The Coannihilation Codex

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with

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Outline

1. Motivation
2. Classification of Simplified Models
3. LHC Phenomenology
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1. Motivation
2. Classification of Simplified Models
3. LHC Phenomenology
Dark Matter

Begeman, Broeils & Sanders, 1991

\[ \Omega_{\text{nb}m} h^2 = 0.1198 \pm 0.0026 \]
Dark Matter

Begeman, Broeils & Sanders, 1991

Planck, 2013

\[ \Omega_{\text{b}m} h^2 = 0.1198 \pm 0.0026 \]
Dark Matter

Begeman

Viel, Becker, Bolton & Haehnelt, 2013
$\Omega_{\text{nbm}} h^2 = 0.1198 \pm 0.0026$
Theoretical Framework

- Dark Matter Effective Field Theories
- Dipole Interactions
- Contact Interactions

Less complete
Theoretical Framework

Less complete

- Dark Matter Effective Field Theories
- Dipole Interactions
- Contact Interactions

More complete

- Minimal Supersymmetric Standard Model
- Complete Dark Matter Models
- Universal Extra Dimensions
- Little Higgs

- The large energies accessible at the LHC call into question the momentum expansion of the dark sector, comparing LHC bounds to the limits following from direct and indirect detection.
- For each operator a single parameter encodes the information on all the heavy states on the "new-physics" scale Λ that suppresses the higher-dimensional operators. Since this is useful in the analysis of LHC Run I data, because it allows to derive stringent bounds.
- Simplified models are able to describe correctly the full kinematics of DM production interactions with the SM, as well as the DM particle itself. Unlike the DM-EFTs, models are characterized by the most important state mediating the DM particle.
- Toward simplified DM models (for early proposals see for example [17–22]). Such underlying the EFT approximation [6, 9–16], and we can expand our level of detail.

Abdallah et al., 1506.03116
The large energies accessible at the LHC call into question the momentum expansion of the dark sector, comparing LHC bounds to the limits following from direct and indirect DM searches is straightforward in the context of DM-EFTs. For each operator a single parameter encodes the information on all the heavy states on the “new-physics” scale $\Lambda$ that suppresses the higher-dimensional operators. Since, this is useful in the analysis of LHC Run I data, because it allows to derive stringent bounds on the interactions with the SM, as well as the DM particle itself. Unlike the DM-EFTs, simplified models are characterized by the most important state mediating the DM particle toward simplified DM models (for early proposals see for example [17–22]). Such models are able to describe correctly the full kinematics of DM production at the LHC, because they resolve the EFT contact interactions into single-particle exchanges. This comes with the price that they typically involve not just one, but a handful of parameters that characterize the dark sector and its interactions.
Simplified Models

Much recent work on simplified models of DM, e.g.,

- Abdallah et al. 1506.03116,
- Abercrombie et al. 1507.00966,
- ...

Simple one particle freeze-out often leads to tensions, e.g., between relic density and direct/indirect constraints.

For some models this is not a good approximation.

Coannihilating models can relieve these tensions and/or give a better approximation.
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  - For some models this is not a good approximation
  - Coannihilating models can relieve these tensions and/or give a better approximation
Motivation

Classification of Simplified Models

LHC Phenomenology

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Coannihilating models can relieve these tensions and/or give a better approximation
Our Goal

A complete classification of simplified coannihilation models
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The Coannihilation Codex
Our Goal

A complete classification of simplified coannihilation models

The Coannihilation Codex

- A bottom-up framework for discovering dark matter at the LHC
- LHC phenomenology testing DM freeze-out
- Identify lesser studied models & searches
- In the event of a signal, gives a framework for the inverse problem
Outline

1. Motivation

2. Classification of Simplified Models

3. LHC Phenomenology
Assumptions

To complete a classification we need to make some assumptions

- DM is a thermal relic
- DM is a colourless, electrically neutral particle in $(1, N, \beta)$
- Coannihilation diagram is 2-to-2 via dimension four, tree-level couplings
- New particles have spin 0, 1/2 or 1
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Coannihilation Diagrams

Motivation
Classification of Simplified Models
LHC Phenomenology

\[ \text{X} \quad \text{SM}_2 \]
\[ \text{DM} \quad \text{SM}_1 \]
\[ \downarrow \]
\[ \text{X} \quad \text{SM}_2 \]
\[ \text{DM} \quad \text{SM}_1 \]
\[ \text{X} \quad \text{SM}_2 \]
\[ \text{DM} \quad \text{SM}_1 \]

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\[ \text{DM} \quad \text{SM}_1 \]
Classification Procedure

- Work in unbroken $SU(2)_L \times U(1)_Y$
- Given SM field content, iterate over SM$_1$ and SM$_2$ to find all possible X using
  - Gauge invariance
  - Lorentz invariance
  - $\mathbb{Z}_2$ parity (to prevent DM decay)
- Then find all s-channel and t-channel mediators, using same restrictions and
  - Dimension four, tree-level couplings
  - Gauge bosons only couple through kinetic terms
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**s-channel classification - sample**

**DM in** $(1, N, \beta)$

| ID   | X                | $\alpha + \beta$ | $M_s$        | Spin | $(SM_1 \ SM_2)$ | SM$_3$ | M-$X$-$X$ |
|------|------------------|------------------|--------------|------|----------------|--------|----------|
| ST11 |                  | $\frac{7}{3}$   | $(3, 2, \frac{7}{3})$ | B    | $(Q_L \ell_R), (u_R \overline{L_L})$ |        |          |
| ST12 | $(3, N \pm 1, \alpha)$ | $\frac{1}{3}$   | $(3, 2, \frac{1}{3})$ | B    | $(d_R \overline{L_L}), (Q_L d_R), (u_R L_L)$ |        |          |
| ST13 |                  | $\frac{1}{3}$   | $(3, 2, \frac{1}{3})$ | F    | $(u_R H), (d_R H) \ Q_L$ |        |          |
| ST14 |                  | $\frac{1}{3}$   | $(3, 2, \frac{1}{3})$ | F    | $(d_R H) \ Q_L$ |        |          |
| ST15 |                  | $\frac{1}{3}$   | $(3, 2, \frac{1}{3})$ | B    | $(Q_L u_R), (Q_L \ell_R), (d_R L_L)$ |        |          |
| ST16 |                  | $\frac{1}{3}$   | $(3, 2, \frac{1}{3})$ | F    | $(d_R H) \ Q_L$ |        |          |
| ST17 | $(3, N \pm 2, \alpha)$ | $\frac{4}{3}$   | $(3, 3, \frac{4}{3})$ | B    | $(Q_L \overline{L_L})$ | $\sqrt{\alpha = -\frac{2}{3}}$ |          |
| ST18 |                  | $\frac{4}{3}$   | $(3, 3, \frac{4}{3})$ | F    | $(Q_L H)$ |        |          |
| ST19 |                  | $\frac{4}{3}$   | $(3, 3, \frac{4}{3})$ | B    | $(Q_L Q_L), (Q_L L_L)$ | $\sqrt{\alpha = \frac{1}{3}}$ |          |
| ST20 |                  | $\frac{4}{3}$   | $(3, 3, \frac{4}{3})$ | F    | $(Q_L H) \ Q_L$ |        |          |

**B:**

- DM
- SM$_1$ SM$_2$ SM$_1$ SM$_2$

**F:**

- DM
- SM$_1$ SM$_2$ SM$_1$ SM$_2$
### DM in (1, N, β)

| ID  | X   | α + β | $M_t$                      | Spin | (SM₁ SM₂) | SM₃ |
|-----|-----|-------|-----------------------------|------|-----------|-----|
| TU26|     | 0     | (1, N ± 1, β − 1)           | I    | (HH†)     |     |
| TU27|     |       | (1, N ± 1, β + 1)           | II   | (LLH)     |     |
| TU28| (1, N ± 2, α) |       | (1, N ± 1, β − 1)           | III  | (HL₉)     |     |
| TU29|     |       | (3, N ± 1, β − 1)           | IV   | (QLQL)    |     |
| TU30|     |       | (1, N ± 1, β + 1)           | IV   | (L₉L₉)    |     |
| TU31|     | −2    | (1, N ± 1, β + 1)           | I    | (H†H†)    |     |
| TU32|     |       | (1, N ± 1, β + 1)           | II   | (LLH†)    |     |
| TU33|     |       | (1, N ± 1, β + 1)           | III  | (H†L₉)    |     |

**Diagrams:**

- **I:** $X \rightarrow M_t \rightarrow SM_2$  
- **II:** $X \rightarrow M_t \rightarrow SM_2$  
- **III:** $X \rightarrow M_t \rightarrow SM_2$  
- **IV:** $X \rightarrow M_t \rightarrow SM_2$
## Classification: hybrid models

| ID  | X              | $\alpha + \beta$ | SM partner                  | Extensions                  |
|-----|----------------|------------------|-----------------------------|------------------------------|
| H1  | $(1, N, \alpha)$ | 0                | $B, W_i^N \geq 2$           | SU1, SU3, TU1, TU4–TU8       |
| H2  |                | $-2$             | $\ell_R$                    | SU6, SU8, TU10, TU11         |
| H3  | $(1, N \pm 1, \alpha)$ | $-1$             | $H^\dagger$                 | SU10, TU18–TU23              |
| H4  | $(1, N \pm 1, \alpha)$ | $-\frac{2}{3}$ | $L_L$                       | SU11, TU16, TU17             |
| H5  | $(3, N, \alpha)$ | $\frac{4}{3}$   | $u_R$                       | ST3, ST5, TT3, TT4           |
| H6  | $(3, N \pm 1, \alpha)$ | $-\frac{2}{3}$ | $d_R$                       | ST7, ST9, TT10, TT11         |
| H7  | $(3, N \pm 1, \alpha)$ | $\frac{1}{3}$   | $Q_L$                       | ST14, TT28–TT31              |

7 models
## Classification: s-channel

### SU type - 17 models

| ID | X | $\alpha + \beta$ | $M_x$ | Spin | (SM1, SM2) | SM3 | M-X-X |
|----|----|------------------|-------|------|------------|-----|-------|
| SU1 | (1, N, $\alpha$) | 0 | (1, 1, 0) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | $B, W, N \geq 2$ | ✓ |
| SU2 | (1, N, $\alpha$) | -1 | (1, 2, -1) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | $B, W, N \geq 2$ | ✓ |
| SU3 | (1, N, $\alpha$) | -2 | (1, 2, -2) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = 0) |
| SU4 | (1, N, $\alpha$) | 0 | (1, 3, 0) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU5 | (1, N, $\alpha$) | -2 | (1, 3, -2) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU6 | (1, N, $\alpha$) | 0 | (1, 3, 0) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU7 | (1, N, $\alpha$) | -2 | (1, 3, -2) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU8 | (1, N, $\alpha$) | 0 | (1, 3, 0) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU9 | (1, N, $\alpha$) | -2 | (1, 3, -2) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU10 | (1, $\alpha$) | 0 | (1, 3, 0) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| SU11 | (1, $\alpha$) | -2 | (1, 3, -2) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |

### SO and SE type - 5 and 7 models

#### SU type - 20 models

| ID | X | $\alpha + \beta$ | $M_x$ | Spin | (SM1, SM2) | SM3 | M-X-X |
|----|----|------------------|-------|------|------------|-----|-------|
| ST1 | (1, N, $\alpha$) | 0 | (1, 1, 0) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| ST2 | (1, N, $\alpha$) | -1 | (1, 2, -1) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| ST3 | (1, N, $\alpha$) | -2 | (1, 2, -2) | B | $\begin{pmatrix} d_R & \nu_R \\ \nu_L & \nu_L \end{pmatrix}$, $(Q_L, Q_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| ST4 | (1, N, $\alpha$) | 0 | (1, 3, 0) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |
| ST5 | (1, N, $\alpha$) | -2 | (1, 3, -2) | B | $(Q_L, Q_L)$, $(Q_L, L_L)$, $(H, H^*)$ | $\ell_R, (L_L, L_L)$, $(H H^*)$ | ✓ | (α = ±1) |

#### U: X uncoloured

#### T: X $SU(3)$ triplet

#### O: $SU(3)$ octet

#### E: $SU(3)$ exotic

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Motivation

Classification of Simplified Models

LHC Phenomenology
| ID  | X          | α + β | M_α | Spin (SM1, SM2) | SM_3 |
|-----|------------|-------|-----|----------------|------|
| TU1 | (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU2 | (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU5 | (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU6 | (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU9 | (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU10| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU13| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU16| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU19| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU22| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU25| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU28| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU31| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |
| TU34| (1, N, α)  | 0     | (1, N ± 1, β + 2) | IV (QLQL) | B, W_1^{N 2/3} |

**Classification: t-channel**

**TU type - 33 models**

**TT type - 52 models**

| ID  | X          | α + β | M_α | Spin (SM1, SM2) | SM_3 |
|-----|------------|-------|-----|----------------|------|
| TO1 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO2 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO3 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO4 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO5 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO6 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO7 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO8 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO9 | (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |
| TO10| (8, N, α)  | 0     | (3, N ± 1, β + 1) | IV (QLQL) | B, W_1^{N 2/3} |

**TO and TE type - 10 and 10 models**

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**Classification of Simplified Models**

**TU type - 33 models**

**TT type - 52 models**
Complete Classification

We have written down all possible simplified models of 2-to-2 coannihilating dark matter!
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Outline

1. Motivation

2. Classification of Simplified Models

3. LHC Phenomenology
Production: s-channel

\[ \bar{q}q \rightarrow \bar{X}, \bar{M} \]

\[ \bar{q}q \rightarrow \bar{X}, \bar{M} \]

\[ q\bar{q} \rightarrow \bar{X}, \bar{M}, \bar{DM} \]

\[ q\bar{q} \rightarrow \bar{X}, \bar{M}, \bar{DM} \]

\[ \bar{q}q \rightarrow \gamma/Z \]

\[ \bar{q}q \rightarrow \gamma/Z \]

\[ q\bar{q} \rightarrow \bar{X}, \bar{M}, D\bar{M} \]

\[ q\bar{q} \rightarrow \bar{X}, \bar{M}, D\bar{M} \]

\[ q\rightarrow FJ \]

\[ q\rightarrow FJ \]

\[ q\rightarrow SM \]

\[ q\rightarrow SM \]
Production: s-channel
Decay: s-channel

\[ X_s \rightarrow \text{DM} \]
\[ M_s \rightarrow \text{SM}_1 + \text{soft} \]
\[ M_s \rightarrow \text{SM}_2 \]

\[ X_s \rightarrow \text{DM} \]
\[ M_s \rightarrow \text{SM}_1 + \text{soft} \]
\[ M_s \rightarrow \text{SM}_2 \]

\[ \vec{E}_T \]

\[ X_s \rightarrow \text{DM} \]
\[ M_s \rightarrow \text{SM}_1 \]
\[ M_s \rightarrow \text{SM}_2 \]

\[ \vec{E}_T \]
\[ + \]
\[ \text{soft} \]
Decay: s-channel

\[
\begin{align*}
X_s & \rightarrow_{\text{DM}} \text{SM}_1 \\
M_s & \rightarrow_{\text{soft}} \text{SM}_2
\end{align*}
\]

\[
\begin{align*}
\text{Resonance} & \rightarrow_{\overline{E}_T} + \\
\text{soft} & 
\end{align*}
\]
Motivation
Classification of Simplified Models
LHC Phenomenology

Decay: s-channel

\[ X_s \rightarrow \text{DM} \quad \text{SM}_1 \quad \left\{ \begin{array}{c} \ell_T \\ + \\ \text{soft} \end{array} \right\} \]

\[ M_s \rightarrow \text{SM}_1 \quad \text{SM}_2 \quad \left\{ \begin{array}{c} \text{Resonance} \end{array} \right\} \]

\[ M_s \rightarrow \text{DM} \quad \text{DM} \quad \text{SM}_1 \quad \left\{ \begin{array}{c} \ell_T \\ + \\ \text{soft} \end{array} \right\} \]
Generic Signatures: s-channel

- **Mono-Y** (Y=jet, photon, Z,...) + $\not{E}_T$ from DM DM, XX,...
  - classic signature

- Single and Double Resonances from M and MM
  - ATLAS/CMS Exotics

- Mono-Y + $\not{E}_T$ + soft from XX,MM,...
  - has been motivated, no searches yet

- **Resonance** + $\not{E}_T$ + soft from MM
  - new signature to explore!
Generic Signatures: s-channel

- **Mono-Y** (Y=jet, photon, Z, . . .) + $\not{E}_T$ from DM DM, XX, . . .
  - classic signature

- **Single and Double Resonances** from M and MM
  - ATLAS/CMS Exotics

- **Mono-Y** + $\not{E}_T$ + soft from XX, MM, . . .
  - has been motivated, no searches yet

- **Resonance** + $\not{E}_T$ + soft from MM
  - new signature to explore!
Generic Signatures: s-channel

- **Mono-Y** (Y=jet, photon, $Z$, \ldots) + $\not{E_T}$ from DM DM, XX,\ldots
  - classic signature
- **Single and Double Resonances** from M and MM
  - ATLAS/CMS Exotics
- **Mono-Y** + $\not{E_T}$ + **soft** from XX,MM,\ldots
  - has been motivated, no searches yet
- **Resonance** + $\not{E_T}$ + **soft** from MM
  - new signature to explore!
Generic Signatures: s-channel

- **Mono-Y** (Y=jet, photon, Z,...) + $E_T$ from DM DM, XX,...
  - classic signature
- **Single and Double Resonances** from M and MM
  - ATLAS/CMS Exotics
- **Mono-Y + $E_T$ + soft** from XX,MM,...
  - has been motivated, no searches yet
- **Resonance + $E_T$ + soft** from MM
  - new signature to explore!
| \(pp \to \cdots\) | Prod. via | Signatures | Search |
|------------------|-----------|-------------|--------|
| DM + DM + ISR | gauge int. or SM\(_1\) \(\in p\) for \(t\)-channel | mono-\(Y + E_T\) | [55,56,62,63,104] |
| \(X \to SM[SM,SM]^{\text{mix}}\) DM | gauge int. or SM\(_2\) \(\in p\) for \(t\)-channel | mono-\(Y + E_T\) | [55,56,62,63,104] |
| DM + X \(\to SM[SM,SM]^{\text{mix}}\) DM + ISR | (SM\(_1\), SM\(_2\)) \(\in p\) | mono-\(Y + E_T\); mono-\(Y + E_T + \leq 4\) SM | Partial coverage [105] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) | 2 resonances | [106-112] |
| DM + X \(\to SM[SM,SM]^{\text{mix}}\) DM | resonance + \(E_T\); resonance + \(E_T + \leq 2\) SM | No search |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 4\) SM | [113-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) | 1 resonance | [125-146] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 2\) SM | [120-122,124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 3\) SM | [104,147-153] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 6\) SM | [113,141,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 8\) SM | [116-118,159-163] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 1\) SM | [55,56,62,63] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 3\) SM | [104,149] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 5\) SM | [113,114,116-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 7\) SM | [159-161,164] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 9\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 10\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 12\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 14\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 16\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 18\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 20\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 22\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 24\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 26\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 28\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 30\) SM | [152,153,156-158] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 32\) SM | [114,120-124] |
| DM + M \(\to SM[SM,SM]^{\text{mix}}\) DM | \(E_T + \leq 34\) SM | [152,153,156-158] |
### Signature Table: Excerpt

| $pp \rightarrow \ldots$ | Prod. via | Signatures | Search |
|-------------------------|-----------|------------|--------|
| $\begin{cases} M_s (\rightarrow [SM_1 \ SM_2]^{\text{res}}) \\ M_s (\rightarrow [SM_1 \ SM_2]^{\text{res}}) \end{cases}$ | gauge int. | 2 resonances | [106-112] |
| $\begin{cases} M_s (\rightarrow [SM_1 \ SM_2]^{\text{res}}) \\ M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$ | | resonance + $E_T$ | No search |
| $\begin{cases} M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \\ M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$ | | resonance + $E_T + \leq 2$ SM | No search |
| $M_s (\rightarrow [SM_1 \ SM_2]^{\text{res}})$ | $(SM_1 \ SM_2) \in p$ | 1 resonance | [125-146] |
| $M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$ | | $E_T + \leq 2$ SM | [120-122, 124] |
| $SM_{1,2} + M_s (\rightarrow [SM_1 \ SM_2]^{\text{res}})$ | $SM_{2,1} \in p$ | 1 resonance + 1 SM | Partial coverage [154,155] |
| $\begin{cases} SM_{1,2} \\ M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$ | | $E_T + 1 \leq 3$ SM | [114,120-124] |

Note: The table entries are simplified for the purpose of this example. The actual table contains more detailed information and references.
Example - ST11

| ID   | X     | $\alpha + \beta$ | $M_s$   | Spin | $(SM_1 \ SM_2)$ | SM$_3$ | M-X-X    |
|------|-------|------------------|---------|------|-----------------|--------|----------|
| ST11 | $(3, N \pm 1, \alpha)$ | $\frac{7}{3}$ | $(3, 2, \frac{7}{3})$ | B    | $(Q_L \ell_R), (u_R \bar{L}_L)$ |        |          |

DM in $(1, N, \beta)$

| Field | Rep. | Spin and mass assignment |
|-------|------|--------------------------|
| DM    | $(1,1,0)$ | Majorana fermion          |
| X     | $(3,2,7/3)$ | Dirac fermion            |
| M     | $(3,2,7/3)$ | Scalar                  |
Example - ST11

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|-----|----------|-------------------|---------|------|-----------------|------|----------------|
| ST11| $(3, N \pm 1, \alpha)$ | $\frac{7}{3}$    | $(3, 2, \frac{7}{3})$ | B    | $(QL\ell_R), (u_R\ell_L)$ |      |                |

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\[
\mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \bar{X} M \text{DM} + y_Q \bar{Q}_L M \ell_R + y_{Lu} \bar{L}_L M^c u_R + \text{h.c.}
\]
Example - ST11

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\[ \mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \bar{X} M DM + y_Q \bar{Q}_L M \ell_R + y_{L_d} \bar{L}_L M^c u_R + h.c. \]
### Example - ST11

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\[
\mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \overline{X} M \overline{\text{DM}} + y_Q \overline{Q}_L M \ell_R + y_{Lu} \overline{L}_L M^c u_R + \text{h.c.}
\]
Example - ST11

\[ \mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \bar{X} M DM \]
\[ + y_Q \bar{Q}_L M_R + y_L \bar{L}_L M^c u_R + h.c. \]

- Strong production
- Lepton-jet resonance + $\mathcal{E}_T$ + soft lepton & jet
- No dedicated LHC search
Example - ST11

\[ \mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \bar{X} M DM + y_Q \ell Q L M \ell_R + y_L u \bar{L} M c u_R + h.c. \]

- Strong production
- Lepton-jet resonance + $E_T$ + soft lepton & jet
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Example - ST11

\[ \mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \bar{X} \, M \, DM + y_Q \bar{Q} L M \ell_R + y_{Lu} \bar{L} L M^c u_R + h.c. \]

- Strong production
- Lepton-jet resonance + $\mathbf{E}_T$ + soft lepton & jet
- No dedicated LHC search
Summary

- Coannihilation Codex gives a complete list of simplified models of coannihilation
- Guaranteed kinetic & coannihilation vertices → signatures
- Classify signatures of a wide range of models
  - Identify new signatures
  - Identify interesting models, e.g., leptoquarks and DM
- Huge number of DM models
  - collider signatures
  - direct and indirect detection
  - precision tests
  - flavour bounds
  - cosmology
  - ...
ST11 - Constraints from New Searches

\[ \Delta = 0.1, \quad \text{Br}(\text{LQ} \rightarrow lq)|_{m_{\text{DM}}=0} = 0.5 \]

\[
\begin{align*}
XX+j \quad (\text{Mixed}) \quad [13 \, \text{TeV}] \\
XX+j \quad (\text{Leptons}) \quad [13 \, \text{TeV}] \\
XX+j \quad (\text{Leptons}) \quad [13 \, \text{TeV}] \\
XX+j \quad (\text{Monojet}) \quad [8 \, \text{TeV}] \\
XX+j \quad (\text{Monojet}) \quad [8 \, \text{TeV}] \\
\end{align*}
\]

\[
\begin{align*}
(p_{T}(l) > 10 \, \text{GeV}) \\
(p_{T}(l) > 25 \, \text{GeV}) \\
\end{align*}
\]

Relic Density + APV (3\(\sigma\) allowed)