Chiral Effective Theory of DM Direct Detection

Or, What is the size of the DM nucleus cross section?

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Talk at HEFT 2017, Lumley Castle, Durham, UK

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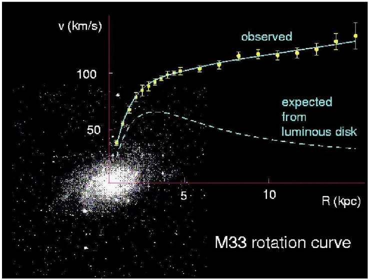
With Fady Bishara, Aaron Gootjes-Dreesbach, Benjamin Grinstein, Michele Tammaro, Jure Zupan

JCAP02(2017)009 [arxiv:1611.00368] & work in progress

Dark Matter Facts

- DM exists
  - All evidence via its gravitation
- Particle nature?
- What we know about DM
  - DM is non-baryonic, cold, and neutral
  - Relic abundance $\Omega_{\mathrm{DM}} h^2 = 0.1198(26)$ [PLANCK / PDG 2014]



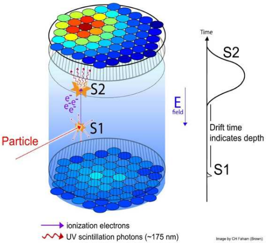
- Thermal history motivates interaction with SM

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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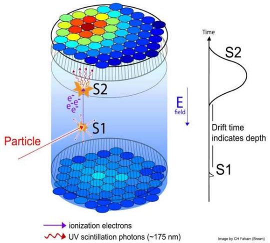
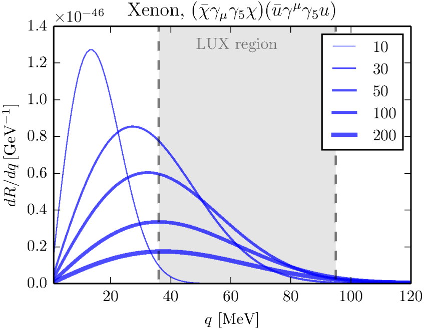
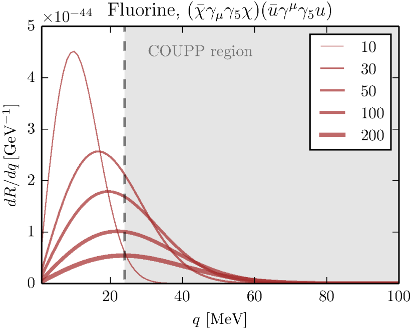
"Experiment" "Astro" "Theory"



LUX

Momentum exchange





- Experiments typically integrate over "sensitivity region"
- Maximum momentum exchange $q \lesssim 200\,\mathrm{MeV}$

Calculating the cross section

- Calculate cross section from 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. $\mathcal{O}_9^p = \vec{S}_\chi \cdot \left(\vec{S}_p \times \frac{i\vec{q}}{m_N}\right)$

Nucleon-level interactions

$$\mathcal{O}_1^N = 1_\chi 1_N \,, \qquad \mathcal{O}_2^N = \left(v_\perp\right)^2 1_\chi 1_N \,,$$

$$\mathcal{O}_3^N = 1_\chi \, \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) , \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N \,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) 1_N \,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right) ,$$

$$\mathcal{O}_7^N = 1_\chi \left(\vec{S}_N \cdot \vec{v}_\perp\right) , \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) 1_N \,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right) , \qquad \mathcal{O}_{10}^N = -1_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right) ,$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right) 1_N \,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right) \ldots$$

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Nuclear response functions

- Write $\mathcal{L} = \sum_i c^i_{\rm NR} \mathcal{O}^N_i$

$$\sum_{\rm spins} |\mathcal{M}|^2_{\rm NR} \propto \sum_{p,n} \Big\{ R_{M,\Sigma',\Sigma''} W_{M,\Sigma',\Sigma''} + \frac{\vec{q}^{\,2}}{m_N^2} R_{\Delta,\Delta\Sigma'} W_{\Delta,\Delta\Sigma'} \Big\}$$

"$\supset c^i_{\rm NR}$" "$\supset \langle \mathcal{O}^N_i \rangle_A$"

- Calculation of nuclear response functions for all NR operators [Fitzpatrick et al. 1203.3542]
  - Nuclear shell model
  - available for F, Na, Ge, I, Xe
- Rough scaling:
  - $W_M \sim \mathcal{O}(A^2)$
  - $W_{\Sigma'}\,, W_{\Sigma''}\,, W_\Delta\,, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$

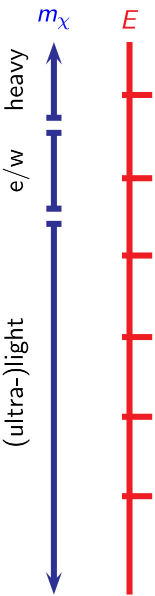
What is the input?

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

- Problems / Questions:
  - c_{NR}^i 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
  - Explicit connection to UV models?
  - Combination with collider / indirect bounds?

- $\Rightarrow$ Need full tower of EFTs

Relevant Scales



Λ – heavy mediators

Simplified models, or "SM-EFT" + DM

v_{EW} – electroweak symmetry breaking

five-flavor QCD + DM

m_b – b-quark threshold

four-flavor QCD + DM

m_c – c-quark threshold

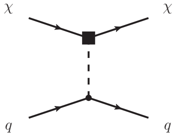
three-flavor QCD + DM

Λ_{QCD} – chiral symmetry breaking

(Heavy Baryon) Chiral Effective Theory

$v, \vec{q}$ – DM-nucleus scattering kinematics

NR theory of nuclear response



Relevant Scales

m_χ E

HEFT lives here

heavy

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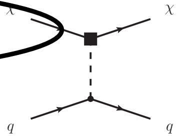

e/w

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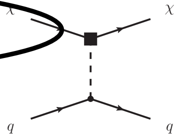

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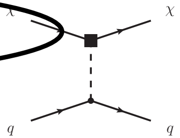
This talk



Effective UV Lagrangian

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

- 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: $\mathcal{Q}_{5,f}^{(7)} = m_f(\bar{\chi}\chi)(\bar{f}f)\,, \ldots$

- Comprises all physics above $\sim 1\,\text{GeV}$:
  - New physics mediators
  - W, Z, Higgs
  - Heavy quarks
  - Electroweak running

Low-energy limit – DM current

- Need "HQET" version of dark matter [Hill, Solon 1111.0016; 1409.8290]
- Essentially low-energy expansion of free fermion spinors
  - $\bar{\chi}\chi \to \bar{\chi}_v \chi_v + \ldots$
  - $\bar{\chi}\gamma^\mu\chi \to v^\mu \bar{\chi}_v \chi_v + \frac{1}{2m_\chi}\bar{\chi}_v i \overleftrightarrow{\partial}^\mu_\perp \chi_v + \frac{1}{2m_\chi}\partial_\nu \big(\bar{\chi}_v \sigma^{\mu\nu}_\perp \chi_v\big) + \cdots$
  - $\bar{\chi}\gamma^\mu\gamma_5\chi \to 2\bar{\chi}_v S^\mu_\chi \chi_v - \frac{i}{m_\chi} v^\mu \bar{\chi}_v S_\chi \cdot \overleftrightarrow{\partial} \chi_v + \cdots$
  - $\bar{\chi} i\gamma_5 \chi \to \frac{1}{m_\chi}\partial_\mu \bar{\chi}_v S^\mu_\chi \chi_v + \ldots$
  - $\bar{\chi}\sigma^{\mu\nu}\chi \to \bar{\chi}_v \sigma^{\mu\nu}_\perp \chi_v + \frac{1}{2m_\chi}\Big(\bar{\chi}_v i v^{[\mu} \sigma^{\nu]\rho}_\perp \overleftrightarrow{\partial}_\rho \chi_v - v^{[\mu}\partial^{\nu]}\bar{\chi}_v \chi_v\Big) + \ldots$
  - $\bar{\chi}\sigma^{\mu\nu} i\gamma_5 \chi \to 2\bar{\chi}_v S^{[\mu}_\chi v^{\nu]}\chi_v + \frac{i}{m_\chi}\bar{\chi}_v S^{[\mu} \overleftrightarrow{\partial}^{\nu]}_\perp \chi_v + \frac{1}{2m_\chi}\epsilon^{\mu\nu\alpha\beta} v_\alpha \partial_\beta \bar{\chi}_v \chi_v + \ldots$

Low-energy limit – hadronic current

- For hadronic current, use 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

Chiral expansion

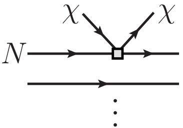
- Recall maximum momentum transfer in DM scattering is $q_{\max} \approx 200\,\mathrm{MeV}$
- Expansion in $q/(4\pi f_\pi)$ is good to $\mathcal{O}(20\%)$
- Can use (Heavy Baryon) Chiral Perturbation Theory (HBChPT)
  [Jenkins et al. Phys.Lett. B255 (1991) 558, see also Hoferichter et al. 1503.04811]
  - Hadronic degrees of freedom are pions, nucleons,...
- Treat DM currents as $SU(3)_L \times SU(3)_R$ spurions
- Can write hadronization of quark currents explicitly, e.g.:
  - Pseudo-scalar meson current: $\bar{q} i \gamma_5 q \to -B_0 f_\pi m_u \big(\pi^0 + \eta/\sqrt{3}\big) + \ldots$
  - Nuclear vector current: $\bar{u}\gamma^\mu u \to v^\mu (2\bar{p}_v p_v + \bar{n}_v n_v) + \ldots$
- Describe hadronic physics in terms of few parameters $(f_\pi, g_A, \mu_N, \sigma_{\pi N} \ldots)$

Chiral power counting

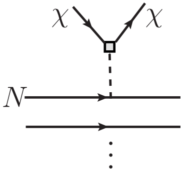
- Questions:
  1. What are the leading contributions?
  2. How large are the corrections?
  3. At what order do two-nucleon interactions enter?
     [E.g. Hoferichter et al., 1503.04811]

- A-nucleon irreducible amplitude scales as $M_{A,\chi} \sim p^{\nu}$
  [Weinberg NP **B363** (1991) 3; Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan 1205.2695]
  - $\nu = 4 - A - 2C + 2L + \sum_i V_i(d_i - n_i/2 - 2) + \epsilon_W$
  - Single-nucleon interactions are always leading

Leading contributions



- Only leading diagram for most DM-SM interactions
- Leading diagram for $A \cdot A$ interaction



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

- Need to go to NLO HBChPT:
  - Pseudoscalar current P starts at $\mathcal{O}(q)$
  - Leading terms cancel for $A \cdot V$ and $V \cdot A$ interactions

Subleading contributions

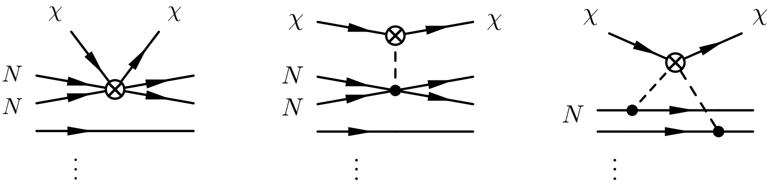
- NLO correction to one-nucleon currents generally enter at $\mathcal{O}(q^{\nu_{\rm LO}+2})$

- Terms are no longer Galilean invariant
  - Underlying theory is Lorentz invariant
  - Need the average nucleon velocity $v_a \equiv (k_1 + k_2)/2m_N$

- New operators appear, e.g.
  - $\mathcal{O}_{15}^N = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\left(\vec{S}_N \times \vec{v}_\perp\right) \cdot \frac{\vec{q}}{m_N}\right)$
  - $\mathcal{O}_{9a}^N = \left(\vec{v}_a \cdot \vec{S}_\chi\right)\left(\vec{v}_a \cdot \vec{S}_N\right)$

- At some order, two-nucleon currents will enter
  - Order depends on interaction

Two-nucleon currents



- Two-nucleon currents enter at...
  - $\mathcal{O}(q^{\nu_{\rm LO}+1})$ for $A \cdot V$, $S \cdot S$, and $P \cdot S$ [E.g. Cirigliano et al., 1205.2695; Körber et al., 1704.01150]
  - $\mathcal{O}(q^{\nu_{\rm LO}+2})$ for $V \cdot V$
  - $\mathcal{O}(q^{\nu_{\rm LO}+3})$ for all other interactions

Effect of NLO operators – meson exchange

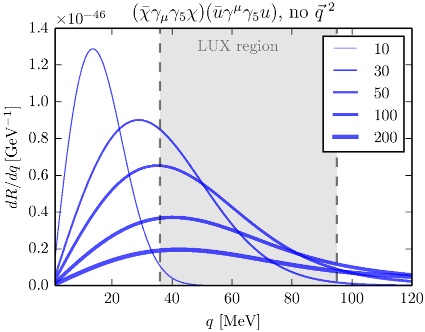
- Axial-vector – axial-vector interaction $\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - E.g. neutralino in the MSSM
  - Contact term: $\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$
  - Previously forgotten meson exchange contribution:

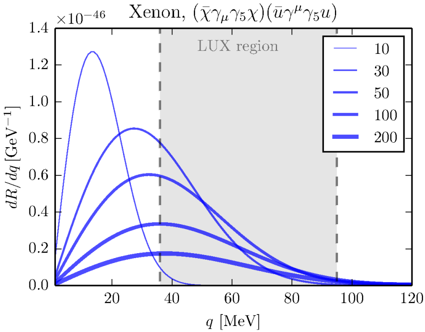
    $\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$

- The coefficients are
  - $c_{\mathrm{NR},4}^p \supset -4\left(\Delta u_p\,\hat{\mathcal{C}}_{4,u}^{(6)} + \Delta d_p\,\hat{\mathcal{C}}_{4,d}^{(6)} + \Delta s\,\hat{\mathcal{C}}_{4,s}^{(6)}\right)$
  - $c_{\mathrm{NR},6}^p \supset m_N^2\left\{\frac{2}{3}\frac{(\Delta u_p+\Delta d_p-2\Delta s)}{m_\eta^2+\vec{q}^{\,2}}\left(\hat{\mathcal{C}}_{4,u}^{(6)} + \hat{\mathcal{C}}_{4,d}^{(6)} - 2\hat{\mathcal{C}}_{4,s}^{(6)}\right) + \frac{2g_A}{m_\pi^2+\vec{q}^{\,2}}\left(\hat{\mathcal{C}}_{4,u}^{(6)} - \hat{\mathcal{C}}_{4,d}^{(6)}\right)\right\}$

Momentum exchange

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





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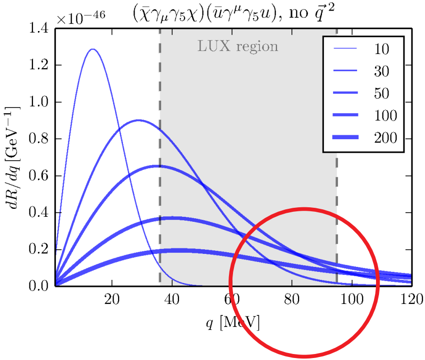
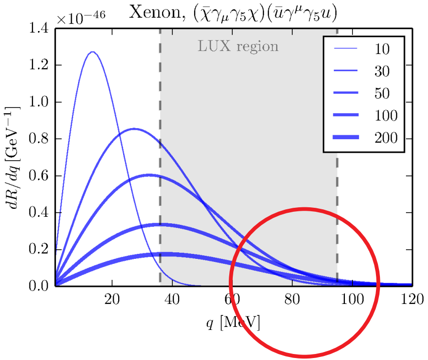
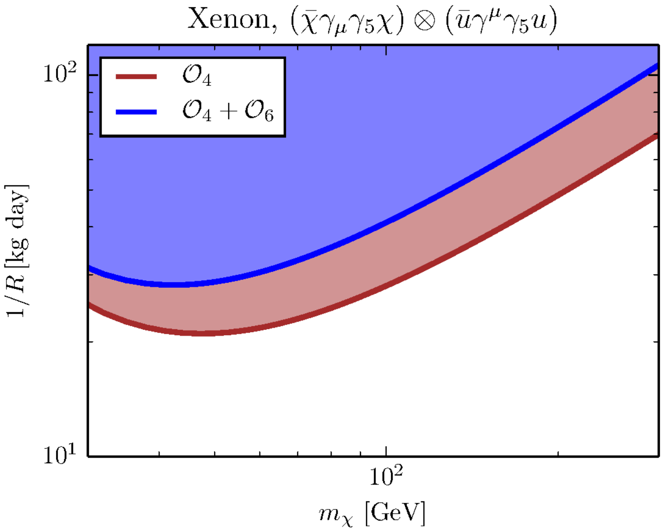


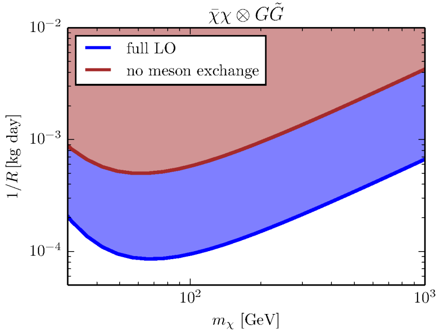


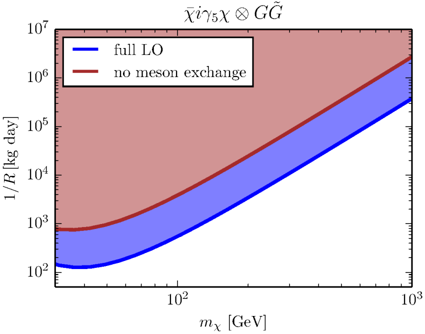
Effect of NLO operators – meson exchange



Effect of NLO operators – meson exchange

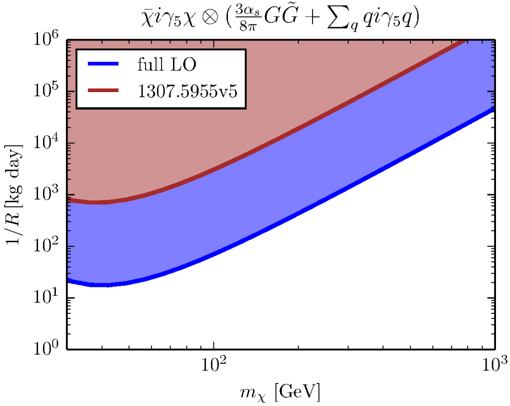
- $\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$, $\quad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$
  - Previously neglected meson exchange is leading contribution!
  - Order-of-magnitude improvement in bound





Effect of NLO operators – meson exchange

- Pseudoscalar "Higgs" exchange with quark couplings $\propto m_q$
  - Previously inconsistently treated meson exchange is leading contribution!
  - More than one order-of-magnitude improvement in bound



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
- Provide public code for automatic running from UV to nuclear scale
  [Bishara, Brod, Grinstein, Zupan, work in progress]
  - Will include systematic estimate of NLO contributions

Appendix

Effect of NLO operators – fine tuning

- Chirally leading terms cancel in $(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu\gamma_5 q)$
  - Only velocity / momentum suppressed interactions
- Electroweak corrections can regenerate LO terms

[Bishara, Brod, Grinstein, Zupan, work in progress]