From Quarks to Nucleons in DM Direct Detection

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– updated version –

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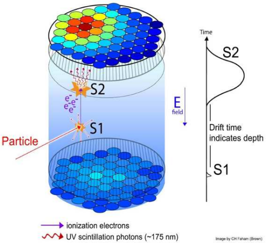
JCAP02(2017)009 [arxiv:1611.00368]; arxiv:1707.06998; arxiv:1708.02678

Direct Detection Basics

- Direct detection – scattering on nuclei
  - Complementary information, proves cosmological lifetime
  - Assume velocity distribution (Maxwell); $v \sim 10^{-3}$
  - Differential event rate:

    [Lewin & Smith, Astropart.Phys.6 (1996)]

$$\frac{dR}{dq} = \frac{\rho_0}{m_A m_\chi} \int_{v_{min}} dv\, v\, f_1(v) \frac{d\sigma}{dq}(v, q)\,.$$



LUX

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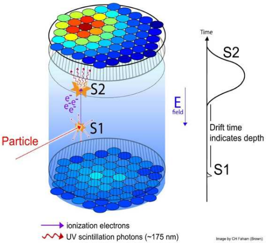
"Experiment" "Astro" "Theory"



LUX

Calculating the cross section

- Nonrelativistic, Galilean-invariant interactions
  [Fitzpatrick et al., 1203.3542]

- Constructed from
  - momentum transfer $i\vec{q}$
  - relative transverse incoming DM velocity $v_T^\perp \equiv \Delta\vec{v} - \vec{q}/(2\mu_{\chi N})$
  - nucleon spin $\vec{S}_N$ (DM spin $\vec{S}_\chi$)

- Lead to six nuclear responses, e.g.
  - Spin-independent ("M"): e.g. $\mathcal{O}_1^p = 1_\chi \, 1_N$
  - Spin-dependent ("Σ', Σ"): e.g. $\mathcal{O}_4^p = \vec{S}_\chi \cdot \vec{S}_N$
  - Nuclear angular momentum ("Δ"): e.g. $\mathcal{O}_9^p = \vec{S}_\chi \cdot \left(\vec{S}_p \times \frac{i\vec{q}}{m_N}\right)$

- Automatic calculation of pheno observables, given the coefficients of $\mathcal{O}_i^N$
  [`Mathematica` package DMFormFactor, Anand et al. 1308.6288]

Problems / Questions

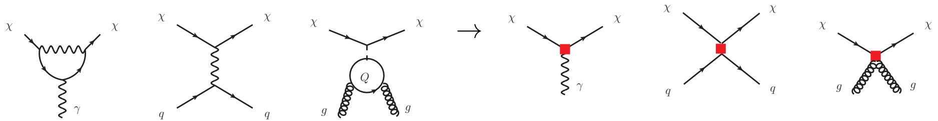
- Explicit connection to UV models?
  - NR operators are often not independent from a “UV” view point
- c^i_{NR} coefficients specified at low scale, can have momentum dependence
  - E.g., due to photon or pion exchange
  - An EFT analysis of these operators [e.g., 1705.02614] is not necessarily helpful for particle physicists
- Combination with collider / indirect bounds?
- $\Rightarrow$ Better to use “partonic” operators

Effective UV Lagrangian

$$\mathcal{L}^{\rm eff} = \mathcal{L}^{(4)}\big|_{n_f} + \mathcal{L}^{\rm DM}\big|_{n_f} + \sum \hat{\mathcal{C}}_j^{(5)}\big|_{n_f} Q_j^{(5)} + \sum \hat{\mathcal{C}}_j^{(6)}\big|_{n_f} Q_j^{(6)} + \sum \hat{\mathcal{C}}_j^{(7)}\big|_{n_f} Q_j^{(7)} + \ldots$$

- Dim.5: $\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \ldots$
- Dim.6: $\mathcal{Q}_{1,f}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar f\gamma^\mu f)\,,$ $\mathcal{Q}_{4,f}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar f\gamma^\mu\gamma_5 f)\,, \ldots$
- Dim.7: $\mathcal{Q}_{5,f}^{(7)} = m_f(\bar\chi\chi)(\bar f f)\,,$ $\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \ldots$

- Comprises all physics above $\sim 1\,$GeV



Low-energy limit – hadronic current

- Matrix elements of hadronic currents parameterized by nuclear form factors:

  [E.g. Hill et al., 1409.8290; Hoferichter et al. 1503.04811]

  - $\langle N'|\bar{q}\gamma^\mu q|N\rangle = \bar{u}'_N\Big[F_1(q^2)\gamma^\mu + \frac{i}{2m_N}F_2(q^2)\sigma^{\mu\nu}q_\nu\Big]u_N$
  - $\langle N'|\bar{q}\gamma^\mu\gamma_5 q|N\rangle = \bar{u}'_N\Big[F_A(q^2)\gamma^\mu\gamma_5 + \frac{1}{2m_N}F_{P'}(q^2)\gamma_5 q^\mu\Big]u_N$
  - ...

- Limitations:
  - Full momentum dependence not known for general hadronic currents
  - How important are two-nucleon interactions?

- Calculate form factor using chiral expansion in $q/(4\pi f_\pi)$
  - Systematic NR limit using HBChPT & "Heavy DM Effective Theory"

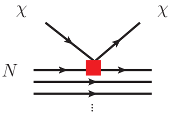
    [Jenkins et al. Phys.Lett. B255 (1991) 558; Hill, Solon 1111.0016; 1409.8290; Bishara et al. 1611.00368; 1707.06998]

Problems / Questions

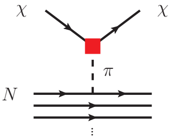
1. What are the leading contributions?

2. How large are the corrections?

Leading contributions



- Leading diagram for most DM-SM interactions



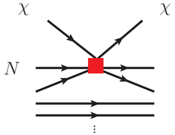
- Leading diagram for $S \cdot P$ and $P \cdot P$
- Gives q-dependent "form factor" $1/(m_\pi^2 + \vec{q}\,^2)$

- For $A \cdot A$, $P \cdot \theta$, and $S \cdot \theta$, both diagrams contribute *at same order!*

- Need to go to higher order in q:
  - Momentum-independent terms cancel for $A \cdot V$ and $V \cdot A$ interactions
  - Pion poles effectively cancel two powers of q

Subleading contributions

- NLO correction to one-nucleon currents generally enter at $\mathcal{O}(q^{\nu_{\rm LO}+2})$
- Can they be numerically important?
  [Bishara et al. 1707.06998]
  - E.g. tensor @ LO: $(\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu}q) \sim \vec{S}_\chi \cdot \vec{S}_N$
  - At NLO, two coherently enhanced operators are generated
  - Coincidentally the effect is numerically small
- At some order, two-nucleon currents will enter
  [E.g. Hoferichter et al., 1503.04811; Gazda et al. 1612.09165; Körber et al. 1704.01150]
  - Order depends on interaction
  - Corrections roughly $\lesssim \mathcal{O}(20\%)$



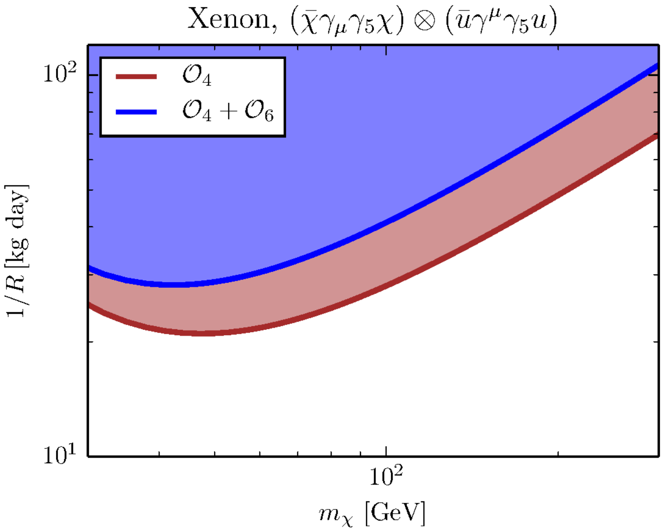
Effects of meson exchange

- Axial-vector – axial-vector interaction $\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - E.g. neutralino in the MSSM
  - Contact term: $\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$
  - Previously forgotten meson exchange contribution:

    $\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$

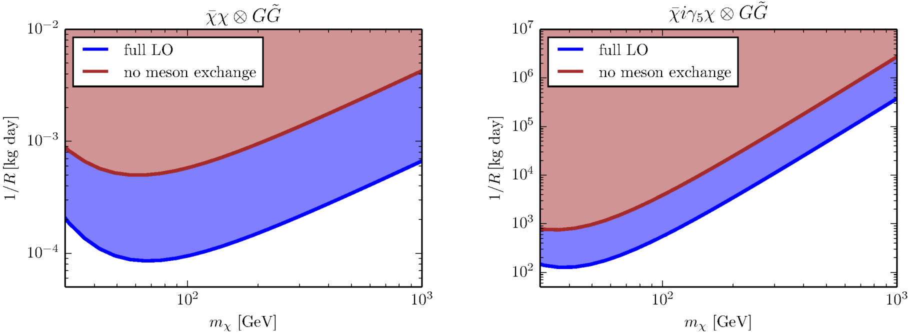
- Pion pole compensates for $\vec{q}^{\,2}$ suppression
- Negative interference reduces cross section

Effects of meson exchange



Effects meson exchange – couplings to heavy quarks

- $\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$
- Order-of-magnitude improvement in bound



DirectDM

- Computer code to calculate the matching and running automatically
  - `Mathematica` version published this week
  - Python version to follow soon
- Seamless interface to `Mathematica` package `DMFormFactor`
  [Anand et al. 1308.6288]
- Available at https://directdm.github.io/

Summary and Outlook

- Established explicit connection between UV and nuclear physics
  - General setup that covers many models
  - Consistent treatment at leading order
  - Meson exchange contributions can have significant impact on interpretation of data
- Provided public code `DirectDM` for automatic running from UV to nuclear scale [Bishara, Brod, Grinstein, Zupan, arxiv:1708.02678]
- Future Extension:
  - Dimension seven operators
  - Electroweak mixing and matching corrections
  - Connection to simplified models at LHC