Nonthermal Dark Matter from Moduli decay

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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
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:

$$DM + DM \leftrightarrow f + \bar{f}$$

Non-relativistic

Freeze-Out: Hubble expansion dominates over the interaction rate

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

freeze out $$T_f \sim \frac{m_{DM}}{20}$$

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

Assuming: $$\langle \sigma v \rangle_f \sim \frac{S}{m_{\chi}^2}$$

$$\alpha_{\chi} \sim O(10^{-2})$$ with $$m_{\chi} \sim O(100)$$ 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 \(\rightarrow\) 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%

$\langle \sigma_{\text{ann}} \nu \rangle_o$ : smaller than the thermal value

Geringer-Sameth, Koushiappas’11, Hooper, Kelso, Queiroz, Astropart.Phys. ‘13
LHC C 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 x 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, Kapla, 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.

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

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

$\tilde{t}_1$ 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/\mu 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

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

- LHC: Determine the model, measure \( \Delta M \)
- DM annihilation from galaxy, extragalactic sources
  - Annihilation into photons: Fermi, HAWC, H.E.S.S.
  - Annihilation into neutrinos: IceCube
  - Annihilation into electron-positrons: AMS
Obtaining correct relic density for \( <\sigma_{\text{ann}}\nu>_f \neq 3\times10^{-26} \text{ cm}^3 \text{s}^{-1} \):

1) (thermal underproduction): \( <\sigma_{\text{ann}}\nu>_f > 3\times10^{-26} \text{ cm}^3 \text{s}^{-1} \)

   \text{Example: mixed Higgsino/axion DM}

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

   \text{Zurek’13}

2) (thermal overproduction): \( <\sigma_{\text{ann}}\nu>_f < 3\times10^{-26} \text{ cm}^3 \text{s}^{-1} \)

   \text{DM from WIMP decay}

   \text{Ex: Axino DM, Gravitino DM}

   \text{Covi, Kim, Roszkowski ‘99}

   \text{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

\[ T_r \sim c^{1/2} \left( \frac{m_{\phi}}{M_p} \right)^{1/2} m_{\phi} \]

\[ T_r > T_{BBN} \approx 3 \text{ MeV} \]

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

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

Abundance of decay products \( Y_{\phi} = \frac{3 T_r}{4 m_{\phi}} \)

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 \[ \frac{n_{DM}}{s} = \min \left[ \left( \frac{n_{DM}}{s} \right)_{obs} \frac{\langle \sigma v \rangle_f^{th}}{\langle \sigma v \rangle_f} \frac{T_f}{T_f}, Y_\phi \right. \]

1. First term on the RHS is the “annihilation scenario”
   Requires: \[ \langle \sigma \text{_{ann}} v \rangle_f = \langle \sigma \text{_{ann}} v \rangle_f^{th} \frac{T_f}{T_r} \]
   Since \( T_r < T_f \), we need \( \langle \sigma \text{_{ann}} v \rangle_f > \langle \sigma \text{_{ann}} v \rangle_f^{th} \) \( \Rightarrow \) wino/Higgsino DM
   Gamma-rays constraints: Dwarf spheroidals, Galactic center \( \Rightarrow \) \( M_{DM} > 40 \text{ GeV}, T_f < 30 \text{ } T_r \Rightarrow T_r > 70 \text{ MeV} \)
   [Hooper, Kelso, Queiroz,; Geringer-Sameth, Koushiappas]

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 \( \text{Br} \phi \rightarrow_{DM} \) from becoming too small
   (actually in realistic scenarios: \( \text{Br} \geq 5 \times 10^{-3} \Rightarrow T_r < 70 \text{MeV} \))
   (for \( m_\phi \approx 5 \times 10^6 \text{ GeV} \))
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
  ($f_a \sim 10^{14}$ 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: \[ \frac{n_B}{S} = Y_\phi \varepsilon B r_{\phi \rightarrow B} \]

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

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

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

\[ \frac{\Omega_b}{\Omega_{DM}} = \frac{1}{m_{DM}} \frac{Y_\phi \varepsilon B r_{\phi \rightarrow B}}{Y_\phi B r_{\phi \rightarrow DM}} = \frac{1}{m_{DM}} \frac{\varepsilon B r_{\phi \rightarrow B}}{B r_{\phi \rightarrow DM}} = \frac{1}{5} \]

\( \Omega = \rho/\rho_c ; \rho = \text{mn} \)

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

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

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

\( N \): 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

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

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

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

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

$$W_{extra} = \lambda_{i\alpha\beta} N_{\beta} u^{c}_{i} X_{\alpha} + \lambda_{ij\alpha} d^{c}_{i} d^{c}_{j} X_{\alpha} + M_{\alpha} X_{\alpha} \overline{X}_{\alpha} + \frac{M_{\beta}}{2} N_{\beta} N_{\beta}$$

From X decay

Typically, $\epsilon_{1,2}$ 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 \( m_{3/2} < 40 \text{ TeV} \) \( \Rightarrow \) Gravitino decays after the BBN

\( m_\phi > 2 \ m_{3/2} \) can lead to DM overproduction

➢ Large branching ratio of moduli into light Axions \( \Rightarrow \) \( N_{\text{eff}} \)

[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 \[ \tau_b \equiv \frac{(T_b + \bar{T}_b)}{2} \]

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

Large volume can be obtained after stabilization of \[ \tau_b \equiv \frac{(T_b + \bar{T}_b)}{2} \]

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

\[ m_{soft} \ll m_{\tau_b} \ll m_{3/2} \quad (m_{soft} m_{3/2} \sim m_{\tau_b}^2) \]

For example, TeV scale SUSY can be obtained for:

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

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

\[ \Rightarrow \text{No Gravitino Problem} \]
NTDM in Large Volume Scenarios

\[ m_{\tau_b} < m_{3/2} \Rightarrow Br_{3/2} = 0 \]

The decay to gauge bosons arises at one-loop level:

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

\[ \phi = \sqrt{\frac{3}{2}} \ln(\tau_b) \]

The decay to Higgs controlled by the Giudice-Masiero term:

\[ \Gamma_{\phi \rightarrow H_uH_d} = \frac{Z^2}{24\pi} \frac{m_{\phi}^3}{M_P^2} \]

The decay to gauginos (and Higgsinos) is mass suppressed:

\[ \Gamma_{\phi \rightarrow \tilde{g}\tilde{g}} \propto \frac{m_{\phi}m_{\text{soft}}^2}{M_P^2} \Rightarrow Br_{\chi} << 1 \]

LVS set up can successfully accommodate non-thermal DM.

\[ Y_\phi \text{ can be quite small } \sim 10^{-10} : \text{branching and annihilations are ok} \]

Allahverdi, Cicoli, Dutta, Sinha’13
If the dominant decay mode is to gauge boson final states
φ 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 \( (m_{gaugino}/m_\phi)^2 \) 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:

$$\Gamma_{\phi \rightarrow a_b a_b} = \frac{1}{48\pi} \frac{m_{\phi}^3}{M_P^2}$$

Cicoli, Conlon, Quevedo’13

Bulk axions are ultra-relativistic and behave as DR.

Contribute to the effective number of neutrinos $N_{\text{eff}}$:

$$\Gamma_{\phi} = \left( c_{\text{vis}} + c_{\text{tot}} \right) \frac{m_{\phi}^3}{48\pi M_P^2} \Rightarrow \Delta N_{\text{eff}} = \frac{43c_{\text{hid}}}{7c_{\text{vis}}}$$

($\Delta N_{\text{eff}} = N_{\text{eff}} - 3.04$)
DM-DR Correlation

Decay to visible sector mainly produces gauge bosons and Higgs:

\[ \Gamma_{\phi \rightarrow gg} \sim \left( \frac{\alpha_{\text{SM}}}{4\pi} \right)^2 \frac{m_\phi^3}{M_P^2} \]

\[ K \supset \frac{Z H_u H_d}{\tau_b + \bar{\tau}_b} + h.c. \]

\[ \Gamma_{\phi \rightarrow H_u H_d} = \frac{Z^2}{24\pi} \frac{m_\phi^3}{M_P^2} \]

\[ \Gamma_{tot} = \Gamma_{\phi \rightarrow H_u H_d} + \Gamma_{\phi \rightarrow a_b a_b} \]

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

\[ \Delta N_{\text{eff}} = 0.48^{+0.48}_{-0.45} \]

\[ \Delta N_{\text{eff}} < 1 \Rightarrow Z > \sqrt{3} \]

We get a lower bound on \( T_r \)
Using

\[ T_r = \left[ \frac{30}{\pi^2 g_*} \right]^{1/4} \rho_{vis}^{1/4} \]

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

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

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

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

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

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

: Branching scenario

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

$$Br_\chi > 3 \times 10^{-3} \ \Rightarrow \frac{n_\chi}{s} > \left( \frac{n_\chi}{s} \right)_\text{obs}$$

: Branching scenario does not work

Avoiding excess of DR within LVS prefers “Annihilation” scenario $\Rightarrow$ Higgsino-type DM.
DM-DR Correlation

Obtaining the correct relic density in “Annihilation” scenario needs:

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

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

Assuming S-wave annihilation, which is valid for the Higgsino-type DM, \( < \sigma_{\text{ann}} \nu >_f \) 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 \( < \sigma_{\text{ann}} \nu >_f \) \( \Rightarrow \) \( T_r \) gets bounded from below
DM-DR Correlation

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

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

Over production in the branching scenario

Allowed by the Fermi data in the annihilation scenario
The Fermi bound is translated to constraint in $\Delta N_{\text{eff}} - m_\chi$ plane:

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

$$\Delta N_{\text{eff}} = \frac{43}{7} \frac{C_{\text{hid}}}{C_{\text{vis}}} \left( \frac{g_+}{5 \times 10^6 \text{ GeV}} \right)^3 \frac{625 \text{ GeV}}{\kappa^2}$$

$T_r \approx \frac{1}{\pi} \left( \frac{5 C_{\text{vis}} C_{\text{hid}}}{288 g_+ (T_r)} \right)^{1/4} m_\phi \sqrt{\frac{m_\phi}{M_p}}$

$T_{rh} \approx \kappa \sqrt{\frac{C_{\text{hid}}}{\Delta N_{\text{eff}}} \left( \frac{68.5}{g_+} \right)^{1/4} \left( \frac{m_\phi}{5 \cdot 10^6 \text{ GeV}} \right)^{3/2}} 0.72 \text{ GeV} \Rightarrow m_{DM} \gtrsim \frac{\Delta N_{\text{eff}}}{c_{\text{hid}}} \sqrt{\frac{g_+}{68.5} \left( \frac{5 \times 10^5 \text{ GeV}}{m_\phi} \right)^3} \frac{625 \text{ GeV}}{\kappa^2}$

$\Delta N_{\text{eff}}, m_\phi$ : set lower bound on DM mass

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

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

\[
W_s = h S X^\alpha \bar{X}_\alpha + \frac{1}{2} m_s S^2 \quad \text{W} = W_s + W_{N,X}
\]

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

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

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

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

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

S Decay + DM Annihilation or no annihilation works

Allahverdi, Dutta, Sinha, ‘13
Model Example 2

S Decay + Branching ratio $\Rightarrow$ Baryogenesis

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

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

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

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

\[ \frac{n_B}{s} = Y_s \text{Br}_N \epsilon \sim 10^{-10} \]
Probe the DM sector directly: \( pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \)

One interesting way:

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

Optimization:
- Tagged jets: \( p_T > 50 \) GeV, \( M_{j1j2} > 1500 \) 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

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

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

\( \Rightarrow \) high \( E_T \) four jets in the final states

new colored states -spin \( \frac{1}{2} \)- are pair produced,

\( \Rightarrow \) 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

Dijet + Missing Energy

Dutta, Gao, Kamon’14
DM via Monojet at LHC

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 $X$

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

For $\lambda_i \sim 1, M_X \sim 1$ 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)
• 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