Dark Sector enhancement of dark matter annihilation

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N.F. Bell, Y. Cai, JBD, R.K. Leane, and T.J. Weiler, 1705.01105

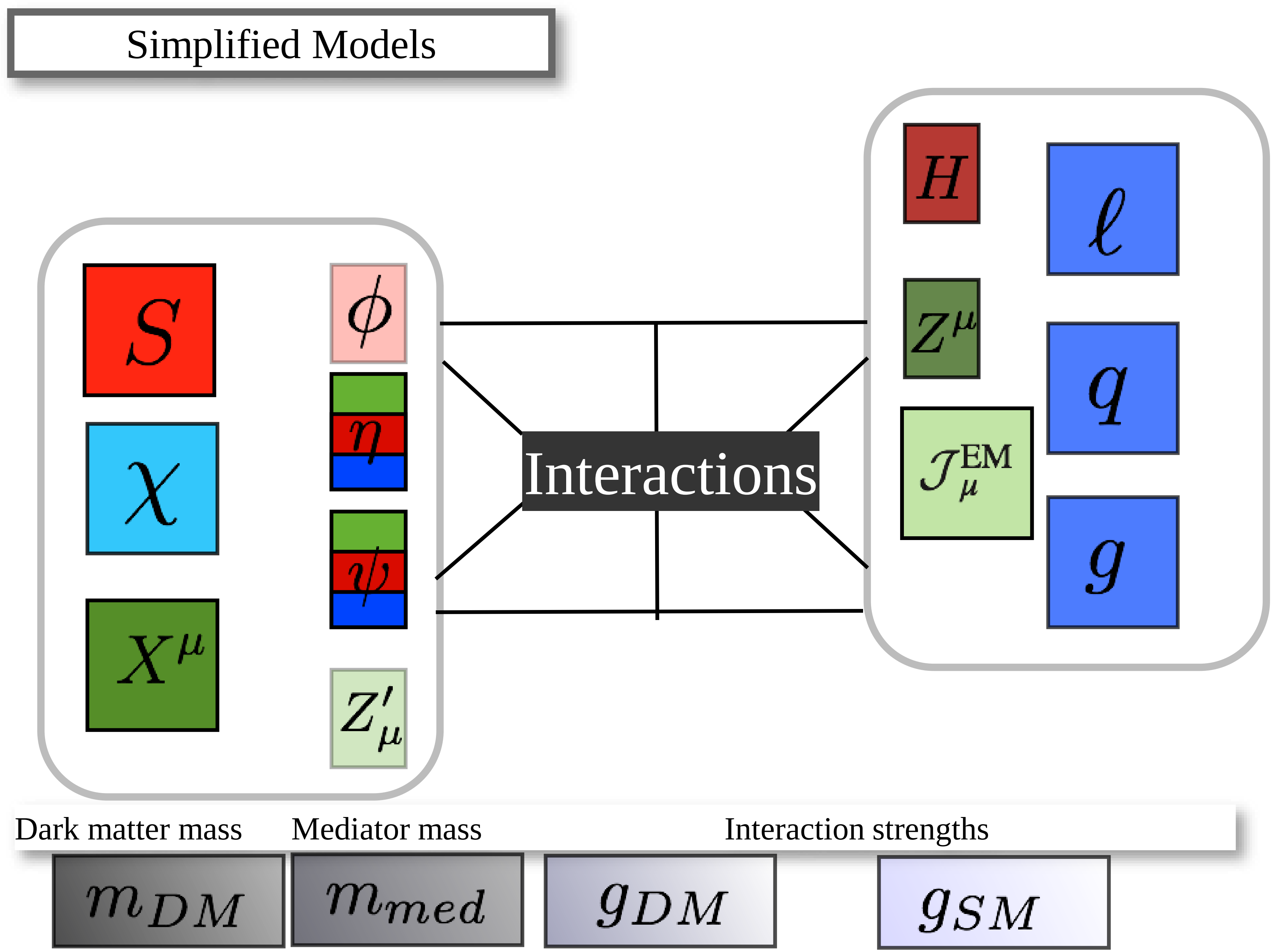
Annihilation cross-sections: relic abundance
Indirect detection

Partial-wave expansion $\sigma v = a + b v^2$

L^{th} partial wave is suppressed as v^{2L}

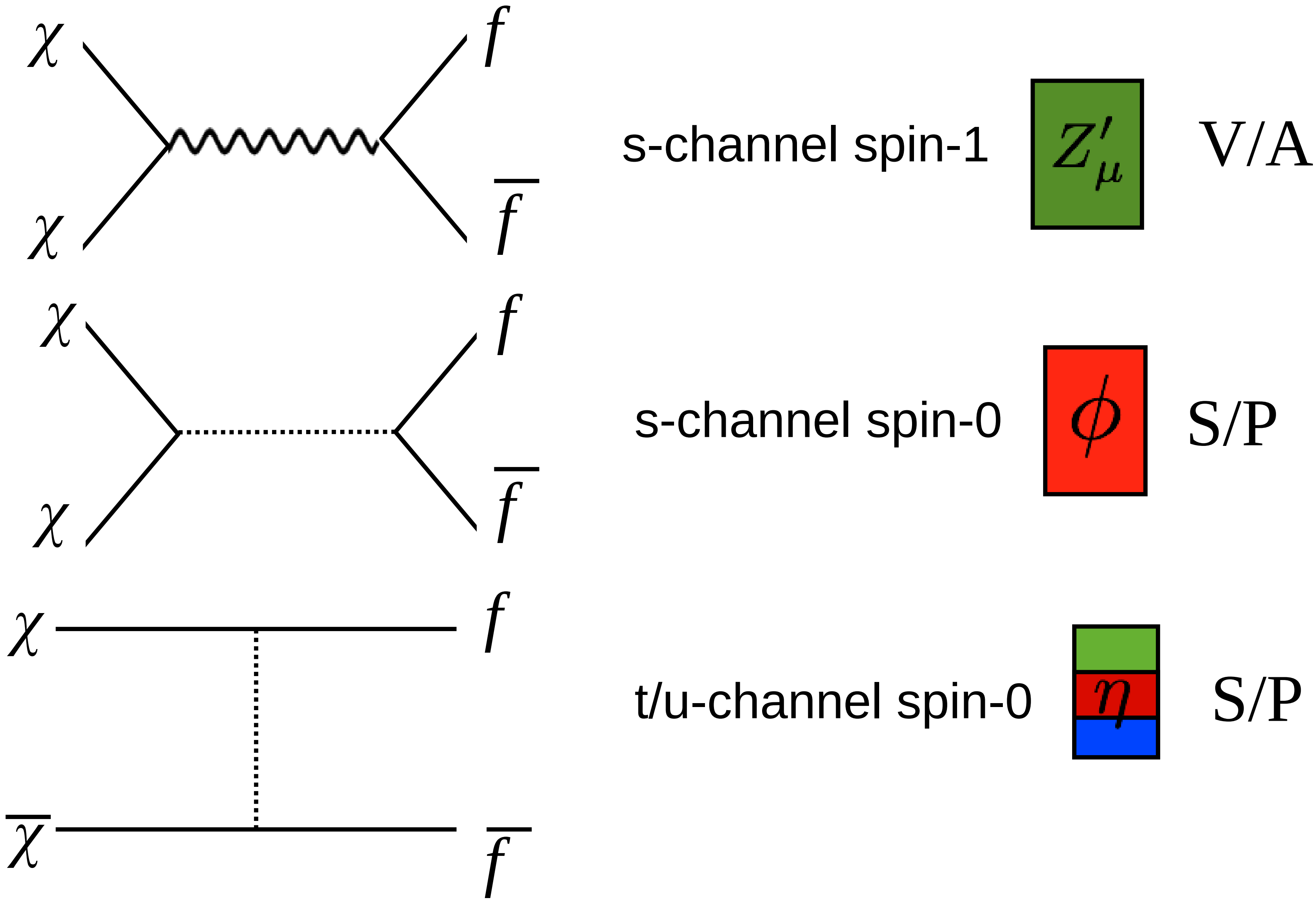
today this is $v^2 \sim 10^{-6}$

We explore dark matter annihilation processes for simplified models and extensions to determine dominant annihilation modes.

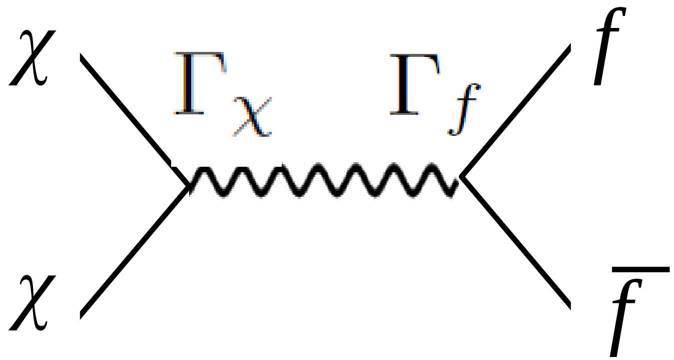


Simplified Models
S
χ
X^μ
ϕ
η
ψ
Z'_μ
Interactions
H
Z^μ
$\mathcal{J}_\mu^{\mathrm{EM}}$
ℓ
q
g
Dark matter mass
Mediator mass
Interaction strengths
m_{DM}
m_{med}
g_{DM}
g_{SM}

Two-to-two $\chi\chi \to \bar{f}f$ processes: mediators and channels

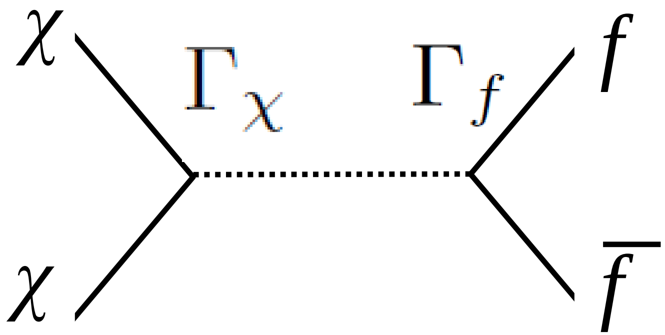


Two-to-two $\chi\chi \to \overline{f}f$ processes: mediators and channels

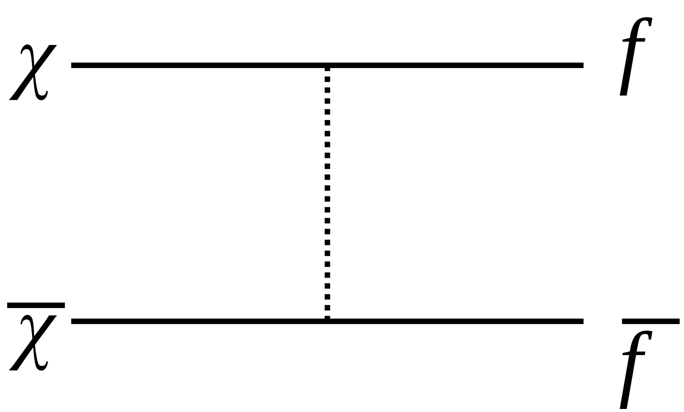


Γ_χ

V: CP = - - L = 0 ***s***-wave
AV: CP = + -/+ L = 0,1:
helicity suppressed ***s***-wave

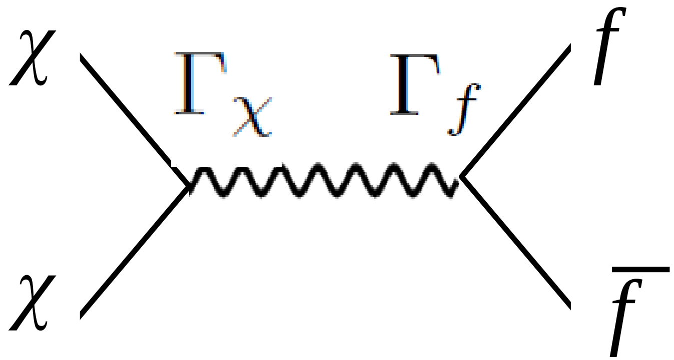


S: CP = ++ L = 1 ***p***-wave
PS: CP = +- L = 0 ***s***-wave



$(m_f/m_\chi)^2$ Helicity suppression

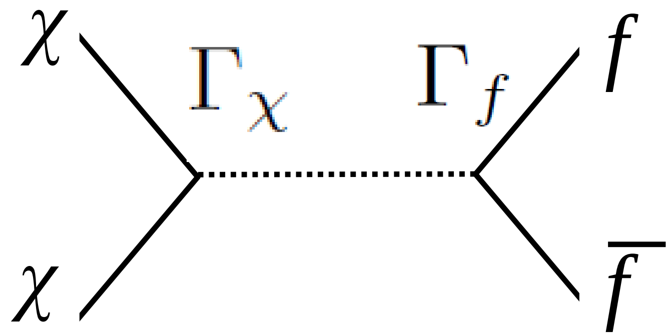
Two-to-two $\chi\chi \to \bar{f} f$ processes: mediators and channels



Γ_χ

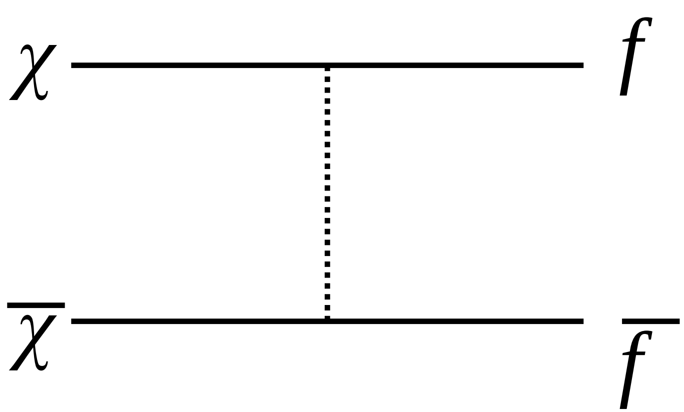
V: CP = - - L = 0 ***s***-wave

Majorana pair is C-even and thus doesn't couple to V



S: CP = ++ L = 1 ***p***-wave

PS: CP = +- L = 0 ***s***-wave



$(m_f/m_\chi)^2$ Helicity suppression

Summary of two-to-two annihilation processes with a single mediator:

$\Gamma_\chi \otimes \Gamma_f$	$\overline{\chi}\chi \to \overline{f}f$
$V \otimes V$	1
$A \otimes V$	v^2
$V \otimes A$	1
$A \otimes A$	$(m_f/m_\chi)^2$
$S \otimes S$	v^2
$P \otimes S$	1
$S \otimes P$	v^2
$P \otimes P$	1

For Majorana DM:
only DM-Pseudoscalar interactions produce unsuppressed annihilation to a fermion/anti-fermion pair.

Simplified Models: unitarity and gauge invariance lead to multi-mediator constructions

$$U(1)_\chi$$

$$Z'$$

For non-zero axial-vector couplings $Z'_L Z'_L$ scattering violates unitarity at high energies. Introducing a dark Higgs solves the issue

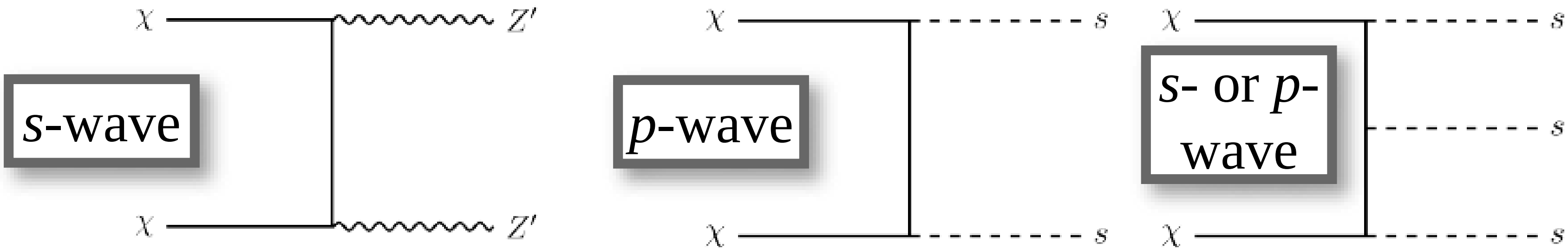
$$s$$

The dark Higgs can provide the mass generation mechanism for the dark vector and dark matter

For example: F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, *JHEP* (2016), 1510.02110

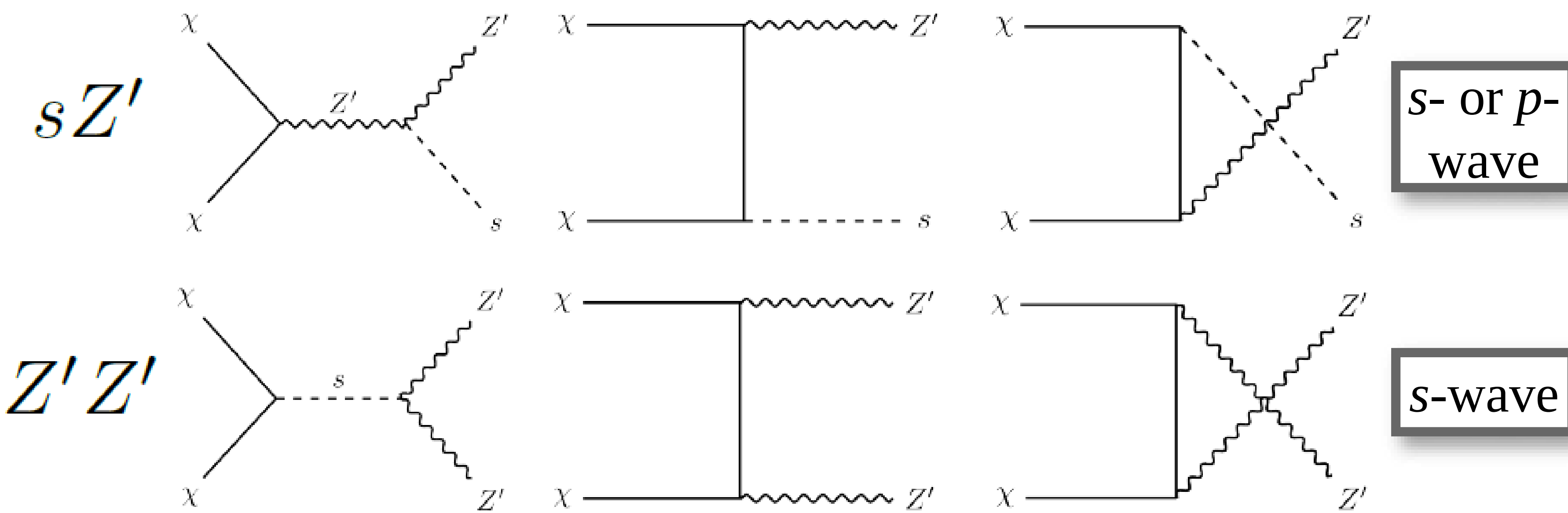
Single Mediator

For example: M. Abdullah, A. DiFranzo, A. Rajaraman, T. Tait, P. Tanedo, A. Wijangco, *PRD* (2014), 1404.6528



Multi-Mediator

New annihilation channels



N.F. Bell, Y. Cai, and R.K. Leane, *JCAP* (2016), 1605.09382

Two-to-two processes: DM to two dark sector particles

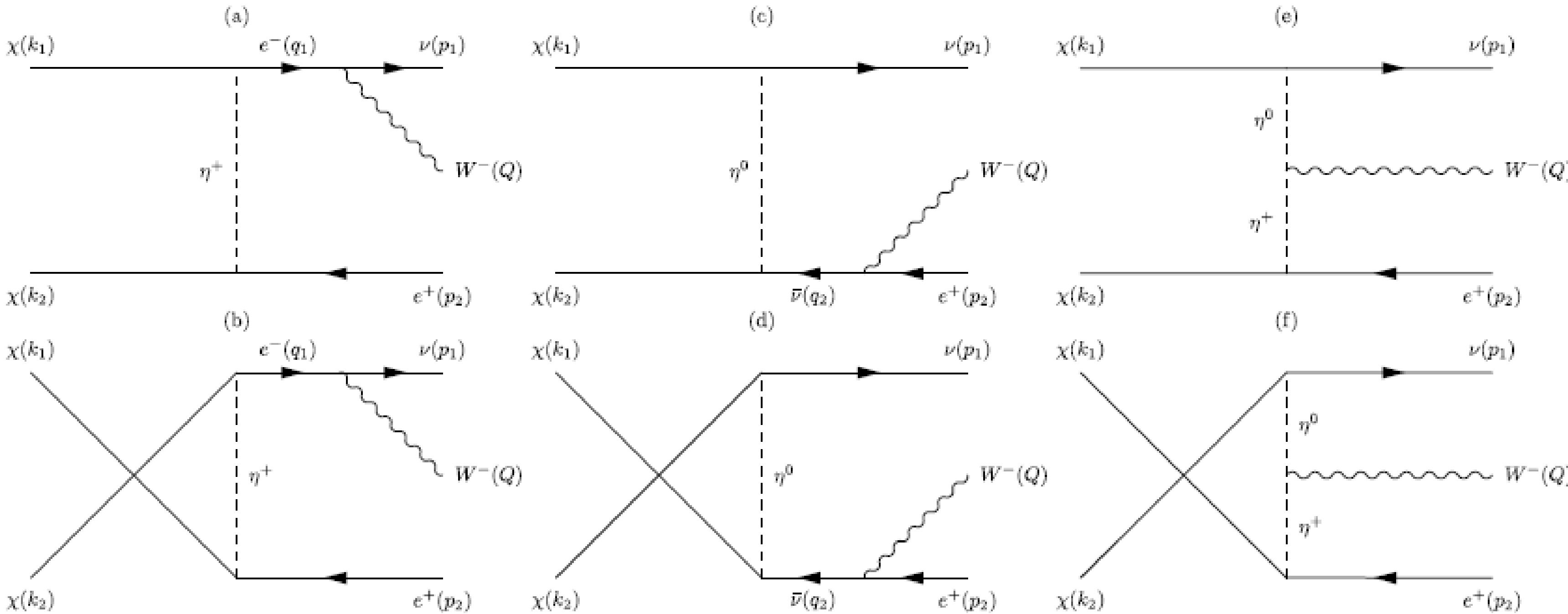
$\Gamma_{M_1} \otimes \Gamma_{M_2}$
$\overline{\chi}\chi \to M_1\, M_2$

$S \otimes S$	$S \otimes P$	$P \otimes P$
v^2	1	v^2

$V \otimes V$	$V \otimes A$	$A \otimes A$
1	1	1

$S \otimes V$	$S \otimes A$	$P \otimes V$	$P \otimes A$
1	v^2	1	v^2

Enhancement in two to three processes: SM cases



γ

L. Bergstrom, *PLB* (1989)

g

R. Flores, K.A. Olive, and S. Rudaz, PLB (1989)

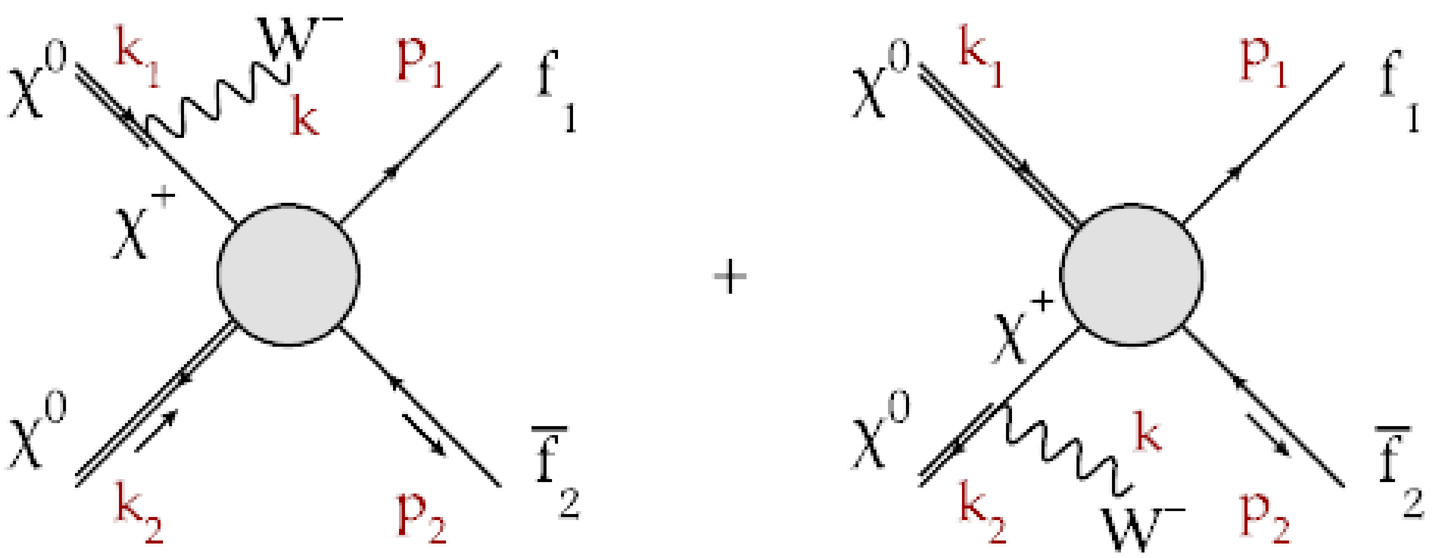
P. Ciafaloni, M. Cirelli, D. Comelli, A. DeSimone, A. Riotto, and A. Urbano, *JCAP* (2011), 1104.2996

W/Z

N.F.Bell, JBD, A.J. Galea, T.D. Jacques, L.M.Krauss, and T.J. Weiler, PLB (2011) 1104.3823

Enhancement in two to three processes:

$SU(2)_L$ charged DM with $W^{+/-}$ ISR



P. Ciafaloni, M. Cirelli, D. Comelli, A. DeSimone, A. Riotto, and A. Urbano, *JCAP* (2011), 1107.4453
M. Garny, A. Ibarra, and S. Vogl, *JCAP* (2012), 1112.5155
P. Ciafaloni, D. Comelli, A. DeSimone, A. Riotto, and A. Urbano, *JCAP* (2012), 1202.0692

Enhancement in two to three processes from dark sector ISR

$\Gamma_\chi \otimes \Gamma_f$	$\overline{\chi}\chi \to \overline{f}f$	$\overline{\chi}\chi \to \overline{f}fZ'$		$\overline{\chi}\chi \to \overline{f}f\phi$	
		$\Gamma_{Z'} = V$	$\Gamma_{Z'} = A$	$\Gamma_\phi = S$	$\Gamma_\phi = P$
$V \otimes V$	1	1	1	1	1
$A \otimes V$	v^2	1	1	v^2	v^2
$V \otimes A$	1	1	1	1	1
$A \otimes A$	$(m_f/m_\chi)^2$	1	1	v^2	v^2
$S \otimes S$	v^2	1	v^2	v^2	1
$P \otimes S$	1	1	v^2	1^*	v^2
$S \otimes P$	v^2	1	v^2	v^2	1^*
$P \otimes P$	1	1	v^2	1	v^2

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Enhancement in two to three processes as well

$\Gamma_\chi \otimes \Gamma_f$	$\overline{\chi}\chi \to \overline{f}f$	$\overline{\chi}\chi \to \overline{f}fZ'$		$\overline{\chi}\chi \to \overline{f}f\phi$	
		$\Gamma_{Z'} = V$	$\Gamma_{Z'} = A$	$\Gamma_\phi = S$	$\Gamma_\phi = P$
$V \otimes V$	1	1	1	1	1
$A \otimes V$	v^2	1	1	v^2	v^2
$V \otimes A$	1	1	1	1	1
$A \otimes A$	$(m_f/m_\chi)^2$	1	1	v^2	v^2
$S \otimes S$	v^2	1	v^2	v^2	1
$P \otimes S$	1	1	v^2	1^*	v^2
$S \otimes P$	v^2	1	v^2	v^2	1^*
$P \otimes P$	1	1	v^2	1	v^2

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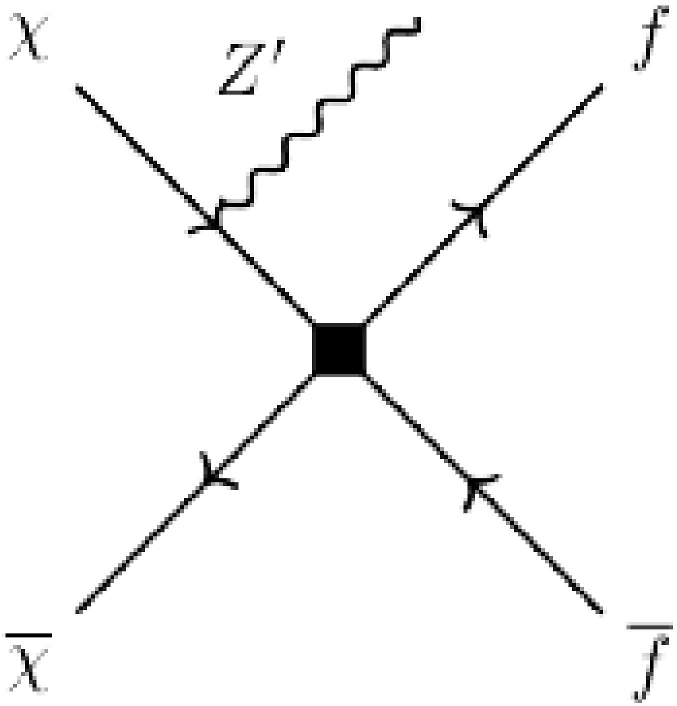
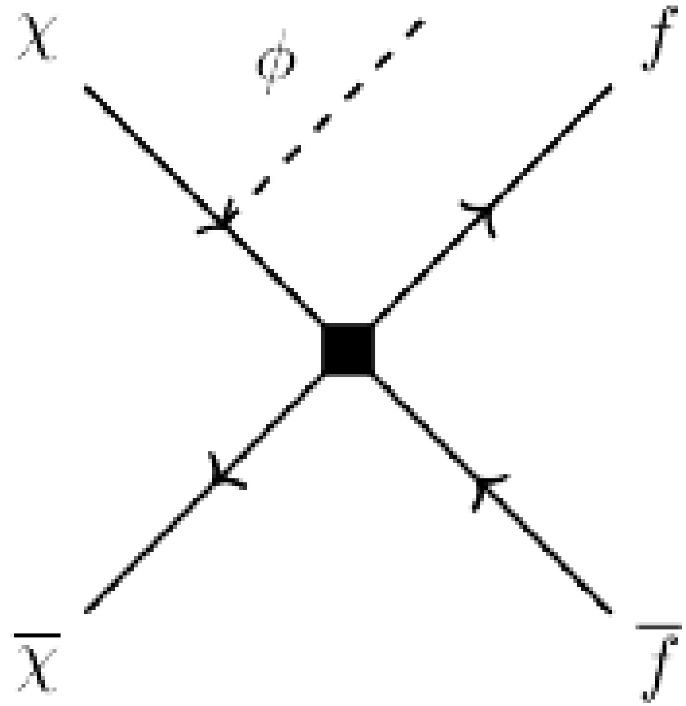
Dark ISR models considered



$\Gamma_{Z'} = V$	$\Gamma_{Z'} = A$

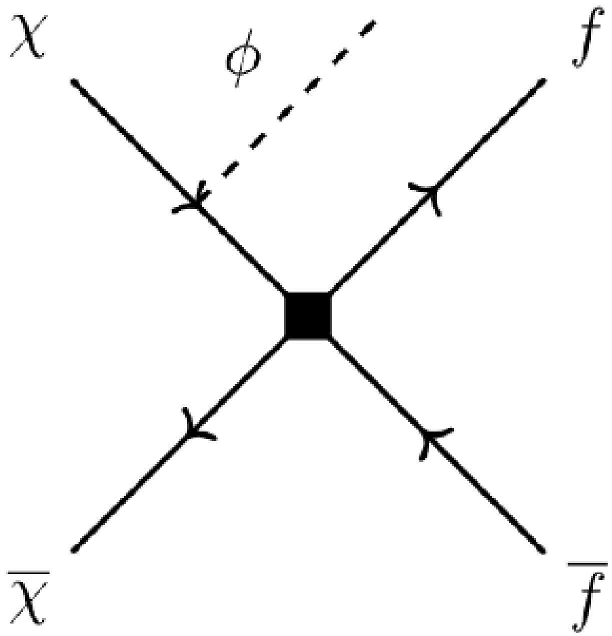


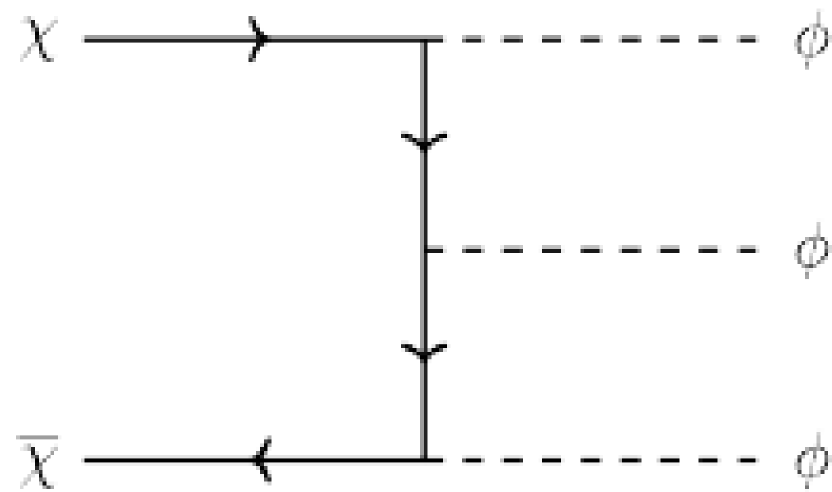
$\Gamma_{\phi} = S$	$\Gamma_{\phi} = P$

$S \otimes S$

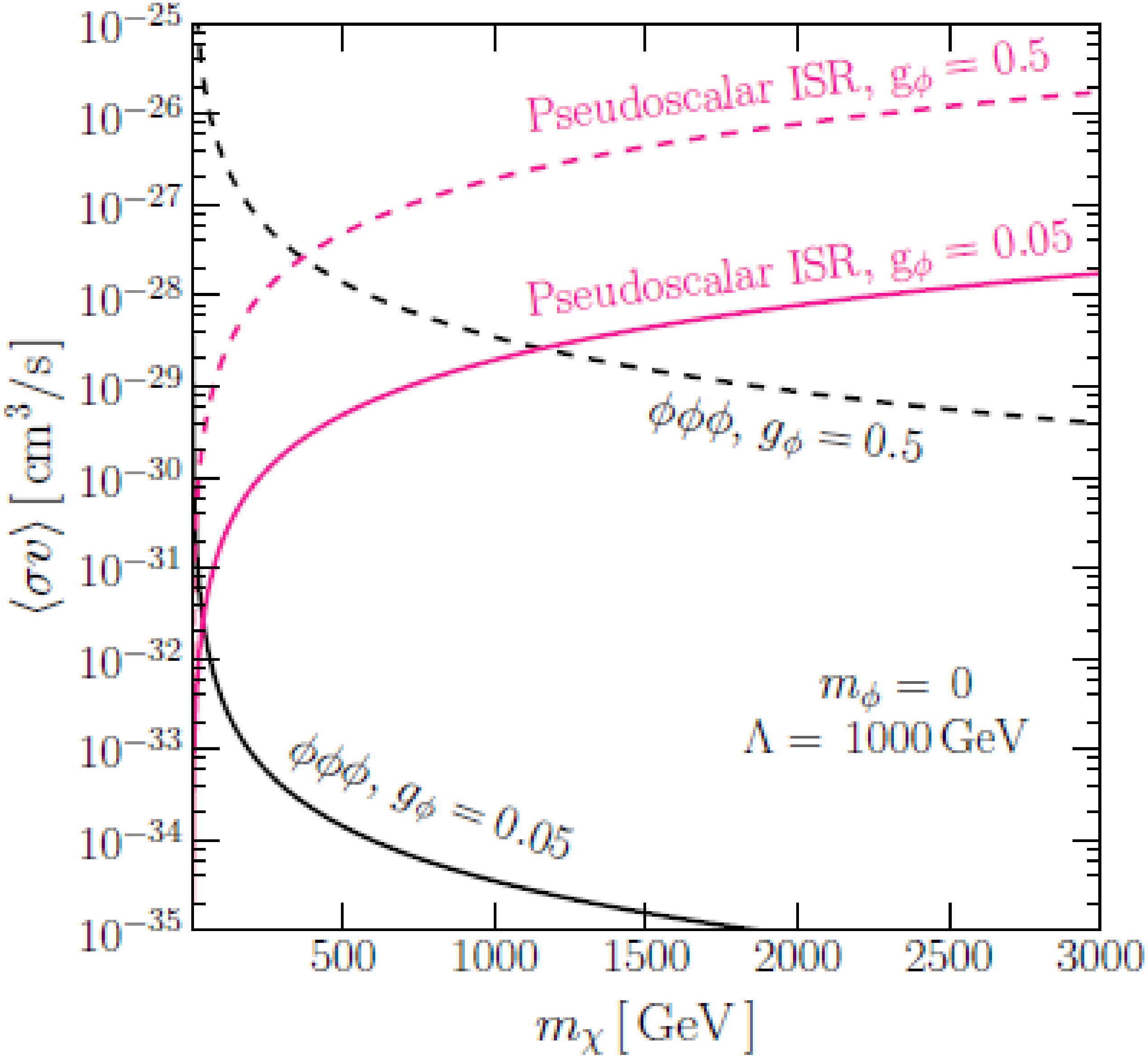
s-wave from 2 to 3 processes

$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}(\overline{\chi}\chi)(\overline{f}f) + i\, g_\phi \phi \overline{\chi}\gamma_5\chi$$

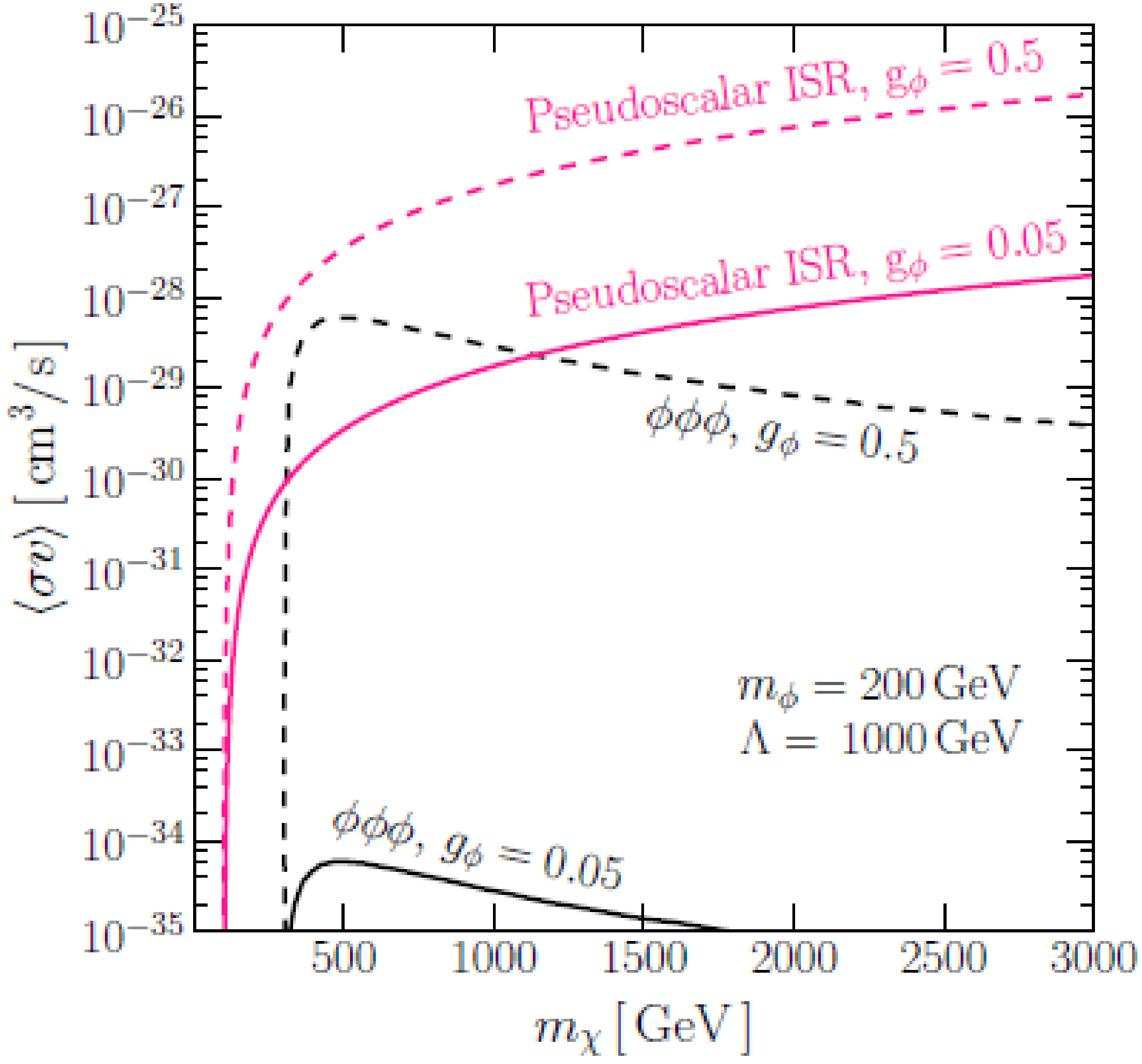




Initial state ISR of a PS and three-body pseudo-scalar final state



Cross-section comparisons

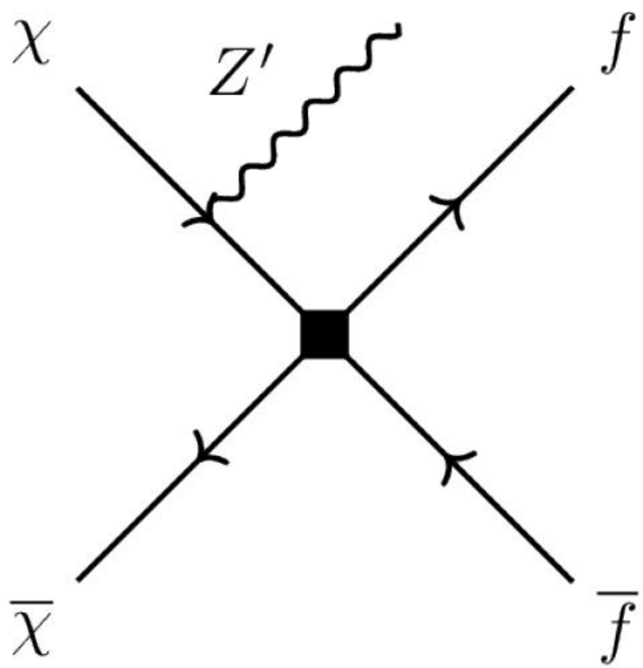


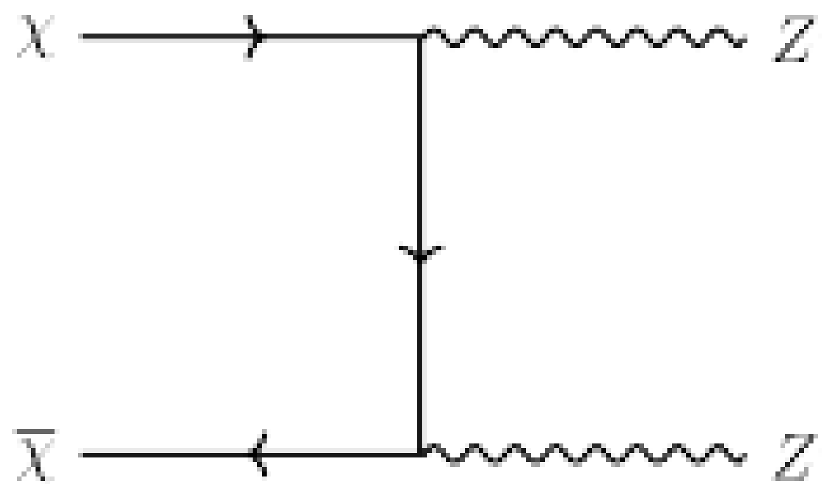
Cross-section comparisons

$$A \otimes A$$

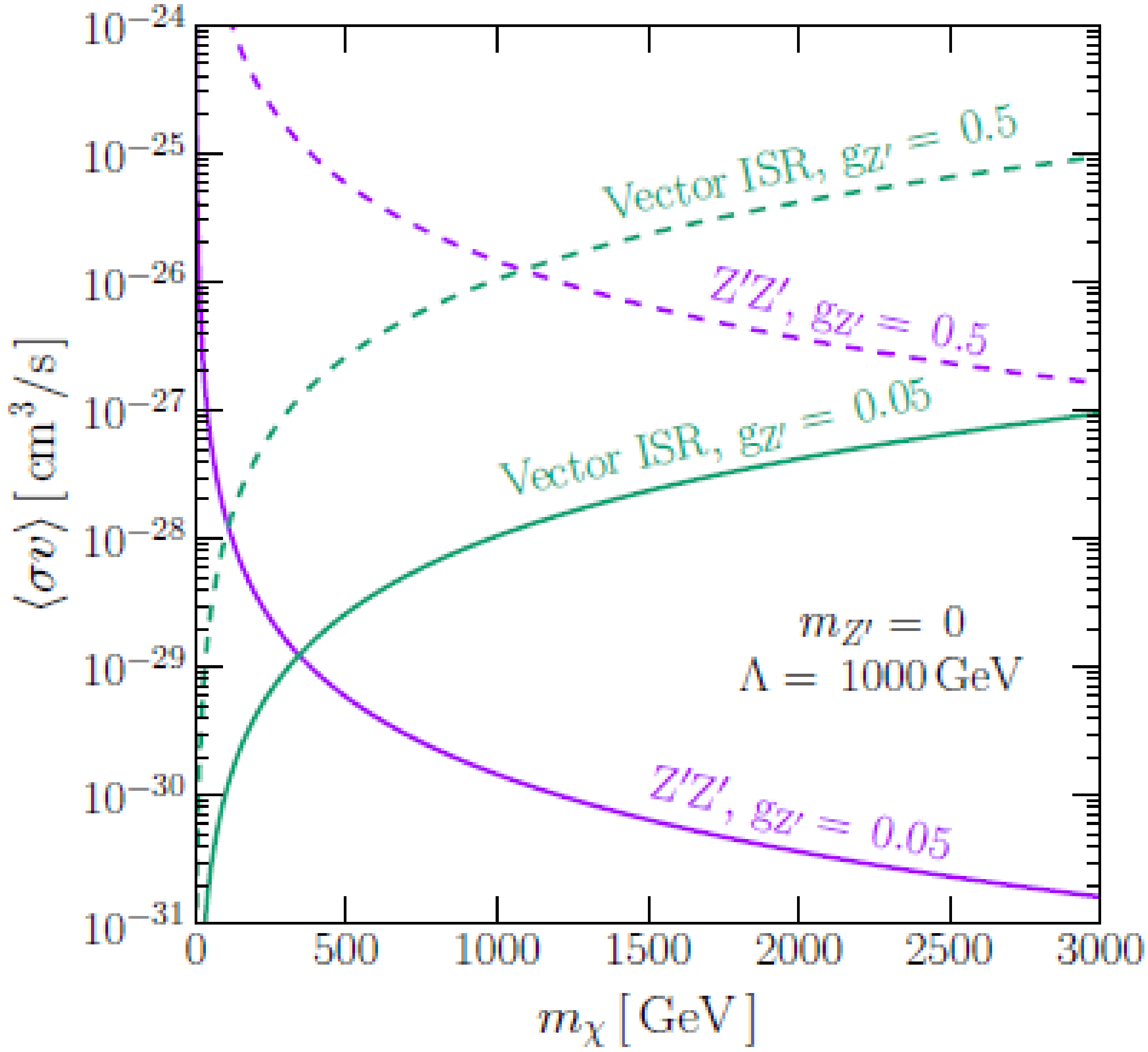
s-wave from 2 to 3 processes

$$\mathcal{L}_{\text{int}} \supset \frac{1}{\Lambda^2} \left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\overline{f}\gamma^\mu\gamma_5 f\right) + g_{Z'}\overline{\chi}\gamma^\mu\chi Z'_\mu$$

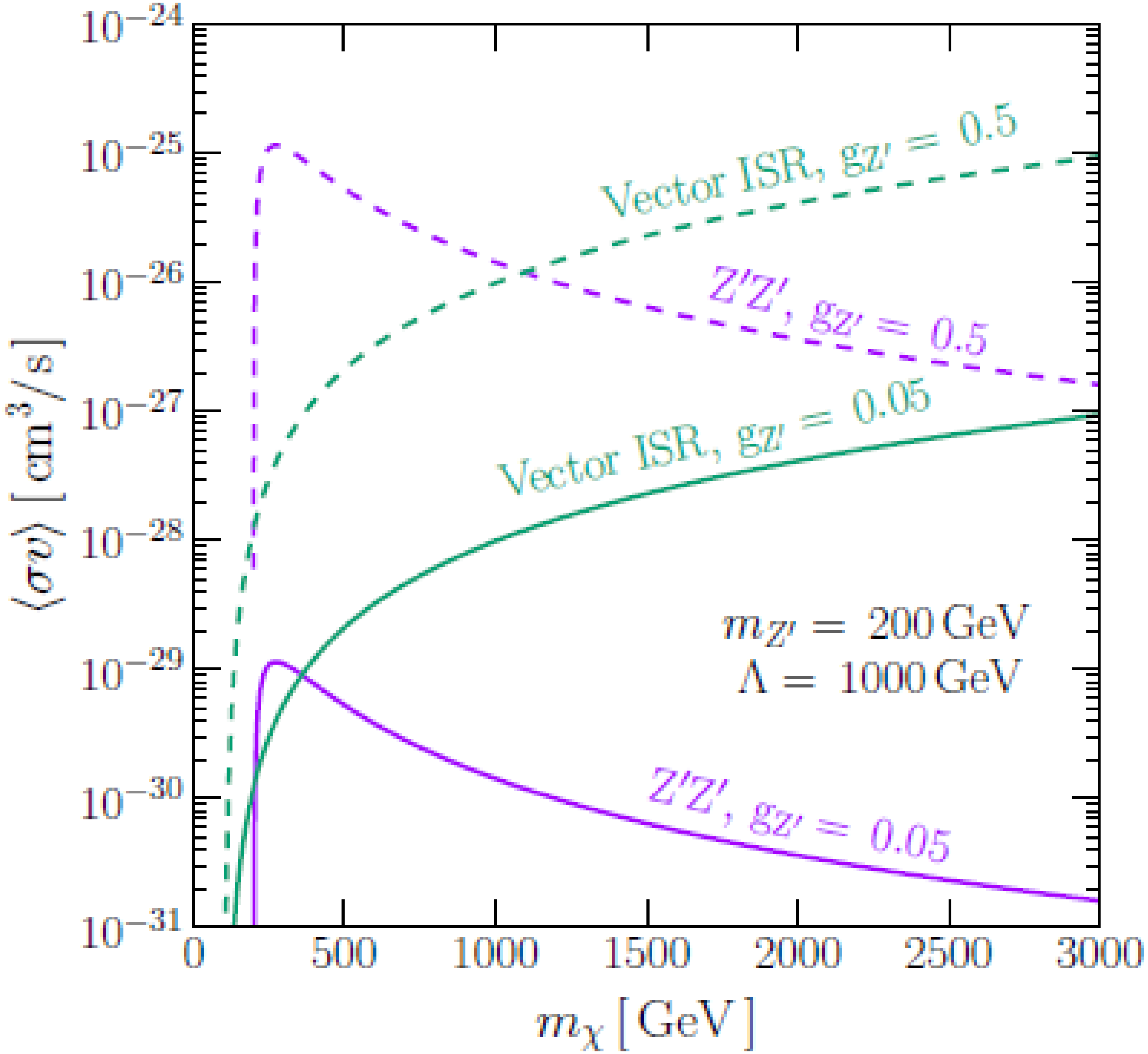




Initial state ISR of a V and two-body A-A final state



Cross-section comparisons



Cross-section comparisons

Summary

Lorentz structures with suppressed cross-sections

$$A \otimes A,\ A \otimes V,\ S \otimes S, \text{ and } S \otimes P$$

ISR of a dark vector opens an s-wave for all of these

ISR of an axial-vector opens an s-wave for $A \otimes A$ and $A \otimes V$

ISR of a pseudoscalar opens an s-wave for $S \otimes S$, and $S \otimes P$

Dark sector ISR can be the dominant annihilation channel

Future prospects: indirect detection implications and complementarity from colliders

Cross-sections

$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}(\overline{\chi}\chi)(\overline{f}f) \qquad \sigma v = \frac{v^2 m_\chi^2 \left(1 - m_f^2/m_\chi^2\right)^{3/2}}{8\pi\Lambda^4}$$

$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}(\overline{\chi}\chi)(\overline{f}f) + i\, g_\phi \phi \overline{\chi}\gamma_5 \chi$$

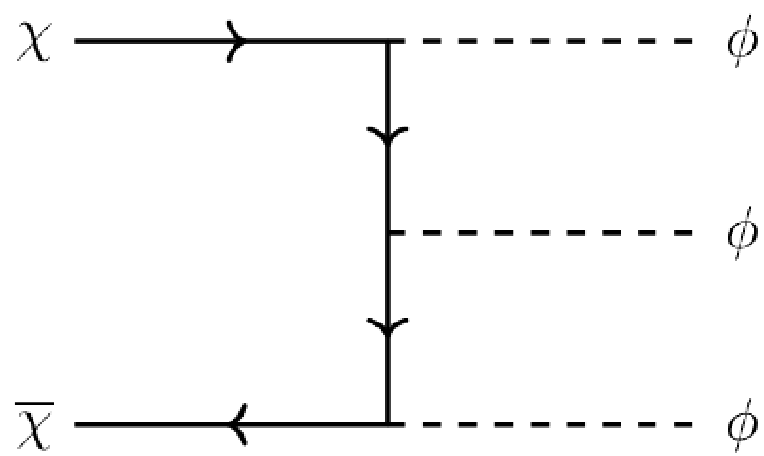
$$\langle \sigma v \rangle_{\chi\overline{\chi}\to f\overline{f}\phi} = \frac{g_\phi^2 m_\chi^2}{48\pi^3\Lambda^4} \times$$

$$\left\{ 1 + 24\rho_\phi^3 \sqrt{1-\rho_\phi^2}(5\rho_\phi^2 - 2)\tan^{-1}\frac{\sqrt{1-\rho_\phi^2}}{\rho_\phi} \right.$$

$$\left. + 21\rho_\phi^2 - 105\rho_\phi^4 + 83\rho_\phi^6 + 12\rho_\phi^2(1 - 9\rho_\phi^2 + 10\rho_\phi^4)\ln\rho_\phi \right\}$$

Cross-sections

$$\sigma v_{\overline{\chi}\chi\to\phi\phi} \simeq \frac{g_\phi^4 v^2}{384\pi m_\chi^2} \qquad \langle\sigma v\rangle_{\overline{\chi}\chi\to\phi\phi\phi} \simeq \frac{g_\phi^6(7\pi^2-60)}{1536\pi^3 m_\chi^2}$$



Cross-sections

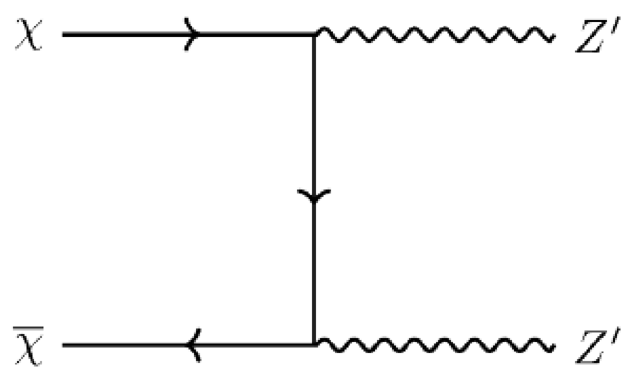
$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}(\overline{\chi}\gamma^\mu\gamma^5\chi)(\overline{f}\gamma^\mu\gamma^5 f) \qquad \langle\sigma v\rangle_{\overline{\chi}\chi\to\overline{f}f} = \frac{m_f^2\sqrt{1-m_f^2/m_\chi^2}}{2\pi\Lambda^4}$$

$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\overline{f}\gamma^\mu\gamma_5 f\right) + g_{Z'}\overline{\chi}\gamma^\mu\chi Z'_\mu$$

$$\langle\sigma v\rangle_{\overline{\chi}\chi\to\overline{f}fZ'} = \frac{g_{Z'}^2 m_\chi^2}{36\pi^3\Lambda^4}\times$$
$$\Bigg\{4 + 24\rho_{Z'}^3(1+5\rho_{Z'}^2)\sqrt{1-\rho_{Z'}^2}\tan^{-1}\frac{\sqrt{1-\rho_{Z'}^2}}{\rho_{Z'}}$$
$$-27\rho_{Z'}^2 - 60\rho_{Z'}^4 + 83\rho_{Z'}^6 + 12\rho_{Z'}^4(10\rho_{Z'}^2-3)\ln\rho_{Z'}\Bigg\}$$

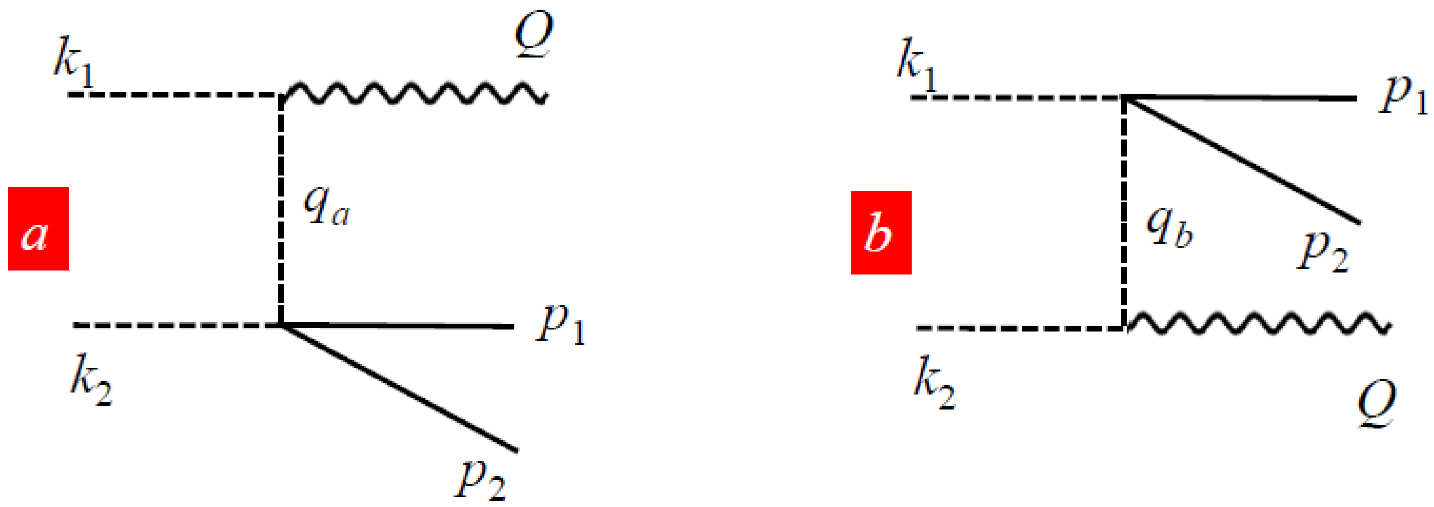
Cross-sections

$$\langle \sigma v \rangle_{\overline{\chi}\chi \to Z' Z'} = \frac{g_{Z'}^4 \left(1 - 4\rho_{Z'}^2\right)^{\frac{3}{2}}}{16\pi m_\chi^2 (1 - 2\rho_{Z'}^2)^2}$$



Scalar dark matter with p-wave suppressed annihilations can also be lifted by dark vector ISR

$$i(S^\dagger \partial_\mu S - \partial_\mu S^\dagger S)\bar{f}\gamma^\mu f$$



$$\sigma v = \frac{g_{Sf}^2 m_S^2}{192\pi^3\Lambda^4}[1 + 4\rho^2(3\ln(\rho) + 4) + 12\rho^3\sqrt{1-\rho^2}(2\sin^{-1}(\rho) - \pi) - \rho^4(17 + 24\ln(\rho))]$$

Mass/coupling relations

$$m_{Z'} = g_\chi w,$$
$$m_\chi = \frac{1}{\sqrt{2}} y_\chi w,$$
$$m_s^2 \simeq -2\mu_s^2,$$
$$m_h^2 \simeq -2\mu_h^2 \ .$$

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

$$\sqrt{s} < \frac{\pi\, m_{Z'}^2}{(g_{\rm DM}^A)^2\, m_{\rm DM}}$$

$$m_s < \frac{\pi\, m_{Z'}^2}{(g_{\rm DM}^A)^2\, m_{\rm DM}}$$

$$m_s \leq \frac{\sqrt{\pi}\, m_{Z'}}{g_{\rm DM}^A} = \sqrt{4\pi} w$$

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

F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, *JHEP* (2016), 1510.02110

N.F. Bell, Y. Cai, and R.K. Leane, *JCAP* (2017), 1610.03063