nEDM Constrains
Direct Detection EFT Prospects

Rahul Mehra
Bethe Center for Theoretical Physics (BCTP)
Physikalisches Institut, Universität Bonn

based on arXiv:1907.xxxxx
with Manuel Drees

XXV International Symposium PASCOS 2019
Manchester, UK

rmehra@th.physik.uni-bonn.de

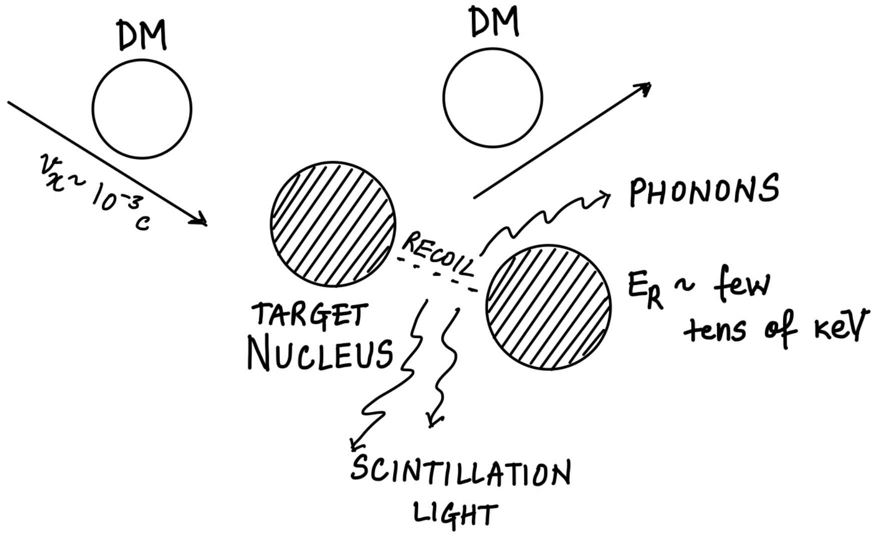
Direct Detection

Goodman and Witten - Phys.Rev. D31 (1985) 3059;
Drukier, Freese and Spergel - Phys.Rev. D33 (1986) 3495-3508

- DM velocity in solar neighbourhood

$$v/c \sim \mathcal{O}(10^{-3})$$ Non-relativistic!

$$|\vec{q}| \leq \min[m_\chi v, m_N v] \leq \mathcal{O}(100\,\mathrm{MeV})$$



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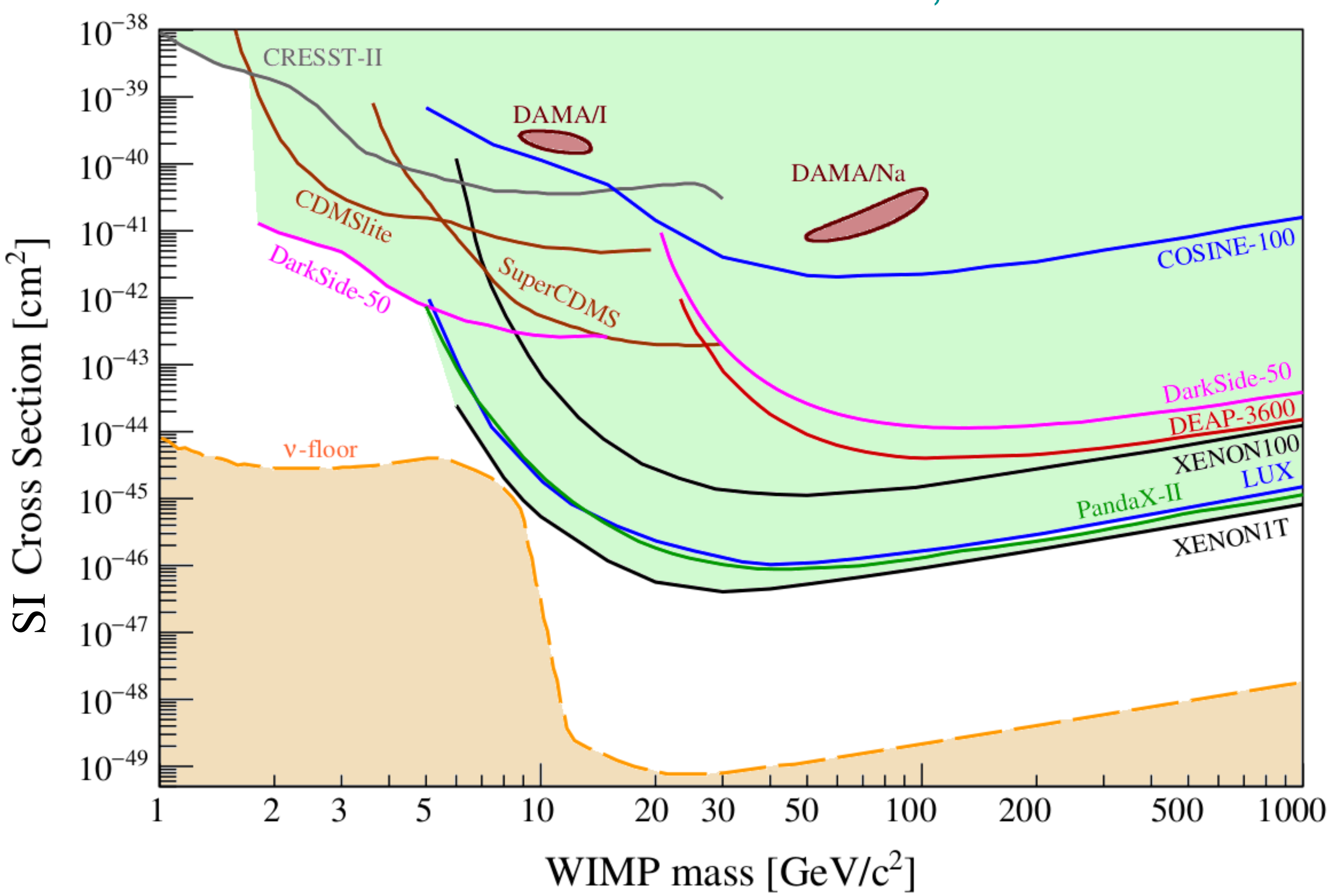

In the limit of vanishing DM velocity, DM-nucleon interactions dominated by

- Spin Independent (SI)
- Spin Dependent (SD)

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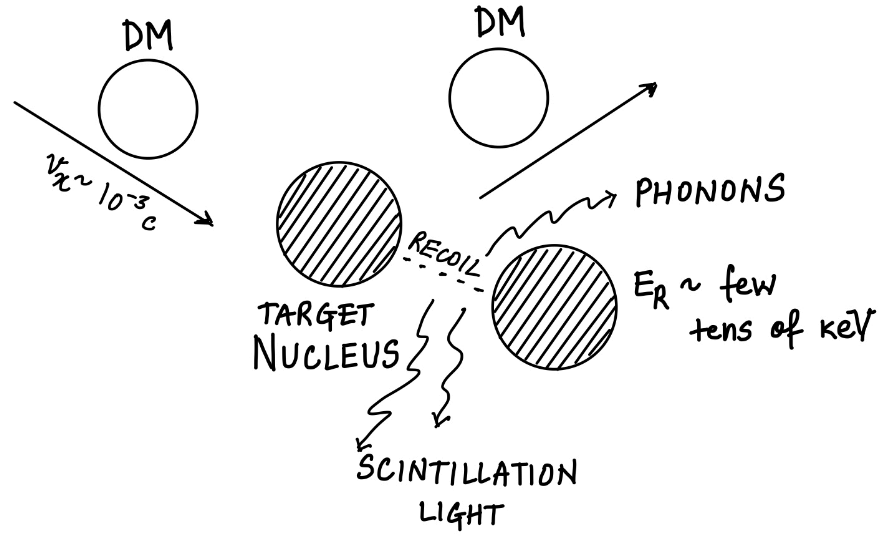

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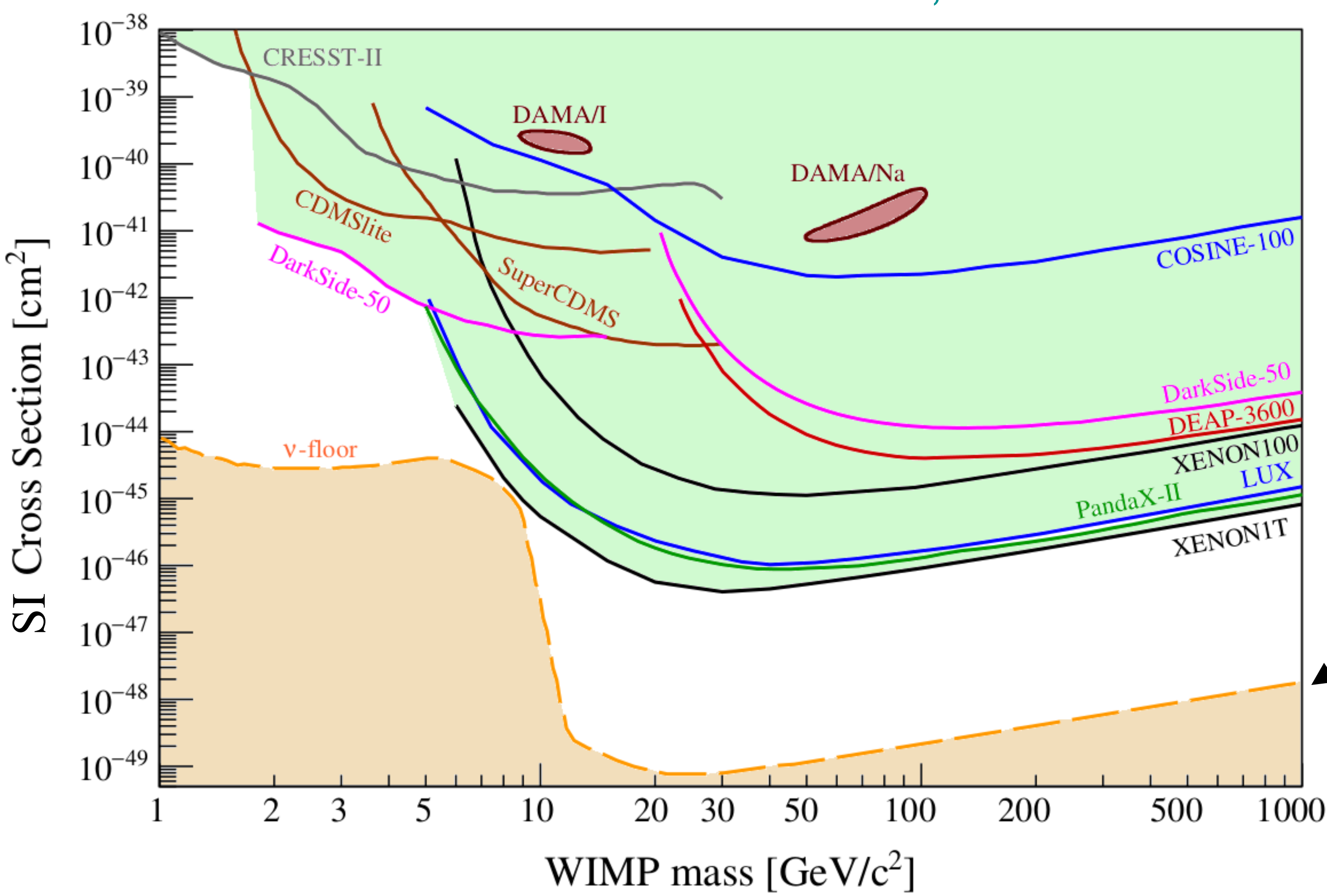

In the limit of vanishing DM velocity, DM-nucleon interactions dominated by

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irreducible background due to coherent neutrino-nucleus scattering

Cabrera, Krauss, Wilczek - Phys.Rev.Lett. 55 (1985) 25;
Monroe and Fisher - Phys.Rev. D76 (2007) 033007

Direct Detection NREFT

Fan, Reece and Wang - JCAP 1011 (2010) 042;
Fitzpatrick et al. - JCAP 1302 (2013) 004;
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- Galilean symmetry dictates the basis of operators

$$i\,\vec{q}, \quad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}, \quad \vec{S}_N, \quad \vec{S}_\chi$$

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P-odd, T-odd

$\vec{v}_T,\, \vec{q} \xrightarrow{P,T} -\vec{v}_T,\, -\vec{q}$

$\vec{S} \xrightarrow{P} \vec{S}$ $\quad i \xrightarrow{T} -i$

$\vec{S} \xrightarrow{T} -\vec{S}$

- SI and SD – zeroth order terms of an EFT with expansion parameter $\vec{v}_T$ or $\frac{\vec{q}}{m_N}$

Hierarchy between operators

- Not all operators are relevant for scattering (if Wilson coefficients are equal)!
- Suppression of operators due to
  - DM velocity $\vec{v}_T^{\,2} \sim \mathcal{O}(10^{-6})$
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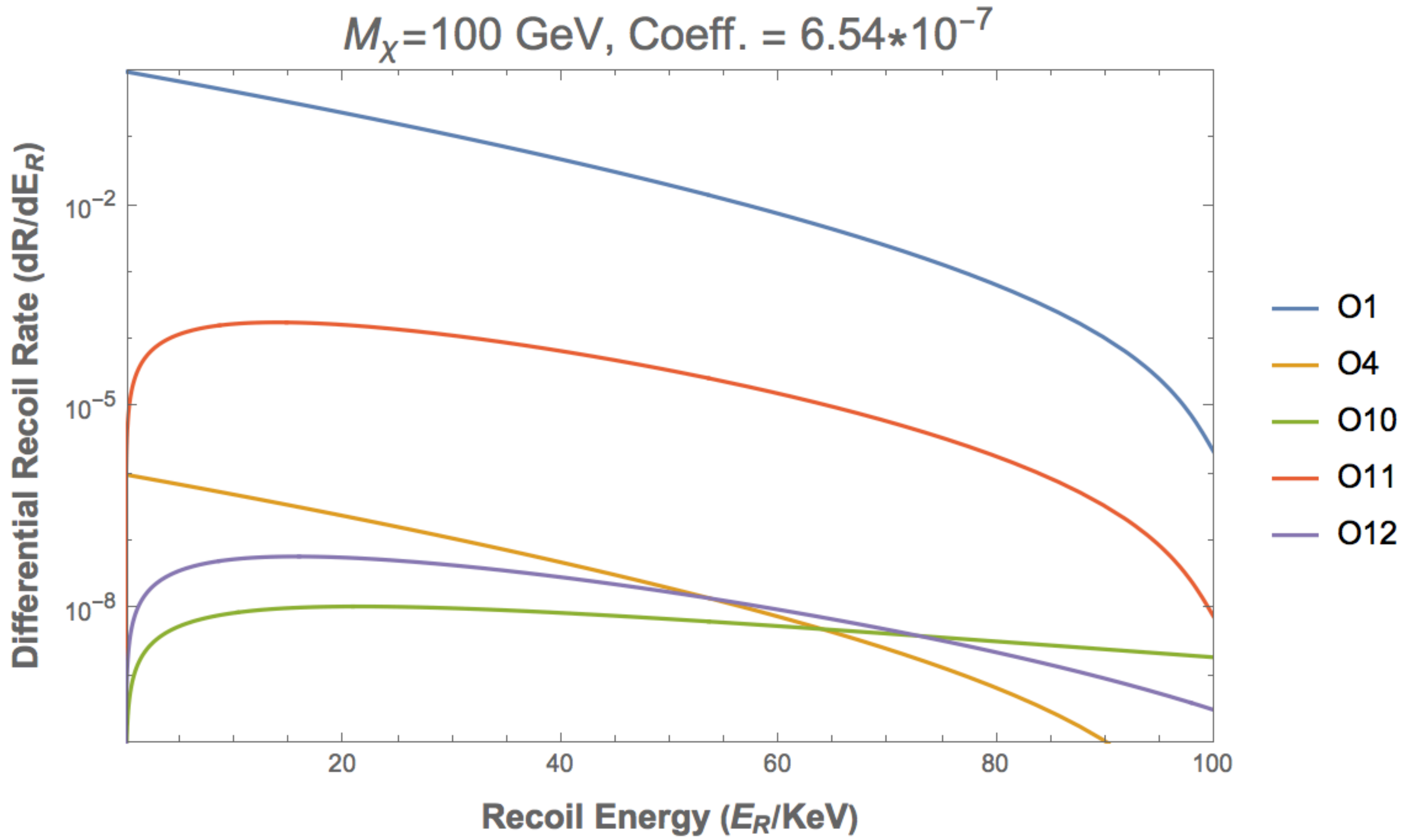

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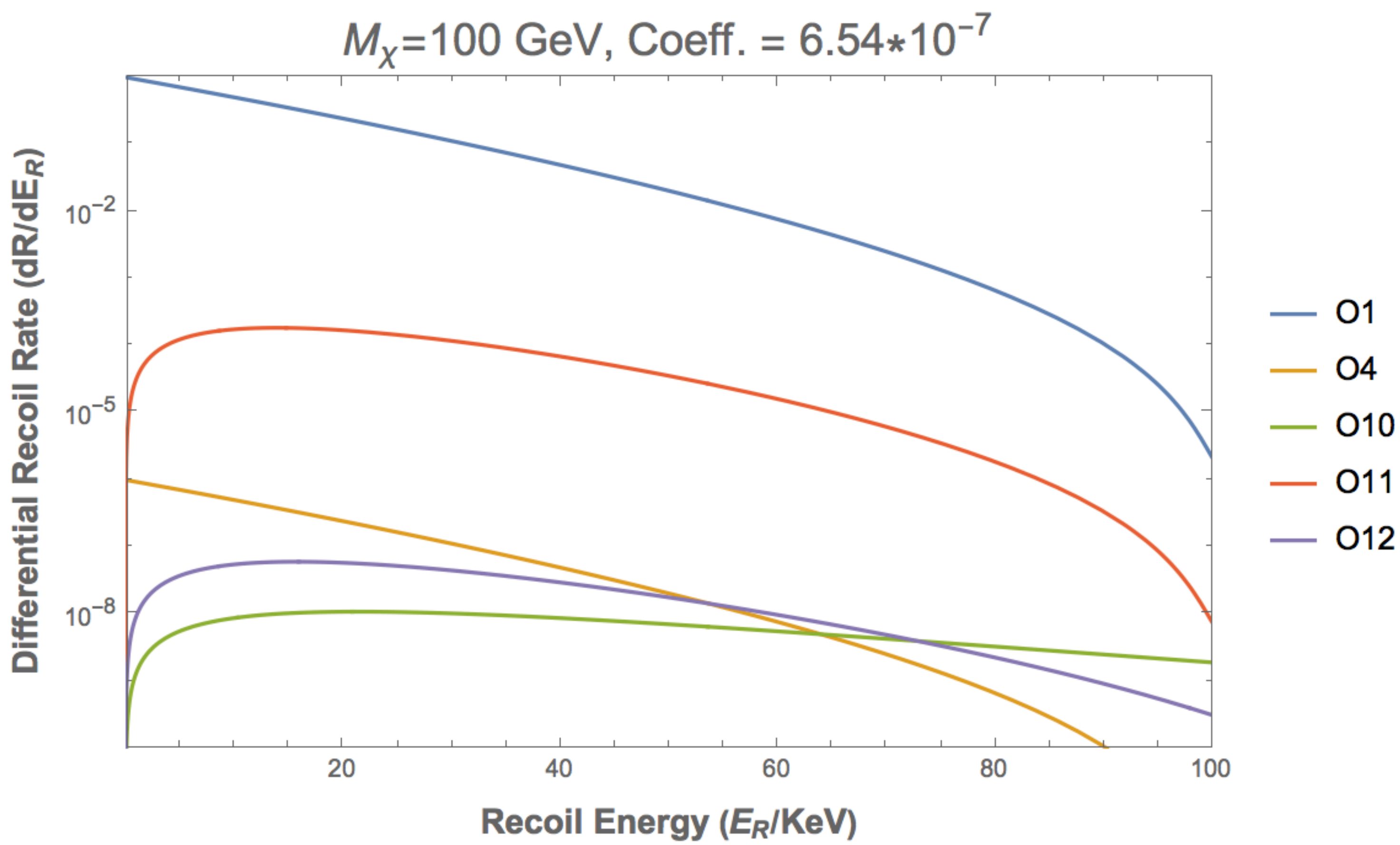

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- Global scans found P-odd, T-odd momentum or velocity suppressed operators are as strongly constrained as zeroth order SD interactions by experiments!

Catena and Gondolo - JCAP 1409 (2014) no.09, 045;
Catena - JCAP 1407 (2014) 055

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  - Need CP violating theory to generate P-odd, T-odd NREFT operators [CPT Theorem]

  - nEDM — a powerful probe of flavour diagonal CP violating extensions of SM

$$|d_n| < 2.9 \times 10^{-26}\,\mathrm{e\,.\,cm} \quad (90\ \%\ \mathrm{C.L.})$$

Particle Data Group (PDG) - Phys.Rev. D98 (2018) no.3, 030001;
Pendelbury et al. - Phys.Rev. D92 (2015) no.9, 092003

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  - We investigate P-odd, T-odd NREFT operators using simplified models respecting SU(3) X U(1) invariance, as per Dent et al. - Phys.Rev. D92 (2015) no.6, 063515

NFREFT Recipe: Two steps of matching

I. Write down the matrix element $\mathcal{M}_{sc}$ for DM-quark scattering

II. Integrate out the heavy mediator from the relativistic theory to construct effective operators

$$\mathcal{L}_{\rm BSM} \longrightarrow \mathcal{L}_{\chi N}^{\rm eff,\ rel} \equiv c_{\rm eff}\, (\chi^+\,\Gamma_\chi\,\chi^-)\,(\bar{N}\,\Gamma_N\,N)$$

III. Match the scattering matrix element to the effective operator

IV. Take the non-relativistic limit of the DM and nucleon bilinears

$$\mathcal{L}_{\chi N}^{\rm eff,\ rel} \longrightarrow \mathcal{L}_{\chi N}^{\rm eff,\ NR} \equiv c_{\rm eff}\, (\chi^+\,\mathcal{O}_\chi\,\chi^-)\,(\bar{N}\,\mathcal{O}_N\,N)$$

V. Match the NR effective Lagrangian to appropriate combinations of NREFT operators

$$\mathcal{L}_{\chi N}^{\rm eff,\ NR} \longrightarrow \sum_{N=n,p} c_i^N\,\mathcal{O}_{i,{\rm NR}}^N \quad \text{where} \quad \mathcal{O}_{i,{\rm NR}} \equiv \mathcal{O}_\chi \cdot \mathcal{O}_N$$

Model I

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- Complex spin-0 WIMP S and heavy quark-like mediator Q; odd under a $\mathbb{Z}_2$
  s-channel scattering

- CP broken explicitly : complex and flavour universal scalar and pseudo-scalar couplings

$$\begin{aligned}\mathcal{L}^{\text{Model I}} = &\mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 \\ &+ i\bar{Q}\not{D}Q - m_Q \bar{Q}Q \\ &- \underline{S\bar{Q}(y_1 + y_2\gamma^5)q - S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger \gamma^5)Q}\end{aligned}$$

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$$\mathcal{L}_{\text{eff}}^{\text{Model I}} \supset c_1^{d5}\,(S^\dagger S)\,\bar{q}\,q \;+\; c_{10}^{d5}\,(S^\dagger S)\,\bar{q}\,i\gamma^5\,q \;+\; c_1^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\,q \;+\; c_7^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\gamma^5\,q$$

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$$S^\dagger S\,\bar{q}i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\text{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\tilde{\Delta}^N\,\mathcal{O}_{10}$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$$

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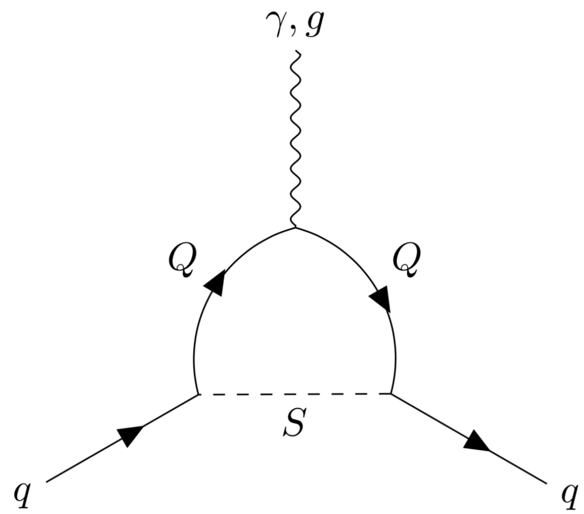
- quark EDM: coefficient of a dim-5 P-odd, T-odd term $\frac{-i}{2}\,\bar{q}\sigma_{\mu\nu}\gamma_5 q\, F^{\mu\nu}$ at vanishing momentum transfer

$$d_q|_{\text{Model I}} = \frac{1}{(4\pi)^2}\, eQ_Q\, m_Q\, \underline{\mathrm{Im}(y_1 y_2^\dagger)}\, F(m_q^2, m_S^2, m_Q^2)$$

$$F(m_q^2, m_S^2, m_Q^2) = \int_0^1 dz \frac{(1-z)^2}{z^2 m_q^2 + z(m_S^2 - m_Q^2 - m_q^2) + m_Q^2}$$



- Use lattice results and QCD sum rules

$$d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s + 1.1\, e\, (0.5\, \tilde{d}_u + \tilde{d}_d)$$

(assume PQ mechanism)

$$g_T^u = -0.233(28) \quad g_T^d = 0.774(66) \quad g_T^s = 0.009(8)$$

PNDME Collaboration - Phys.Rev. D92 (2015) no.9, 094511 ;
Bhattacharya et al. - Phys.Rev.Lett. 115 (2015) no.21, 212002;
Pospelov and Ritz - Phys.Rev. D63 (2001) 073015

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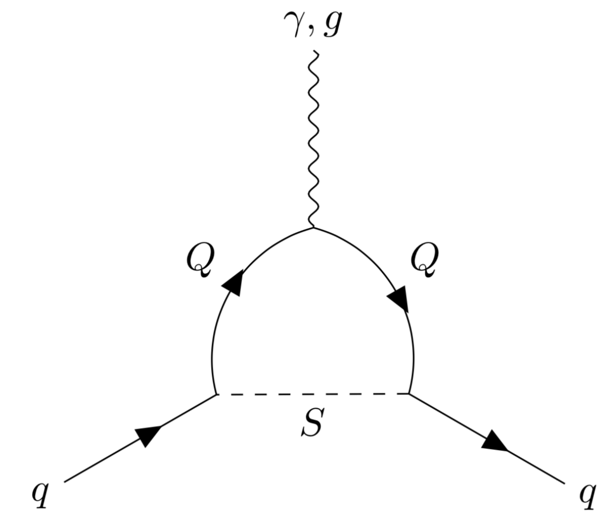

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- However, $\mathcal{O}_1$ dominates scattering*;

$$S^\dagger S\, \bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \cancel{\frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}}\right) f_{Tq}^N\, \mathcal{O}_1$$

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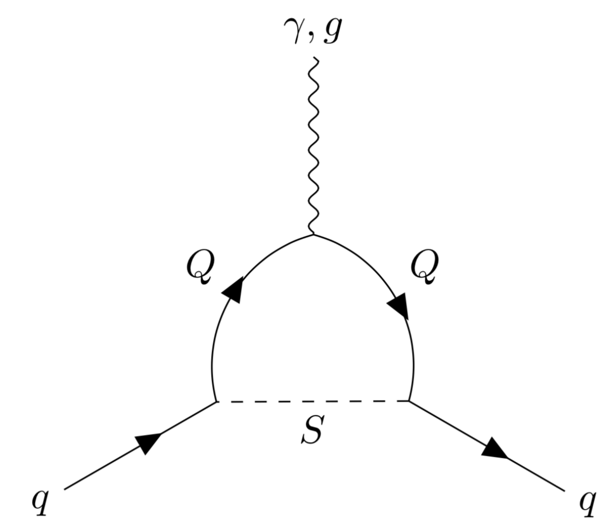
*unless its Wilson coefficient squared is suppressed by a factor of 10^{-6} or less

- quark EDM: coefficient of a dim-5 P-odd, T-odd term $\frac{-i}{2}\,\bar{q}\sigma_{\mu\nu}\gamma_5 q\, F^{\mu\nu}$ at vanishing momentum transfer

$$d_q|_{\text{Model I}} = \frac{1}{(4\pi)^2}\, eQ_Q\, m_Q\, \underline{\mathrm{Im}(y_1 y_2^\dagger)}\, F(m_q^2, m_S^2, m_Q^2)$$

$$F(m_q^2, m_S^2, m_Q^2) = \int_0^1 dz \frac{(1-z)^2}{z^2 m_q^2 + z(m_S^2 - m_Q^2 - m_q^2) + m_Q^2}$$



  - Use lattice results and QCD sum rules

$$d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s + 1.1\, e\,(0.5\,\tilde{d}_u + \tilde{d}_d)$$

(assume PQ mechanism)

$$g_T^u = -0.233(28) \quad g_T^d = 0.774(66) \quad g_T^s = 0.009(8)$$

PNDME Collaboration - Phys.Rev. D92 (2015) no.9, 094511 ;
Bhattacharya et al. - Phys.Rev.Lett. 115 (2015) no.21, 212002;
Pospelov and Ritz - Phys.Rev. D63 (2001) 073015

- However, $\mathcal{O}_1$ dominates scattering*; its contribution to scattering can be made to vanish if

$$S^\dagger S\, \bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \cancel{\frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}}\right) f_{Tq}^N\, \mathcal{O}_1$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\, \bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\, \mathcal{N}_q^N\, \mathcal{O}_1$$

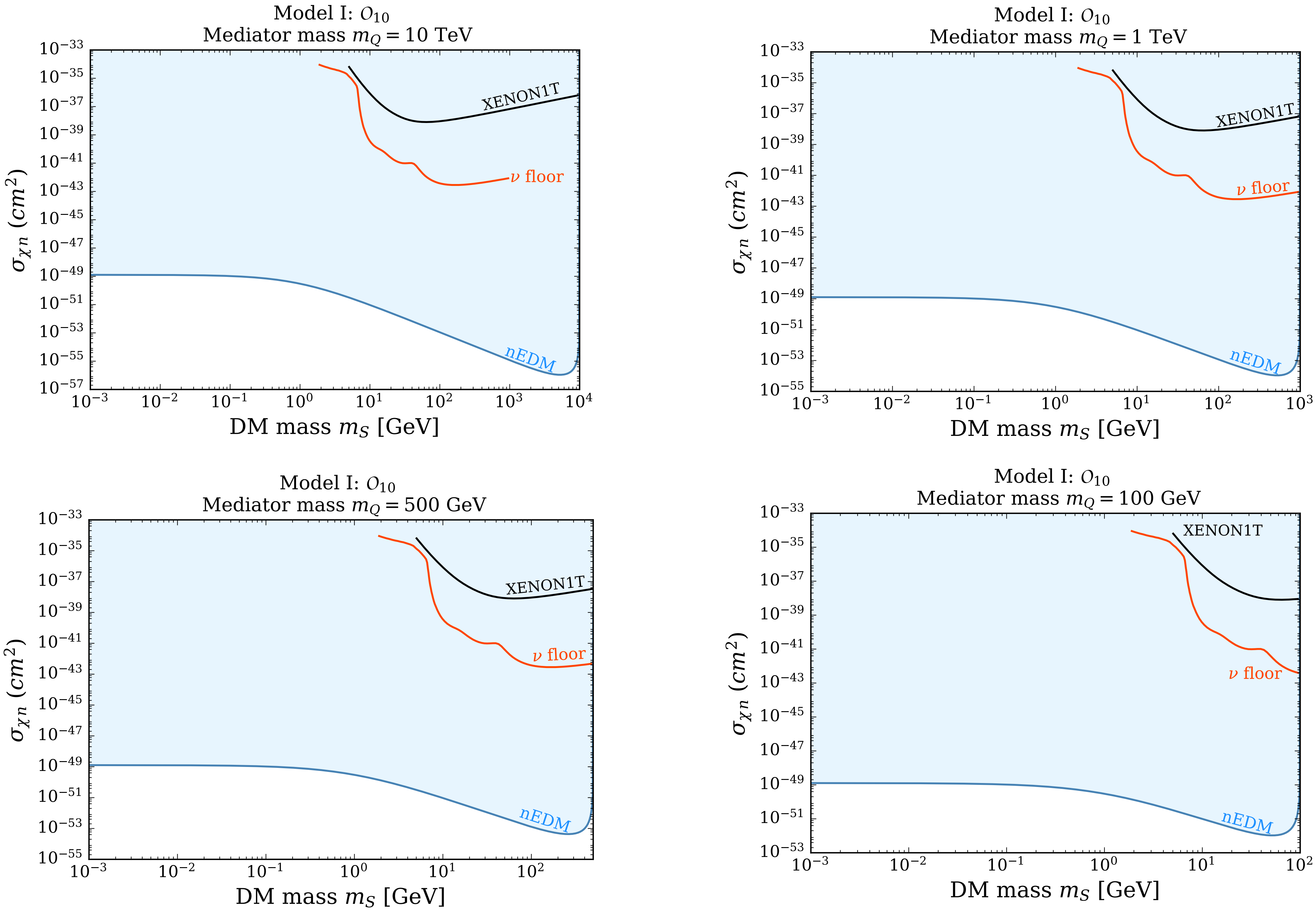
$$\boxed{|y_1^N|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}{1 + \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}\right)|y_2^N|^2}$$

$$f_T^N \equiv \textstyle\sum_q \langle \bar{N}|\, \bar{q}q\, |N\rangle$$
$$\mathcal{N}^N \equiv \textstyle\sum_q \langle \bar{N}|\, \bar{q}\gamma^\mu q\, |N\rangle$$

*unless its Wilson coefficient squared is suppressed by a factor of 10^{-6} or less

- Convert the constraint on $\mathrm{Im}(y_1 y_2^\dagger)$ from nEDM into a cross section using $\sigma_{\mathcal{O}_{10}} = \frac{3\mu_{\chi N}^2}{\pi}\,(c_{10}^N)^2$

$$d_q|_{\text{Model I}} = \frac{1}{(4\pi)^2}\, eQ_Q\, m_Q\, \mathrm{Im}(y_1 y_2^\dagger)\, F(m_q^2, m_S^2, m_Q^2) \qquad S^\dagger S\, \bar{q} i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\mathrm{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\, 2\tilde{\Delta}^N\, \mathcal{O}_{10}$$



Model II

- Fermionic DM χ and a complex spin-0 mediator Φ ; both odd under a $\mathbb{Z}_2$ s-channel scattering; flavour universal scalar and pseudo-scalar couplings

$$
\begin{aligned}
\mathcal{L}^{\text{Model II}} = &\ \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi \bar{\chi}\chi \\
&+ (\partial_\mu \Phi^\dagger)(\partial^\mu \Phi) - m_\Phi^2 \Phi^\dagger \Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 \\
&- \underline{(l_1 \Phi^\dagger \bar{\chi} q + l_2 \Phi^\dagger \bar{\chi}\gamma_5 q + h.c.)}
\end{aligned}
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- generates 9 distinct NREFT operators (and 10 effective dim-6 operators)

- integrating out the heavy complex scalar and using Fierz identities results in

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$$
\begin{array}{lcl lcl}
\bar{\chi}\chi\,\bar{q}q & \longrightarrow & \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N \mathcal{O}_1 & \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q & \longrightarrow & \frac{\mathrm{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N (\mathcal{O}_8 + \mathcal{O}_9) \\
\bar{\chi}\chi\,\bar{q}i\gamma^5 q & \longrightarrow & -\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta\tilde{q}^N \mathcal{O}_{10} & \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q & \longrightarrow & \frac{\mathrm{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta_q^N (-\mathcal{O}_7 + \frac{m_N}{m_\chi}\mathcal{O}_9) \\
\bar{\chi}i\gamma^5\chi\,\bar{q}q & \longrightarrow & -\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N \mathcal{O}_{11} & \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q & \longrightarrow & -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N \mathcal{O}_4 \\
\bar{\chi}i\gamma^5\chi\,\bar{q}i\gamma^5 q & \longrightarrow & \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N \mathcal{O}_6 & \bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q & \longrightarrow & \frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2}\delta_q^N \mathcal{O}_4 \\
\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q & \longrightarrow & -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N \mathcal{O}_1 & \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q & \longrightarrow & \frac{2\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\delta_q^N \left(\mathcal{O}_{11} - \frac{m_N}{m_\chi}\mathcal{O}_{10} - 4\mathcal{O}_{12}\right)
\end{array}
$$

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  s-channel scattering; flavour universal scalar and pseudo-scalar couplings

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- generates 9 distinct NREFT operators (and 10 effective dim-6 operators)

- integrating out the heavy complex scalar and using Fierz identities results in

$$\bar{\chi}\chi\,\bar{q}q \longrightarrow \frac{1}{4}\frac{|l_2|^2-|l_1|^2}{m_\Phi^2-m_\chi^2}f_{Tq}^N\,\mathcal{O}_1$$

$$\boxed{\bar{\chi}\chi\,\bar{q}i\gamma^5 q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2-m_\chi^2}\Delta\tilde{q}^N\,\mathcal{O}_{10}}$$

$$\boxed{\bar{\chi}i\gamma^5\chi\,\bar{q}q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2-m_\chi^2}\frac{m_N}{m_\chi}f_{Tq}^N\,\mathcal{O}_{11}}$$

$$\bar{\chi}i\gamma^5\chi\,\bar{q}i\gamma^5 q \longrightarrow \frac{1}{4}\frac{|l_2|^2-|l_1|^2}{m_\Phi^2-m_\chi^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\,\mathcal{O}_6$$

$$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2+|l_1|^2}{m_\Phi^2-m_\chi^2}\mathcal{N}_q^N\,\mathcal{O}_1$$

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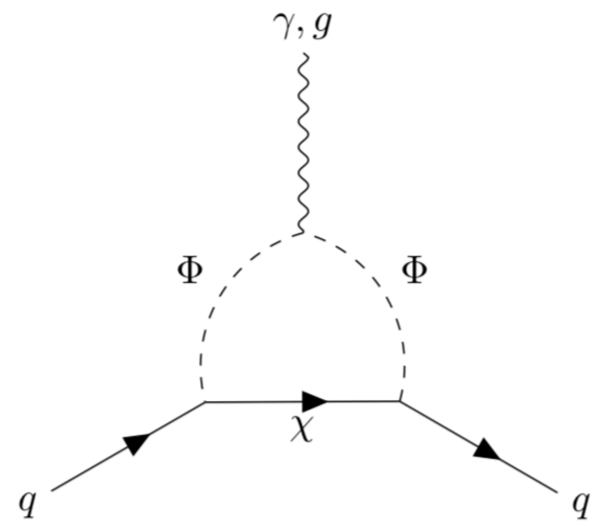
$$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2+|l_1|^2}{m_\Phi^2-m_\chi^2}\Delta_q^N\mathcal{O}_4$$

$$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q \longrightarrow \frac{|l_2|^2-|l_1|^2}{m_\Phi^2-m_\chi^2}\delta_q^N\mathcal{O}_4$$

$$\boxed{\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q \longrightarrow \frac{2\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2-m_\chi^2}\delta_q^N\left(\mathcal{O}_{11}-\tfrac{m_N}{m_\chi}\mathcal{O}_{10}-4\mathcal{O}_{12}\right)}$$

$$d_q|_{\text{Model II}} = \frac{1}{(4\pi)^2}\, eQ_\Phi\, m_\chi\, \underline{\mathrm{Im}(l_1 l_2^\dagger)}\, G(m_q^2, m_\Phi^2, m_\chi^2)$$

$$G(m_q^2, m_\Phi^2, m_\chi^2) = \int_0^1 dz\, \frac{z(1-z)}{z^2 m_q^2 + z(m_\chi^2 - m_\Phi^2 - m_q^2) + m_\Phi^2}$$



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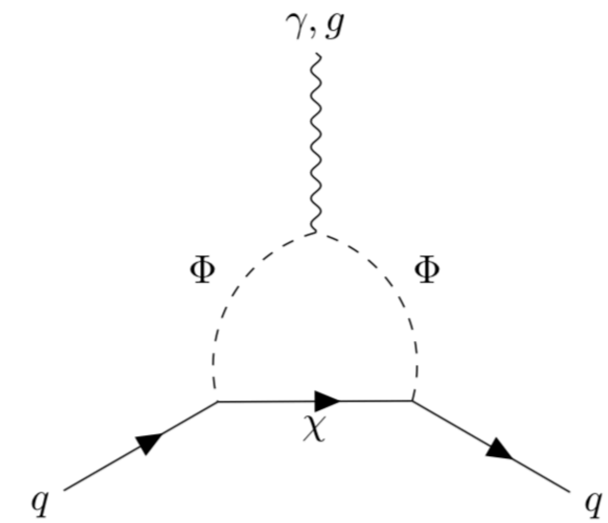

- Like in Model I, almost all of the parameter space is dominated by $\mathcal{O}_1$ unless its coefficient squared is suppressed by a factor of 10^{-4} or less

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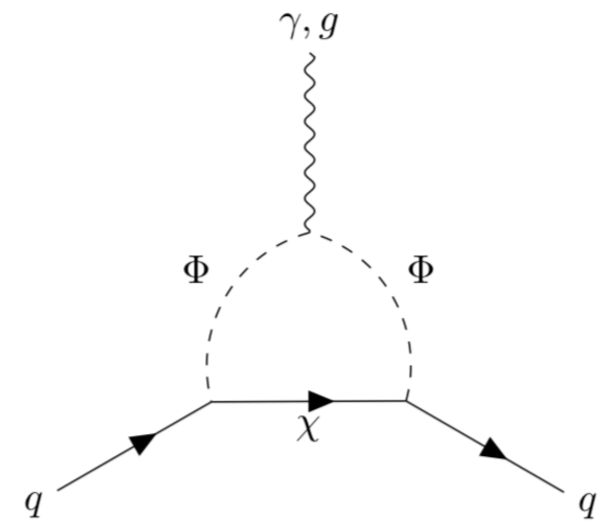

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$$\bar\chi\chi\,\bar q q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N\,\mathcal{O}_1$$

$$\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,\mathcal{O}_1$$

$$\bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N\,\mathcal{O}_4$$

$$\bar\chi i\gamma^5\chi\,\bar q q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\,\mathcal{O}_{11}$$

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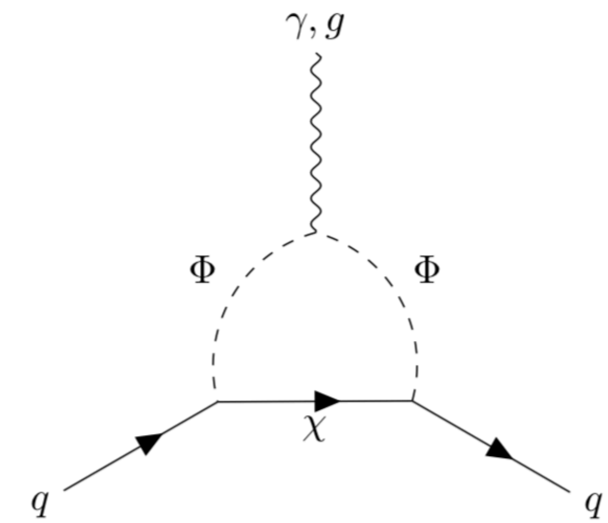

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$$\bar{\chi}\chi\, \bar{q}q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N \mathcal{O}_1 \qquad \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N \mathcal{O}_4$$

$$\bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N \mathcal{O}_1 \qquad \bar{\chi}i\gamma^5\chi\, \bar{q}q \longrightarrow -\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N \mathcal{O}_{11}$$

- or when the $\mathcal{O}_1$ contribution vanishes with $$\boxed{\left|l_1^N\right|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}}{1 + \frac{\mathcal{N}^N}{f_T^N}}\right)\left|l_2^N\right|^2}$$

$f_T^N \equiv \sum_q \langle \bar{N}|\, \bar{q}q\, |N\rangle$
$\mathcal{N}^N \equiv \sum_q \langle \bar{N}|\, \bar{q}\gamma^\mu q\, |N\rangle$

$$d_q|_{\text{Model II}} = \frac{1}{(4\pi)^2}\, eQ_\Phi\, m_\chi\, \underline{\mathrm{Im}(l_1 l_2^\dagger)}\, G(m_q^2, m_\Phi^2, m_\chi^2)$$

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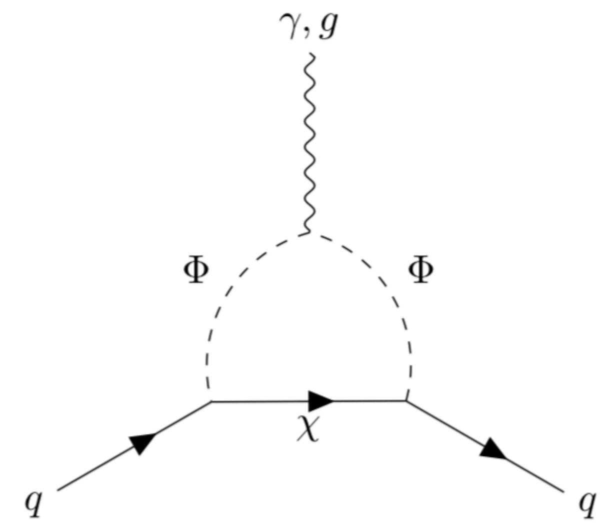


- Like in Model I, almost all of the parameter space is dominated by $\mathcal{O}_1$ unless its coefficient squared is suppressed by a factor of 10^{-4} or less

$$\bar\chi\chi\,\bar q q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N \mathcal{O}_1 \qquad \bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N \mathcal{O}_4$$

$$\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N \mathcal{O}_1 \qquad \bar\chi i\gamma^5\chi\,\bar q q \longrightarrow -\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N \mathcal{O}_{11}$$

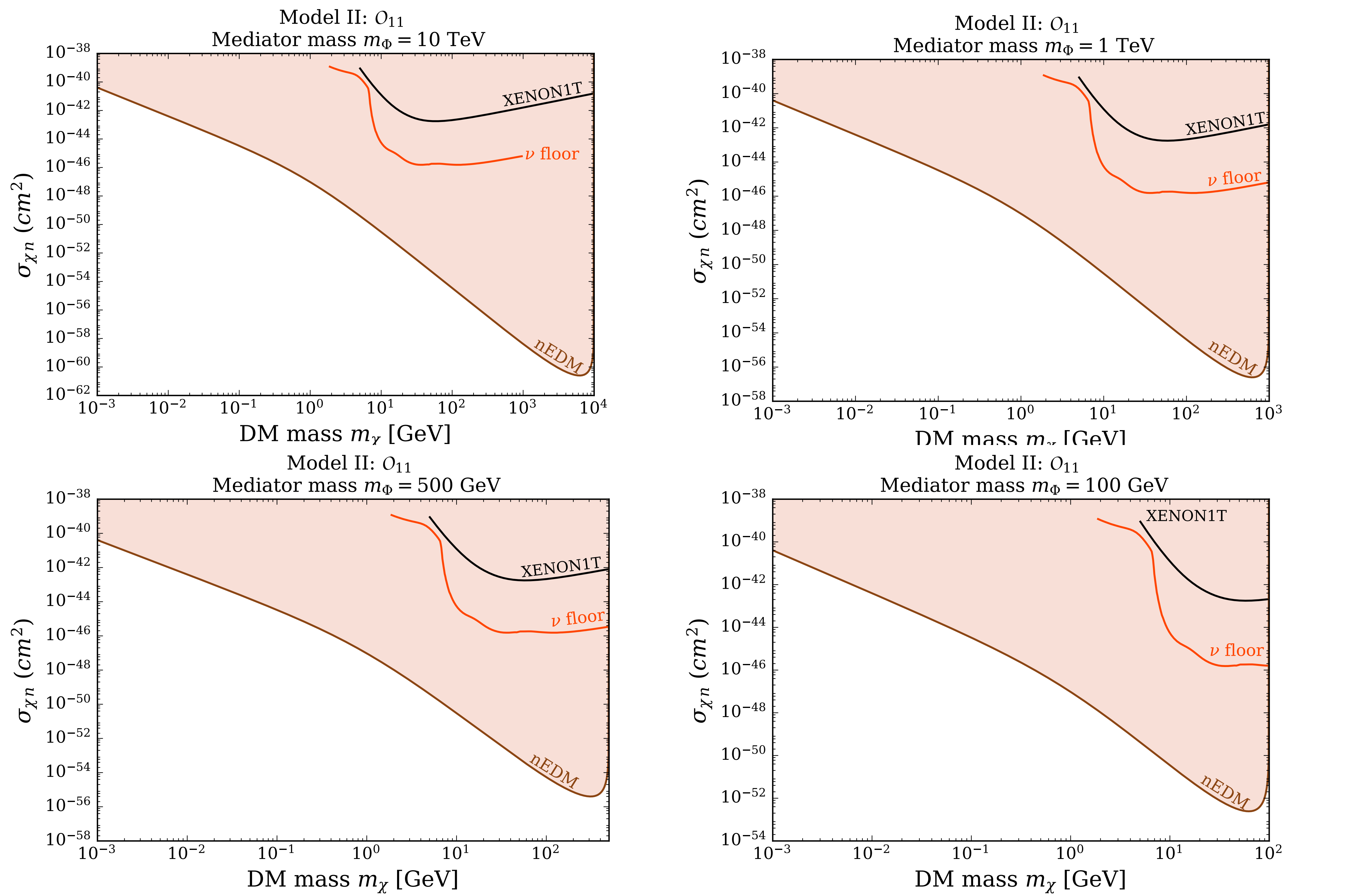
- or when the $\mathcal{O}_1$ contribution vanishes with $\boxed{\left|l_1^N\right|^2 = \left(\dfrac{1 - \frac{\mathcal{N}^N}{f_T^N}}{1 + \frac{\mathcal{N}^N}{f_T^N}}\right)\left|l_2^N\right|^2}$

$$f_T^N \equiv \sum_q \langle \bar N |\, \bar q q \,| N\rangle$$
$$\mathcal{N}^N \equiv \sum_q \langle \bar N |\, \bar q \gamma^\mu q \,| N\rangle$$

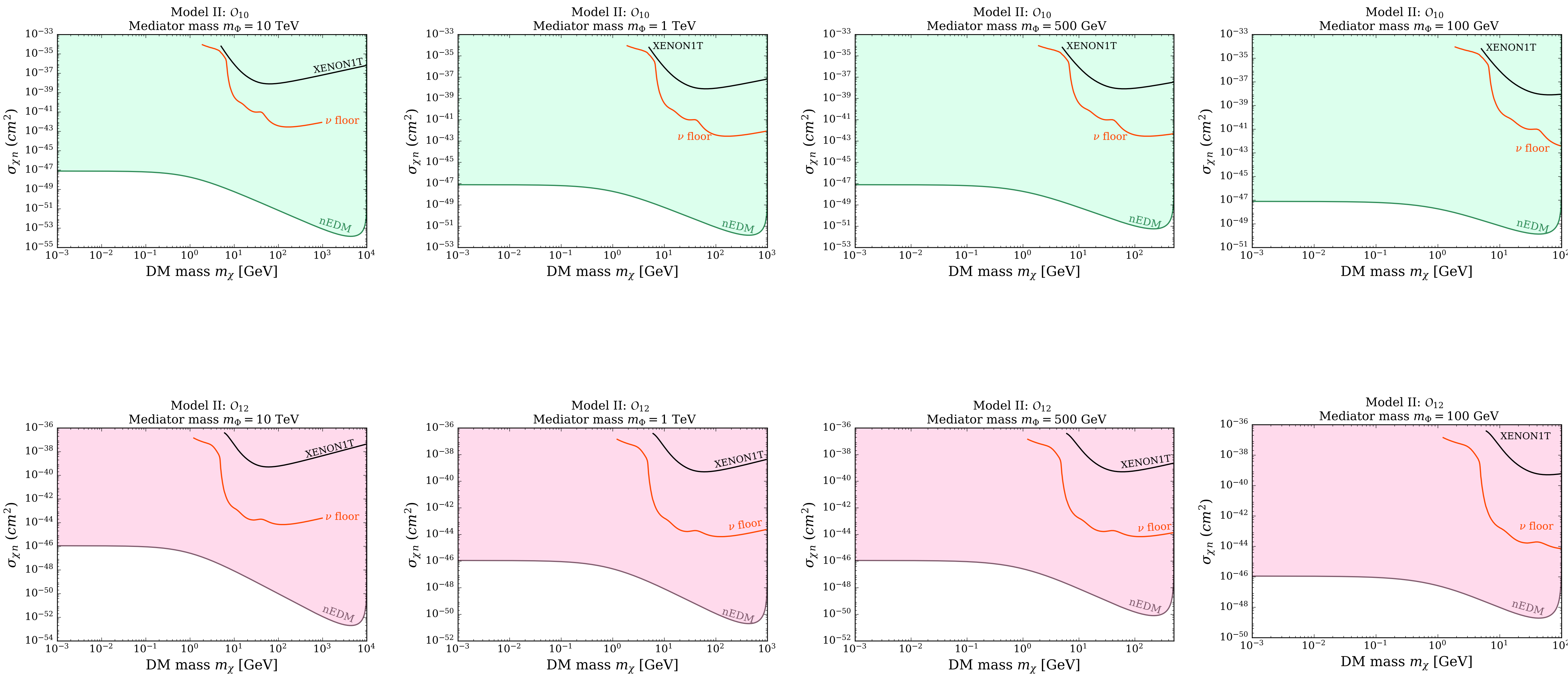
- Scattering (on Xe) is now dominated by the SI operator $\mathcal{O}_{11}$ and not by the traditional SD $\mathcal{O}_4$!

- Convert the constraint on $\mathrm{Im}(l_1 l_2^\dagger)$ from nEDM into a cross section using $\sigma_{\mathcal{O}_{11}} = \frac{\mu_{\chi N}^2}{\pi} (c_{11}^N)^2$

$$d_q|_{\text{Model II}} = \frac{1}{(4\pi)^2}\, eQ_\Phi\, m_\chi\, \mathrm{Im}(l_1 l_2^\dagger)\, G(m_q^2, m_\Phi^2, m_\chi^2) \qquad \bar{\chi} i\gamma^5 \chi\, \bar{q}q \longrightarrow -\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\, \mathcal{O}_{11}$$



- in the unlikely scenario, if in some region of the parameter space for Model II, either $\mathcal{O}_{10}$ or $\mathcal{O}_{12}$ dominates scattering



Summary

- nEDM constraints on P-odd, T-odd NREFT cross sections are many orders of magnitude stronger than the neutrino floor for sub-GeV to TeV DM mass range;
- current and future direct detection experiments are not sensitive to such interactions
- global scans can be misleading; must take into account particle physics considerations
- NREFT has phenomenological redundancies;
  not all operators are relevant; deserves further scrutiny

Backup Slides

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi m_N}{2\pi m_\chi} \int_{v_{\min}}^{v_{\rm esc}} \frac{f(v)}{v} \; J_\chi \, J_N \, \sum_{\rm spins} |\mathcal{M}_{\rm sc}|^2 \; d^3 v$$

$$J_\chi J_N \sum_{\rm spins} |\mathcal{M}_{\rm sc}|^2 = \sum_{\substack{k'=M,\Sigma'',\\ \Sigma''}} R_k^{NN'}(v^2, \vec{q}^{\,2})\, W_k^{NN'}(\vec{q}^{\,2} b^2) + \sum_{\substack{k'=\Delta,\Delta\Sigma',\\ \Phi'',\Phi'' M}} \frac{\vec{q}^{\,2}}{m_N^2} R_k^{NN'}(v^2, \vec{q}^{\,2})\, W_k^{NN'}(\vec{q}^{\,2} b^2)$$

DM Response Functions

Anand, Fitzpatrick and Haxton - Phys.Rev. C89 (2014) no.6, 065501

$$\begin{aligned}
R_M^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= 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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= 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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'} + \right. \\
&\quad \left. \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'} + \right. \\
&\quad \left. \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \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'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].
\end{aligned}$$

Model I

$$\boxed{\begin{aligned}\mathcal{M}_{Sq\to Sq} &= \frac{m_Q}{m_Q^2 - m_S^2}\Big[(|y_1|^2 - |y_2|^2)\ \bar{u}(k_2)\, u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\ \bar{u}(k_2)\, i\gamma^5\, u(p_2)\Big] \\ &+ \frac{1}{m_Q^2 - m_S^2}\,(|y_1|^2 + |y_2|^2)\Big[\, m_q\, \bar{u}(k_2)\, u(p_2) + \ \bar{u}(k_2)\, \frac{\not{p}_1 + \not{k}_1}{2}\, u(p_2)\Big] \\ &+ \frac{1}{m_Q^2 - m_S^2}\ 2\,\mathrm{Re}(y_1 y_2^\dagger)\ \Big[\,\bar{u}(k_2)\, \frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\, u(p_2)\Big]\end{aligned}}$$

Model I

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2$$
$$+ i\bar{Q}\not{D}Q - m_Q \bar{Q}Q$$
$$- S\bar{Q}(y_1 + y_2\gamma^5)q - S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger\gamma^5)Q$$

$$\boxed{\begin{aligned} \mathcal{M}_{Sq\to Sq} = {} & \frac{m_Q}{m_Q^2 - m_S^2}\Big[(|y_1|^2 - |y_2|^2)\,\bar{u}(k_2)\,u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\,\bar{u}(k_2)\,i\gamma^5\,u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\,(|y_1|^2 + |y_2|^2)\Big[m_q\,\bar{u}(k_2)\,u(p_2) + \bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\,u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\,2\,\mathrm{Re}(y_1 y_2^\dagger)\,\Big[\bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\,u(p_2)\Big] \end{aligned}}$$

Model I

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2$$
$$+ i\bar{Q}\not{D}Q - m_Q \bar{Q}Q$$
$$- S\bar{Q}(y_1 + y_2\gamma^5)q \; - \; S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger \gamma^5)Q$$

$$\boxed{\begin{aligned} \mathcal{M}_{Sq\to Sq} = & \frac{m_Q}{m_Q^2 - m_S^2}\Big[(|y_1|^2 - |y_2|^2)\, \bar{u}(k_2)\, u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\, \bar{u}(k_2)\, i\gamma^5\, u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\, (|y_1|^2 + |y_2|^2)\Big[\, m_q\, \bar{u}(k_2)\, u(p_2) + \; \bar{u}(k_2)\, \frac{\not{p}_1 + \not{k}_1}{2}\, u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\; 2\,\mathrm{Re}(y_1 y_2^\dagger)\; \Big[\,\bar{u}(k_2)\, \frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\, u(p_2)\Big] \end{aligned}}$$

$$\mathcal{L}_{\text{eff}}^{\text{Model I}} \supset c_1^{d5}\; (S^\dagger S)\, \bar{q}\, q \; + \; c_{10}^{d5}\; (S^\dagger S)\, \bar{q}\, i\gamma^5\, q \; + \; c_1^{d6}\; (iS^\dagger \overleftrightarrow{\partial_\mu} S)\, \bar{q}\, \gamma^\mu\, q \; + \; c_7^{d6}\; (iS^\dagger \overleftrightarrow{\partial_\mu} S)\, \bar{q}\, \gamma^\mu \gamma^5\, q$$

Model I

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 + i\bar{Q}\not{D}Q - m_Q \bar{Q}Q - S\bar{Q}(y_1 + y_2\gamma^5)q - S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger\gamma^5)Q$$

$$\boxed{\begin{aligned}\mathcal{M}_{Sq\to Sq} = {} & \frac{m_Q}{m_Q^2 - m_S^2}\Big[(|y_1|^2 - |y_2|^2)\,\bar{u}(k_2)\,u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\,\bar{u}(k_2)\,i\gamma^5\,u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\,(|y_1|^2 + |y_2|^2)\Big[m_q\,\bar{u}(k_2)\,u(p_2) + \bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\,u(p_2)\Big] \\ & + \frac{1}{m_Q^2 - m_S^2}\,2\,\mathrm{Re}(y_1 y_2^\dagger)\,\Big[\bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\,u(p_2)\Big]\end{aligned}}$$

$$\mathcal{L}_{\text{eff}}^{\text{Model I}} \supset c_1^{d5}\,(S^\dagger S)\,\bar{q}\,q + c_{10}^{d5}\,(S^\dagger S)\,\bar{q}\,i\gamma^5\,q + c_1^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\,q + c_7^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\gamma^5\,q$$

$$S^\dagger S\,\bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\right) f_{Tq}^N\,\mathcal{O}_1$$

$$S^\dagger S\,\bar{q}i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\mathrm{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\tilde{\Delta}^N\,\mathcal{O}_{10}$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu\gamma^5 q \longrightarrow -\frac{\mathrm{Re}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\Delta_q^N\,\mathcal{O}_7$$

Model I

$$\mathcal{L}^{\text{Model I}} = \mathcal{L}_{SM} + \partial_\mu S^\dagger \partial_\mu S - m_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2$$
$$+ i\bar{Q} \not{D} Q - m_Q \bar{Q} Q$$
$$- S\bar{Q}(y_1 + y_2\gamma^5) q \; - \; S^\dagger \bar{q}(y_1^\dagger - y_2^\dagger \gamma^5) Q$$

$$\boxed{\begin{aligned} \mathcal{M}_{Sq\to Sq} = \frac{m_Q}{m_Q^2 - m_S^2}\Big[(|y_1|^2 - |y_2|^2)\,\bar{u}(k_2)\,u(p_2) - 2\,\mathrm{Im}(y_1 y_2^\dagger)\,\bar{u}(k_2)\,i\gamma^5\,u(p_2)\Big] \\ + \frac{1}{m_Q^2 - m_S^2}\,(|y_1|^2 + |y_2|^2)\Big[m_q\,\bar{u}(k_2)\,u(p_2) + \bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\,u(p_2)\Big] \\ + \frac{1}{m_Q^2 - m_S^2}\,2\,\mathrm{Re}(y_1 y_2^\dagger)\,\Big[\bar{u}(k_2)\,\frac{\not{p}_1 + \not{k}_1}{2}\gamma^5\,u(p_2)\Big] \end{aligned}}$$

$$\mathcal{L}_{\text{eff}}^{\text{Model I}} \supset c_1^{d5}\,(S^\dagger S)\,\bar{q}\,q \; + \; c_{10}^{d5}\,(S^\dagger S)\,\bar{q}\,i\gamma^5\,q \; + \; c_1^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\,q \; + \; c_7^{d6}\,(iS^\dagger \overleftrightarrow{\partial_\mu} S)\,\bar{q}\,\gamma^\mu\gamma^5\,q$$

$$S^\dagger S\,\bar{q}q \longrightarrow \left(\frac{m_Q}{m_S}\frac{|y_1|^2 - |y_2|^2}{m_Q^2 - m_S^2} + \frac{m_q}{m_S}\frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\right) f_{Tq}^N\,\mathcal{O}_1$$

$$\boxed{S^\dagger S\,\bar{q}i\gamma^5 q \longrightarrow \frac{m_Q}{m_S}\frac{\mathrm{Im}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\tilde{\Delta}^N\,\mathcal{O}_{10}}$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu q \longrightarrow \frac{|y_1|^2 + |y_2|^2}{m_Q^2 - m_S^2}\,\mathcal{N}_q^N\,\mathcal{O}_1$$

$$i\left(S^\dagger \overleftrightarrow{\partial_\mu} S\right)\,\bar{q}\gamma^\mu\gamma^5 q \longrightarrow -\frac{\mathrm{Re}(y_1 y_2^\dagger)}{m_Q^2 - m_S^2}\,2\Delta_q^N\,\mathcal{O}_7$$

Model II

$$\mathcal{L}^{\text{Model II}} = \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi$$
$$+ (\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2$$
$$- (l_1\Phi^\dagger\bar{\chi}q + l_2\Phi^\dagger\bar{\chi}\gamma_5 q + h.c.)$$

$$\boxed{\begin{aligned}\mathcal{M}_{\chi q\to\chi q} = \frac{1}{m_\Phi^2 - m_\chi^2}\Big(& l_1 l_1^\dagger\ [\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)v(p_2)] - l_1 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)v(p_2)] \\ &+ l_1^\dagger l_2\ [\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)] - l_2 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)]\Big)\end{aligned}}$$

Model II

$$\mathcal{L}^{\text{Model II}} = \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi \bar{\chi}\chi$$
$$+ (\partial_\mu \Phi^\dagger)(\partial^\mu \Phi) - m_\Phi^2 \Phi^\dagger \Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2$$
$$- (l_1 \Phi^\dagger \bar{\chi} q + l_2 \Phi^\dagger \bar{\chi}\gamma_5 q + h.c.)$$

$$\boxed{\begin{aligned}\mathcal{M}_{\chi q \to \chi q} = \frac{1}{m_\Phi^2 - m_\chi^2}\Big(& l_1 l_1^\dagger\ [\bar{u}(k_2) v(k_1)]\,[\bar{v}(p_1) v(p_2)] - l_1 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1) v(p_2)] \\ & + l_1^\dagger l_2\ [\bar{u}(k_2) v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)] - l_2 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)]\Big)\end{aligned}}$$

Model II

$$\begin{aligned}\mathcal{L}^{\text{Model II}} &= \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\ &+ (\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 \\ &- (l_1\Phi^\dagger\bar{\chi}q + l_2\Phi^\dagger\bar{\chi}\gamma_5 q + h.c.)\end{aligned}$$

$$\boxed{\begin{aligned}\mathcal{M}_{\chi q\to\chi q} = \frac{1}{m_\Phi^2 - m_\chi^2}\Big(& l_1 l_1^\dagger\ [\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)v(p_2)] - l_1 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)v(p_2)] \\ &+ l_1^\dagger l_2\ [\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)] - l_2 l_2^\dagger\ [\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)]\Big)\end{aligned}}$$

$$\bar{\chi}\chi\ \bar{q}q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N\,\mathcal{O}_1$$

$$\bar{\chi}\chi\ \bar{q}i\gamma^5 q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta\tilde{q}^N\,\mathcal{O}_{10}$$

$$\bar{\chi}i\gamma^5\chi\ \bar{q}q \longrightarrow -\frac{1}{2}\frac{\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\,\mathcal{O}_{11}$$

$$\bar{\chi}i\gamma^5\chi\ \bar{q}i\gamma^5 q \longrightarrow \frac{1}{4}\frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\mathcal{O}_6$$

$$\bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu q \longrightarrow -\frac{1}{4}\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,\mathcal{O}_1$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu q \longrightarrow \frac{\text{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,(\mathcal{O}_8 + \mathcal{O}_9)$$

$$\bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu\gamma^5 q \longrightarrow \frac{\text{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta_q^N\,(-\mathcal{O}_7 + \tfrac{m_N}{m_\chi}\mathcal{O}_9)$$

$$\bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu\gamma^5 q \longrightarrow -\frac{|l_2|^2 + |l_1|^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N\mathcal{O}_4$$

$$\bar{\chi}\sigma^{\mu\nu}\chi\ \bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q \longrightarrow \frac{|l_2|^2 - |l_1|^2}{m_\Phi^2 - m_\chi^2}\delta_q^N\mathcal{O}_4$$

$$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\ \bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q \longrightarrow \frac{2\text{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\delta_q^N\left(\mathcal{O}_{11} - \tfrac{m_N}{m_\chi}\mathcal{O}_{10} - 4\mathcal{O}_{12}\right)$$

Model II

$$\mathcal{L}^{\text{Model II}} = \mathcal{L}_{SM} + i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi + (\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 - (l_1\Phi^\dagger\bar{\chi}q + l_2\Phi^\dagger\bar{\chi}\gamma_5 q + h.c.)$$

$$\boxed{\mathcal{M}_{\chi q\to\chi q} = \frac{1}{m_\Phi^2 - m_\chi^2}\Big(l_1 l_1^\dagger\,[\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)v(p_2)] - l_1 l_2^\dagger\,[\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)v(p_2)] + l_1^\dagger l_2\,[\bar{u}(k_2)v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)] - l_2 l_2^\dagger\,[\bar{u}(k_2)\gamma^5 v(k_1)]\,[\bar{v}(p_1)\gamma^5 v(p_2)]\Big)}$$

$\bar{\chi}\chi\;\bar{q}q$	$\longrightarrow$	$\frac{1}{4}\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2} f_{Tq}^N\,\mathcal{O}_1$	$\bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{\mathrm{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,(\mathcal{O}_8 + \mathcal{O}_9)$
$\boxed{\bar{\chi}\chi\;\bar{q}i\gamma^5 q}$	$\longrightarrow$	$\boxed{-\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta\tilde{q}^N\,\mathcal{O}_{10}}$	$\bar{\chi}\gamma^\mu\chi\;\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{\mathrm{Re}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\Delta_q^N\,(-\mathcal{O}_7 + \frac{m_N}{m_\chi}\mathcal{O}_9)$
$\boxed{\bar{\chi}i\gamma^5\chi\;\bar{q}q}$	$\longrightarrow$	$\boxed{-\frac{1}{2}\frac{\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi} f_{Tq}^N\,\mathcal{O}_{11}}$	$\bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{\lvert l_2\rvert^2 + \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\Delta_q^N\mathcal{O}_4$
$\bar{\chi}i\gamma^5\chi\;\bar{q}i\gamma^5 q$	$\longrightarrow$	$\frac{1}{4}\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\frac{m_N}{m_\chi}\,\Delta\tilde{q}^N\mathcal{O}_6$	$\bar{\chi}\sigma^{\mu\nu}\chi\;\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q$	$\longrightarrow$	$\frac{\lvert l_2\rvert^2 - \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\delta_q^N\mathcal{O}_4$
$\bar{\chi}\gamma^\mu\chi\;\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{1}{4}\frac{\lvert l_2\rvert^2 + \lvert l_1\rvert^2}{m_\Phi^2 - m_\chi^2}\mathcal{N}_q^N\,\mathcal{O}_1$	$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\;\bar{q}\bar{\chi}\sigma_{\mu\nu}\chi q$	$\longrightarrow$	$\frac{2\mathrm{Im}(l_1 l_2^\dagger)}{m_\Phi^2 - m_\chi^2}\delta_q^N\left(\mathcal{O}_{11} - \frac{m_N}{m_\chi}\mathcal{O}_{10} - 4\mathcal{O}_{12}\right)$

Cancellation Relation

$$f_T^N = \sum_{u,d,s} \frac{m_N}{m_q} f_{Tq}^N + \frac{2}{27}\left(1 - \sum_{u,d,s} f_{Tq}^N\right) \sum_{c,b,t} \frac{m_N}{m_q}$$

$$\frac{\mathcal{N}^N}{f_T^N} = \begin{cases} 0.212^{+0.043}_{-0.038}, & N = n \\ 0.219^{+0.051}_{-0.044}, & N = p \end{cases}$$

strong isospin violation

$$\left|y_1^N\right|^2 = \left(\frac{1 - \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}{1 + \frac{\mathcal{N}^N}{f_T^N}\frac{m_S}{m_Q}}\right)\left|y_2^N\right|^2$$

$$|y_1^n|^2 = \left(\frac{1 - 0.212^{+0.043}_{-0.038}\frac{m_S}{m_Q}}{1 + 0.212^{+0.043}_{-0.038}\frac{m_S}{m_Q}}\right)|y_2^n|^2$$

$$|y_1^p|^2 = \left(\frac{1 - 0.219^{+0.051}_{-0.044}\frac{m_S}{m_Q}}{1 + 0.219^{+0.051}_{-0.044}\frac{m_S}{m_Q}}\right)|y_2^p|^2$$

Cancellation Relation

$$f_T^N = \sum_{u,d,s} \frac{m_N}{m_q} f_{Tq}^N + \frac{2}{27} \left(1 - \sum_{u,d,s} f_{Tq}^N \right) \sum_{c,b,t} \frac{m_N}{m_q}$$

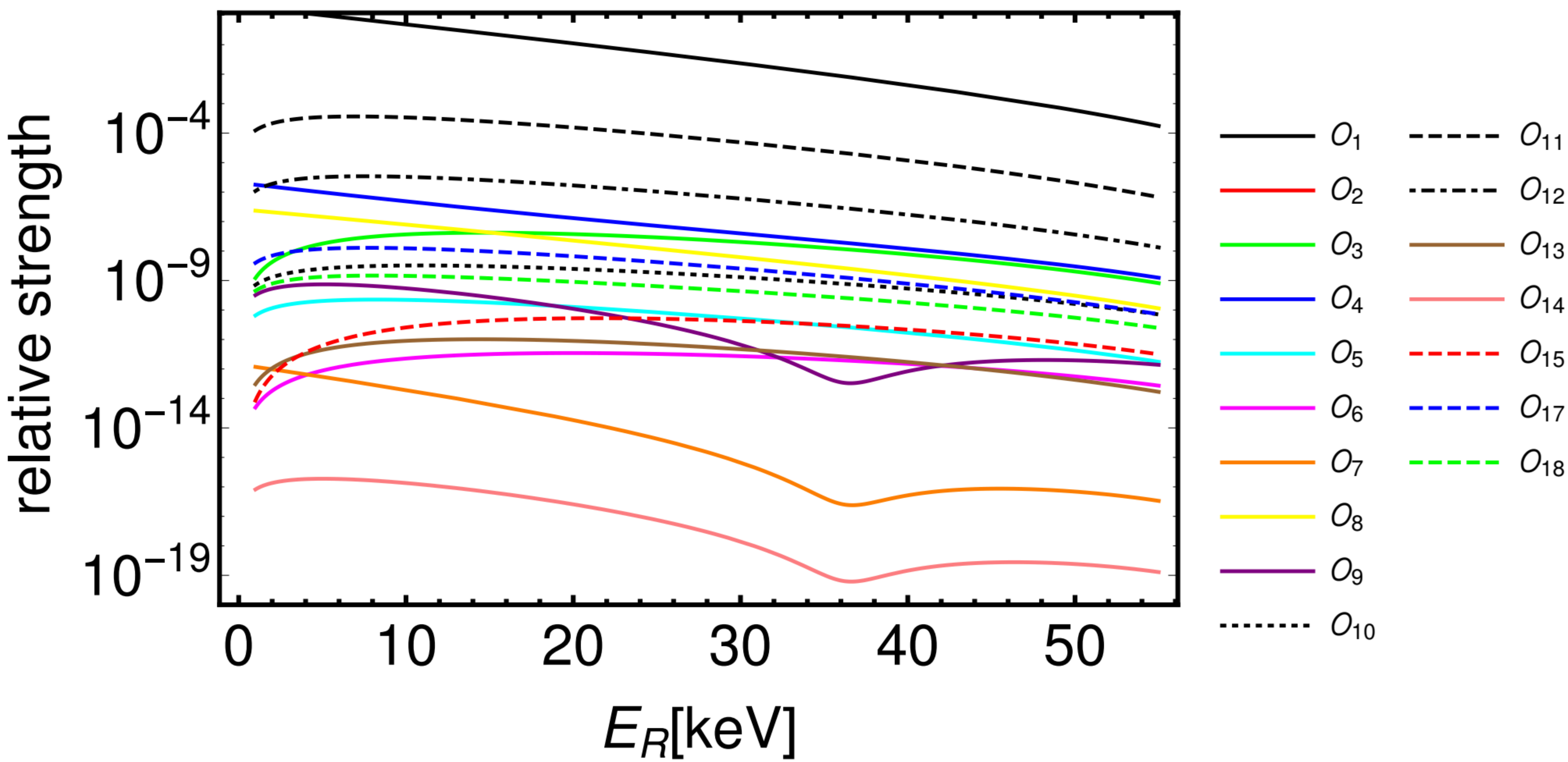
$$\frac{\mathcal{N}^N}{f_T^N} = \begin{cases} 0.212^{+0.043}_{-0.038}, & N = n \\ 0.219^{+0.051}_{-0.044}, & N = p \end{cases}$$

strong isospin violation

$$\left|y_1^N\right|^2 = \left(\frac{1 - \dfrac{\mathcal{N}^N}{f_T^N} \dfrac{m_S}{m_Q}}{1 + \dfrac{\mathcal{N}^N}{f_T^N} \dfrac{m_S}{m_Q}} \right) \left|y_2^N\right|^2$$

$$|y_1^n|^2 = \left(\frac{1 - 0.212^{+0.043}_{-0.038} \dfrac{m_S}{m_Q}}{1 + 0.212^{+0.043}_{-0.038} \dfrac{m_S}{m_Q}} \right) |y_2^n|^2$$

$$|y_1^p|^2 = \left(\frac{1 - 0.219^{+0.051}_{-0.044} \dfrac{m_S}{m_Q}}{1 + 0.219^{+0.051}_{-0.044} \dfrac{m_S}{m_Q}} \right) |y_2^p|^2$$


relative strength
10^{-4}
10^{-9}
10^{-14}
10^{-19}
0
10
20
30
40
50
E_R[keV]
O_1
O_2
O_3
O_4
O_5
O_6
O_7
O_8
O_9
O_{10}
O_{11}
O_{12}
O_{13}
O_{14}
O_{15}
O_{17}
O_{18}

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