Non-SUSY WIMPS:
Simplified models and DM@LHC

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Quy Nhon - July 27th, 2017

13th Rencontres du Vietnam: Exploring the Dark Universe
Simplified models
DM “models”

**FULL THEORIES**
- SUSY, KK, ...
- many particles and parameters

**SIMPLIFIED MODELS**
- 2 new particle (DM + mediator)
- few parameters ($M, m_{DM}$, couplings)

**EFFECTIVE THEORIES**
- 1 new particle (DM)
- 2 parameters ($\Lambda, m_{DM}$)
The simplest description is EFT with initial state radiation

- Write a complete set of operators (e.g. in the s-channel)
- Suppose DM interact only through one of those
- Derive bounds on the plane \( (m_{\text{DM}} - \Lambda) \)
- Easy comparison with other searches

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
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</thead>
<tbody>
<tr>
<td>D1</td>
<td>( \bar{\chi} \chi \bar{q}q )</td>
<td>( m_q/\Lambda^3 )</td>
</tr>
<tr>
<td>D1'</td>
<td>( \bar{\chi} \chi \bar{q}q )</td>
<td>( 1/\Lambda^2 )</td>
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<tr>
<td>D2</td>
<td>( \bar{\chi} \gamma^5 \chi \bar{q}q )</td>
<td>( i m_q/\Lambda^3 )</td>
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<tr>
<td>D3</td>
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<tr>
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<td>( m_q/\Lambda^3 )</td>
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<td>( \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q )</td>
<td>( 1/\Lambda^2 )</td>
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<tr>
<td>D5</td>
<td>( \bar{\chi} \gamma \mu \chi \bar{q} \gamma^\mu q )</td>
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<tr>
<td>D6</td>
<td>( \bar{\chi} \gamma \mu \gamma^5 \chi \bar{q} \gamma^\mu q )</td>
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<td>D7</td>
<td>( \bar{\chi} \gamma \mu \chi \bar{q} \gamma^\mu \gamma^5 q )</td>
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<tr>
<td>D8</td>
<td>( \bar{\chi} \gamma \mu \gamma^5 \chi \bar{q} \gamma^\mu \gamma^5 q )</td>
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<tr>
<td>D9</td>
<td>( \bar{\chi} \sigma_{\mu \nu} \chi \bar{q} \sigma_{\mu \nu} q )</td>
<td>( 1/\Lambda^2 )</td>
</tr>
<tr>
<td>D10</td>
<td>( \bar{\chi} \sigma_{\mu \nu} \gamma^5 \chi \bar{q} \sigma_{\mu \nu} q )</td>
<td>( i/\Lambda^2 )</td>
</tr>
<tr>
<td>D11</td>
<td>( \bar{\chi} \chi G^{\mu \nu} G_{\mu \nu} )</td>
<td>( \alpha_s/4 \Lambda^3 )</td>
</tr>
<tr>
<td>D12</td>
<td>( \bar{\chi} \gamma^5 \chi G^{\mu \nu} G_{\mu \nu} )</td>
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<tr>
<td>D13</td>
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<tr>
<td>D14</td>
<td>( \bar{\chi} \gamma^5 \chi G^{\mu \nu} \bar{G}_{\mu \nu} )</td>
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<tr>
<td>DT1</td>
<td>( (\bar{\chi} P_L q) (\bar{q} P_R \chi) )</td>
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</table>
The validity of EFTs is limited in energy by their cut-off scale

\[ \sim \frac{g_\chi g_q}{Q_{tr}^2 - M^2} = -\frac{g_\chi g_q}{M^2} \left[ 1 + \frac{Q_{tr}^2}{M^2} + \ldots \right] \]

\[ \equiv \frac{1}{\Lambda^2} (\bar{\chi} \Gamma_A \chi)(\bar{q} \Gamma_B q) \]

One should be sure that the energy scale of the process under study is below the cut-off \( \Lambda \) (assuming \( \mathcal{O}(1) \) couplings).
Simplified Models

- Can grasp the most relevant physical features of a full theory including DM
- Theoretically consistent
- Richer phenomenology: other channels and searches complementary to mono-X
- More parameters (couplings) → higher dimensional space to constrain
- No exhaustive list
- Not always applicable (e.g. strong coupling)
A joint effort between experimentalists and theorists, built on the previous ATLAS-CMS DM forum (final report 1507.00966, with more than 100 people involved)

- Define recommendations for well-defined and exhaustive benchmark models
- Encourage communication between experimentalists and theorists working on collider physics (and possibly other probes)

https://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
Naive construction: s-channel mediator

Bottom-up approach: build simplified models by expanding the effective operators.

\[ \mathcal{L}_S \supset -\frac{1}{2} M_{\text{med}}^2 S^2 - y_\chi S \bar{\chi} \chi - y_q S \bar{q}_i q_j + \text{h.c.}, \]

\[ \mathcal{L}_P \supset -\frac{1}{2} M_{\text{med}}^2 P^2 - y'_\chi P \bar{\chi} \gamma_5 \chi - y'_q P \bar{q}_i \gamma_5 q_j + \text{h.c.}, \]

\[ \mathcal{L}_V \supset \frac{1}{2} M_{\text{med}}^2 V_\mu V^\mu - g_\chi V_\mu \bar{\chi} \gamma^\mu \chi - g_q V_\mu \bar{q}_i \gamma^\mu q_j, \]

\[ \mathcal{L}_A \supset \frac{1}{2} M_{\text{med}}^2 A_\mu A^\mu - g'_\chi A_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi - g'_q A_\mu \bar{q}_i \gamma^\mu \gamma_5 q_j, \]

Common benchmarks:

\[ V : \begin{cases} g_\chi = 1, g_q = 0.25, g_\ell = 0 \\ g_\chi = 1, g_q = 0.1, g_\ell = 0.01 \end{cases} \quad A : \begin{cases} g_\chi = 1, g_q = 0.25, g_\ell = 0 \\ g_\chi = 1, g_q = 0.1, g_\ell = 0.1 \end{cases} \]
Naive construction: t-channel mediator

Coloured scalar mediator in the t-channel:

\[ \mathcal{L} \supset g_M \sum_i \left( \bar{Q}_L^i Q_L^i + \bar{u}_R^i u_R^i + \bar{d}_R^i d_R^i \right) \chi + \text{mass terms} + c.c. \]

Mono-jet: gluon emission from the mediator

Even stronger constraints from di-jet + MET

Kinematical distribution altered wrt EFT

Absent in the EFT approx.

Papucci, Vichi, Zurek, 1402.2285
LHC results on simplified models

mono-jet

mono-\(\gamma/Z\)

resonant searches: di-jet, di-leptons...

di-jet + MET

mono-higgs

di-top/bottom + MET
LHC results on simplified models

Axial-vector mediator, Dirac DM
\( g_R = 0.25, g_L = 0, g_{\text{DM}} = 1 \)

All limits at 95% CL
LHC results on simplified models

Axial-vector mediator, Dirac DM
$g_\mu = 0.1$, $g = 0.1$, $g_{DM} = 1$

All limits at 95% CL
(...) the bad and the ugly
Enlarged parameter space

More free parameters

EFT
\[ \Lambda, m_\chi \]

Simp. mods.
\[ M_{\text{med}}, m_\chi, g_q, g_\chi, \Gamma \]

Higher dim. scan not feasible

- Fixed benchmarks \((g, \Gamma = \ldots)\)
Enlarged parameter space

More free parameters

- EFT $\Lambda, m_\chi$
- Simp. mods. $M_{med}, m_\chi, g_q, g_\chi, \Gamma$

Higher dim. scan not feasible
- Fixed benchmarks $(g, \Gamma = \ldots)$
- Clever idea: scale the cross section to set limits on the couplings:

$$\sigma \propto (g_q \cdot g_\chi)^2, (g_q \cdot g_\chi)^2/\Gamma \ (1)$$
Simplified models – a critical look

Naive construction

\[
\text{EFT} \quad \Lambda^4 \quad \text{Simp. mods.} \quad (p^2 - M^2)^2 + \Gamma^2 M^2
\]

Theoretical issues (not just aesthetics)

- Perturbative unitary violated: requires completion
- Gauge invariance under the full SM group
- Cancellation of gauge anomalies: not automatic, but necessary for loop corrections
Consider a model with different couplings to up and down quarks. Explicit breaking of SU(2) → spurious enhancement of mono-W cross section

Affects also mono-jet
Consider a model with different couplings to up and down quarks. Explicit breaking of SU(2) → spurious enhancement of mono-W cross section

Can be cured in a full SU(2)-symmetric model

Bell+ 1503.07874, 1512.00476
Haisch+ 1603.01267
The scalar model

\[ \mathcal{L}_S \supset -\frac{1}{2} M_{\text{med}}^2 S^2 - y_\chi S\bar{\chi}\chi - y_{ij}^q S\bar{q}_i q_j + \text{h.c.} \]

is intrinsically not gauge invariant.
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Scalar mediators: 2HDM + s

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**Higgs - singlet mixing**

$$-y_\chi S\bar{\chi}\chi - y_q^i H\bar{Q}_i d_j - \lambda_{hs} |H|^2 S^2 \rightarrow \begin{cases} \text{Higgs} \rightarrow \text{inv.} \\ \text{EW precision obs.} \end{cases}$$
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**2 Higgs doublets**

$$H_u, \ H_d, \ S, \ V(H_u, H_d, S)$$

Gonçalves+ 1611.04593, Busoni+ 1612.03475
Perturbative unitarity

**Vector mediator**

\[ \mathcal{L} \supset - \sum_{f=q,\ell,\nu} Z'_{\mu} \bar{f} \left[ g^V_f \gamma_\mu + g^A_f \gamma_\mu \gamma^5 \right] f - Z'_{\mu} \bar{\chi} \left[ g^V_{DM} \gamma_\mu + g^A_{DM} \gamma_\mu \gamma^5 \right] \chi \]

Perturbative unitarity is violated in 2-2 scattering (similarly to SM without the Higgs):

\[ f \bar{f} \rightarrow f \bar{f} \quad f \bar{f} \rightarrow Z'Z' \]

Can be cured by adding a new scalar particle \( s \) that gives mass to the \( Z' \) and to DM. **New phenomenology:**

- \( \lambda_{hs} (S^* S)(H^\dagger H) \rightarrow s - h \) mixing
- loop-induced spin-dependent scattering in DD
- resonant annihilation \( \chi \chi \rightarrow s \rightarrow Z'Z \) affects the relic density

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110
Importance of anomaly cancellation

Annihilation through fermion loops relevant for ID

In a $U(1)'$ model, divergences do not cancel unless charges are chosen appropriately.

If new fermions (DM) are uncharged under the SM gauge group, the charges of SM fermions are linear combinations of $B - L$ and hypercharge

$$c_f = Y \cos \theta + (B - L) \sin \theta$$
Consequences: correlations and new channels

Example: U(1)' extension of the SM (Z' gauge boson)

- Fermion charges are correlated (otherwise new fermions are needed)
- Not only the fermions: Higgs is charged

\[ H \bar{Q}d \quad H \bar{Q}u \]

- "Extra" channels: \( Z'Zh \) at tree level

\[ (D_\mu H)^\dagger (D^\mu H) \rightarrow vZ'Zh \]

- Additional Higgs \( S \) adds new phenomenology
Conclusions

Simplified models

- Bottom-up: Simplified models introduced as a small step above EFTs
- Richer phenomenology
- Valid up to high energy

Limitations

- More parameters: choose benchmarks or find a way to scan?
- More (too many) interesting models to look at. Should we really abandon EFT completely? Recasts are possible.
- "Less simplified" models required for theoretical consistency.
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