Improving limits on a Simplified Model of Dark Matter

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With
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Why a Simplified Model?

• Many models feature a Dark Matter candidate.

• Many models; many parameters; difficult drawing general conclusions.

• An EFT approach is very general and could cover all models; Validity of EFT at large momentum transfer? Not UV complete. Limitations when comparing between experiments that operate at different energy scales.

• Simplified model — A UV complete theory (not necessarily simplification of a more complete/complicated theory). Captures essential features of classes of models.
Spectrum of Theory Space

Effective Field Theories

Less Complete

UV Complete
Models

Dipole Interactions
Simplified Models
Z'
dark photon
UED
UV Complete Models

Contact Interactions
Squarks
Higgs portal
More Complete

Sketches of Models

Little Higgs
mSUGRA

Models

From Tim Tait
Outline

- Objective: Take a Simplified model and calculate everything with better precision.

- Direct Detection constraints @ 1-loop.

- Include Renormalization Group Evolution effects.

- LHC constraints @NLO.

- Understand importance of improving precision. Is it worth the effort?
A Simplified Model

• Construction—Inspired by more complete models, consider models that contain dark matter as well as the most important mediator(s).

• Example—Consider a class of models in which dark matter interacts with quarks through colored scalar mediators—looks like the MSSM, but simpler with three parameters; dark matter mass, mediator mass, coupling strength.

\[
\{ M_X, M_{\tilde{q}_L}, g_{DM} \} \quad \mathcal{L}_{int} = \sum_{q=u,d,s,c,b,t} g_{DM} (\tilde{q}_L^* \bar{\chi} P_L q + h.c.)
\]

• Dark matter can be Dirac or Majorana fermion.

A. DiFranzo, K. Nagao, A. Rajaraman, T. Tait 2013
Direct Detection

- Tree level calculation tells us that model has only a spin dependent cross-section.

- Limits from direct detection are weak—large values of $g_{\text{DM}}$ allowed.

\[
\mathcal{M}_{DD} \approx \frac{ig_{\text{DM}}^2}{M_{q_L}^2 - M_\chi^2} \frac{1}{8} \left[ (\bar{\chi}\gamma^\mu \chi)(\bar{u}\gamma_\mu u) - (\bar{\chi}\gamma^\mu \gamma^5 \chi)(\bar{u}\gamma_\mu \gamma^5 u) \right]
\]

\[
\sigma_p = \frac{4}{\pi} \left( \frac{M_\chi m_p}{M_\chi + m_p} \right)^2 |\langle \mathcal{M}_{DD} \rangle_{NR}|^2
\]

SD

Pico-60
Determine Wilson Coefficients for effective operators

\[
\mathcal{L}_{\text{eff}}^g = \mathcal{L}_{\text{eff}}^{(1)} + \mathcal{L}_{\text{eff}}^{(2)}
\]

\[
\mathcal{L}_{\text{eff}}^{(1)} = f_q m_q \bar{\chi} \chi \bar{q} q + \frac{g_q(1)}{m_\chi} \bar{\chi} i \partial^\mu \gamma^\nu \chi \mathcal{O}_{\mu\nu}^1 + \frac{g_q(2)}{m_\chi^2} \bar{\chi} (i \partial^\mu) (i \partial^\nu) \chi \mathcal{O}_{\mu\nu}^2,
\]

\[
\mathcal{L}_{\text{eff}}^{(2)} = f_G \bar{\chi} \gamma^\mu \chi \mathcal{O}_{\mu\nu}^g + \frac{g_G(1)}{m_\chi} \bar{\chi} i \partial^\mu \gamma^\nu \chi \mathcal{O}_{\mu\nu}^g + \frac{g_G(2)}{m_\chi^2} \bar{\chi} (i \partial^\mu) (i \partial^\nu) \chi \mathcal{O}_{\mu\nu}^g.
\]

Spin 0
Dimension 6

Evaluate matrix element for the elastic scattering process in the non-relativistic limit.

\[
f_N/m_N = \sum_{q=u,d,s} f_q f_T q + \sum_{q=u,d,s,c,b} \frac{3}{4} (q(2) + \bar{q}(2)) \left(g_q(1) + g_q(2)\right)
\]

\[
- \frac{8\pi}{9\alpha_s} f_T G f_G + \frac{3}{4} G(2) \left(g_G(1) + g_G(2)\right).
\]

Tools: FeynArts, FORM, PackageX
Constraints improve by an order of magnitude.
RGE of Wilson Coefficients

- Nucleon DM cross-sections at Non-Relativistic velocities.

- At what scale do we define coupling and masses? If at scale $\mu \sim 0$, then to compare with LHC we should run up. If at $\mu \sim$ LHC energy, then to compare we should run down.

- RGE not necessary if no comparisons being made at different energy scales.

$$c_i(\mu_l) = R_{ij}(\mu_l, \mu_h) c_j(\mu_h).$$

$$c_i(\mu_Q) = M_{ij}(\mu_Q) c_j'(\mu_Q).$$

R. Hill, M. Solon 2014
How important is RGE?
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Factor 2~3 increase in matrix element when performing RGE.

Factor 4-9 enhancement in cross-section
LHC Constraints

- Colored scalar mediator pair production—production cross-section (mostly QCD) depends on mass of mediator alone.

- Acceptance depends on mass of dark matter candidate also.

- Associated production of colored mediator and dark matter candidate—depends on all three model parameters.
Pure QCD
Independent of DM coupling ($g_{DM}$)

Tools: FeynRules, NLOCT, MadGraph5_aMC@NLO, MadAnalysis5
Complementarity of DD & LHC experiments

The diagram illustrates the complementarity of direct detection (DD) and LHC monojet experiments in the parameter space of dark matter (DM) mass ($m_X$) and LHC monojet mass ($M_{q_L}$). The color scale on the right represents the DM coupling strength ($g_{DM}$). The dark and shaded regions indicate the regions of interest or exclusion for these experiments.

- **$m_X$ [GeV]**: The DM mass is shown on the y-axis, ranging from 0 to 2000 GeV.
- **$M_{q_L}$ [GeV]**: The LHC monojet mass is shown on the x-axis, ranging from 0 to 2000 GeV.
- **$g_{DM}$**: The color map on the right indicates the coupling strength, with values ranging from 0.1 to 1.0.

The diagram highlights the regions where DM can be probed by both LHC and DD experiments, showing a complementary overlap in their sensitivity regions.
Complementarity of DD & LHC experiments

LHC Pair production

LHC Associated production

SI Limits
Conclusions

- Simplified models— useful to capture essential features of classes of models; one can make generic statements.

- Can easily evaluate LHC constraints @ NLO precision.

- Demonstrated importance of going beyond LO for determining direct-detection constraints (order of magnitude increase).

- Demonstrated importance of RGE effects (factor 7 increase).

- Able to make proper comparison between experiments that operate at different energy scales.