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

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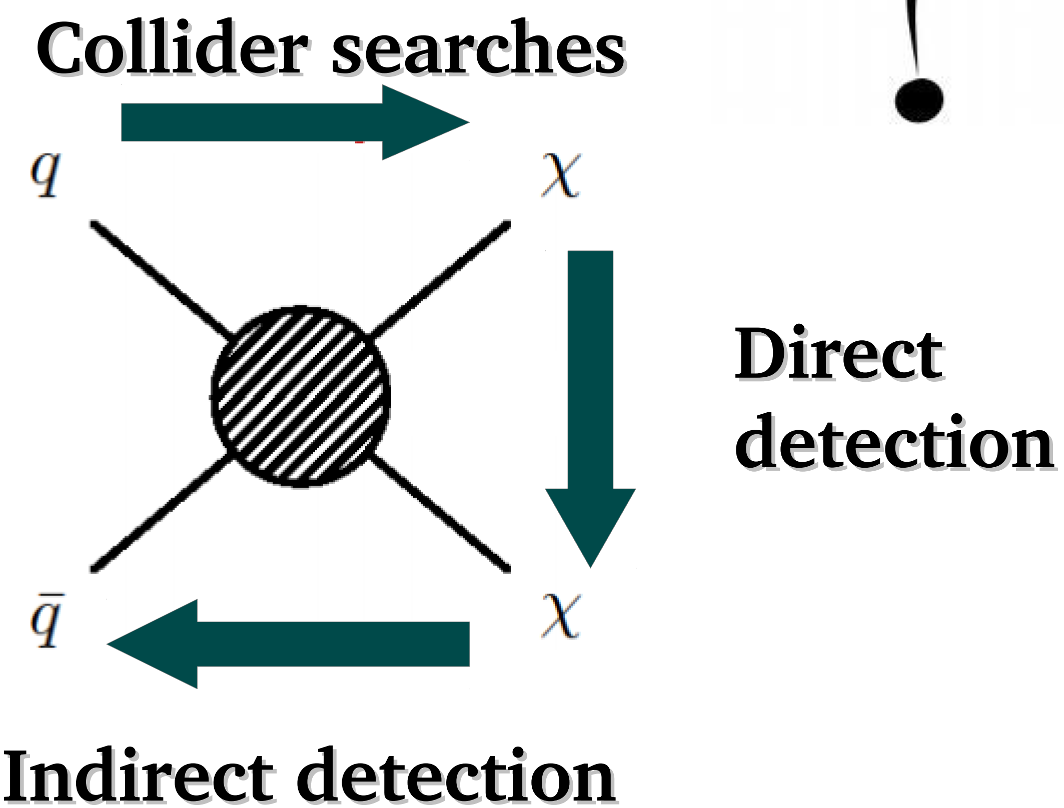
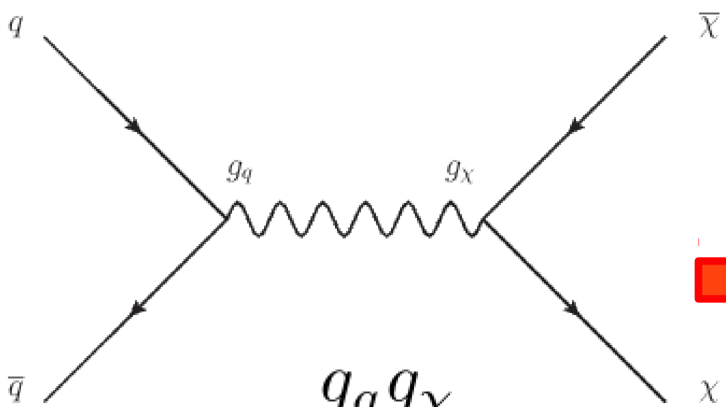
What is dark matter?

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



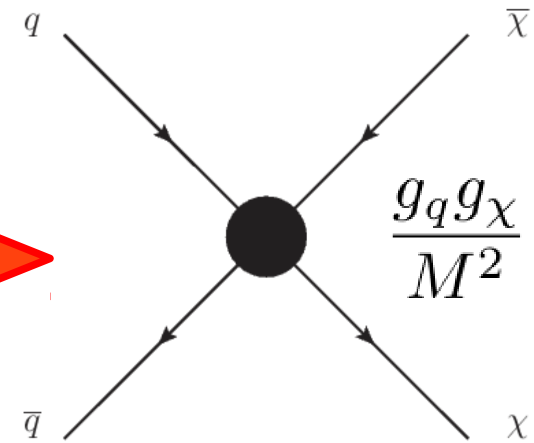
Searches provide complementary information

Simplified Models vs. EFTs



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

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

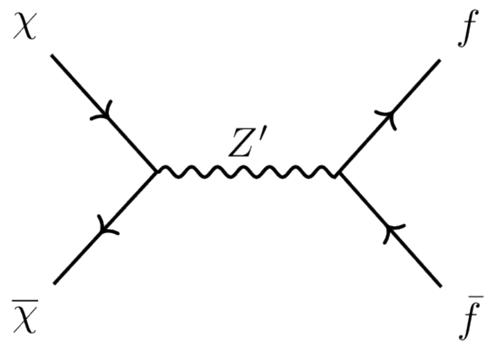


$$\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

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

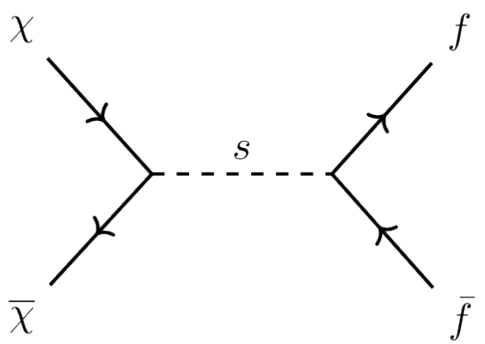
- Both fairly model independent
- EFTs useful at low energies only, simplified models valid for a larger range
- Simplified models are becoming the norm for DM searches, and allow for richer phenomenology.

Simplified Model Benchmarks



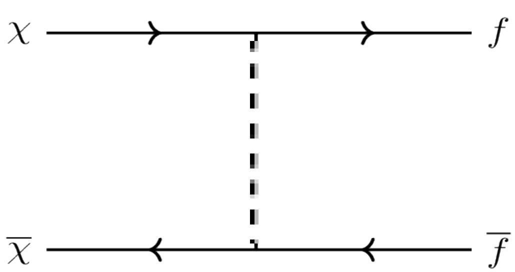
$$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$



$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right),$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi}\gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right).$$



$$\mathcal{L}_{\text{int}} = g \sum_{i=1,2} (\phi_{(i),L} \bar{Q}_{(i),L} + \phi_{(i),u,R} \bar{u}_{(i),R} + \phi_{(i),d,R} \bar{d}_{(i),R})\chi$$

…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.

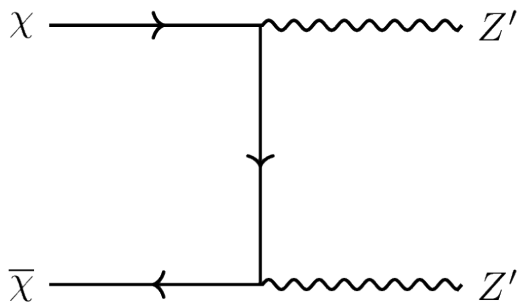
These issues motivate a scenario in which the vector and the scalar mediators appear together within the same theory.

Spin-1 Simplified Model

Kahlhoefer et al, 1510.02110

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5\right] \psi$$

Consider high energy production of longitudinal Z' bosons:



$$\epsilon_L^\mu(k) = k^\mu / m_{Z'}$$

violates unitarity at high energies, for axial-vector Z'-DM couplings.

Introduces a unitarity bound.

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

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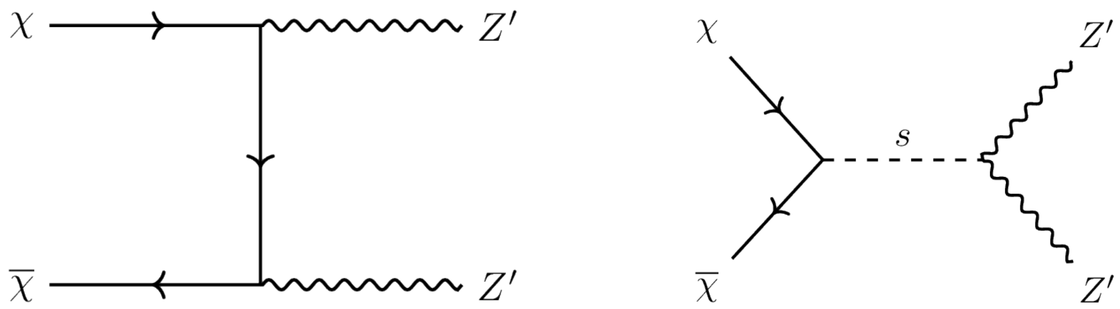

Bad high energy behaviour cancelled by additional scalar!

Introduces a unitarity bound.

$$m_s \lesssim \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

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

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.

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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:

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

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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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$$+ g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

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

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

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

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

How does this compare to simplified models?

Indirect Detection with Simplified Models

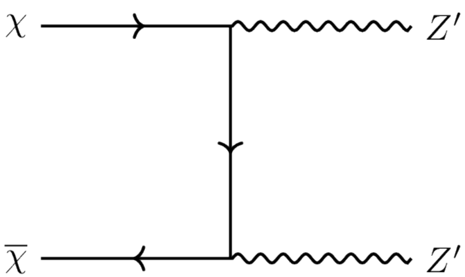
- In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$.

$$\sigma v = a + bv^2 + \cdots$$

- Collider and direct detection experiments introducing increasing tension between allowed DM parameters and the thermal WIMP paradigm.

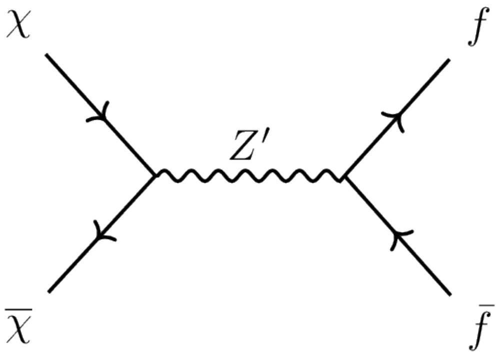
- Hidden on-shell models popular way to avoid this.

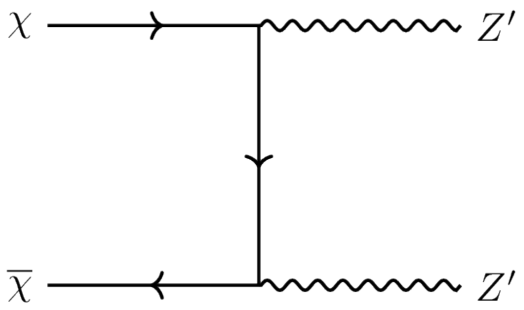
(Abdullah et al, 1404.6528)



Spin-1 Indirect Detection

For fermionic DM:



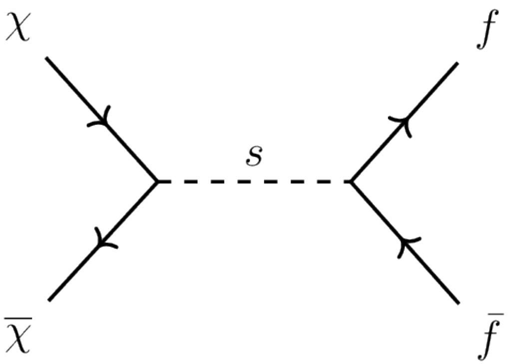


Vector: p-wave
Axial-vector: s or p-wave

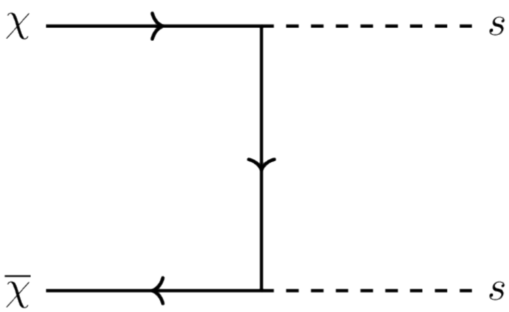
s-wave for all couplings!

Spin-0 Indirect Detection

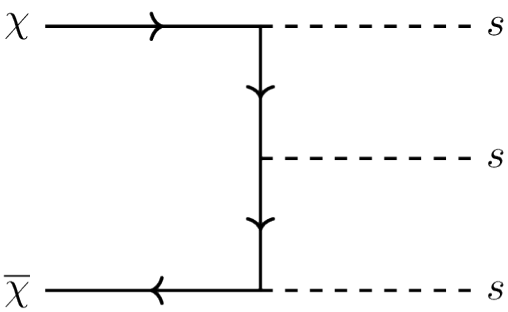
Analogous diagrams not quite the same.



Pseudoscalar: s-wave
Scalar: p-wave



Always p-wave!

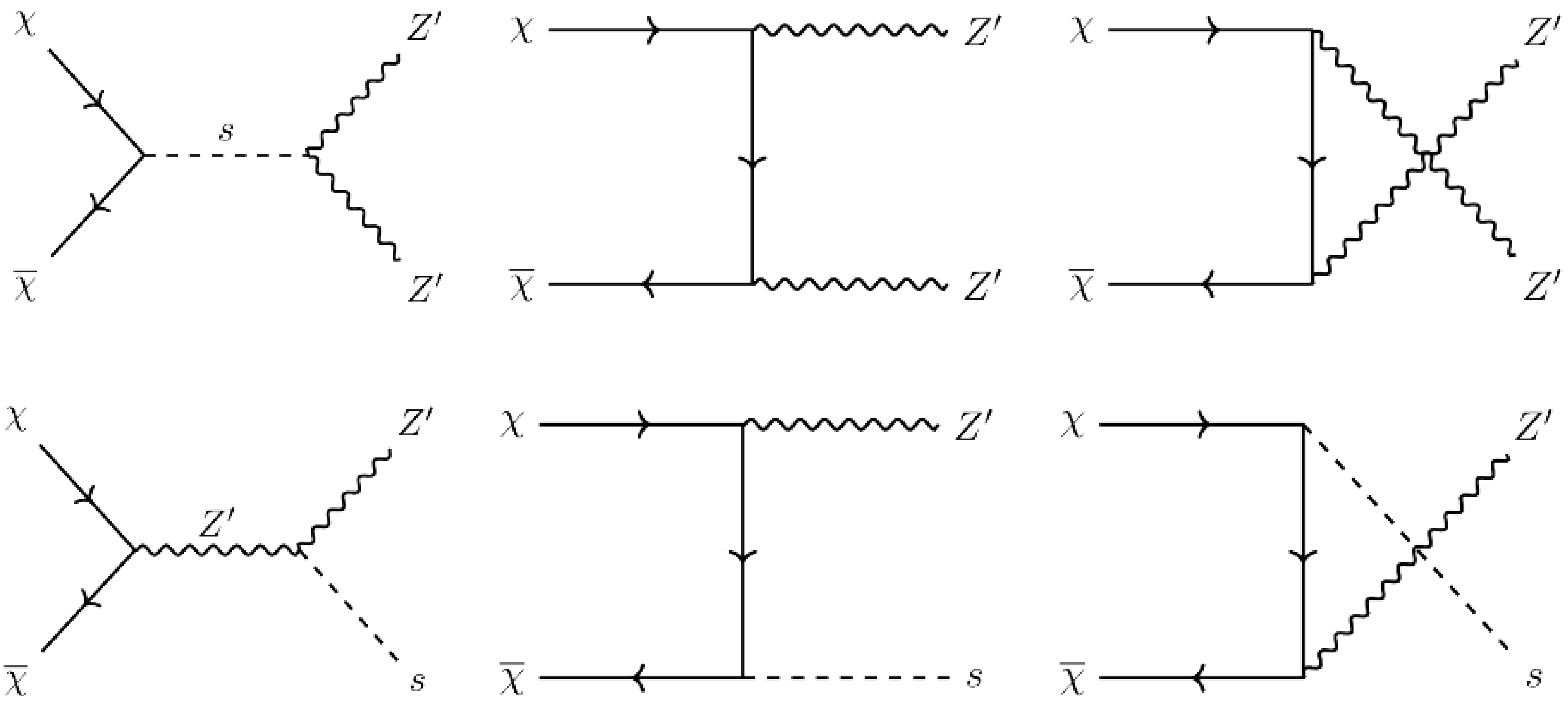


Pseudoscalar: s-wave
Scalar: p-wave

No s-wave diagram for scalars!

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

Annihilation Processes

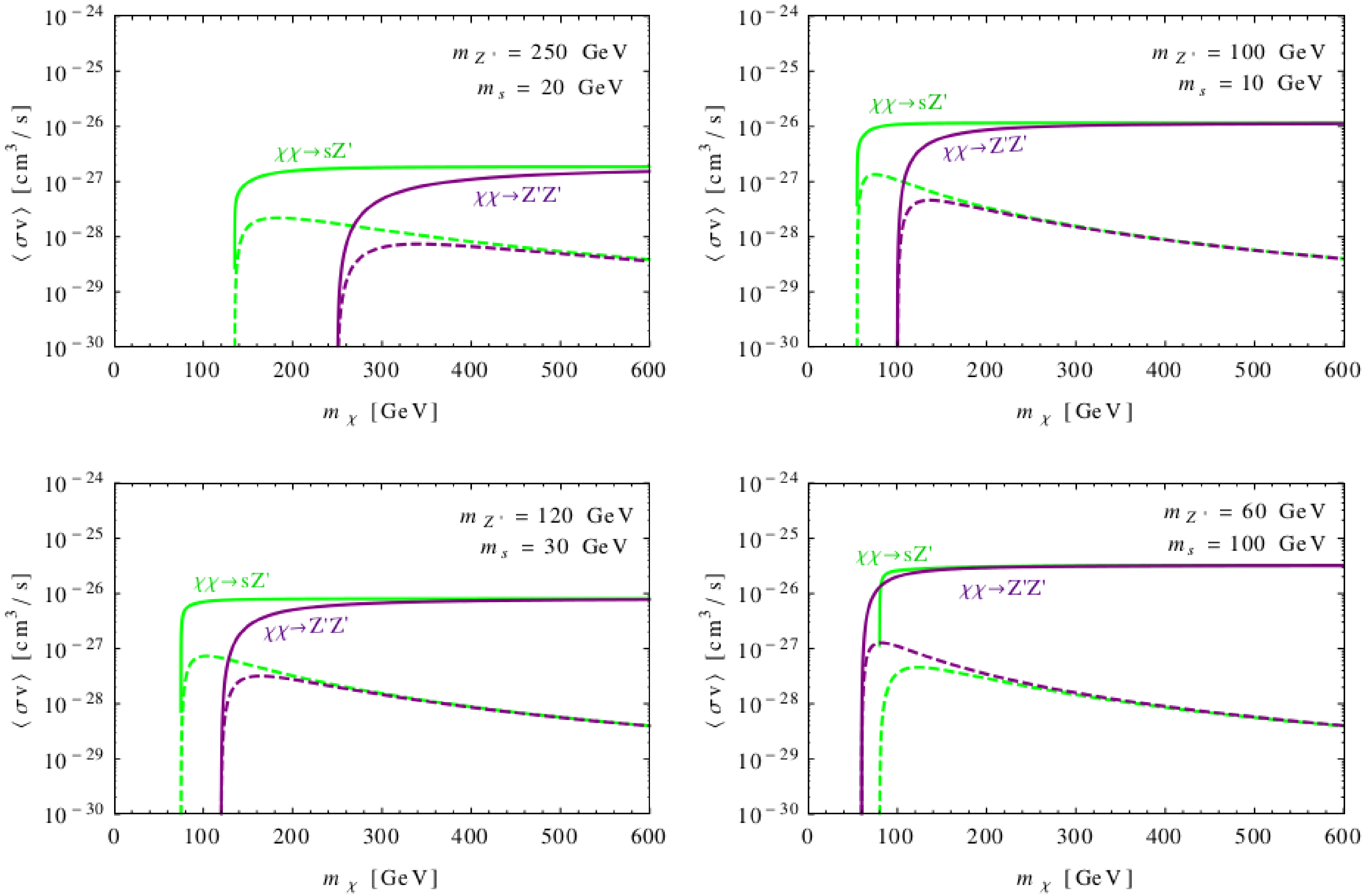


This opens up a new s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z', that is not ruled out by other exps.

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

but how large is its annihilation rate?

Annihilation cross sections



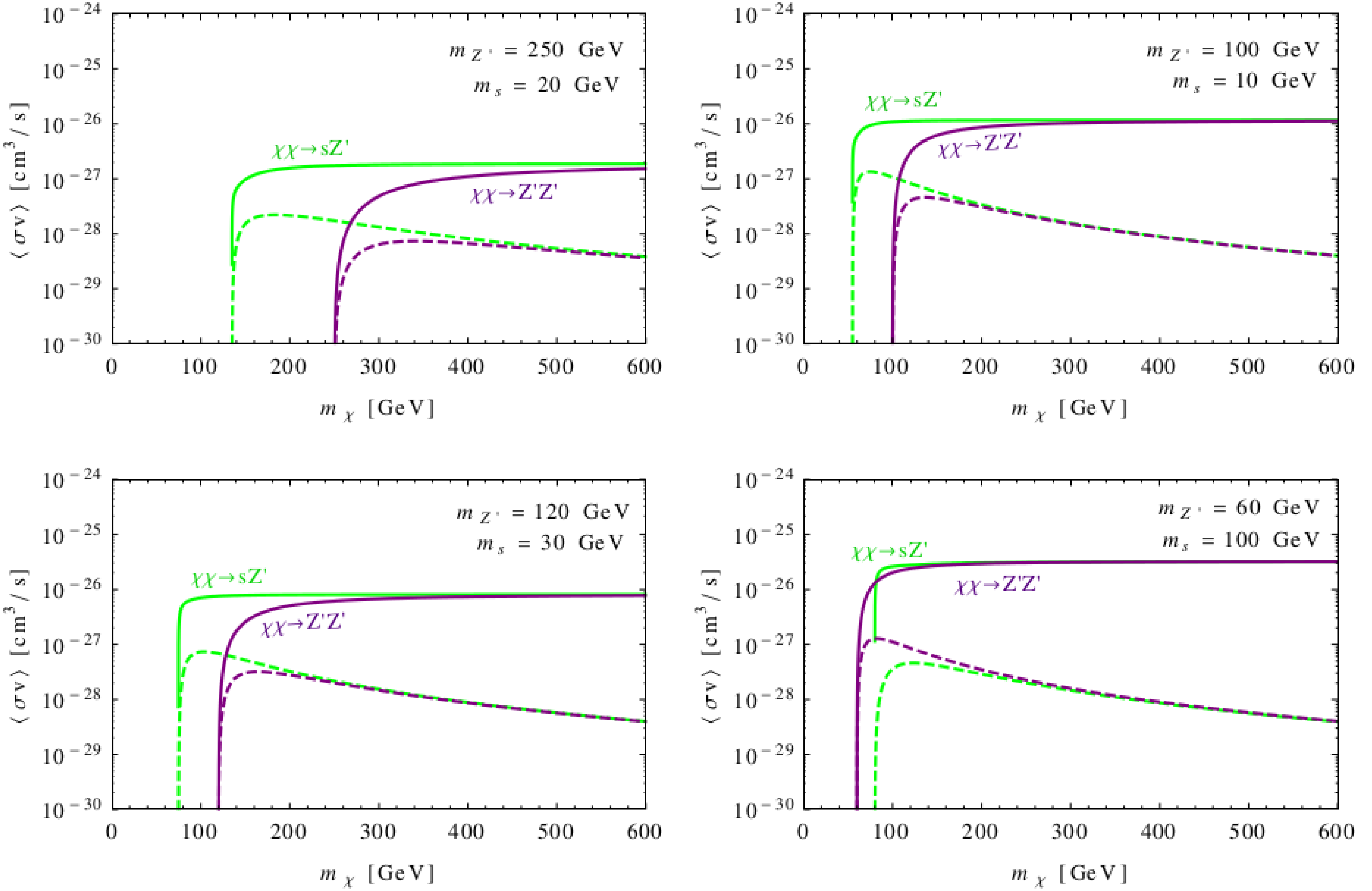
Cross section behavior

- <u>Majorana DM:</u>
  - total model cross section is changed for most of parameter space.
  - different mediators decay differently, will get different energy spectra!
  - only transverse Z' modes are contributing.

$$\langle \sigma v \rangle_{\chi\overline{\chi}\to sZ'} = \frac{g_\chi^4 \left(m_s^4 - 2m_s^2\left(4m_\chi^2 + m_{Z'}^2\right) + \left(m_{Z'}^2 - 4m_\chi^2\right)^2\right)^{3/2}}{1024\pi m_\chi^4 \left(m_{Z'}^2 - 4m_\chi^2\right)^2}$$

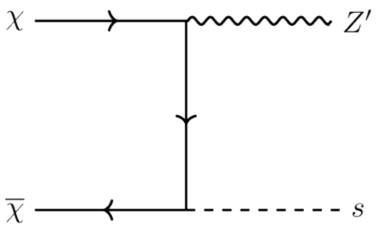
$$\langle \sigma v \rangle_{\chi\overline{\chi}\to Z'Z'} = \frac{g_\chi^4 \left(1 - \frac{m_{Z'}^2}{m_\chi^2}\right)^{3/2}}{256\pi m_\chi^2 \left(1 - \frac{m_{Z'}^2}{2m_\chi^2}\right)^2}$$

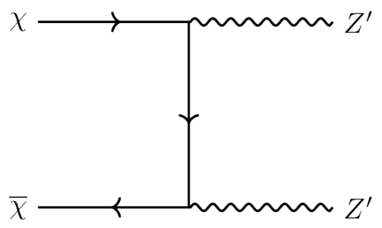
Annihilation cross sections



Cross section behavior

- <u>Dirac DM:</u>
  - can now get a large rate for higher DM masses
  - Z'Z' and sZ' cross sections linked by goldstone boson equivalence theorem





$$\langle \sigma v \rangle_{\chi\overline{\chi}\to sZ'} = \frac{g_\chi^4 \sqrt{\left(m_{Z'}^2 - 4m_\chi^2\right)^2 - 2m_s^2\left(4m_\chi^2 + m_{Z'}^2\right) + m_s^4} \times A}{512\pi m_\chi^4 m_{Z'}^2 \left(m_{Z'}^2 - 4m_\chi^2\right)^2 \left(m_s^2 - 4m_\chi^2 + m_{Z'}^2\right)^2}$$

$$\langle \sigma v \rangle_{\chi\overline{\chi}\to Z'Z'} = \frac{g_\chi^4 \left(1 - \frac{m_{Z'}^2}{m_\chi^2}\right)^{3/2}}{32\pi m_{Z'}^2 \left(1 - \frac{m_{Z'}^2}{2m_\chi^2}\right)}$$

Indirect Detection Limits

- Dwarf Spheriodal Galaxies, most DM dense objects in our sky.
- Can't just take existing limits on the cross section due to different final states and different kinematics

  → generate spectra ourselves, compare to Fermi data and find limits.

- AMS-02 limits for electron final states very strong. Only dominates in low DM mass region and is approximately flat here, so we take the cascade limits previously found.

The Photon Energy Spectra

$$\frac{d^2\Phi}{d\Omega dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left(\sum_f \frac{dN}{dE_\gamma}Br_f\right)J(\phi,\gamma)$$

Z' partial width taken analytically:

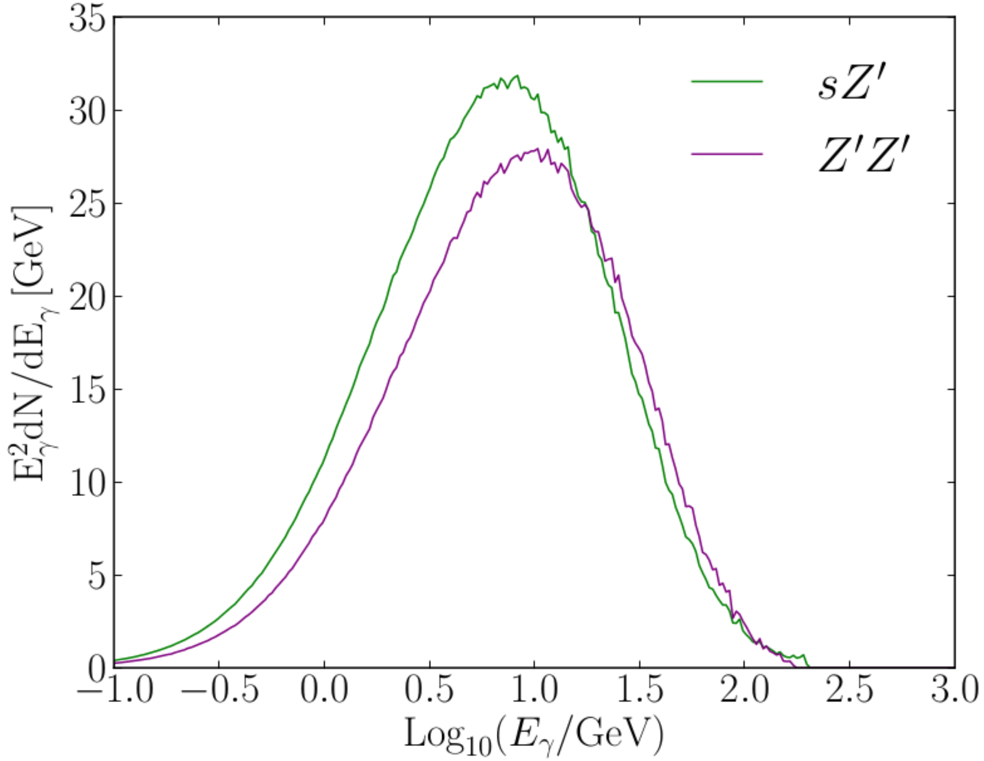
$$\Gamma(Z' \to f\bar{f}) = \frac{m_{Z'}N_c}{12\pi}\sqrt{1-\frac{4m_f^2}{m_{Z'}^2}}\left[g_{f,V}^2\left(1+\frac{2m_f^2}{m_{Z'}^2}\right)+g_{f,A}^2\left(1-\frac{4m_f^2}{m_{Z'}^2}\right)\right]$$

For dark Higgs, use Fortran package HDecay, as higher order corrections and loops can be relevant. Ensures accurate calculation of all branching fractions.

The Photon Energy Spectra

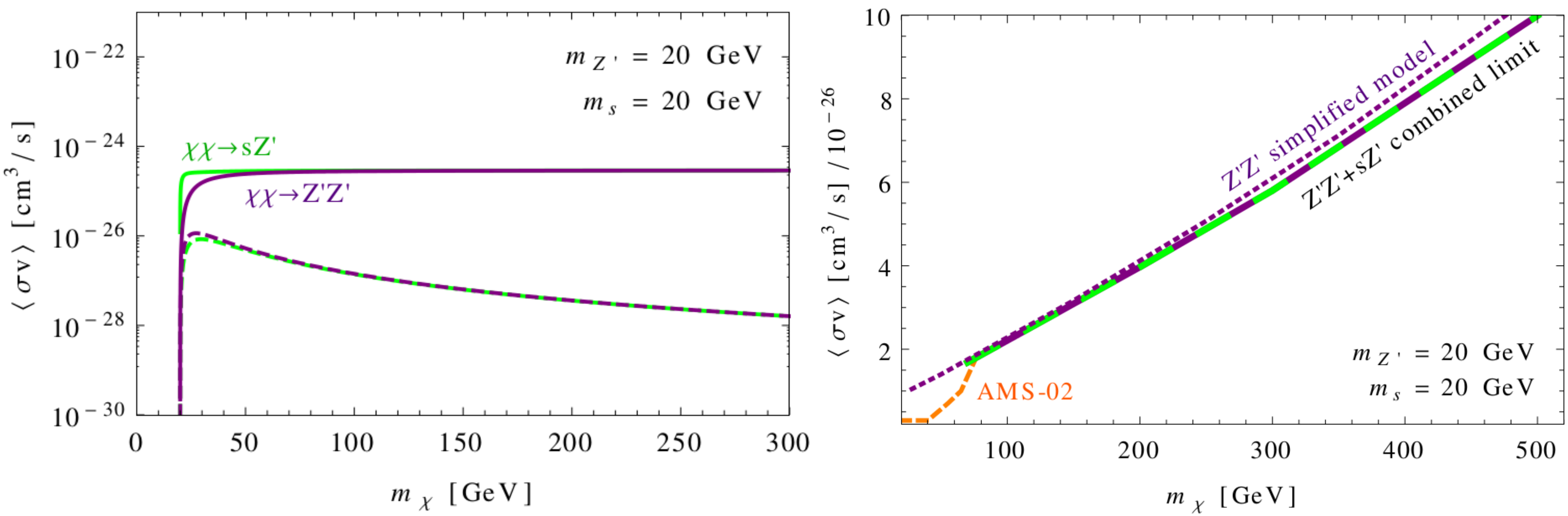
Generate in Pythia, make effective resonance in particle CoM frame, then average the separate spectra.

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

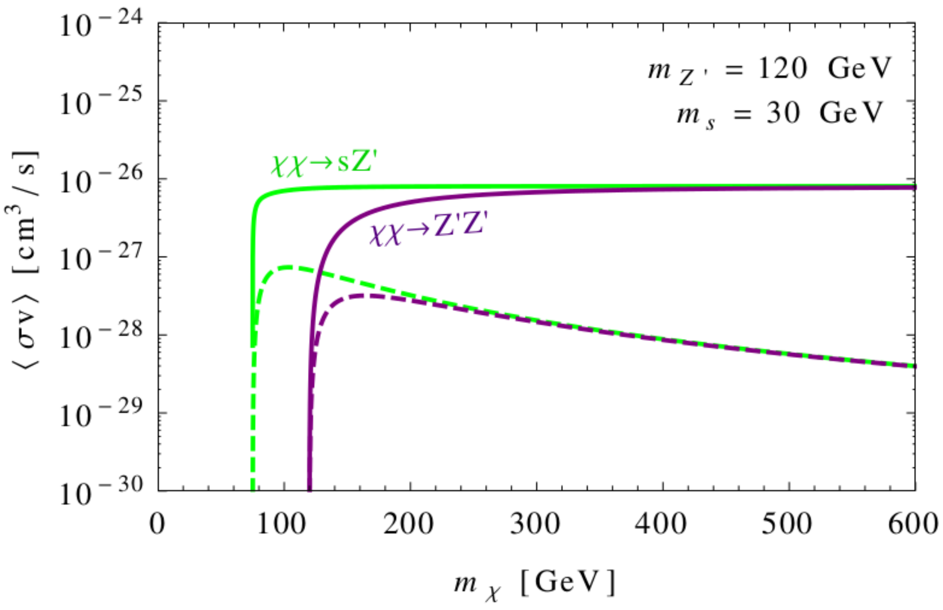


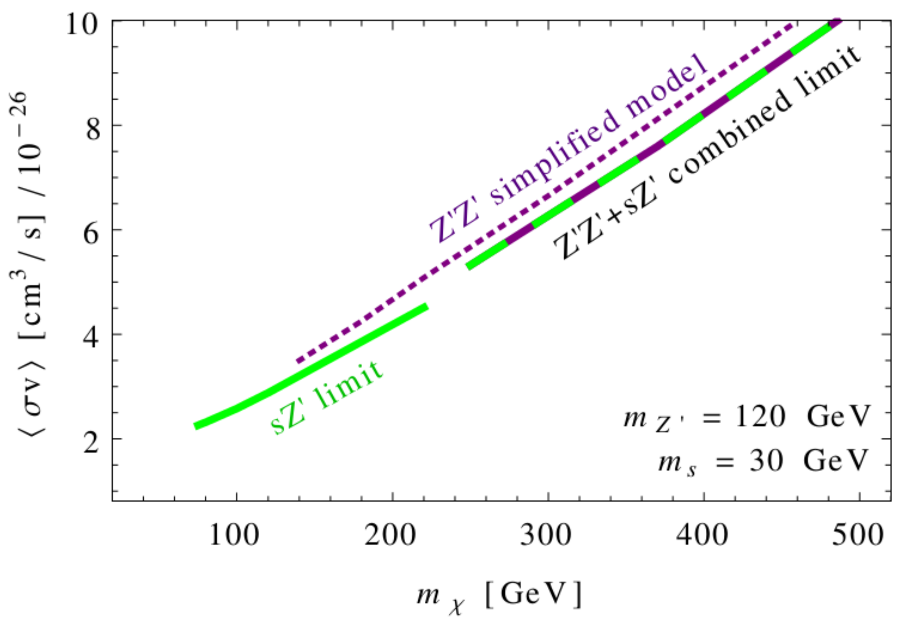
$$E_{CoM}^{Z'} = \frac{s + m_{Z'}^2 - m_s^2}{2\sqrt{s}}, \quad E_{CoM}^{s} = \frac{s + m_s^2 - m_{Z'}^2}{2\sqrt{s}}.$$

Indirect Detection Limits

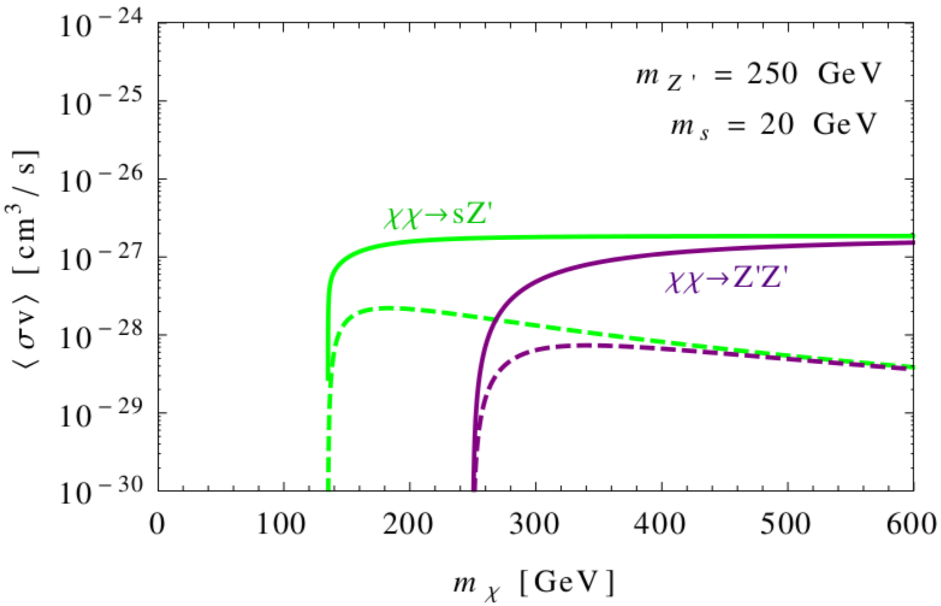


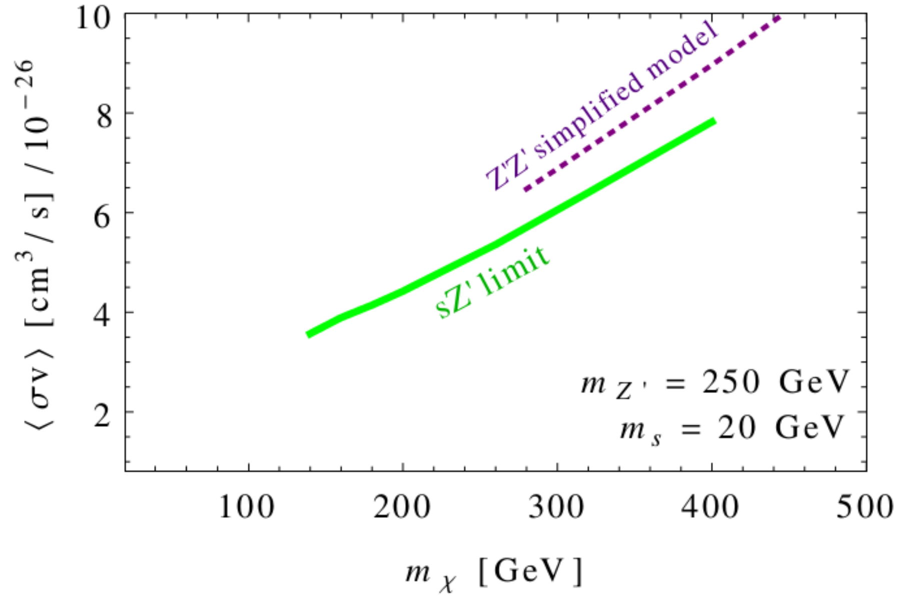
Indirect Detection Limits





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.

Dirac DM extensions

Combinations of mass generation mechanisms possible:

- Vectorlike Dirac DM:
  1. Bare DM mass, Z' mass from Stueckelberg.
  2. DM mass from dark Higgs, Z' mass from Stueckelberg.
  3. Bare DM mass, Z' mass from dark Higgs.
- Chiral Dirac DM:
  1. Both DM and Z' get mass from dark Higgs.
  Requires both axial and vector Z'-DM couplings to be present!

If it turns out that any of these scenarios are realized by nature, simplified model constraints and pheno will be different!

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 Majorana DM it is necessary to include the scalar in the theory.
- Leads to interesting phenomenology: previously unconsidered s-wave process, which for some couplings can dominate the annihilation rate. Different shaped spectra can also lead to stronger cross section limits.
- 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

Unitarity Bounds

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

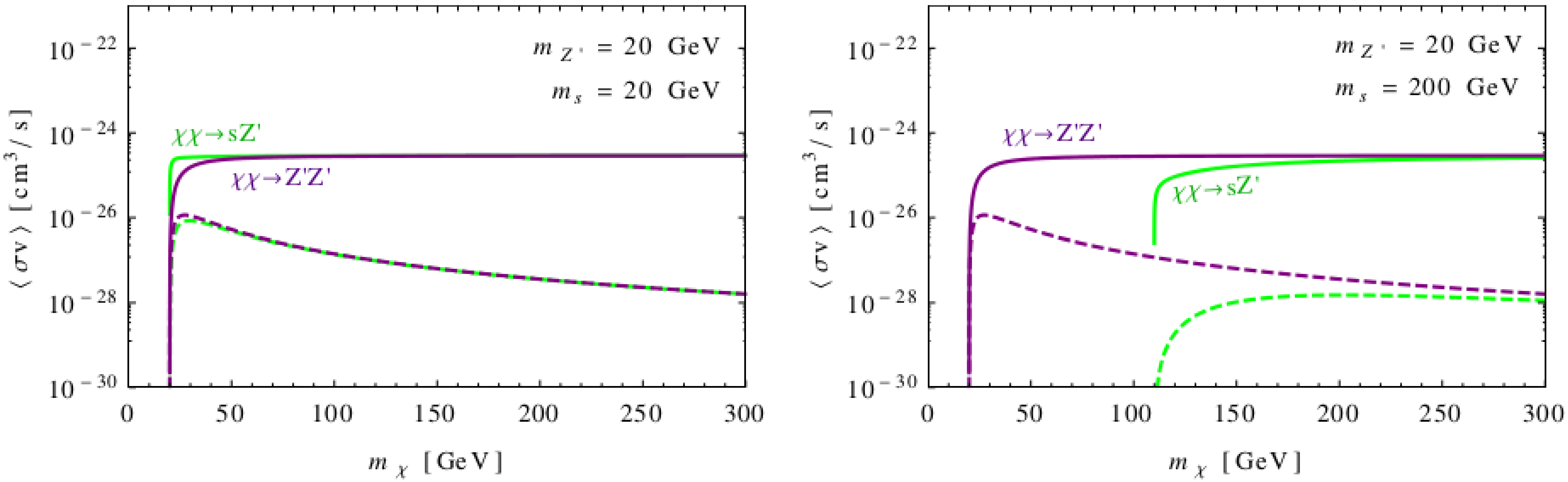
$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

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

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

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

More cross sections



More indirect detection