A long-lived stop as a signature of a hidden sector freeze-in dark matter

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This talk is based on

1. Amin Aboubrahimb, Wan-Zhe Feng and Pran Nath, arXiv:1910.14092 [hep-ph].

2. Amin Aboubrahimb, Wan-Zhe Feng and Pran Nath, arXiv:1912.xxXxx [hep-ph].

Overview

Puzzles of dark matter

Dark matter is an unidentified type of matter comprising approximately 27% of the mass and energy in the observable Universe. There are various puzzles:

- What is dark matter? Gravitational effect or particle?
- Why the amount of dark matter and visible matter are of the same order?
- How dark matter connects with the Standard Model?

Dark matter

- The astrophysical evidence for the presence of dark matter points to the existence of new physics beyond the Standard Model (SM).
- The dark matter can be realized in a hidden sector. A hidden sector is referred to the sector that contains not yet discovered particles which do not interact directly via strong and electroweak gauge bosons. Hidden sectors usually include gauge groups independent from the SM gauge groups.
- In the R-parity conserving minimal supersymmetric standard model (MSSM) the decay chain always ends up with the LSP along with standard model particles, and thus the LSP is naturally the dark matter candidate.

SUSY signatures

- Sadly, there is no signal for supersymmetry. LHC has analyzed up to 139 fb^{-1} of data for each of ATLAS and CMS and the results are consistent with the SM.
- Traditional SUSY signals, such as final states with large missing energy due to a neutralino as the LSP, hard jets arising from the decay of squarks and gluinos, or high momentum leptons coming from the decay of electroweak gauginos are now significantly more constrained.
- Constraints are less severe for more rare processes because of their small production cross-sections.
- Another search which is still not highly constrained is long-lived particles.

Long-lived particles

- If the particle is charged and stable over detector length it can be identified by the track it leaves in the inner tracker and in the muon spectrometer. Other signatures are possible such as a disappearing track where a charged particle can decay into very soft final states which escape the trigger threshold.
- ATLAS and CMS were not designed to look for long-lived particles and part of the upcoming upgrade is to further their capabilities to become more sensitive to such searches.
- Most long-lived particle searches at the LHC consider an NLSP very close in mass to the LSP ($\Delta m \sim$ few GeV down to MeV) resulting in a highly suppressed phase space. This leads to a small decay width for the NLSP and thus a long-lived particle.
- Long-lived particles can also arise in SUSY models with a hidden sector if the hidden sector has ultraweak interactions with the visible sector and the LSP of the visible sector decays into the hidden sector.

Issues of neutralino dark matter

- The measured value of the Higgs boson mass at 125 GeV indicates the size of weak scale supersymmetry lies in the TeV region.
- Direct detection of stop and gluino at the LHC also point to a SUSY breaking scale in the multi-TeV regime.
- Meanwhile, direct searches for relic WIMP dark matter by LUX PandaX failed to detect the SUSY WIMP.
- Indirect WIMP searches from Fermi-LAT (expecting to detect WIMP annihilation to gamma rays) also place strong limits on SUSY WIMPs.

Under such conditions, the LSP is expected to be a mainly higgsino-like neutralino with non-negligible gaugino components (required by naturalness). The computed thermal WIMP abundance in natural SUSY models is then found to be typically a factor 5-20 below its measured value [Baer Barger Sengupta Tata, 2018].

Solution

- Models where the WIMP relic density (taken to be its thermal value) forms just $\sim 5 - 20\%$ of the measured CDM density survive the combined constraints from LHC as well as from direct and indirect searches.
- To gain concordance with observations, either an additional DM particle (e.g., the axion is a well-motivated possibility) must be present or additional non-thermal mechanisms must augment the neutralino abundance.

Freeze-in dark matter

- The feebly interacting massive particle (FIMP) as dark matter candidate can be created by the ultraweak renormaizable interaction [Hall Jedamzik March-Russell West, 2009].
- These particles never achieved thermal equilibrium in the thermal bath.
- Although the interactions are feeble they still lead to some FIMP production.
- Dominant production of FIMP occurs at $T \sim M_{\text{FIMP}}$.
- Increasing the interaction strength increases the dark matter number density, opposite to the freeze-out case.

Possible experimental signatures

- Long lived LOSP (lightest observable supersymmetric particle) at the LHC.
- Signals for BBN: LOSP decaying late could have implication for BBN.
- Enhanced indirect and direct detection: Relic abundance and DM annihilation cross section no longer related. Freeze-in dominantly produces DM abundance annihilation cross section can be large.

The Boltzmann equation

For the reaction $X \leftrightarrows Y + \xi$ where both X and Y are in the thermal bath and ξ is the dark matter particle, the Boltzmann equation for the number density of ξ reads

$$\dot{n}_\xi + 3Hn_\xi = \int \mathrm{d}\Pi_\xi \mathrm{d}\Pi_X \mathrm{d}\Pi_Y (2\pi)^4 \delta^4(p_X - p_Y - p_\xi) \times \left[|\overline{\mathcal{M}}|^2_{X\to Y+\xi} f_X(1 \pm f_Y)(1 \pm f_\xi) - |\overline{\mathcal{M}}|^2_{Y+\xi\to X} f_Y f_\xi (1 \pm f_X) \right] ,$$

where $\mathrm{d}\Pi_i = \frac{\mathrm{d}^3 p_i}{(2\pi)^3 2E_i}$ are phase space elements, f_i is the phase space density defined by

$$f_i = \frac{1}{\exp(E_i - \mu_{c_i})/T \pm 1} ,$$

where the plus sign is for bosons and minus for fermions. Using the assumption the initial ξ abundance is zero, i.e., $f_\xi = 0$, the term corresponding to $Y + \xi \to X$ vanishes.

Freeze-in dark matter relic density

The decay width of the process $X \to Y + \xi$ is given by

$$\Gamma_X = \frac{1}{2m_X}\left(\prod_i \frac{\mathrm{d}^3 p_i}{(2\pi)^3}\frac{1}{2E_i}\right)|\mathcal{M}|^2_{X\to Y+\xi}(2\pi)^4\delta^4(p_X - p_Y - p_\xi)\,,$$

one then arrives further assuming $f_Y \to 0$

$$\dot{n}_\xi + 3Hn_\xi = \frac{m_X^2 g_X \Gamma_X}{2\pi^2} T K_1(x_X),$$

where $K_1(x_X) = \int \mathrm{d}u\ x_X(u^2-1)^{1/2}e^{-ux_X}$ is the Bessel function of the second kind and degree one. Using the conservation of entropy per comoving volume ($sR^3 = \text{const}$), one has $\dot{n}_X + 3Hn_X = s\dot{Y}_X$, where $Y_X \equiv n_X/s$ the number density of X per comoving volume. Finally one reaches

$$Y_X \approx \int_{T_{\min}}^{T_{\max}} \frac{g_X m_X^2 \Gamma_X}{2\pi^2 sH} K_1\left(\frac{m_X}{T}\right)\mathrm{d}T\,.$$

micrOMEGAs5.0

Finally by using

$$\Omega h^2 = mYs_0h^2/\rho_c$$

we calculate the Freeze-in (FI) contribution to the relic density, $(\Omega h^2)_{\mathrm{FI}}$, where s_0 is today's entropy density, ρ_c is the critical density and $h = 0.678$.

MicrOMEGAs5.0 does a more general calculation numerically by keeping the contribution from the phase space density f_i's. Though the numerical results differ from the simplified results by less then 5%.

The Model

- In this work we discuss an MSSM/SUGRA model extended by an extra $U(1)_X$ gauge group with a gauge kinetic mixing [Holdom 1985] and Stueckelberg mass mixing [Kors and Nath 2005] between the $U(1)_X$ and the SM hypercharge $U(1)_Y$.
- The model contains additional chiral scalar superfields S and $\bar{S}$ and a vector superfield C. The fermionic component of S and $\bar{S}$ and the gaugino components of C mix with the MSSM neutralino fields producing a 6×6 neutralino mass matrix. The input mass hierarchy of the neutralino sector allows us to have the hidden neutralino as the real LSP of our model.
- The decay of the NLSP and any other heavier MSSM field into the hidden sector LSP is highly suppressed by the mixing parameters, and the LSP will be produced out of equilibrium in the early universe.

The dark neutralino

We label the mass eigenstates as

$$\tilde{\xi}_1^0,\ \tilde{\xi}_2^0;\ \tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0\,.$$

Since the mixing parameter δ is very small, the first two neutralinos $\tilde{\xi}_1^0$ and $\tilde{\xi}_2^0$ reside mostly in the hidden sector while the remaining four $\tilde{\chi}_i^0$ $(i = 1 \cdots 4)$ reside mostly in the MSSM sector.

For the case when the lighter hidden neutralino $\tilde{\xi}_1^0$ is the least massive of all sparticles in the $U(1)_X$-extended SUGRA model, $\tilde{\xi}_1^0$ is the real LSP and thus the dark matter candidate.

Neutral gauge bosons

- For the charge-neutral gauge vector boson sector, the 2×2 mass-squared matrix of the standard model is enlarged to become a 3×3 mass-squared matrix in the $U(1)_X$-extended SUGRA model.
- After spontaneous electroweak symmetry breaking and the Stueckelberg mass growth the 3×3 mass-squared matrix of neutral vector bosons in the basis (A^3_μ, B_μ, C_μ). After diagonalization of the 3×3 mass-squared matrix, one then arrives the physical mass eigenbasis (γ, Z, Z').

The sources for relic density

- For MSSM coupled to the hidden sector by ultraweak interactions, the LSP relic density cannot be satisfied by the usual freeze-out mechanism. Indeed, its freeze-out (FO) relic density arising from its pair annihilation would be negligible because of the ultraweak coupling.
- Yet the observed relic density can be achieved by a combination of the freeze-in and freeze-out mechanisms.
- Here the freeze-out contribution arises from the decay of the NLSP (in our case, stop) after it freezes out. Despite the tiny decay widths of all heavier MSSM sparticles into the LSP, this decay will eventually happen over a period of time thus producing the desired contribution to the dark matter relic abundance.

Freeze-in contribution

- We assume hidden sector particles having negligible abundance in the early universe.
- Since the lighter hidden neutralino $\tilde{\xi}_1^0$ is the lightest particle in the thermal bath, all the heavier R-parity odd particles, though ultraweakly coupled to $\tilde{\xi}_1^0$, will eventually decay into it.
- This implies that the abundance of $\tilde{\xi}_1^0$ will rise as the temperature T drops until the decaying particles run out leading to a saturation in the abundance of $\tilde{\xi}_1^0$.
- As a general feature of freeze-in dark matter, for a decaying particle of mass M the dominant production of $\tilde{\xi}_1^0$ occurs at $T \sim M$.
- In summary the freeze-in contribution is given by

$$(\Omega h^2)_{\rm FI} = \sum_{\text{all heavy sparticles}} (\Omega h^2)_{\rm FI}\,.$$

Freeze-out contribution

The second contribution to the relic density is due to the freeze-out process from the NLSP, i.e., stop. Once out of equilibrium, the stops then decay to $\tilde{\xi}_1^0$ to make up the FO portion of the relic density. Using the standard FO considerations, one can determine the relic density of the stops, $(\Omega h^2)_{\rm FO}^{\tilde{t}}$, and thus the freeze-out contribution of $\tilde{\xi}_1^0$ relic density is given by

$$(\Omega h^2)_{\rm FO} = \frac{m_{\tilde{\xi}_1^0}}{m_{\tilde{t}}}(\Omega h^2)_{\rm FO}^{\tilde{t}}\,.$$

Hence the total relic density is given by

$$\Omega h^2 = (\Omega h^2)_{\rm FO} + (\Omega h^2)_{\rm FI} = 0.1198 \pm 0.0012,\ .$$

as measured by the Planck experiment.

Benchmark models

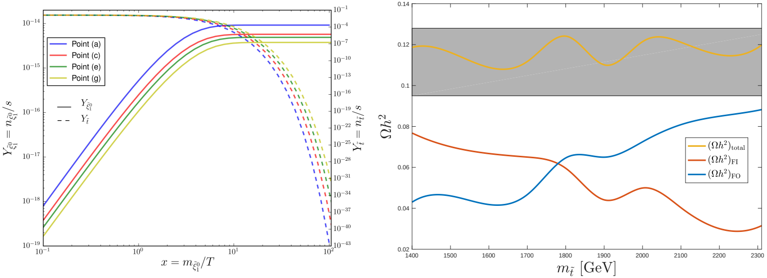
The input parameters of the $U(1)_X$-extended non-universal SUGRA model with parameters as below (at the GUT scale)

$$m_0,\quad A_0,\quad m_1,\quad m_2,\quad m_3,\quad M_1,\quad M_{XY},\quad \delta,\quad \tan\beta,\quad \text{sgn}(\mu).$$

where $m_0,\ A_0,\ m_1,\ m_2,\ m_3,\ \tan\beta$ and $\text{sgn}(\mu)$ are the soft parameters in the MSSM sector, and M_1 and M_{XY} are hidden sector mass parameters. We select ten benchmarks satisfying all the previous constraints and are displayed in the following Table

Model	h^0	μ	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\xi}_1^0$	$\tilde{t}$	$\tilde{g}$	$(\Omega h^2)_{\text{FO}}$	$(\Omega h^2)_{\text{FI}}$	Ωh^2	τ_0
(a)	124.2	3122	1416	1759	1129	1409	3218	0.044	0.076	0.119	0.79
(b)	125.5	3168	1529	2218	1223	1502	2709	0.046	0.070	0.116	0.81
(c)	124.4	2324	1678	1727	1355	1618	2821	0.038	0.089	0.127	0.97
(d)	125.6	3665	1907	2587	1314	1702	2817	0.047	0.065	0.112	0.43
(e)	125.5	3556	1836	2310	1484	1804	3737	0.065	0.059	0.124	0.91
(f)	125.4	2763	2085	2773	1525	1903	2575	0.065	0.044	0.110	0.84
(g)	125.8	2900	2254	2737	1649	2005	3224	0.073	0.050	0.122	0.96
(h)	125.6	3513	3461	3519	1722	2102	3284	0.081	0.040	0.121	0.92
(i)	126.8	3444	2316	3465	1673	2201	3033	0.085	0.030	0.115	0.66
(j)	123.7	4454	3034	4360	1742	2304	3460	0.088	0.031	0.119	0.55

Relic density



Left panel: a plot of the comoving number density $Y_{\tilde{\xi}_1^0}$ and $Y_{\tilde{t}}$ versus $x \equiv m_{\tilde{\xi}_1^0}/T$ for four illustrative benchmarks (a), (c), (e) and (g) for the freeze-in situation. Right panel: A plot of the relic density versus the stop mass for all the benchmark models. The FI and FO contributions are shown along with their sum which lies inside the grey patch shows the allowed region of the relic density taking theoretical uncertainties into account.

Two subtle points

- The lifetime of the NLSP, i.e., stop in our model is about $\mathcal{O}(0.1)$ second, and thus in our model stops would decay after BBN. Models with NLSP having smaller lifetime might upset the BBN bound.
- For the calculation of freeze-in dark matter relic density from heavier sparticles

$$Y_X \approx \int_{T_{\min}}^{T_{\max}} \frac{g_X m_X^2 \Gamma_X}{2\pi^2 s H} K_1 \left(\frac{m_X}{T}\right) \mathrm{d}T \,.$$

$T_{\min}$ value should be $T_{\text{freeze out}}$ rather than the current temperature of our Universe.

Stop R-hardrons as the collider signature

- Long-lived stops (with a decay width $\lesssim 0.2$ GeV) immediately hadronize forming color-neutral R-hadrons, $R_{\tilde{t}}$, which can be thought of as a stop surrounded by a “cloud” of light quarks. Around 93% of $R_{\tilde{t}}$ formed are R-mesons $\tilde{t}\bar{q}$ and the rest are R-baryons $\tilde{t}qq$.
- Then most of the $R_{\tilde{t}}$ transform from mesons to baryons. This transition leads to charge flipping where an R-hadron can go from being electrically charged to neutral and vice-versa.
- On the average, almost half of the R-hadrons end up flipping sign [Hohansen, 2006] as they travel the detector length and will therefore, leave a track in the inner detector tracker (ID) and in the muon spectrometer (MS).
- Due to the charge flipping property, tracks may suddenly disappear or appear which is a feature used by experimental collaborations to look for R-hadrons.

Stop R-hardrons as the collider signature

- In summary, a long-lived stop hadronizes into an R-hadron made up of the stop parton surrounded by light standard model quarks. The R-hadron is color neutral but electrically charged and can be identified by the track it leaves in the detector. It is characterized by its large transverse momentum and slow speed β_s.
- In our analysis we focused on information from the tracker and we showed that half of the benchmarks corresponding to a stop in the mass range 1.4 TeV to 1.8 TeV can be discovered at HL-LHC while all the benchmarks are discoverable at HE-LHC. At HL-LHC, an integrated luminosity $\sim 230\,\mathrm{fb}^{-1}$ is needed to discover a 1.4 TeV stop which is right around the corner once the LHC is back to collecting more data.

Conclusion

1. The SUSY WIMP is highly constrained by the combined results from LHC as well as from direct and indirect searches.
2. The ultraweak interactions generated freeze-in dark matter allow us to reconstruct the MSSM spectrum, and gives us more choices for the parameter space: more papers to come.
3. For example, we could have a long-lived stop with life time of order 0.1-1 sec as the LSP in the "visible sector", which will have very distinct experimental signatures.
4. The real LSP is the dark neutralino from the hidden sector and is the dark matter candidate.

Thank You!