Fitting the relic density with contributions from dim. five operators

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Based on recent work
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A. A theoretical motivation

- Relic density fit

B. Detection

- Astrophysical
- Collider
The universe is ~25% dark matter, ~70% dark energy, ~5% ordinary baryonic matter.

Observed DM density, or relic density, is a constant.

Cold non-baryonic candidates strongly constrained by $\Omega_{DM} h^2 = 0.1186 \pm 0.0020$

($\sim$ annihilation cross section $SS > xx$)

- We consider a heavy candidate $S$ with $200 \text{ GeV} \lesssim m_S \lesssim 3 \text{ TeV}$
“Contact interactions and top-philic scalar dark matter”
(arXiv 2104.12795, accepted to JHEP June 2021)

Relic density: theory and fit

- Models of Dark Matter strongly constrained by relic density
- DM may emerge from a composite Higgs model (usually light)
- Extension of previous heavy top-philic DM model + contact term
- Semi-analytic fit of the relic density

Visibility at experiment

- Astrophysical constraints: direct detection, indirect detection
- Collider constraints
Our setup

- $SS \rightarrow t\bar{t}$ annihilation dominates
- Heavy fermionic mediator, $m_S < m_T$

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Could $S$, $T$ emerge as heavy resonances in a CH model?

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Extension of 1804.05068 (Colucci, Fuks, Giacchino, Lopez Honorez, Tytgat, Vandecasteele)

- Featuring $S$, $T$ both heavy, NLO is NB

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Real scalar coupling to $t_R$

$\sigma v_{tt}\big|_{NLO} \approx \begin{cases} \sigma v_{tt} & m_S < 300 \text{ GeV}, \\ \sigma v_{ttg}\big|_{m_t=0} + \sigma v_{tt} & m_S > 300 \text{ GeV}. \end{cases}$
Fitting the relic density with contributions from dimension-five operators

\[ \mathcal{L} = i \bar{T} \not\!\! \! \partial T - m_T \bar{T}T + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 + \left[ \tilde{y}_t S \bar{T} P_R t + h.c. \right] + \frac{1}{2} \lambda S^2 \phi^\dagger \phi + \frac{C}{\Lambda} S S \bar{t} \bar{t} \]

- Addition of generic dim-5 operator with \( \mathcal{O}(1) \) Wilson coefficient
- Contact term competes with Yukawa term in annihilation
- Modification of the relic density

Our setup

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Simulation ecosystem

User inputs → Lagrangian

FeynRules + Mathematica:
- Feynman rules + Feynman diagrams

FeynRules/FeynArts/FormCalc/CalcHEP:
- UFO: set of particles/parameters/vertices/couplings
- Colour structures and Lorentz vertices

MadGraph5_aMC:
- Matrix element generation
- Cross sections

Pythia8:
- Parton showering

Delphes:
- Detector simulation

Collider

micrOMEGAS:
- Relic density simulations

Madanalysis5 Mathematica Analysis

Astro
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Naive relic density fit: \[ \frac{C}{\Lambda} = f(m_S, m_T, \tilde{y}_t) \]

DM relic density obeys the Boltzmann eq. \[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right) \]

With an approximate solution.

\[ \Omega_{DM} h^2 \approx \frac{1.04 \times 10^9}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{a + 3b/x_F} \]

Given \[ \Omega_{DM} h^2 \approx \frac{b'(x_F, g_*(x_F))}{\langle \sigma v \rangle_{full}} = \frac{b'(x_F, g_*(x_F))}{C^2/\Lambda^2 \langle \sigma v \rangle_{SStt} + y^4 \langle \sigma v \rangle_{NLO}} \]

We finally have

\[ \frac{C}{\Lambda} \approx \frac{1}{\sqrt{A(m_S)}} \sqrt{b'(x_F, g_*(x_F)) - B(m_S, m_T) \tilde{y}_t^4} \]
Coannihilations

- Define $r = \frac{m_T}{m_S} - 1$

- When $S$ and $T$ get close in mass, the coannihilations of $T$ with $S$ are no longer negligible ($r \leq 0.8$)
Fitting the relic density with contributions from dimension-five operators

- The Boltzmann equation is generalised to a set of coupled equations

\[ \sigma_{\text{eff}}(x) = \sigma_{SS} + \sigma_{ST} \frac{g_S g_T}{g_{\text{eff}}^2} \left( \frac{m_T}{m_S} \right)^{3/2} \exp[-x \cdot r] \]

\[ \frac{C}{\Lambda} \approx f(m_S, m_T, \tilde{y}_t) = \frac{1}{\sqrt{A(m_S)}} \sqrt{b' - B(m_S, m_T) \left( \tilde{y}_t - \alpha \left[ \beta_\gamma m_S^\Lambda \right] \right)^4} \]

\[ r = \frac{m_T}{m_S} - 1 \]

\[ s(m_S, m_T) = 0.4 \cdot 0.003^r \]
Fitting the relic density with contributions from dimension-five operators

\[ A(m_S) = \frac{\Lambda^2 \langle \sigma v \rangle_{SStt}}{C^2} = \frac{N_c}{4\pi} \left(1 - \frac{m_t^2}{m_S^2} \right)^{3/2}, \]

\[ B(m_S, m_T) = \frac{\sigma v_{q\bar{q}} + \sigma v_{VIB}^{(0)}}{y_t^4} \]

\[ = \frac{N_c}{4\pi m_S^2} \left( \frac{m_t^2(m_S^2 - m_t^2)^{3/2}}{m_S(m_S^2 + m_T^2 - m_t^2)^2} \right. \]

\[ + \frac{\alpha_S C_F}{2\pi} \left[ (r+1)^2 + 1 \right] \left( \frac{\pi^2}{6} - \log^2 \frac{1 + (r+1)^2}{2(r+1)^2} \right) - 2\text{Li}_2 \left( \frac{1 + (r+1)^2}{2(r+1)^2} \right) \]

\[ + \frac{4(r+1)^2 + 3}{(r+1)^2 + 1} + \frac{4(r+1)^2 - 3(r+1)^2 - 1}{2(r+1)^2 - 1} \log \frac{(r+1)^2 - 1}{(r+1)^2 + 1} \right), \]

\[ b'(x_F, g_*(x_F)) = \left(7.19 \times 10^{-10} \text{ GeV}^{-2}\right) \frac{x_F}{\sqrt{g_*(x_F)}}. \]
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Direct detection

- Scattering off atomic nuclei: DM gluon interactions
- (top quark absent from nucleus!)

\[ \mathcal{L} = C_s^g \partial^g_S = C_s^g \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu} \]
Indirect detection

In indirect detection of DM, experiments aim to measure the annihilation or decays of the WIMPS via the SM particles produced during these processes.

Check behaviour and for rescaling of bounds:

\[ \sigma v_{\text{ann}} = \sigma_{bb} \frac{N_b}{N_{\gamma}} \]

\[ E_{\gamma} \text{ [GeV]} \]

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\[ m_s = 250 \text{ GeV} \]

Max. \( \tilde{y}_\gamma \)
Max. \( \tilde{y}_\Lambda \)
\( \tilde{y}_\gamma \) only

\[ \sigma v_{\text{ann}} \text{ [cm}^3\text{s}^{-1}] \]

\[ m_s \text{ [GeV]} \]

10^{-28} to 10^{-24}

10^{-3} to 10^{-5}
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Collider: $pp \rightarrow t\bar{t}SS$

Recasting previous ATLAS and CMS analyses using MadAnalysis5

\[ \sigma_{t\bar{t}SS}(M_T, M_S) = \sigma_{t\bar{t}SS}^0(M_T, M_S) + \frac{C}{\Lambda} \delta_{t\bar{t}SS}^{\text{int}}(M_T, M_S) + \frac{C^2}{\Lambda^2} \delta_{t\bar{t}SS}^{\text{dim5}}(M_S) \]

- Mono-jet negligible
- Additional operator yields no significant modification
Exclusions

- LHC bounds due to extrapolation to full Run-2
- Larger luminosities hold even more potential
- Wilson coefficient dep. on underlying theory, but collider immune

• Complementarity of collider constraints with astrophysical ones (more affected by the contact term)
• Semi-analytic fit to the relic density shows interplay of new term
• Opening up of parameter space
• Co-annihilation effects should not be neglected
• Astrophysical constraints strengthened
• No impact on collider - complementarity!

Thank you
Fitting the relic density with contributions from dimension-five operators

Direct detection

$m_5 = 500$ GeV, $r = 1.1$

$m_5 = 3247$ GeV, $r = 0.11$
Mono-jet: ATLAS_EXOT_2016_27 (energetic jet and large missing momentum, 36.1 fb\(^{-1}\))

- Shown previously to have minimal contribution.
Fitting the relic density with contributions from dimension-five operators

Collider: $pp \rightarrow t\bar{t}SS$

Recasting previous ATLAS and CMS analyses using MadAnalysis5

Collider signatures $(pp \rightarrow t\bar{t} + \not{E}_T)$ can be probed using existing DM searches focusing on the mono-jet / multi-jet / ttbar + MET signatures

$$\sigma_{t\bar{t}SS}(M_T, M_S) = \sigma_{t\bar{t}SS}^0(M_T, M_S) + \frac{C}{\Lambda} \hat{\sigma}_{t\bar{t}SS}^{int}(M_T, M_S) + \frac{C^2}{\Lambda^2} \hat{\sigma}_{t\bar{t}SS}^{dim5}(M_S)$$
Collider: Madanalysis5 recasting

- Multi-jet: ATLAS_CONF_2019_040 (≥ 2 hard jets + $p_T^{\text{miss}}$, 139 fb$^{-1}$)
- ttbar + MET: CMS_SUS_17_001 ($\ell^+\ell^- + p_T^{\text{miss}}$, 35.9 fb$^{-1}$)
- Additional operator yields no significant modification

Re scaling: see 1910.11418 (Araz, Frank, Fuks)