Recasting the scotogenic FIMP

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mostly based on
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FIMP: Non-thermal dark matter candidate

- FIMP: feebly interacting massive particle
- interaction strength $\ll$ weak interaction strength
- FIMP is never in thermal equilibrium in the early universe
- produced by freeze-in

popularized by Hall, Jedamzik, March-Russell, West 2009
earlier candidates: keV sterile neutrino

Why should FIMP be connected to long-lived particles?

Thermal equilibrium and the LHC

- in order to avoid thermalization the interaction rate has to be small compared to the Hubble rate

$$\Gamma_\phi \lesssim H$$

- if taken as decay rate of a heavy particle ϕ

$$y \lesssim 20\sqrt{\frac{T_{max}^2}{m_\phi M_{Pl}}} \approx 10^{-8}\,\frac{m_\phi}{100\text{ GeV}}$$

$$c\tau \gtrsim \frac{1}{H} \approx \frac{M_{Pl}}{\sqrt{g_*}m_\phi^2} \approx 100\left(\frac{\text{GeV}^2}{m_\phi^2}\right)\text{m}$$

- no thermal equilibrium indicates long-lived particles

Schematic FIMP production

- SM $+ \chi$ (FIMP) $+ \phi$ (heavy new particle)
- decay $\phi \to \chi +$ ...
- ϕ is in thermal equilibrium with SM plasma
- χ is not in thermal equilibrium
- production described by Boltzmann equation for $Y = \frac{n_\chi}{s}$

$$\frac{dY_\chi}{dx_\phi} = \frac{1}{3H} \frac{ds}{dx_\phi} \left[-\frac{\Gamma}{s} Y_\phi + ... \right]$$

- either solve Boltzmann equation numerically
- or analytic approximation if number of degrees of freedom approximately constant

$$Y_\chi \approx \frac{135 g_\phi}{8\pi^3 (1.66) g_*^s \sqrt{g_*^\rho}} \frac{M_{Pl}\Gamma}{m_\phi^2}$$

Hall, Jedamzik, March-Russell, West 2009

What is the phenomenology?

Scotogenic Model

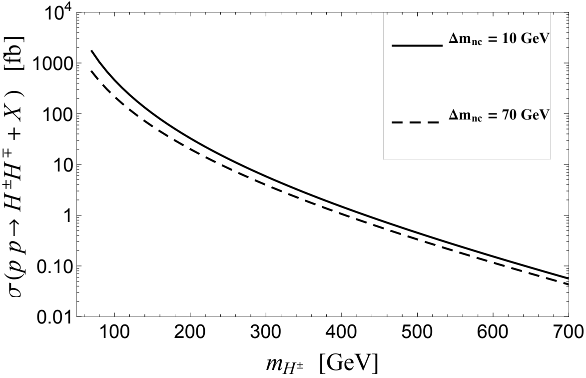
- model for radiative neutrino masses and dark matter Ma 2006
- content: 3 Majorana fermions N_i, one scalar doublets H_2, one Z_2 symmetry
- all new particles odd under Z_2
  $\rightarrow$ lightest Z_2 odd particle stable DM candidate

$$
\begin{aligned}
\mathcal{L}_{\text{int}} = & \lambda_3 \, (H_1^\dagger H_1)\,(H_2^\dagger H_2) + \lambda_4 \, (H_1^\dagger H_2)\,(H_2^\dagger H_1) + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + \text{h.c.}\right] \\
& + \left[Y^\nu_{\alpha i} \, (\overline{\nu}_{\alpha L} H_2^0 - \overline{\ell}_{\alpha L} H^+)\, N_i + \text{h.c.}\right] \\
& + \text{gauge interactions}
\end{aligned}
$$

- N_1 FIMP candidate with

$$
\Omega_{N_1} h^2 \approx 0.12 \frac{M_{N_1}}{10\ \text{keV}} \frac{100\ \text{GeV}}{m_S} \left(\frac{y_1}{2 \cdot 10^{-9}} \right)^2
$$

LHC production rates



- scalars produced by Drell-Yan process and through Higgs portal
- fermions have small ($N_{2/3}$) or very small couplings (N_1) $\rightarrow$ fermion production is negligible

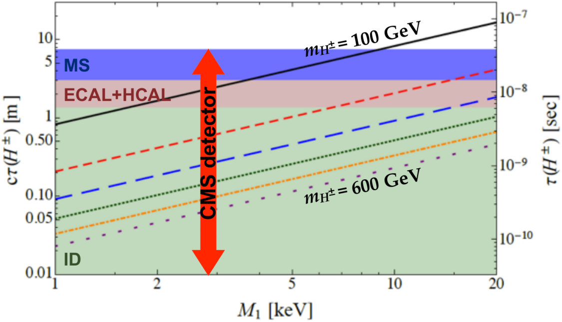
LHC signatures, searches and reinterpretation

Signatures

Signatures depend on open decays, i.e. mass spectrum

- $m_{N_1} < m_{H,A} < m_{N_{2/3}}, m_H^+$
  - H, A long-lived
  - decay $H \to N_1 \nu$ invisible
- some cases do not give us detectable long-lived particles

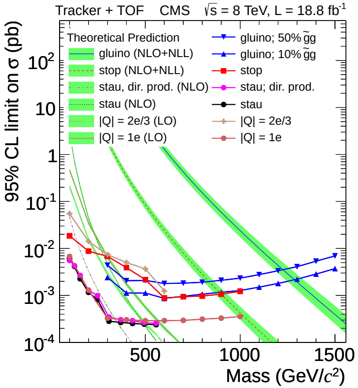
Long-lived charged particles: $m_{N_1} < m_{H^+} < m_{N_{2/3}}, m_H, m_A$



- freeze-in fixed coupling/lifetime as function of masses $\rightarrow H^\pm$ long-lived

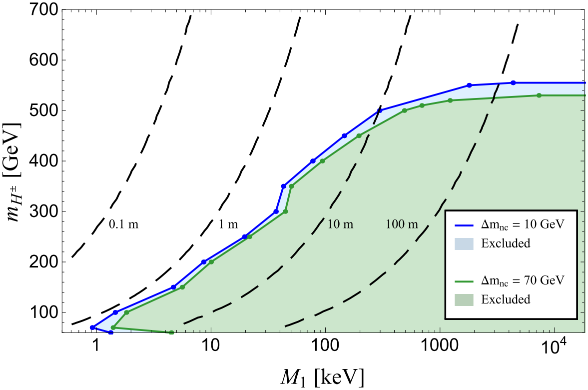
$$c\tau \approx 8.3m \left(\frac{M_{N_1}}{10\text{ keV}}\right)\left(\frac{100\text{ GeV}}{m_{H^\pm}}\right)^2$$

Long-lived particle search at CMS



- CMS/ATLAS can search for stable massive long-lived particles with time of flight analysis and search for anomalous energy loss in tracker figure from CMS [1305.0491]

Recast of long-lived particle search



- search efficiency depends on production mode (angular dependence/ boost factors etc.) and decay length
- CMS provides tabulated efficiencies in η, γ 1502.02522
- lazy phenomenologists dream recast, excellent job by experimentalist

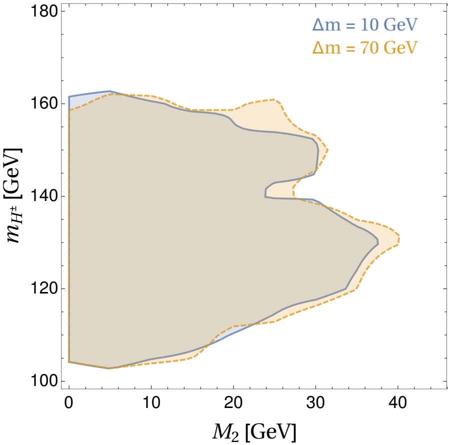
Prompt decays: $m_{N_1} < m_{N_2} < m_{m_{H^\pm}}, m_H, m_A$

- $y_1 \ll y_2 \Rightarrow$ all scalars decay to N_2
- neutrino masses constrain N_2 Yukawa: $10^{-5} < y_2 < 10^{-2}$
- typical decay length less than mm $\rightarrow$ prompt decay
- decay $N_2 \rightarrow l \bar{l} N_1$ suppressed by very small FIMP coupling, smallish y_2 and three-body phase space

$$c\tau(N_2) \approx 2 \times 10^{13}\,\mathrm{m} \left(\frac{M_1}{10\ \mathrm{keV}}\right) \left(\frac{m_H}{500\ \mathrm{GeV}}\right)^3 \left(\frac{100\ \mathrm{GeV}}{M_2}\right)^5 \left(\frac{10^{-3}}{y_2}\right)^2$$

- N_2 stable in detector $\Rightarrow$ missing energy
- standard signature: leptons + MET

Recast SUSY searches



- SUSY search for leptons + MET (electroweak slepton production) ATLAS 1403.5294
- excellent recasting tools available (here: CheckMATE)
- low sensitivity: $m_{H^\pm} \gtrsim 160$ GeV is fine

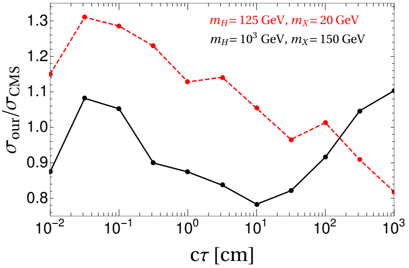
$m_{N_1} < m_{N_2} < m_{N_3} < m_{m_{H^\pm}}, m_H, m_A$

- N_2 still stable on detector scales
- N_3 potentially long-lived
- $N_3 \to l^+ l^- N_1$ i.e. displace dileptons

$$c\tau(N_3) \approx 0.4\,\text{m} \left(\frac{100\text{ GeV}}{M_3}\right) \left(\frac{m_H}{M_3}\right)^4 \left(\frac{10^{-3}}{y_2}\right)^2 \left(\frac{10^{-3}}{y_3}\right)^2$$

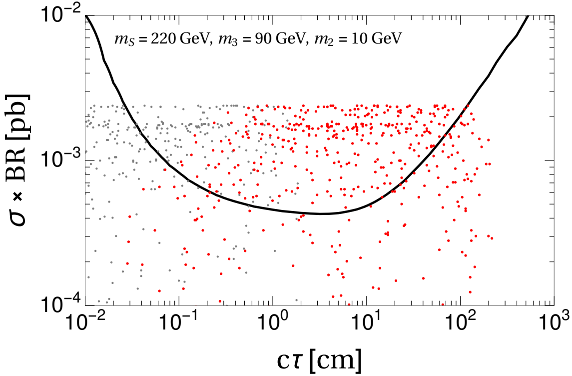
- life-time and branching ratios set by Yukawa couplings of N_2 and N_3
  $\to$ connection to radiative neutrino masses

Do it yourself reinterpretation



- recast CMS search for displaced dileptons 1411.6977
- use publicly available data on tracker performance to estimate detection efficiency
- validate by comparison with experimental search
  $\rightarrow$ difference $\lesssim 30\%$
- comment: lepton flavor violation in long-lived searches

Testing neutrino mass generation



- branching ratio into testable final states depends on details of neutrino mass generation
- decay length forced into testable range by neutrino masses and $\mu \to e\gamma$ limits
- bulk of model space testable but cancellations and or hierarchical Yukawa couplings possible

Conclusion

- FIMPs point towards particles with long-lifetime
- rich phenomenology at LHC
- reinterpretation of LHC searches varies
- excellent tools and experimental help available
- not everything covered yet