Dark Matter: Thermal Versus Non-thermal

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Outline

Thermal and Non-thermal Dark Matter (DM)

Moduli Decay and DM

Baryogenesis from the Decay of Moduli

Necessary Conditions for Successful Models

Example of a moduli model

Dark Radiation (DR) and DM correlation

Example of visible sector model

Non-Thermal Scenarios at the LHC and Direct Detection Expt.

Conclusion
Questions

Important questions:

What is the origin of dark matter?

How does it explain the dark matter content?

Is there any correlation between baryon and dark matter abundance?

Consequences for:

- Particle Physics Models
- Thermal History of the Universe
Dark Matter: Thermal

Production of thermal non-relativistic DM:

\[ DM + DM \Leftrightarrow f + \bar{f} \]

Universe cools

\[ DM + DM \Rightarrow f + \bar{f} \]

\[ DM + DM \nleftrightarrow f + \bar{f} \]

Boltzmann equation

\[
\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle_{eq} [n^2_{DM} - n^2_{DM,eq}]
\]

\[
\langle \sigma v \rangle_{eq} = \frac{\int d^3 p_1 d^3 p_2 \sigma \rho v e^{-(E_1 + E_2)/T}}{(2\pi)^6}
\]

\[
Y = \frac{n}{s} = \frac{n}{g_* s T^3}
\]

\[
m/T
\]

\[
n = g \int \frac{d^3 p f (\vec{p}, t)}{(2\pi)^3} \equiv \text{nos. / vol}
\]
Dark Matter: Thermal

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

$$\Omega_{\text{DM}} = \frac{m_{\text{DM}} n_{\text{DM}}}{\rho_c} \sim \frac{1}{\langle \sigma \nu \rangle}$$

$$\rho_c = \frac{3H_0^2}{8\pi G_N}$$

freeze out \(\Rightarrow\) \(T_f \sim \frac{m_{\text{DM}}}{20}\)

\(\Rightarrow\) \(\langle \sigma \nu \rangle = 3 \times 10^{-26} \text{ cm}^3\)\text{s}^{-1}

Assuming: \(\langle \sigma \nu \rangle_f \sim \frac{s}{\alpha_{\chi}^2} \frac{\sigma}{m_{\chi}^2}\)

\(\alpha_{\chi} \sim \mathcal{O}(10^{-2})\) with \(m_{\chi} \sim \mathcal{O}(100)\) GeV

leads to the correct relic abundance

\[Y \text{ becomes constant for } T > T_f\]
Thermal Dark Matter

Dark Matter content: \[ \Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle} \]

\[ \langle \sigma v \rangle_f \sim \frac{\alpha^2}{m^2} \]

freeze out \[ T_f \sim \frac{m_{\text{DM}}}{20} \]

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s} \]

Weak scale physics:
\[ \alpha_\chi \sim O(10^{-2}) \text{ with } m_\chi \sim O(100) \text{ GeV} \] leads to the correct relic abundance
Suitable DM Candidate: Weakly Interacting Massive Particle (WIMP)

Typical in Physics beyond the SM (LSP, LKP, …)

Most Common: Neutralino (SUSY Models)

Neutralino: Mixture of Wino, Higgsino and Bino

Larger/Smaller Annihilation  ➔ Problem for thermal scenario
Status of Thermal DM

Experimental constraints: $<\sigma_{\text{ann}}\nu>$

Gamma-rays constraints:
Dwarf spheroidals, Galactic center

Thermal DM $\rightarrow$ 27%

Large Cross-section is constrained

$<\sigma_{\text{ann}}\nu>_o$ : smaller than the thermal value

Geringer-Sameth, Koushiappas’11, Hooper, Kelso, Queiroz, Astropart.Phys. ‘13
Latest result from Planck

Dark Matter Pair Annihilation

Dark matter annihilation cross-section:

\[ \langle \sigma v \rangle = a + b \cdot v^2 \]

a, b are constants

If S wave is suppressed then the cross-section is dominated by P wave \(\Rightarrow b \cdot v^2 \gg a\)

\(\Rightarrow \langle \sigma v \rangle\) is much smaller today compared to the freeze-out time

Thermal Relic Density:
At freeze-out, \(\langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3/\text{s}\)

- High b/a lowers the cross-section at small v (Present Epoch)
- For S wave domination, cross-section remains same (constant)
- Annihilation cross-section can be larger today compared to the Freeze-out time due to Sommerfeld enhancement
LHC Constraints and Status of DM

LHC constraints on first generation squark mass + Higgs mass:

**Natural SUSY and dark matter** [Baer, Barger, Huang, Mickelson, Mustafayev and Tata’12; Gogoladze, Nasir, Shafi’12, Hall, Pinner, Ruderman,’11; Papucchi, Ruderman, Weiler’11],

**Higgs mass 125 GeV & Cosmological gravitino solution** [Allahverdi, Dutta, Sinha’12]

- **Higgsino dark matter**
  
  Higgsino dark matter has larger annihilation cross-section
  
  Typically > $3 \times 10^{-26}$ cm$^3$/sec for sub-TeV mass

- **Thermal underproduction of sub-TeV Higgsino**

- **Unnatural SUSY: Wino DM**
  
  Larger annihilation cross-section
  
  Arkani-Hamid, Gupta, Kaplan, Weiner, Zorawsky’12 (for smaller wino mass)
Recent Higgs search results from Atlas and CMS indicate that $m_h \sim 126$ GeV → in the tight MSSM window <135 GeV

$m_{\tilde{q}}$ (1st gen.) $\sim m_{\tilde{g}} \geq 1.7$ TeV

For heavy $m_{\tilde{q}}$, $m_{\tilde{g}} \geq 1.3$ TeV

$\tilde{t}_1$ produced from $\tilde{g}$, $m_{\tilde{t}_1} \geq 700$ GeV

$\tilde{t}_1$ produced directly, $m_{\tilde{t}_1} \geq 660$ GeV (special case)

$\tilde{e}/\tilde{\mu}$ excluded between 110 and 280 GeV for a mass-less $\tilde{\chi}_1^0$ or for a mass difference >100 GeV, small $\Delta M$ is associated with small missing energy → Can lead to over production of relic abundance

$\tilde{\chi}_1^\pm$ masses between 100 and 600 GeV are excluded for mass-less $\tilde{\chi}_1^0$ for $\tilde{\chi}_1^\pm$ or for the mass difference >50 GeV decaying into e/μ → Can lead to over production of relic abundance
Thermal equilibrium above $T_f$ is an assumption.

Non-standard thermal history at $T < T_f$ is generic in some explicit UV completions of the SM.

Acharya, Kumar, Bobkov, Kane, Shao’08
Acharya, Kane, Watson, Kumar’09
Allahverdi, Cicoli, Dutta, Sinha,’13

DM content will be different in non-standard thermal histories (i.e., if there is entropy production at $T < T_f$).

Barrow’82, Kamionkowski, Turner’90

DM will be a strong probe of the thermal history after it is discovered and a model is established.
Thermal, Non-thermal

\[ \langle \sigma_{\text{ann}} v \rangle : \text{Large} \rightarrow \text{multicomponent/non-thermal}; \]
Small \rightarrow \text{Non-thermal}

➢ LHC: Investigate colorless particles, establish the model

➢ DM annihilation from galaxy, extragalactic sources

  Annihilation into photons: Fermi, HAWC, H.E.S.S.

  Annihilation into neutrinos: IceCube

  Annihilation into electron-positrons: AMS
Beyond Thermal DM

Obtaining correct relic density for \( <\sigma_{\text{ann}}v>_f \neq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \):

1) (thermal underproduction): \( <\sigma_{\text{ann}}v>_f > 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \)

   *Baer, Box, Summy’09*

Multi-component DM (WIMP + non-WIMP)
Example: mixed Higgsino/axion DM

Asymmetric DM (DM content can have large \( <\sigma_{\text{ann}}v>_f \) )

*Zurek’13*

2) (thermal overproduction): \( <\sigma_{\text{ann}}v>_f < 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \)

DM from WIMP decay
Ex: Axino DM,

Gravitino DM

*Covi, Kim, Roszkowski ‘99*

Feng, Rajaraman, Takayama’03
Non-Thermal DM

Dark Matter from Moduli decay:

Moduli are heavy scalar fields that acquire mass after SUSY breaking and are gravitationally coupled to matter

The moduli decay width: \[ \Gamma_\phi = \frac{c}{2\pi} \frac{m_\phi^3}{M_p^2} \]

- start oscillating when \( H < m_\tau \)
- dominate the Universe before decaying and reheating it

\[ T_r \sim c^{1/2} \left( \frac{m_\phi}{M_p} \right)^{1/2} m_\phi \quad T_r > T_{BBN} \approx 3 \text{ MeV} \]

\[ \Rightarrow m_\phi > 50 \text{ TeV} \]

For \( T_r < T_f \): Non-thermal dark matter

Abundance of decay products \[ Y_\phi \equiv \frac{3T_r}{4m_\phi} \]

e.g., Moroi, Randall’99; Acharya, Kane, Watson’08, Randall; Kitano, Murayama, Ratz’08; Dutta, Leblond, Sinha’09; Allahverdi, Cicoli, Dutta, Sinha,’13
Dark Matter from Moduli

DM abundance \( \frac{n_{DM}}{s} = \min \left[ \left( \frac{n_{DM}}{s} \right)_{obs} \right] \quad \left( \frac{\langle \sigma v \rangle^{Th}_{f}}{\langle \sigma v \rangle_{f}} \right) \frac{T_{f}}{T_{r}}, \phi, Br_{\phi \rightarrow DM} \)  

1. First term on the RHS is the “annihilation scenario”

Requirements: \( \langle \sigma_{ann} v \rangle_{f} = \langle \sigma_{ann} v \rangle^{th}_{f} \frac{T_{f}}{T_{r}} \)

Since \( T_{r} < T_{f} \), we need \( \langle \sigma_{ann} v \rangle_{f} > \langle \sigma_{ann} v \rangle^{th}_{f} \)

\( \Rightarrow \) wino/Higgsino DM

Gamma-rays constraints: Dwarf spheroidals, Galactic center \( \Rightarrow M_{DM} > 40 \) GeV, \( T_{f} < 30 \) \( T_{r} \Rightarrow T_{r} > 70 \) MeV

2. Second term on the RHS is the “branching scenario”

Can accommodate large and small annihilation cross-sections

Bino/Wino/Higgsino are all ok

\( Y_{\phi} \) is small to prevent the \( Br_{\phi \rightarrow DM} \) from becoming too small

(actually in realistic scenarios: \( Br \geq 5 \times 10^{-3} \Rightarrow T_{r} < 70 \) MeV)

(for \( m_{\phi} \sim 5 \times 10^6 \) GeV)
Dark Matter from Moduli

φ Decays dilutes any previous relics

- Thermal DM gets diluted if $T_r < T_f \sim m_{DM}/20 \sim O(10)$ GeV
- Axionic DM gets diluted if $T_r < \Lambda_{QCD} \sim 200$ MeV
  ($f_a \sim 10^{14}$ GeV is allowed for $T_r \geq T_{BBN}$) [Fox, Pierce, Thomas’04]
- Baryon asymmetry gets diluted if produced before φ decay

Non-thermal DM Production from φ decay

- Annihilation scenario for $T_r$ close to $T_f$
  - DM production with large cross-section: Wino/Higgsino
- Branching scenario for smaller $T_r$
  (annihilation cross-section does not matter)

Baryon asymmetry from φ decay ⇒ Cladogenesis of DM and Baryogenesis [Allaverdi, Dutta, Sinha’11]
“Branching scenario” solves the coincidence problem

Baryon abundance in this model: \[ \frac{n_B}{s} = Y_\phi \varepsilon Br_{\phi \rightarrow B} \]

\( Y_\phi \) appears in the DM abundance as well, \( Y_\phi \sim 10^{-7} - 10^{-9} \)

\( \varepsilon Br_{\phi \rightarrow B} \sim 10^{-1} - 10^{-3} \) easy to satisfy for baryogenesis,

\( \varepsilon \) (one loop factor) \( \sim 10^{-1} - 10^{-2} \)

\[
\frac{\Omega_b}{\Omega_{DM}} = \frac{1}{m_{DM}} \frac{Y_\phi \varepsilon Br_{\phi \rightarrow B}}{Y_\phi Br_{\phi \rightarrow DM}} = \frac{1}{m_{DM}} \frac{\varepsilon Br_{\phi \rightarrow B}}{Br_{\phi \rightarrow DM}} = \frac{1}{5} \quad \Omega = \frac{\rho}{\rho_c}; \quad \rho = mn
\]

For \( m_{DM} \sim 5 \ m_B \), \( \varepsilon \ BR_{\phi \rightarrow B} \sim BR_{\phi \rightarrow DM} \rightarrow n_B \sim n_{DM} \)

The DM abundance and Baryon asymmetry are mostly saturated by \( Y_\phi \), \( Brs \) contribute the remaining \( \rightarrow \) not much particle physics uncertainty
Baryogenesis from Moduli

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} X^c_{\alpha} N^\beta \bar{u}_i + \lambda_{ij\alpha} d^c_i d^c_j \bar{X}^\alpha + M_{\alpha X} \bar{X}^\alpha + \frac{M^\beta}{2} N^\beta N^\beta \]

\( N \): SM singlet; \( X, \bar{X} \): Color triplet, hypercharge \( \pm 4/3 \)

Baryogenesis from decays of \( X, \bar{X} \) or \( N \)

\( \tilde{N} \): can be the DM candidate: Allahverdi, Dutta, Mohapatra, Sinha’12

\[ \eta_B = \frac{n_b - n_{\bar{b}}}{s} = Y_\phi Br_N \epsilon \]

\( Br_N \): branching ratio of moduli decay to \( N \)

\( \epsilon \): asymmetry factor in the \( N \) decay

\( Y_\phi \sim 10^{-9} - 10^{-7}, \quad \epsilon < 0.1, \quad Br_N \sim 10^{-2} - 1 \Rightarrow \eta_B = 9 \times 10^{-11} \)
Baryogenesis from Moduli

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \bar{X}_\alpha + M_\alpha X_\alpha \bar{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta \]

From X decay

Similarly, \( \varepsilon_2 \)

Typically, \( \varepsilon_{1,2} \) is \( O(10^{-2}) \) for CP violating phase \( O(1) \) and \( \lambda \sim O(1) \)
Conditions for Models

Two typical problems for moduli decay

- **Gravitino Problem:**
  
  [Endo, Hamaguchi, Takahashi’06][Nakamura, Yamaguchi’06]
  
  If \( m_{3/2} < 40 \text{ TeV} \) ➞ Gravitino decays after the BBN
  
  \( m_\phi > 2 m_{3/2} \) can lead to DM overproduction

- **Large branching ratio of moduli into light Axions ➞ \( N_{\text{eff}} \)**
  
  [Cicoli, Conlon, Quevedo’12][Higaki, Takahashi’12]

  \[
  \rho_{\text{rad}} = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\text{eff}} \right)
  \]

  Current bound from Planck+WMAP9+ACT+SPT+BAO+HST

  (at 95% CL) : \( N_{\text{eff}} = 3.52^{+0.48}_{-0.45} \)
Large volume can be obtained after stabilization of $\tau_b \equiv (T_b + \bar{T}_b) / 2$

$$\nu = \tau_b^{3/2} - \tau_{np}^{3/2} - \tau_{vis}^{3/2}$$

Cicoli, Conlon, Quevedo’08

For large volume, one can have a sequestered scenario such that:

$$m_{soft} << m_{\tau_b} << m_{3/2} \quad (m_{soft}m_{3/2} \sim m_{\tau_b}^2)$$

For example, TeV scale SUSY can be obtained for:

$$m_{3/2} \sim 10^{10} \text{ GeV} \quad , \quad m_{\tau_b} \sim 5 \times 10^6 \text{ GeV} \quad , \quad m_{soft} \sim 1 \text{ TeV}$$

Detailed Mass spectra, Aparicio, Cicoli, Krippendorf, Maharana, Quevedo’14

⇒ No Gravitino Problem
The decay to gauge bosons arises at one-loop level:
\[ m_{\tau_b} < m_{3/2} \Rightarrow Br_{3/2} = 0 \]

The decay to Higgs controlled by the Giudice-Masiero term:
\[ \Gamma_{\phi \rightarrow gg} \sim \left( \frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \phi = \sqrt{\frac{3}{2}} \ln(\tau_b) \]

The decay to gauginos (and Higgsinos) is mass suppressed:
\[ \Gamma_{\phi \rightarrow \tilde{g} \tilde{g}} \propto \frac{m_\phi m_{soft}^2}{M_P^2} \Rightarrow Br_\chi << 1 \]

LVS set up can successfully accommodate non-thermal DM.
\[ Y_\phi \text{ can be quite small } \sim 10^{-10} : \text{branching and annihilations are ok} \]

\[ \text{Allahverdi, Cicoli, Dutta, Sinha’13} \]

\[ \text{NT DM in Large Volume Scenarios} \]
If the dominant decay mode is to gauge boson final states
\( \phi \) decays into DM particle via 3-body: \( \phi \rightarrow g\tilde{g}\tilde{g} \)

\[
BR_{\phi \rightarrow DM} \geq 10^{-3}
\]

Since \( \tilde{g} \) produces dark matter at the end of the decay chain

The 3 body decay width larger than the 2-body decay width
of moduli into gauginos
[\( \phi \rightarrow g\tilde{g}\tilde{g} \) is suppressed by \( (m_{\text{gaugino}}/m_\phi)^2 \) compared to \( \phi \rightarrow gg \) ]

\( \Rightarrow Y_\phi \sim 10^{-10} \) (using \( m_\phi \sim 5 \times 10^6 \) GeV)

\( \Rightarrow Y_{DM}: Y_\phi \ BR_{\phi \rightarrow DM} \sim 10^{-12} \Rightarrow m_{DM} \sim O(100) \) GeV is allowed

\( \Rightarrow \) Solves the coincidence problem
DM-DR Correlation in LVS:

The axionic partner of $\tau_b$, denoted by $a_b$ is not eaten up by anomalous U(1)’s.

$a_b$ acquires an exponentially suppressed mass $m_{a_b} \approx 0$

$a_b$ is produced from $\phi$ decay:

$$\Gamma_{\phi \rightarrow a_b a_b} = \frac{1}{48\pi} \frac{m^3_\phi}{M^2_P}$$

Bulk axions are ultra-relativistic and behave as DR.

contribute to the effective number of neutrinos $N_{eff}$:

$$\Gamma_{\phi} = \frac{(c_{vis} + c_{tot})}{48\pi} \frac{m^3_\phi}{M^2_P} \Rightarrow \Delta N_{eff} = \frac{43c_{hid}}{7c_{vis}}$$

(Cicoli, Conlon, Quevedo’13)
Decay to visible sector mainly produces gauge bosons and Higgs:

$$\Gamma_{\phi \to gg} \sim \left( \frac{\alpha_{SM}}{4\pi} \right)^2 \frac{m_{\phi}^3}{M_P^2}$$

$$\Gamma_{\phi \to a_b a_b} \ll \Gamma_{\phi \to g g}$$

$$K \supset \frac{Z H_u H_d}{\tau_b + \bar{\tau}_b} + h.c.$$  $$\Gamma_{\phi \to H_u H_d} = \frac{Z^2}{24 \pi} \frac{m_{\phi}^3}{M_P^2}$$

$$\Gamma_{tot} = \Gamma_{\phi \to H_u H_d} + \Gamma_{\phi \to a_b a_b}$$

**Bound from Planck+WMAP9+ACT+SPT+BAO+HST at 95%**

$$\Delta N_{eff} = 0.48^{+0.48}_{-0.45}$$

$$\Delta N_{eff} < 1 \Rightarrow Z > \sqrt{3}$$

We get a lower bound on $T_r$
Using \[ T_r = \left[ \frac{30}{\pi^2 g_*} \right]^{1/4} \rho_{vis}^{1/4} \]

\[ T_r \approx \frac{1}{\pi} \left( \frac{5 C_{vis} C_{tot}}{288 g_*(T_r)} \right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_P}} \]

\[ \Gamma_{tot} = \frac{C_{tot}}{24 \pi} \frac{m_\phi^3}{M_P^2}, \Gamma_{vis} = \frac{C_{vis}}{24 \pi} \frac{m_\phi^3}{M_P^2} \]

\[ C_{vis} = 2Z^2, C_{tot} = 1 + 2Z^2 \]

\[ O(MeV) \leq T_r \leq O(TeV) \]

\[ \Rightarrow 10.75 \leq g_* \leq 228.75 \]
Abundance of DM particles produced from $\phi$ decay:

$$Y_\phi = \frac{n_\chi}{s} = \frac{3T_r}{4m_\phi} Br_\chi$$ : Branching scenario

$$Z > \sqrt{3}, \ m_\phi \sim 5 \times 10^6 \ GeV \ \Rightarrow \ T_r \geq O(\text{GeV}) \ \Rightarrow \ Y_\phi \geq 10^{-6}$$

$$Br_\chi > 3 \times 10^{-3} \ \Rightarrow \ \frac{n_\chi}{s} > \left(\frac{n_\chi}{s}\right)_{\text{obs}}$$ : Branching scenario does not work

$\Rightarrow$ Small annihilation cross-sections will be hard to accommodate

Avoiding excess of DR within LVS prefers “Annihilation” scenario $\Rightarrow$ Higgsino-type DM.
Obtaining the correct relic density in “Annihilation” scenario needs:

\[ T_r = T_f \left( \frac{3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} \nu \rangle_f} \right) \]

\[ T_f \sim \frac{m_\chi}{20} \]

Assuming S-wave annihilation, which is valid for the Higgsino-type DM, \( \langle \sigma_{\text{ann}} \nu \rangle_f \) is directly constrained by Fermi.

For Higgsino-type DM, using the b final state, the bound reads:

\[ m_\chi \geq 40 \text{ GeV} \]

\[ T_r \geq (18 \text{ GeV}) \sqrt{\frac{1 \text{ GeV}}{m_\chi}} \]

Upper bound on \( \langle \sigma_{\text{ann}} \nu \rangle_f \) \( \Rightarrow \) \( T_r \) gets bounded from below
Over production in the branching scenario

Allowed by the Fermi data in the annihilation scenario

\[ T_r = T_f \left( \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} \nu \rangle_f} \right) \quad T_f \sim \frac{m_\chi}{20} \]
The Fermi bound is translated to constraint in $\Delta N_{\text{eff}} - m_\chi$ plane:

$$m_\phi \sim 5 \times 10^6 \text{ GeV}$$

Allahverdi., Cicoli, Dutta, Sinha’14
Model Examples: 2

ϕ can be a visible sector field S (moduli is a hidden sector field)

\[ W_s = h S X^\alpha \overline{X}_\alpha + \frac{1}{2} m_s S^2 \]

\[ W_{N,X} = \lambda' d^c d^c \overline{X} + \lambda N u^c X + \frac{m_N}{2} NN + m_X X \overline{X} \]

\[ m_c \sim O(1) \text{ TeV}, \ m_X \sim O(10) \text{ TeV}, \ m_N \sim O(0.5) \text{ TeV} \]

\[ \text{BR}_{\phi \rightarrow \text{DM}} \sim 10^{-6} \]

\[ Y_s = \frac{(3/4) T_r}{m_s} \sim 10^{-4} \]

\[ n_{\text{DM}}/s \sim 10^{-10} \]

S Decay + DM Annihilation or no annihilation works

Allahverdi, Dutta, Sinha, ‘13
Model Example 2

S Decay + Branching ratio \(\rightarrow\) Baryogenesis

\[ \text{Br}_{N_1} \approx \left( \frac{\lambda}{g_3} \right)^4 \left( \frac{m_{N_1}}{m_S} \right)^2 \sim 0.01 \]

\[ \varepsilon \sim \frac{1}{8\pi} \left( \frac{m_{N_1}}{m_X} \right)^2 \lambda^2 \sim 10^{-4} \]

for \( (m_{N_1}/m_X) \sim 10^{-2} \)

\[ Y_s = (3/4)Tr/m_s \sim 10^{-4} \]

\[ \frac{n_B}{s} = Y_s \text{Br}_N \varepsilon \sim 10^{-10} \]
Non-thermal Scenarios @LHC

Probe the DM sector directly: \[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]

One interesting way:

Preselection:
missing \( E_T > 50 \text{ GeV} \),
2 leading jets \((j_1, j_2) : p_T(j_1), p_T(j_2) > 30 \text{ GeV} \)
\(|\Delta \eta(j_1, j_2)| > 4.2 \) and \( \eta_{j1} \eta_{j2} < 0 \).

Optimization:
Tagged jets: \( p_T > 50 \text{ GeV}, M_{j1j2} > 1500 \text{ GeV} \);
Events with loosely identified leptons\((l = e; \mu; \tau_h)\) and b-quark jets: rejected.
Missing \( E_T \): optimized for different value of the LSP mass.

Delannoy, Dutta, Gurrola, Kamon, Sinha et al’13
Non-Thermal scenario @ LHC

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha + M_\alpha X_\alpha \overline{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta \]

Final states at the LHC

New Particles: Heavy colored states: \( X, \overline{X} \)

SM Singlet: \( N \)

LHC signals: new colored states -spin 0- are pair produced
- high \( E_T \) four jets in the final states

new colored states -spin \( \frac{1}{2} \)- are pair produced,
- high \( E_T \) four jets + missing energy
  [via cascade decays into squarks etc]

Distinguishing Feature:
4 high \( E_T \) jets and 4 high \( E_T \) jets + missing energy
Non-Thermal scenario @ LHC

If N is the DM candidate, i.e., $m_N \sim m_p$

Monojet

Dijet

Dijet pair

Dutta, Gao, Kamon’14

Dijet + Missing Energy
DM via Monojet at LHC

Monojet $p_T$ distribution for $M_{X_1}=1$ TeV

Also, Mono-top, di-tops in this model

Combining various observable, we can probe ann. cross-section
Direct Detection

Dark Matter Candidates: \( \tilde{N}, N, \tilde{\chi}_1^0 \)

Direct detection scattering cross-section: \( \lambda_i \tilde{N} X u_i^c \)

Suppose: \( \tilde{N} \) is the DM particle (spin-0)

\( \tilde{N} \) Scatters off a quark via s-channel exchange of X

\[
\sigma_{\tilde{N}_1 - p}^{SI} \sim \frac{|\lambda_1|^4}{16\pi} \frac{m_p^2}{M_X^4}
\]

For \( \lambda_i \sim 1 \), \( M_X \sim 1 \text{ TeV} \),
\[
\sigma_{\tilde{N}_1 - p}^{SI} \sim O(10^{-41}) \text{ cm}^2.
\]

If \( N \) (spin \( \frac{1}{2} \)) is DM, \( M_N \sim m_p \) (to prevent N decay and p-decay), \( \sigma_{N-p} \) is \( 10^{-51} \text{ cm}^2 \) (SI) and \( 10^{-42} \text{ cm}^2 \) (SD)
Large cross-section for smaller $T_r$ ➔ More Higgsino domination

Apparicio, Cicoli, Dutta, Kippendorf, Maharana, Muia, Quevedo, 1502.05672
The origin of DM content is a big puzzle. We will be able to understand the history of the early universe.

Thermal DM is a very attractive scenario. However, it contains certain assumptions about thermal history.

Alternatives with a non-standard thermal history are motivated. Typically arise in UV completions. Can ease the tension with tightening experimental limits.

Non-thermal DM arising from moduli decay is a viable scenario. Can yield the correct density for large & small annihilation rates. Successful realization in explicit constructions is nontrivial.