# A Unified Approach to DM Searches

Joachim Brod

UNIVERSITY OF Cincinnati

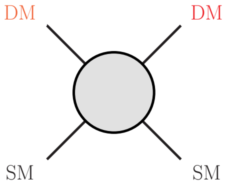
Talk at IPA 2018, Cincinnati
October 11, 2018

With F. Bishara, A. Gootjes-Dreesbach, B. Grinstein, E. Stamou, M. Tammaro, J. Zupan

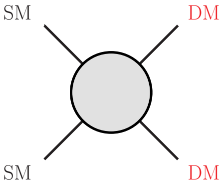
JCAP 1702 (2017) 009 [arxiv:1611.00368]; JHEP 1711 (2017) 059 [arxiv:1707.06998]; arxiv:1708.02678; arxiv:1710.10218; JHEP 1802 (2018) 174 [arxiv:1801.04240]

With F. Bishara, M. Gorbahn – work in progress

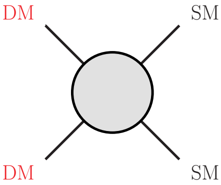
# Three roads to discovery




Direct detection

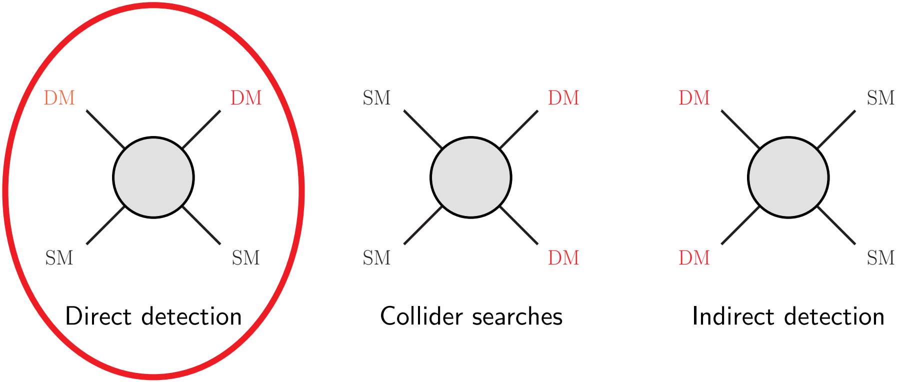



Collider searches




Indirect detection

# Three roads to discovery



# Direct Detection Basics

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

# Direct Detection Basics

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

“Experiment” “Astro” “Theory”

# 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 (“$\Sigma'$, $\Sigma$”): e.g. $\mathcal{O}_4^p = \vec{S}_\chi \cdot \vec{S}_N$
  - Nuclear angular momentum (“$\Delta$”): e.g. $\mathcal{O}_9^p = \vec{S}_\chi \cdot \left(\vec{S}_p \times \frac{i\vec{q}}{m_N}\right)$

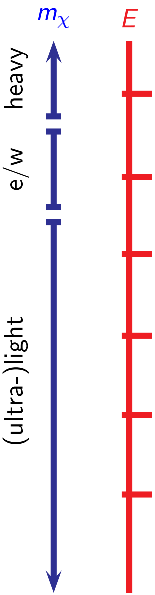
# Extension needed

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

- Questions / Problems:
  - Are all of the operators needed?
  - $c_{\rm NR}^i$ coefficients specified at low scale, can have momentum dependence
  - Explicit connection to UV models?
  - Combination with collider / indirect bounds?

- $\Rightarrow$ Need full tower of EFTs

# Relevant Scales




$\Lambda$ – heavy mediators

Simplified models, or "SM-EFT" + DM

$v_{\mathbf{EW}}$ – 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

$\Lambda_{\mathbf{QCD}}$ – chiral symmetry breaking

(Heavy Baryon) Chiral Effective Theory

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

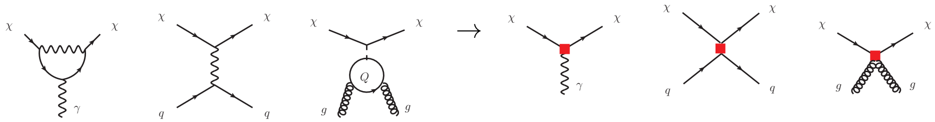
NR theory of nuclear response

# Partonic Effective 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: $\mathcal{Q}_{5,f}^{(7)} = m_f(\bar{\chi}\chi)(\bar{f}f)\,,$ $\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \ldots$

- Comprises all physics above $\sim 1\,\text{GeV}$



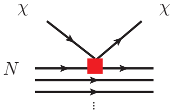
# Low-energy limit – hadronic current

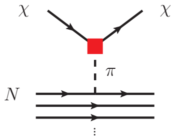
- Matrix elements of hadronic currents parameterized by nuclear form factors:
  [E.g. Hill et al., 1409.8290; Hoferichter et al. 1503.04811; Bishara et al. 1707.06998]
  - $\langle N'|\bar{q}\gamma^\mu q|N\rangle = \bar{u}'_N\Big[F_1(q^2)\gamma^\mu + \frac{i}{2m_N}F_2(q^2)\sigma^{\mu\nu}q_\nu\Big]u_N$
  - $\langle N'|\bar{q}\gamma^\mu\gamma_5 q|N\rangle = \bar{u}'_N\Big[F_A(q^2)\gamma^\mu\gamma_5 + \frac{1}{2m_N}F_{P'}(q^2)\gamma_5 q^\mu\Big]u_N$
  - ...
- Full momentum dependence not known for general
- Calculate form factor using chiral expansion in $q/m_N \lesssim 0.2$
  - 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]

# 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: $\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$
  - Meson exchange contribution:

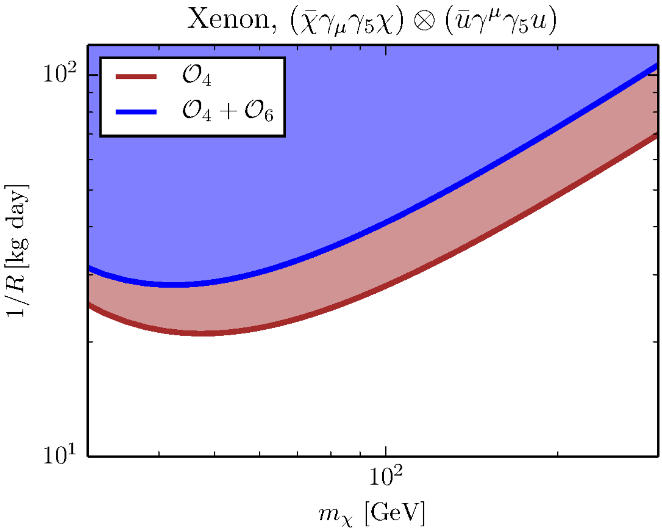
    $\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$



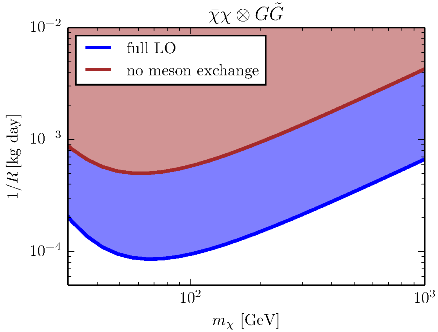

- Pion pole compensates for $\vec{q}^2$ suppression

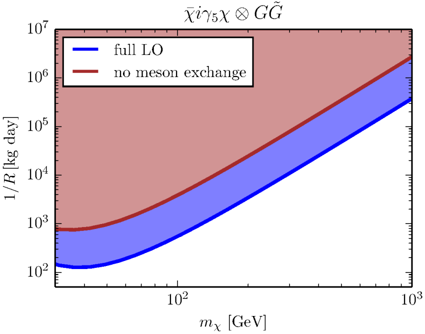
# Effects of meson exchange



# Effect of NLO operators – meson exchange

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



# Connecting to the UV

# Effective Lagrangian above $v_{EW}$

- Assume DM is an electroweak multiplet $\chi$, with $m_\chi \sim v_{ew}$

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{DM}} + \sum \frac{C_j^{(5)}}{\Lambda} Q_j^{(5)} + \sum \frac{C_j^{(6)}}{\Lambda^2} Q_j^{(6)} + \dots$$

- Expansion in inverse mediator mass $\Lambda$
- Generalizes "SM-EFT"

  [Buchmüller et al. Nucl.Phys. B268 (1986) 621, Grzadkowski et al. 1008.4884]

  - Dim.5: $Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)B_{\mu\nu}\,, \quad Q_3^{(5)} = (\bar\chi\chi)(H^\dagger H)$
  - Dim.6: $Q_{2,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar Q_L^i\gamma^\mu Q_L^i)\,, \quad Q_{16}^{(6)} = (\bar\chi\gamma^\mu\chi)(H^\dagger i \overleftrightarrow{D}_\mu H)$

# Importance of electroweak loops

- Start with

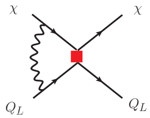
  $$-Q^{(6)}_{6,3} + Q^{(6)}_{7,3} + Q^{(6)}_{8,3} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{t}\gamma^\mu\gamma_5 t + \bar{b}\gamma^\mu\gamma_5 b)$$

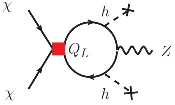
  - Vanishing (tiny) nuclear matrix element

- $Y_\chi = 0$ to exclude $Z$-exchange contribution
- $I_\chi = 1$ leads to a one- and two-loop e/w contributions [Hisano et al. 1104.0228]

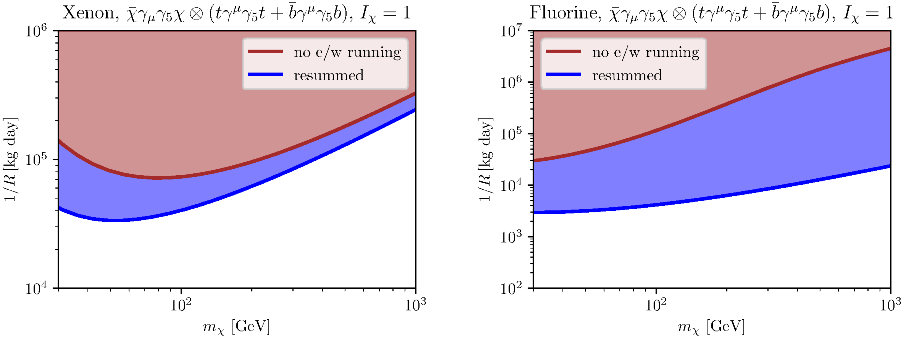
- RG generates third gen. VV and $Z$ exchange

$$C^{(6)}_{1,3}(M_W) = 12\,\frac{\alpha_2}{4\pi}\log\frac{M_W}{\Lambda}\,, \qquad C^{(6)}_{18}(M_W) = -12\,\frac{\alpha_t}{4\pi}\log\frac{M_W}{\Lambda}$$



# Scattering Rate on Xenon and Fluorine

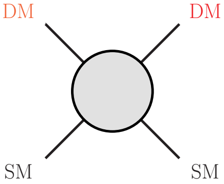


# DirectDM

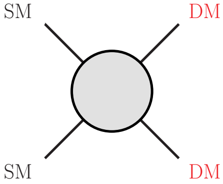
- Computer code to calculate the matching and running automatically
  - Electroweak running for Dirac DM
  - QCD / QED running for Dirac, Majorana, Scalar DM
- Seamless interface to `Mathematica` package `DMFormFactor` [Anand et al. 1308.6288]
- Available at https://directdm.github.io/

# Beyond EFT

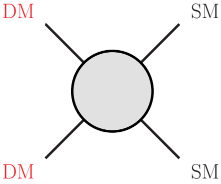
# Three roads to discovery




Direct detection

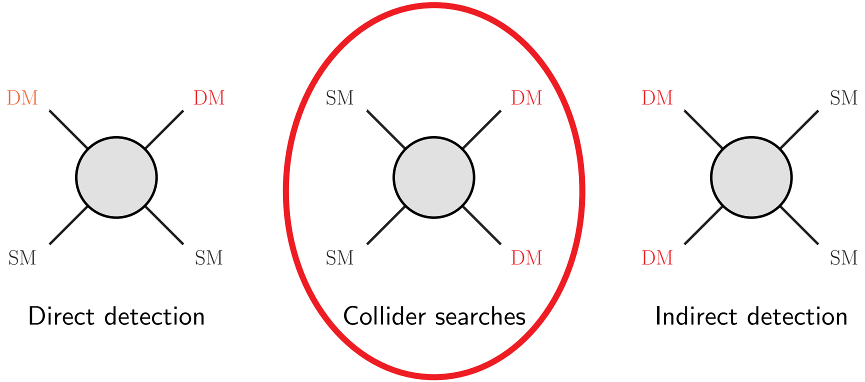



Collider searches



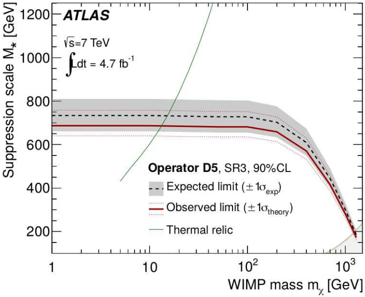

Indirect detection

# Three roads to discovery



# Simplified Models

- EFT is of limited use at colliders
- Use simplified models
  [E.g. Abdallah et al., 1506.03116]
- General enough? Renormalizability?
  - Connection to flavor / precision observables?
  - Redundant couplings?




$$D5 \simeq \frac{1}{M_*^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$

[ATLAS 1210.4491]

# "Generic Lagrangian"

$$\mathcal{L}_3 = \sum_{f_1 f_2 s_1 \sigma} y^{\sigma}_{s_1 \bar{f}_1 f_2} h_{s_1} \bar{\psi}_{f_1} P_\sigma \psi_{f_2} + \sum_{f_1 f_2 v_1 \sigma} g^{\sigma}_{v_1 \bar{f}_1 f_2} V_{v_1,\mu} \bar{\psi}_{f_1} \gamma^\mu P_\sigma \psi_{f_2}$$

$$+ \frac{i}{6} \sum_{v_1 v_2 v_3} g_{v_1 v_2 v_3} \Big( V_{v_1,\mu} V_{v_2,\nu}\, \partial^{[\mu} V^{\nu]}_{v_3} + V_{v_3,\mu} V_{v_1,\nu}\, \partial^{[\mu} V^{\nu]}_{v_2} + V_{v_2,\mu} V_{v_3,\nu}\, \partial^{[\mu} V^{\nu]}_{v_1} \Big)$$

$$+ \frac{1}{2} \sum_{v_1 v_2 s_1} g_{v_1 v_2 s_1}\, V_{v_1,\mu} V^{\mu}_{v_2} h_{s_1} - \frac{i}{2} \sum_{v_1 s_1 s_2} g_{v_1 s_1 s_2}\, V^{\mu}_{v_1} \Big( h_{s_1}\, \partial_\mu h_{s_2} - \left(\partial_\mu h_{s_1}\right) h_{s_2} \Big) \,.$$

- Perturbative unitarity $\rightarrow$ massive vectors from SSB
- Low-energy theory is $SU(3) \times U(1)$ symmetric

# “Generic Renormalization”

- Can we develop a general framework that is consistent beyond tree level?
- Renormalizability fixed by high-energy behaviour:
  - Gauge structure of Greens functions determined by Slavnov - Taylor identities
  - Traditionally used in high-energy scattering (“Goldstone-boson Equivalence Theorem”)
  - At the same time, UV behaviour controls renormalization properties
- Generic finite results for rare meson decays [Brod, Gorbahn, to appear]

# Applications to DM?

- Provide a consistent framework for collider constraints
  - renormalizable
  - minimal amount of couplings
  - natural connection to flavor
- Match to EFT tower for direct detection
  - including loop level (e.g. dark matter interacting via dipoles)
    [Bishara, Brod, Gorbahn, work in progress]
- Naturally also applicable for indirect detection

# Summary

- Established explicit connection between UV and nuclear physics
  - Consistent treatment at leading order
  - Meson contributions can have significant impact on interpretation of data
  - Full electroweak corrections (Dirac DM)
    [Bishara, Brod, Grinstein, Zupan; arxiv:1809.03506]
- Provided public code `DirectDM` for automatic running from UV to nuclear scale [Bishara, Brod, Grinstein, Zupan, arxiv:1708.02678]
- Future Extension: A "unified framework" for DM searches