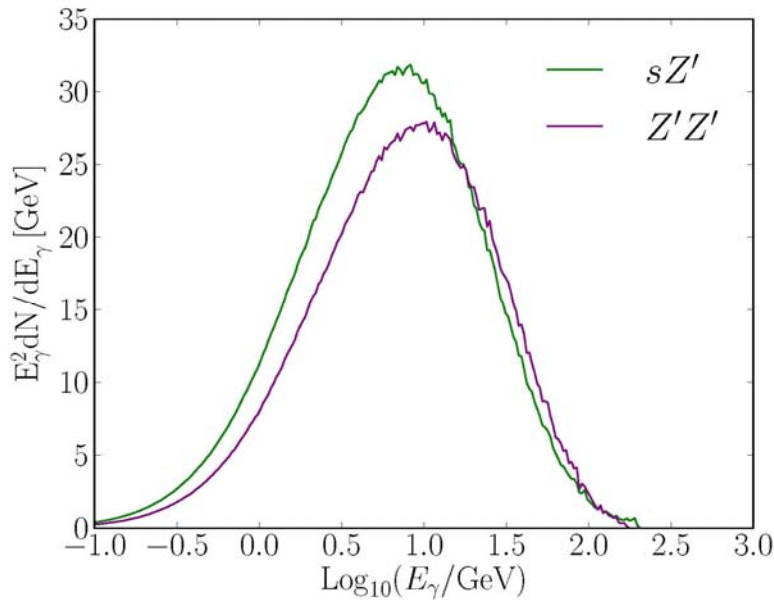sZ' process dominates over Z'Z' when kinematically allowed.

sZ' enhanced by Z'_L: $(\sigma v)_{sZ'} \sim \dfrac{m_\chi^2}{m_{Z'}^4}$

Bell, Cai & Leane, arXiv:1605.09382

Indirect detection limits from Fermi dSphs

- Z' decay to SM via small kinetic mixing term
- S decays to SM via small Higgs mixing term
- Resulting gamma ray spectra are similar

Dark sector mass generation

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 non-zero axial coupling
    - Dark Higgs gives mass to *both* Z' and DM (like Majorana)

  - If Z' has pure vector couplings
    - Z' mass: either Higgs or Stueckelberg mechanism
    - DM mass: bare mass or Higgs mechanism
    - → mass mechanisms not necessarily connected.

Dark sector mass generation (Dirac)

Case	DM mass	Z' mass	DM-Z' coupling	Annihilations	Z' polarization
I	Bare mass	Stueckelberg	Vector	$\bar{\chi}\chi \to Z'Z'$	transverse
II	Dark Higgs	Dark Higgs	Axial & Vector or pure Axial (Axial ≠ 0)	$\bar{\chi}\chi \to Z'Z'$ $\bar{\chi}\chi \to sZ'$	transverse & longitudinal
III	Dark Higgs	Stueckelberg	Vector	$\bar{\chi}\chi \to Z'Z'$ $\bar{\chi}\chi \to sZ'$	transverse
IV	Bare mass	Dark Higgs	Vector	$\bar{\chi}\chi \to Z'Z'$ $\bar{\chi}\chi \to sZ'$	transverse

Bell, Cai & Leane, arXiv:1610.03063

$\chi\chi \rightarrow Z'Z'$
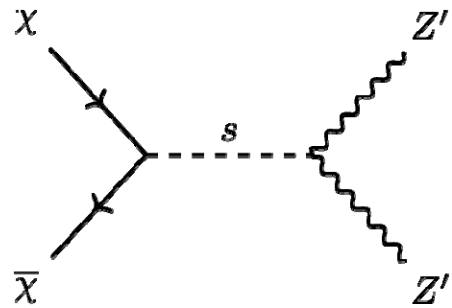
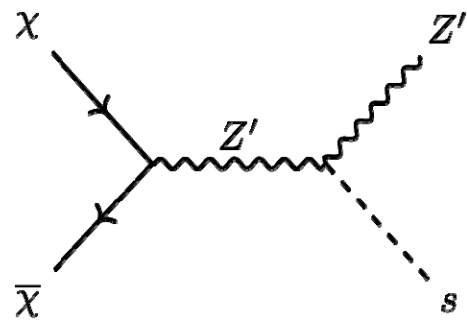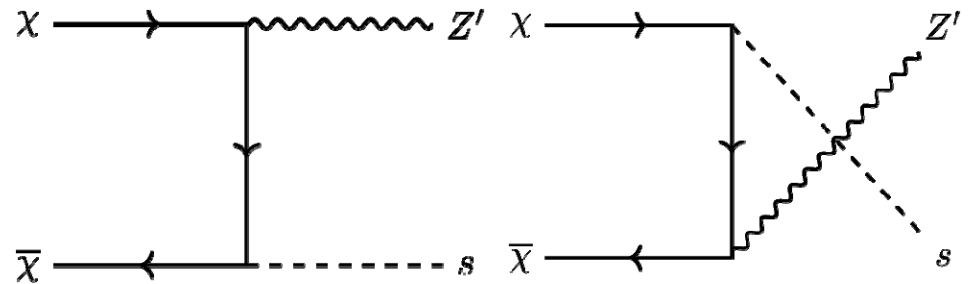Case II only
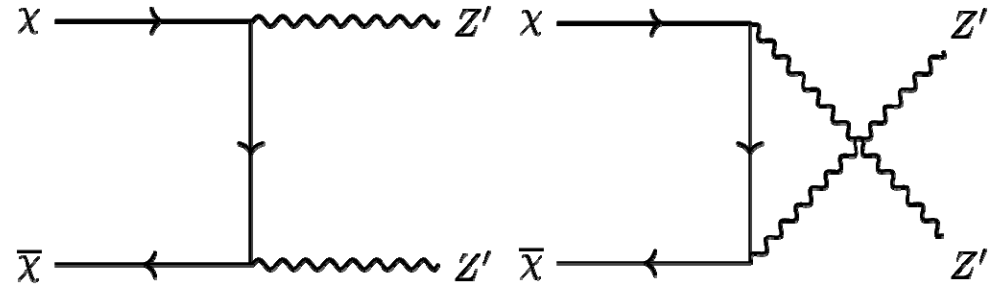
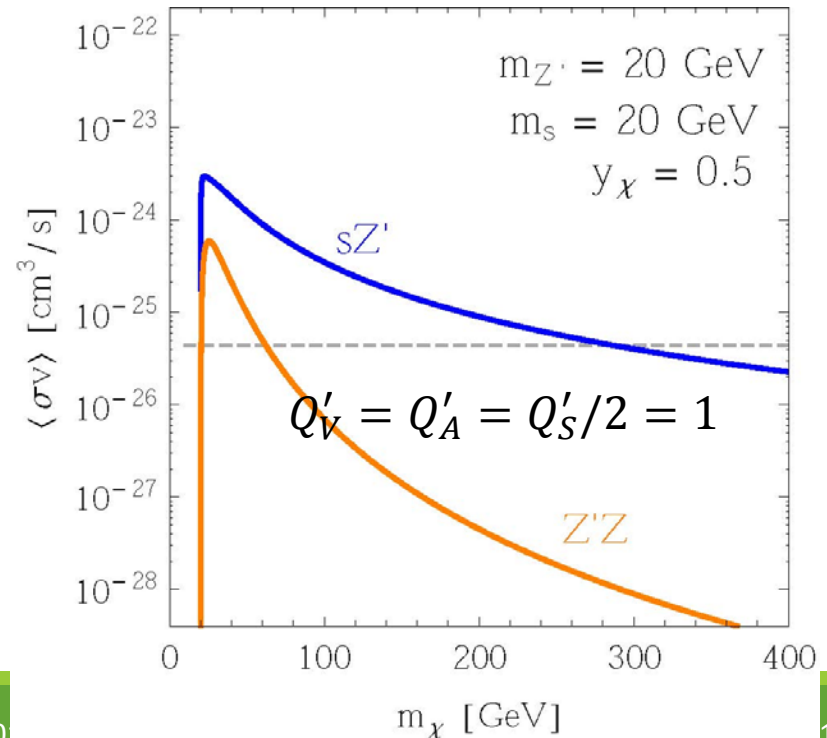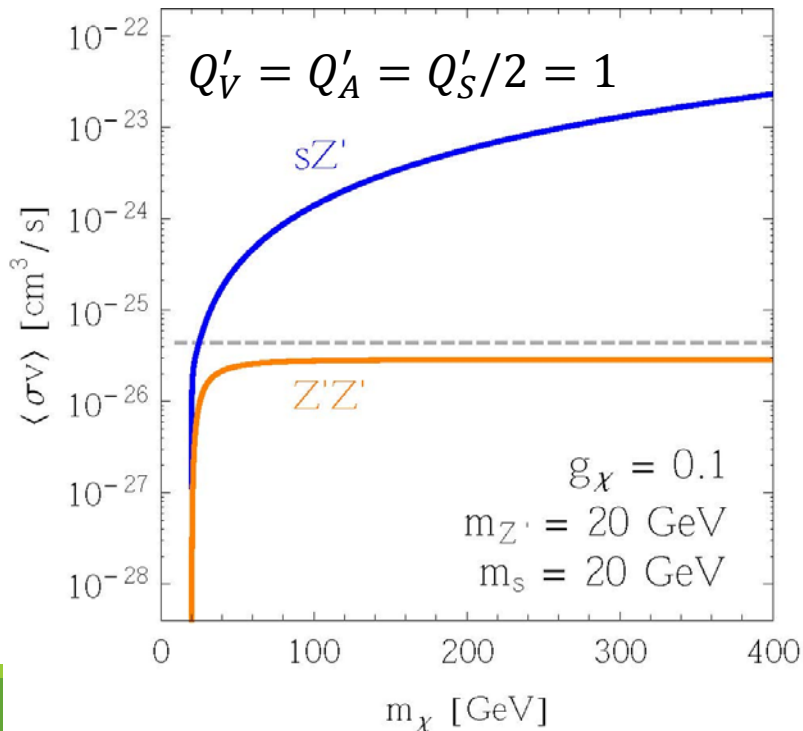Case I, II, III, IIII

$\chi\chi \rightarrow sZ'$

Case II, IV

Case II, III

Z' and DM mass from dark Higgs

- Couplings related: $\dfrac{y_\chi}{g_\chi} = \dfrac{\sqrt{2}\,m_\chi}{m_Z'}$

- $Q_S' = Q_{\chi_L}' - Q_{\chi_R}' \equiv 2Q_A', \quad Q_V' = unconstrained$

- 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)

DM mass from dark Higgs & Z' mass from Stueckelberg

- y_χ and g_χ unrelated
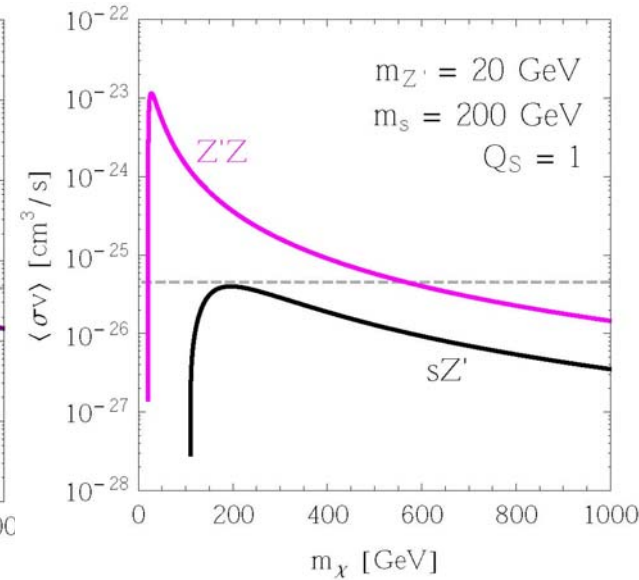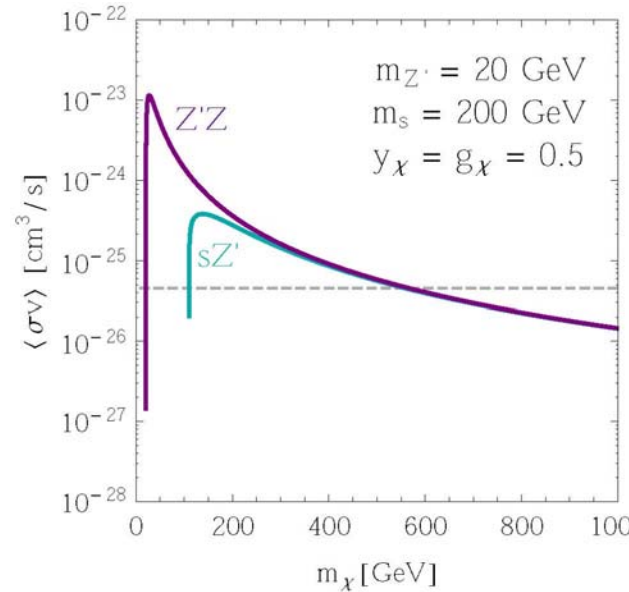 - → freedom to dial relative strength of the two annihilation processes
- Only transverse polarized Z'
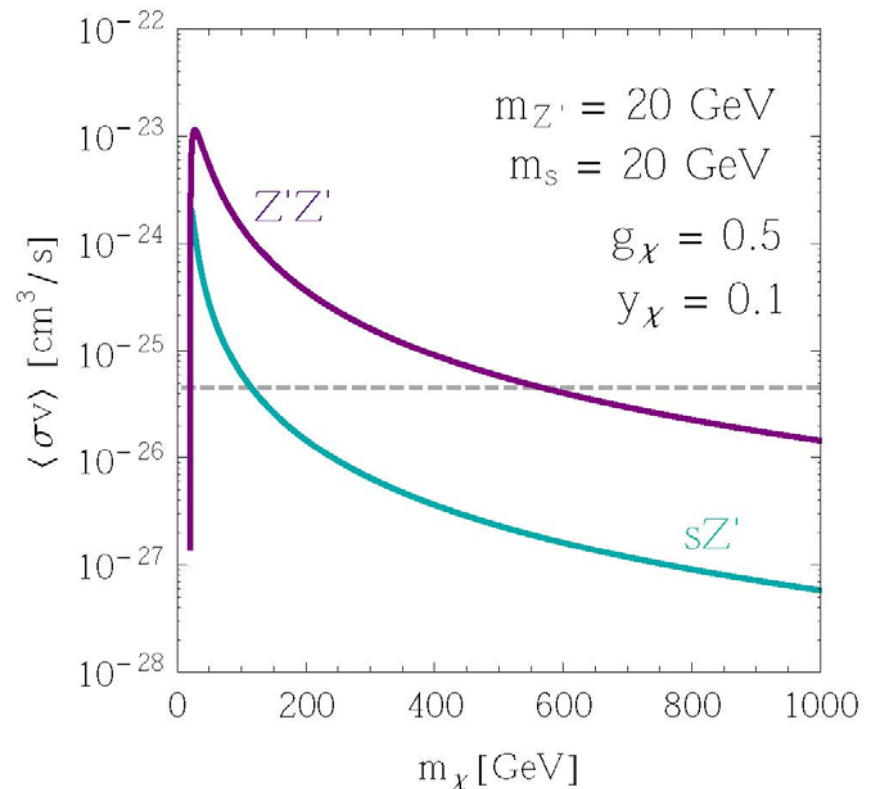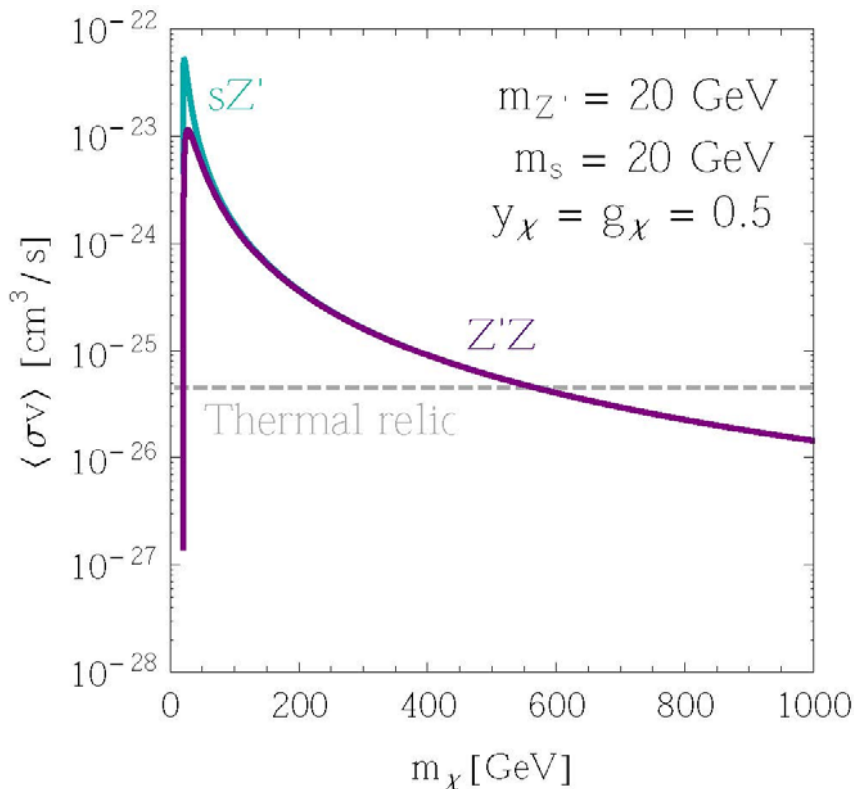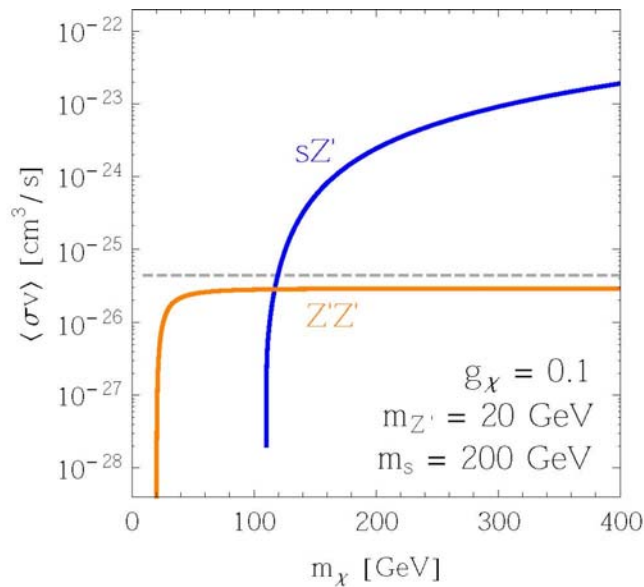
Bare DM mass & Z' mass from dark Higgs

- $U(1)$ charge of Z' and S unrelated
- → freedom to dial relative strength of the two annihilation process
- Only transverse polarized Z'
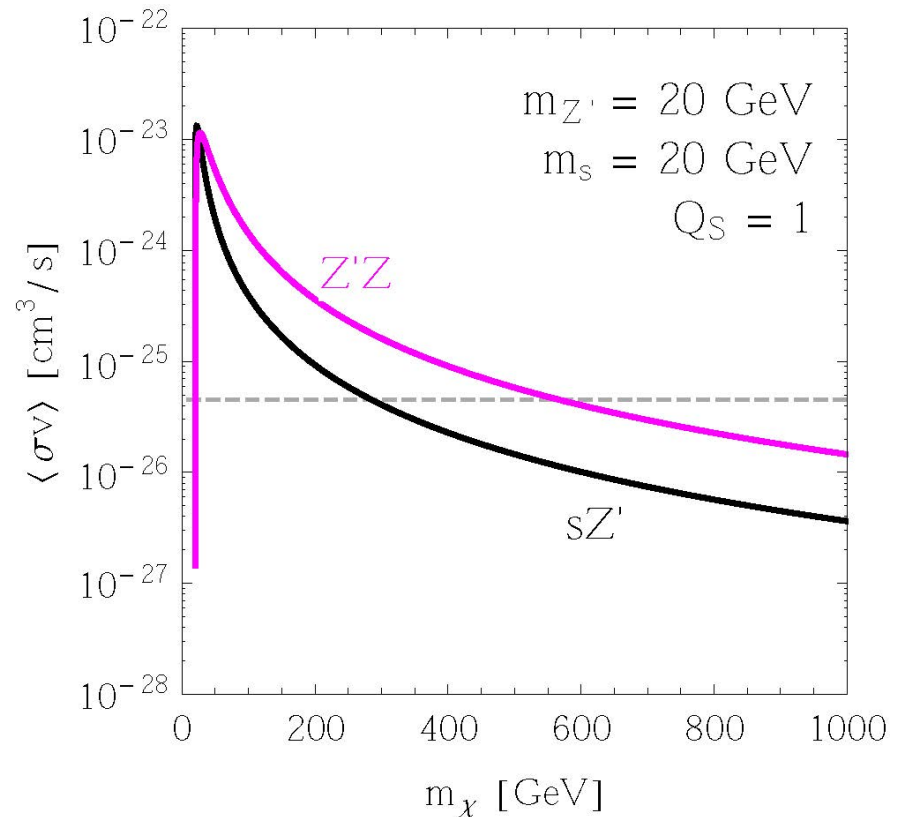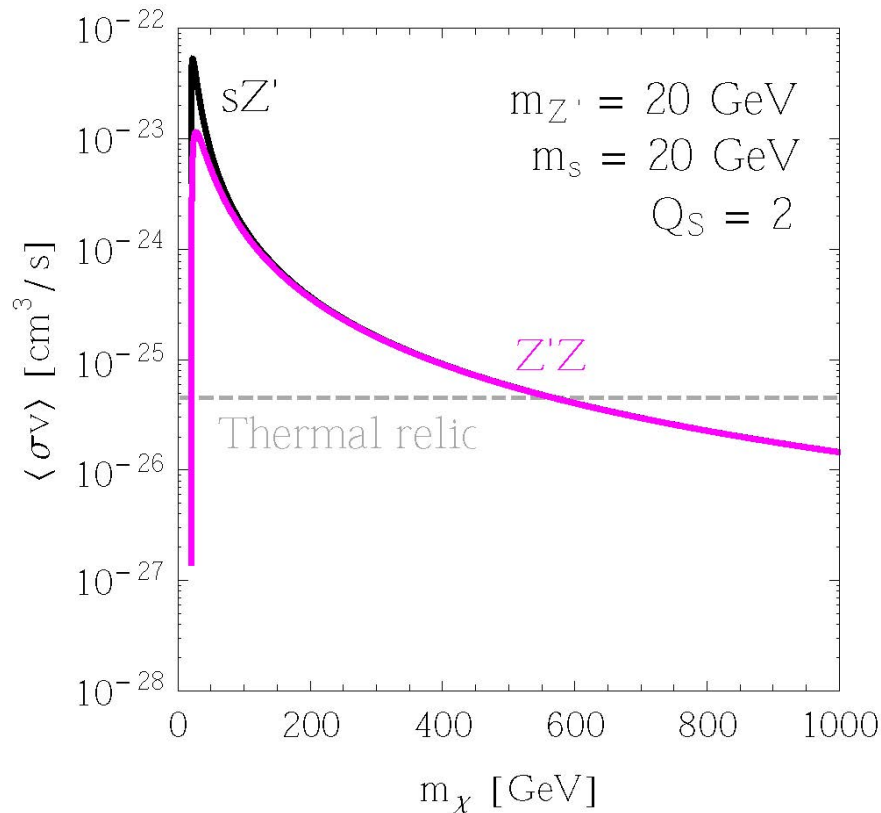
Enhancement from longitudinal Z' only for axial couplings

Bell, Cai & Leane, arXiv:1610.03063

Summary

❖ Some single-mediator Simplified Models are not self consistent
  ➢ Two mediators can be required by gauge invariance
    ➢ Phenomenology not captured by single-mediator model

❖ Axial vector Z' requires dark Higgs (S) to unitarize Z'_L
  ➢ New, dominant, s-wave annihilation channel $\chi\chi \rightarrow sZ'$

❖ Dark sector generation mechanisms should not be ignored
  ➢ Choice of mass generation mechanism dictates the allowed coupling structure and annihilation processes