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

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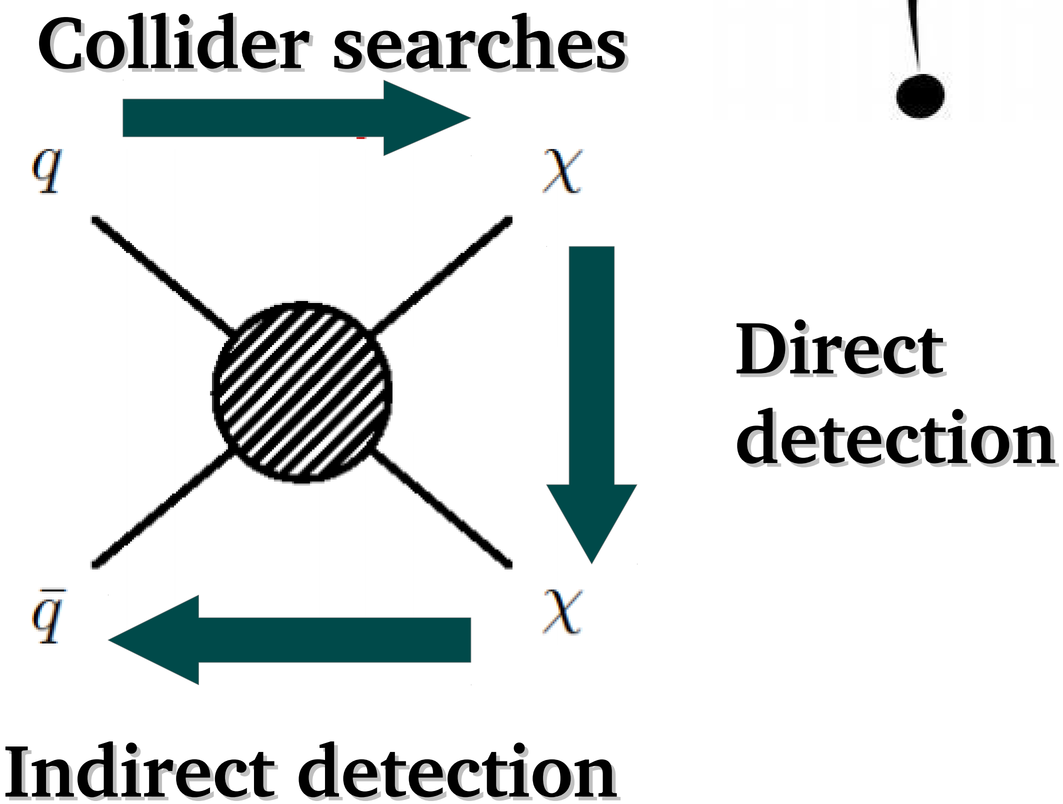
What is dark matter?

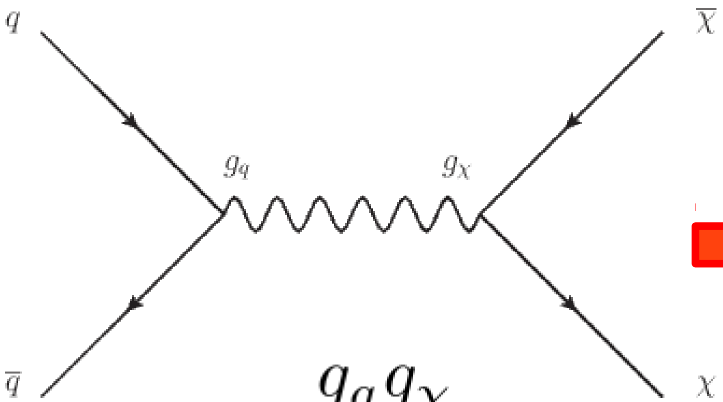
- Still no idea about fundamental nature
- WIMP dark matter well motivated
- Realistic detection prospects

Searches provide complementary information



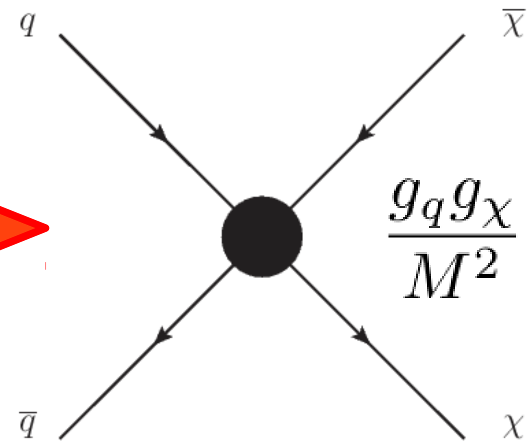
EFTs in a nutshell

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\Gamma_\chi\chi\right)\left(\overline{f}\Gamma_f f\right)$$



$$\frac{g_q g_\chi}{p^2 - M^2}$$

$$M^2 \gg p^2$$



$$\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

- Model independent
- Useful at low energies, i.e. direct detection

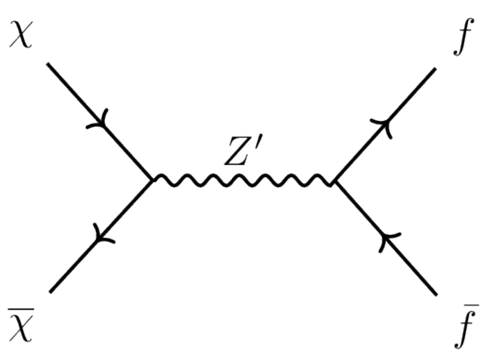
Colliders? Need to be careful… !

Simplified Models for Dark Matter

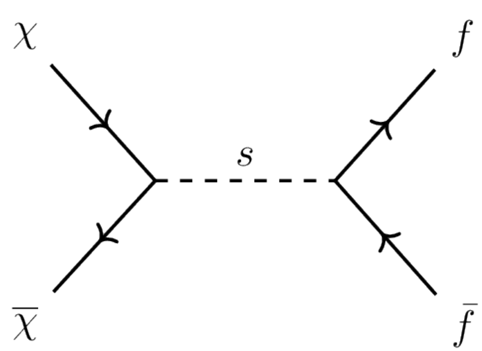
- Still no idea about fundamental nature of DM, model independent framework desirable where possible
- EFTs → issues at high momentum transfer, not generically applicable
- Simplified models: only lightest mediator is retained, set limits on couplings and mediators. Allow for richer phenomenology.

Benchmark simplified models:

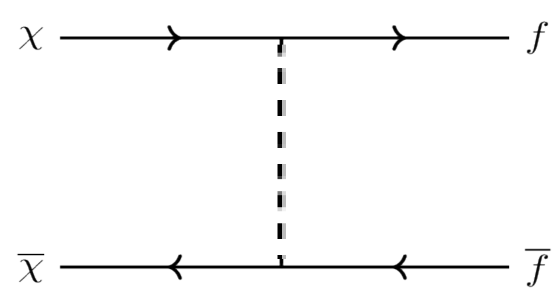
s-channel spin-1



s-channel spin-0



t-channel spin-0.



…this can run into problems!

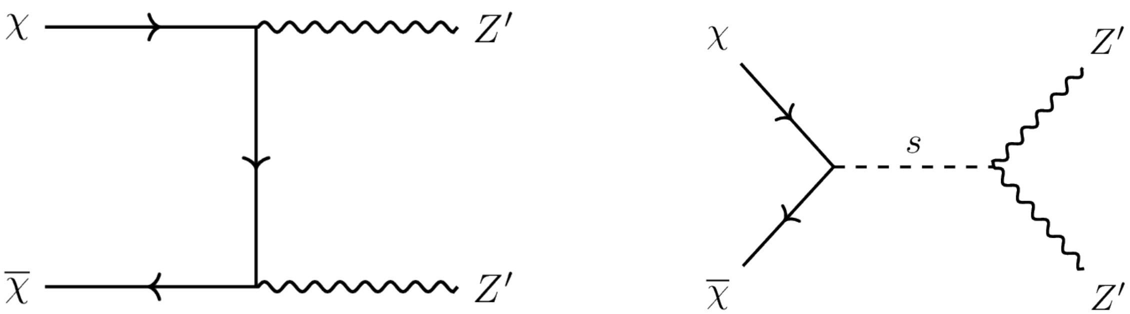
- Not intrinsically capable of capturing full phenomenology of UV complete theories.

- Separate consideration of these benchmarks can lead to physical problems and inconsistencies.

These issues motivate a scenario in which the vector and the scalar mediators appear together within the same theory.

Spin-1 Simplified Model

Consider high energy production of longitudinal Z' bosons:



Bad high energy behaviour cancelled by additional scalar!

Particularly well motivated if
taken to be dark Higgs.

Simple Model instead

New particle content:

1. Majorana DM

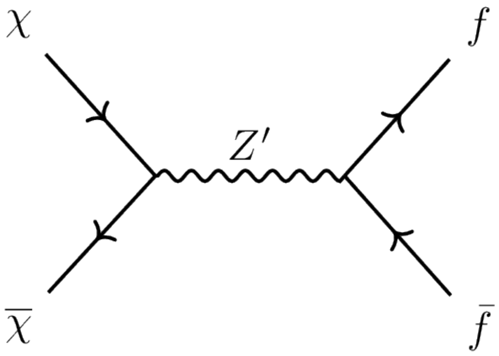
2. New Vector: Z'

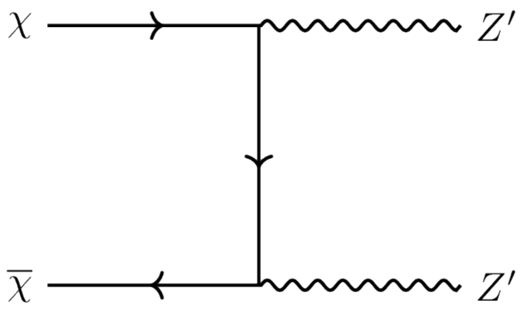
3. New Scalar: dark Higgs

How does this compare to simplified models?

Spin-1 Indirect Detection

For fermionic DM:



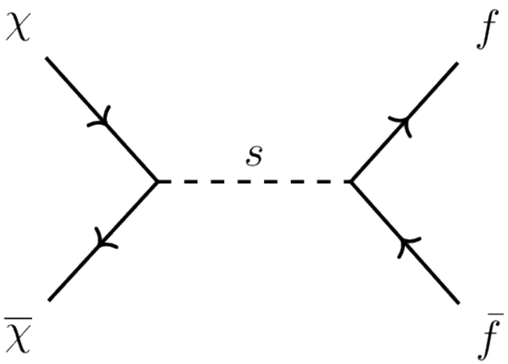


Vector: p-wave
Axial-vector: s or p-wave

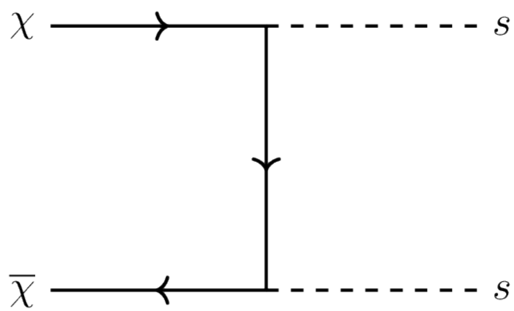
s-wave for all couplings!

Spin-0 Indirect Detection

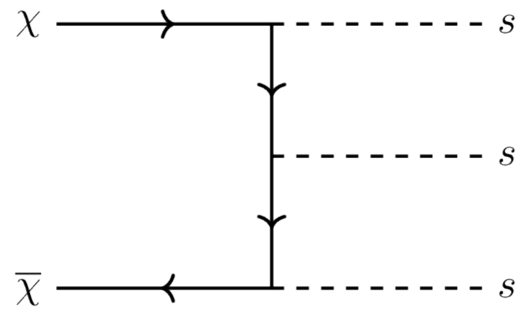
Analogous diagrams not quite the same.



Pseudoscalar: s-wave
Scalar: p-wave



Always p-wave!

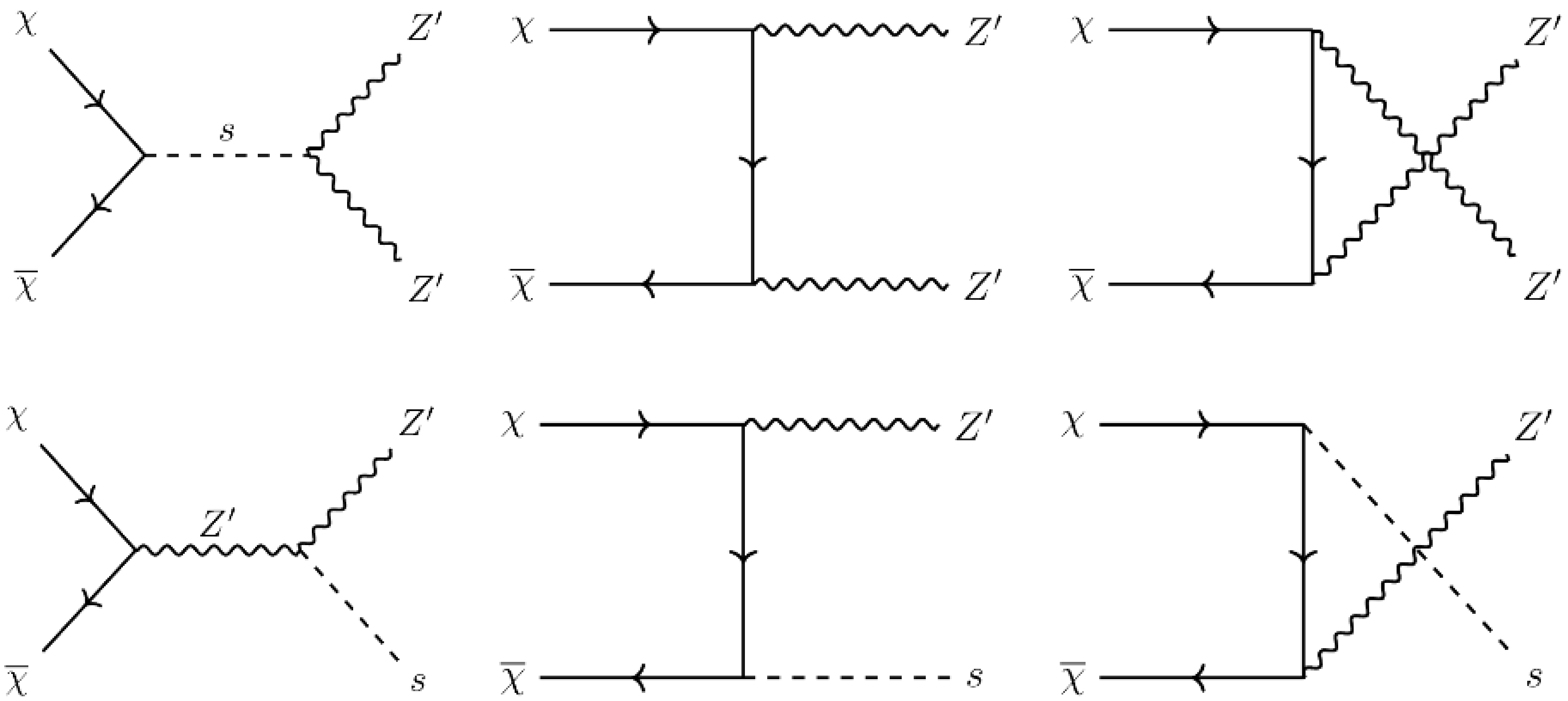


Pseudoscalar: s-wave
Scalar: p-wave

No s-wave diagram for scalars!

What happens when we consider the self-consistent dark sector?

Annihilation Processes

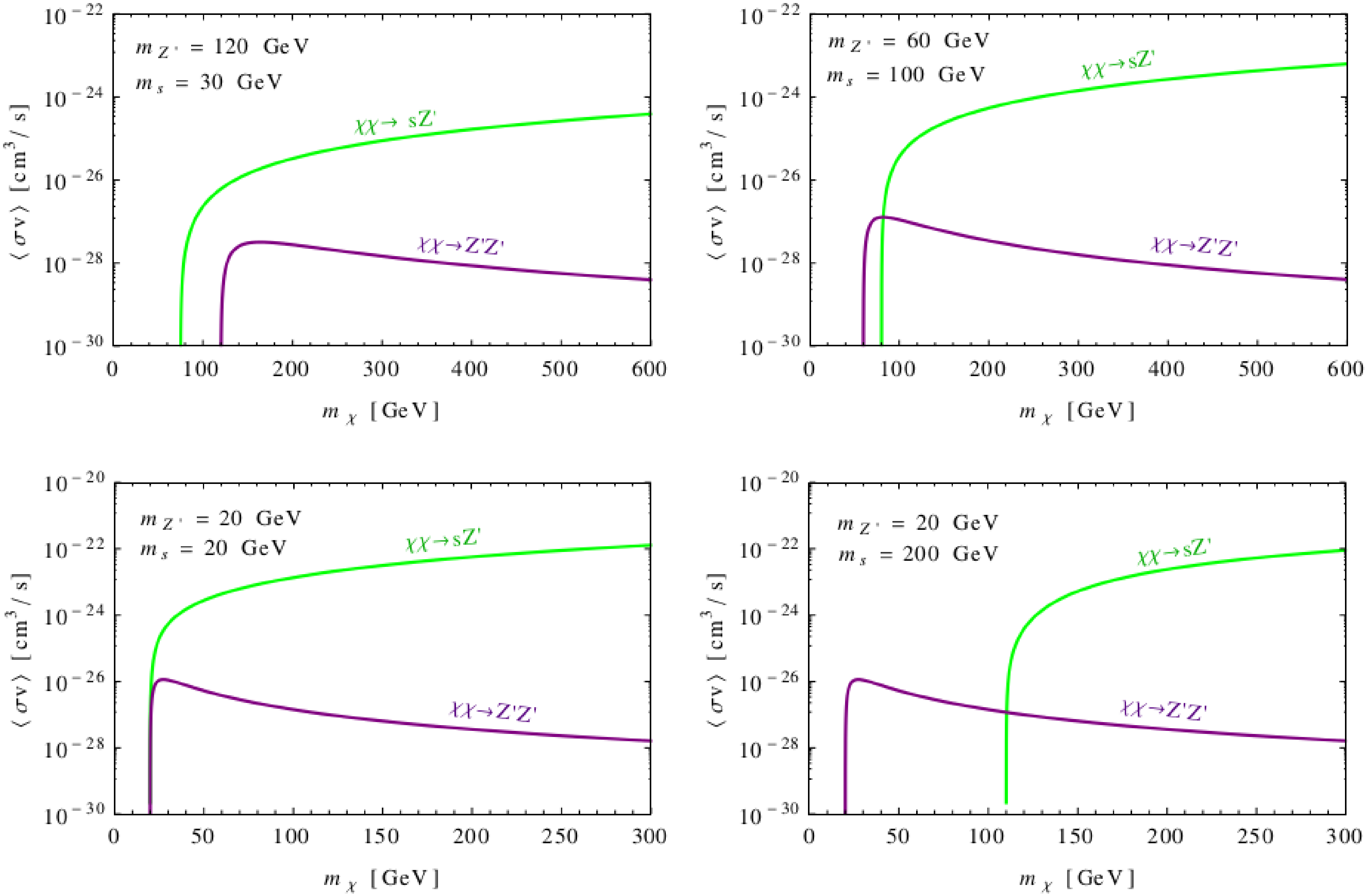


This opens up a new s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z', that is not ruled out by other exps.

So we know we have a new s-wave process….

but how large is its annihilation rate?

Annihilation cross sections

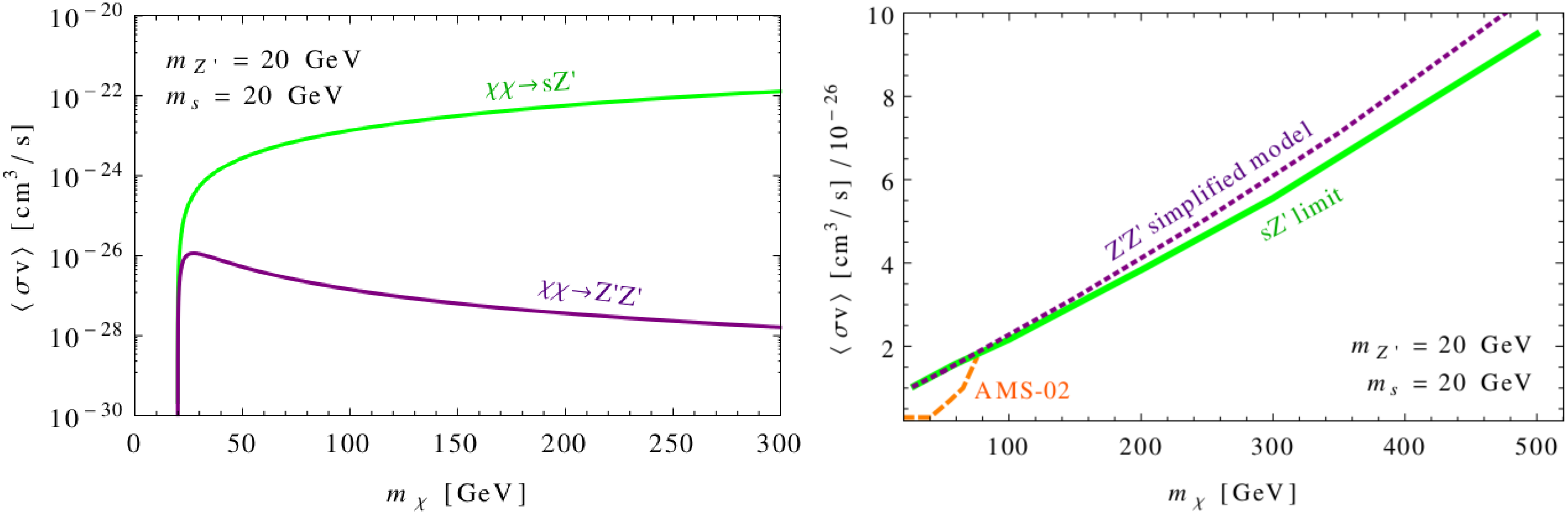


Indirect Detection Limits

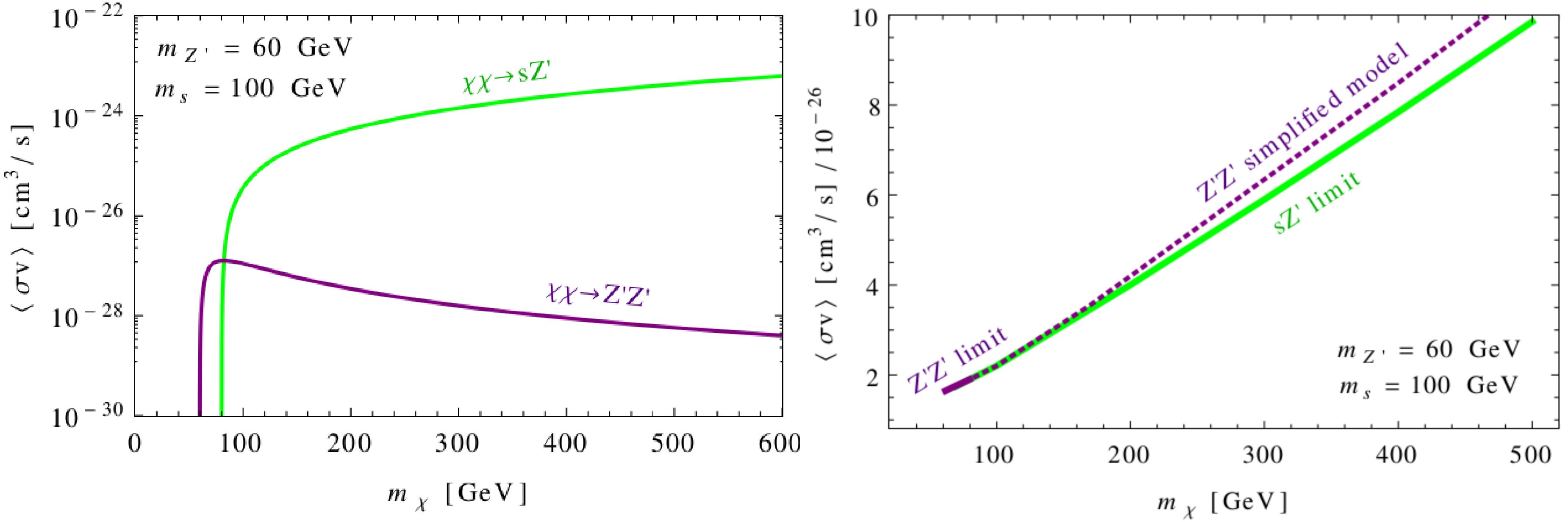
- For most of parameter space, strongest limits come from Fermi measurements of Dwarf Spheriodal Galaxies, most DM dense objects in our sky.

- At lower DM masses, and for electron positron final states, AMS-02 can provide stronger limits.

Indirect Detection Limits



Indirect Detection Limits



Other Limits?

- Small couplings between the dark and visible sector… almost vanishing!
- Can effectively remove direct detection and collider bounds.
  - Given WIMP DM is becoming increasingly constrained, this is also nicely motivated.
- Can't have arbitrarily small couplings, as need the mediator to decay within the lifetime of the galaxy, also needs to decay quickly enough to avoid BBN bounds.

Summary

- Simplified models are a popular framework for setting limits on the properties of DM.
- However, they are not intrinsically capable of capturing the full phenomenology of UV complete theories.
- In fact, it can be inconsistent to consider benchmarks separately, and for Majorana DM it is necessary to include the scalar in the theory.
- Leads to interesting phenomenology: previously unconsidered s-wave process, which dominates the annihilation rate.
- Also allows the properties of the scalar to be probed in this context with comparable strength to the vector!

Understanding nature of DM one of foremost goals of physics community – want to ensure we are searching correctly!

Back up slides

Spin-1 Simplified Model

Consequences for both Majorana and Dirac DM.

Majorana DM: vector current is vanishing, leaving pure axial-vector interactions.

*** Inclusion of the dark Higgs is unavoidable! ***

Furthermore, can't write down Majorana mass term without breaking the $U(1)_\chi$ symmetry.

Dirac DM: axial-vector Z' interactions will yield same issues.

However, possible to have pure vector couplings to a Z'.
Stueckelberg mechanism may give mass to the Z', and a bare mass term for the DM is possible.

Higgs mechanism is what is realized by nature, well motivated to consider dark Higgs together with Dirac DM.

Simple renormalizable theory

Gauge symmetry group:

$$SU(3)_c \otimes SU(2)_W \otimes U(1)_Y \otimes U(1)_\chi$$

$$D_\mu = D_\mu^{SM} + iQ' g_\chi Z'_\mu$$

Fermion mass terms generated as

$$\mathcal{L}^{\rm Yuk} = -y_{ij}\, \overline{\chi}_i P_L \chi_j S + h.c.$$

Charge constraints!

Majorana DM: $Q'_S + 2\, Q'_{\chi_j} = 0$

Dirac DM: $Q'_S - Q'_{\chi_i} + Q'_{\chi_j} = 0$

Simple renormalizable theory

For Majorana DM, the model lagrangian is:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{i}{2}\overline{\chi}\partial\!\!\!/\chi - \frac{1}{4}g_\chi Z'^\mu \overline{\chi}\gamma_5\gamma_\mu\chi - \frac{1}{2}y_\chi \overline{\chi^c}\chi S - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu}$$
$$+ \left[(\partial^\mu + ig_\chi Z'^\mu)S\right]^\dagger \left[(\partial_\mu + ig_\chi Z'_\mu)S\right] - \mu_s^2 S^\dagger S - \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H)$$

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After symmetry breaking and mixing, relevant terms are:

$$\mathcal{L} \supset \frac{1}{2}m_{Z'}^2 Z'^\mu Z'_\mu - \frac{1}{2}m_s^2 s^2 - \frac{1}{2}m_\chi\overline{\chi}\chi - \frac{1}{4}g_\chi Z'^\mu\overline{\chi}\gamma_5\gamma_\mu\chi - \frac{y_\chi}{2\sqrt{2}}s\overline{\chi}\chi$$
$$+ g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

Component fields of S and H, in broken phase, are:

$$S \equiv \frac{1}{\sqrt{2}}(w+s+ia) \qquad\qquad H = \left\{G^+, \frac{1}{\sqrt{2}}(v+h+iG^0)\right\}$$

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- New field content: Z', dark Higgs, DM candidate.
- Interactions with visible sector via Higgs portal or hypercharge portal
- Mass generation achieved with the dark Higgs.
- Well behaved at high energies.

Simple renormalizable theory

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Couplings and masses in the theory are all related to each other!

$$m_{Z'} = g_\chi w,$$

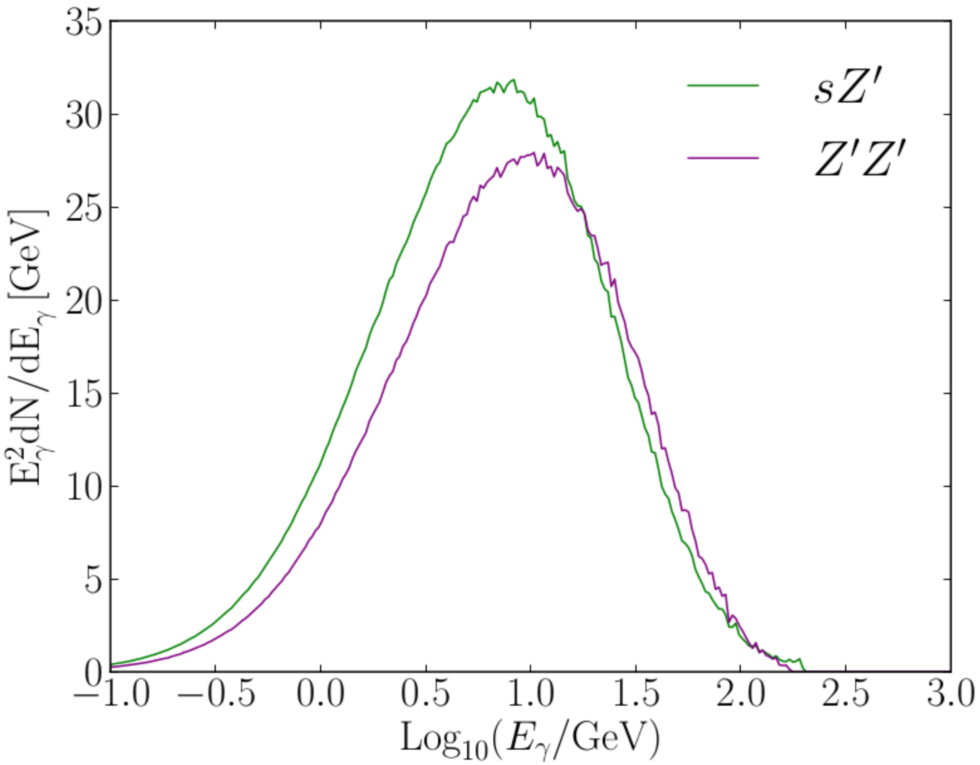
$$m_\chi = \frac{1}{\sqrt{2}}wy_\chi,$$

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

The Photon Energy Spectra

Generate in Pythia, make effective resonance in particle CoM frame, then average the separate spectra.

Perform this average again for regions where both sZ' and Z'Z' cross sections are the same, to obtain combined limit.



$$E_{CoM}^{Z'} = \frac{s + m_{Z'}^2 - m_s^2}{2\sqrt{s}}, \quad E_{CoM}^{s} = \frac{s + m_s^2 - m_{Z'}^2}{2\sqrt{s}}.$$

Unitarity Bounds

$$\sqrt{s} < \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

Parameters in the theory are all related to each other. Need to ensure sensible choices are made to avoid unitarity problems, i.e. Yukawas:

$$m_{Z'} = g_\chi w,$$

$$m_\chi = \frac{1}{\sqrt{2}} w y_\chi, \qquad y_\chi = \frac{\sqrt{2} g_\chi m_\chi}{m_{Z'}}.$$