Dark Matter Connection of Particle Physics Models: Where Do We Stand?

Bhaskar Dutta

Texas A&M University

22nd September ’10
We will try to understand:

- The mechanism for generating masses

- The physics behind the scale of $W, Z$ boson mass scale
  \[ \sim \text{electroweak scale} \]
  \[ M_{\text{planck}} \gg M_W \]

- Do we have any further evidence of grand unification?

- The origin of dark matter

- The origin of inflation

Is there any particle physics connection?

- Why $\Omega_b(4\%) \sim \Omega_{\text{DM}}(23\%)$?

- ...
The Standard Model (SM) describes all these particles and 3 of 4 forces. We have confirmed the existence of those in the laboratory experiments.

+ Higgs boson

Higgs has not yet been discovered

The mass is constrained from data:

\[ 114 \text{ GeV} < M_H < 154 \text{ GeV} \]
SM problems and solutions

The Standard Model:
- Cannot provide a dark matter candidate.
- Has a serious Higgs mass divergence problem due to quantum correction.
- Cannot accommodate masses for neutrinos.
- Cannot provide enough matter-antimatter asymmetry.
- ➔ Standard Model has fallen!

What is the new model?

Supersymmetry:
- Provides a candidate for dark matter ~ neutralino.
- Solves the Higgs mass problem in a very elegant way.
- Supersymmetric grand unified models include neutrinos!
- Can produce correct matter-antimatter asymmetry
- Can provide Inflation
- Can provide new sources of CP violation, e.g., $B_s \rightarrow \psi \phi$
  [Recently observed $3.2\sigma$ deviation at Tevatron]
SUSY is an interesting class of models to provide a weakly interacting massive neutral particle ($M \sim 100$ GeV).
The fundamental law(s) of nature is hypothesized to be symmetric between bosons and fermions.

Fermion ↔ Boson

Have they been observed? Not yet.
SUSY partner of \( W \) boson: chargino

SUSY partner of \( \tau \) lepton: stau

SUSY partner of \( Z \) boson: neutralino

Lightest neutralinos are always in the final state! This neutralino is the dark matter candidate!!
The grand unification of forces occur in SUSY models.

Unification scale can also be pushed to $10^{17-18}$ GeV

Ameliorates Proton decay problem in the very successful SO(10) model

Search for SUSY-upcoming days

Large Hadron Collider-
susy particles will be directly produced

Existence of Higgs will be explored

- Higgs mass in the well motivated SUSY models: < 150 GeV
  Current experimental bound: 114 - 154 GeV

Direct detection experiment, CDMS, Xenon 100, LUX etc
CDMS has observed two DM candidate events! Excess at DAMA/Libra, COGENT

Indirect detection experiments, e.g., PAMELA has already observed excess of positron excess in cosmic ray

Fermi Gamma Ray Space Telescope:
Sensitive to gamma ray from Dark Matter annihilation

IceCube: Sensitive to neutrinos from DM annihilation

Tevatron search for $B_s \rightarrow \mu^+ \mu^-$ (highest reach on SUSY masses)
SUSY Models and dark matter:

MSSM: supersymmetric SM (more than 100 parameters)
SUGRA: Gravity mediated ➔ mSUGRA (minimal model)
Other possibilities: Gauge mediated, Moduli mediated etc

DM candidates: Lightest neutralino $\tilde{\chi}_1^0$ (most common)
Sneutrino $\tilde{\nu}$
Gravitino $\tilde{G}$

Inflation: Low scale or High scale in these models
Low scale can be tied to the SUSY breakings
LHC, PLANCK data etc.
What we hope for: 
The upcoming data from the LHC + Direct –Indirect detection experiments + WMAP-PLANCK data ➔ Establish a model

The model would tell us:

The origin of the electroweak scale
whether our dark matter picture is correct
explain the observed baryon density, inflation etc.
Establishing a Model at the LHC

The signal: jets + leptons + missing Energy

Colored particles get produced and decay into weakly interacting stable particles.

The energy of jets and leptons depend on the sparticle masses which are given by models.
Final states → Model Parameters

Reconstruct sparticle masses, e.g.,

\[ \tilde{Q} \rightarrow q + l + \tilde{\chi}_1^0 \]
\[ \tilde{L} \rightarrow l + \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_2,3,4 \rightarrow Z, h, \bar{l}l + \tilde{\chi}_1^0 \]

etc.

We may not be able to solve for masses of all the sparticles from a model

Solving for the MSSM: Very difficult due to too many parameters
SUSY at the LHC

We can use simpler models to understand the cascades and solve for the model parameters

Calculate the Dark Matter content

The best strategy:

Solve for the minimal model: mSUGRA →
4 parameters: \( m_0, m_{1/2}, A_0, \tan\beta \) and \( \text{Sign}(\mu) \)

The cascades can be understood in a simpler way [hopefully!]

Next step:
Next to minimal model (Higgs nonuniversality)
Then …
Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:

4 parameters + 1 sign

- $\tan \beta$ : $<H_u>/H_d$ at $M_Z$
- $m_{1/2}$ : Common gaugino mass at $M_{GUT}$
- $m_0$ : Common scalar mass at $M_{GUT}$
- $A_0$ : Trilinear coupling at $M_{GUT}$
- sign($\mu$) : Sign of $\mu$ in $W^{(2)} = \mu H_u H_d$

Key Experimental Constraints

- $M_{Higgs} > 114$ GeV
- $M_{chargino} > 104$ GeV
- $2.2 \times 10^{-4} < \mathcal{B} (b \to s \gamma) < 4.5 \times 10^{-4}$
- $(g-2)_\mu : 3 \sigma$ deviation from SM
- $0.094 < \Omega \tilde{\chi}_1^0 h^2 < 0.129$

Dark Matter Allowed Region

- Higgs Mass ($M_h$)
- Branching Ratio $b \to s \gamma$
- Magnetic Moment of Muon
- WMAP Favored region

Co-annihilation Region

$\Delta M = 5 \sim 15$ GeV

No Neutralino LSP

Mass of Gauginos

Mass of Squarks and Sleptons

Excluded
A near degeneracy occurs naturally for light stau in mSUGRA.

\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx \]

\[ < \sigma_{\text{ann}} v > \sim \frac{\alpha^2}{M^2} \sim 1 \text{ pb} \]

\[ (\Omega_{\text{CDM}})^{-1} \propto \]

Co-annihilation (CA) Process

Griest, Seckel '91

\[ \Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_i^0} \]
Goal for the analysis

✓ Establish the “dark matter allowed region” signal

✓ Measure SUSY masses

✓ Determine Model parameters

✓ Calculate $\Omega_{\chi} h^2$ and compare with $\Omega_{\text{CDM}} h^2$
DM Allowed Regions in mSUGRA

[Focus point region] the lightest neutralino has a larger Higgsino component

[Stau-Neutralino CA region]

[Bulk region] is almost ruled out

Overdense region
Signals of the Allowed Regions

- **Neutralino-stau coannihilation (CA) region**: jets + taus (low energy) + missing energy

- **Focus point**: jets + leptons + missing energy
  [Dutta, Flanagan, Kamon, Krislock, to appear; Tovey, PPC 2007; Baer, Barger, Salughnessy, Summy, Wang, *PRD*, 75, 095010 (2007)]

- **Bulk region**: jets + leptons + missing energy [Nojiri, Polsello, Tovey'05]

- **Overdense regions**: Higgs+Jets, Z+jets, taus+jets+missing energy [Dutta, Gurrola, Kamon, Krislock, Lahanas, Mavromatos, Nanopoulos, arXiv:0808.1372]

- **Non Universal Higgs Models**: W+jets+taus + missing energy [Dutta, Kamon, Krislock, Kolev, Oh, arXiv:1008.3380]
Low energy taus exist in the CA region. However, one needs to measure the model parameters to predict the dark matter content in this scenario.

\[ \Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV} \]
Low energy $\tau$'s are an enormous challenge for the detectors

We need to involve the low energy $\tau$'s in our analysis

\[ \tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau}_1 \rightarrow \tau \tau \tilde{\chi}_1^0 \]

($\Delta M = 5.7 \text{ GeV}$)

\[ \tilde{g} = 831 \text{ GeV} \]
\[ \tilde{\chi}_2^0 = 264 \text{ GeV} \]
\[ \tilde{\chi}_1^0 = 137.4 \text{ GeV} \]
\[ \tilde{\tau}_1 = 143.1 \text{ GeV} \]

End point = 62.0 GeV

Arnowitt, Dutta, Kamon, Kolev, Toback  PLB 639 (2006) 46
$E_T^{miss} + 2\tau + 2j$ Analysis

Cuts to reduce the SM backgrounds ($W$+jets, ...)

$E_T^{miss} > 180$ GeV, $N(\text{jet}) \geq 2$ with $E_T > 100$ GeV

$E_T^{miss} + E_T^{j1} + E_T^{j2} > 600$ GeV; $N(\tau) \geq 2$ with $P_T > 40, 20$ GeV

CATEGORIZE opposite sign (OS) and like sign (LS) ditau events

OS $\tau\tau$

$M_{\tau\tau}$ histogram

LS $\tau\tau$

$M_{\tau\tau}$ histogram

We use ISAJET + PGS4
Arnowitt, Dutta, Kamon, Kolev, Toback
PLB 639 (2006) 46
Extracting One side: \(j \tau \tau\)

OS-LS selection of ditaus selects \(\tilde{\chi}_2^0\), but if we need to reconstruct the entire side

\[
\begin{align*}
\text{We use the following subtraction scheme:}
\end{align*}
\]

\[
\begin{align*}
\text{The OS-LS } \tau \text{ pair has momentum related to the momentum of this Same Event Jet.}
\end{align*}
\]

We collect all \(2 \tau + \text{Jet pairs: get related pairs plus random pairs.}

Using Jets from Previous Events: get only random pairs.

Normalize and perform the Same Jet - Previous Jet subtraction:

- Random pairs will cancel.
- Only the related pairs remain.

\[
\begin{align*}
\text{BEST: Bi Event Subtraction Technique}
\end{align*}
\]

\[
\begin{align*}
\text{peak} = 414.9 \pm 7.5 \text{ GeV}
\end{align*}
\]
Observables

1. Sort $\tau$’s by $E_T$ ($E_T^1 > E_T^2 > ...$)
   • Use OS–LS method to extract $\tau$ pairs from the decays

   \[ N_{\tau^+\tau^-} - N_{\tau^+\tau^-} \]
   SM+SUSY Background gets reduced

   • Ditau invariant mass: $M_{\tau\tau}$
   • Jet-$\tau$-$\tau$ invariant mass: $M_{j\tau\tau}$
   • Jet-$\tau$ invariant mass: $M_{j\tau}$
   • $P_T$ of the low energy $\tau$
   • $M_{\text{eff}}$: 4 jets +missing energy
   • $M_{\text{eff}}(b)$: 4 jets +missing energy

All these variables depend on masses $\rightarrow$ model parameters

Since we are using 7 variables, we can measure the model parameters and the grand unified scale symmetry (a major ingredient of this model)
Determining SUSY Masses (10 fb⁻¹)

7 Eqs (as functions of SUSY parameters)

\[ M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ \text{Slope} = f_2(\Delta M, \tilde{\chi}_1^0) \]

\[ M_{j\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M_{j1\tau}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M_{j2\tau}^{(2)\text{peak}} = f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L) \]

\[ M_{\text{eff}}(b) = f_7(\tilde{g}, \tilde{q}_L, \tilde{t}, \tilde{b}) \]

Invert the equations to determine the masses

10 fb⁻¹

\[ M_{\tilde{q}_L} = 748 \pm 25; \ M_{\tilde{g}} = 831 \pm 21; \]

\[ M_{\tilde{\chi}_2^0} = 260 \pm 15; \ M_{\tilde{\chi}_1^0} = 141 \pm 19; \]

\[ \Delta M = 10.6 \pm 2.0 \]

\[ M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1 \pm 0.2 \ (\text{theory} = 3.19) \]

\[ M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \ (\text{theory} = 5.91) \]

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback

[1] Established the CA region by detecting low energy τ's ($p_T^{vis} > 20$ GeV)

[2] Determined SUSY masses using: $M_{\tau\tau}$, Slope, $M_{\tilde{j}\tau}$, $M_{\tilde{j}\tau}$, $M_{\text{eff}}$

\[ \text{e.g., Peak}(M_{\tau\tau}) = f(M_{\text{gluino}}, M_{\text{stau}}, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}) \]

[3] Predict the dark matter relic density by determining $m_0$, $m_{1/2}$, $\tan\beta$, and $A_0$

[4] We can also predict the dark matter-nucleon scattering cross section $\sigma_{\tilde{\chi}_1^0-p}$ but it has large theoretical error
Determining mSUGRA Parameters

✓ Solved by inverting the following functions:

\[ M_{j\tau\tau} = f_1(m_{1/2}, m_0) \]
\[ M_{\tau\tau} = f_2(m_{1/2}, m_0, \tan\beta, A_0) \]
\[ M_{\text{eff}} = f_3(m_{1/2}, m_0) \]
\[ M_{\text{eff}}^{(b)} = f_4(m_{1/2}, m_0, \tan\beta, A_0) \]

\[
\begin{align*}
m_0 &= 210 \pm 5 \\
m_{1/2} &= 350 \pm 4 \\
A_0 &= 0 \pm 16 \\
\tan\beta &= 40 \pm 1
\end{align*}
\]

Solved by inverting the following functions:

\[
\begin{align*}
M_{j\tau\tau} &= f_1(m_{1/2}, m_0) \\
M_{\tau\tau} &= f_2(m_{1/2}, m_0, \tan\beta, A_0) \\
M_{\text{eff}} &= f_3(m_{1/2}, m_0) \\
M_{\text{eff}}^{(b)} &= f_4(m_{1/2}, m_0, \tan\beta, A_0)
\end{align*}
\]

\[
\begin{align*}
m_0 &= 210 \pm 5 \\
m_{1/2} &= 350 \pm 4 \\
A_0 &= 0 \pm 16 \\
\tan\beta &= 40 \pm 1
\end{align*}
\]

\[ \Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2}, \tan\beta, A_0) \]

\[ \delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 = 6.2\% (30 \text{ fb}^{-1}) = 4.1\% (70 \text{ fb}^{-1}) \]

\[ \Delta\sigma_{\tilde{\chi}_1^0-p} / \sigma_{\tilde{\chi}_1^0-p} \approx 7\% (30 \text{ fb}^{-1}) \]

Direct Detection
Determining $\Omega h^2$ in different models

Region where $\chi_2^0$ decays to Higgs (signal: Higgs+jets+missing energy)

$$\frac{\delta \Omega_{CDM}}{\Omega_{CDM}} \sim 150\% \ (1000 \ fb^{-1})$$

Region where $\chi_2^0$ decays to stau and Higgs

$$\frac{\delta \Omega_{CDM}}{\Omega_{CDM}} \sim 20\% \ (500 \ fb^{-1})$$

Dutta, Flanagan, Kamon, Krislock, to appear

$$\frac{\delta \Omega h^2}{\Omega h^2} \sim 28\% (300 \ fb^{-1})$$

Signal: jets+ dileptons+missing energy

$$\frac{\delta \Omega \tilde{\chi}_1^0 h^2 / \Omega \tilde{\chi}_1^0 h^2}{= 6.2\% (30 \ fb^{-1})} = 4.1\% (70 \ fb^{-1})$$

Signal: jets+ditaus+missing energy

Dutta, Gurrola, Kamon, Krislock, Nanopoulos, Lahanas, Mavromatos, PRD 09
Nature may not be so kind … Our studies have been done based on a minimal scenario (= mSUGRA)… Let’s consider a non-universal scenario: Higgs non-universality: $m_{H_u}, m_{H_d} \neq m_0$ (most plausible extension) → easy to explain the DM content:

**Signal:** $W + \text{jets} + \text{taus} + \text{missing energy}$

$m_0 = 366 \pm 26 \text{GeV}, m_{1/2} = 499.5 \pm 3.2 \text{GeV},$

$m_{H_u} = 726.7 \pm 9.9 \text{GeV}, \tan \beta = 39.5 \pm 3.8, A_0 = 3 \pm 34 \text{GeV}$

$\Omega h^2 = 0.094^{+0.107}_{-0.038}$ For 1000 fb$^{-1}$

$m_0 = 367 \pm 57 \text{GeV}, m_{1/2} = 499.6 \pm 9.3 \text{GeV},$

$m_{H_u} = 727 \pm 13 \text{GeV}, \tan \beta = 39.5 \pm 4.6, A_0 = 0 \pm 73 \text{GeV}$

$\Omega h^2 = 0.08^{+0.189}_{-0.018}$ For 100 fb$^{-1}$

Dutta, Kamon, Kolev, Krislock, Oh, arXiv: 1008.3380
DM Particle: Direct Detection?

The measurement at the LHC will pinpoint the parameters of SUSY models. We can predict the direct detection probability of dark matter particles.

Complementary measurements
Ongoing/future projects: CDMS, LUX, XENON100, COGENT, EDELWEISS etc

Status:

- DAMA/LIBRA, COGENT claim to have observed some events.
- CDMS claims to have observed two events
- Xenon 100 is taking more data
The bounds from CDMS/Xenon 100 have started becoming competitive with $b \rightarrow s \gamma$ and Higgs mass constraints.
Recent results on anti-particle flux:

PAMELA has reported an excess of positrons up to 100 GeV, but no excess in anti-proton

In addition, ATIC has reported excess in $\mu^+ + \mu^-$ spectrum with a peak around 600 GeV.

Fermi: Abdo, et al., arXiv:0905.0025
MSSM x U(1)_{B-L} and PAMELA

Dark Matter and positron excess:
- Wimp annihilation rate today: \[ n \ B \ <\sigma v> \]
  \( B \) is the boost factor
  \[ <\sigma v>_f = 3 \times 10^{-26} \text{ cm}^3/\text{s} \]
  annihilation cross-section around the freeze-out time
- Model independent analysis shows: \( B \sim 10 \ (ee) - 10^3 (\tau\tau) \)
- Source of Boost: Astrophysics, particle physics
MSSM is further suppressed since the annihilation cross-section mostly is p-wave suppressed
  \[ <\sigma v> \propto v^2 \Rightarrow <\sigma v>_{\text{today}} = 10^{-5} <\sigma v>_f \]
- MSSM needs to be extended, e.g., with a U(1)_{B-L}
- Non-thermal scenario can explain PAMELA
  anti proton/positron data
  Leblond, Dutta, Sinha, PRD, 09;
  Allahverdi, Dutta, Santoso, PLB 09
Conclusion

- SM of particle physics has fallen.
- Supersymmetry seems to be natural in the rescue act and the dark matter content of the universe can be explained in this theory.
- The SUGRA model is consistent with the existing experimental results.

[1] LHC can probe the minimal SUGRA, non-universal SUGRA model directly.
  - All the dark matter allowed regions can be probed at the LHC
  - The dark matter content can be measured with a good accuracy
  - This accuracy depends on the final states

[2] This analysis can be applied to any SUSY model
Conclusion...

[3] Direct detection experiments will simultaneously confirm the existence of these models.

[4] Indirect detection experiments will also confirm the existence of SUSY models.

[5] Very exciting time ahead...