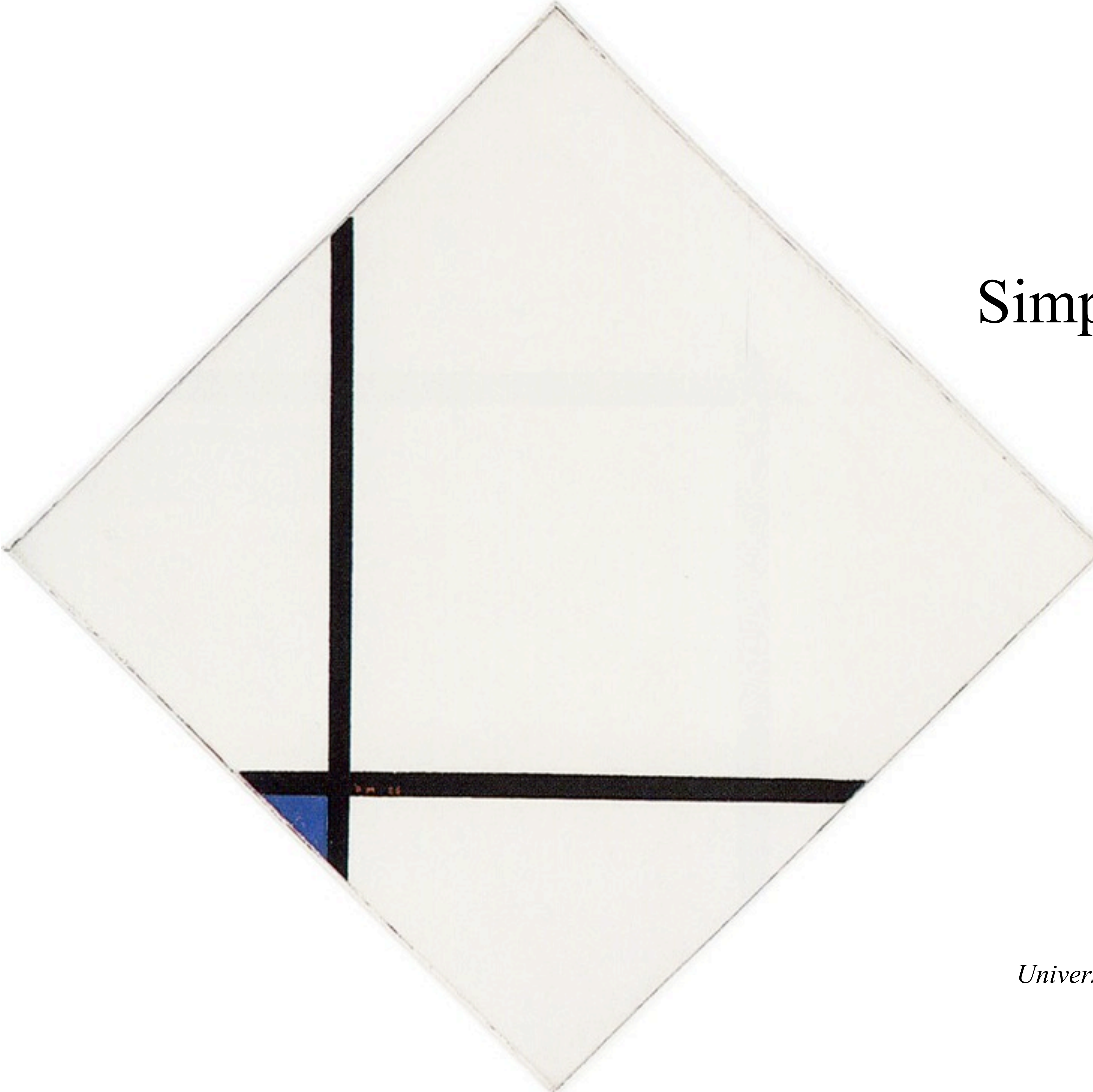
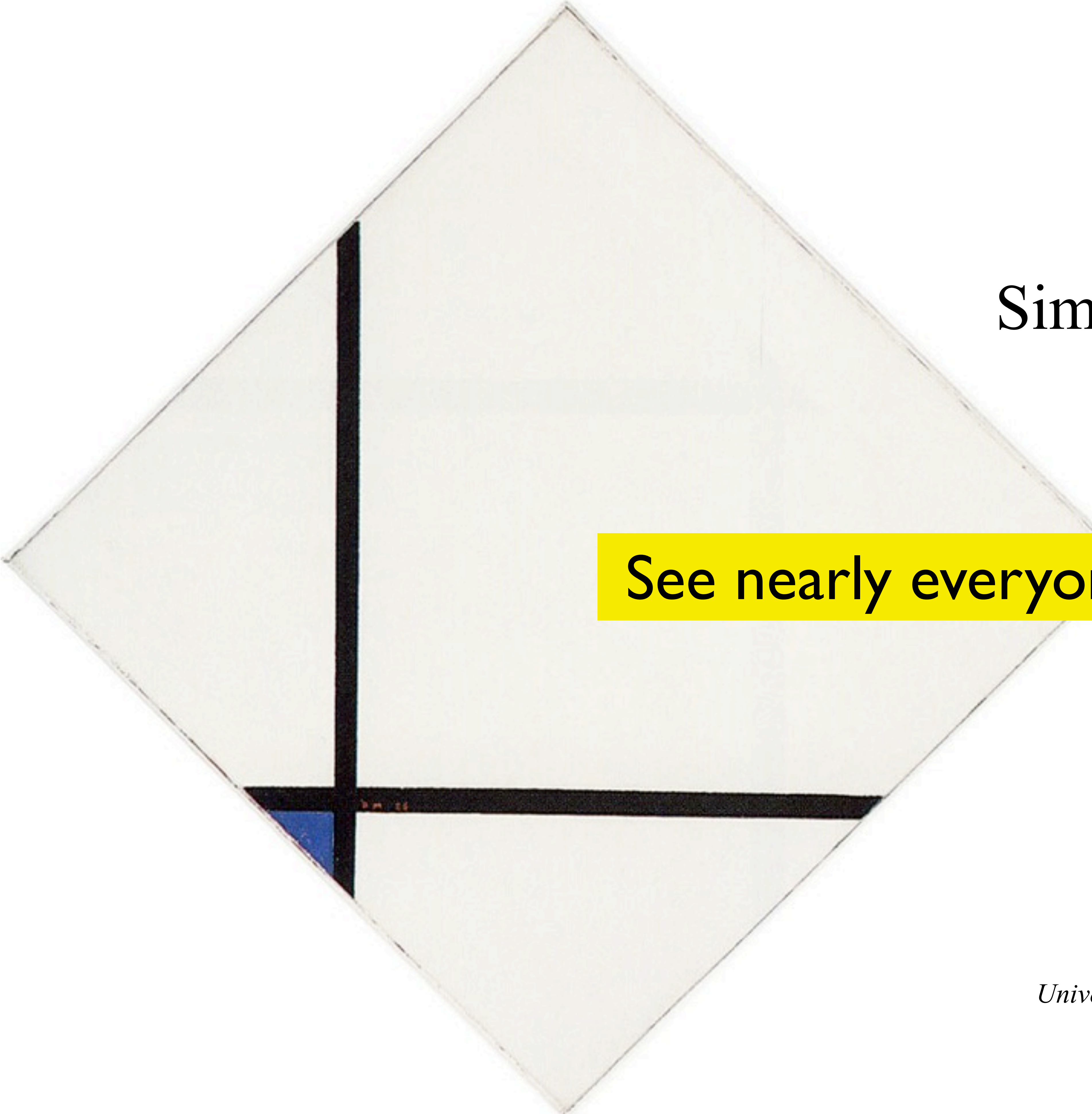


Simplified Models

James Dent
University of Louisiana at Lafayette



Simplified Models

See nearly everyone else's talk

James Dent
University of Louisiana at Lafayette

Outline

An example

Properties

Portals

Mapping onto Direct Detection

Neutrino Floor

Connecting Scales

An introductory example

contact interactions take the form

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

heavy mediator and couplings

$$\Lambda = \frac{M}{\sqrt{g_1 g_2}}$$

The validity may break down even before hitting the scale of new physics

for example: unitarity violation from W_L scattering

Various contact operators have been studied that do not respect $SU(2)_L$

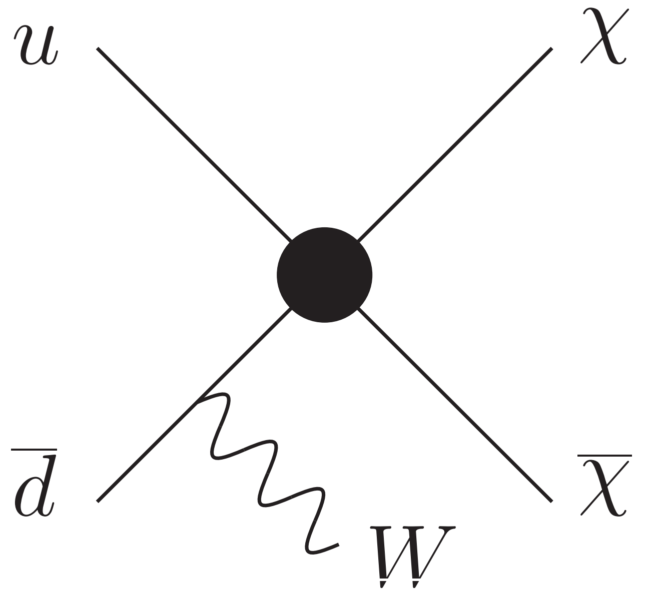
$$\frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}q\right) = \frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}_L q_R + h.c.\right)$$

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{u}\gamma_\mu u + \xi\overline{d}\gamma_\mu d\right)$$

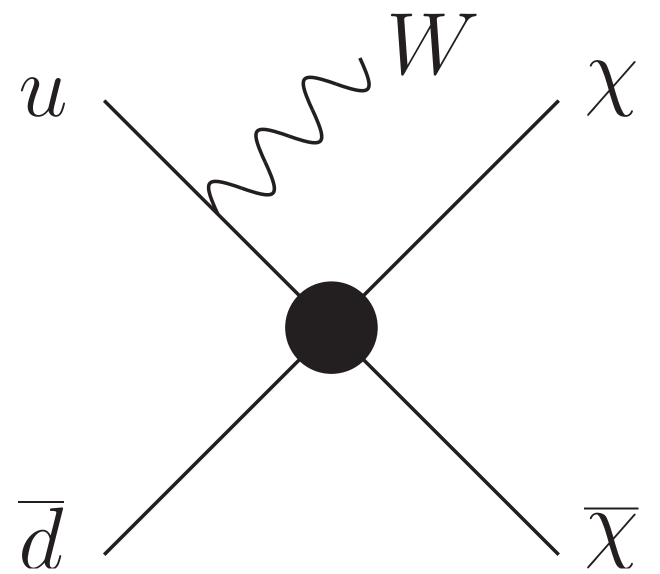
which respects $SU(2)_L$ for $\xi = 1$

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}\gamma_\mu q\right) = \frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}_L\gamma_\mu q_L + \overline{q}_R\gamma_\mu q_R\right)$$

N.F. Bell, Y. Cai, JBD, R.K. Leane, and T.J. Weiler,1503.07874



(a)$\mathcal{M}_1$



(b)$\mathcal{M}_2$

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{u}\gamma_\mu u+\xi\overline{d}\gamma_\mu d\right)$$

enhancement for $\xi \neq 1$

due to longitudinal *W* production

$$\mathcal{M}_1^\alpha = \frac{1}{\Lambda^2}\left[\bar{v}(p_2)\gamma^\alpha\frac{-g_W}{\not{p}_2-\not{q}}\gamma^\mu\frac{P_L}{\sqrt{2}}u(p_1)\right]\left[\bar{u}(k_1)\gamma_\mu v(k_2)\right]$$

$$\mathcal{M}_2^\alpha = \frac{\xi}{\Lambda^2}\left[\bar{v}(p_2)\gamma^\mu\frac{g_W}{\not{p}_1-\not{q}}\gamma^\alpha\frac{P_L}{\sqrt{2}}u(p_1)\right]\left[\bar{u}(k_1)\gamma_\mu v(k_2)\right]$$

at high energy the polarization vector is

$$\epsilon^L_\alpha = \frac{q_\alpha}{m_W}+\mathcal{O}\left(\frac{m_W}{E}\right)\sim\frac{\sqrt{s}}{m_W}$$

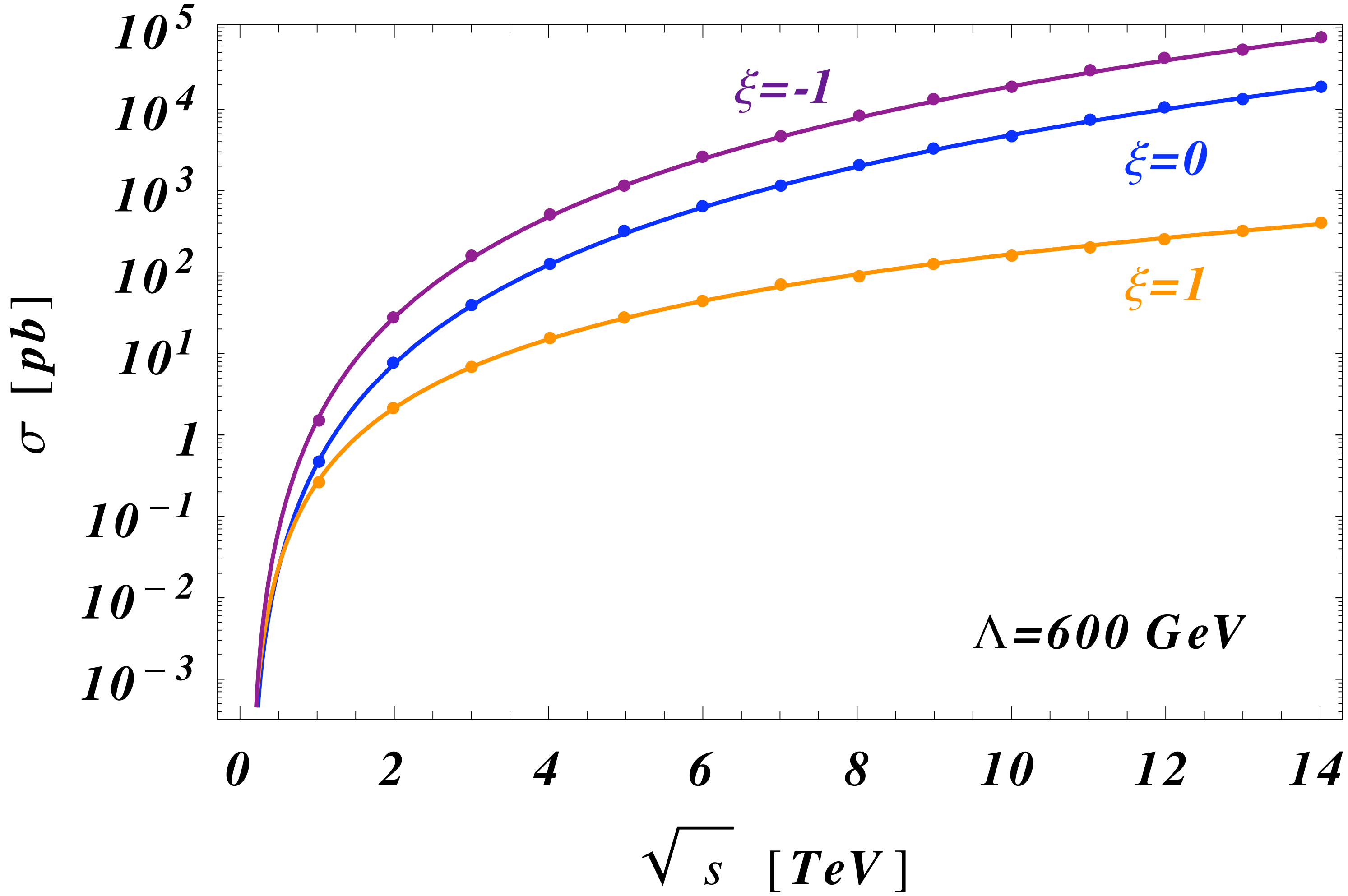
which contributes to the polarization sum

$$\sum_\lambda \epsilon^\lambda_\alpha \epsilon^{\lambda\,*}_\beta = -g_{\alpha\beta}+\frac{q_\alpha q_\beta}{m_W^2}$$

$$\epsilon^L_\alpha\epsilon^{L\,*}_\beta \approx q_\alpha q_\beta/m_W^2 \sim s/m_W^2$$

Ward identity $\mathcal{M} \equiv \mathcal{M}^{\alpha} \epsilon^{\lambda}_{\alpha}(q) \equiv (\mathcal{M}^{\alpha}_{1} + \mathcal{M}^{\alpha}_{2}) \epsilon^{\lambda}_{\alpha}(q)$

$$q_{\alpha} \mathcal{M}^{\alpha} = \frac{g_W}{\Lambda^2} \left[\bar{v}(p_2) \, (1 - \xi) \, \gamma^{\mu} \frac{P_L}{\sqrt{2}} u(p_1) \right] [\bar{u}(k_1) \gamma_{\mu} v(k_2)]$$



At LHC energies the cross sections are dominated by the unphysical terms arising from the longitudinal polarization

unitarity violation arises $s \gg m_W^2$

$$q_{\alpha} q_{\beta} / m_W^2 \sim s / m_W^2$$

A simplified model

$$\mathcal{L}_{\rm int} = f\overline{Q_L}\eta\chi_R + h.c$$
$$= f_{ud}\left(\eta_u\overline{u}_L + \eta_d\overline{d}_L\right)\chi_R + h.c.$$

M. Garny, A. Ibarra, S. Vogl, 1105.5367

with scalar potential

$$V = m_1^2(\Phi^\dagger\Phi) + \frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + m_2^2(\eta^\dagger\eta) + \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2$$
$$+ \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi).$$

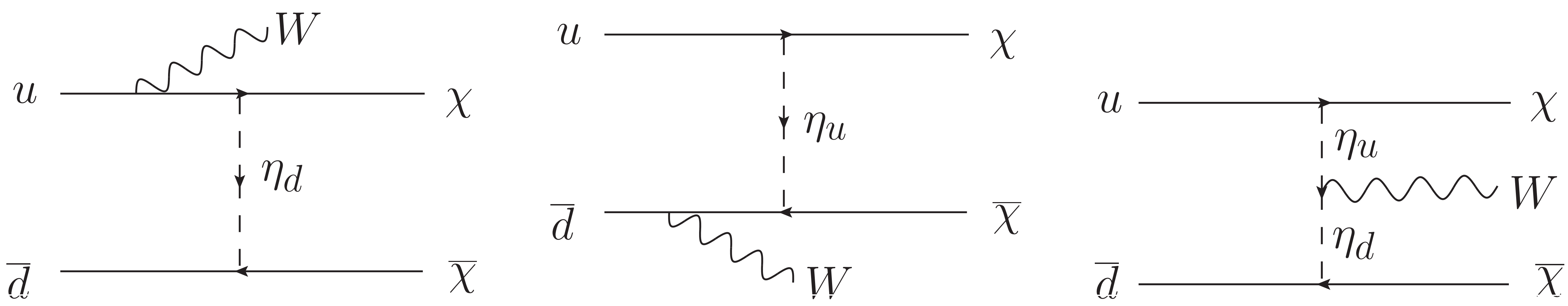
$m_1^2 < 0$ and $m_2^2 > 0$ Higgs obtains a vev

Mass splitting controlled by v_{EW}

$$m_{\eta_d}^2 = m_2^2 + (\lambda_3 + \lambda_4)v_{\rm EW}^2,$$
$$m_{\eta_u}^2 = m_2^2 + \lambda_3 v_{\rm EW}^2\ ,$$

$$\xi = 1/(1+\delta m_\eta^2/\Lambda^2) = 1/(1+\lambda_4\, v_{EW}^2/\Lambda^2)$$

Now mono-W proceeds through the gauge invariant diagrams



(a) (b) (c)

(c) same dim-8 order as the gauge violating effects and W_L only arises for the case of mass splitting

other completions can produce different values of

For example, charging DM and the SM Higgs under a new *U(1)*, and integrating out the gauge boson provides a negative ξ

Aspects of Simplified Models

Resolve the mediator, with mediator searches becoming a priority at colliders

Respect gauge invariance and unitarity, providing further model constraints

Flavor Violation constraints (MFV)

Provide a bridge between contact operators and complete models

Allow a focus on a smaller set of parameters

Lend themselves to a systematic study

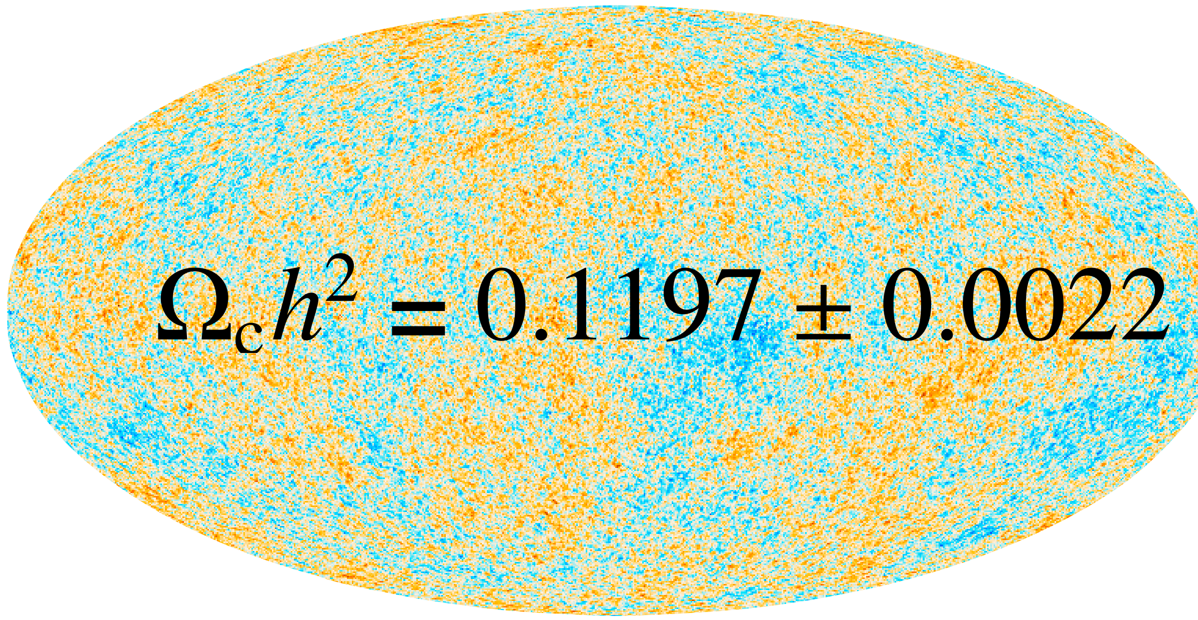
D. Abercrombie, et al., 1507.00966   J. Abdallah, et al., 1506.03116

Dark matter types

Scalar | Fermion | Vector

Mediator types

Scalar/ Pseudoscalar | Vector/Axial Vector | Fermionic



Channels and interaction types

s-channel | t/u-channel

s-wave/p-wave | nuclear response and suppression | interference

Collider Signals

X+MET | jets | leptons | ...

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

S

ϕ

$$\lambda \phi^2 |H|^2$$

H

ℓ

χ

η

q

X^μ

ψ

Z^μ

g

Z'_μ

$$\delta m^2\, Z^\mu Z'_\mu - \frac{1}{2} \sin\epsilon\, F'^{\mu\nu} B_{\mu\nu}$$

$\mathcal{J}_\mu^{\mathrm{EM}}$

S

χ

X^μ

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

ϕ

$$\lambda \phi^2 |H|^2$$

H

ℓ

η

q

ψ

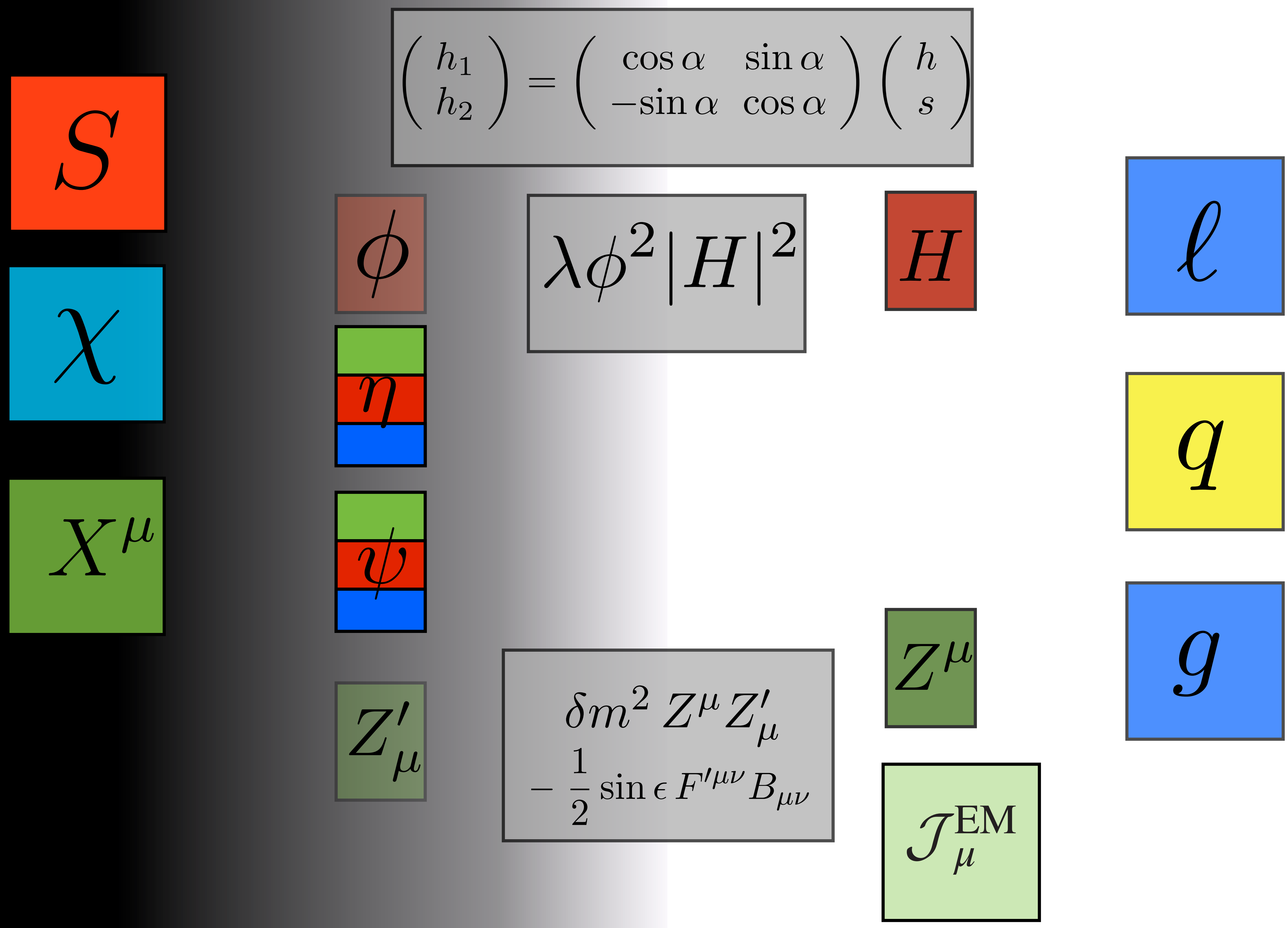
Z^μ

g

Z'_μ

$$\delta m^2 \, Z^\mu Z'_\mu - \frac{1}{2} \sin\epsilon \, F'^{\mu\nu} B_{\mu\nu}$$

$\mathcal{J}^{\mathrm{EM}}_\mu$


S
χ
X^μ
$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$
ϕ
$\lambda\phi^2|H|^2$
H
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g
Z^μ
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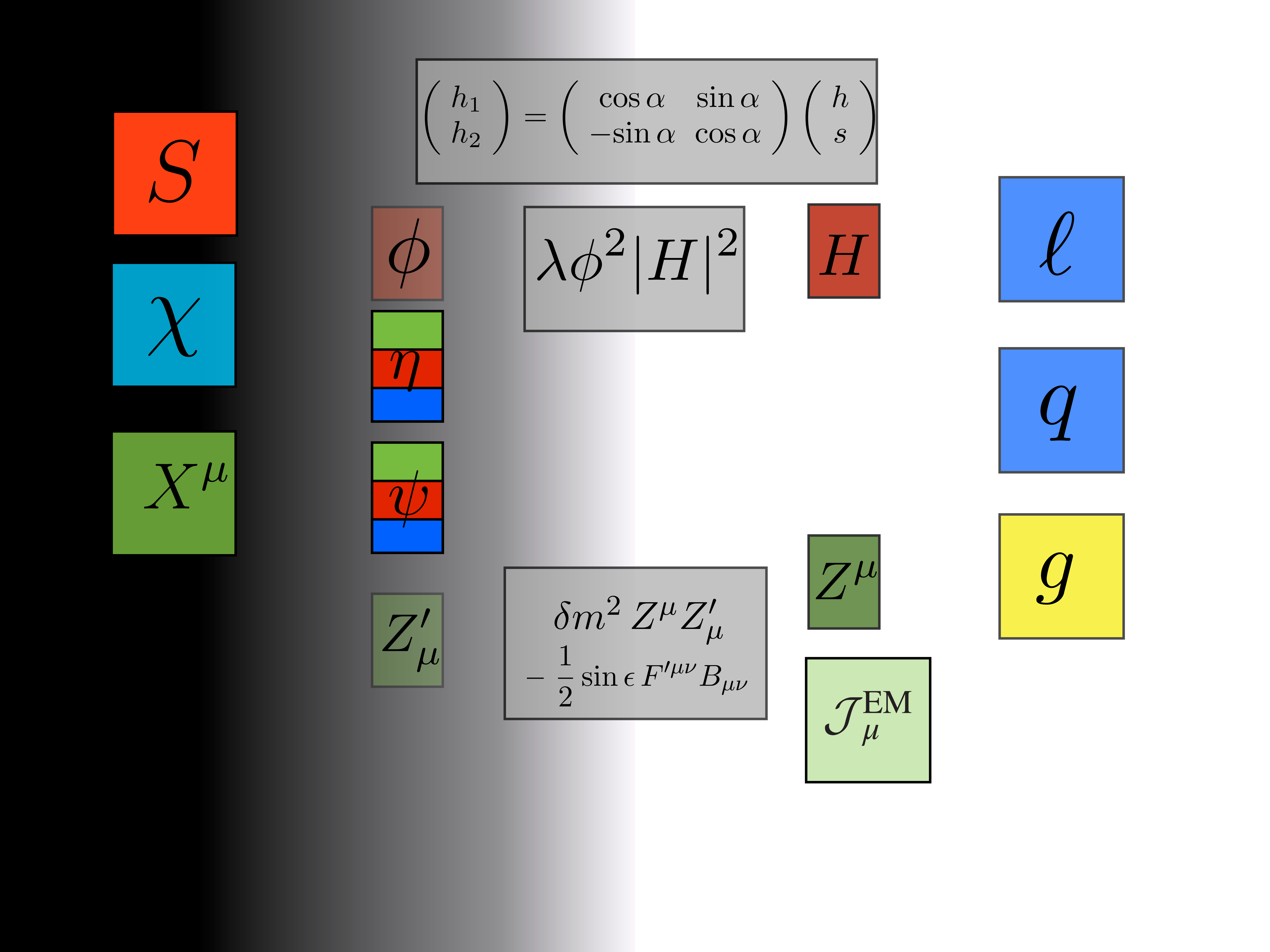
$\delta m^2 \, Z^\mu Z'_\mu - \frac{1}{2}\sin\epsilon \, F'^{\mu\nu} B_{\mu\nu}$
$\mathcal{J}_\mu^{\mathrm{EM}}$


$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$
S
χ
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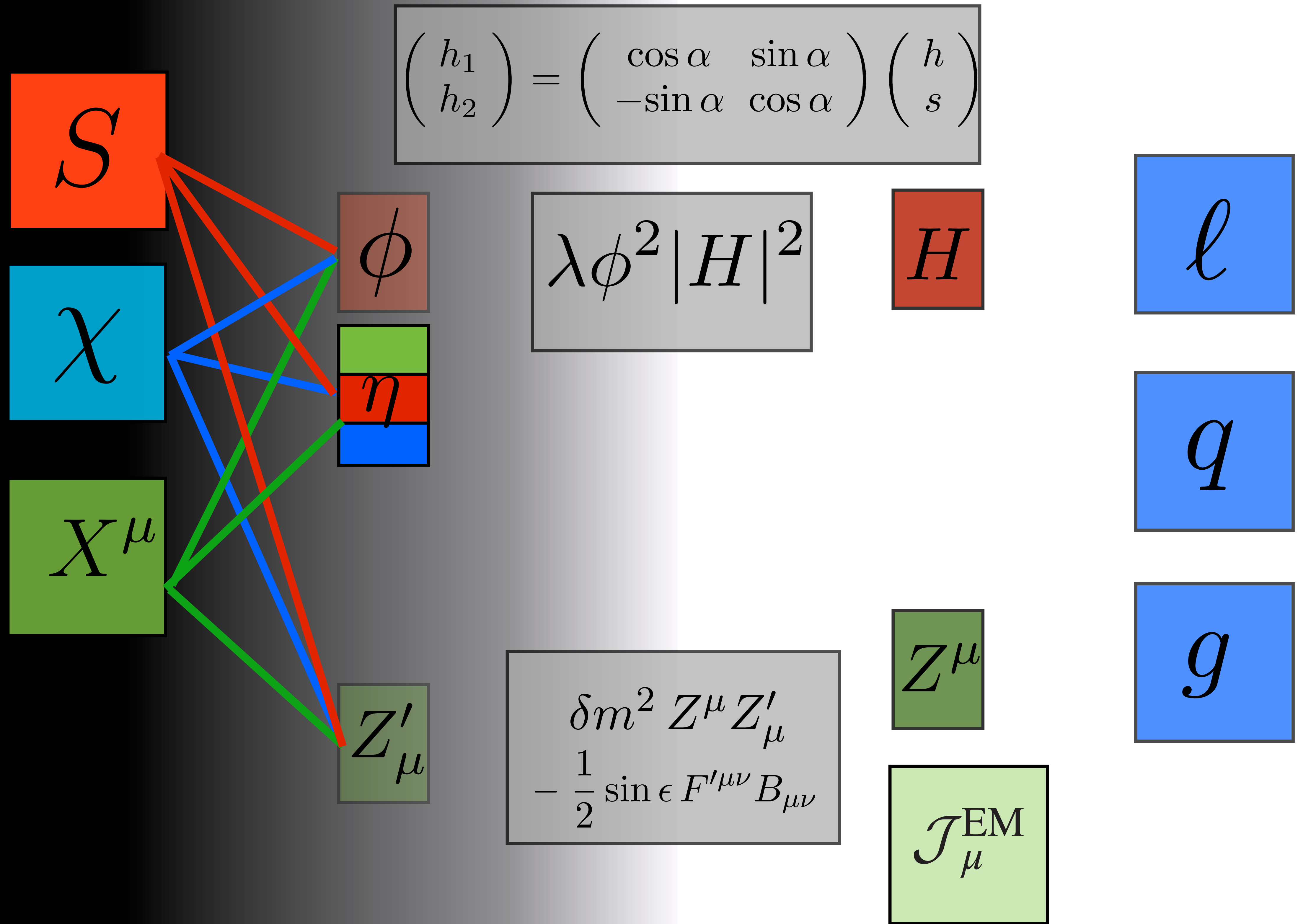
$\lambda\phi^2|H|^2$
H
ℓ
q
g
Z^μ
$$\delta m^2\, Z^\mu Z'_\mu - \frac{1}{2}\sin\epsilon\, F'^{\mu\nu} B_{\mu\nu}$$
$\mathcal{J}^{\mathrm{EM}}_\mu$


S
χ
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$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$
$\lambda\phi^2|H|^2$
H
$\delta m^2 Z^\mu Z'_\mu - \frac{1}{2}\sin\epsilon\, F'^{\mu\nu} B_{\mu\nu}$
Z^μ
$\mathcal{J}^{\text{EM}}_\mu$
ℓ
q
g

DM-SM Connections

$$\mathcal{L}_{\rm scalar} \supset -\frac{1}{2} m_{\rm MED}^2 S^2 - g_{\rm DM} S\, \bar{\chi}\chi - \sum_q g_{SM}^q S\, \bar{q}q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm pseudo-scalar} \supset -\frac{1}{2} m_{\rm MED}^2 P^2 - i g_{\rm DM} P\, \bar{\chi}\gamma^5\chi - \sum_q i g_{SM}^q P\, \bar{q}\gamma^5 q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm vector} \supset \frac{1}{2} m_{\rm MED}^2 Z'_\mu Z'^\mu - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_{SM}^q Z'_\mu \bar{q}\gamma^\mu q - m_{\rm DM}\bar{\chi}\chi\,,$$

$$\mathcal{L}_{\rm axial} \supset \frac{1}{2} m_{\rm MED}^2 Z''_\mu Z''^\mu - g_{\rm DM} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q - m_{\rm DM}\bar{\chi}\chi$$

$$\{g_{DM}, g_{SM}, m_{DM}, m_{MED}, \Gamma\}$$

DM Annihilation

Fermion/anti-fermion $C : (-1)^{L+S}$ $P : (-1)^{L+1}$

Boson/anti-boson $C : (-1)^{L+S}$ $P : (-1)^{L}$

Initial state DM

bilinear	C	P	J	state
$\bar{\psi}\psi$	+	+	0	$S=1,\ L=1$
$\imath\bar{\psi}\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^0\psi$	-	+	0	none
$\bar{\psi}\gamma^i\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\gamma^0\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^i\gamma^5\psi$	+	+	1	$S=1,\ L=1$
$\bar{\psi}\sigma^{0i}\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\sigma^{ij}\psi$	-	+	1	$S=0,\ L=1$
$\phi^\dagger\phi$	+	+	0	$S=0,\ L=0$
$\imath Im(\phi^\dagger\partial^0\phi)$	-	+	0	none
$\imath Im(\phi^\dagger\partial^i\phi)$	-	-	1	$S=0,\ L=1$
$B^\dagger_\mu B^\mu$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$\imath Im(B^\dagger_\nu\partial^0 B^\nu)$	-	+	0	none
$\imath Im(B^\dagger_\nu\partial^i B^\nu)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$\imath(B^\dagger_i B_j - B^\dagger_j B_i)$	-	+	1	$S=1,\ L=0,2$
$\imath(B^\dagger_i B_0 - B^\dagger_0 B_i)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$\epsilon^{0ijk}B_i\partial_j B_k$	+	-	0	$S=1,\ L=1$
$-\epsilon^{0ijk}B_0\partial_j B_k$	+	+	1	$S=2,\ L=2$
$B^\nu\partial_\nu B_0$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$B^\nu\partial_\nu B_i$	+	-	1	$S=1,\ L=1$

Final State fermions (...bosons)

S	L	J	$J_z = S_z$	fermion helicities
0	0	0	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	0	1	1	$f_R,\ \bar{f}_R$
1	0	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	0	1	-1	$f_L,\ \bar{f}_L$
0	1	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	1	0	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	1	1	1	$f_R,\ \bar{f}_R$
1	1	1	0	-
1	1	1	-1	$f_L,\ \bar{f}_L$
1	2	1	1	$f_R,\ \bar{f}_R$
1	2	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	2	1	-1	$f_L,\ \bar{f}_L$

J. Kumar and D. Marfatia, 1305.1611

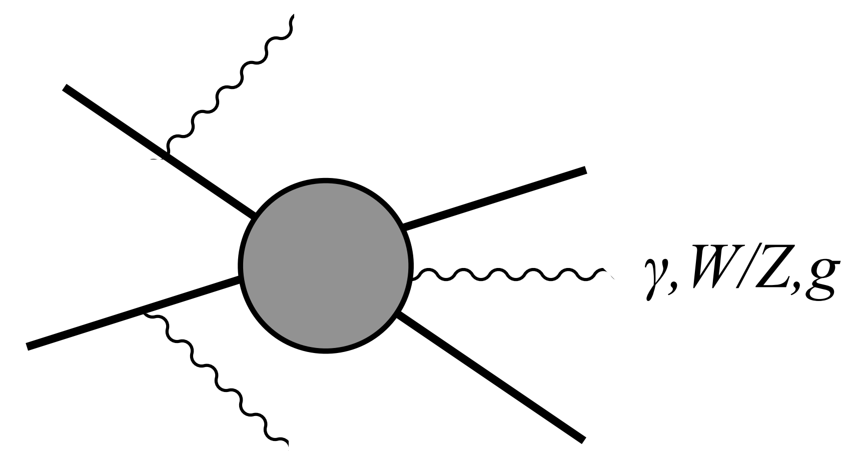
Interaction Structure	s-wave?
$\bar{X}X\bar{q}q$	No
$\bar{X}\gamma^5 X\bar{q}q$	Yes
$\bar{X}X\bar{q}\gamma^5 q$	No
$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	Yes
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	Yes
$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	No
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	Yes
$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$\propto m_f^2/m_X^2$
$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	Yes
$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	Yes
$\phi^\dagger\phi\bar{q}q$ or $\phi^2\bar{q}q$	Yes
$\phi^\dagger\phi\bar{q}\gamma^5 q$ or $\phi^2\bar{q}\gamma^5 q$	Yes
$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu q$	No
$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	No
$B_\mu^\dagger B^\mu\bar{q}q$ or $B_\mu B^\mu\bar{q}q$	Yes
$B_\mu^\dagger B^\mu\bar{q}\gamma^5 q$ or $B_\mu B^\mu\bar{q}\gamma^5 q$	Yes
$B_\nu^\dagger\partial_\mu B^\nu\bar{q}\gamma^\mu q$	No
$B_\nu^\dagger\partial_\mu B^\nu\bar{q}\gamma^\mu\gamma^5 q$	No
$(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu} q$	Yes
$(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu}\gamma^5 q$	Yes
$B_\nu^\dagger\partial^\nu B_\mu\bar{q}\gamma^\mu q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$	No
$B_\nu^\dagger\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$	$\propto m_f^2/m_X^2$
$\epsilon^{\mu\nu\rho\sigma}B_\nu^\dagger\partial_\rho B_\sigma\bar{q}\gamma_\mu q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No
$\epsilon^{\mu\nu\rho\sigma}B_\nu^\dagger\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$	No

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

s-wave: v^0

chirality suppression

(chirality suppression can be lifted in some 2 to 3 processes with IVB)



γ L. Bergstrom, PLB **225** (1989)

g R. Flores, K.A. Olive, and S. Rudaz, PLB **232** (1989)

W/Z N.F. Bell, JBD, T.D.Jacques,,and T.J. Weiler, 0805.3423

this type of analysis has been applied in the simplified model framework for IDD

A. Berlin, D. Hooper, and S.D. McDermott 1404.0022

Higgs portal

Scalar singlet

ϕ

↓

Direct interaction

$$\lambda\phi^2|H|^2$$

invisible decay or $m_\phi > m_h/2$

$$\Gamma(h \to \phi\phi)$$

SI DD σ_p^{SI}

100TeV study, see: N. Craig, H. K. Lou, M. McCullough, and A. Thlapillil, 1412.0258

Higgs portal

Scalar singlet

ϕ

Direct interaction

$$\lambda \phi^2 |H|^2$$

invisible decay

$$\Gamma(h \to \phi\phi)$$

SI DD $\sigma_p^{\rm SI}$

Fermion singlet

+

Scalar singlet mediator

scalar mixing

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

vevs $\langle S \rangle$ $\langle H \rangle$

$$\Gamma(H_1 \to \chi\bar{\chi})$$

$$\Gamma(H_2 \to XX) = \sin^2\alpha \Gamma(H_1 \to XX)\Big|_{m_{H_1} \to m_{H_2}}$$

Universal suppression of SM couplings

$$\mathcal{L}_{\rm int} = -(H_1 \cos\alpha + H_2 \sin\alpha) \left[\sum_f \frac{m_f}{v_H} \bar{f} f - \frac{2m_W^2}{v_H} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_H} Z_\mu Z^\mu \right]$$

$$+ \lambda (H_1 \sin\alpha - H_2 \cos\alpha) \bar{\chi}\chi$$

$\sigma_p^{\rm SI}$

interference effects

Higgs portal

Scalar singlet

ϕ

Direct interaction

$$\lambda \phi^2 |H|^2$$

invisible decay

$$\Gamma(h \to \phi\phi)$$

SI DD $\sigma_p^{\rm SI}$

Fermion singlet

+

Scalar singlet mediator

scalar mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

vevs $\langle S \rangle$ $\langle H \rangle$

Fermion singlet/doublet

Majorana Dirac

Fermion doublet/triplet

Majorana Dirac

100 TeV: A. Freitas, S. Westhoff, and J. Zupan, 1506.04149.

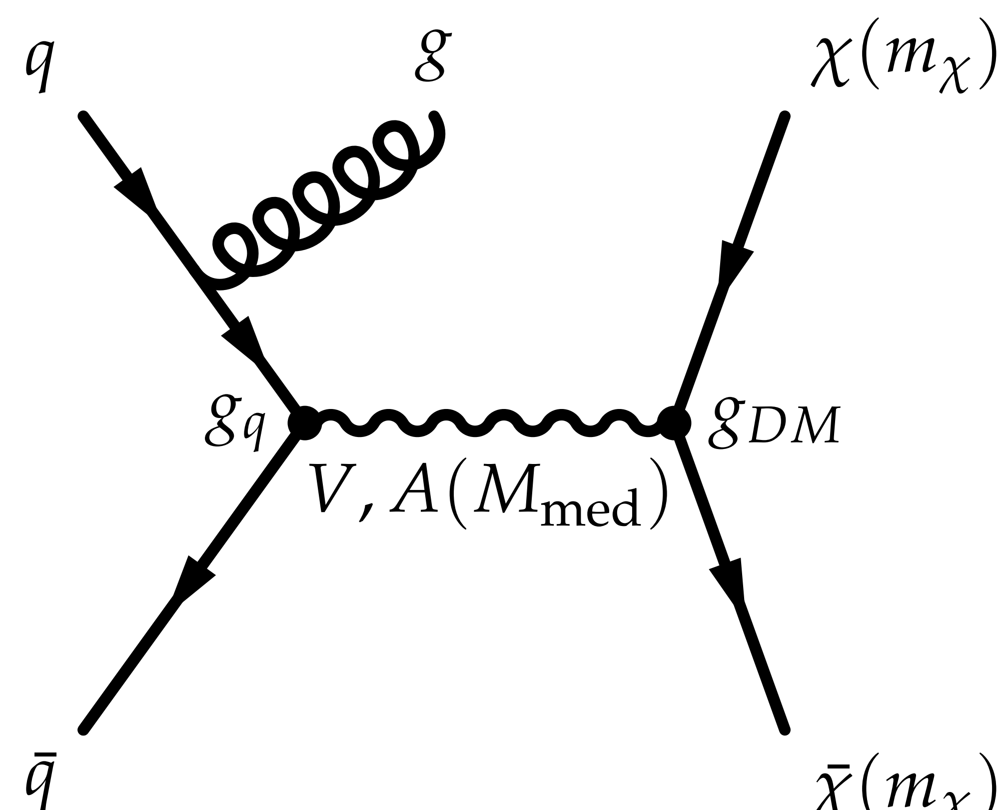
Vector mediator
s-channel interactions

Introduce a new gauge group $U(1)'$ with general interactions

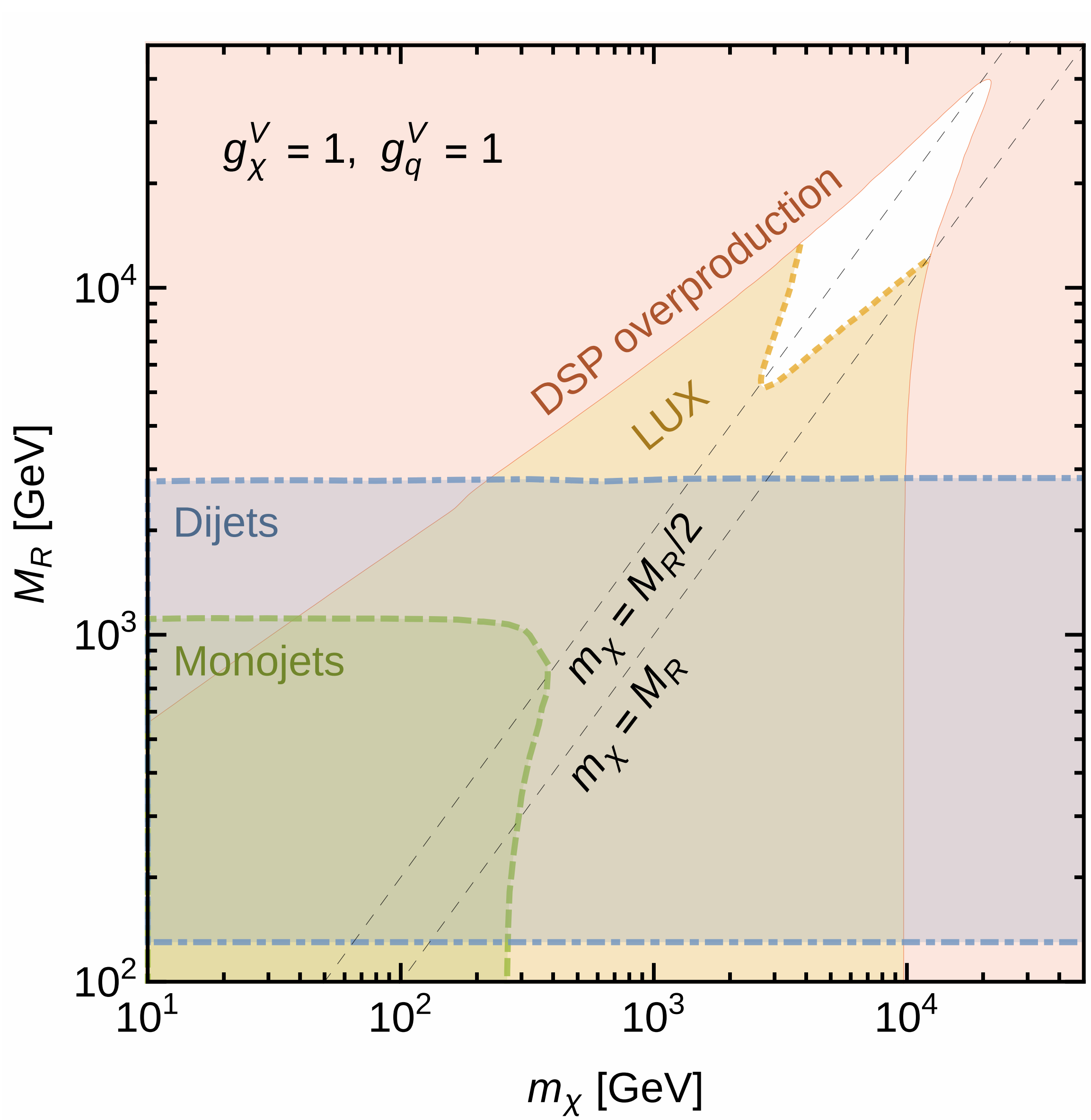
$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\,\bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\,\bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

$$\mathcal{L} = -\sum_{q,\ell,\nu} Z'_\mu \bar{f}\gamma^\mu (g_f^V + g_f^A \gamma_5) f - i g_S Z'_\mu (S^* \partial^\mu S - S \partial^\mu S^*)$$

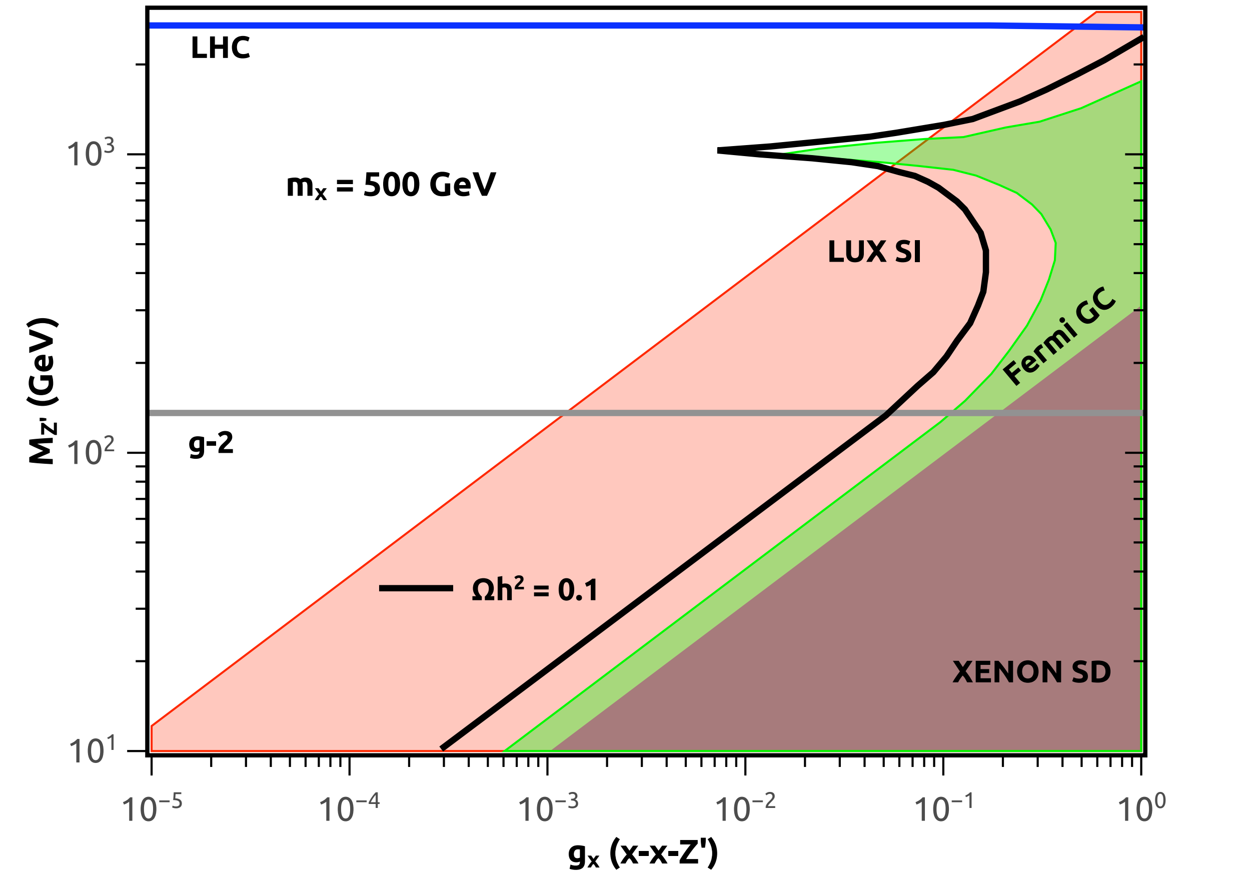
SM **V-V** DM
SM **A-V** DM
SM **V-A** DM
SM **A-A** DM
SM mixture DM



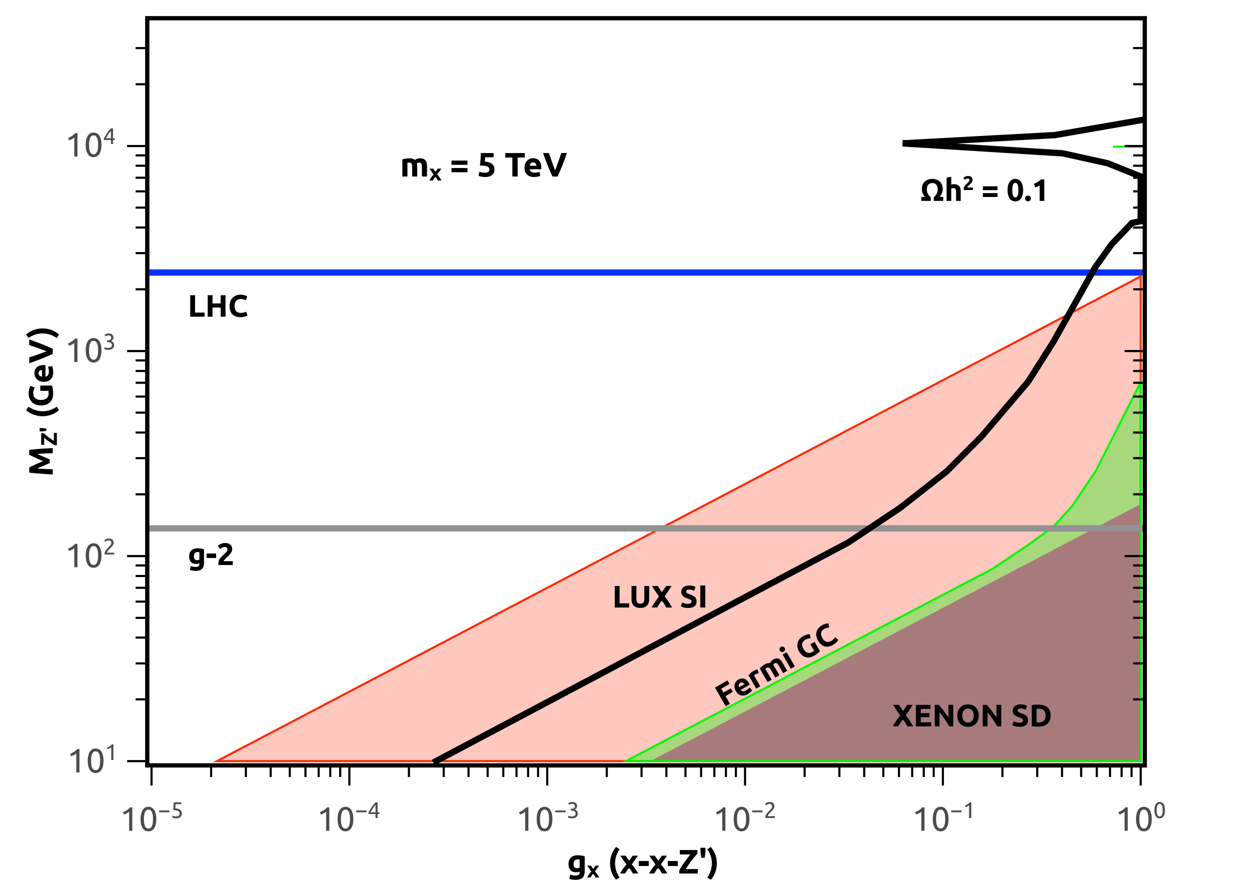
The vector-vector couplings are highly constrained already through SI direct detection bounds from LUX, LHC, and thermal abundance constraints.



M. Chala, F. Kahlhoefer, M. McCullough, G. Nardini, and K. Schmidt-Hoberg, 1503.05916



A. Alves, A. Berlin, S. Profumo, and F.S. Queiroz, 1501.03490



For a non-zero axial coupling of the new vector to fermions unitarity violation in $Z'_L Z'_L$ scattering will occur unless

$$\sqrt{s} \lesssim \frac{\sqrt{2}\pi m_{Z'}^2}{(g_f^A)^2 m_\psi}$$

J. Shu, 0711.2516

which will then be the bound on the mass of a dark Higgs which gives the vector its mass. Vector portal becomes vector + Higgs portal.

For fermion scattering one finds the unitarity bounds

$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m'_Z}{g_f^A}$$

M. S. Chanowitz, M. A. Furman, and I. Hinchlffe, Nucl. Phys. B153 (1979) 402

M. Chala, F. Kahlhoefer, M. McCullough, G. Nardini, and K. Schmidt-Hoberg, 1503.05916

F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, 1510.02110

For dark matter with axial charge, *q,* a scalar Higgs *S* with charge -2*q* can generate mass for the dark matter and vector

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g^A_{\rm DM}Z'^{\mu}\bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}(P_L S + P_R S^*)\psi\,,$$

$$\mathcal{L}_S = \left[(\partial^\mu + i\,g_S\,Z'^{\mu})S\right]^\dagger\left[(\partial_\mu + i\,g_S\,Z'_\mu)S\right] + \mu_s^2\,S^\dagger S - \lambda_s\left(S^\dagger S\right)^2$$

F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, 1510.02110

On the SM side, gauge invariance of the Yukawa terms implies the charge assignments

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

leading to the V and A couplings

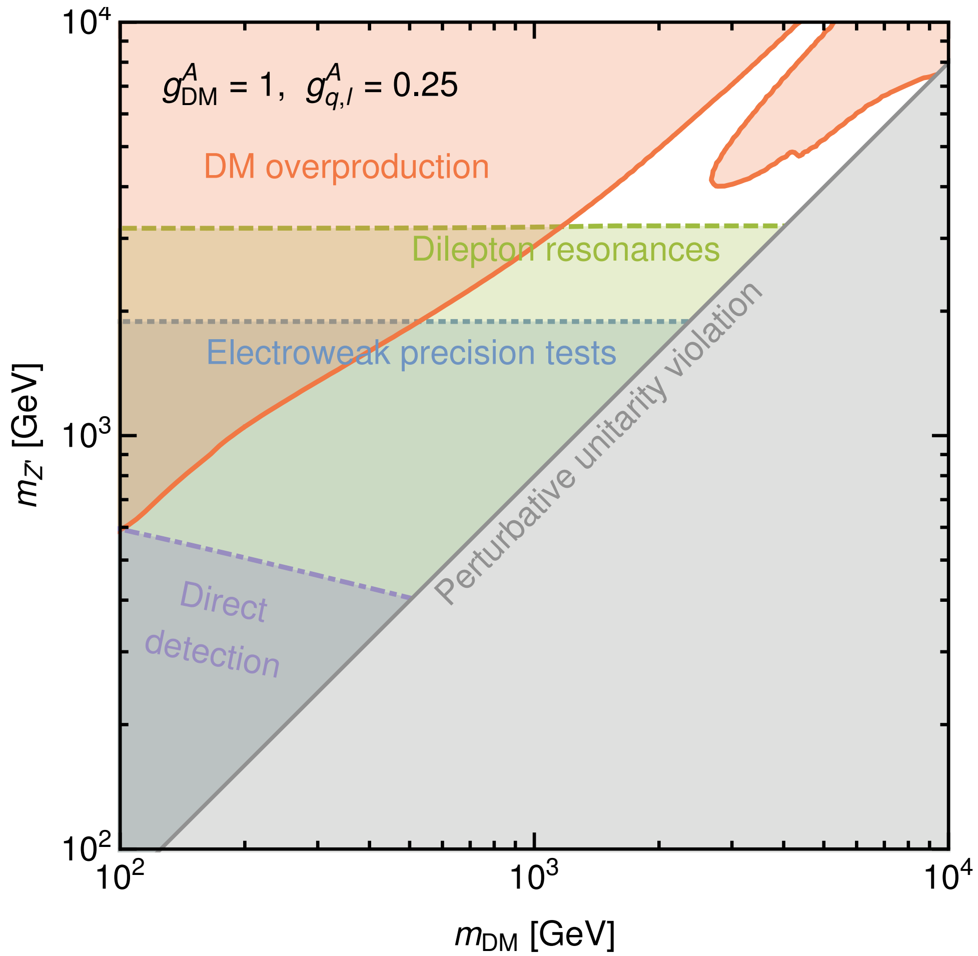
$$g_f^V = \frac{1}{2} g' (q_{f_R} + q_{f_L}), \quad g_f^A = \frac{1}{2} g' (q_{f_R} - q_{f_L})$$

$$\mathcal{L}'_{\rm SM} = \frac{1}{2} \left[(D^\mu H)^\dagger (-i\, g'\, q_H\, Z'_\mu\, H) + \text{h.c.} \right] + \frac{g'^2\, q_H^2}{2} Z'^\mu Z'_\mu H^\dagger H$$
$$- \sum_{f=q,\ell,\nu} g'\, Z'^\mu \left[q_{f_L}\, \bar{f}_L \gamma_\mu f_L + q_{f_R}\, \bar{f}_R \gamma_\mu f_R \right] ,$$

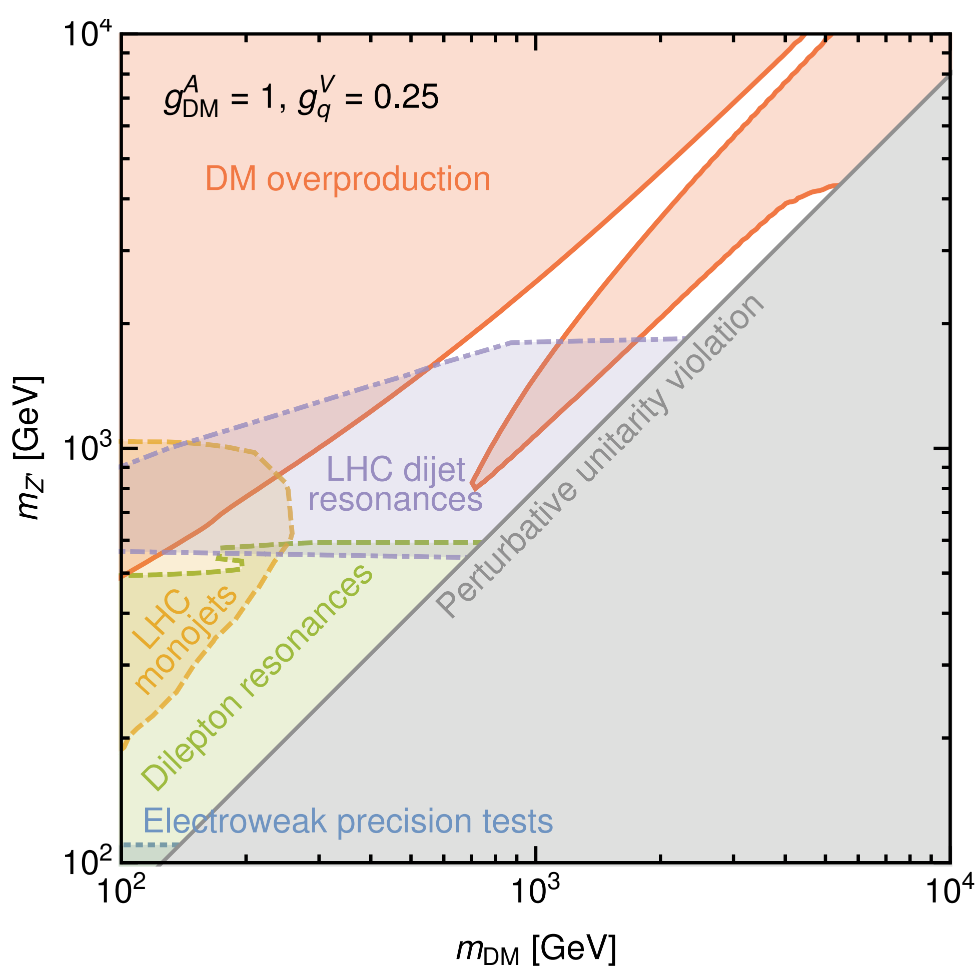
g_f^V cannot be consistently set to zero for both up and down types

mass mixing $Z - Z'$ leads to EWPT constraints

dilepton resonances become constraining

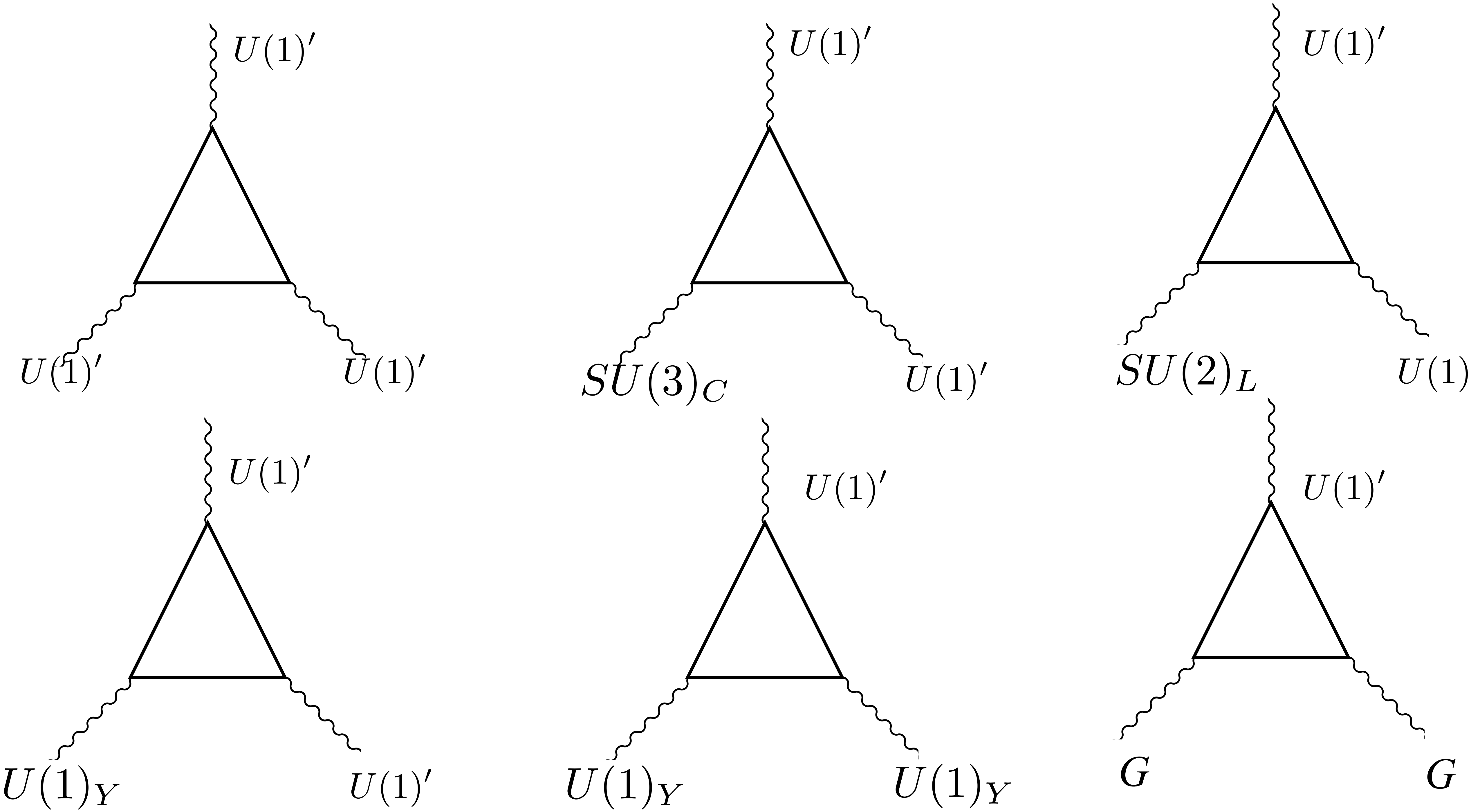


The SM(Axial) DM(Axial) scenario is highly constrained for a thermal relic



The SM(Vector) DM(Axial) scenario is highly constrained for a thermal relic

Anomalies



Anomalies should vanish, or be cancelled, for example by new fermions with which are vector-like under the SM and obey the unitarity bound on their masses

M. Carena, A. Daleo, B.A. Dobrescu, and T.P. Tait, hep-ph/0408098

B.A. Dobrescu and C. Frugiuele 1404.3947

D. Hooper, 1411.4079

Kinematics Orientation

Recoil energy O(10keV)

$$E_{\mathrm{R}} = E_{\mathrm{i}} r \frac{(1-\cos\theta)}{2}$$

$$r \equiv \frac{4\mu_A^2}{M_\chi M_A} = \frac{4 M_\chi M_A}{(M_\chi + M_A)^2}$$

Incident energy

$$E_i = \frac{m_\chi v^2}{2}$$

Max energy O(100keV)

$$E_{max} = \frac{1}{2} r m_\chi v_{esc}^2$$

Momentum Exchanged O(<100MeV)

$$q = \sqrt{2 m_T E_R}$$

Coherent scattering

$$q < \frac{1}{R_{nucleus}}$$

Min energy

$$v_{\min} = \frac{1}{\sqrt{2 E_R m_N}} \left(\frac{E_R m_N}{\mu_{\chi N}} + \delta \right)$$

WIMP-Nucleus scattering cross-section

$$\sigma_{0\mathrm{WN}} = \frac{4\mu_A^2}{\pi}\left[Zf_{\mathrm{p}} + (A-Z)f_{\mathrm{n}}\right]^2 + \frac{32G_{\mathrm{F}}^2\mu_A^2}{\pi}\frac{J+1}{J}\left(a_{\mathrm{p}}\langle S_{\mathrm{p}}\rangle + a_{\mathrm{n}}\langle S_{\mathrm{n}}\rangle\right)^2$$

Spin-independent

Spin-dependent

formulated in terms of the definition for the scattering cross-section off of a single nucleon

$$\sigma_{n,p} = \frac{\mu_{n,p}^2 f_{n,p}^2}{\pi}$$

In order to account for any momentum dependence, a **form factor** is introduced

$$\frac{d\sigma_{\mathrm{WN}}(q)}{dq^2} = \frac{1}{\pi v^2}|\mathcal{M}|^2 = \frac{\sigma_{0\mathrm{WN}}F^2(q)}{4\mu_A^2 v^2}$$

The differential recoil rate is the primary quantity of interest

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{min}} \frac{C_T}{M_T} \frac{d\sigma_T}{dE_R} \frac{\rho_0}{m_\chi} v f(v,t) d^3v$$

astrophysics input

particle input

One must also account for the detector’s efficiency and energy resolution.

It has been shown that the standard approach neglects a large set of possible non-relativistic operators beyond the SI/SD ones

$$1_\chi 1_N \qquad\qquad \vec{S}_\chi \cdot \vec{S}_N$$

Spin-independent   Spin-dependent

There also exist four more nuclear responses that arise in the most general nucleus-WIMP elastic scattering as compared to the standard approach

$$M, \Phi'', \Sigma', \Delta, \Sigma'', \tilde{\Phi}'$$

$$\vec{S}_\chi \cdot \vec{S}_N \equiv (\vec{S}_\chi \cdot \hat{q})(\vec{S}_N \cdot \hat{q}) + (\vec{S}_\chi \times \hat{q}) \cdot (\vec{S}_N \times \hat{q})$$

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, 1203.3542

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, 1211.2818

N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89 (2014)

There are fifteen combinations of these operators

Spin-independent

Spin-dependent

$\mathcal{O}_1$	$1_\chi 1_N$	$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
		$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

Two additional non-relativistic operators arise in the vector dark matter case

$$\mathcal{O}_{17} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp$$

$$\mathcal{O}_{18} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N$$

$$S_{ij} = \frac{1}{2}\left(\epsilon_i^\dagger \epsilon_j + \epsilon_j^\dagger \epsilon_i\right)$$

Effective Action   Non-rel limit   Operator Matching

j	$\mathcal{L}^j_{\text{int}}$	Nonrelativistic reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar{\chi}\chi\bar{N}N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i\bar{\chi}\chi\bar{N}\gamma^5 N$	$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$\mathcal{O}_{10}$	O/O
3	$i\bar{\chi}\gamma^5\chi\bar{N}N$	$-i\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$	O/O
4	$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$	$-\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$	E/E
5	$\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
6	$\bar{\chi}\gamma^\mu\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$\frac{\vec{q}^{\,2}}{2m_N m_{\rm M}}1_\chi 1_N + 2\left(\frac{\vec{q}}{m_\chi}\times\vec{S}_\chi + i\vec{v}^\perp\right)\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_N\right)$	$\frac{\vec{q}^{\,2}}{2m_N m_{\rm M}}\mathcal{O}_1 - 2\frac{m_N}{m_{\rm M}}\mathcal{O}_3 + 2\frac{m_N^2}{m_{\rm M}m_\chi}\left(\frac{q^2}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$	E/E
7	$\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N$	$-2\vec{S}_N\cdot\vec{v}^\perp + \frac{2}{m_\chi}i\vec{S}_\chi\cdot(\vec{S}_N\times\vec{q})$	$-2\mathcal{O}_7 + 2\frac{m_N}{m_\chi}\mathcal{O}_9$	O/E
8	$i\bar{\chi}\gamma^\mu\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$2i\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_N$	$2\frac{m_N}{m_{\rm M}}\mathcal{O}_{10}$	O/O
9	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar{N}\gamma_\mu N$	$-\frac{\vec{q}^{\,2}}{2m_\chi m_{\rm M}}1_\chi 1_N - 2\left(\frac{\vec{q}}{m_N}\times\vec{S}_N + i\vec{v}^\perp\right)\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_\chi\right)$	$-\frac{\vec{q}^{\,2}}{2m_\chi m_{\rm M}}\mathcal{O}_1 + \frac{2m_N}{m_{\rm M}}\mathcal{O}_5 - 2\frac{m_N}{m_{\rm M}}\left(\frac{\vec{q}^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6\right)$	E/E
10	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$4\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_\chi\right)\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_N\right)$	$4\left(\frac{\vec{q}^{\,2}}{m_{\rm M}^2}\mathcal{O}_4 - \frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_6\right)$	E/E
11	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar{N}\gamma^\mu\gamma^5 N$	$4i\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_\chi\right)\cdot\vec{S}_N$	$4\frac{m_N}{m_{\rm M}}\mathcal{O}_9$	O/E
12	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-\left[i\frac{\vec{q}^{\,2}}{m_\chi m_{\rm M}} - 4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_\chi\right)\right]\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_N$	$-\frac{m_N}{m_\chi}\frac{\vec{q}^{\,2}}{m_{\rm M}^2}\mathcal{O}_{10} - 4\frac{\vec{q}^{\,2}}{m_{\rm M}^2}\mathcal{O}_{12} - 4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_{15}$	O/O
13	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu N$	$2\vec{v}^\perp\cdot\vec{S}_\chi + 2i\vec{S}_\chi\cdot\left(\vec{S}_N\times\frac{\vec{q}}{m_N}\right)$	$2\mathcal{O}_8 + 2\mathcal{O}_9$	O/E
14	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$4i\vec{S}_\chi\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_N\right)$	$-4\frac{m_N}{m_{\rm M}}\mathcal{O}_9$	O/E
15	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4\vec{S}_\chi\cdot\vec{S}_N$	$-4\mathcal{O}_4$	E/E
16	$i\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}\gamma^5 N$	$4i\vec{v}^\perp\cdot\vec{S}_\chi\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_N$	$4\frac{m_N}{m_{\rm M}}\mathcal{O}_{13}$	E/O
17	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar{N}\gamma_\mu N$	$2i\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_\chi$	$2\frac{m_N}{m_{\rm M}}\mathcal{O}_{11}$	O/O
18	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}N$	$\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_\chi\left[i\frac{\vec{q}^{\,2}}{m_N m_{\rm M}} - 4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_{\rm M}}\times\vec{S}_N\right)\right]$	$\frac{\vec{q}^{\,2}}{m_{\rm M}^2}\mathcal{O}_{11} + 4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_{15}$	O/O
19	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$	$-4i\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_\chi\vec{v}_\perp\cdot\vec{S}_N$	$-4\frac{m_N}{m_{\rm M}}\mathcal{O}_{14}$	E/O
20	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_{\rm M}}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_{\rm M}}\gamma^5 N$	$4\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_\chi\frac{\vec{q}}{m_{\rm M}}\cdot\vec{S}_N$	$4\frac{m_N^2}{m_{\rm M}^2}\mathcal{O}_6$	E/E

N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89 (2014)

In the long wavelength limit these correspond to various physical interpretations

$$\Delta_{JM} \equiv \vec{M}_{JJ}^{M}(qx_i) \cdot \frac{1}{q}\vec{\nabla}_i$$

$$\Sigma'_{JM} \equiv -i\left\{\frac{1}{q}\vec{\nabla}_i \times \vec{M}_{JJ}^{M}(q\vec{x}_i)\right\} \cdot \vec{\sigma}(i)$$

$$\Sigma''_{JM} \equiv \left\{\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right\} \cdot \vec{\sigma}(i)$$

$$\tilde{\Phi}'_{JM} \equiv \left[\frac{1}{q}\vec{\nabla}_i \times \vec{M}_{JJ}^{M}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right] + \frac{1}{2}\vec{M}_{JJ}^{M}(q\vec{x}_i) \cdot \vec{\sigma}(i)$$

$$\Phi''_{JM} \equiv i\left[\frac{1}{q}\vec{\nabla}_i M_{JM}(q\vec{x}_i)\right] \cdot \left[\vec{\sigma}(i) \times \frac{1}{q}\vec{\nabla}_i\right]$$

X		$\frac{4\pi}{2J+1} W_X^{(p,p)}(0)$
M	spin-independent	Z^2
Σ''	spin-dependent (longitudinal)	$4\,\frac{J+1}{3J}\langle S_p\rangle^2$
Σ'	spin-dependent (transverse)	$8\,\frac{J+1}{3J}\langle S_p\rangle^2$
Δ	angular-momentum-dependent	$\frac{1}{2}\,\frac{J+1}{3J}\langle L_p\rangle^2$
Φ''	angular-momentum-and-spin-dependent	$\sim\langle \vec{S}_p \cdot \vec{L}_p\rangle^{2\text{a}}$

M.I. Gresham and K.M. Zurek, 1401.3739

Projection	Charge/current	Operator	Even J	Odd J
Charge	Vector charge	M_{JM}	E-E	O-O
Charge	Axial-vector charge	$\tilde{\Omega}_{JM}$	O-E	E-O
Longitudinal	Spin current	Σ''_{JM}	O-O	E-E
Transverse magnetic	”	Σ_{JM}	E-O	O-E
Transverse electric	”	Σ'_{JM}	O-O	E-E
Longitudinal	Convection current	$\tilde{\Delta}''_{JM}$	E-O	O-E
Transverse magnetic	”	Δ_{JM}	O-O	E-E
Transverse electric	”	Δ'_{JM}	E-O	O-E
Longitudinal	Spin-velocity current	Φ''_{JM}	E-E	O-O
Transverse magnetic	”	$\tilde{\Phi}_{JM}$	O-E	E-O
Transverse electric	”	$\tilde{\Phi}'_{JM}$	E-E	O-O

Within this framework

- Include general dark matter particle types
- Include general mediator particle types
- Explore possible operator degeneracies
- Determine the dominant operators
- Determine distinguishability at detectors
- Connect to models for astrophysical and collider searches

Simplified models for tree-level, renormalizable interactions have been examined

single dark matter particle, single mediator

P. Agrawal, Z. Chacko, C. Kilic, and R.K. Mishra, 1003.1912

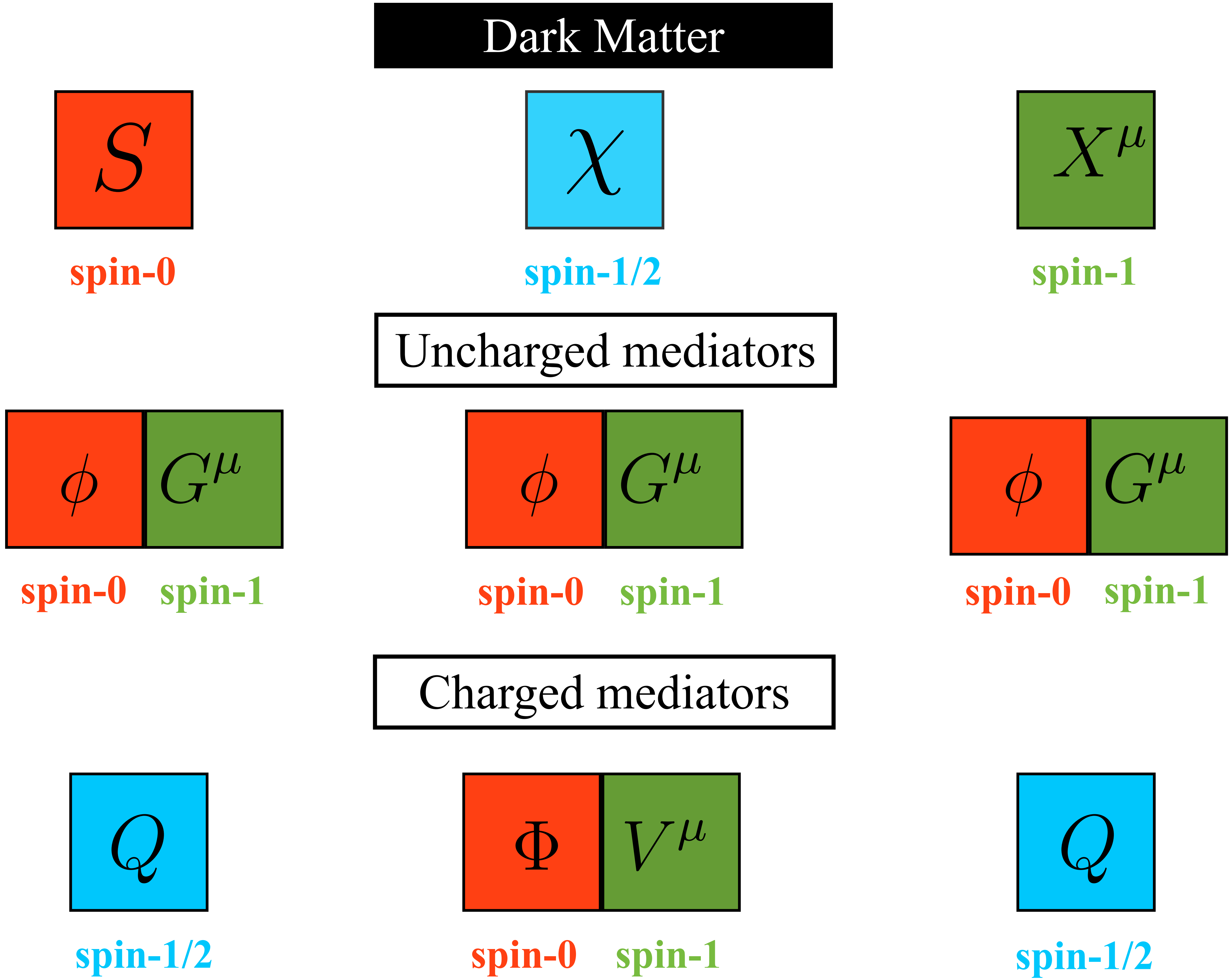
N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C**89**, (2014)

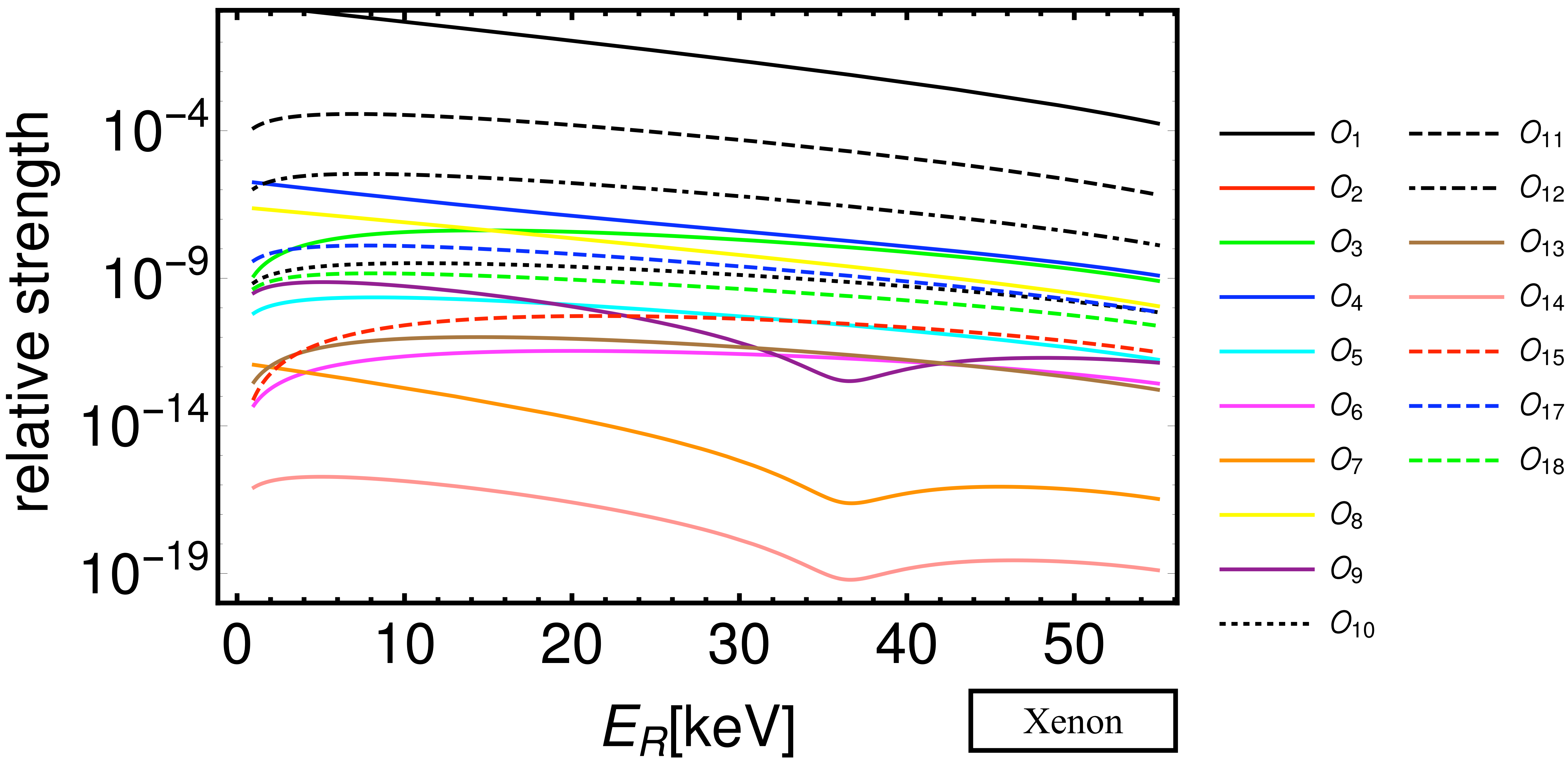
JBD, L.M. Krauss, J.L. Newstead, and S. Sabharwal, 1505.03117

non-relativistic reduction
match onto dark matter
and nuclear responses

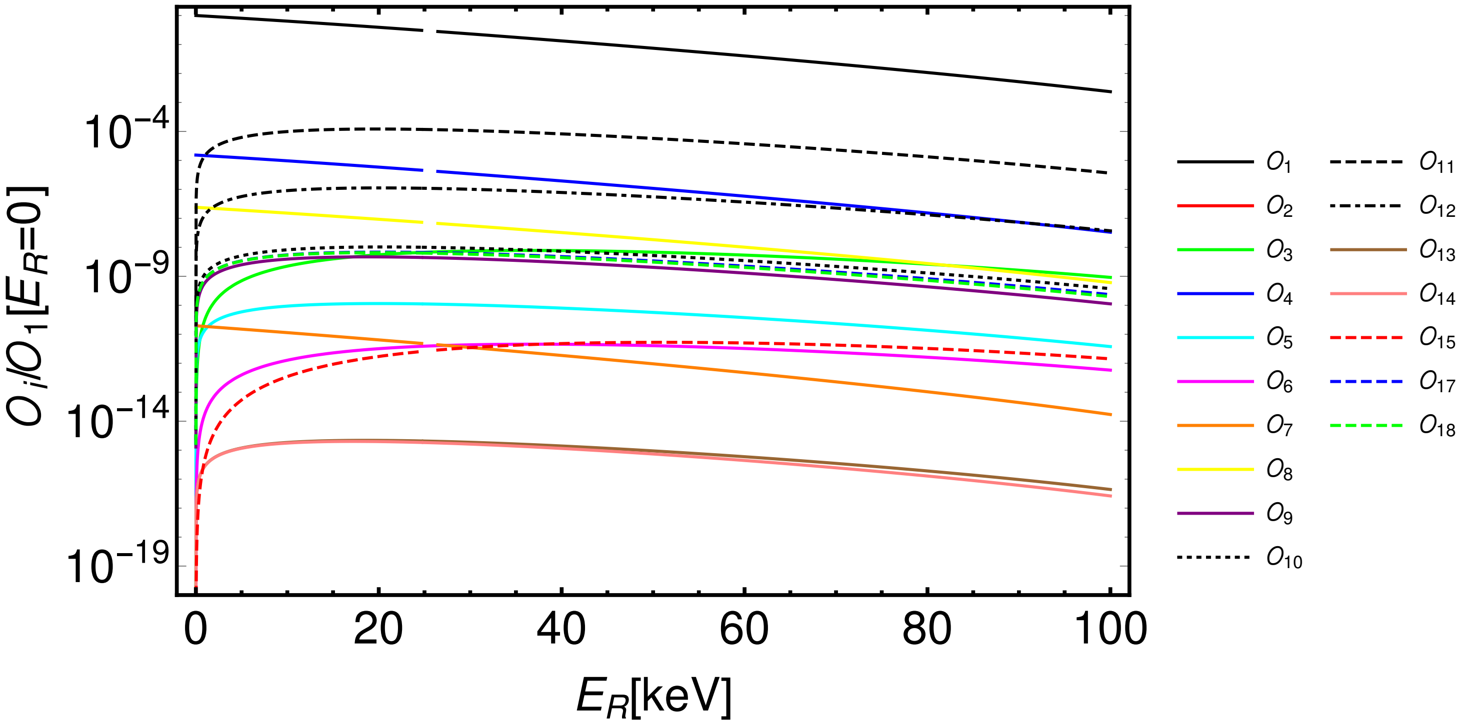
$$\mathcal{L}$$

$$\frac{dR}{dE_R}$$

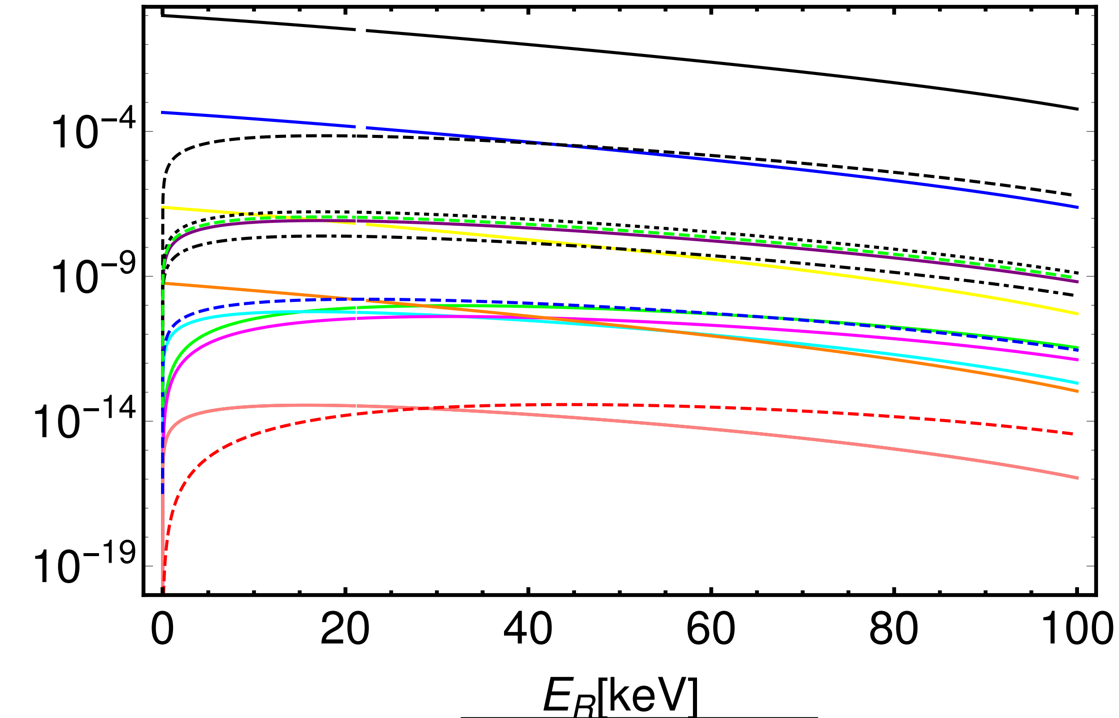

Dark Matter
S
spin-0
χ
spin-1/2
X^μ
spin-1
Uncharged mediators
ϕ G^μ
spin-0 spin-1
ϕ G^μ
spin-0 spin-1
ϕ G^μ
spin-0 spin-1
Charged mediators
Q
spin-1/2
Φ V^μ
spin-0 spin-1
Q
spin-1/2



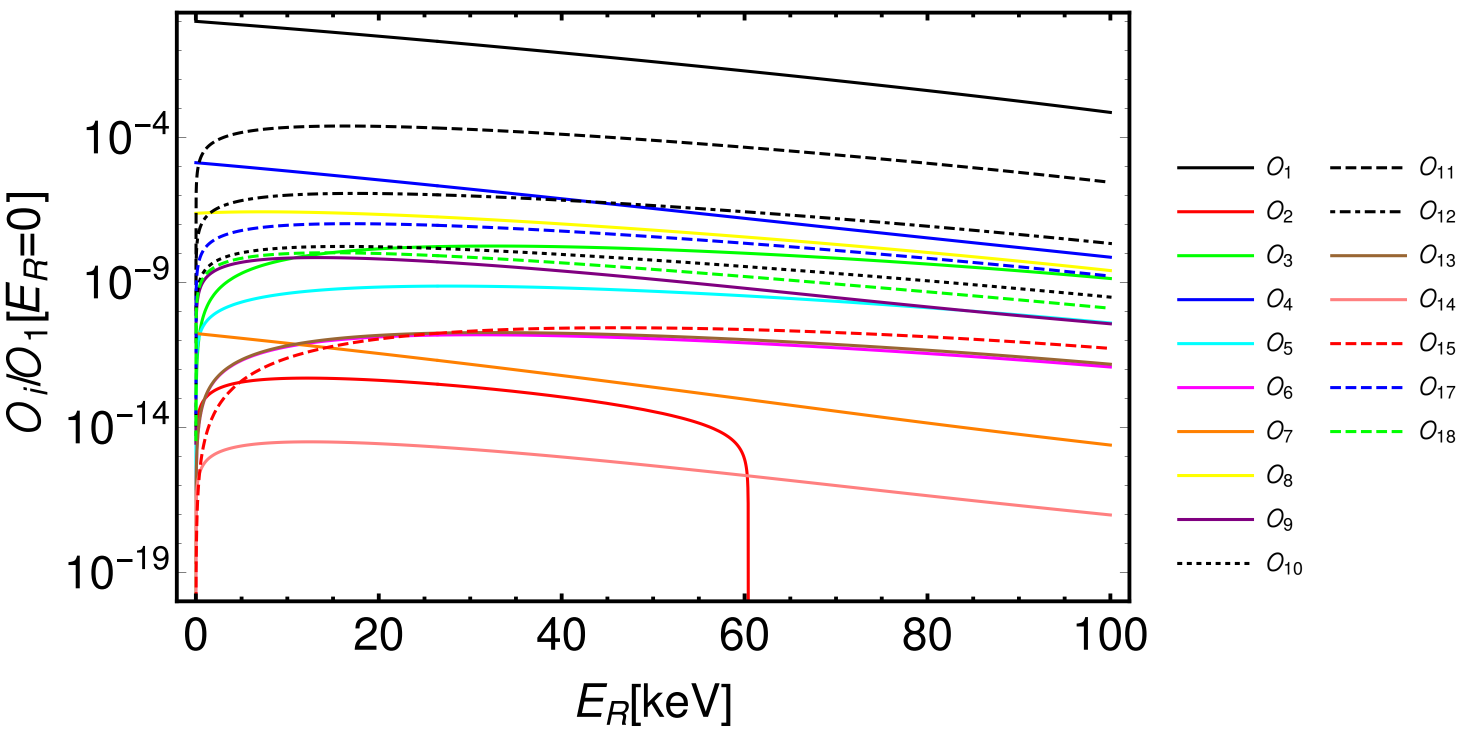
Relative strength of operators, in order to compare which operators dominate when more than one are present



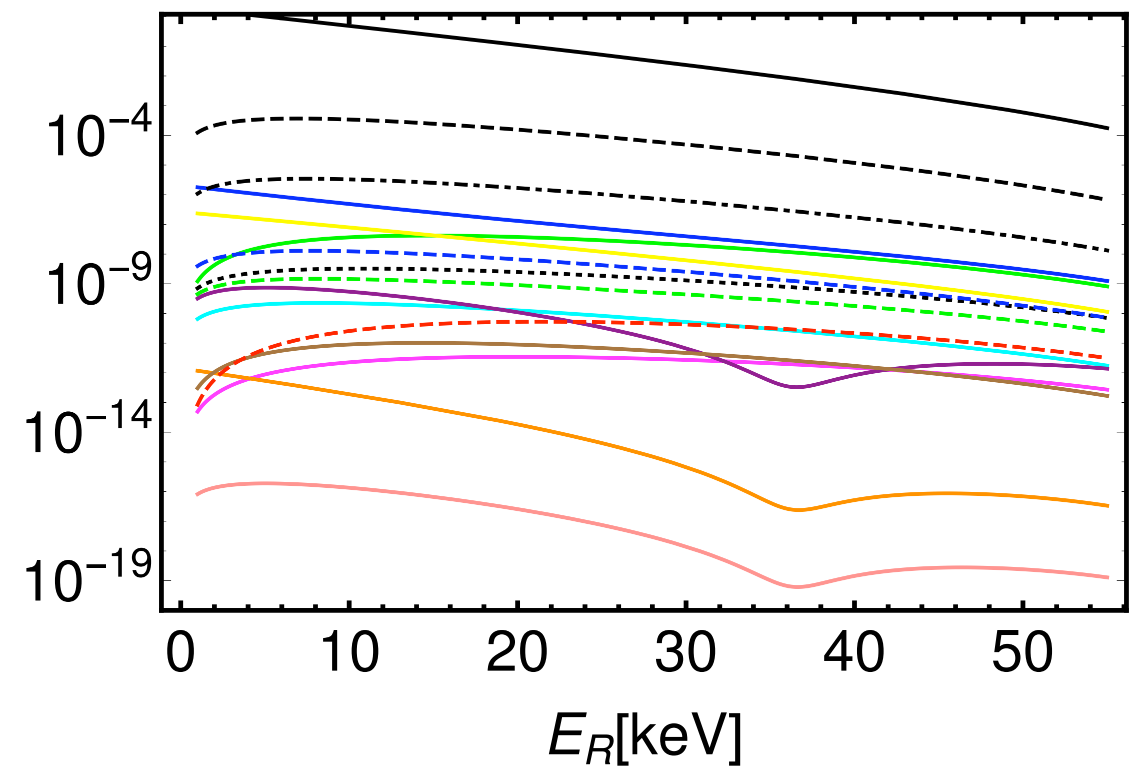
Silicon



Fluorine

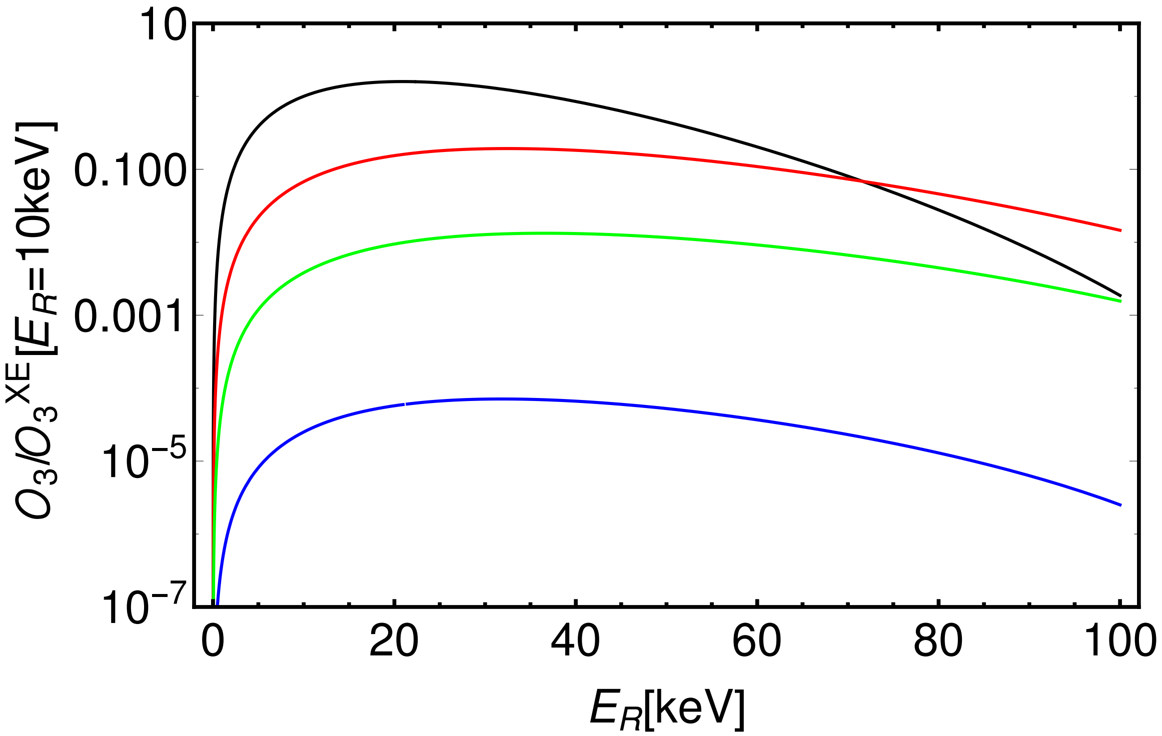


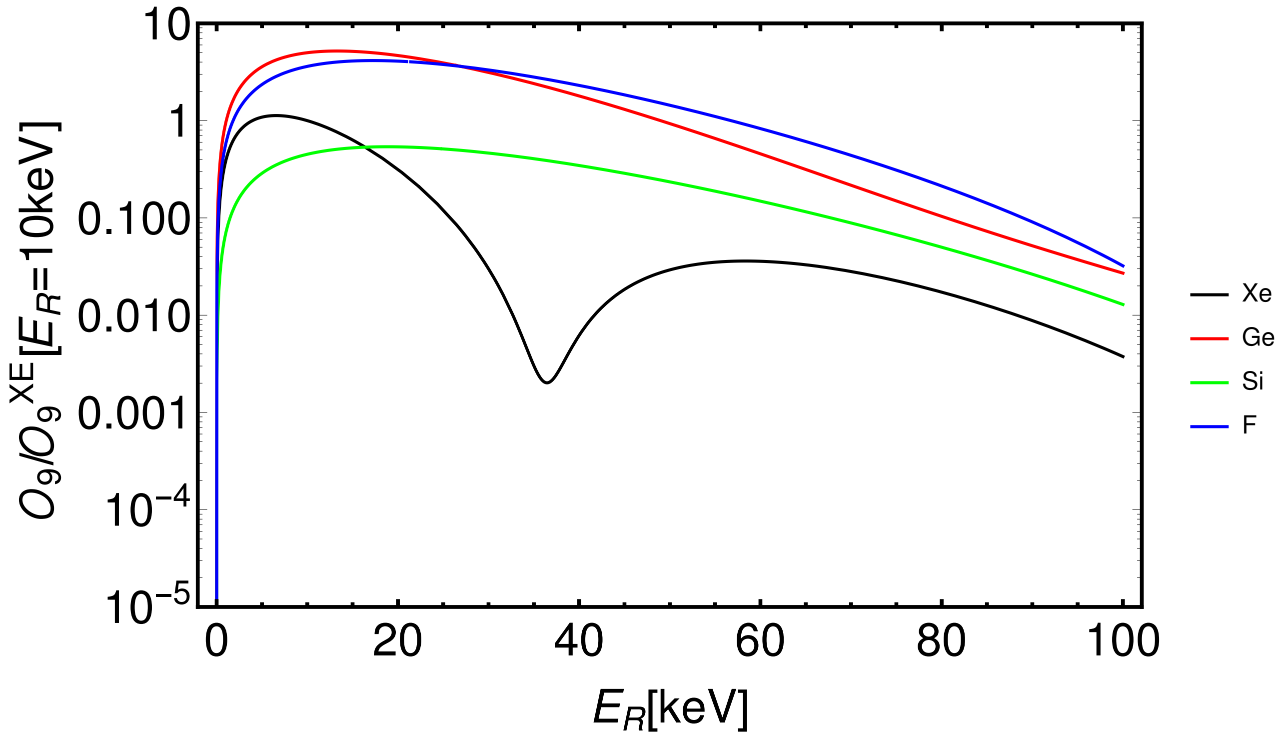
Germanium



Xenon

Relative strength of operators, in order to compare which operators dominate when more than one are present





$$\mathcal{O}_3 \qquad i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right)$$

$$\mathcal{O}_9 \qquad i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

Response of a given operator shown for various target elements

S

spin-0

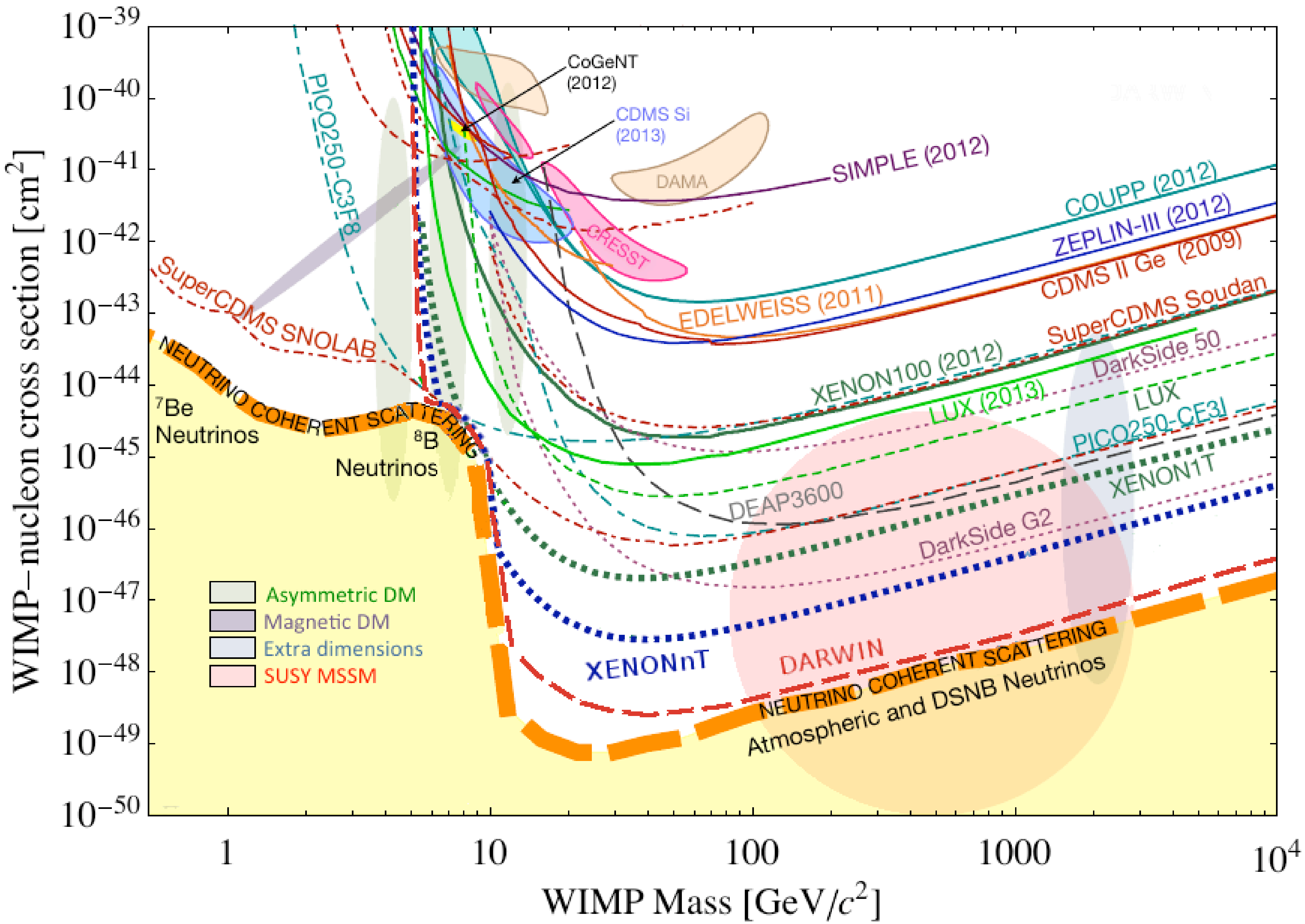
EFT form	Operator		Response	Suppression
$(S^\dagger S)(\bar{q}q)$	$\mathcal{O}_1$	$1_\chi 1_N$	M	
$(S^\dagger S)(\bar{q}\gamma^5 q)$ $i(S^\dagger \partial_\mu S - \partial_\mu S^\dagger S)(\bar{q}\gamma^\mu\gamma^5 q)$	$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$	Σ''	$\frac{q^2}{m_N^2}$

χ **spin-1/2**

EFT form	Operator	Response	Suppression
$\bar{\chi}\chi\bar{q}q$ $\quad$ $\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	$\mathcal{O}_1$	M	
$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$	$\mathcal{O}_4$	Σ'' Σ'	
$\bar{\chi}\chi\bar{q}\gamma^{5}q$	$\mathcal{O}_{10}$	Σ''	$\frac{q^2}{m_N^2}$

χ **spin-1/2**

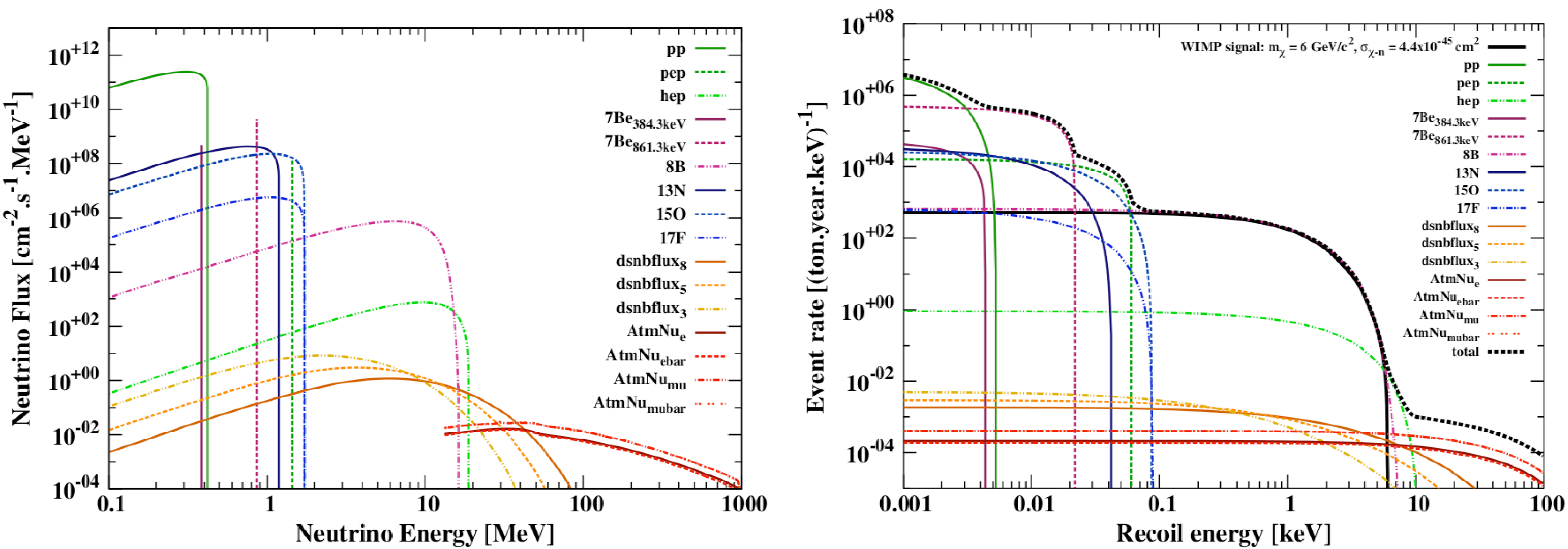
EFT form	Operator	Response	Suppression
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\mathcal{O}_{11}$	M	$\frac{q^2}{m_N^2}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\mathcal{O}_6$	Σ''	$\frac{q^4}{m_N^4}$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\mathcal{O}_9$	Σ'	$\frac{q^2}{m_N^2}$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\mathcal{O}_7$	Σ'	$v_T^{\perp 2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\mathcal{O}_8$	Δ	$\frac{q^2}{m_N^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\mathcal{O}_9$	Σ'	$\frac{q^2}{m_N^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\mathcal{O}_8/\mathcal{O}_9$	$\Delta\Sigma'$	$\frac{q^2}{m_N^2}$



The ultimate reach and extent of direct detection experiments?

Background neutrino rate

Both coherent nuclear elastic scattering →at worst practically indistinguishable



Ruppin et al. 1408.3581

Non-relativistic EFT for DD

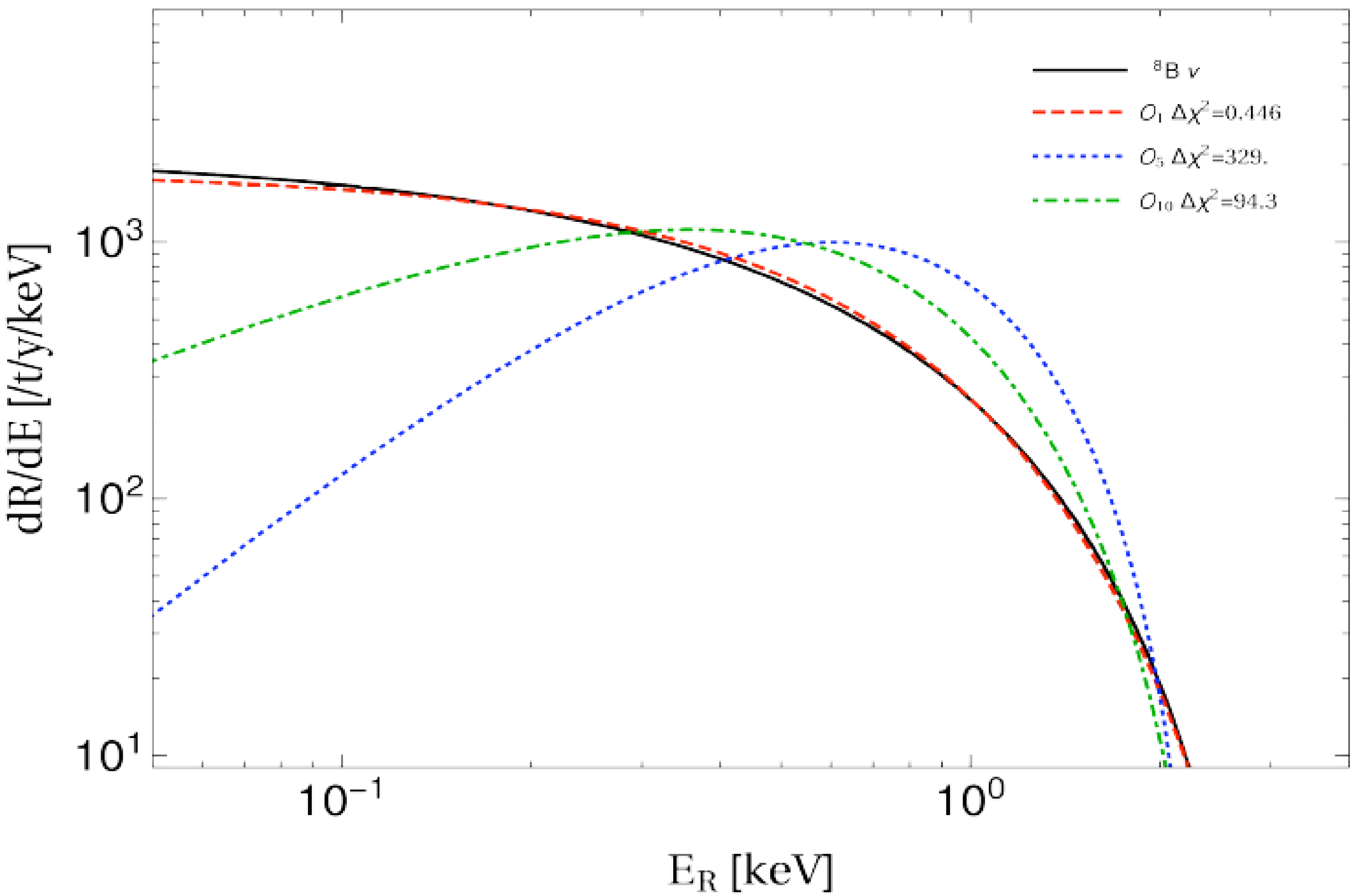
- WIMP spin $\vec{S}_\chi$
- Nucleon spin $\vec{S}_N$
- Momentum transfer $i\vec{q}$
- velocity $\vec{v}^\perp$

$\mathcal{O}_1$	$1_\chi 1_N$	← Spin independent
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	← Spin dependent
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$	
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$	
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$	
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$	
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$	
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$	
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$	

EFT fits to neutrino rate

Find best fit with a binned Poisson likelihood:

$$\mathcal{L} = \prod_{i=1}^{b} \frac{\nu_i^{n_i} e^{\nu_i}}{n_i!}$$

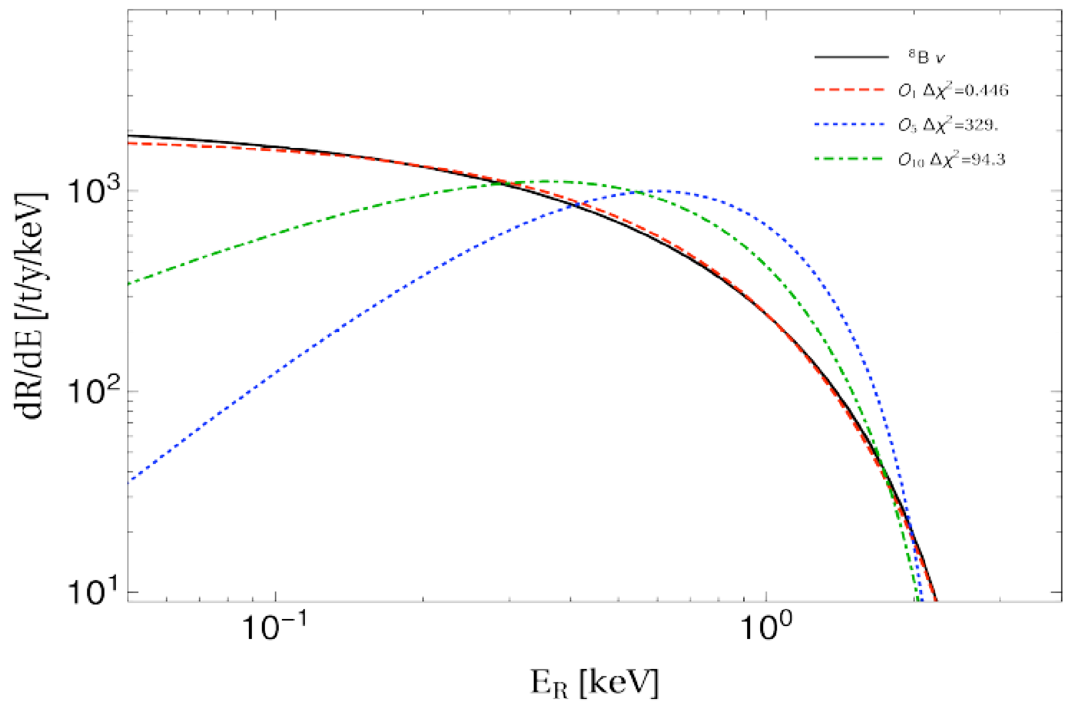


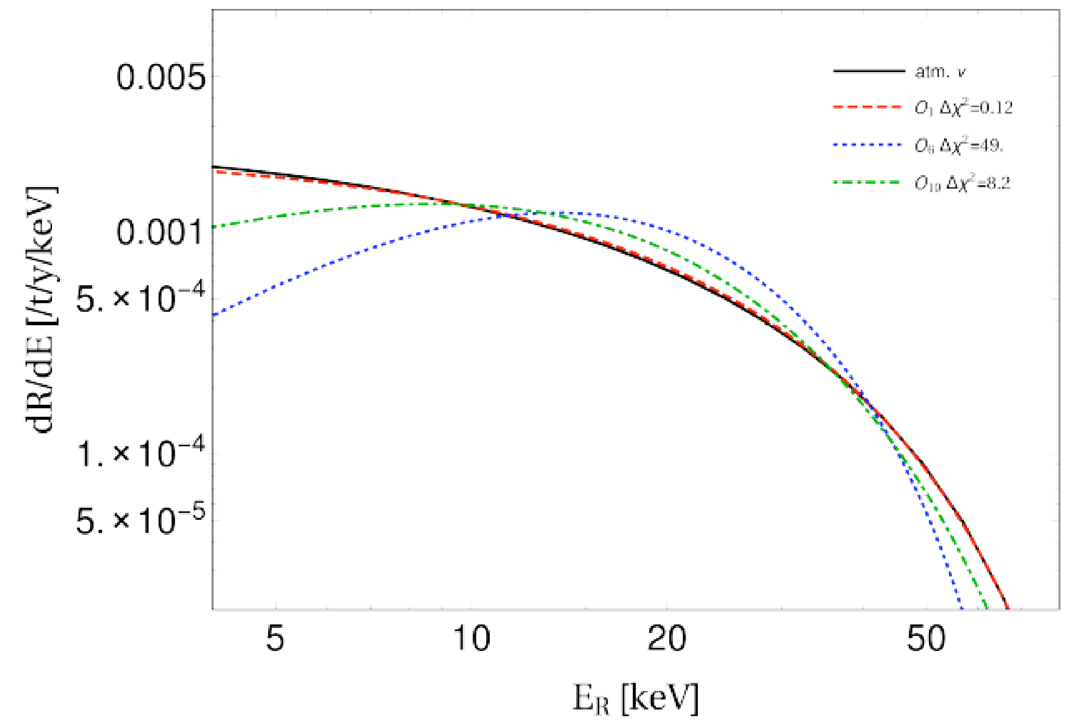
Operator	Mass (GeV)	Exp. (t.y)
$\mathcal{O}_1$	6	2.9
$\mathcal{O}_4$	6	3.5
$\mathcal{O}_7$	6.2	4.3
$\mathcal{O}_8$	6.3	3.6
q^2 and $q^2 v_T^2$		
$\mathcal{O}_5$	4.8	0.43
$\mathcal{O}_9$	4.6	0.34
$\mathcal{O}_{10}$	4.6	0.36
$\mathcal{O}_{11}$	4.6	0.40
$\mathcal{O}_{12}$	4.6	0.44
$\mathcal{O}_{14}$	4.8	0.43
$q^2 v_T^2$, q^4 and $q^4 v_T^2$		
$\mathcal{O}_3$	4.2	0.27
$\mathcal{O}_6$	4.2	0.29
$\mathcal{O}_{13}$	4.2	0.27
$\mathcal{O}_{15}$	4.1	0.21

Fits to neutrino rate

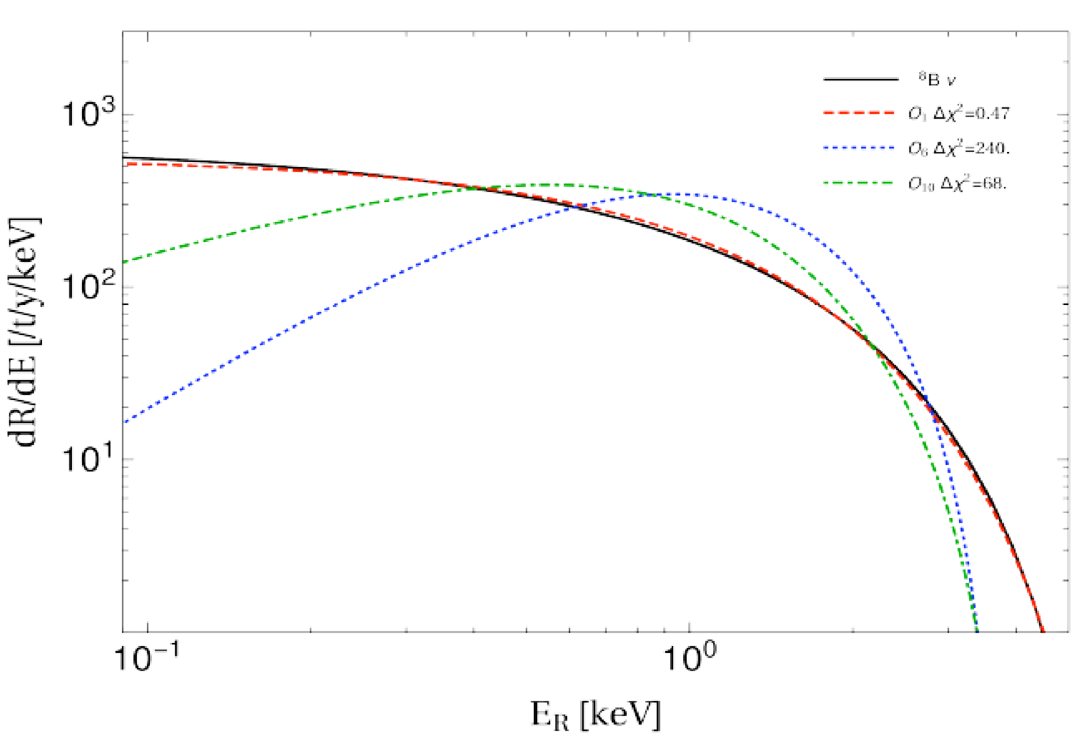
Boron-8 | Atmospheric

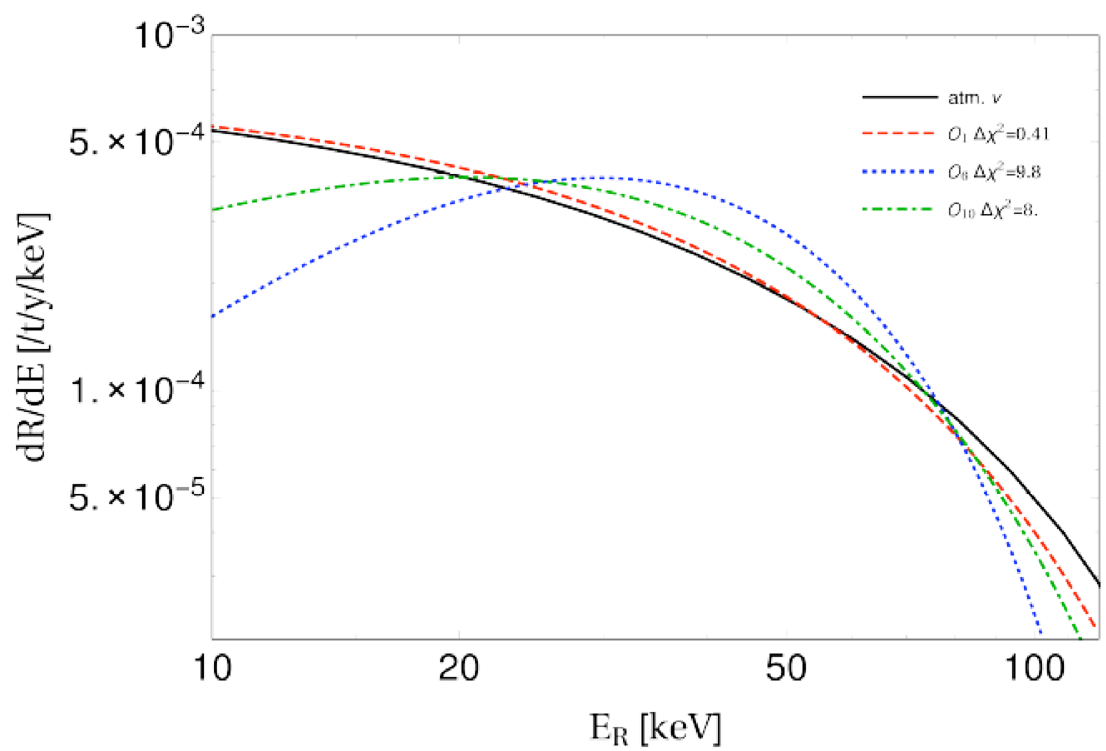
Xe





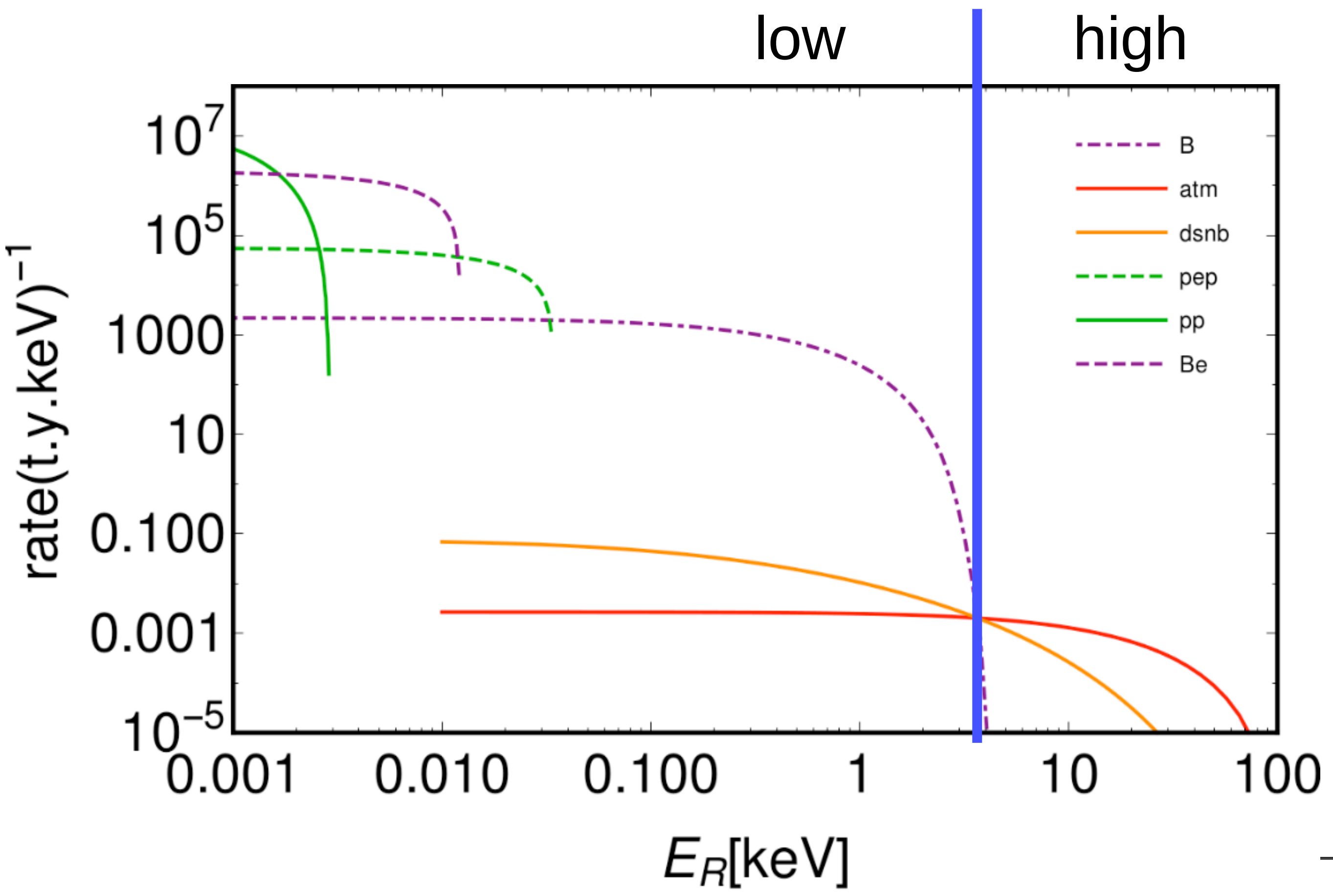
Ge





Two regions of interest

Neutrino rates in xenon:



Low region – solar neutrino background

High region – atmospheric neutrino background

	low region (keV)	high region (keV)
xenon	0.003 - 3	4.0 - 100
germanium	0.0053 - 7	7.9 - 120
silicon	0.014 - 18	20 - 300
flourine	0.033 - 25	28 - 500

Discovery evolution

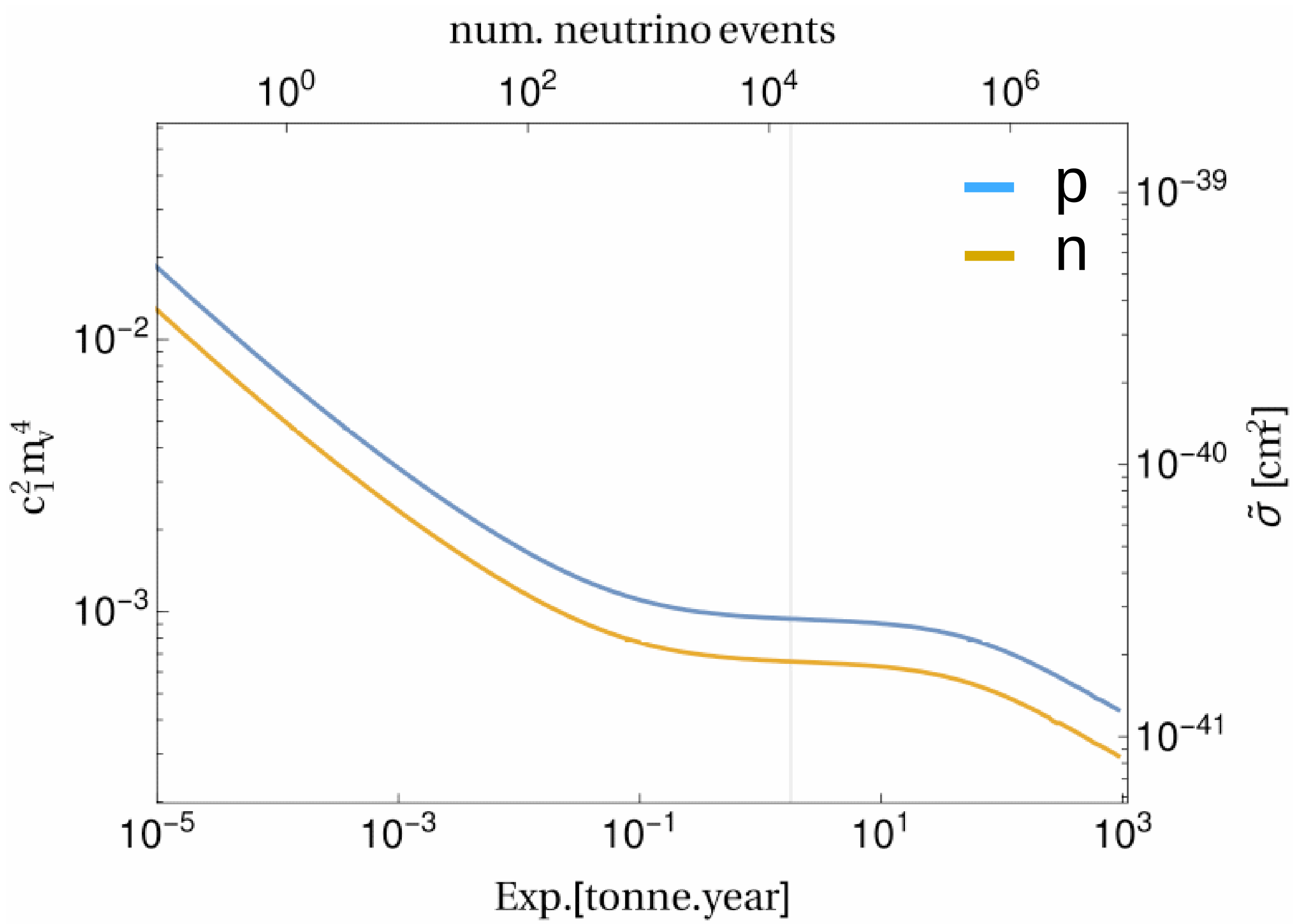
Include flux uncertainty in likelihood:

$$\mathcal{L} = \mathcal{L}_{Poisson} \prod_j e^{-\frac{1}{2}(1-N_j)^2 \left(\frac{\phi_j}{\sigma_j}\right)^2}$$

Test statistic for discovery:

$$q_0 = \begin{cases} -2\log\frac{\mathcal{L}(\sigma=0,\hat{\theta})}{\mathcal{L}(\hat{\sigma},\hat{\hat{\theta}})} & \sigma \geq \hat{\sigma} \\ 0 & \sigma < \hat{\sigma} \end{cases}$$

Xenon-low   O1 (SI):



For a given exposure, find the cross section which produces a 3σ deviation from the null hypothesis 90% of the time

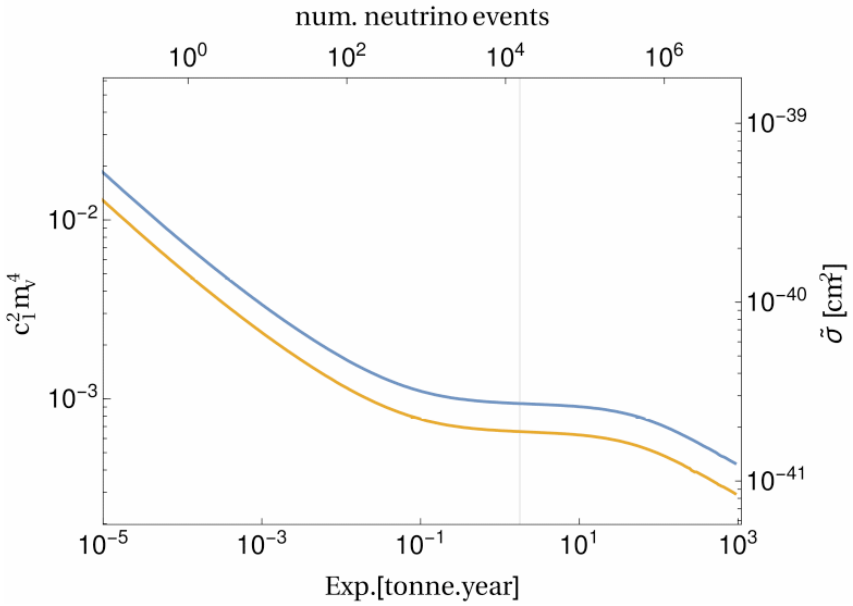
Discovery evolution

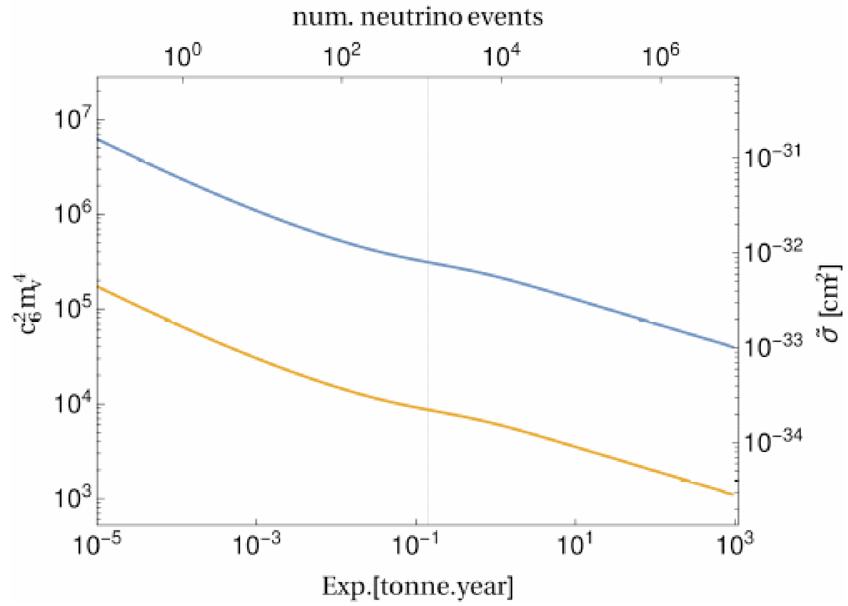
Group 2 and 3 operators only experience a weak saturation – no strong nu-floor

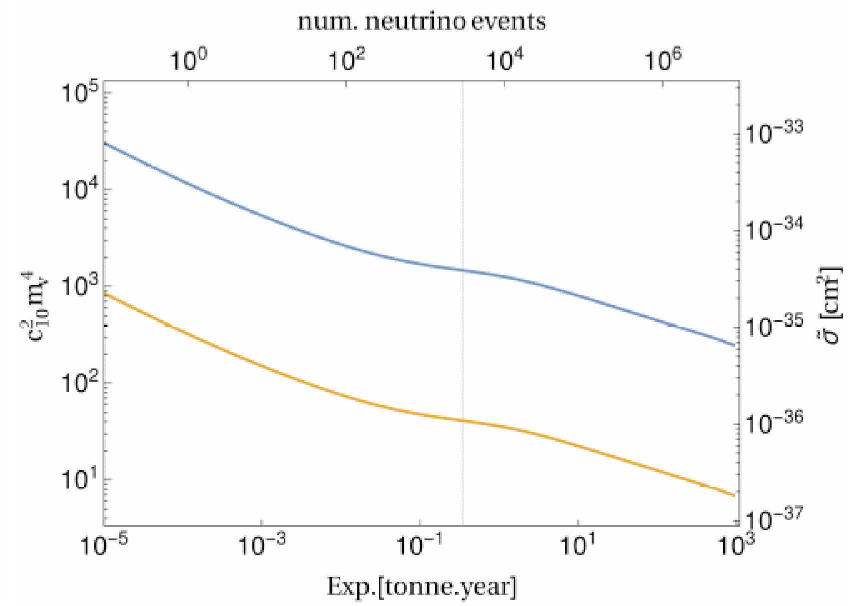
p
n

O1 O6 O10

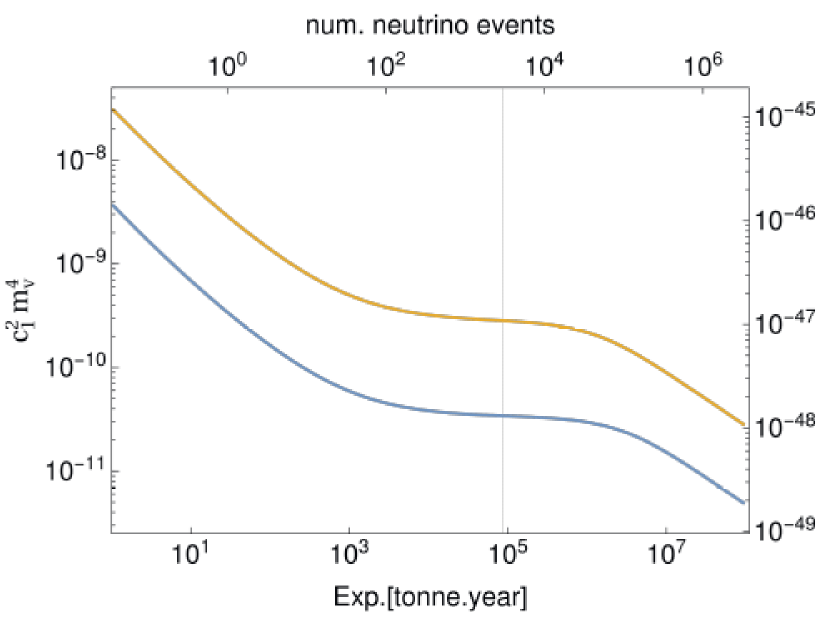
low

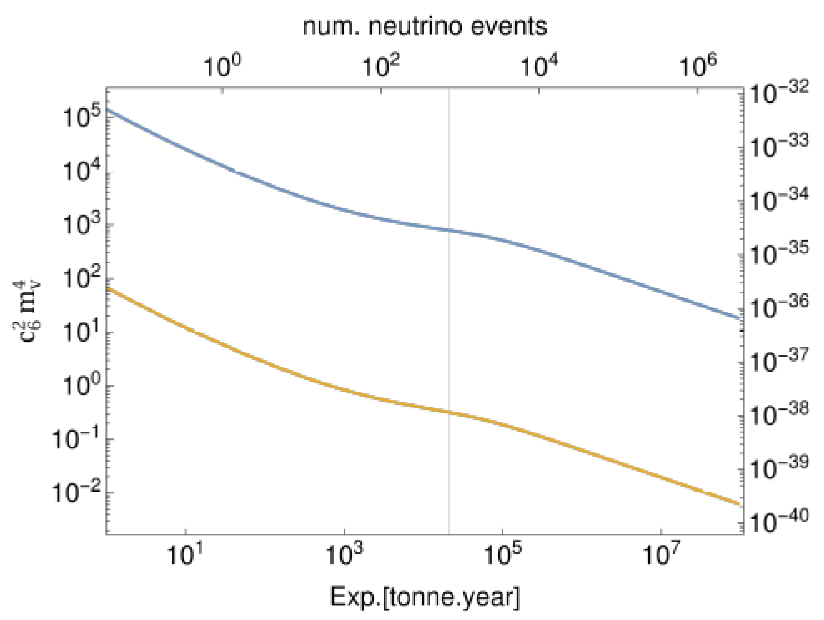


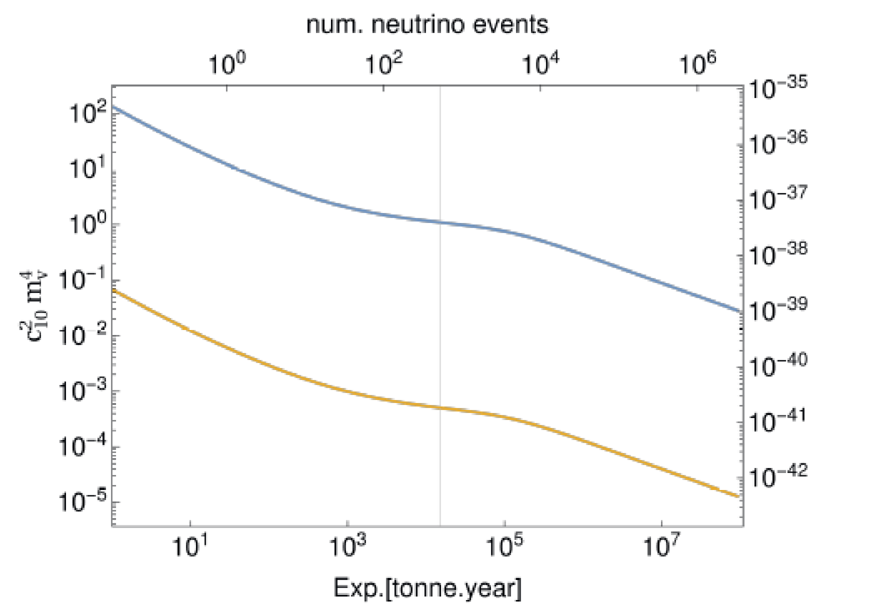




high





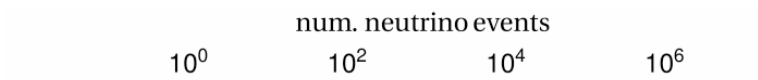


Discovery evolution

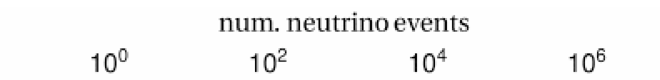
Group 2 and 3 operators only experience a weak saturation – no strong nu-floor

p
n

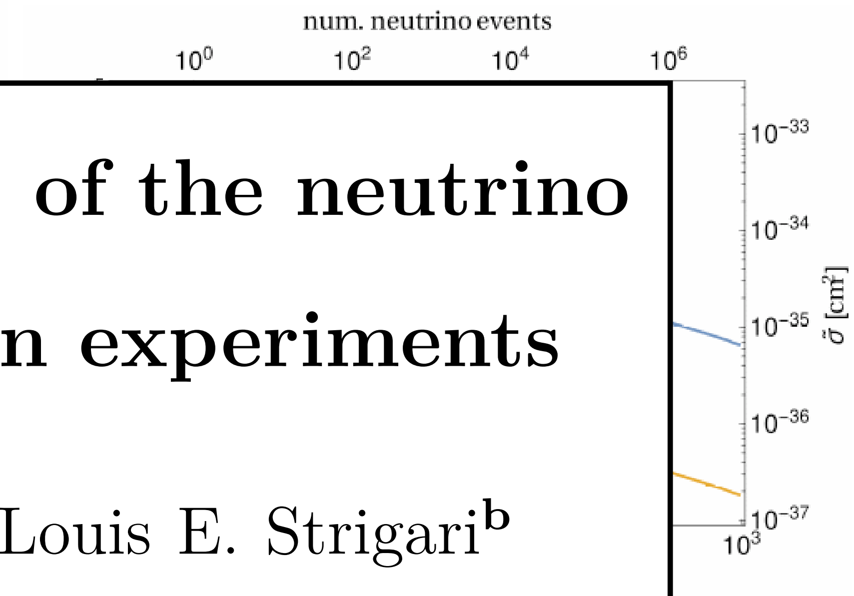
O1



O6



O10

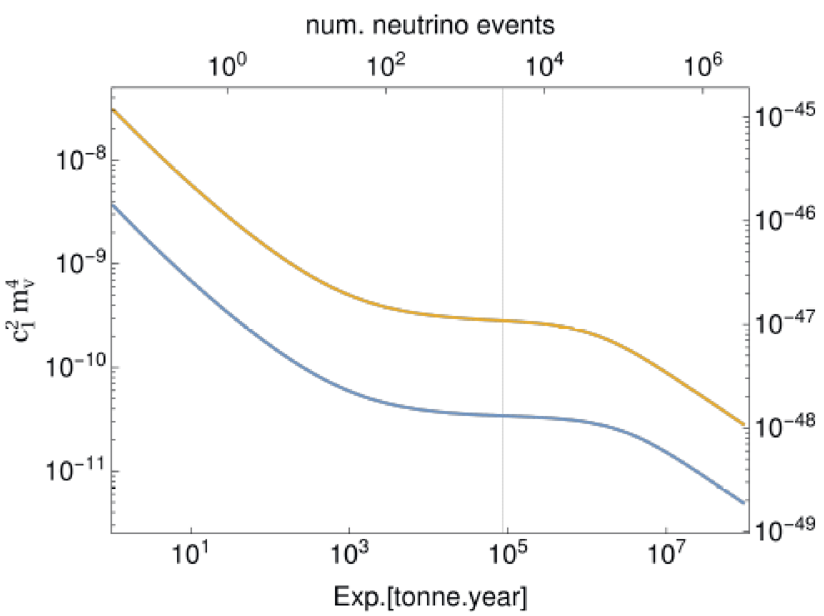


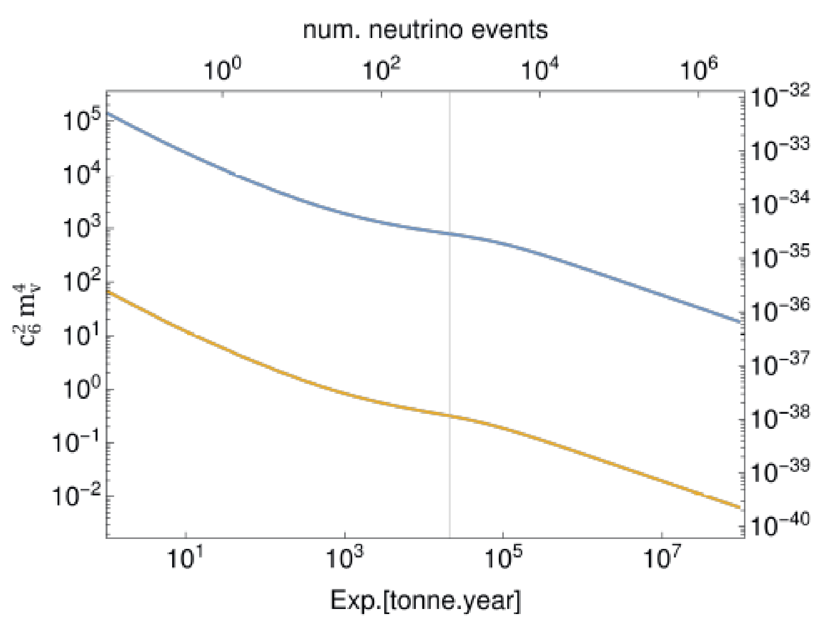
No ν floors: Effective field theory treatment of the neutrino background in direct dark matter detection experiments

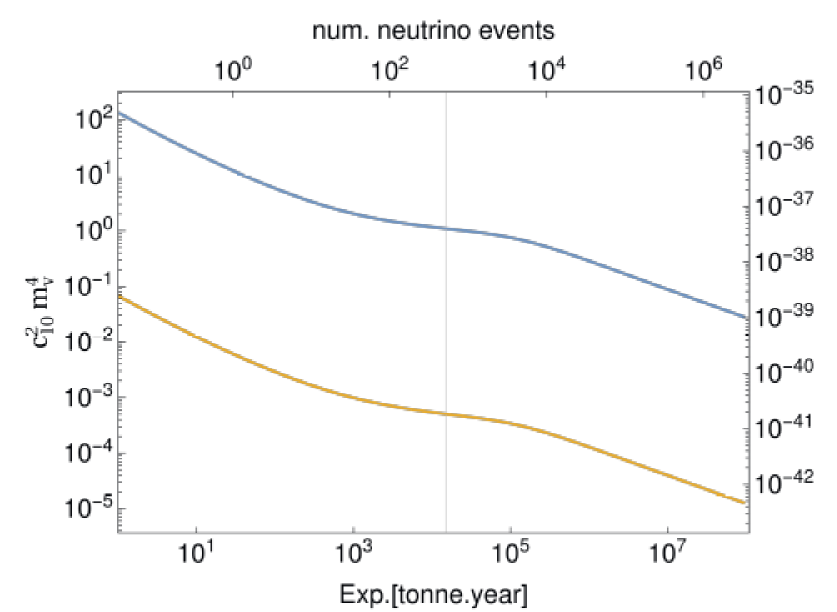
James Dent[a], Bhaskar Dutta[b], Jayden Newstead[c], and Louis E. Strigari[b]

lo

high







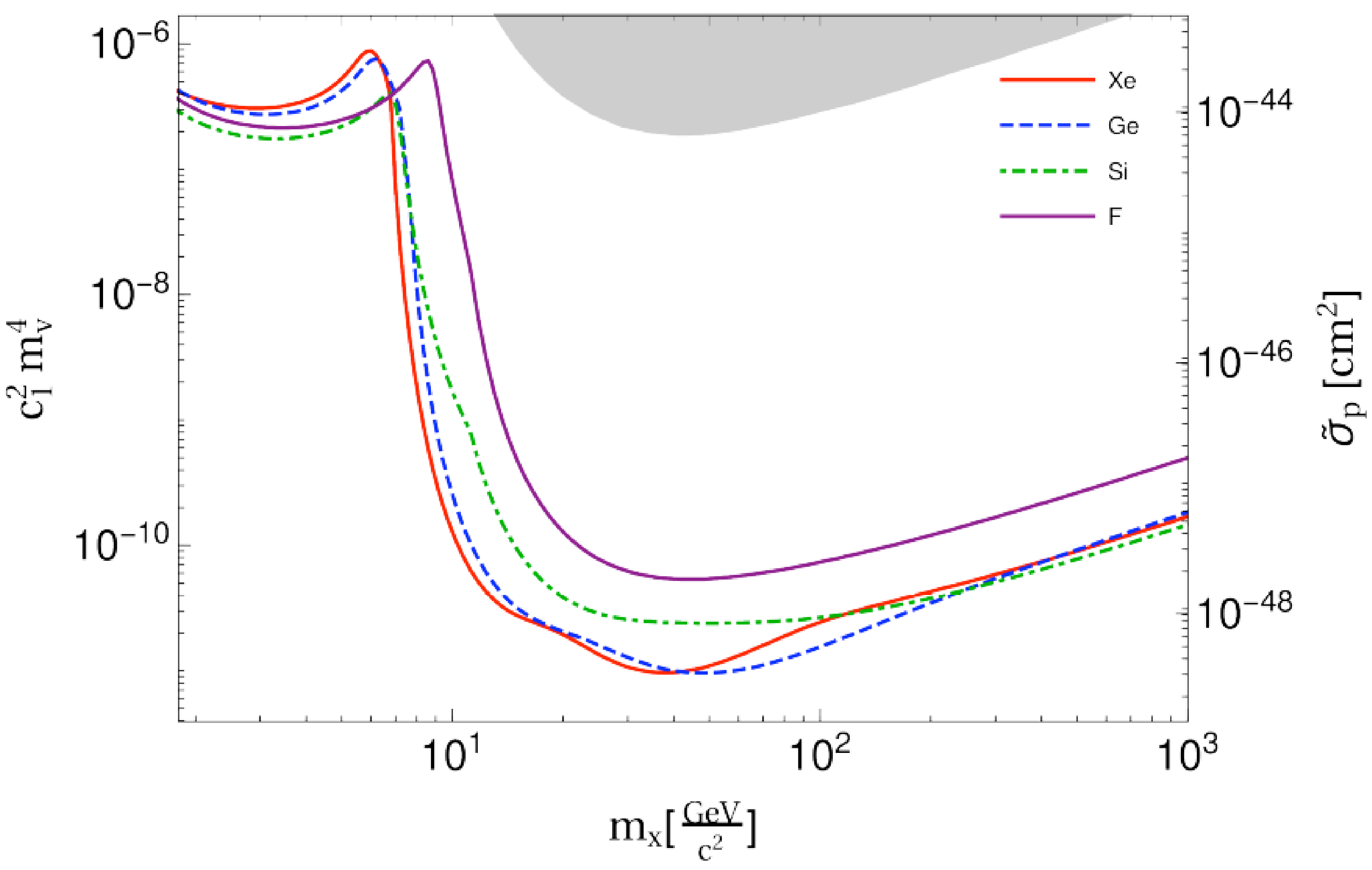
Discovery limits

Target	exposure^{low} (t.y)	exposure^{high} (kt.y)
xenon	1.76	58
germanium	3.26	87
silicon	10.4	206
flourine	16.3	278

Test statistic for discovery:

$$q_0 = \begin{cases} -2\log\frac{\mathcal{L}(\sigma=0,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\sigma},\hat{\theta})} & \sigma \geq \hat{\sigma} \\ 0 & \sigma < \hat{\sigma} \end{cases}$$

O1 (SI):



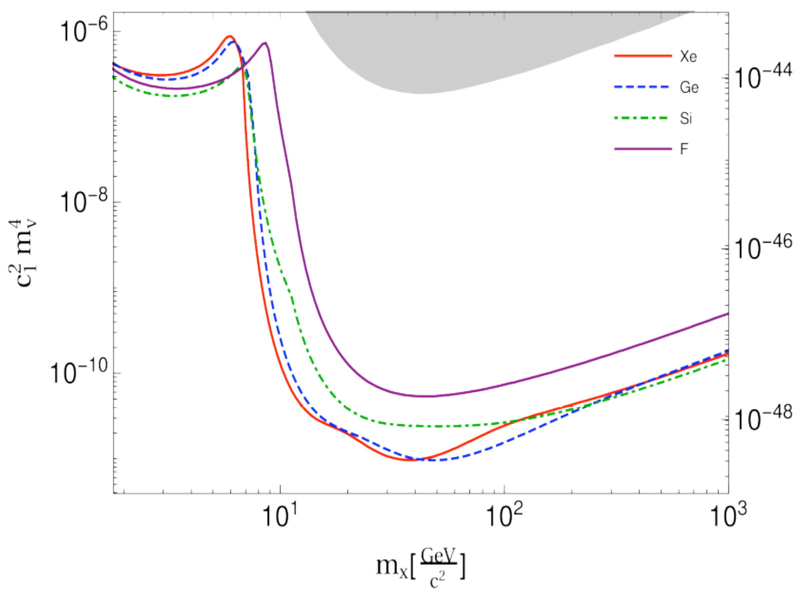
For saturated exposure, find the cross section which produces a 3σ deviation from the null hypothesis 90% of the time

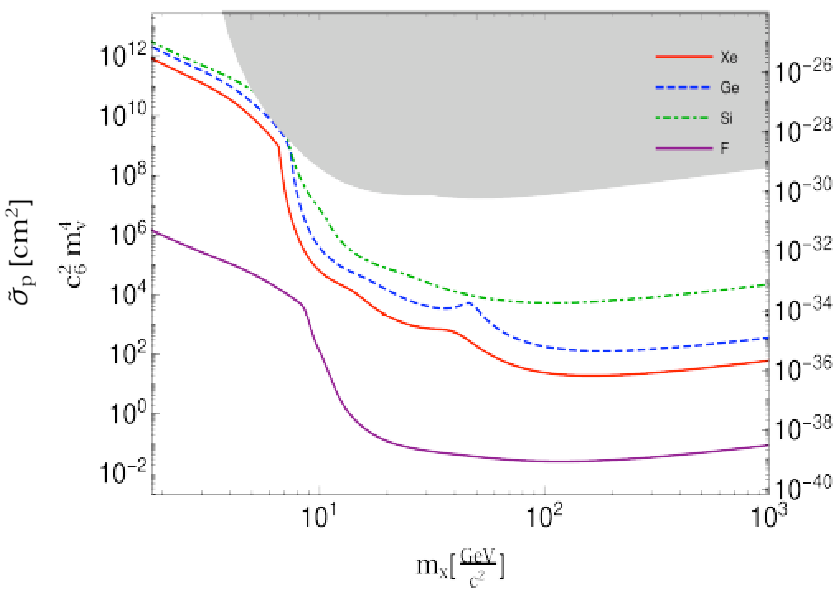
Discovery limits

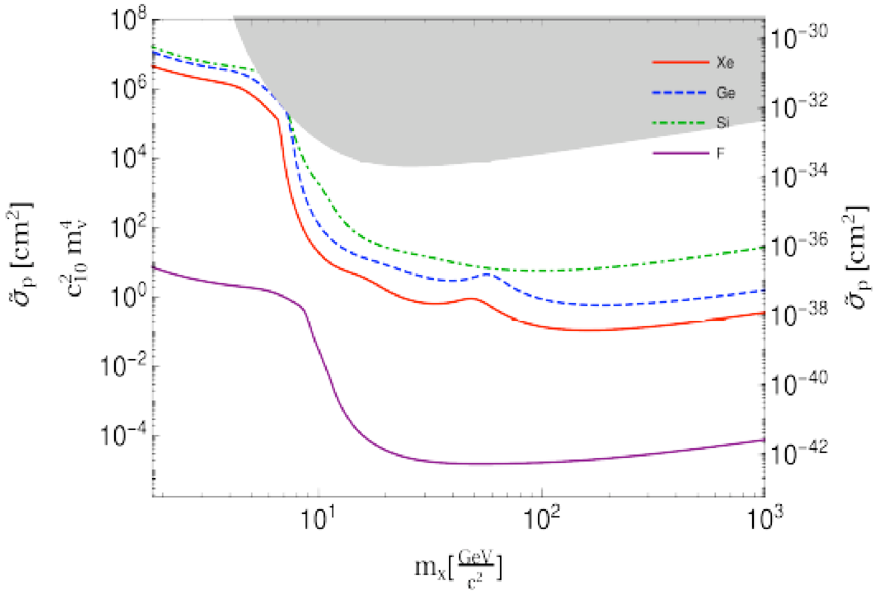
Group 2 and 3 operators only experience a weak saturation – no strong nu-floor

O1 O6 O10

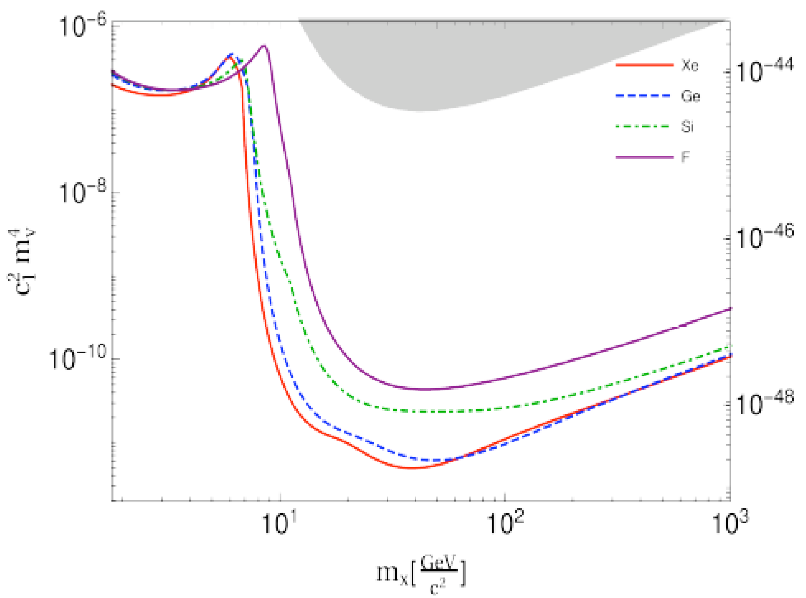
proton

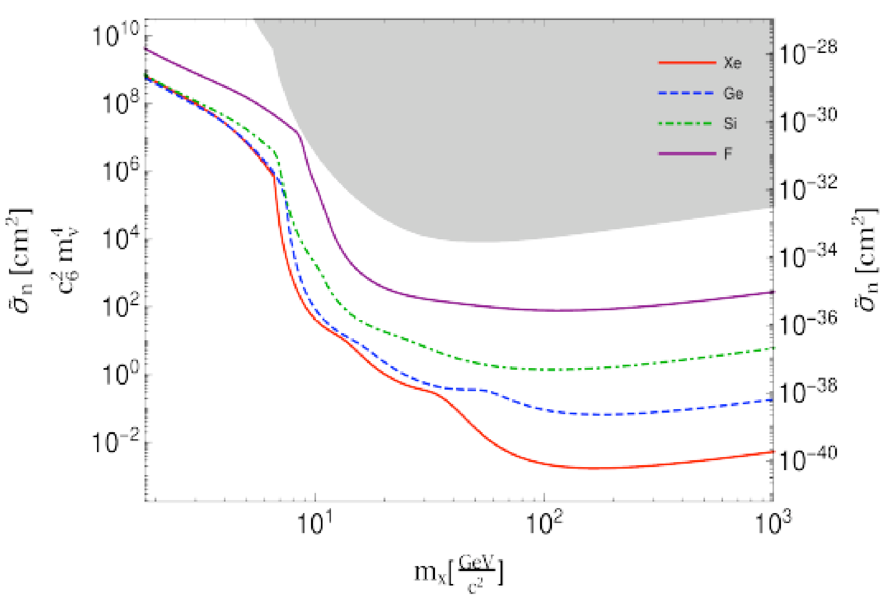


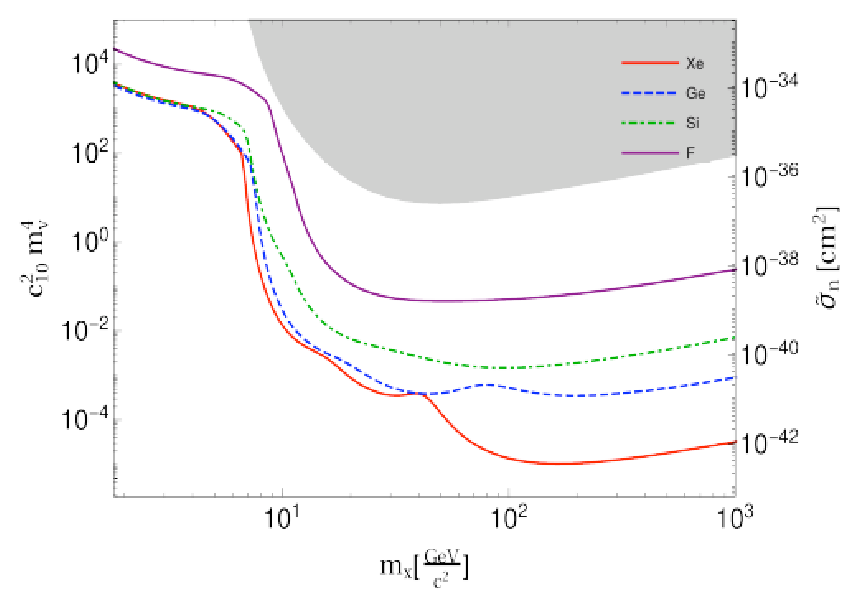




neutron



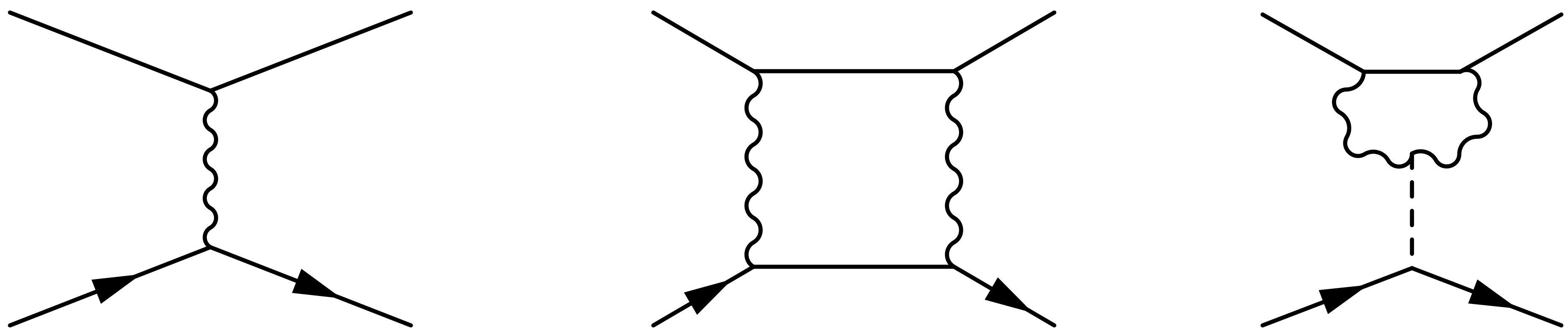




SD

Operator Uniqueness

An issue that arises is whether tree level interactions with one type of operator as dominant become sub-dominant when loop/running effects are included. Does SD dominate?



(a) Tree level (b) Loop processes

$$\frac{g_2^2}{2\cos^2\theta_W} T_3^q \frac{Q}{2} \frac{1}{m_Z^2} \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$$

SD

$$\frac{1}{4\pi} \frac{g_2^4\,Q^2}{\cos^4\theta_W\,m_Z} \left[\frac{(T_3^q)^2}{2m_Z^2} + \frac{1}{4m_h^2}\right] m_q\,\bar{\chi}\chi\,\bar{q}q$$

SI

Once Higgs and/or Z-mixing arise, SI elastic scattering can be generated, dependent on the DM-mediator coupling strength.

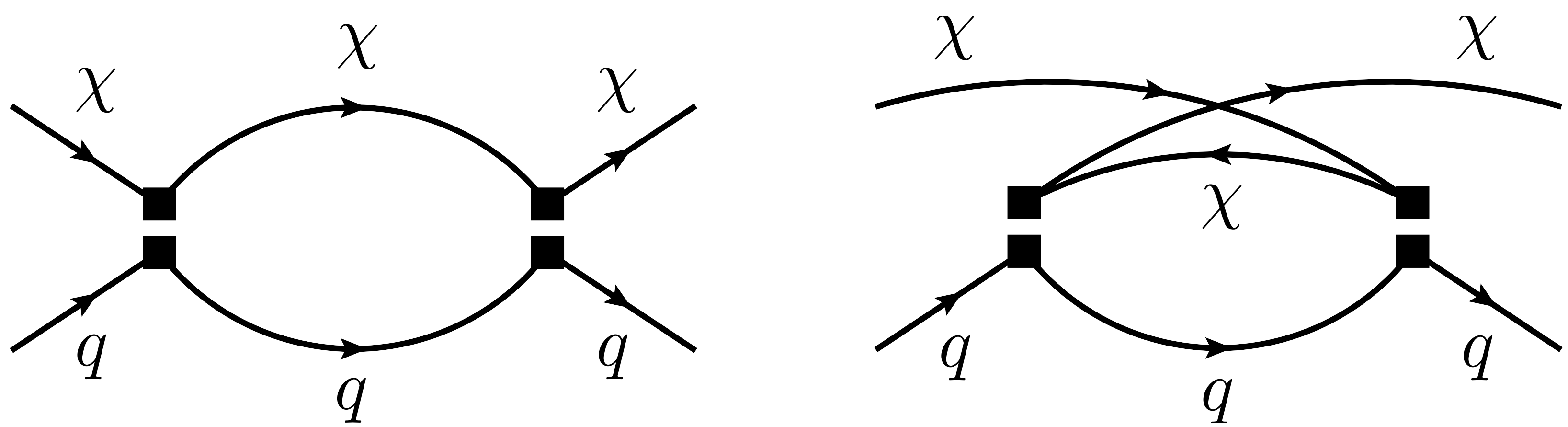
For vector exchange, the loop induced SI can be competitive, while SD remains dominant for pseudoscalar exchange

M. Freytsis and Z. Ligeti, 1012.5317

Operator Uniqueness

For example, beginning with a pure axial-vector exchange (SD and kinematically unsuppressed)

$$\frac{1}{M_*^2}\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\bar{q}\gamma^\mu\gamma_5 q\right)$$



The loop process induces a contribution

$$\mathcal{C}_S \simeq -\frac{1}{2\pi^2}\frac{m_\chi}{M_*}\ln\frac{M_*^2}{m_\chi^2}$$

to the spin-independent operator

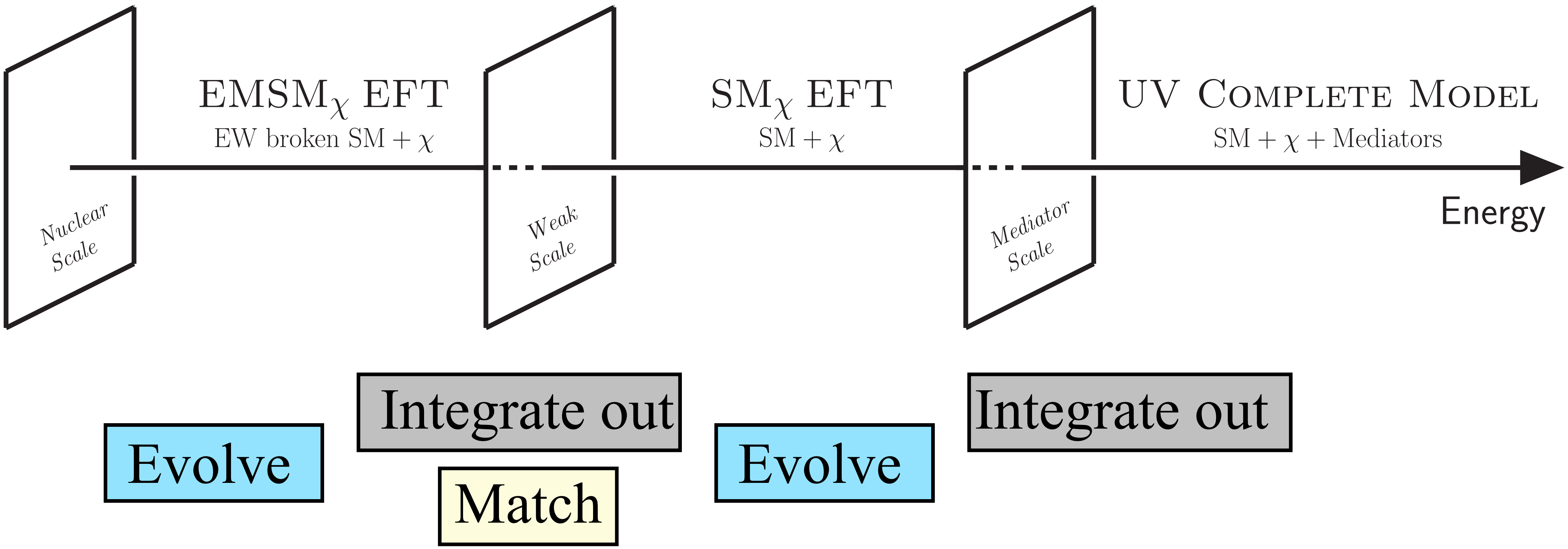
$$\mathcal{O}_S = \frac{m_q}{M_*^3}\,\mathcal{C}_S\left(\bar{\chi}\chi\right)\left(\bar{q}q\right)$$

giving the spin-independent cross-section

$$\sigma_N^{\rm SI} = \frac{f_N^2}{\pi}\frac{m_{\rm red}^2 m_N^2}{M_*^6}\,\mathcal{C}_S^2$$

U. Haisch and F. Kahlhoefer, 1302.4454

In order to fully exploit complementarity between direct detection and collider searches, one needs to properly connect the scale of the mediator mass to the nuclear scale



$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{\Lambda^{d-4}}\mathcal{O}_\alpha^{(d)}$$

F. D'Eramo and M. Procura, 1411.3342

R.J. Hill and M.P. Solon, 1409.8290

Operator Uniqueness

Another example of mixing was obtained for the Higgs portal interaction

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}\left(i\partial\!\!\!/ - M_0\right)\chi + \Lambda^{-1}\left(\cos\theta\ \bar{\chi}\chi + \sin\theta\ \bar{\chi}i\gamma_5\chi\right) H^\dagger H$$

After EWSB: $$H^\dagger H \longrightarrow \frac{\langle v\rangle^2}{2} + \langle v\rangle h + \frac{h^2}{2}$$

A chiral rotation and field redefinition is needed for a real mass

$$\chi \to \exp\left(i\gamma_5\ \alpha/2\right)\chi \quad \Rightarrow \quad \bar{\chi} \to \bar{\chi}\exp\left(i\gamma_5\ \alpha/2\right)$$

It is found that even for an initially pure pseudoscalar interaction $\cos\theta = 0,\ \sin\theta = \pm 1$

a scalar term will be generated

$$\Lambda^{-1}\left[-\frac{\langle v\rangle^2}{2\Lambda M}\ \bar{\chi}\chi \pm \sqrt{1-\left(\frac{\langle v\rangle^2}{2\Lambda M}\right)^2}\ \bar{\chi}i\gamma_5\chi\right]\left(\langle v\rangle h + h^2/2\right)$$

M.A. Fedderke, J.-Y. Chen, E.W. Kolb, and L.-T. Wang, JHEP **1408** (2014), arXiv:1404.2283

$$\sigma_{\rm SI}^{\chi N}$$

Other work which discusses this effect includes:
S. Matsumoto, S. Mukhopadhyay, Y.-L. Sming Tsai, JHEP **1410** (2014), arXiv:1407.1859
R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1409.8290

SM_χ EFT

Symbol	Operator	Symbol	Operator	Symbol	Operator
$\mathcal{O}^{(i)}_{\Gamma q}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{q^i_L}\gamma_\mu q^i_L$	$\mathcal{O}^{(i)}_{\Gamma l}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{l^i_L}\gamma_\mu l^i_L$	$\mathcal{O}^{(i)}_{\Gamma H}$	$\overline{\chi}\,\Gamma^\mu\chi\,H^\dagger i\overleftrightarrow{D}_\mu H$
$\mathcal{O}^{(i)}_{\Gamma u}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i_R}\gamma_\mu u^i_R$	$\mathcal{O}^{(i)}_{\Gamma e}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i_R}\gamma_\mu e^i_R$		
$\mathcal{O}^{(i)}_{\Gamma d}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i_R}\gamma_\mu d^i_R$				

Wilson coefficients are evolved

$$\frac{d\,\mathcal{C}_{\mathrm{SM}_\chi}}{d\ln\mu} = \gamma_{\mathrm{SM}_\chi}\mathcal{C}_{\mathrm{SM}_\chi}$$

Wilson coefficients are matched at the EWSB scale including effects from integrating out weak scale particles

EMSM_χ

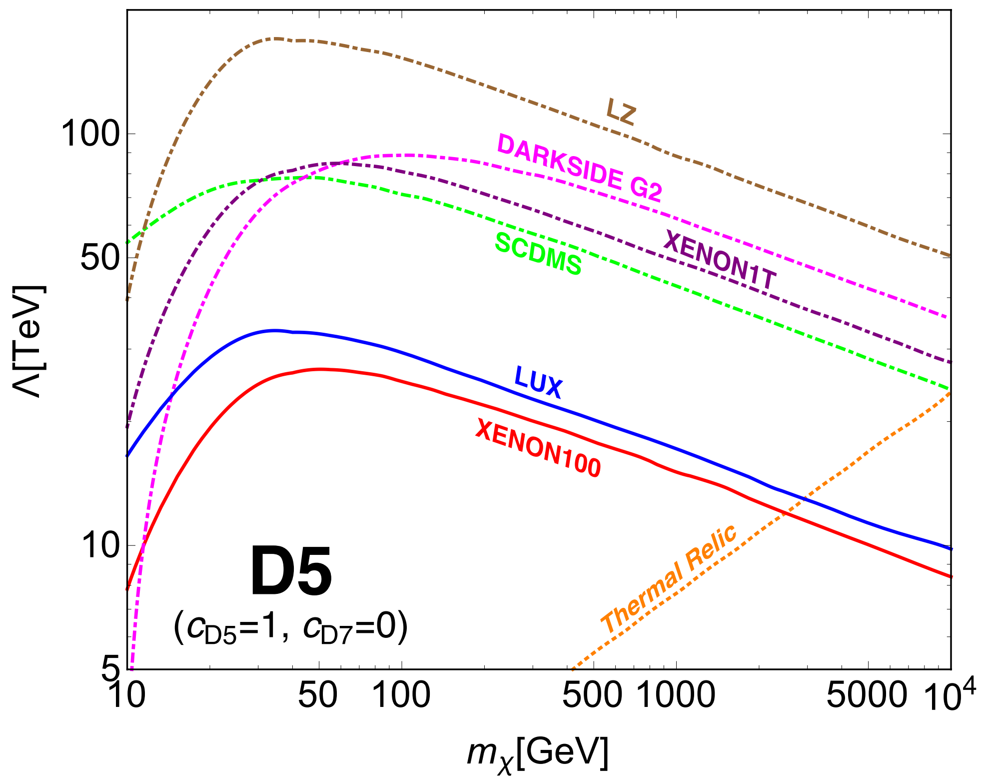
Symbol	Operator	Symbol	Operator	Symbol	Operator
$\mathcal{O}^{(i)}_{\Gamma Vu}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{\Gamma Vd}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{\Gamma Ve}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{\Gamma Au}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{\Gamma Ad}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{\Gamma Ae}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$

Wilson coefficients are evolved

$$\frac{d\,\mathcal{C}_{\mathrm{EMSM}_\chi}}{d\ln\mu} = \gamma_{\mathrm{EMSM}_\chi}\mathcal{C}_{\mathrm{EMSM}_\chi}$$

Arrive at Wilson coefficients at the nuclear scale $\quad c_N$

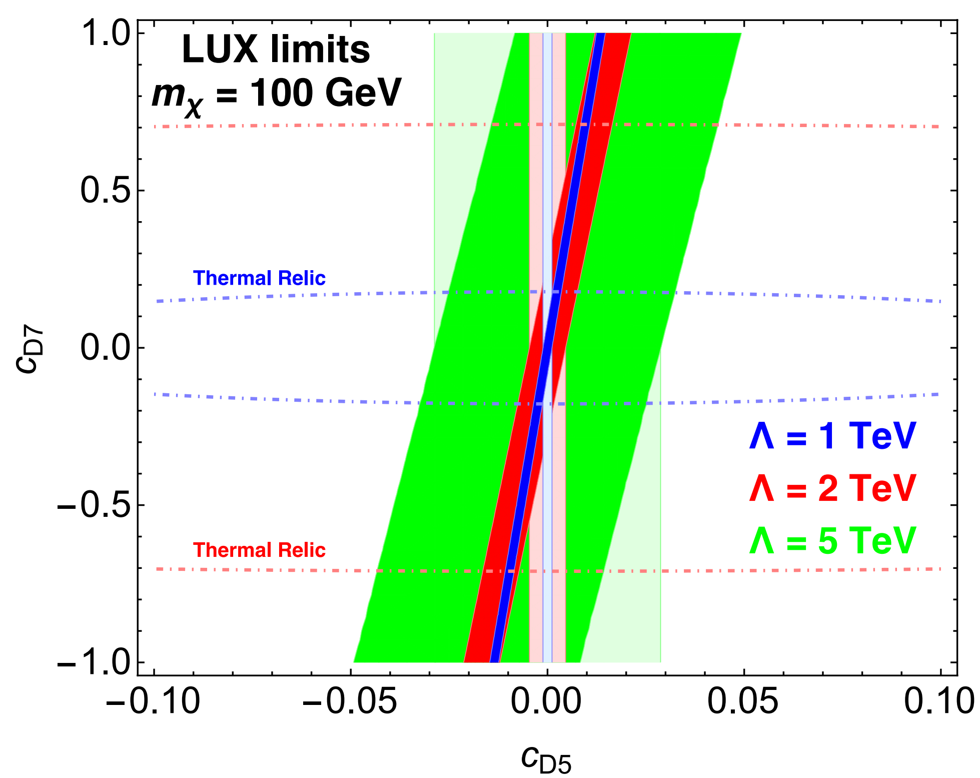
Operator Mixing

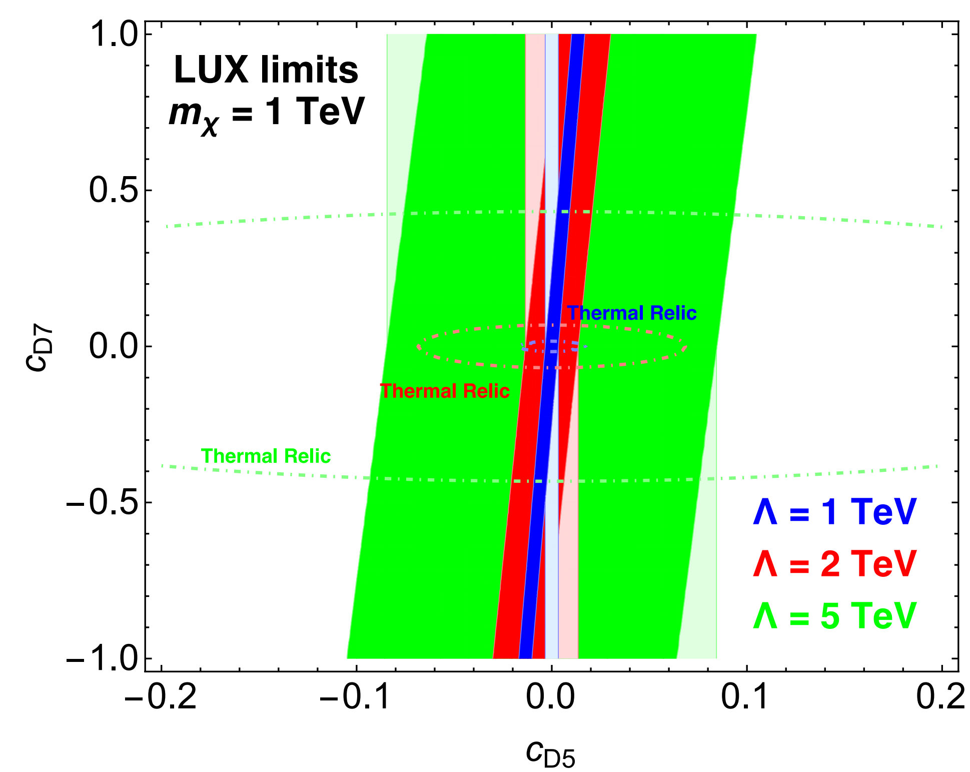


$$\mathcal{L}_{\rm D5} = \frac{c_{\rm D5}}{\Lambda^2}\,\overline{\chi}\,\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu u^i + \sum_i \overline{d^i}\gamma_\mu d^i\right]$$

$$\mathcal{L}_{\rm D7} = \frac{c_{\rm D7}}{\Lambda^2}\,\overline{\chi}\,\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu\gamma_5 u^i + \sum_i \overline{d^i}\gamma_\mu\gamma_5 d^i\right]$$

Limits can be altered when loop effects are included...

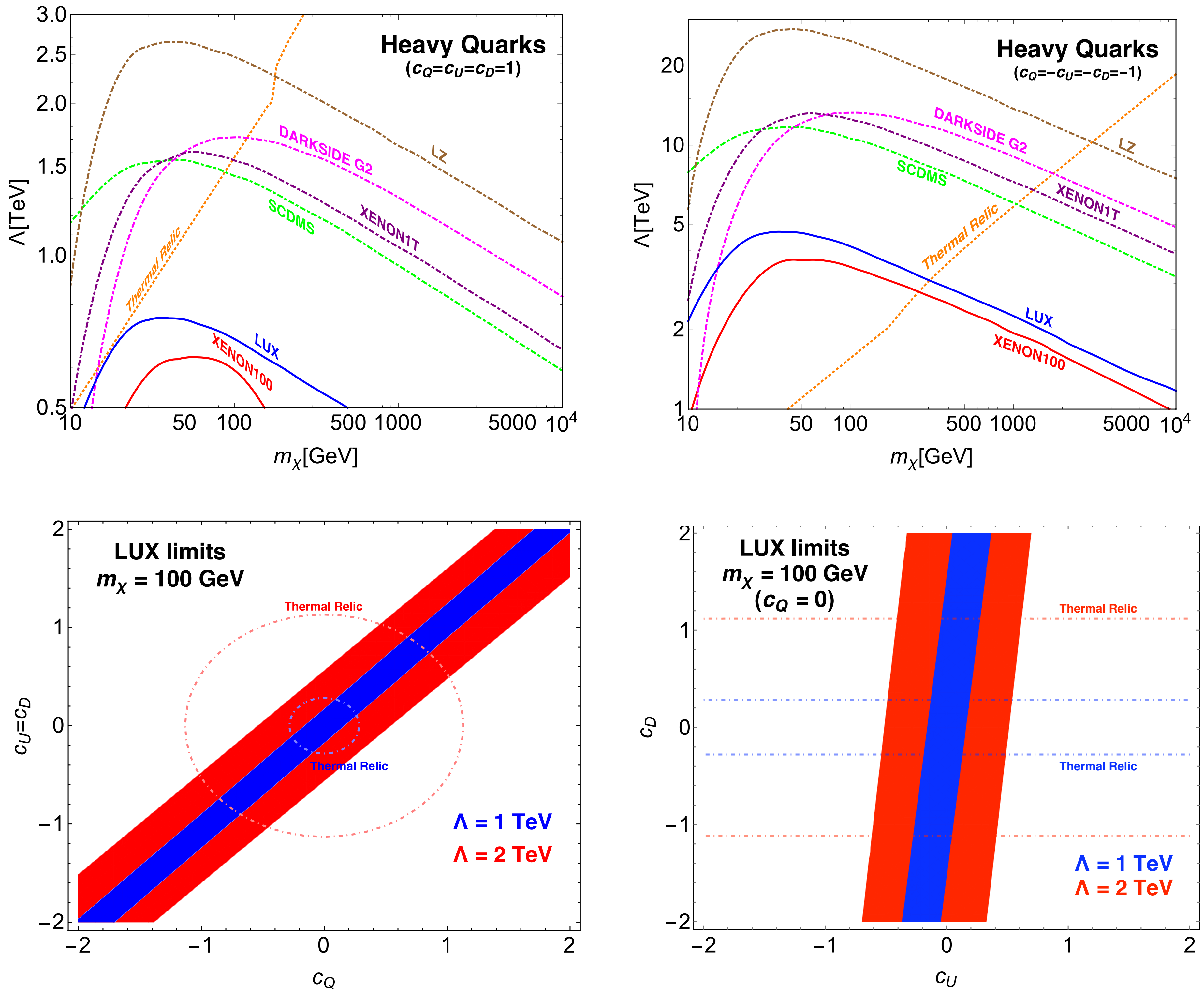




Operator Mixing

Vector and axial-vector current coupling to heavy quarks

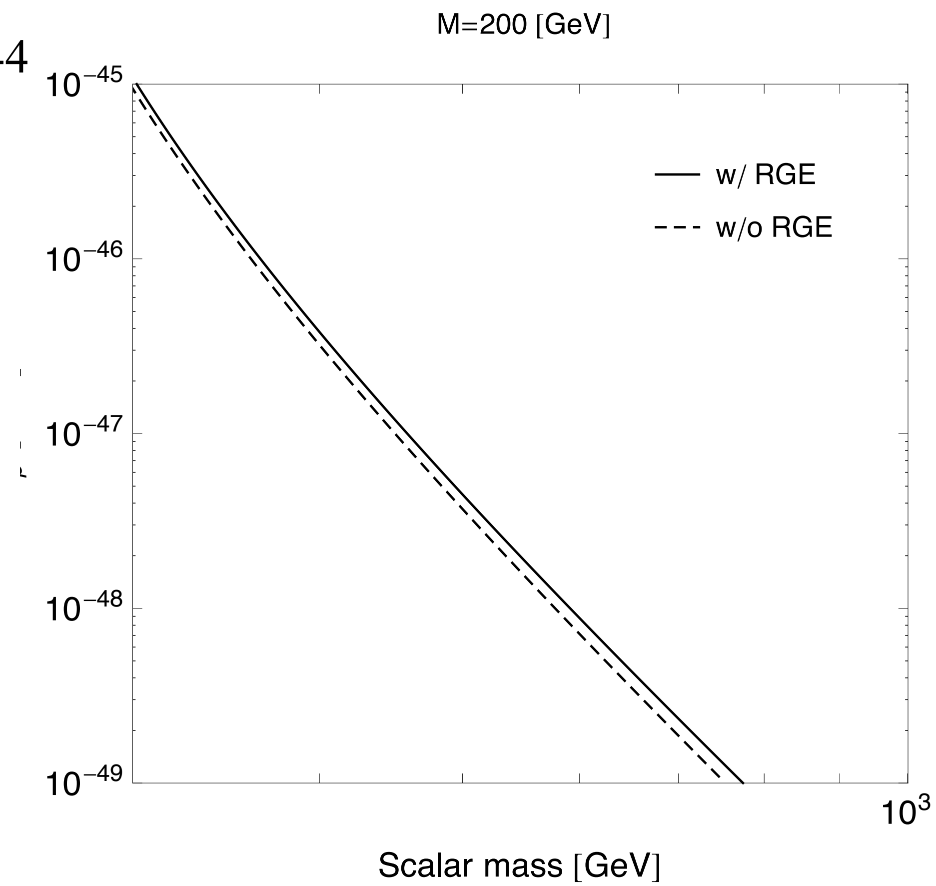
loops as the leading order contribution



Leading order QCD loop effects on the Wilson coefficients for colored mediator exchanges have been calculated for Majorana, scalar, and real vector boson dark matter

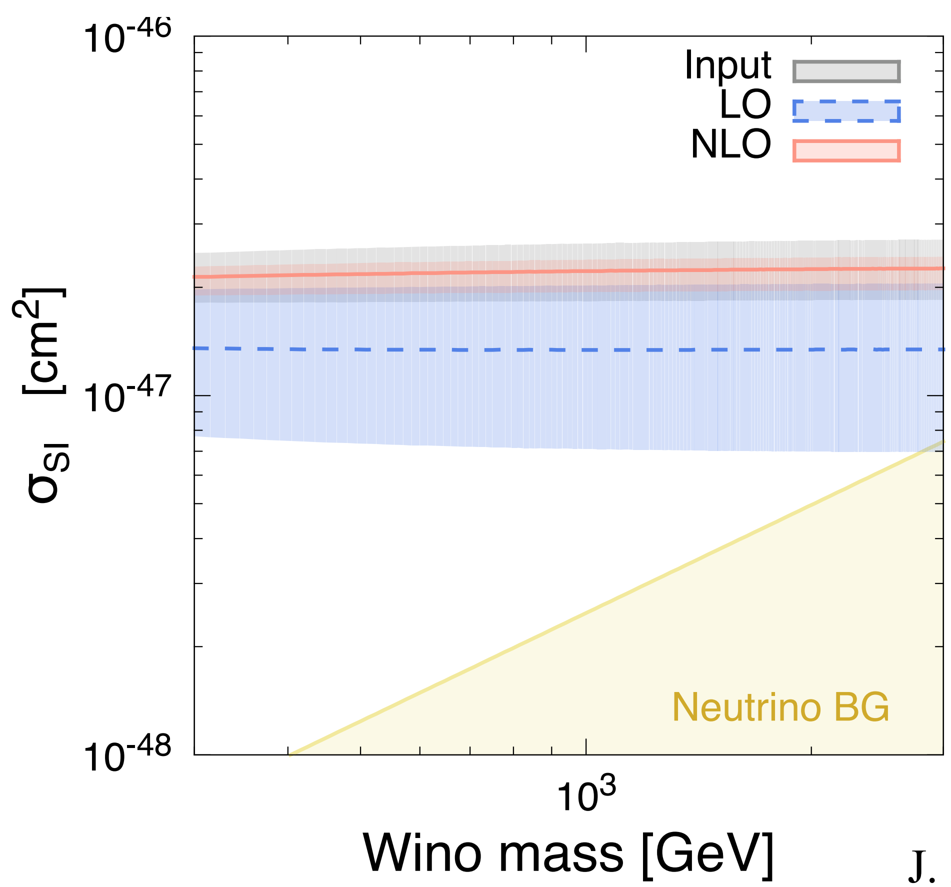
J. Hisano, R. Nagai, and N. Nagata, JHEP **1505** (2015), arXiv:1502.02244

$\mathcal{O}(10)\%$ effects on the cross-section were found



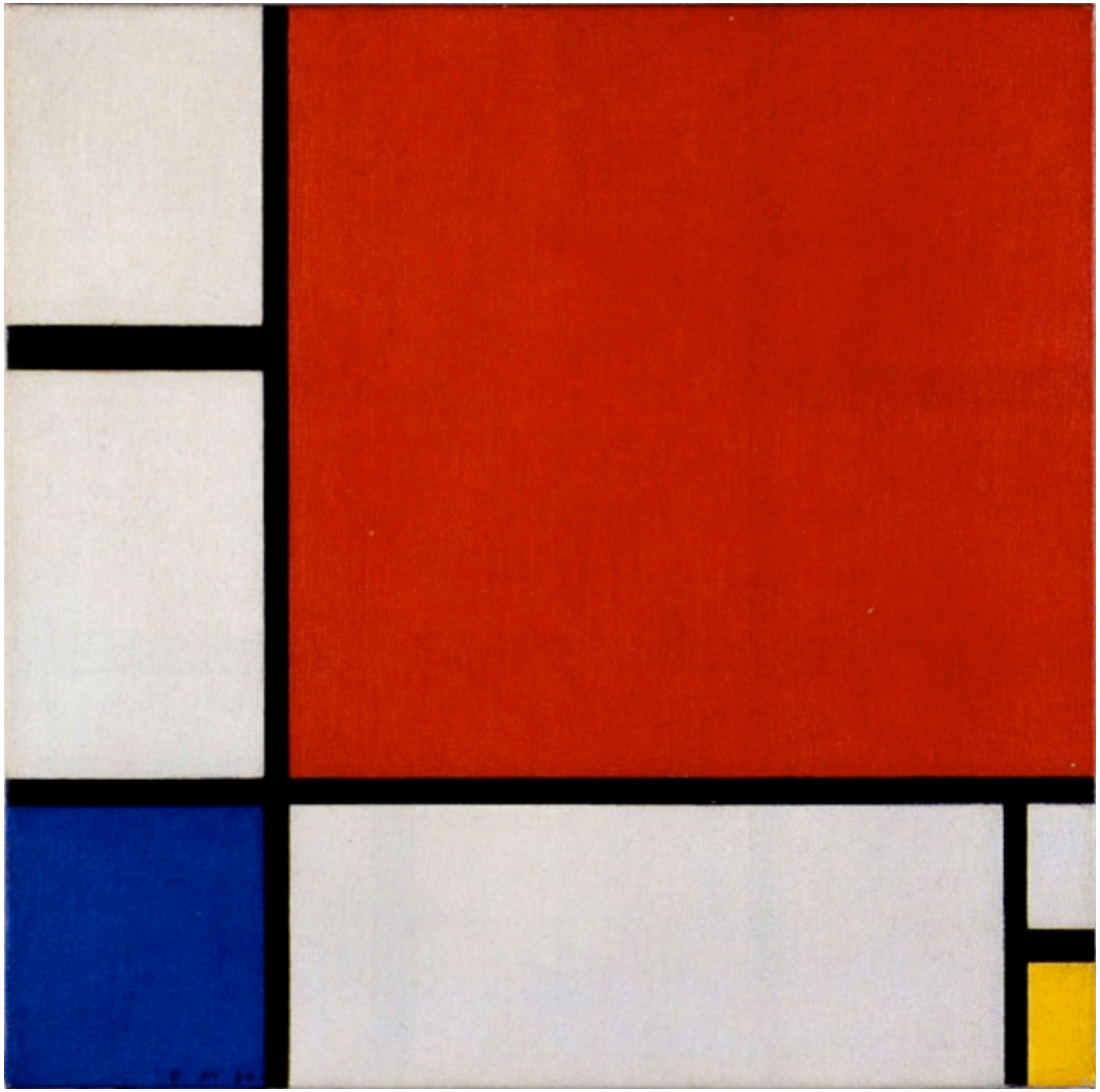
Scattering cross section σ_p

An NLO calculation for WINO dark matter (and a generic $SU(2)_L$ dark matter) was carried out



The theoretical uncertainty is much smaller and the central cross-section value is about 70% larger than for LO corrections alone.

J. Hisano, K. Ishiwata, and N. Nagata, JHEP **1506** (2015), arXiv:1504.00915



Summary

Simplified Models

but not too simple...consistency

capture some broad features of DM searches

combinatorics

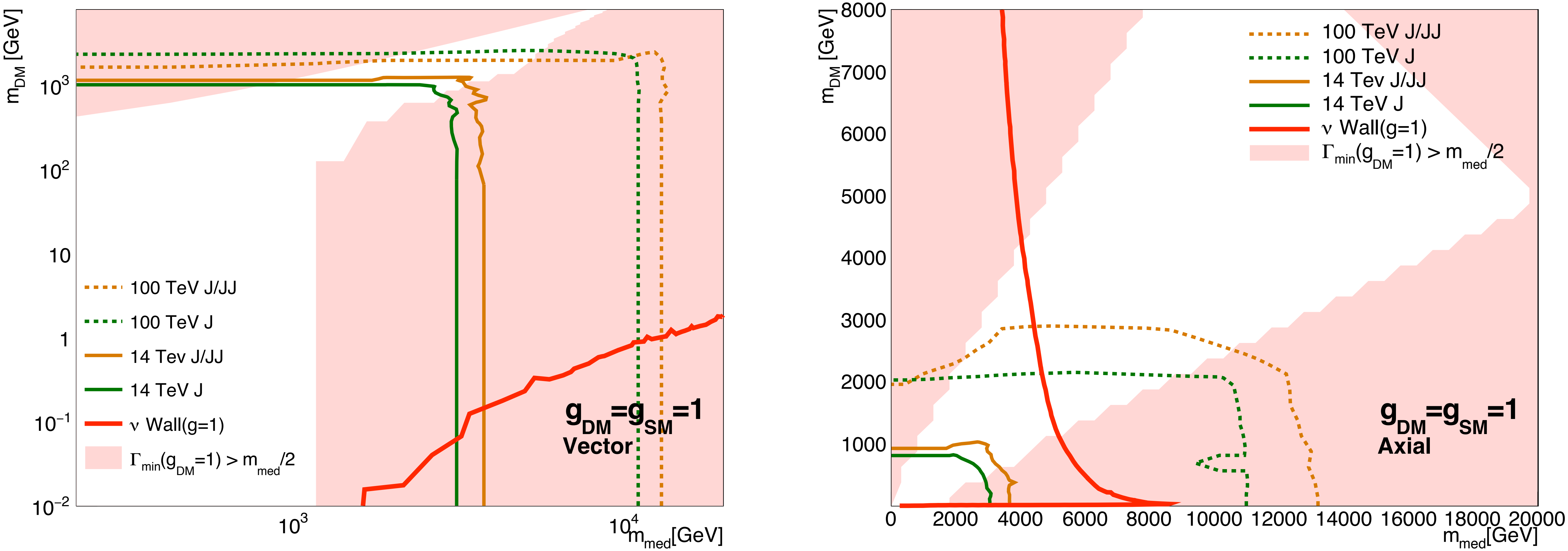
non-standard feature exploration

Neutrino Floor?

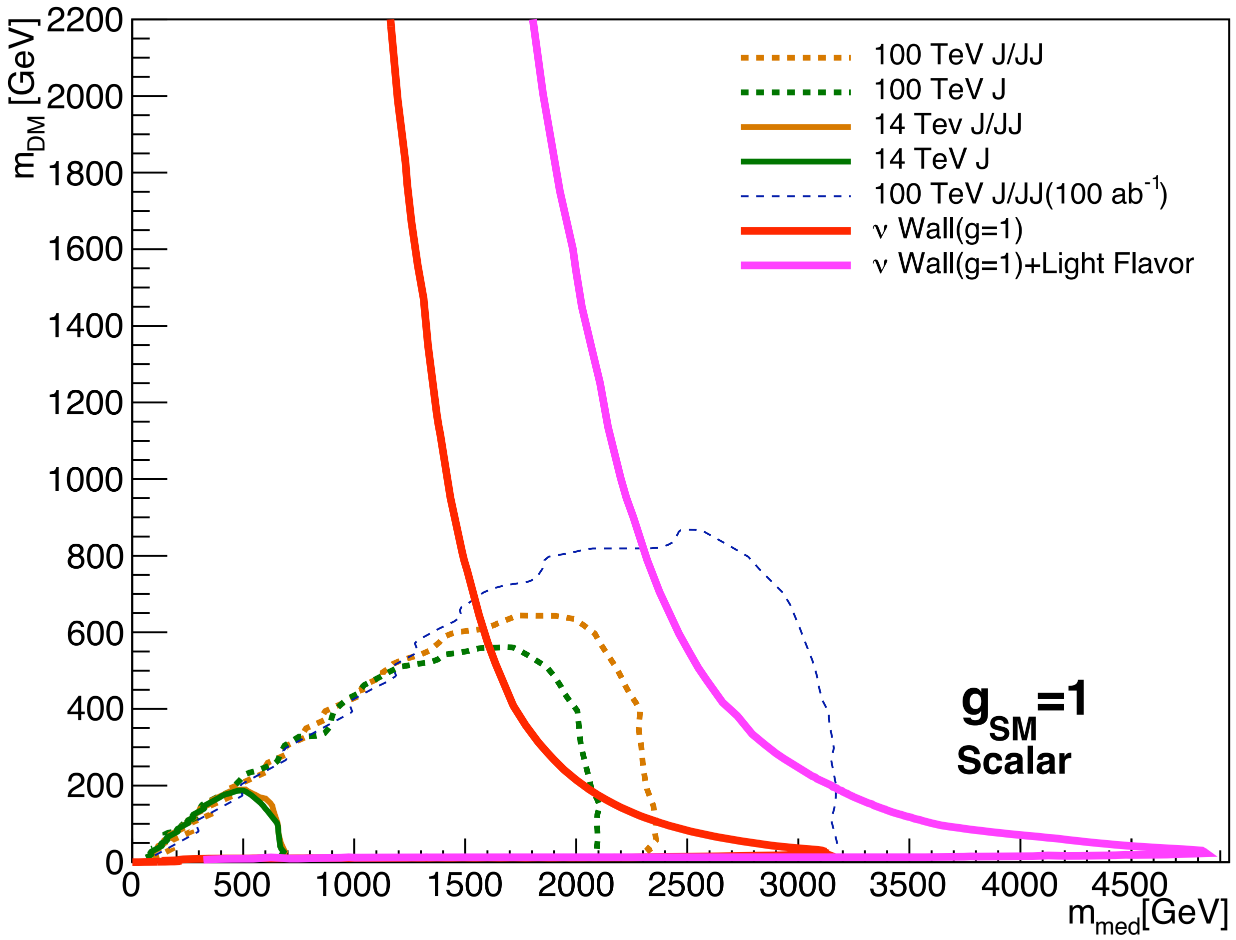
Complimentarity

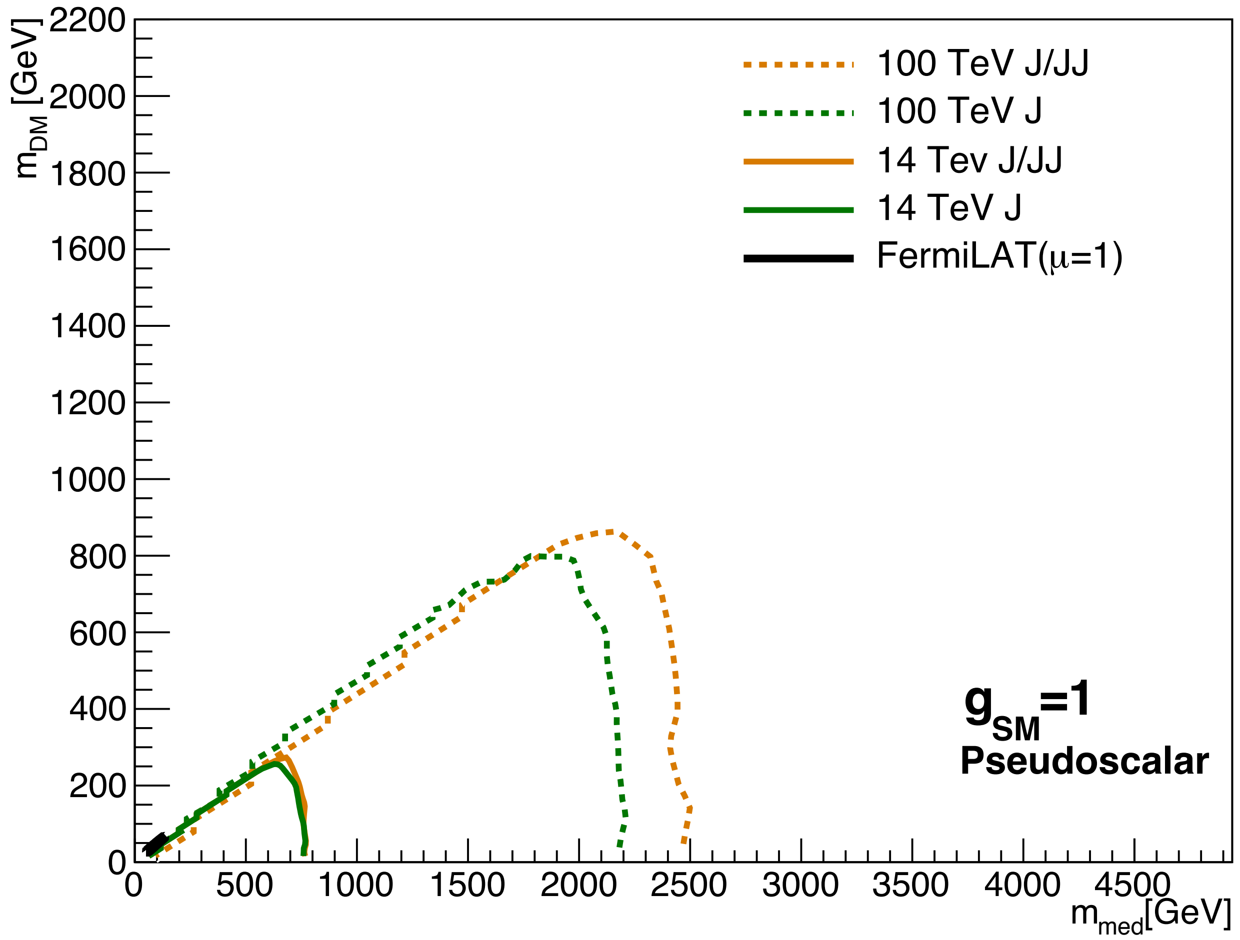
$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_\omega^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F_{SI}^2(E_r)$$

$$Q_\omega = N - (1 - 4\sin^2\theta_\omega)Z$$

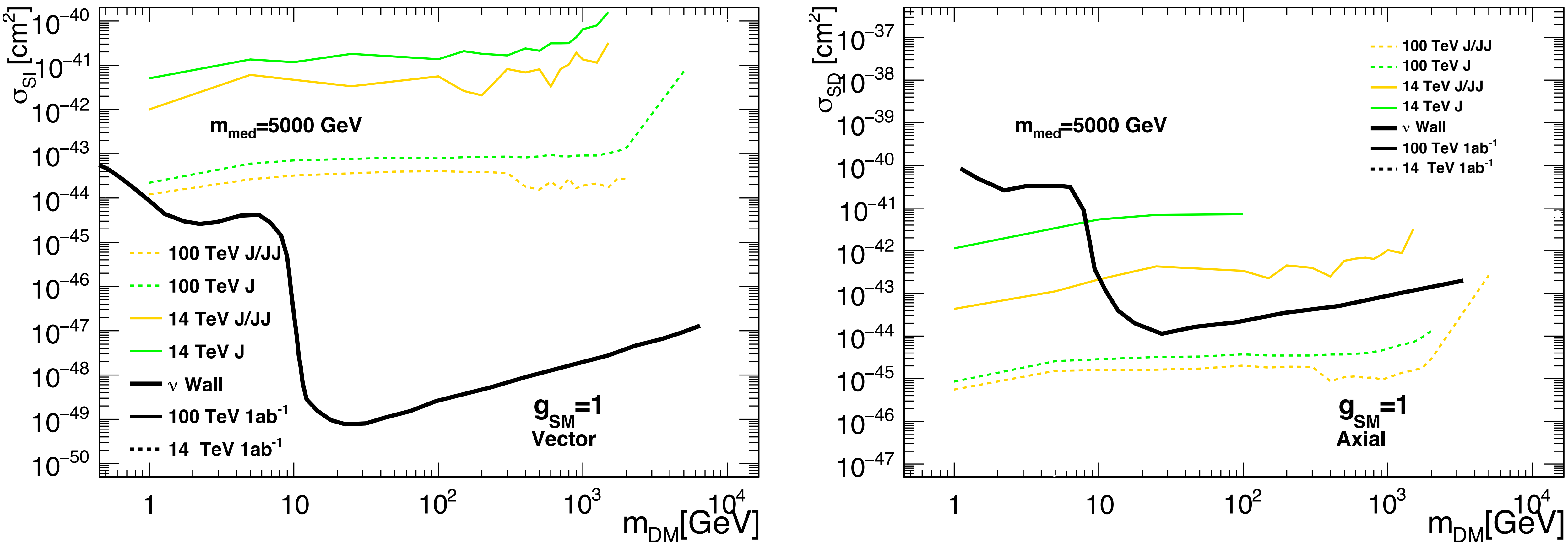


P. Harris, V.V. Khoze, M. Spannowsky, and C. Williams, 1509.02904

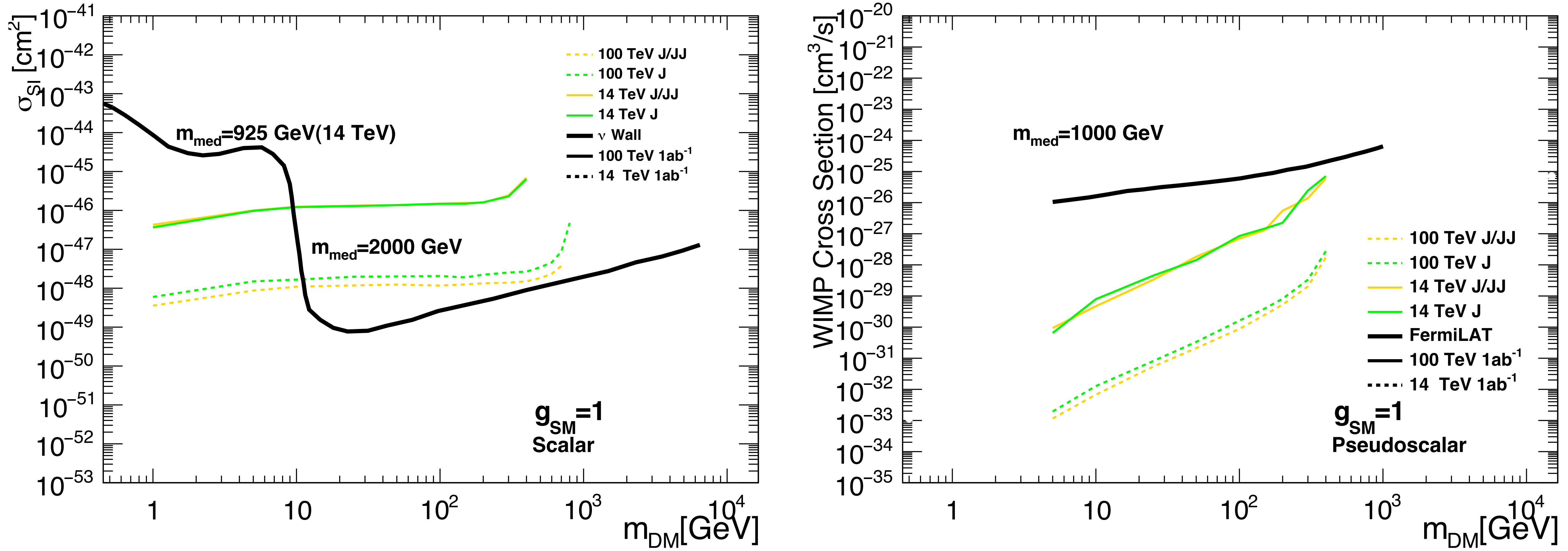




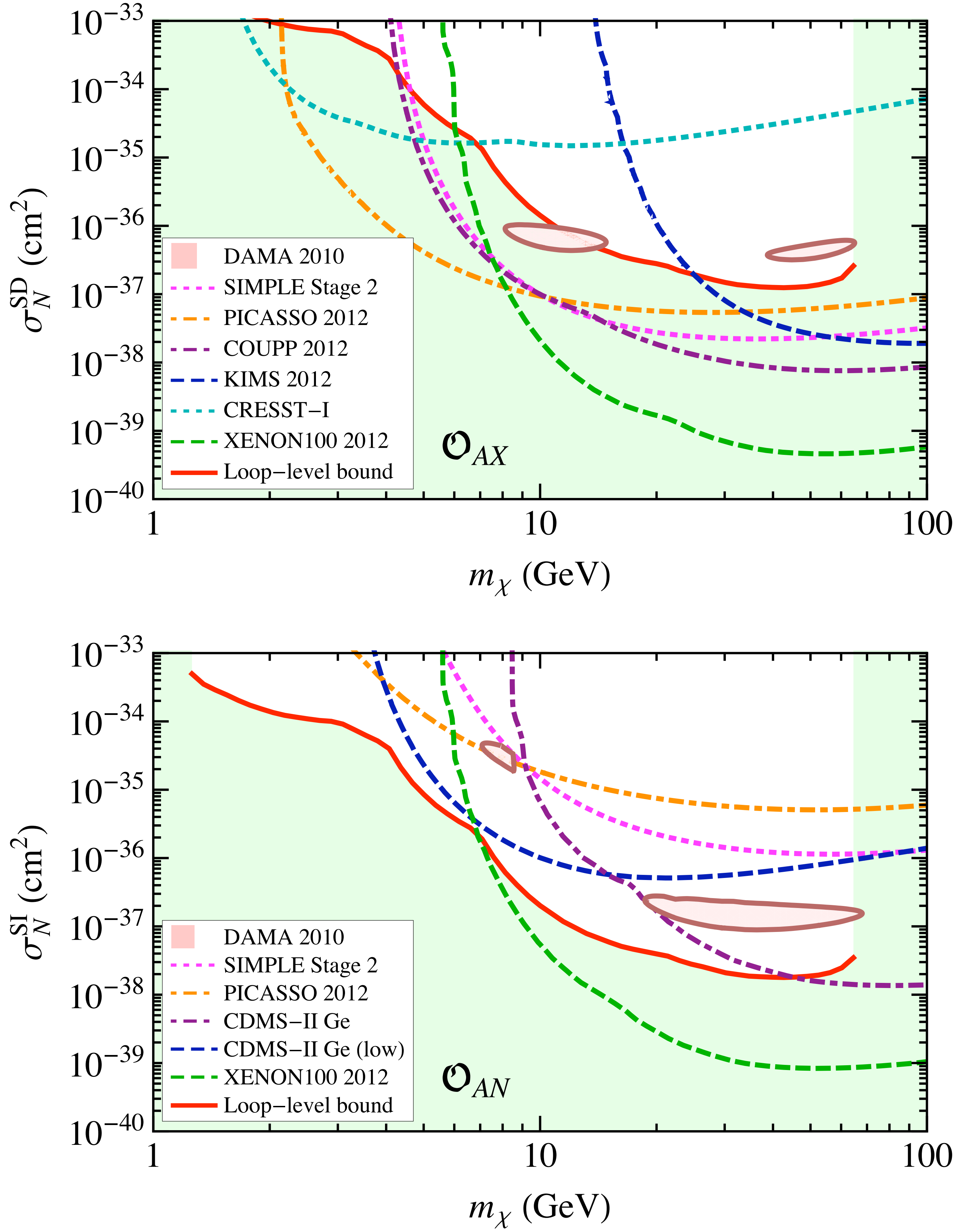
P. Harris, V.V. Khoze, M. Spannowsky, and C. Williams, 1509.02904



σ_{SI} [cm^2]
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
m_{med}=5000 GeV
100 TeV J/JJ
100 TeV J
14 TeV J/JJ
14 TeV J
ν Wall
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
g_{SM}=1
Vector
1
10
10^2
10^3
10^4
m_{DM}[GeV]
σ_{SD} [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
m_{med}=5000 GeV
100 TeV J/JJ
100 TeV J
14 TeV J/JJ
14 TeV J
ν Wall
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
g_{SM}=1
Axial
1
10
10^2
10^3
10^4
m_{DM}[GeV]



σ_{SI} [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
10^{-53}
1
10
10^2
10^3
10^4
m_{DM}[GeV]
100 TeV J/JJ
100 TeV J
14 TeV J/JJ
14 TeV J
ν Wall
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
m_{med}=925 GeV(14 TeV)
m_{med}=2000 GeV
g_{SM}=1
Scalar
WIMP Cross Section [cm^3/s]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
1
10
10^2
10^3
10^4
m_{DM}[GeV]
m_{med}=1000 GeV
100 TeV J/JJ
100 TeV J
14 TeV J/JJ
14 TeV J
FermiLAT
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
g_{SM}=1
Pseudoscalar



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$$\Gamma^{V}_{f\overline{f}} = \frac{g_f^2(m_{\mathrm{MED}}^2 + 2m_f^2)}{12\pi m_{\mathrm{MED}}}\sqrt{1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}} \quad , \quad \Gamma^{A}_{f\overline{f}} = \frac{g_f^2(m_{\mathrm{MED}}^2 - 4m_f^2)}{12\pi m_{\mathrm{MED}}}\sqrt{1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}}$$

$$\Gamma^{S}_{f\overline{f}} = \frac{g_f^2}{8\pi}\, m_{\mathrm{MED}} \left(1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}\right)^{\frac{3}{2}} \quad , \quad \Gamma^{P}_{f\overline{f}} = \frac{g_f^2}{8\pi}\, m_{\mathrm{MED}} \left(1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}\right)^{\frac{1}{2}}$$

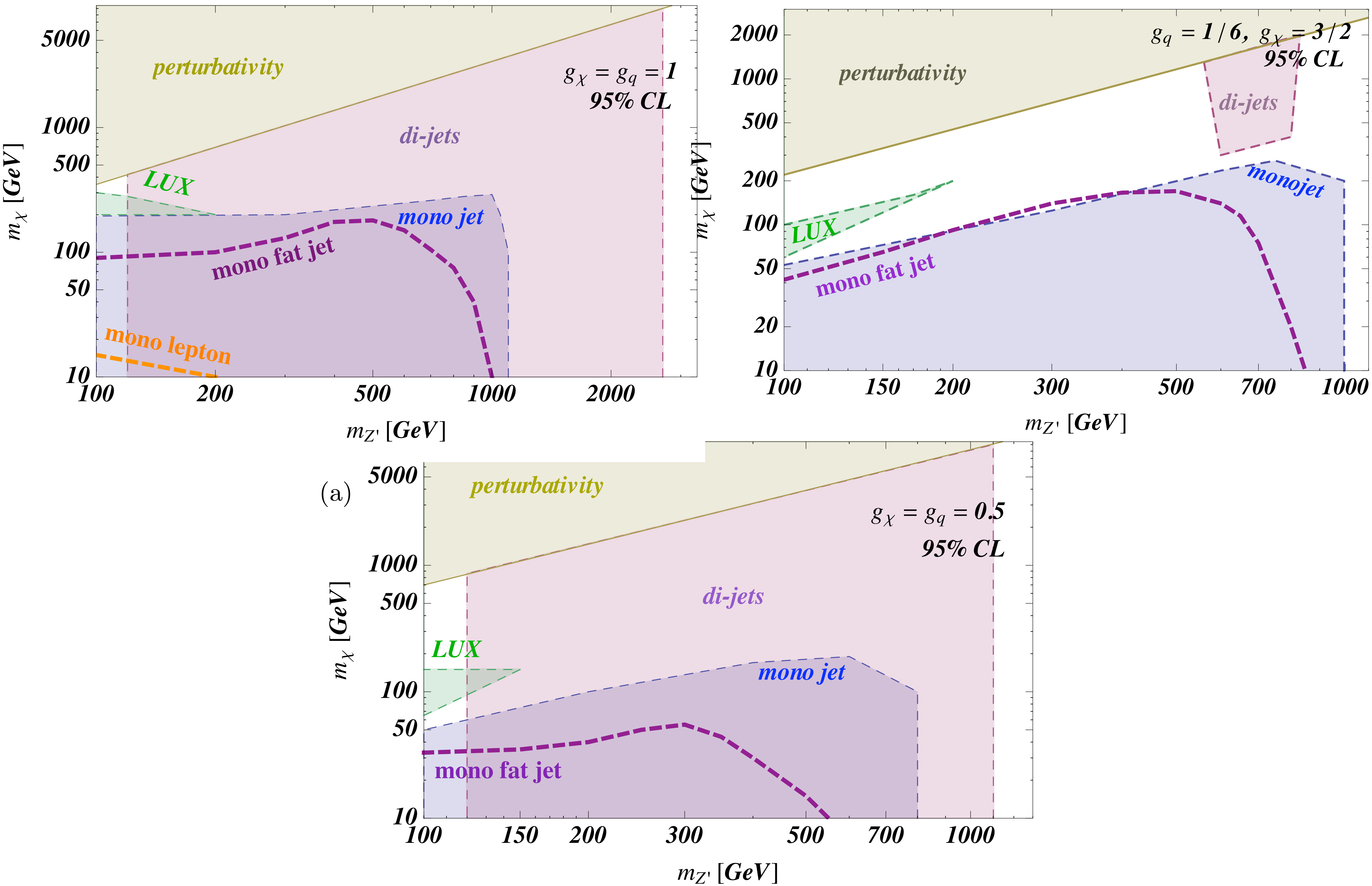


Figure 5. Parameter space for the s-channel Z' model, for choices of (a) $g_q = g_\chi = 1$ and (b) $g_q = g_\chi = 0.5$ and (c) $g_q = 1/6$ and $g_\chi = 3/2$. Exclusions are shown as shaded regions for LUX and for mono-jet and di-jets at 8 TeV, and the reaches are shown for the mono lepton ((a) only) and mono fat jet searches at 14 TeV 3000 fb^{-1}. Note differing axes.

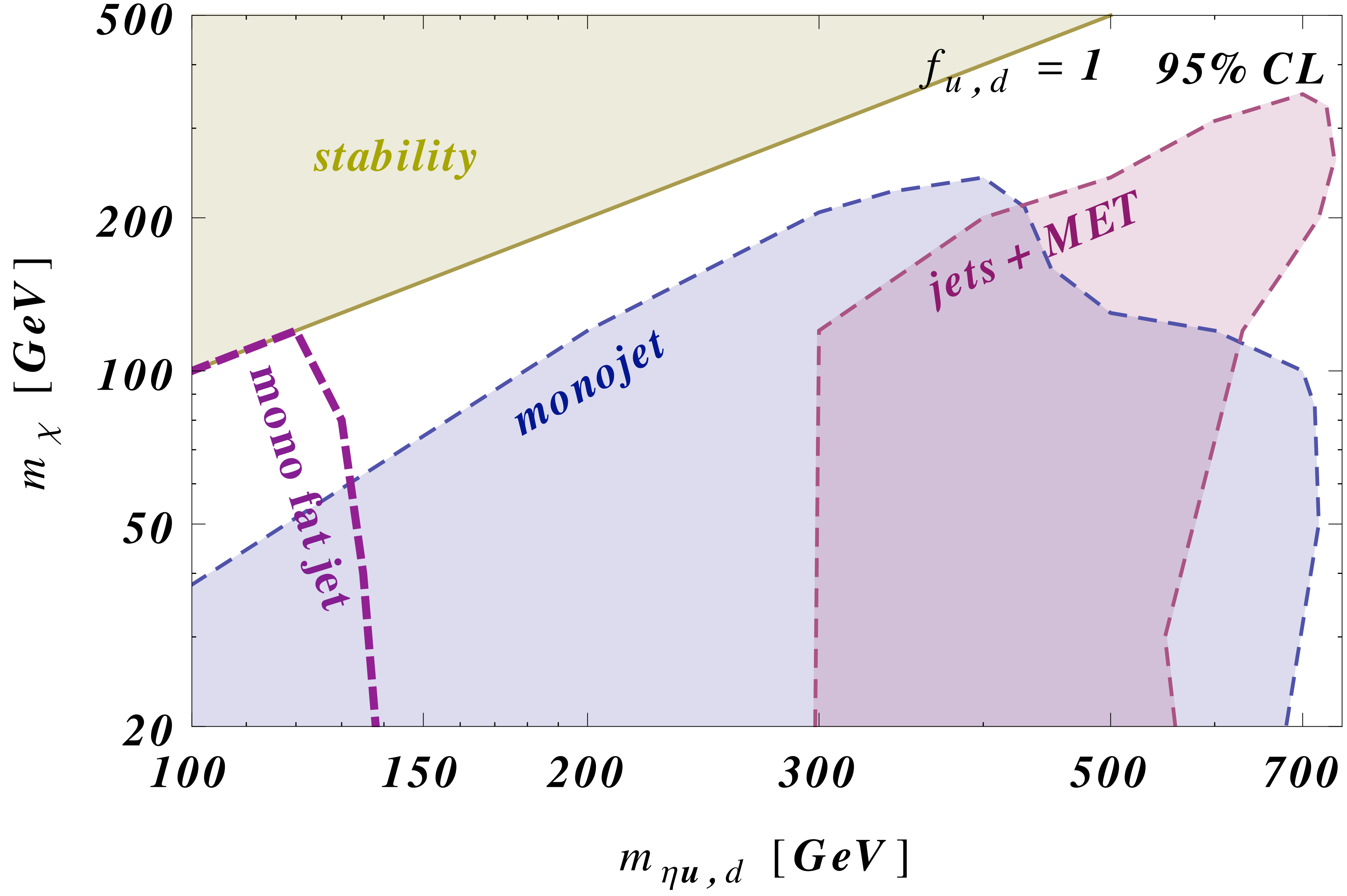


Figure 4. Parameter space for the t-channel colored scalar model, for $f_{u,d} = 1$. Exclusions are shown as shaded regions for the mono and multi jet at 8 TeV, and the reach is shown for the mono fat jet at 14 TeV 3000 fb^{-1}.

Scalar mediator

Interaction Tables

DM bilinear	***SM fermion bilinear***			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2$, $\sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim v_\perp^2$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim 1}$

Interaction Tables

DM bilinear	***SM fermion bilinear***			
scalar DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\phi^\dagger\phi$	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^2}$	$-$	$-$
$\phi^\dagger\overleftrightarrow{\partial}_\mu\phi$ (complex only)	$-$	$-$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim v_\perp^2$
vector DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$X^\mu X_\mu^\dagger$	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^2}$	$-$	$-$
$X^\nu\partial_\nu X_\mu^\dagger$	$-$	$-$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim q^2 \cdot v_\perp^2$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim q^2$

DM	***Mediator***	***Interaction***	***Assessment***
Dirac Fermion	Spin-0	$1 \pm \gamma^5$	$\boldsymbol{\sigma v \sim 1}$, LHC OK
Dirac Fermion	Spin-1	$\gamma^\mu(1 \pm \gamma^5)$	$\boldsymbol{\sigma v \sim 1}$, LHC OK
Majorana Fermion	Spin-0	$1 \pm \gamma^5$	$\sigma v \sim v^2$
Majorana Fermion	Spin-1	$\gamma^\mu(1 \pm \gamma^5)$	$\sigma v \sim v^2$
Real Scalar	Spin-1/2	$1 \pm \gamma^5$	$\sigma v \sim 1$, LHC Excluded
Complex Scalar	Spin-1/2	$1 \pm \gamma^5$	$\sigma v \sim v^2$
Real Vector	Spin-1/2	$\gamma^\mu(1 \pm \gamma^5)$	$\boldsymbol{\sigma v \sim 1}$, LHC OK
Complex Vector	Spin-1/2	$\gamma^\mu(1 \pm \gamma^5)$	$\boldsymbol{\sigma v \sim 1}$, LHC OK

Interaction Tables

Model Number	***DM***	***Mediator***	***Interactions***	**Elastic Scattering**	**Near Future Reach?**	
					Direct	**LHC**
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Interaction Tables

$\langle S \rangle_{\mathrm{DM}}$	**Type**	**Interaction**	**Elastic Scattering**	**Kinematic Suppression**
1/2	Dirac	$\bar{\chi}\gamma^5\chi\bar{q}q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Majorana	$\bar{\chi}\gamma^5\chi\bar{q}q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Majorana	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	SI (vector)	1
1/2	Dirac	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	SD	$(q/2m_n)^2$ or $(q/2m_\chi)^2$
1/2	Dirac	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	SD	1
1/2	Majorana	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	SD	1
0	Complex	$\phi^\dagger\phi\bar{q}q$	SI (scalar)	1
0	Real	$\phi^2\bar{q}q$	SI (scalar)	1
0	Complex	$\phi^\dagger\phi\bar{q}\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
0	Real	$\phi^2\bar{q}\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
1	Complex	$B^\dagger_\mu B^\mu\bar{q}q$	SI (scalar)	1
1	Real	$B_\mu B^\mu\bar{q}q$	SI (scalar)	1
1	Complex	$B^\dagger_\mu B^\mu\bar{q}\gamma^5 q$	SD	$(q/2m_n)^2$
1	Real	$B_\mu B^\mu\bar{q}\gamma^5 q$	SD	$(q/2m_n)^2$

Interaction Tables

S	L	J	C	P
0	0	0	+	-
0	1	1	-	+
1	0	1	-	-
1	1	0,1,2	+	+
1	2	1,2,3	-	-
1	3	2,3,4	+	+

S	L	J	C	P
0	0	0	+	+
0	1	1	-	-
1	0	1	-	+
1	1	0,1,2	+	-
1	2	1,2,3	-	+
2	0	2	+	+
2	1	1,2,3	-	-
2	2	0,1,2,3,4	+	+
2	3	1,2,3,4,5	-	-
2	4	2,3,4,5,6	+	+

Interaction Tables

bilinear	C	P	J	state
$\bar{\psi}\psi$	+	+	0	$S = 1,\ L = 1$
$\imath\bar{\psi}\gamma^5\psi$	+	-	0	$S = 0,\ L = 0$
$\bar{\psi}\gamma^0\psi$	-	+	0	none
$\bar{\psi}\gamma^i\psi$	-	-	1	$S = 1,\ L = 0, 2$
$\bar{\psi}\gamma^0\gamma^5\psi$	+	-	0	$S = 0,\ L = 0$
$\bar{\psi}\gamma^i\gamma^5\psi$	+	+	1	$S = 1,\ L = 1$
$\bar{\psi}\sigma^{0i}\psi$	-	-	1	$S = 1,\ L = 0, 2$
$\bar{\psi}\sigma^{ij}\psi$	-	+	1	$S = 0,\ L = 1$
$\phi^\dagger\phi$	+	+	0	$S = 0,\ L = 0$
$\imath Im(\phi^\dagger\partial^0\phi)$	-	+	0	none
$\imath Im(\phi^\dagger\partial^i\phi)$	-	-	1	$S = 0,\ L = 1$
$B_\mu^\dagger B^\mu$	+	+	0	$S = 0,\ L = 0;\ S = 2,\ L = 2$
$\imath Im(B_\nu^\dagger\partial^0 B^\nu)$	-	+	0	none
$\imath Im(B_\nu^\dagger\partial^i B^\nu)$	-	-	1	$S = 0,\ L = 1;\ S = 2,\ L = 1, 3$
$\imath(B_i^\dagger B_j - B_j^\dagger B_i)$	-	+	1	$S = 1,\ L = 0, 2$
$\imath(B_i^\dagger B_0 - B_0^\dagger B_i)$	-	-	1	$S = 0,\ L = 1;\ S = 2,\ L = 1, 3$
$\epsilon^{0ijk}B_i\partial_j B_k$	+	-	0	$S = 1,\ L = 1$
$-\epsilon^{0ijk}B_0\partial_j B_k$	+	+	1	$S = 2,\ L = 2$
$B^\nu\partial_\nu B_0$	+	+	0	$S = 0,\ L = 0;\ S = 2,\ L = 2$
$B^\nu\partial_\nu B_i$	+	-	1	$S = 1,\ L = 1$

Interaction Tables

S	L	J	$J_z = S_z$	fermion helicities
0	0	0	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	0	1	1	$f_R,\ \bar{f}_R$
1	0	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	0	1	-1	$f_L,\ \bar{f}_L$
0	1	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	1	0	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	1	1	1	$f_R,\ \bar{f}_R$
1	1	1	0	-
1	1	1	-1	$f_L,\ \bar{f}_L$
1	2	1	1	$f_R,\ \bar{f}_R$
1	2	1	0	$f_L,\ \bar{f}_R;\ f_R,\ \bar{f}_L$
1	2	1	-1	$f_L,\ \bar{f}_L$

Interaction Tables

Name	Interaction Structure	$\sigma_{\rm SI}$ suppression	$\sigma_{\rm SD}$ suppression	s-wave?
F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
F9	$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes
S1	$\phi^\dagger\phi\bar{q}q$ or $\phi^2\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	Yes
S2	$\phi^\dagger\phi\bar{q}\gamma^5 q$ or $\phi^2\bar{q}\gamma^5 q$	0	q^2 (SM)	Yes
S3	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu q$	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); $v^{\perp 2}$ (DM)	No
S4	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	0	$v^{\perp 2}$ (SM or DM)	No
V1	$B_\mu^\dagger B^\mu\bar{q}q$ or $B_\mu B^\mu\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	Yes
V2	$B_\mu^\dagger B^\mu\bar{q}\gamma^5 q$ or $B_\mu B^\mu\bar{q}\gamma^5 q$	0	q^2 (SM)	Yes
V3	$B_\nu^\dagger\partial_\mu B^\nu\bar{q}\gamma^\mu q$	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); $v^{\perp 2}$ (DM)	No
V4	$B_\nu^\dagger\partial_\mu B^\nu\bar{q}\gamma^\mu\gamma^5 q$	0	$v^{\perp 2}$ (SM or DM)	No
V5	$(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu} q$	$q^2 v^{\perp 2}$ (SM)	1	Yes
V6	$(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu}\gamma^5 q$	q^2 (SM)	$v^{\perp 2}$ (SM)	Yes
V7	$B_\nu^\dagger\partial^\nu B_\mu\bar{q}\gamma^\mu q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$	$v^{\perp 2}$ (SM); q^2 (DM)	q^2 (SM); q^2 (DM)	No
V8	$B_\nu^\dagger\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	q^2 (DM)	$\propto m_f^2/m_X^2$
V9	$\epsilon^{\mu\nu\rho\sigma}B_\nu^\dagger\partial_\rho B_\sigma\bar{q}\gamma_\mu q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (DM or SM)	q^2 (SM)	No
V10	$\epsilon^{\mu\nu\rho\sigma}B_\nu^\dagger\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	No

Interaction Tables

J	S_{init}	L_{init}	S_{final}	L_{final}	Interaction structure
0	0	0	0	0	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$, $\bar{X}\gamma^0\gamma^5 X\bar{q}\gamma^0\gamma^5 q$
0	0	0	1	1	$\bar{X}\gamma^5 X\bar{q}q$
0	1	1	0	0	$\bar{X}X\bar{q}\gamma^5 q$
0	1	1	1	1	$\bar{X}X\bar{q}q$
1	0	1	0	1	$\bar{X}\sigma^{ij}X\bar{q}\sigma^{ij}q$
1	0	1	1	0	$\bar{X}\sigma^{ij}X\bar{q}\sigma^{ij}\gamma^5 q$
1	1	0	0	1	$\bar{X}\sigma^{ij}\gamma^5 X\bar{q}\sigma^{ij}q$
1	1	0	1	0	$\bar{X}\gamma^i X\bar{q}\gamma^i q$, $\bar{X}\sigma^{ij}\gamma^5 X\bar{q}\sigma^{ij}\gamma^5 q$
1	1	1	1	1	$\bar{X}\gamma^i\gamma^5 X\bar{q}\gamma^i\gamma^5 q$
1	1	0	1	1	$\bar{X}\gamma^i X\bar{q}\gamma^i\gamma^5 q$
1	1	1	1	0	$\bar{X}\gamma^i\gamma^5 X\bar{q}\gamma^i q$
0	0	0	0	0	$B^\dagger_\mu B^\mu\bar{q}\gamma^5 q$, $B^\nu\partial_\nu B_0\bar{q}\gamma^0\gamma^5 q$
0	0	0	1	1	$B^\dagger_\mu B^\mu\bar{q}q$
0	1	1	0	0	$\epsilon^{0ijk}B_i\partial_j B_k\bar{q}\gamma^0\gamma^5 q$
1	0	1	0	1	$\imath(B^\dagger_i B_0 - B^\dagger_i B_0)\bar{q}\sigma^{0i}\gamma^5 q$
1	0	1	1	0	$\imath(B^\dagger_i B_0 - B^\dagger_i B_0)\bar{q}\sigma^{0i}q$, $\imath Im(B^\dagger_\nu\partial_i B^\nu)\bar{q}\gamma^i q$
1	0	1	1	1	$\imath Im(B^\dagger_\nu\partial_i B^\nu)\bar{q}\gamma^i\gamma^5 q$
1	1	0	0	1	$\imath(B^\dagger_i B_j - B^\dagger_i B_j)\bar{q}\sigma^{ij}q$
1	1	0	1	0	$\imath(B^\dagger_i B_j - B^\dagger_i B_j)\bar{q}\sigma^{ij}\gamma^5 q$
1	1	1	1	0	$B^\nu\partial_\nu B_i\bar{q}\gamma^i q$
1	1	1	1	1	$B^\nu\partial_\nu B_i\bar{q}\gamma^i\gamma^5 q$
1	2	2	1	0	$\epsilon^{0ijk}B_j\partial_0 B_k\bar{q}\gamma_i q$
1	2	2	1	1	$\epsilon^{0ijk}B_j\partial_0 B_k\bar{q}\gamma_i\gamma^5 q$

	Interaction Structure	SI (S_X-dep.)	SD (S_X-dep.)	SD (S_{SM}-dep.)	SI Class	SD Class
F1	$\bar{X}X\bar{q}q$	1	1	$S_{\hat{\eta}}$	1	C
F2	$\bar{X}\gamma^5 X\bar{q}q$	$S_{\hat{q}}$	$S_{\hat{q}}$	$S_{\hat{\eta}}$	2	F
F3	$\bar{X}X\bar{q}\gamma^5 q$	-	1	$S_{\hat{q}}$	-	A
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	-	$S_{\hat{q}}$	$S_{\hat{q}}$	-	D
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	1	1	$S_{\hat{\eta}}$	1	C
	(vanishes for Majorana X)		$S_{\hat{v}^\perp}$	$S_{\hat{v}^\perp}$		H
			$S_{\hat{\eta}}$	$S_{\hat{\eta}}$		L
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$S_{\hat{v}^\perp}$	$S_{\hat{\eta}}$	$S_{\hat{v}^\perp}$	3	K
			$S_{\hat{v}^\perp}$	$S_{\hat{\eta}}$		I
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$	$S_{\hat{v}^\perp}$	1	$S_{\hat{v}^\perp}$	3	B
	(vanishes for Majorana X)		$S_{\hat{v}^\perp}$	$S_{\hat{\eta}}$		I
			$S_{\hat{\eta}}$	$S_{\hat{v}^\perp}$		K
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$S_{\hat{\eta}}$	$S_{\hat{q}}$	$S_{\hat{q}}$	4	D
			$S_{\hat{v}^\perp}$	$S_{\hat{v}^\perp}$		H
			$S_{\hat{\eta}}$	$S_{\hat{\eta}}$		L
F9	$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$	1 , $S_{\hat{\eta}}$	$S_{\hat{q}}$	$S_{\hat{q}}$	$1, 4$	D
	(vanishes for Majorana X)		$S_{\hat{v}^\perp}$	$S_{\hat{v}^\perp}$		H
			$S_{\hat{\eta}}$	$S_{\hat{\eta}}$		L
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$	$S_{\hat{q}}$	1	$S_{\hat{q}}$	2	A
	(vanishes for Majorana X)		$S_{\hat{q}}$	$S_{\hat{\eta}}$		F
			$S_{\hat{\eta}}$	$S_{\hat{q}}$		J

	Interaction Structure	SI (S_X-dep.)	SD (S_X-dep.)	SD (S_{SM}-dep.)	SI Class	SD Class
V1	$B^\dagger_\mu B^\mu \bar{q}q$ or $B_\mu B^\mu \bar{q}q$	1	1	$S_{\hat{\eta}}$	1	C
V2	$B^\dagger_\mu B^\mu \bar{q}\gamma^5 q$ or $B_\mu B^\mu \bar{q}\gamma^5 q$	-	1	$S_{\hat{q}}$	-	A
V3	$B^\dagger_\nu \partial_\mu B^\nu \bar{q}\gamma^\mu q$	1	1	$S_{\hat{\eta}}$	1	C
V4	$B^\dagger_\nu \partial_\mu B^\nu \bar{q}\gamma^\mu \gamma^5 q$	-	1	$S_{\hat{v}^\perp}$	1	B
V5	$(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu} q$	$S_{\hat{\eta}}$	$S_{\hat{q}}$ $S_{\hat{v}^\perp}$ $S_{\hat{\eta}}$	$S_{\hat{q}}$ $S_{\hat{v}^\perp}$ $S_{\hat{\eta}}$	4	D H L
V6	$(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}\gamma^5 q$	$S_{\hat{q}}$	$S_{\hat{q}}$ $S_{\hat{\eta}}$	$S_{\hat{\eta}}$ $S_{\hat{q}}$	2	F J
V7	$B^\dagger_\nu \partial^\nu B_\mu \bar{q}\gamma^\mu q$ or $B_\nu \partial^\nu B_\mu \bar{q}\gamma^\mu q$	$\Pi_{\hat{q}\hat{v}^\perp}$	$\Pi_{\hat{q}\hat{v}^\perp}$ $\Pi_{\hat{q}\hat{\eta}}$	$S_{\hat{\eta}}$ $S_{\hat{v}^\perp}$		
V8	$B^\dagger_\nu \partial^\nu B_\mu \bar{q}\gamma^\mu \gamma^5 q$ or $B_\nu \partial^\nu B_\mu \bar{q}\gamma^\mu \gamma^5 q$	$S_{\hat{q}}$ $\Pi_{\hat{q}\hat{\eta}}$	$\Pi_{\hat{q}\hat{v}}$ $\Pi_{\hat{q}\hat{q}}$ $\Pi_{\hat{q}\hat{\eta}}$	$S_{\hat{v}}$ $S_{\hat{q}}$ $S_{\hat{\eta}}$	2	
V9	$\epsilon^{\mu\nu\rho\sigma} B^\dagger_\nu \partial_\rho B_\sigma \bar{q}\gamma_\mu q$ or $\epsilon^{\mu\nu\rho\sigma} B_\nu \partial_\rho B_\sigma \bar{q}\gamma_\mu q$	$S_{\hat{v}^\perp}$	$S_{\hat{v}^\perp}$ $S_{\hat{\eta}}$	$S_{\hat{\eta}}$ $S_{\hat{v}^\perp}$	3	I K
V10	$\epsilon^{\mu\nu\rho\sigma} B^\dagger_\nu \partial_\rho B_\sigma \bar{q}\gamma_\mu \gamma^5 q$ or $\epsilon^{\mu\nu\rho\sigma} B_\nu \partial_\rho B_\sigma \bar{q}\gamma_\mu \gamma^5 q$	$S_{\hat{\eta}}$	$S_{\hat{q}}$ $S_{\hat{v}^\perp}$ $S_{\hat{\eta}}$	$S_{\hat{q}}$ $S_{\hat{v}^\perp}$ $S_{\hat{\eta}}$	4	D H L

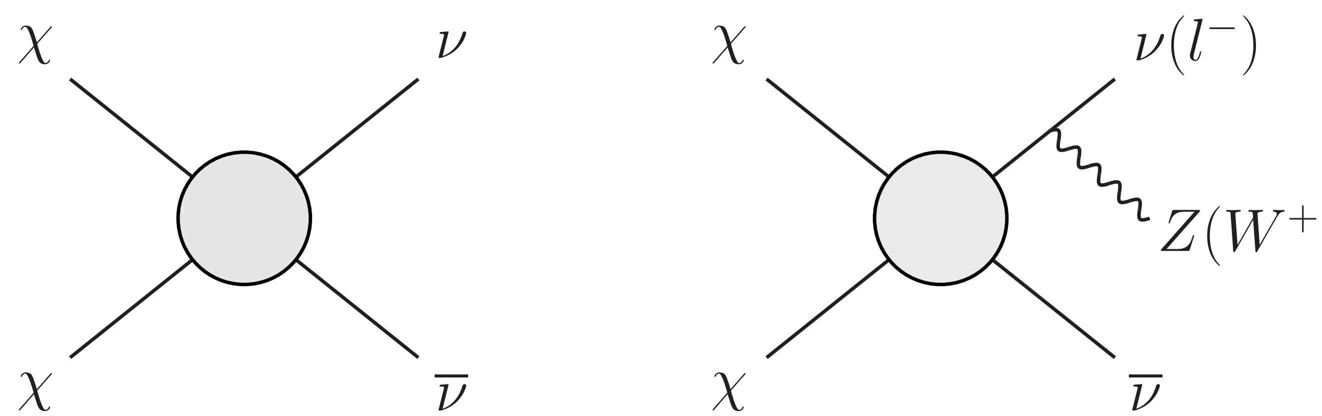
	Powers of q and $v^\perp$	Interaction structures
SI	0	$(\bar{X}X\bar{q}q,\ \bar{X}\gamma^\mu X\bar{q}\gamma_\mu q)$
	2	$(\bar{X}\gamma^5 X\bar{q}q,\ \bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q),\ \bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$
	4	$(\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q,\ \bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q)$
	6	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$
SD	0	$(\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q\ ,\ \bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q)$
	2	$(\bar{X}X\bar{q}\gamma^5 q,\ \bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q),\ (\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q,\ \bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q)$
	4	$(\bar{X}X\bar{q}q,\ \bar{X}\gamma^\mu X\bar{q}\gamma_\mu q),\ \bar{X}\gamma^5 X\bar{q}\gamma^5 q$
	6	$\bar{X}\gamma^5 X\bar{q}q$

Operator	Structure	Dim D
V1	$(1/\Lambda) B_\mu^\dagger B^\mu \bar{q} q$	5
V2	$(1/\Lambda) \imath B_\mu^\dagger B^\mu \bar{q} \gamma^5 q$	5
V3	$(1/2\Lambda^2) \imath (B_\nu^\dagger \partial_\mu B^\nu - B^\nu \partial_\mu B_\nu^\dagger) \bar{q} \gamma^\mu q$	6
V4	$(1/2\Lambda^2) \imath (B_\nu^\dagger \partial_\mu B^\nu - B^\nu \partial_\mu B_\nu^\dagger) \bar{q} \gamma^\mu \gamma^5 q$	6
V5	$(1/\Lambda) \imath B_\mu^\dagger B_\nu \bar{q} \sigma^{\mu\nu} q$	5
V6	$(1/\Lambda) B_\mu^\dagger B_\nu \bar{q} \sigma^{\mu\nu} \gamma^5 q$	5
V7$_+$	$(1/2\Lambda^2) (B_\nu^\dagger \partial^\nu B_\mu + B_\nu \partial^\nu B_\mu^\dagger) \bar{q} \gamma^\mu q$	6
V7$_-$	$(1/2\Lambda^2) \imath (B_\nu^\dagger \partial^\nu B_\mu - B_\nu \partial^\nu B_\mu^\dagger) \bar{q} \gamma^\mu q$	6
V8$_+$	$(1/2\Lambda^2) (B_\nu^\dagger \partial^\nu B_\mu + B_\nu \partial^\nu B_\mu^\dagger) \bar{q} \gamma^\mu \gamma^5 q$	6
V8$_-$	$(1/2\Lambda^2) \imath (B_\nu^\dagger \partial^\nu B_\mu - B_\nu \partial^\nu B_\mu^\dagger) \bar{q} \gamma^\mu \gamma^5 q$	6
V9$_+$	$(1/2\Lambda^2) \epsilon^{\mu\nu\rho\sigma} (B_\nu^\dagger \partial_\rho B_\sigma + B_\nu \partial_\rho B_\sigma^\dagger) \bar{q} \gamma_\mu q$	6
V9$_-$	$(1/2\Lambda^2) \imath \epsilon^{\mu\nu\rho\sigma} (B_\nu^\dagger \partial_\rho B_\sigma - B_\nu \partial_\rho B_\sigma^\dagger) \bar{q} \gamma_\mu q$	6
V10$_+$	$(1/2\Lambda^2) \epsilon^{\mu\nu\rho\sigma} (B_\nu^\dagger \partial_\rho B_\sigma + B_\nu \partial_\rho B_\sigma^\dagger) \bar{q} \gamma_\mu \gamma^5 q$	6
V10$_-$	$(1/2\Lambda^2) \imath \epsilon^{\mu\nu\rho\sigma} (B_\nu^\dagger \partial_\rho B_\sigma - B_\nu \partial_\rho B_\sigma^\dagger) \bar{q} \gamma_\mu \gamma^5 q$	6

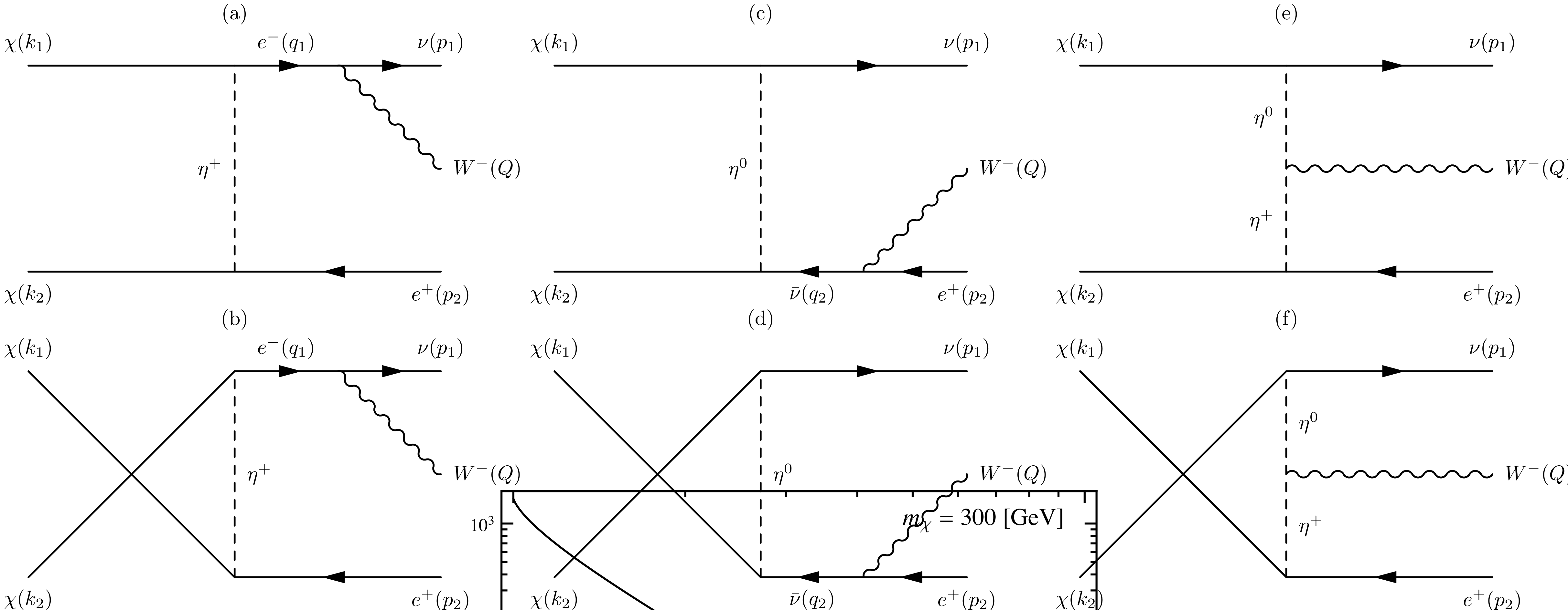
Operator	Term	C_B	P_B	J	State
V1	$(1/\Lambda)B_\mu^\dagger B^\mu \bar{q}q$	+	+	0	$L=0,\ S=0;\ L=2,\ S=2$
V2	$(1/\Lambda)\imath B_\mu^\dagger B^\mu \bar{q}\gamma^5 q$	+	+	0	$L=0,\ S=0;\ L=2,\ S=2$
V3	$(1/2\Lambda^2)\imath(B_\nu^\dagger \partial_i B^\nu - B^\nu \partial_i B_\nu^\dagger)\bar{q}\gamma^i q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V4	$(1/2\Lambda^2)\imath(B_\nu^\dagger \partial_i B^\nu - B^\nu \partial_i B_\nu^\dagger)\bar{q}\gamma^i \gamma^5 q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V5	$(1/\Lambda)\imath B_i^\dagger B_j \bar{q}\sigma^{ij} q$	-	+	1	$L=0,2,\ S=1$
	$(1/2\Lambda)\imath(B_0^\dagger B_i - B_i^\dagger B_0 \bar{q})\bar{q}\sigma^{0i} q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V6	$(1/\Lambda)B_i^\dagger B_j \bar{q}\sigma^{ij}\gamma^5 q$	-	+	1	$L=0,2,\ S=1$
	$(1/2\Lambda)(B_0^\dagger B_i - B_i^\dagger B_0)\bar{q}\sigma^{0i}\gamma^5 q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V7$_+$	$(1/2\Lambda^2)(B_\nu^\dagger \partial^\nu B_i + B_\nu \partial^\nu B_i^\dagger)\bar{q}\gamma^i q$	+	-	1	$L=1,\ S=1$
V7$_-$	$(1/2\Lambda^2)\imath(B_\nu^\dagger \partial^\nu B_i - B_\nu \partial^\nu B_i^\dagger)\bar{q}\gamma^i q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V8$_+$	$(1/2\Lambda^2)(B_\nu^\dagger \partial^\nu B_i + B_\nu \partial^\nu B_i^\dagger)\bar{q}\gamma^i \gamma^5 q$	+	-	1	$L=1,\ S=1$
V8$_-$	$(1/2\Lambda^2)\imath(B_\nu^\dagger \partial^\nu B_i - B_\nu \partial^\nu B_i^\dagger)\bar{q}\gamma^i \gamma^5 q$	-	-	1	$L=1,\ S=0;\ L=1,3,\ S=2$
V9$_+$	$(1/2\Lambda^2)\epsilon^{i0jk}(B_0^\dagger \partial_j B_k + B_0 \partial_j B_k^\dagger)\bar{q}\gamma_i q$	+	+	1	$L=2,\ S=2$
V9$_-$	$(1/2\Lambda^2)\imath\epsilon^{i0jk}(B_0^\dagger \partial_j B_k - B_0 \partial_j B_k^\dagger)\bar{q}\gamma_i q$	-	+	1	$L=0,2,\ S=1$
	$(1/2\Lambda^2)\imath\epsilon^{ij0k}(B_j^\dagger \partial_0 B_k - B_j \partial_0 B_k^\dagger)\bar{q}\gamma_i q$	-	+	1	$L=0,2,\ S=1$
V10$_+$	$(1/2\Lambda^2)\epsilon^{i0jk}(B_0^\dagger \partial_j B_k + B_0 \partial_j B_k^\dagger)\bar{q}\gamma_i \gamma^5 q$	+	+	1	$L=2,\ S=2$
V10$_-$	$(1/2\Lambda^2)\epsilon^{i0jk}(B_0^\dagger \partial_j B_k - B_0 \partial_j B_k^\dagger)\bar{q}\gamma_i \gamma^5 q$	-	+	1	$L=0,2,\ S=1$
	$(1/2\Lambda^2)\epsilon^{ij0k}(B_j^\dagger \partial_0 B_k - B_j \partial_0 B_k^\dagger)\bar{q}\gamma_i \gamma^5 q$	-	+	1	$L=0,2,\ S=1$

Operators	Dimension enhancement	Polarization enhancement
V1, V2, V5, V6	E/Λ	$(E/m_B)^2$
V3, V4, V7$_-$, V8$_-$	$(E/\Lambda)^2$	$(E/m_B)^2$
V7$_+$, V8$_+$, V9$_\pm$, V10$_\pm$	$(E/\Lambda)^2$	E/m_B

Operator	Constraint	Benchmark $\Lambda_{\rm min}$ (TeV)
V1, V2	$\frac{E\sqrt{E^2-m_B^2}}{16\pi^2\Lambda^2}\left(3+\frac{4E^2}{m_B^4}(E^2-m_B^2)\right)\leq 1$	1.59×10^5
V3, V4	$\frac{E(E^2-m_B^2)^{3/2}}{72\pi^2\Lambda^4}\left(3+\frac{4E^2}{m_B^4}(E^2-m_B^2)\right)\leq 1$	274
V5, V6	$\frac{E\sqrt{E^2-m_B^2}}{72\pi^2\Lambda^2}\left(\frac{4E^2}{m_B^2}+\frac{2E^2}{m_B^4}(E^2-m_B^2)-1\right)\leq 1$	5.31×10^4
$V7_+$, $V8_+$	$\frac{E^3(E^2-m_B^2)^{3/2}}{18\pi^2 m_B^2\Lambda^4}\leq 1$	8.66
$V9_+$, $V10_+$	$\frac{E(E^2-m_B^2)^{5/2}}{18\pi^2 m_B^2\Lambda^4}\leq 1$	8.66
$V7_-$, $V8_-$	$\frac{E^3(E^2-m_B^2)^{3/2}}{18\pi^2 m_B^2\Lambda^4}\left(1+\frac{E^2}{m_B^2}\right)\leq 1$	274
$V9_-$, $V10_-$	$\frac{E^3(E^2-m_B^2)^{1/2}}{32\pi^2\Lambda^4}\left(1+2\frac{E^2}{m_B^2}\right)\leq 1$	8.66



(a) (b)



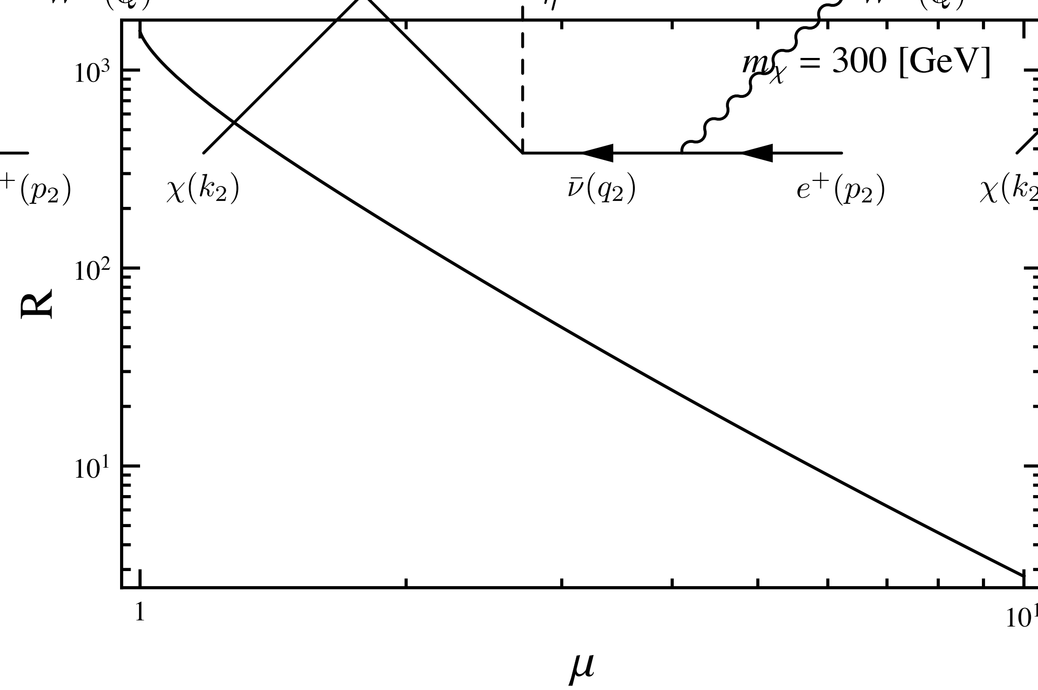


FIG. 2. The ratio $R = v\,\sigma(\chi\chi \to e^+\nu W^-)/v\,\sigma(\chi\chi \to e^+e^-)$ as a function of $\mu = (m_\eta/m_\chi)^2$, for $m_\chi = 300$ GeV. We have used $v = 10^{-3}c$, appropriate for the Galactic halo.

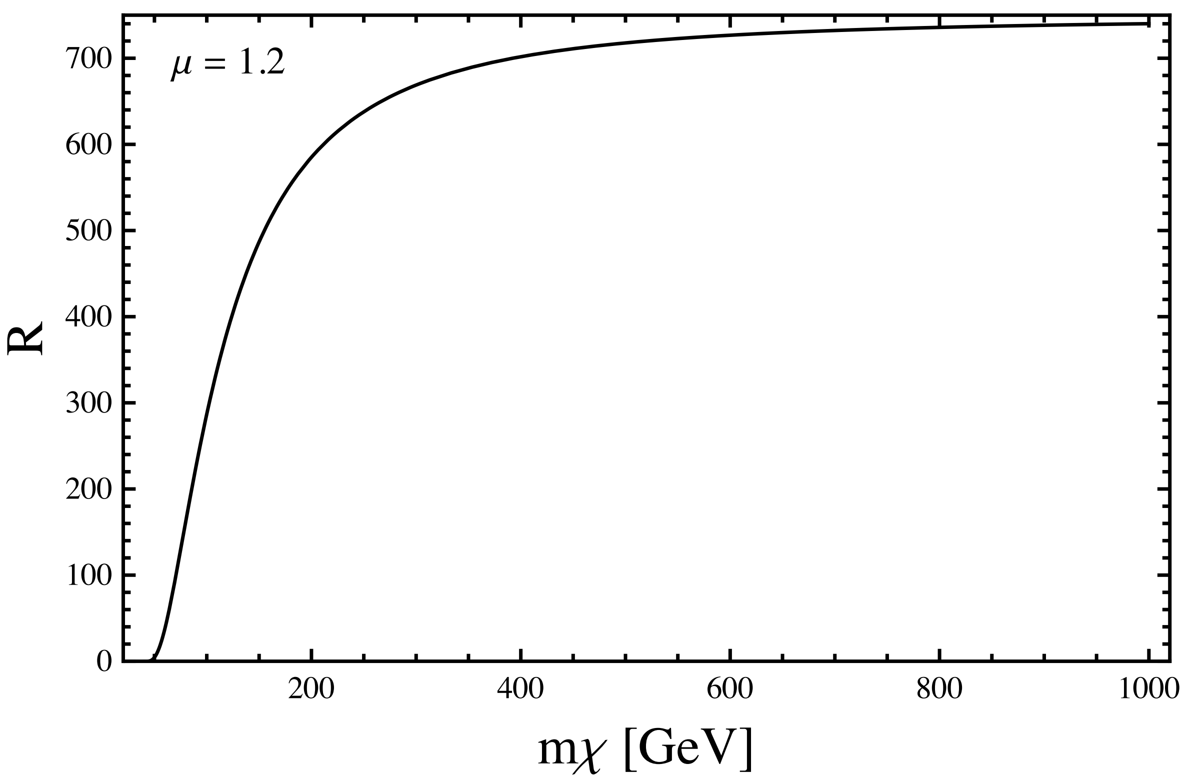


FIG. 3. The ratio $R = v\,\sigma(\chi\chi \to e^+\nu W^-)/v\,\sigma(\chi\chi \to e^+e^-)$ as a function of the DM mass m_χ, for $\mu = 1.2$ GeV. We have used $v = 10^{-3}c$, appropriate for the Galactic halo.

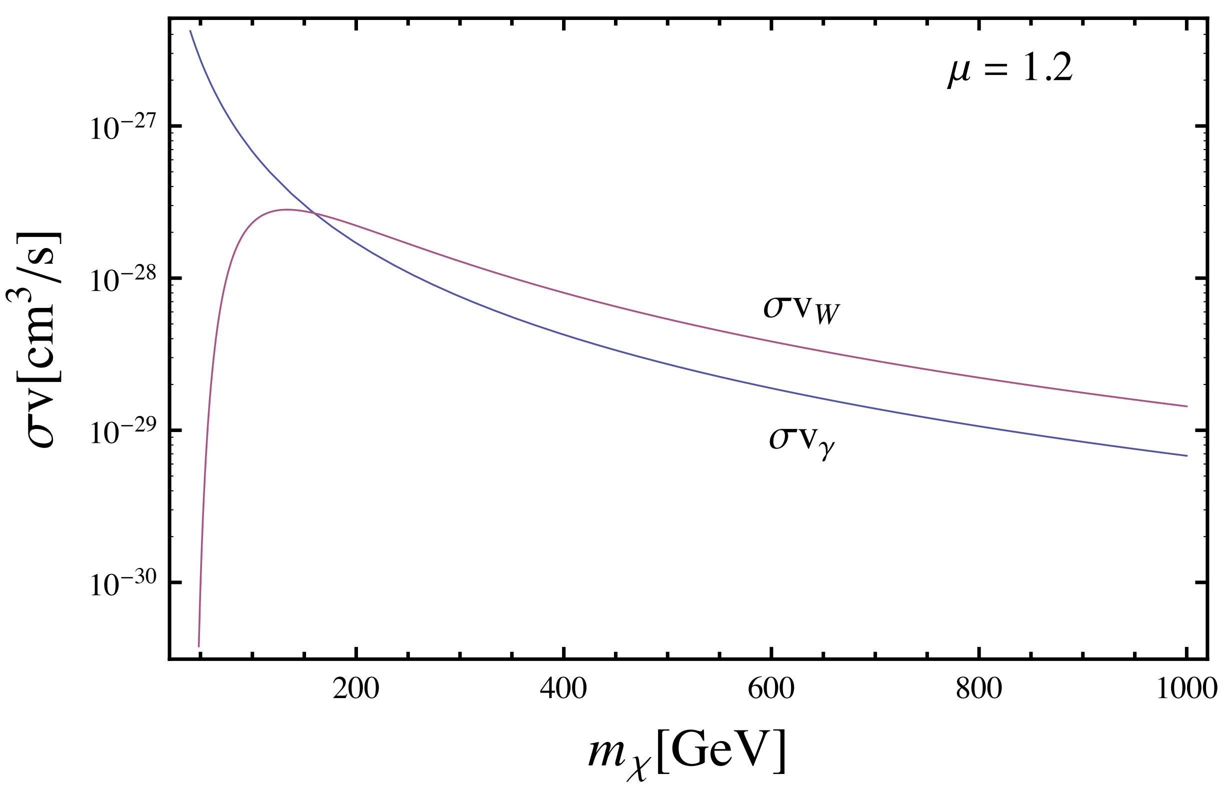


FIG. 4. The cross sections for $\chi\chi \to e^+\nu W^-$ (red) and $\chi\chi \to e^+e^-\gamma$ (blue), for $\mu = 1.2$ and coupling $f = 1$. For large DM mass, the cross sections differ by a factor of $1/(2\sin^2\theta_W) = 2.17$ while for m_χ comparable to m_W the W bremsstrahlung cross section is suppressed by phase space effects.

$$\mathcal{L}_{\chi\chi Z} = \frac{c_H}{\Lambda^2}\,\overline{\chi}\,\Gamma^\mu\chi\,\left\langle H^\dagger\right\rangle\, i\overleftrightarrow{D}_\mu\,\langle H\rangle = -\frac{c_H}{\Lambda^2}\,v^2\,\sqrt{g^2+g'^{\,2}}\,\overline{\chi}\,\Gamma^\mu\chi\,Z_\mu$$

$$\mathcal{L}^{Z}_{\mathrm{N.C.}} = \frac{g}{2c_w}\,Z_\mu J_0^\mu$$

$$J_0^\mu = \sum_f \left[g_{Vf}\,\overline{f}\gamma^\mu f + g_{Af}\,\overline{f}\gamma^\mu\gamma^5 f\right]$$

$$g_{Vf} = T_f^3 - 2s_w^2 Q_f\ ,$$

$$g_{Af} = -\,T_f^3\ .$$

$$g_{Vu} = \tfrac{1}{2} - \tfrac{4}{3}s_w^2\ , \qquad g_{Vd} = -\tfrac{1}{2} + \tfrac{2}{3}s_w^2\ , \qquad g_{Ve} = -\tfrac{1}{2} + 2s_w^2$$

$$g_{Au} = -\tfrac{1}{2}\ , \qquad g_{Ad} = \tfrac{1}{2}\ , \qquad g_{Ae} = \tfrac{1}{2}\ .$$

$$\mathcal{L}_{\mathrm{Fermi}} = -\frac{G_F}{\sqrt{2}}\,J_0^\mu J_{0\mu}$$

$$c^{(i)}_{\Gamma V u} = \frac{c^{(i)}_{\Gamma q} + c^{(i)}_{\Gamma u}}{2} + c_H \, g_{V u} \ ,$$

$$c^{(i)}_{\Gamma V d} = \frac{c^{(i)}_{\Gamma q} + c^{(i)}_{\Gamma d}}{2} + c_H \, g_{V d} \ ,$$

$$c^{(i)}_{\Gamma V e} = \frac{c^{(i)}_{\Gamma l} + c^{(i)}_{\Gamma e}}{2} + c_H \, g_{V e} \ ,$$

$$c^{(i)}_{\Gamma A u} = \frac{-c^{(i)}_{\Gamma q} + c^{(i)}_{\Gamma u}}{2} + c_H \, g_{A u} \ ,$$

$$c^{(i)}_{\Gamma A d} = \frac{-c^{(i)}_{\Gamma q} + c^{(i)}_{\Gamma d}}{2} + c_H \, g_{A d} \ ,$$

$$c^{(i)}_{\Gamma A e} = \frac{-c^{(i)}_{\Gamma l} + c^{(i)}_{\Gamma e}}{2} + c_H \, g_{A e} \ .$$

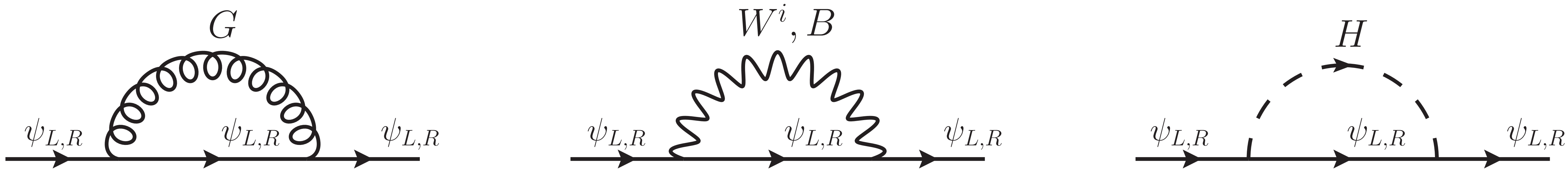
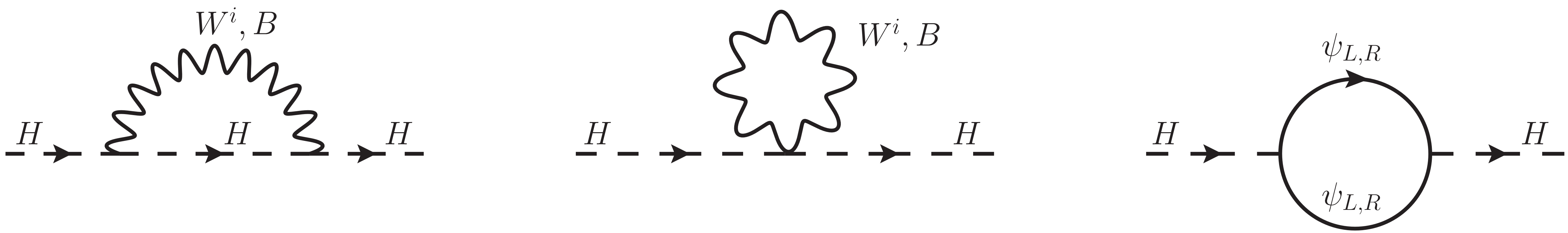
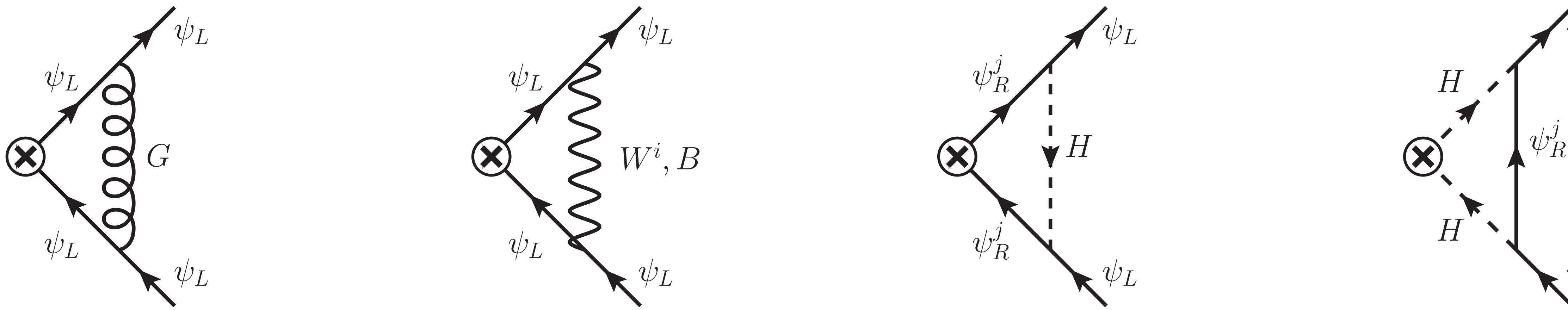
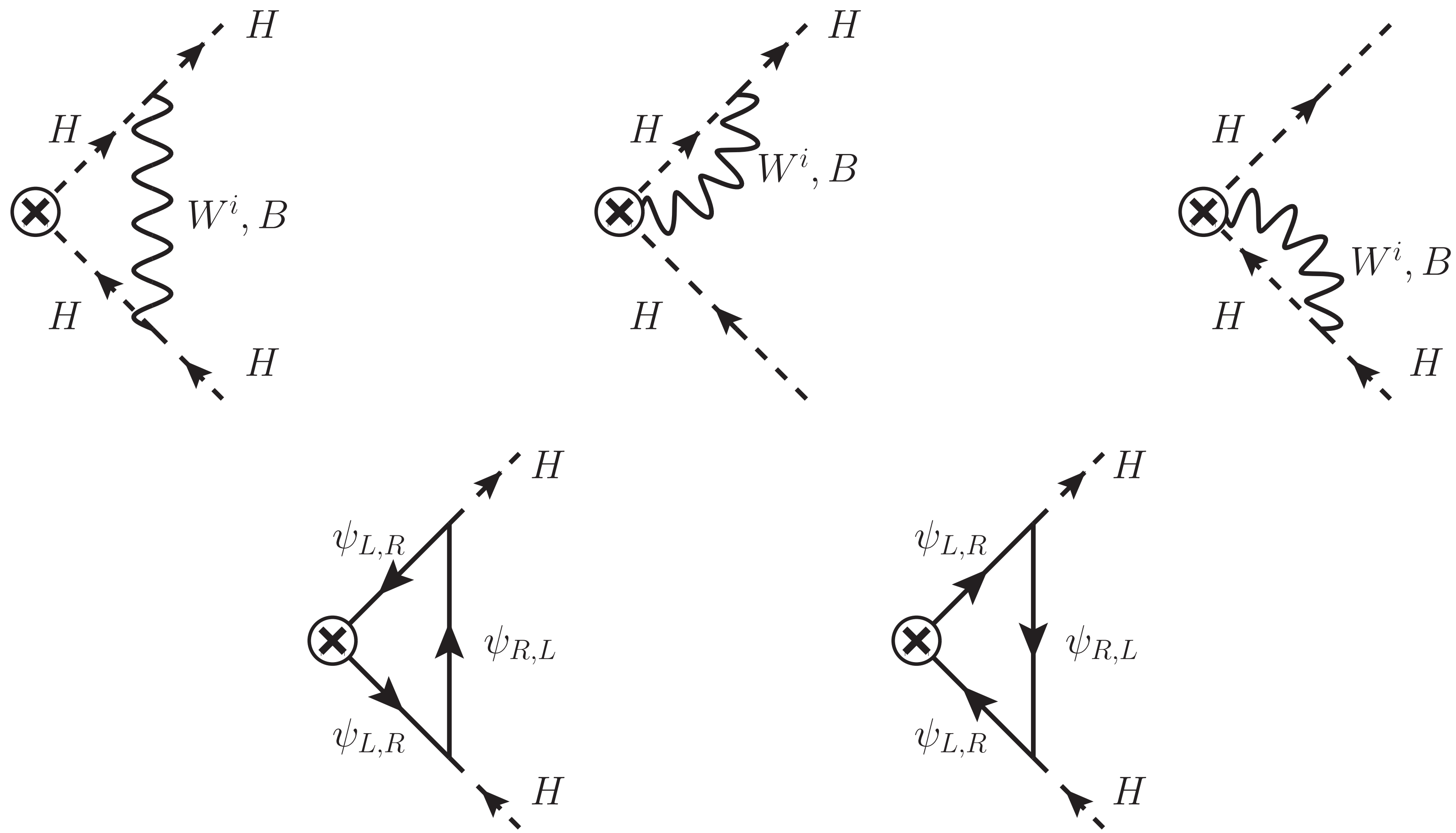


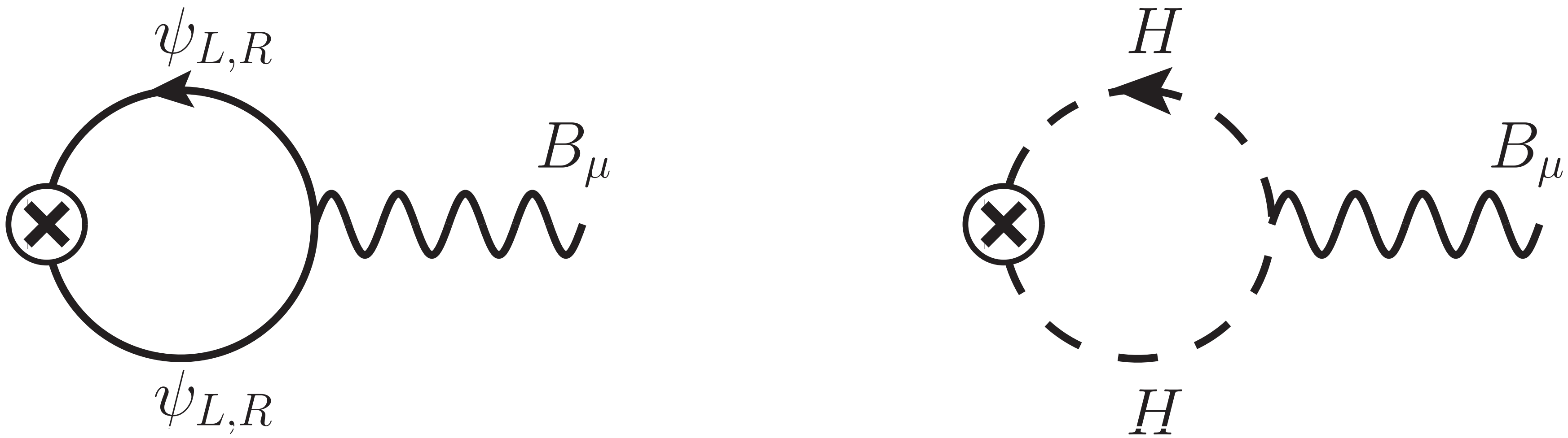
Figure 2. External legs corrections for SM fermions.





One loop corrections to the Wilson coefficient c_L in the SM_χ EFT.

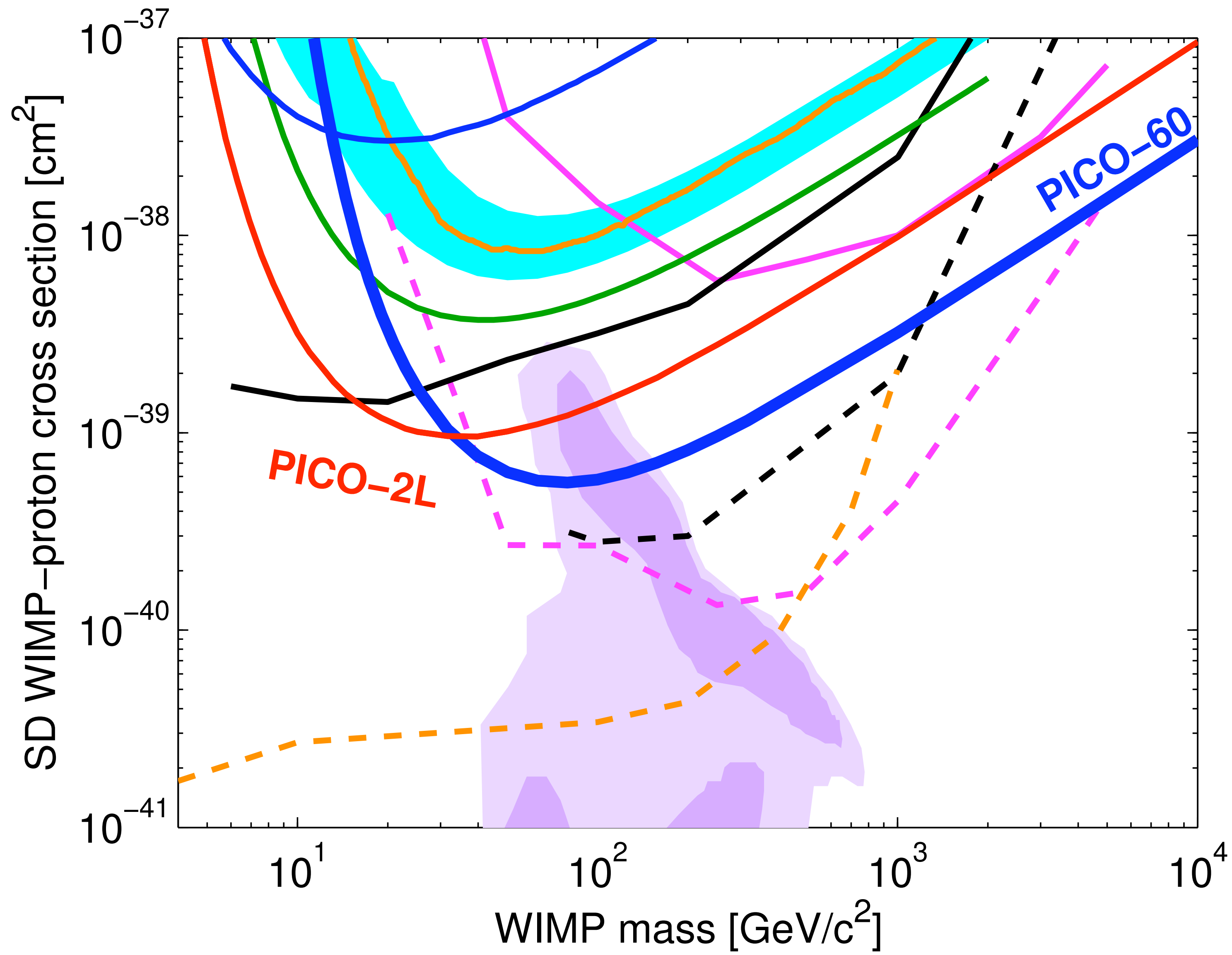




$$\gamma_{\mathrm{SM}_\chi} = \gamma_{\mathrm{SM}_\chi}\Big|_\lambda + \gamma_{\mathrm{SM}_\chi}\Big|_Y$$

Operator Uniqueness

A. Berlin, D. Hooper, and S.D. McDermott, 1508.05390



Spin dependent limits

Higgs portal: DM-SM via the Higgs

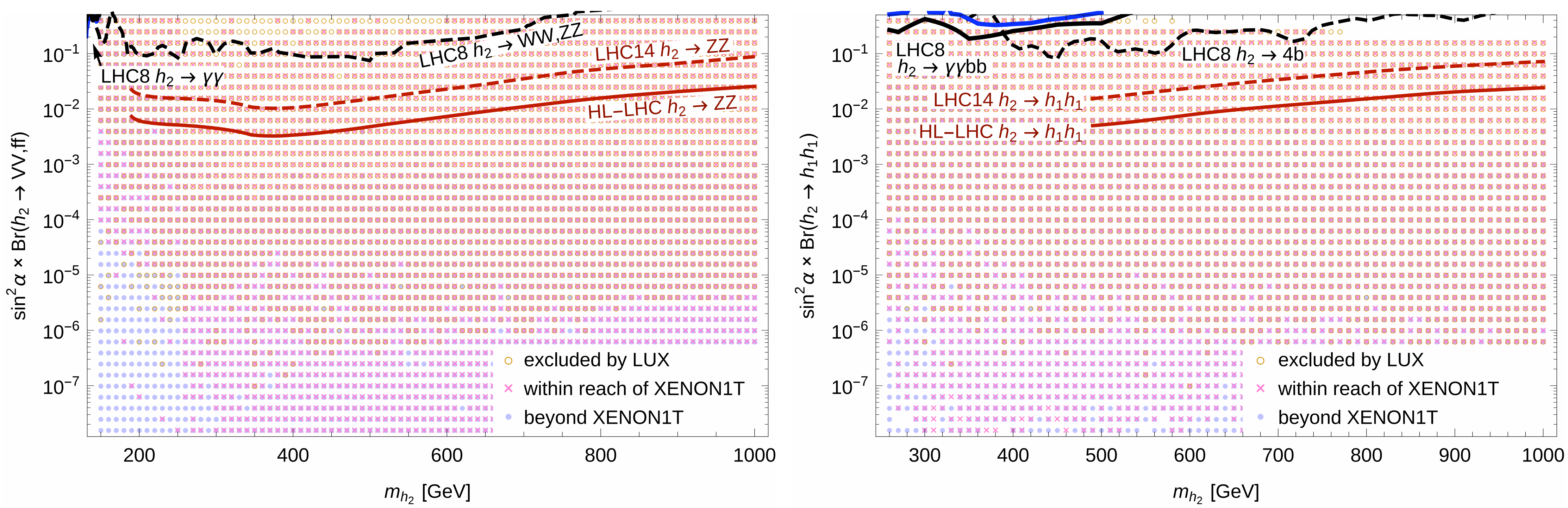


FIG. 4: Left: Existing bounds on s_α^2 in the singlet-singlet model from $h_2 \to \gamma\gamma$ (solid lines from ATLAS [50] and CMS [51]) and from $h_2 \to WW, ZZ$ (dashed black line, CMS [52]) as a function of the heavy scalar mass, m_{h_2}. Right: Bounds on $s_\alpha^2 \times \text{Br}(h_2 \to h_1 h_1)$ from $h_2 \to h_1 h_1 \to 2\gamma 2b$ (solid black from CMS [53], solid blue from ATLAS [54]) and from $h_2 \to h_1 h_1 \to 4b$ (dashed black from CMS [55]). The projected exclusions at the 14-TeV LHC with 300 fb^{-1} (3000 fb^{-1}) [56] are shown as dashed (solid) red lines. The colored points indicate the parameter region consistent with the relic density constraint, $\Omega_\chi = \Omega_{\text{DM}}$, with the different colors (shapes) denoting current and future 90% C.L. exclusions from direct detection experiments.

Higgs portal: DM-SM via the Higgs

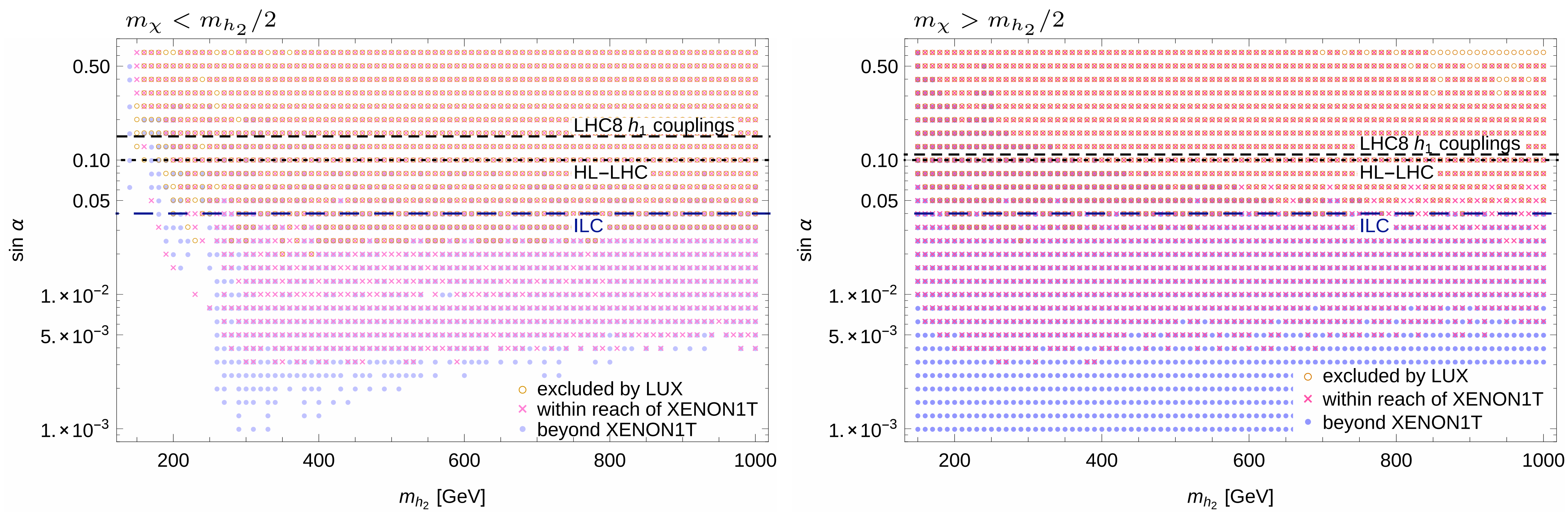
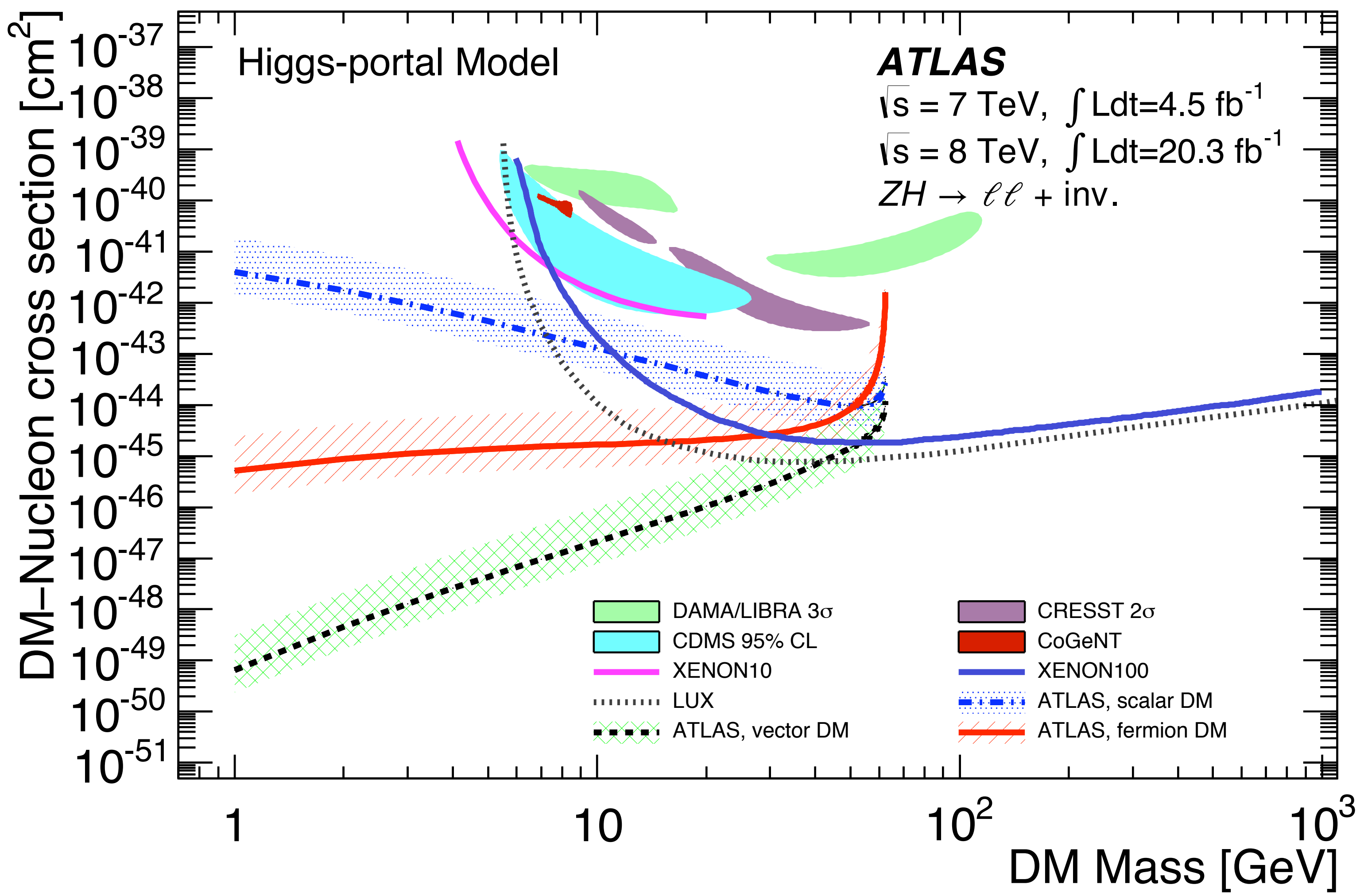
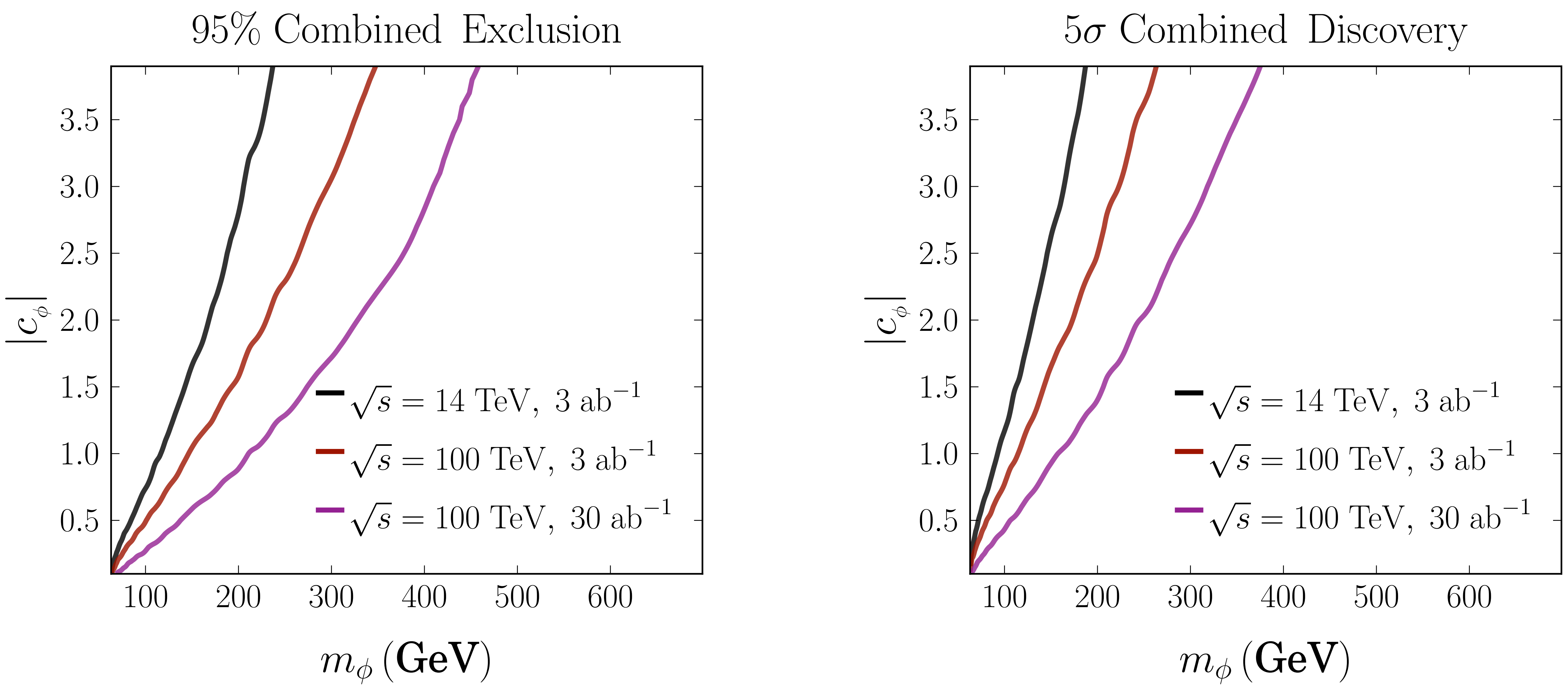


FIG. 3: Allowed parameter space for the singlet-singlet model consistent with the requirement that the thermal relic density of χ accounts for all dark matter in the universe, $\Omega_\chi = \Omega_{\rm DM}$. The different colors (shapes) of the points indicate current and future 90% C.L. exclusions from direct detection experiments. Also shown are current 95% C.L. limits from Higgs coupling measurements at the LHC (dashed line), and future projections for LHC14 with 3000 fb^{-1} (dotted) and ILC with $\sqrt{s} \leq 500$ GeV (long dashed). The left panel corresponds to $m_\chi < m_{h_2}/2$, which forbids the annihilation channels $\chi\chi \to h_2 h_{1,2}$, while in the right panel $m_\chi > m_{h_2}/2$.

ATLAS Bounds on invisible Higgs decays



Higgs portal: DM-SM via the Higgs



reach of 100TeV machine including above threshold $m_\phi > 2m_h$

N. Craig, H. K. Lou, M. McCullough, and A. Thlapillil, 1412.0258

Universal suppression to all SM particles

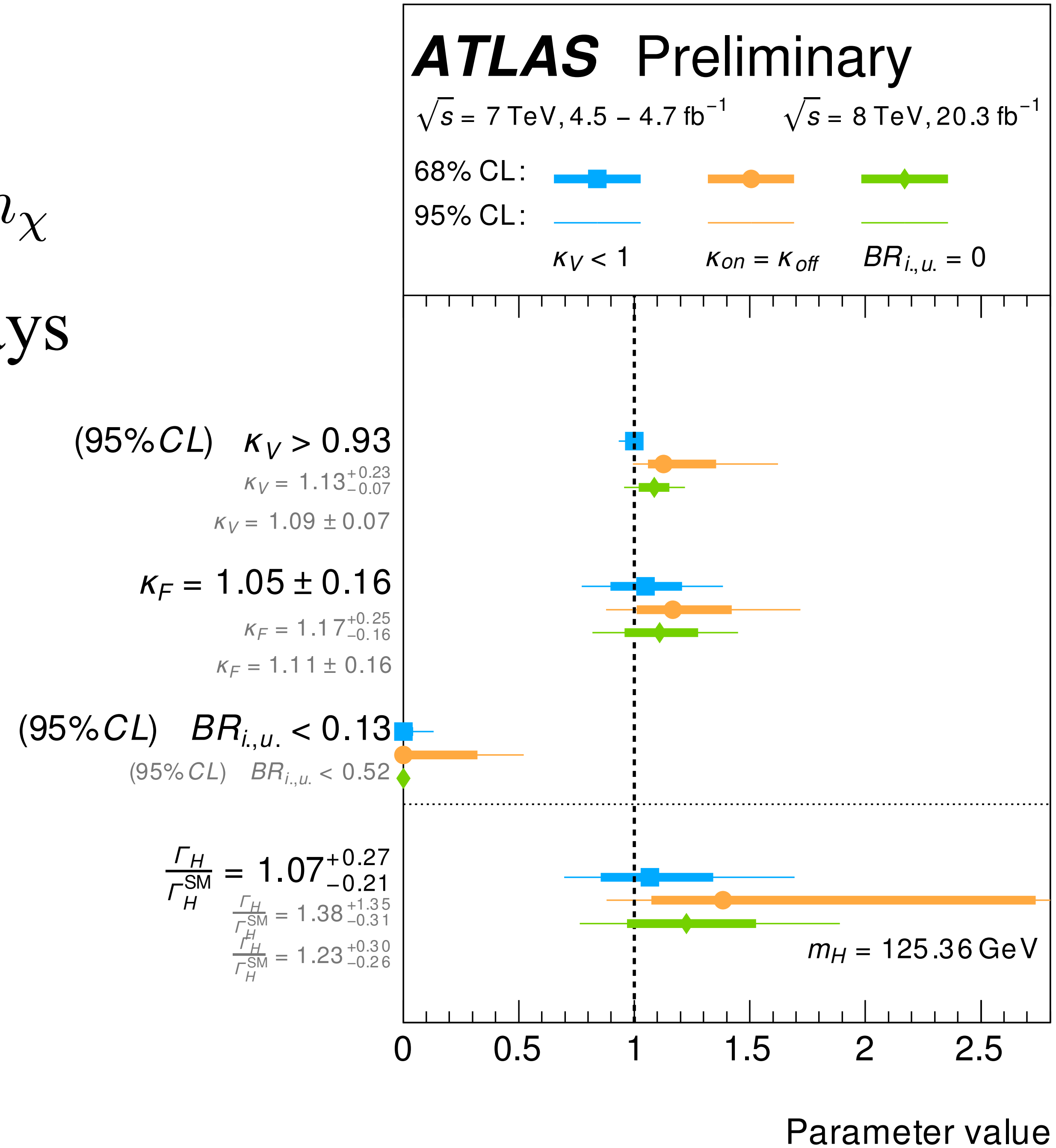
$$\mathcal{L}_{\rm int} = -(H_1 \cos\alpha + H_2 \sin\alpha)\left[\sum_f \frac{m_f}{v_H}\bar{f}f - \frac{2m_W^2}{v_H}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_H}Z_\mu Z^\mu\right] + \lambda(H_1 \sin\alpha - H_2\cos\alpha)\bar{\chi}\chi$$

1506.06556

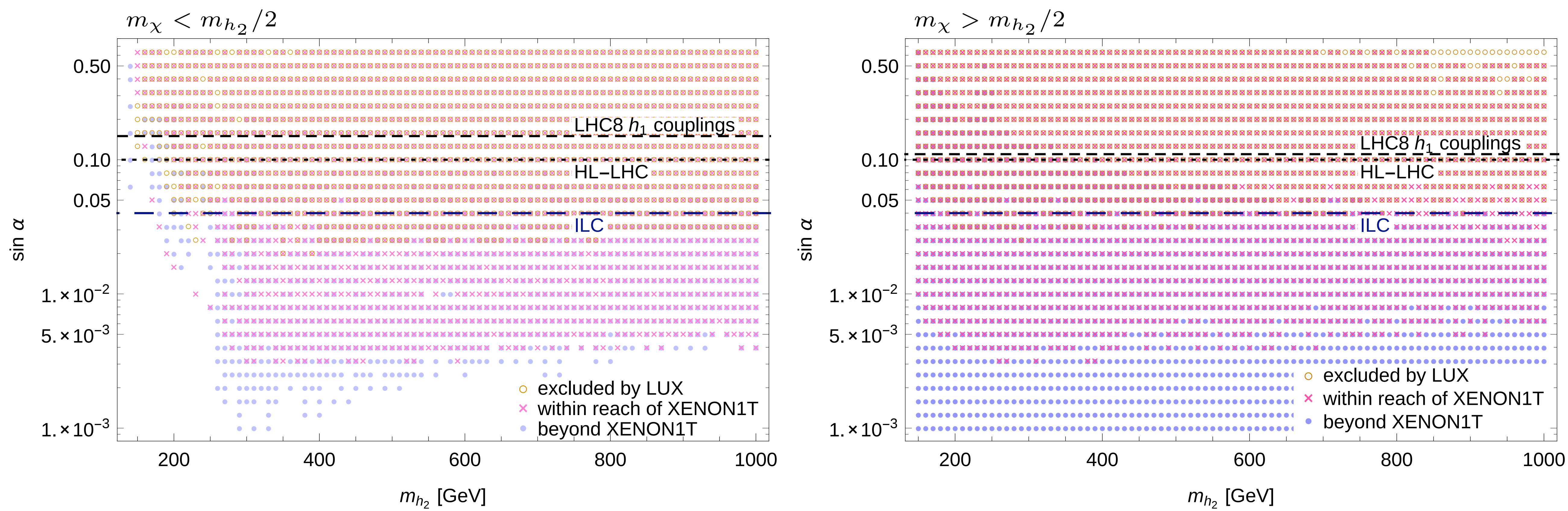
$$m_{H_1} > 2m_\chi$$

Higgs decays

$$\kappa_i \equiv \frac{g_{H_1,ii}}{g_{hii}^{SM}}$$



Future projections



A. Freitas, S. Westhoff, and J. Zupan, JHEP **1509** (2015) 015, arXiv:1506.04149.

Higgs portal: DM-SM via the Higgs

Scalar singlet

Fermion singlet

+

Scalar singlet mediator

Fermion singlet/doublet

- Majorana
- Dirac

Fermion doublet/triplet

- Majorana
- Dirac

Electroweak Precision Tests

$$\begin{aligned}\alpha S &= 4\xi c_W^2 s_W \tan\chi \\ \alpha T &= \xi^2 \left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 1\right) + 2\xi s_W \tan\chi\end{aligned}$$

K.S. Babu, C. Kolda, 97

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R				·	·	$-1-x/3$	·
ψ^l_L	1	2	-1	-1	·	$-(1+x)/3$	$-2x/5$
ψ^l_R				$-x$	·	$2/3$	$(-1+x/5)/3$
ψ^e_L	1	1	-2	-1	·	·	·
ψ^e_R				$-x$	·	·	·
ψ^d_L	3	1	$-2/3$	·	·	$-2/3$	$(1-4x/5)/3$
ψ^d_R				·	·	$(1+x)/3$	$x/15$

Anomalies

M. Carena, A. Daleo, B.A. Dobrescu, and T.P. Tait, PRD **70** hep-ph/0408098

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Axial A	Axial B	Leptophobic A	Leptophobic B	Leptophobic C	Axial-Leptophobic
q_L	3	2	1/3	1/3	1/3	1/3	1/3	2/3	1/3
u_R	3	1	4/3	-1/3	-1/3	1/3	1/3	2/3	-1/3
d_R	3	1	-2/3	-1/3	-1/3	1/3	1/3	2/3	-1/3
l_L	1	2	-1	1/3	-1/3	0	0	0	0
e_R	1	1	-2	-1/3	-2/3	0	0	0	0
ν_R	1	1	0	-1/3	–	-1	-3	–	-5/3
ν'_R	1	1	0	-4/3	–	–	2	–	–
χ_L	1	1	0	–	1/3	–	–	1	–
χ_R	1	1	0	–	-4/3	–	–	-1	–
ψ_L^d	3	1	-2/3	-2/3	2/3	–	–	–	-1/3
ψ_R^d	3	1	-2/3	2/3	-2/3	–	–	–	1
ψ_L^l	1	2	-1	-2/3	2/3	-1	2	-1	-1
ψ_R^l	1	2	-1	2/3	1/3	–	3	1	–
ψ_L^e	1	1	-2	–	–	-1	3	1	–
ψ_R^e	1	1	-2	–	–	–	2	-1	-1/3

D. Hooper, PRD **91** 1411.4079

Simplified Model Comparison

A Minimal Simplified Dark Matter Model with a vector mediator has been used to compare collider and direct detection constraints

$$\mathcal{L}_{\rm vector} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu q - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \chi \qquad \text{SI}$$

$$\mathcal{L}_{\rm axial} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma^5 q - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi \qquad \text{SD}$$

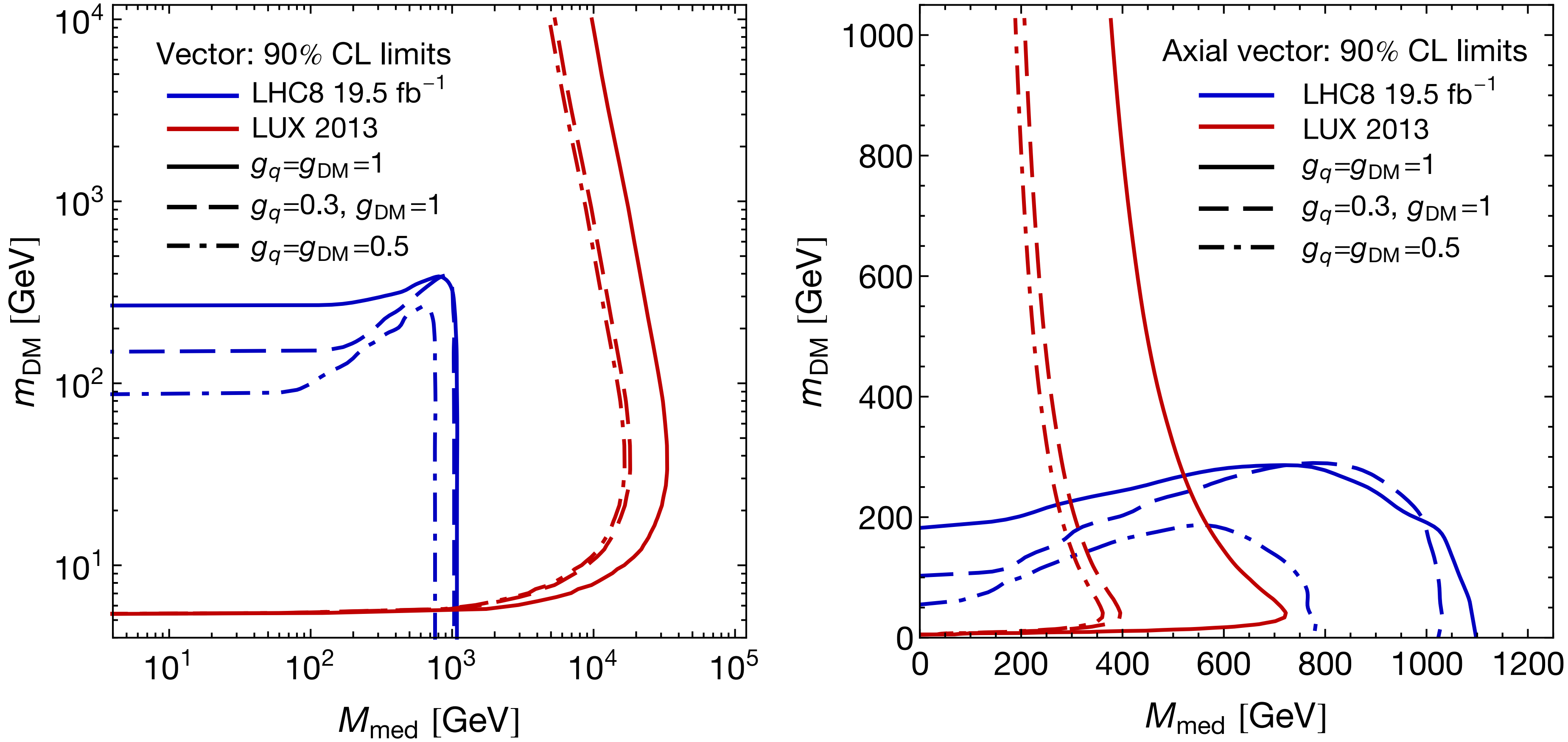
This model depends on just two masses and two couplings

$$m_{\rm DM},\ M_{\rm med},\ g_{\rm DM}\ \text{and}\ g_q$$

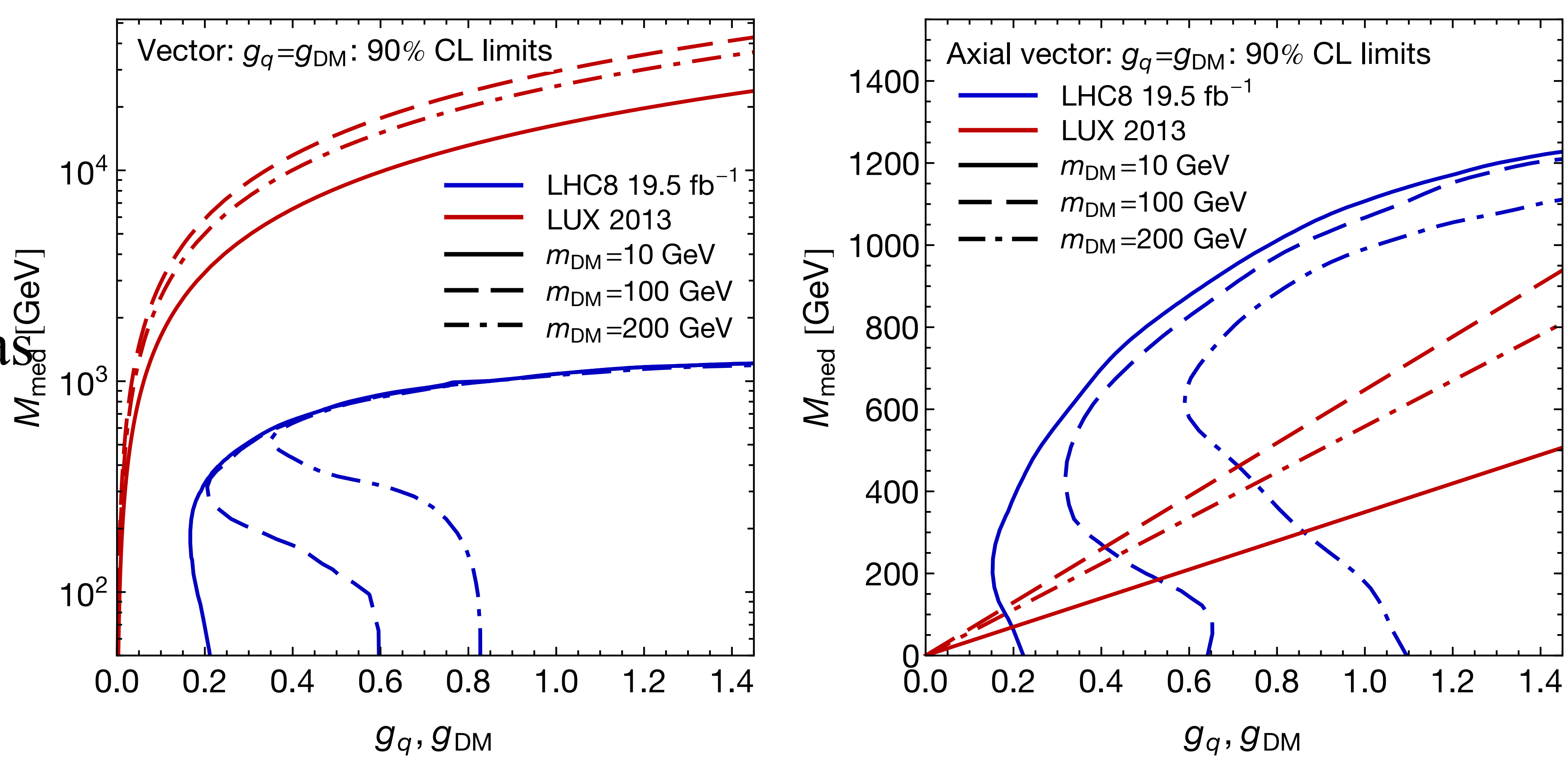
O. Buchmueller, M.J. Dolan, S.A. Malik, and C. McCabe, JHEP **1501** (2015), arXiv:1407.8257

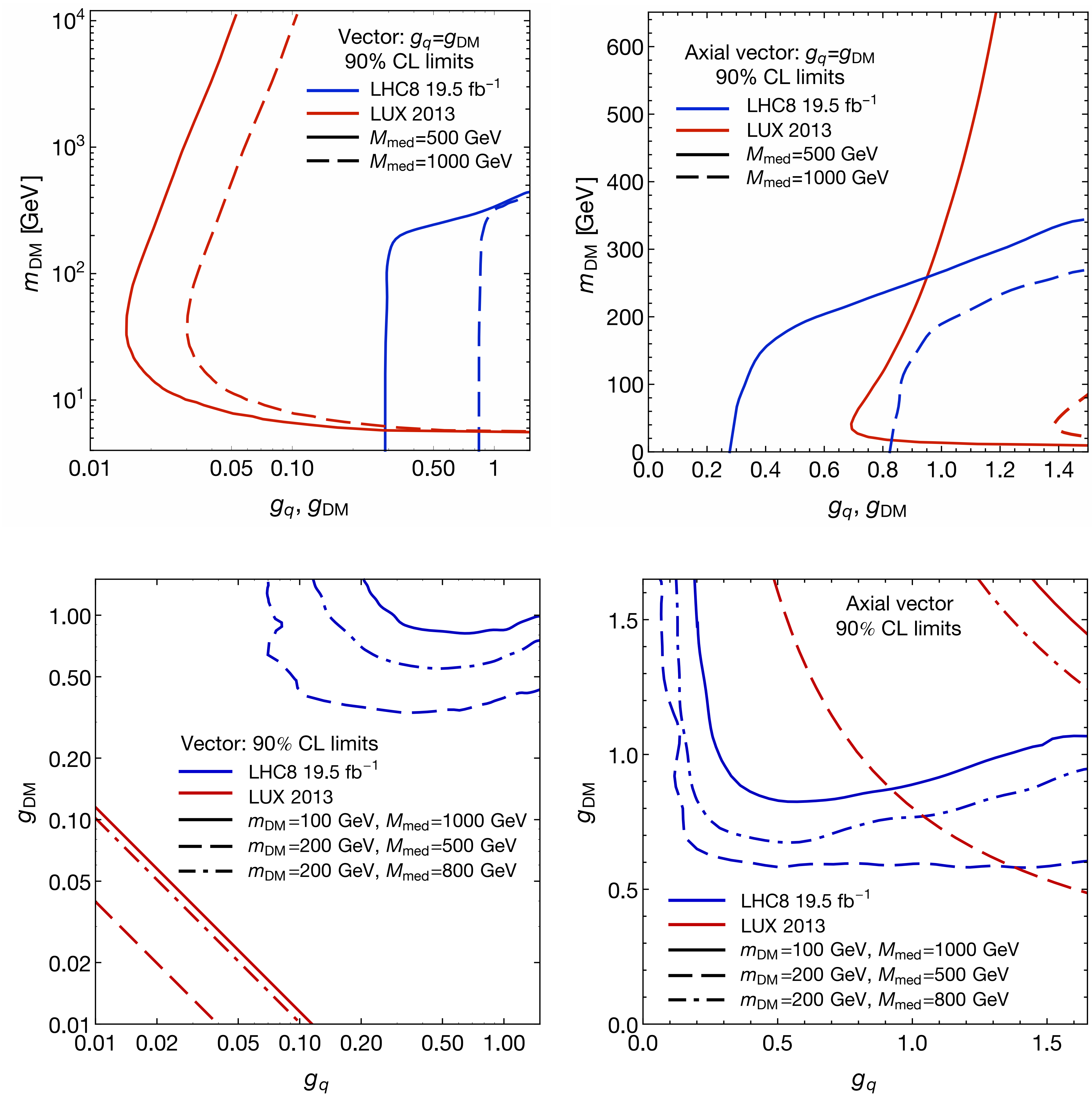
S. Malik *et al.*, arXiv:1409.4075

Constraints from various combinations of these four parameters



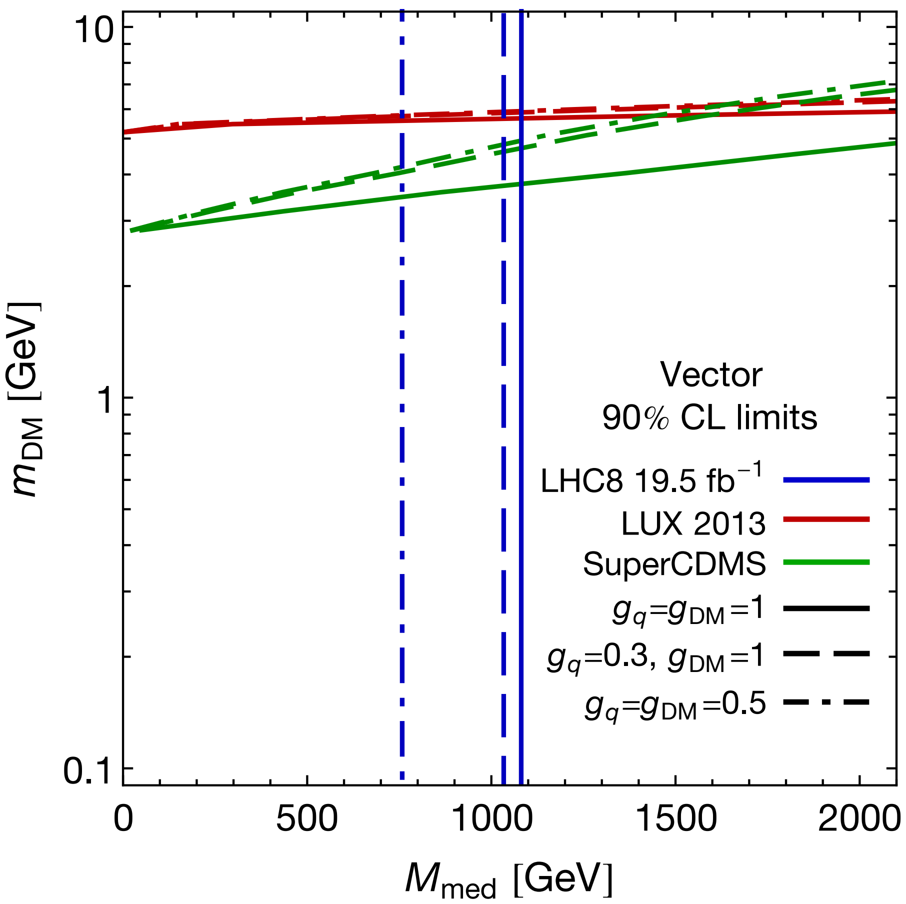
LUX has stronger bounds on Vectors (SI) while LHC has stronger bounds on Axial vectors (SD)

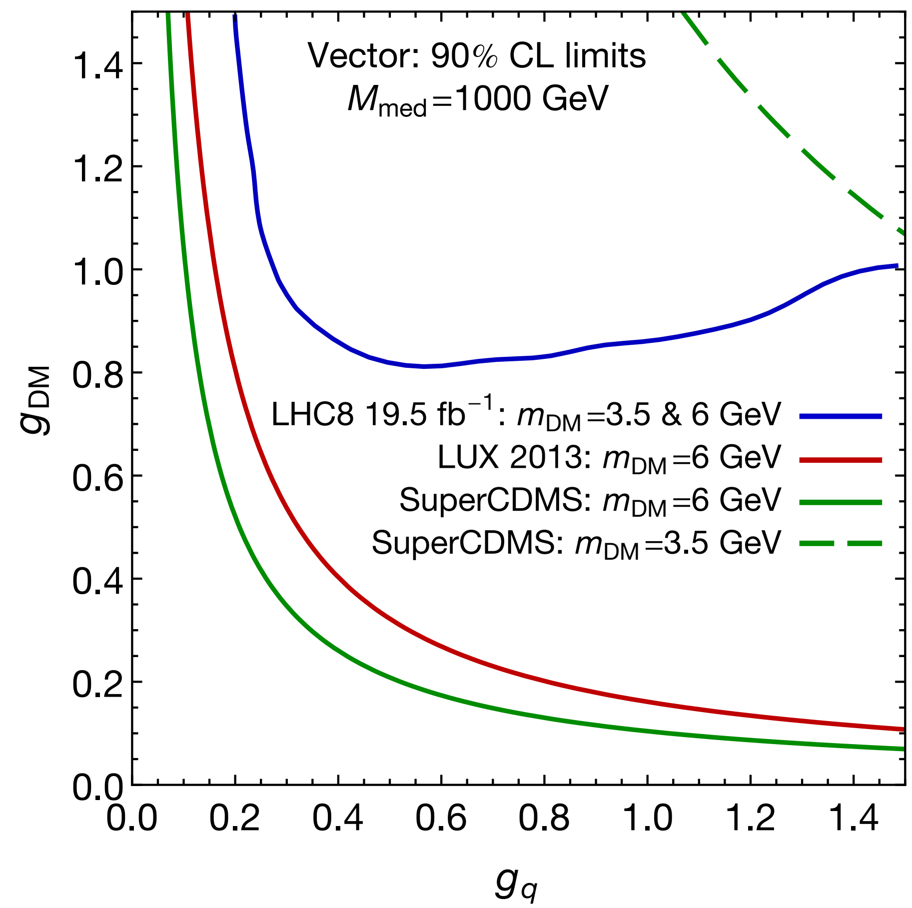




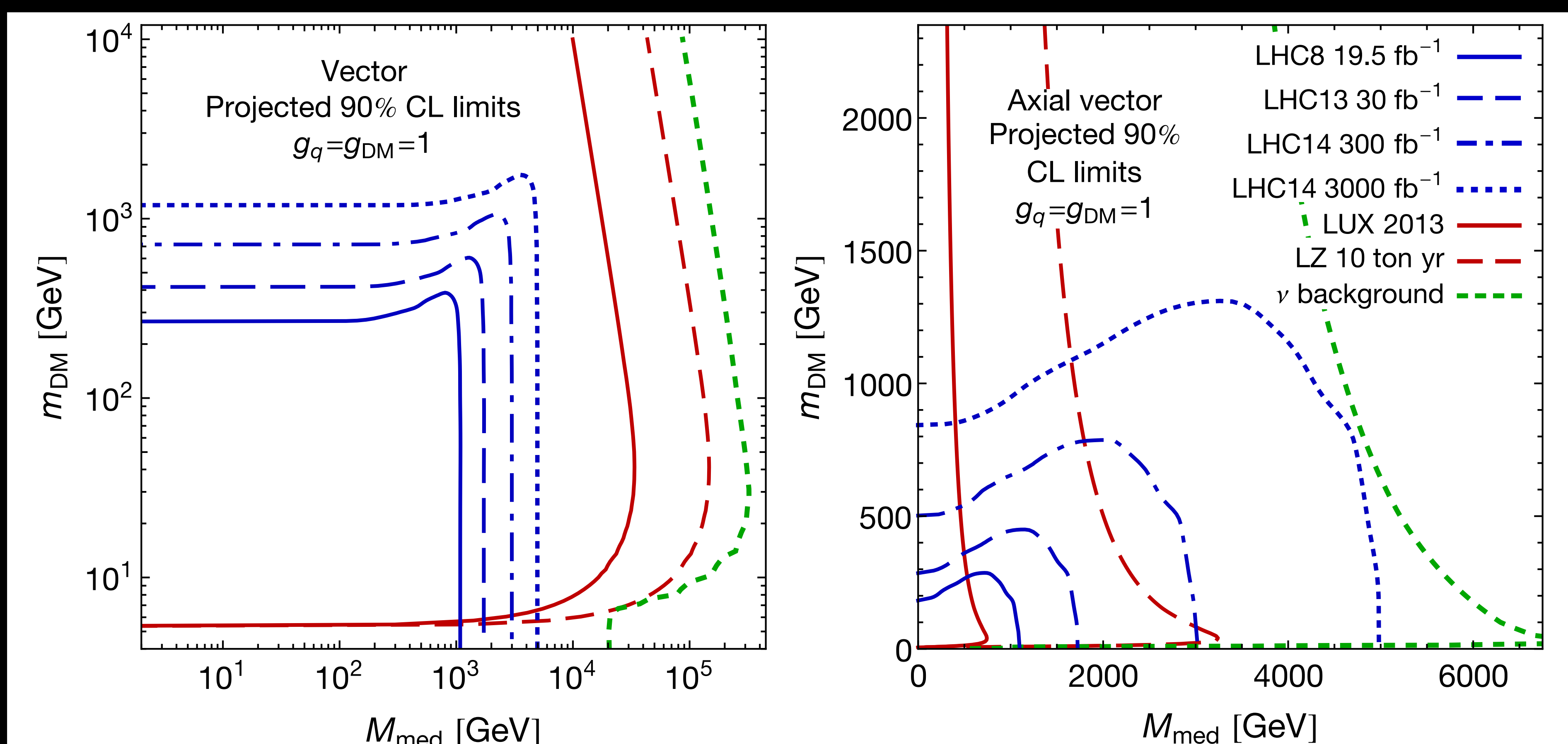
Vector: g_q=g_{DM}
90% CL limits
LHC8 19.5 fb^{-1}
LUX 2013
M_{med}=500 GeV
M_{med}=1000 GeV
m_{DM} [GeV]
g_q, g_{DM}
Axial vector: g_q=g_{DM}
90% CL limits
LHC8 19.5 fb^{-1}
LUX 2013
M_{med}=500 GeV
M_{med}=1000 GeV
m_{DM} [GeV]
g_q, g_{DM}
Vector: 90% CL limits
LHC8 19.5 fb^{-1}
LUX 2013
m_{DM}=100 GeV, M_{med}=1000 GeV
m_{DM}=200 GeV, M_{med}=500 GeV
m_{DM}=200 GeV, M_{med}=800 GeV
g_{DM}
g_q
Axial vector
90% CL limits
LHC8 19.5 fb^{-1}
LUX 2013
m_{DM}=100 GeV, M_{med}=1000 GeV
m_{DM}=200 GeV, M_{med}=500 GeV
m_{DM}=200 GeV, M_{med}=800 GeV
g_{DM}
g_q

Low mass Dark Matter





Future projections



$$\mathcal{L}_{\text{int}} = -(H_1 \cos\alpha + H_2 \sin\alpha)\left[\sum_f \frac{m_f}{v_H}\bar{f}f - \frac{2m_W^2}{v_H}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_H}Z_\mu Z^\mu\right] + \lambda(H_1 \sin\alpha - H_2 \cos\alpha)\bar{\chi}\chi$$

Operator Uniqueness

Another example was obtained for the Higgs portal interaction

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi}\left(i\partial\!\!\!/ - M_0\right)\chi + \Lambda^{-1}\left(\cos\theta\ \bar{\chi}\chi + \sin\theta\ \bar{\chi}i\gamma_5\chi\right) H^\dagger H$$

After EWSB: $H^\dagger H \longrightarrow \frac{\langle v\rangle^2}{2} + \langle v\rangle h + \frac{h^2}{2}$

A chiral rotation and field redefinition is needed for a real mass

$$\chi \to \exp\left(i\gamma_5\ \alpha/2\right)\chi \quad \Rightarrow \quad \bar{\chi} \to \bar{\chi}\exp\left(i\gamma_5\ \alpha/2\right)$$

It is found that even for an initially pure pseudoscalar interaction $\cos\theta = 0,\ \sin\theta = \pm 1$

a scalar term will be generated

$$\Lambda^{-1}\left[-\frac{\langle v\rangle^2}{2\Lambda M}\ \bar{\chi}\chi \pm \sqrt{1 - \left(\frac{\langle v\rangle^2}{2\Lambda M}\right)^2}\ \bar{\chi}i\gamma_5\chi\right]\left(\langle v\rangle h + h^2/2\right)$$

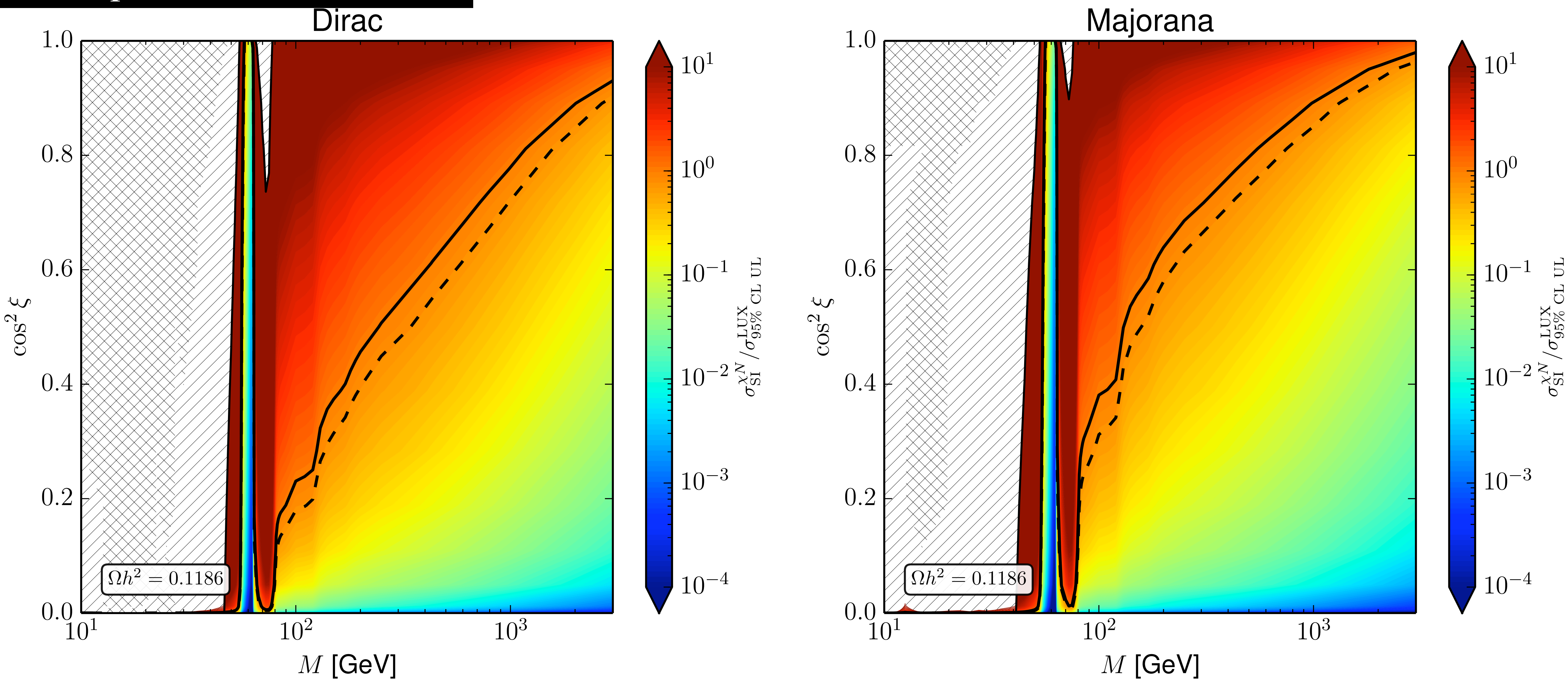
M.A. Fedderke, J.-Y. Chen, E.W. Kolb, and L.-T. Wang, JHEP **1408** (2014), arXiv:1404.2283

Other work which discusses this effect includes:
S. Matsumoto, S. Mukhopadhyay, Y.-L. Sming Tsai, JHEP **1410** (2014), arXiv:1407.1859
R.J. Hill and M.P. Solon, PRD **91** (2015) arXiv:1409.8290

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\chi} i \partial\!\!\!/ \chi - \bar{\chi} M \chi + \Lambda^{-1} \left(\langle v \rangle h + \frac{1}{2} h^2 \right) \left[\cos\xi \; \bar{\chi}\chi + \sin\xi \; \bar{\chi} i \gamma_5 \chi \right]$$

$$\cos\xi = \frac{M_0}{M} \left[\cos\theta - \frac{\langle v \rangle^2}{2\Lambda M_0} \right] \qquad \text{and} \qquad \sin\xi = \frac{M_0}{M} \sin\theta$$

Spin-Independent Constraints



$$\sigma_{\rm SI}^{\chi N} = \frac{\langle |\mathcal{M}| \rangle}{16\pi (M + M_N)^2} = \frac{1}{\pi} \left(\frac{\mu_{\chi N}}{m_h^2} \right)^2 \left(\frac{f_N}{\Lambda} \right)^2 \left[\cos^2\xi + \frac{1}{2} \left(\frac{\mu_{\chi N}}{M} \right)^2 \nu_\chi^2 \right]$$

Beyond Simplified Models

(Higgs Portal Example)

Renormalizable Lagrangian for singlet fermion dark matter

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S^{'}}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

The second scalar field can develop a vev, and one rotates to the physical states

$$S(x) \to \langle S \rangle + s(x)$$

$$H_1 = h\cos\alpha - s\sin\alpha, \qquad H_2 = h\sin\alpha + s\cos\alpha.$$

The direct detection cross-section is then altered

$$\sigma_p \approx \frac{m_r^2}{\pi}\lambda_p^2 \qquad \frac{\lambda_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{\lambda_q}{m_q} + \frac{2}{27} f_{Tg}^{(p)} \sum_{q=c,b,t} \frac{\lambda_q}{m_q}$$

Interference effect $\frac{\lambda_q}{m_q} = \frac{\lambda \sin\alpha\cos\alpha}{v_H}\left(\frac{1}{m_1^2} - \frac{1}{m_2^2}\right)$

S. Baek, P. Ko and W.-I. Park, JHEP **1202** (2012), arXiv:1112.1847
S. Baek, P. Ko and W.-I. Park, Phys.Rev.D **90** (2014), arXiv:1405.3530
A. Freitas, S. Westhoff, and J. Zupan, JHEP **1509** (2015) 015, arXiv:1506.04149.
S. Baek, P. Ko, M. Park, W.-I. Park and C. Yu, arXiv:1506.06556

One needs to include the effects of both scalar particles in scattering amplitudes

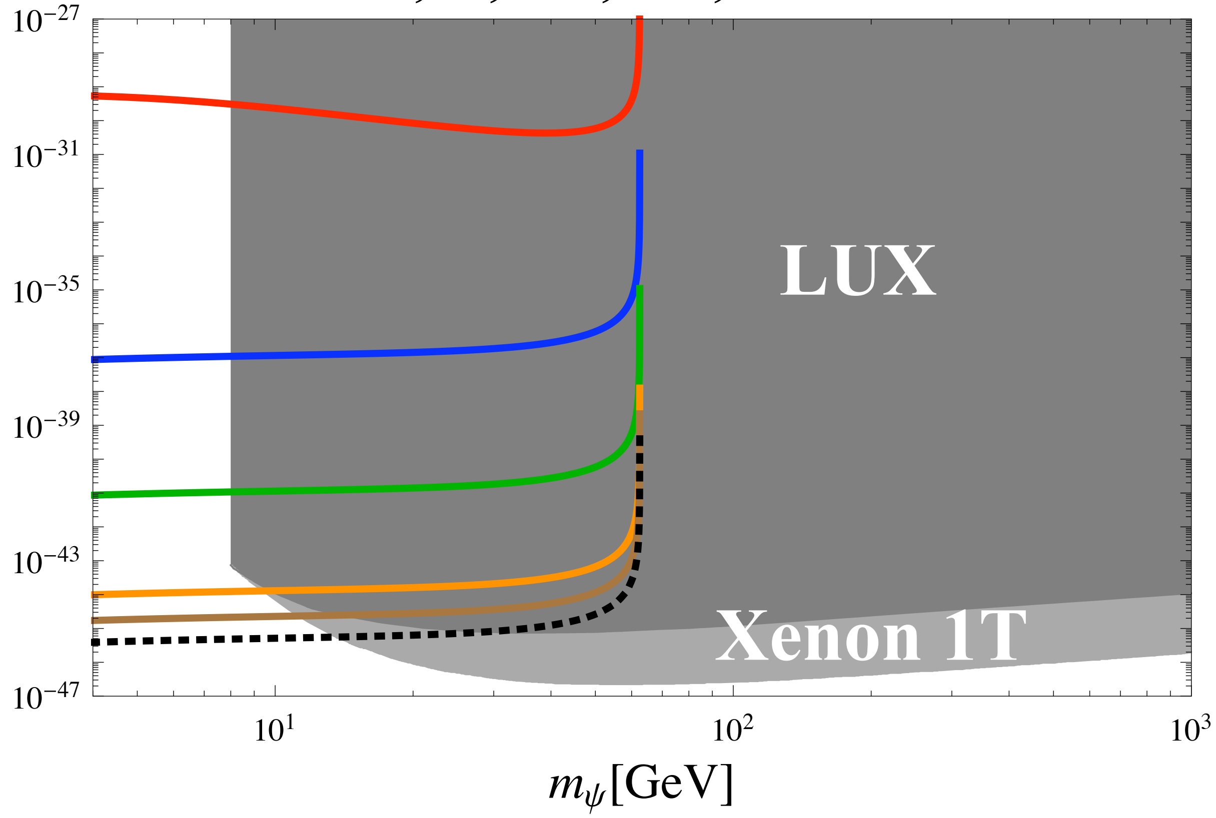
$$\begin{aligned}\mathcal{M} &= -\overline{u(p')}u(p)\overline{u(k')}u(k)\ \frac{m_q}{v_H}\lambda\sin\alpha\cos\alpha\ \left[\frac{1}{t-m_{H_1}^2+im_{H_1}\Gamma_{H_1}}-\frac{1}{t-m_{H_2}^2+im_{H_2}\Gamma_{H_2}}\right] \\ &\to \overline{u(p')}u(p)\overline{u(k')}u(k)\ \frac{m_q}{2v_H}\lambda\sin 2\alpha\left[\frac{1}{m_{H_1}^2}-\frac{1}{m_{H_2}^2}\right]\equiv\frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(k')}u(k),\end{aligned}$$

Interference effects arise due to the inclusion of the second scalar. This is a consequence of imposing the full SM gauge symmetry.

$$\begin{aligned}\Lambda_{dd}^3 &\equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha}\left(1-\frac{m_{H_1}^2}{m_{H_2}^2}\right)^{-1} \\ \bar{\Lambda}_{dd}^3 &\equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha},\end{aligned}$$

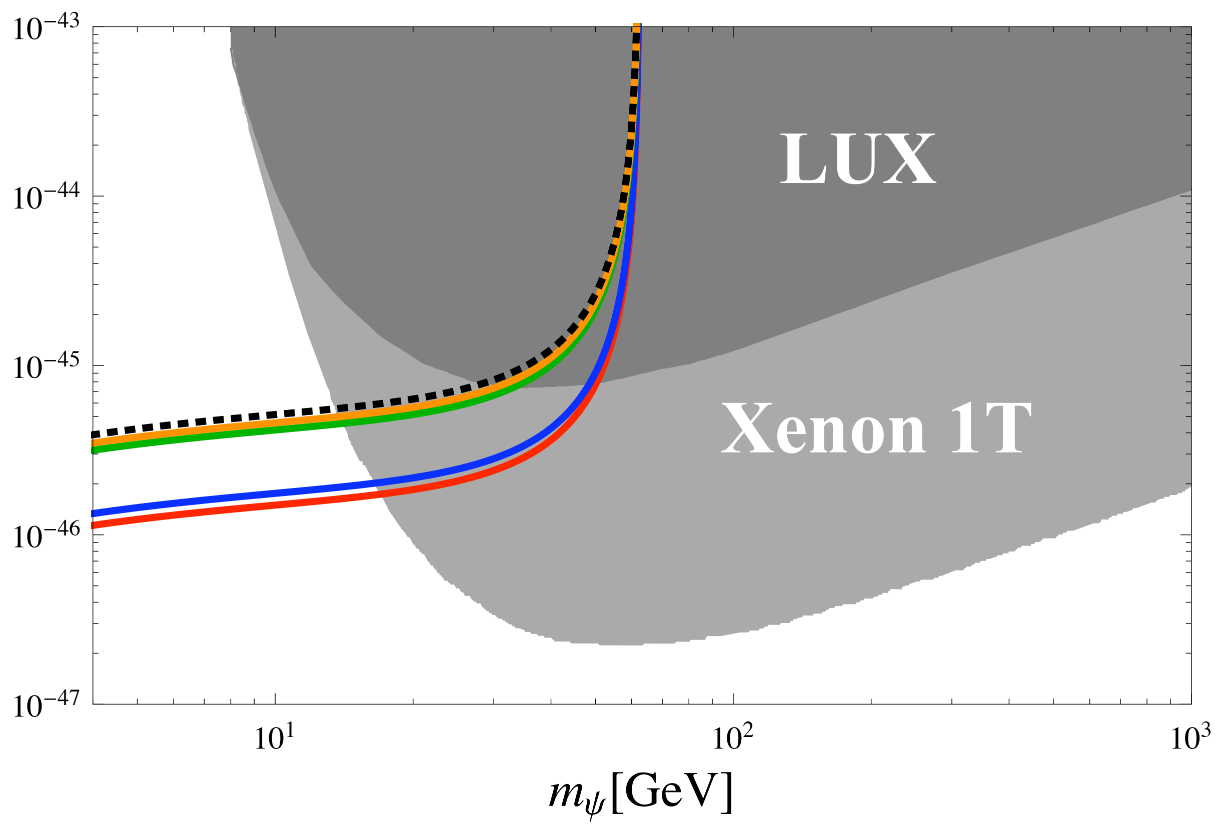
Mixing angle impact

$\alpha \; = \; 0.2 \quad m_2 = .01,\, 1,\, 10,\, 50,\, 70$ GeV



$$\sigma_p^{\rm SI} \;=\; c_\alpha^4 m_h^4 \mathcal{F}(m_\psi, \{m_i\}, v) \times \frac{B_h^{\rm inv}\Gamma_h^{\rm SM}}{(1-B_h^{\rm inv})} \frac{8m_r^2}{m_h^5 \beta_\psi^3} \left(\frac{m_p}{v_H}\right)^2 f_p^2$$

$$\mathcal{F} \;=\; \frac{1}{4m_\psi^2 v^2}\left[\sum_i \left(\frac{1}{m_i^2} - \frac{1}{4m_\psi^2 v^2 + m_i^2}\right) - \frac{2}{(m_2^2-m_1^2)} \sum_i (-1)^{i-1} \ln\left(1 + \frac{4m_\psi^2 v^2}{m_i^2}\right)\right]$$



Model independent comparisons are rendered more difficult to come by

$m_2 = 100,\, 200,\, 500,\, 1000$ GeV

Operator Uniqueness and Mixing

- Some EFT O_i terms do not appear at leading order

- Aside from scalar WIMPs each particular spin produces some leading non-relativistic operators that are unique to that spin

- Two non-relativistic operators, O_1 and O_{10}, are ubiquitous, arising for all WIMP spins 0, 1/2, and 1

$$\boxed{\mathcal{O}_1} \quad 1_\chi 1_N \quad M \qquad\qquad i\frac{\vec{q}}{m_N}\cdot\vec{S}_N \quad \boxed{\mathcal{O}_{10}} \quad \Sigma''$$

- In five scenarios for spin 0, 1/2, or 1 dark matter, relativistic operators generate unique non-relativistic operators at leading order.

- The operators can produce radically different energy dependence for scattering off different nuclear targets. Thus, a complementary use of different target materials will be helpful in order to reliably distinguish between different particle physics model possibilities for WIMP dark matter.

Standard practice has been to start with effective interaction terms, and then reduce in the non-relativistic limit

$$\mathcal{L}_{\text{int}}^{\text{SI}}(\vec{x}) = c_1 \bar{\Psi}_\chi(\vec{x}) \Psi_\chi(\vec{x}) \bar{\Psi}_N(\vec{x}) \Psi_N(\vec{x})$$

$$\mathcal{L}_{\text{int}}^{\text{SD}} = c_4 \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma_\mu \gamma^5 N$$

$$c_1 1_\chi 1_N$$

$$-4 c_4 \vec{S}_\chi \cdot \vec{S}_N$$

From the relativistic EFT there are 20 combinations of fermionic bilinears

From two scalar

$\bar{\chi}\chi$ $\bar{\chi}\gamma^5\chi$

2×2

$\bar{\chi}\gamma^\mu\chi$ $\bar{\chi}\gamma^\mu\gamma^5\chi$

and four vector terms

4×4

$P^\mu\bar{\chi}\chi$ $P^\mu\bar{\chi}\gamma^5\chi$

20

After performing a non-relativistic reduction, these 20 operators can be written in terms of the 15 O_i

To calculate cross-sections, one needs to square the amplitude, average over initial spins and sum over final states.

$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{c_i^\tau c_j^{\tau'}\right\}\right) W_k^{\tau\tau'}(\vec{q}^{\,2}b^2)$$

$$R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

$$R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{\vec{q}^{\,2}}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right)$$

$$R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'}$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{\vec{q}^{\,2}}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^{\,4}}{m_N^4} c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{1}{8}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^{\,2}}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right]$$

$$R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right]$$

$$R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].$$

DM response functions

operator interference is evident

Nuclear response functions

$$W_M^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \ M_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ M_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\Sigma''}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \ \Sigma''_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \Sigma''_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\Sigma'}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \ \Sigma'_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \Sigma'_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\Phi''}^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \ \Phi''_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \Phi''_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\Phi'' M}^{\tau\tau'}(y) = \sum_{J=0,2,\ldots}^{\infty} \langle j_N || \ \Phi''_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ M_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\tilde{\Phi}'}^{\tau\tau'}(y) = \sum_{J=2,4,\ldots}^{\infty} \langle j_N || \ \tilde{\Phi}'_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \tilde{\Phi}'_{J;\tau'}(q) \ || j_N \rangle$$

Response function interference occurs

$$W_{\Delta}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \ \Delta_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \Delta_{J;\tau'}(q) \ || j_N \rangle$$

$$W_{\Delta\Sigma'}^{\tau\tau'}(y) = \sum_{J=1,3,\ldots}^{\infty} \langle j_N || \ \Delta_{J;\tau}(q) \ || j_N \rangle \langle j_N || \ \Sigma'_{J;\tau'}(q) \ || j_N \rangle.$$

Interference Effects

In the full amplitude, two types of interference effects arise

$c_i^{\tau} c_j^{\tau'}$

isoscalar/isovector

operator/operator

$\mathcal{O}_1/\mathcal{O}_3$

$\mathcal{O}_4/\mathcal{O}_5$

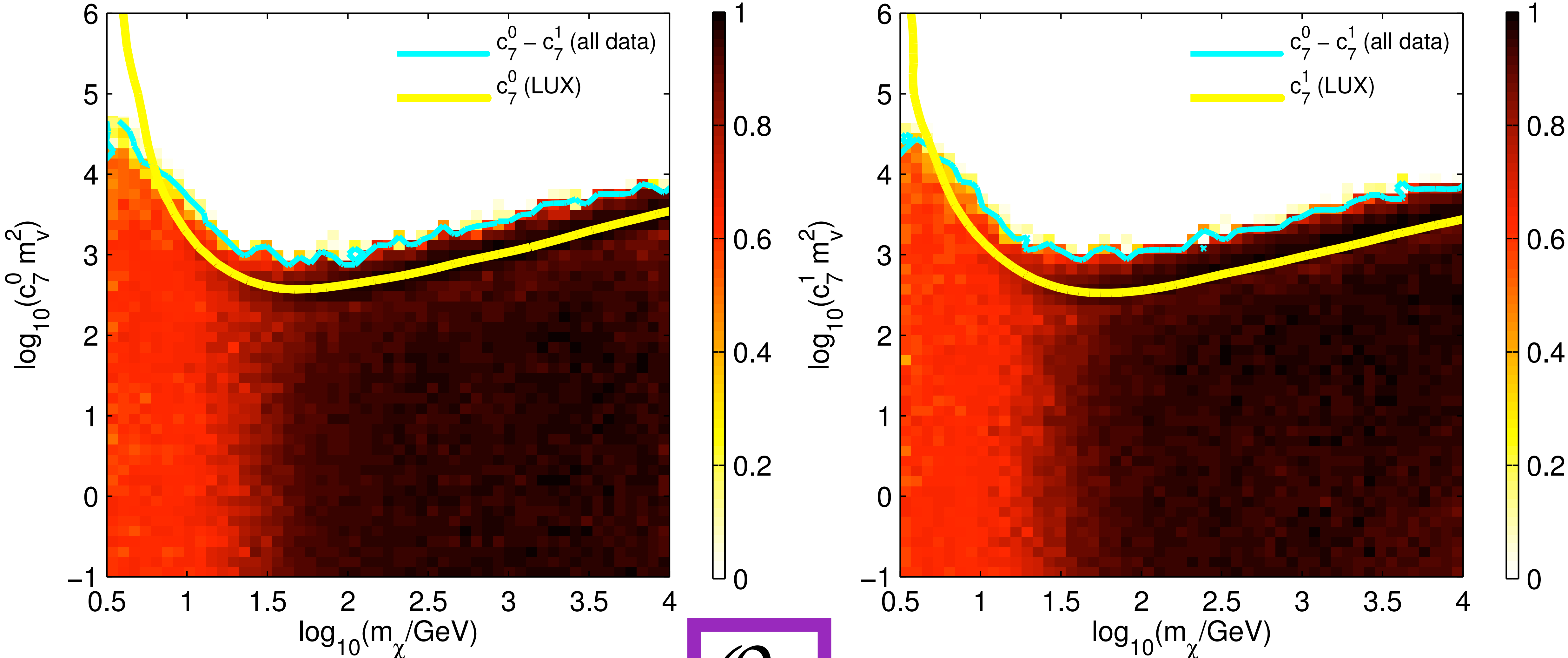
$\mathcal{O}_4/\mathcal{O}_6$

$\mathcal{O}_8/\mathcal{O}_9$

$\mathcal{O}_{11}/\mathcal{O}_{12}$

$\mathcal{O}_{11}/\mathcal{O}_{15}$

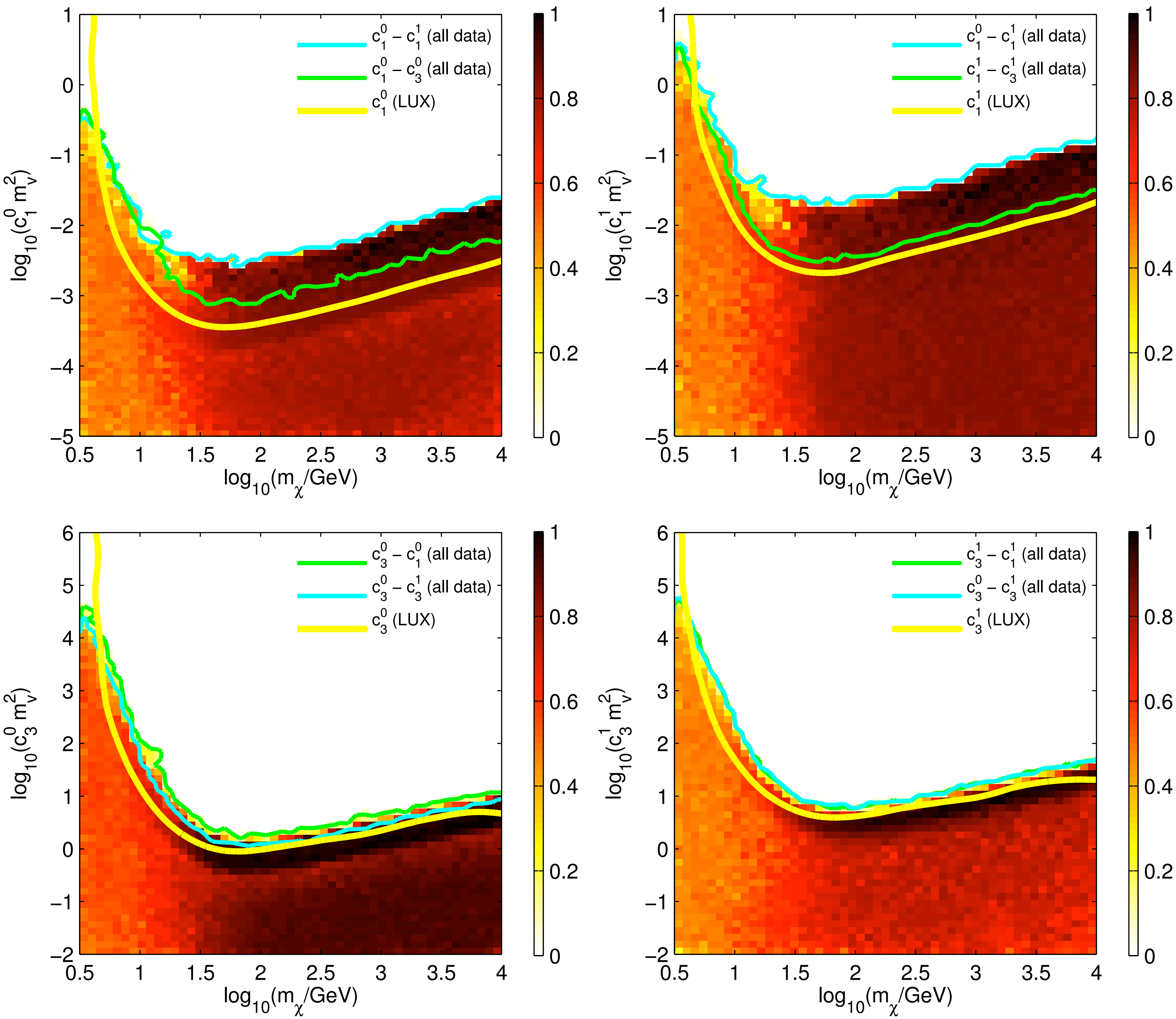
$\mathcal{O}_{12}/\mathcal{O}_{15}$



$\mathcal{O}_7$

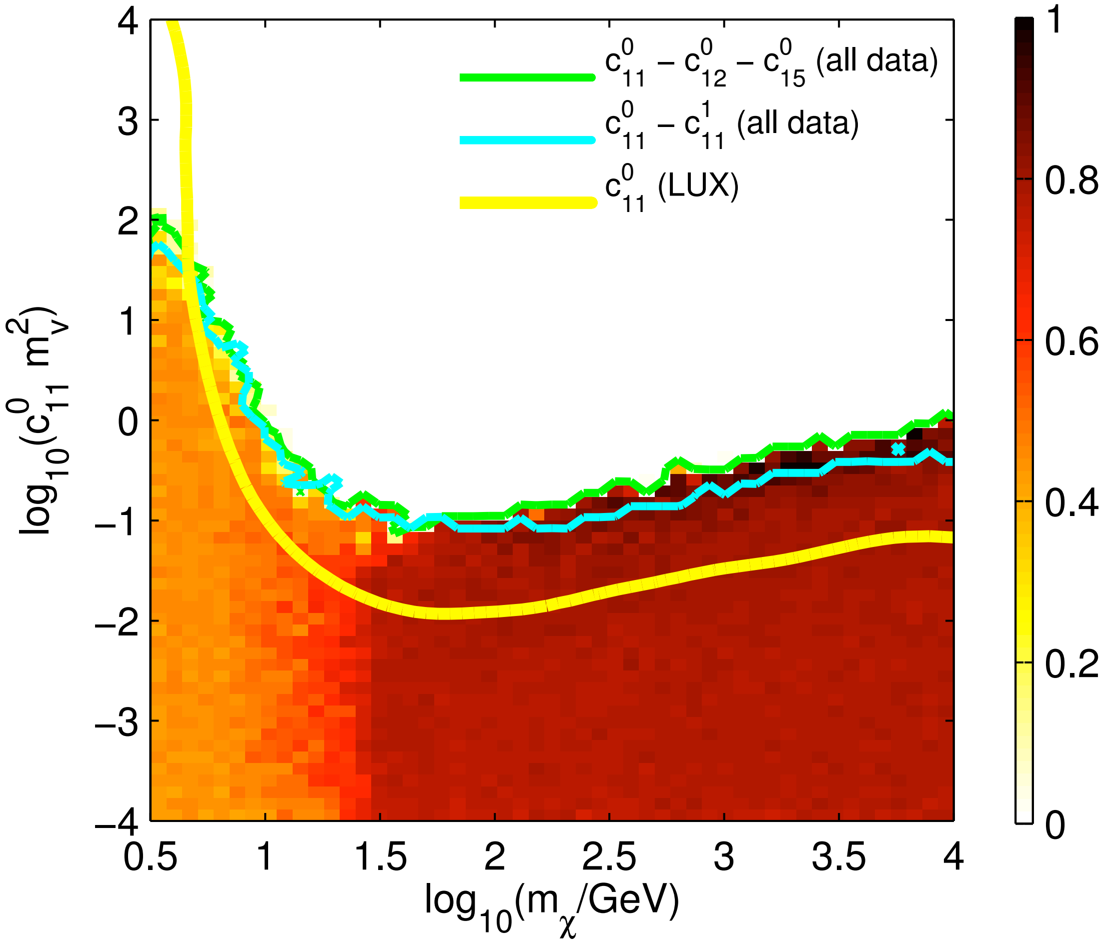
A global analysis of current data shows isoscalar/isovector interference generally makes exclusion limits weaker

R. Catena and P. Gondolo, JCAP **1508** (2015), arXiv:1504.06554

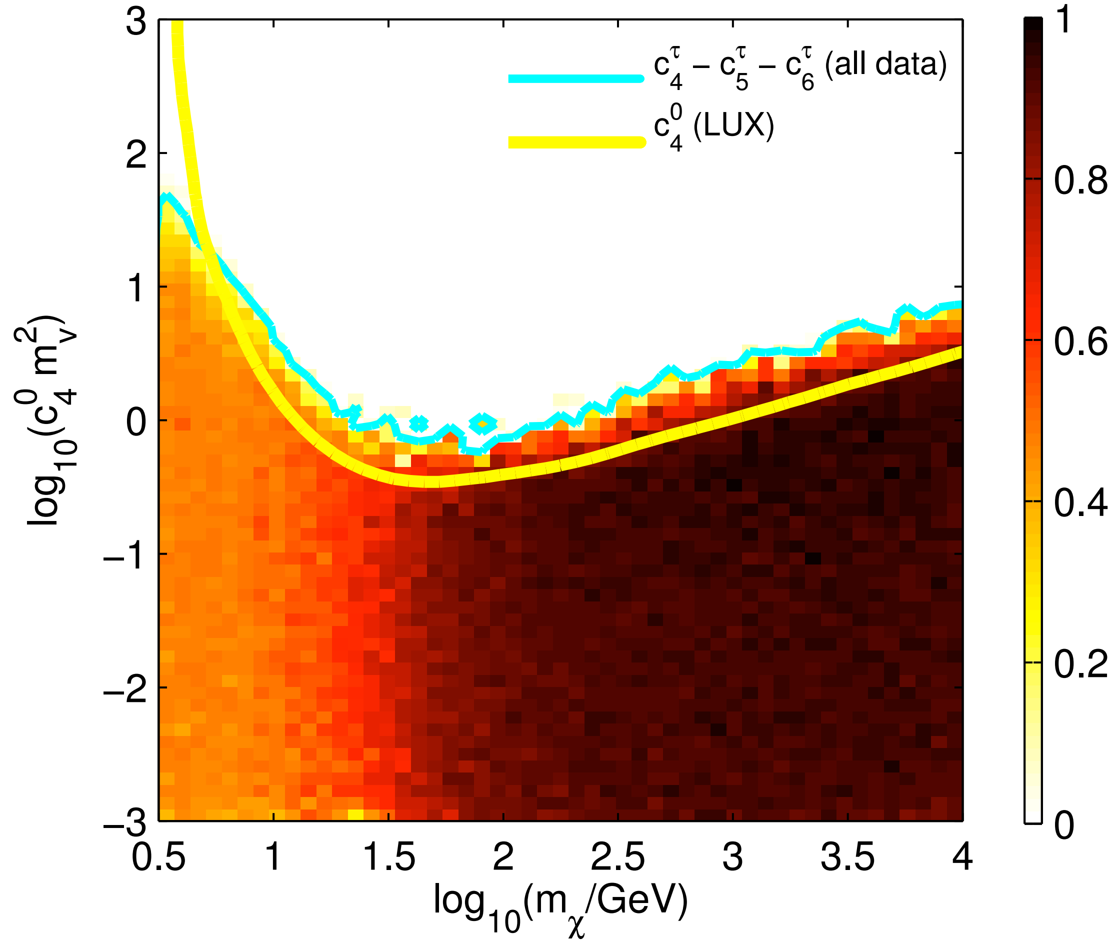


$\mathcal{O}_1/\mathcal{O}_3$

Interference between operators tends to have a smaller effect



$\mathcal{O}_{11}$



$\mathcal{O}_4$

Current experiments constrain some non-standard interactions at the same level or more than the standard spin-dependent interaction

R. Catena and P. Gondolo, JCAP **1409** (2014), arXiv:1405.2637

Simplified Models

In general one can write down the non-relativistic Lagrangian

$$\mathcal{L}_{NR} = \sum_{\alpha=n,p} \sum_{i=1}^{15} c_i^\alpha \mathcal{O}_i^\alpha$$

General isospin (isoscalar/isovector) couplings to protons and neutrons is incorporated

$$\mathcal{L}_{NR} = \sum_{\tau=0,1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau \qquad c_i^0 = \frac{1}{2}(c_i^{\mathrm{p}} + c_i^n) \quad c_i^1 = \frac{1}{2}(c_i^p - c_i^n)$$

The scattering probability is a factorized product of particle and nuclear physics responses

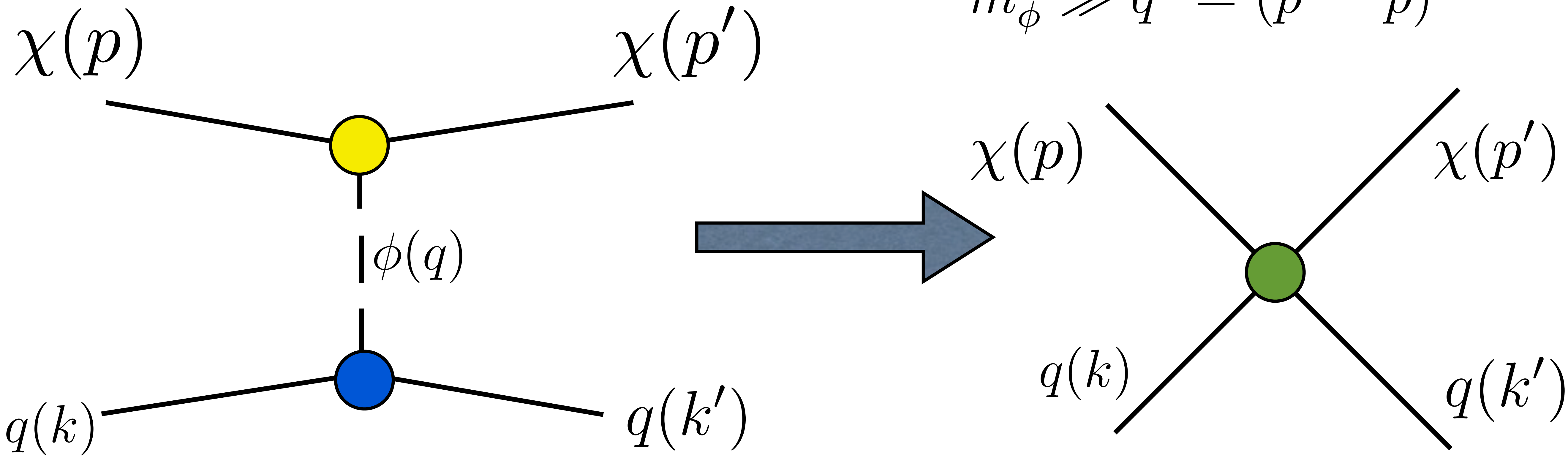
$$\frac{1}{2j_\chi + 1} \frac{1}{2j_N + 1} \sum_{\text{spins}} |\mathcal{M}|^2 \equiv \sum_k \sum_{\tau=0,1} \sum_{\tau'=0,1} R_k \left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{ c_i^\tau c_j^{\tau'} \right\} \right) W_k^{\tau\tau'}(\vec{q}^{\,2} b^2)$$

particle nuclear

A.L. Fitzpatrick, W.C. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302 (2013) 004, arXiv:1203.3542
N. Anand, A.L. Fitzpatrick, and W.C. Haxton, Phys.Rev. C89, 065501 (2014) arXiv:1308.6288

The effective field theory approach is valid for mediators more massive than the momentum exchanged

$$m_\phi^2 \gg q^2 = (p' - p)^2$$

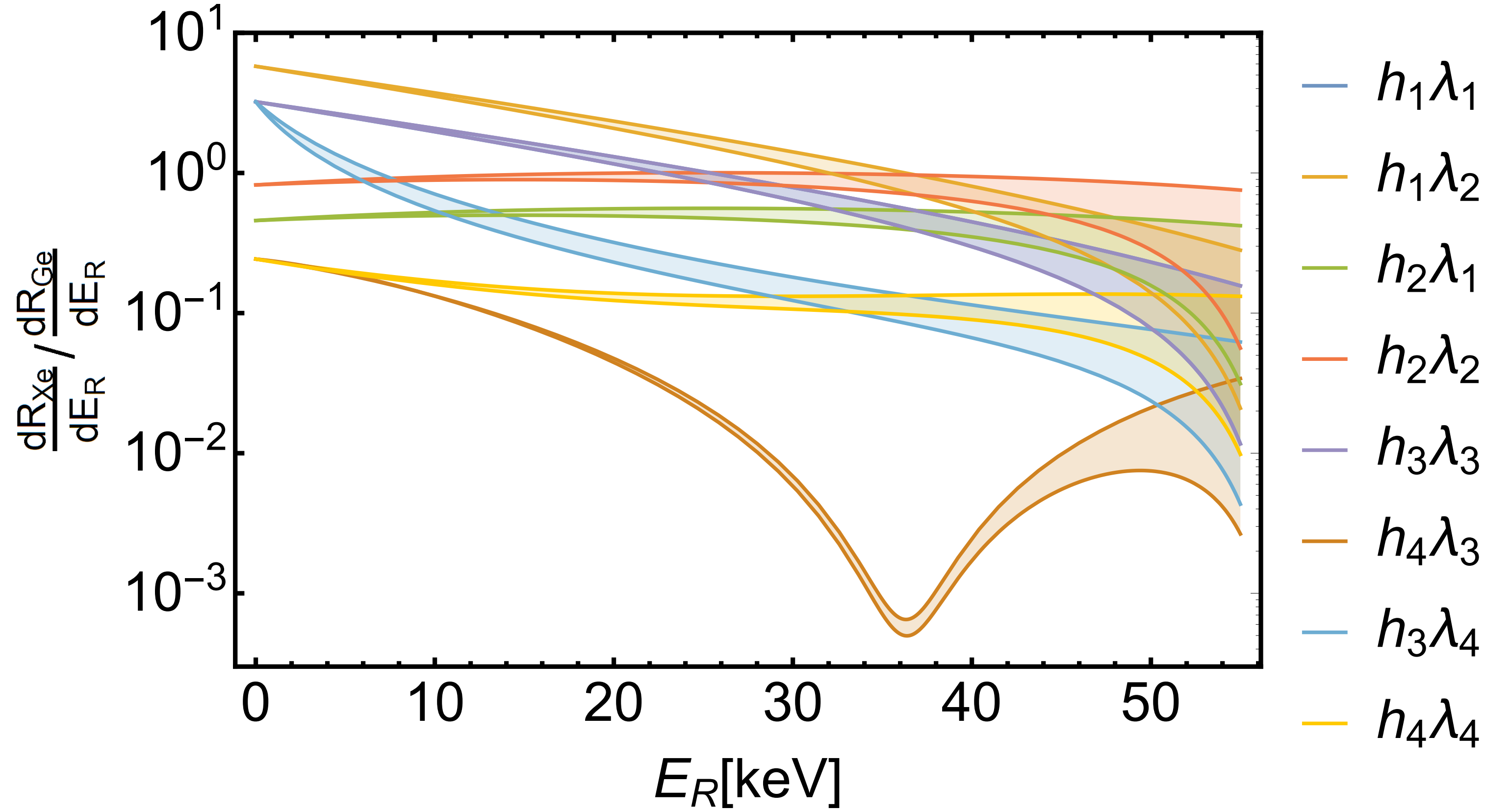


$$\mathcal{L}_{\chi\phi q} = i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi$$
$$+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{m_\phi\mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4$$
$$+i\bar{q}\not{D}q - m_q\bar{q}q$$
$$-\lambda_1\phi\bar{\chi}\chi - i\lambda_2\phi\bar{\chi}\gamma^5\chi - h_1\phi\bar{q}q - ih_2\phi\bar{q}\gamma^5 q$$

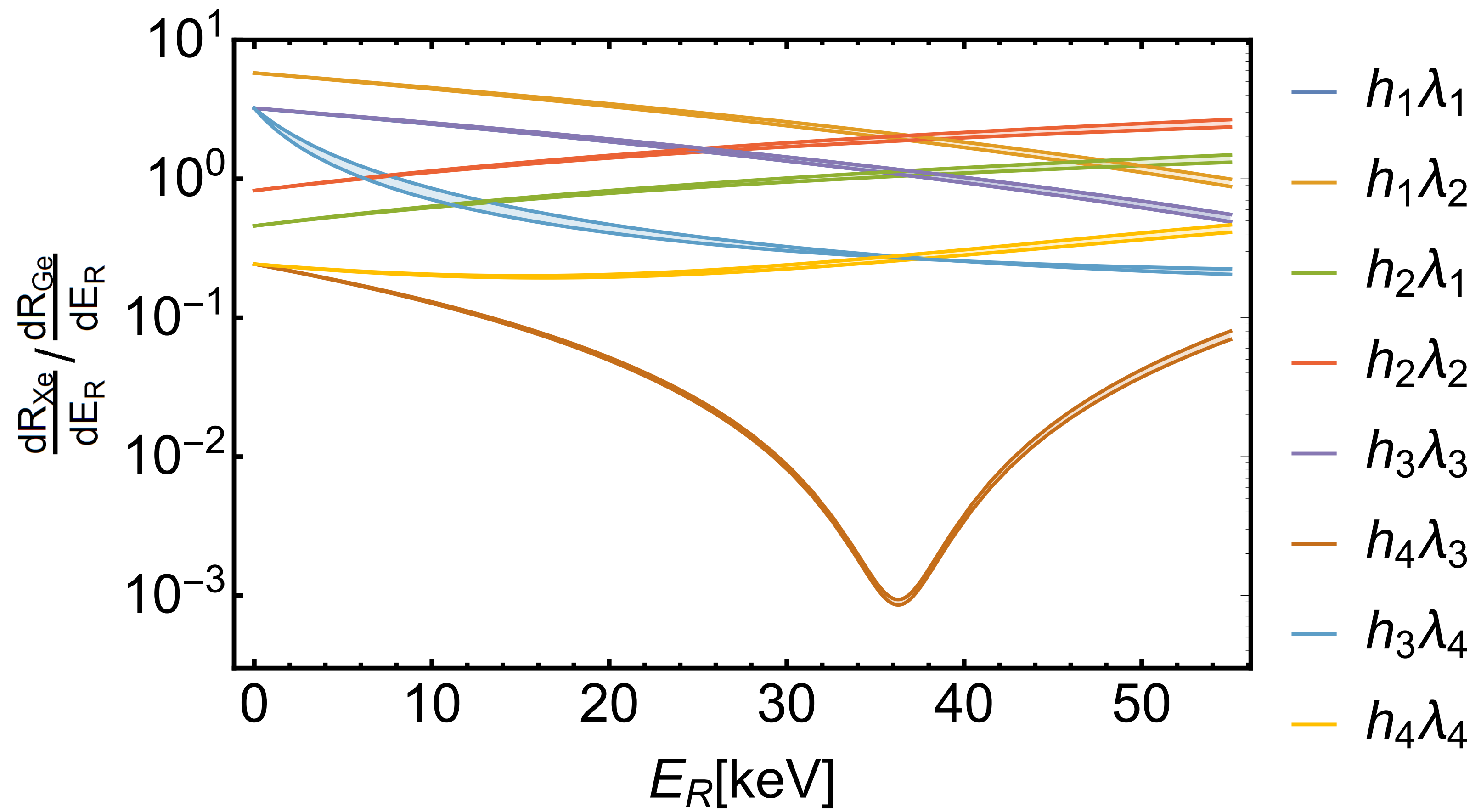
$$\mathcal{L}_{eff} \supset \frac{\lambda_1 h_1}{m_\phi^2}\bar{\chi}\chi\bar{q}q$$

Ratio of rates for 50GeV spin-1/2 WIMP off Xe and Ge including astrophysical uncertainties

50GeV



500GeV



Ratio of rates for 500GeV spin-1/2 WIMP off Xe and Ge including astrophysical uncertainties