Current Status of Particle Theory Models

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Some Outstanding Issues of High Energy Theory

1. Dark Matter content ($\Omega_{DM}$ is 27\%)

2. Electroweak Scale

3. Baryon Content ($\Omega_b$ is 5\%)

4. Rapid Expansion of the Early Universe

5. Neutrino Mass

Need: Theory, Experiment and Observation
Questions
Current Status

Collider Experiments: LHC
Direct Detection Experiments: DAMA, CDMS, XENON 100, CoGeNT, LUX etc.
Indirect Detection Experiments: Fermi, AMS, PAMELA
Cosmic Microwave Sky: Planck, WMAP
Neutrino Experiments: T2K, Daya Bay, Double CHOOZ, RENO etc.

➡️ What have we learnt? What is the status of theory models?
➡️ What do we expect in the near future?
➡️ Are we closing in?
(i) What have we learnt so far?  
LHC, Direct and Indirect Detection Experiments, Planck Data, Neutrino Experiments

(ii) Dark Matter: Thermal vs. Non-thermal

(iii) Dark Matter and Baryon Contents

(iv) Dark Matter at the LHC

(v) Concluding Insights
Higgs Boson has been found (Mass: 125 GeV) + Completes Standard Model

3 families of quarks, leptons, Gauge Bosons (force carriers): $W^\pm$, $Z$, $\gamma$, $g$

Higgs mechanism breaks the SM symmetry spontaneously and generates mass for quarks, leptons, $W$, $Z$ and Higgs

Symmetry breaking scale (Electroweak scale): 246 GeV

Much lower than the Planck scale: $1.22 \times 10^{19}$ GeV
LHC: Higgs

• Higgs mass increases rapidly with scale $m_h^2 = m_0^2 + k \Lambda^2$: divergence problem $\Rightarrow$ solution needs fine tuning (1 part in $10^{32}$)

• SM prediction:
  $m_h < 850$ GeV to satisfy the unitarity in W scattering

• Fine tuning problem solved in supersymmetry due to fermions $\leftrightarrow$ bosons symmetry

• Higgs mass predicted in SUSY Model?
  Minimal Supersymmetry Standard Model (MSSM):
  $M_h^2 = M_Z^2 \cos^2 2\beta + \text{loop correction}$
  prediction: $m_h < 135$ GeV

• Measured mass (125 GeV) appears in the tight MSSM window
Fundamental law of nature hypothesized to be symmetric between bosons and fermions

Fermion ↔ Boson

Lightest neutralino is in the final state → dark matter candidate!!

New colored particles: Squarks, gluinos
New non-colored particles: Sleptons, Neutralinos, Charginos etc
LHC: Supersymmetry

Motivation: supersymmetry (SUSY) or beyond the SM
SM does not provide solutions to any of the outstanding issues

No explanations for
- 27% of the Universe (DM)
- Higgs mass divergence problem
- Baryon content
- Origin of Electroweak scale
- Inflation
- Neutrino mass
- Anomalous magnetic moment of muon measurement excess

Have we seen SUSY? Not yet
LHC: Supersymmetry

Most models predict: 1-3 TeV (colored particle masses)
So far: No colored particle up to 1.5 TeV

Non-colored SUSY particles: 100 GeV to 1-2 TeV
(Major role in the DM content of the Universe)
Weak LHC bound for non-colored particles → hole in searches!

Trouble in Models with very tight correlation between colored and non-colored particles, e.g., minimal SUGRA/CMSSM

LHC + Direct Detection + Indirect Detection → quite constraining
Direct Detection Experiments

Status of New physics/SUSY in the direct detection experiments:

Any parameter space left?

CDMS, DAMA, CoGeNT:
Signal for Low mass DM

LUX: No signal for Low or High DM mass

- Astrophysical and nuclear matrix element uncertainties
- No signal: some particle physics models are ruled out

arXiv:1310.8214
Indirect Detection

The current rate of annihilation of DM particles: \(< \sigma_{\text{ann}} v >_o \)

DM content: \( \Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle} \)

\(< \sigma_{\text{ann}} v >_o \): constrained by Fermi

Gamma-rays constraints: Dwarf spheroidals, Galactic center

Hooper, Kelso, Queiroz, Astropart. Phys. 46 (2013) 55

\(< \sigma_{\text{ann}} v >_o \): smaller than the thermal value

Large cross-section is constrained
Indirect Detection

Excess of positrons has been found by both AMS, PAMELA and Fermi

Is this excess due to DM annihilation?

Need Larger Cross-section (larger than the thermal cross-section $3 \times 10^{-26} \text{ cm}^3/\text{sec}$)

Dark Matter Mass: More than 100 GeV
No anti-proton excess found?
Theory Models predictions: The excess will fall off
Pulsar can produce this excess
Planck Measurements

- Accurate measurement of cosmic microwave background ➔ Precision cosmology

- Number of relativistic degrees of freedom: 
  \[ N_{\text{eff}} = 3.30 \pm 0.27 \]

- For Inflation:
  - What is the scale of inflation?
  - Can we have more than one inflaton field?
  - What types of inflation models are okay?
  - Can we accommodate these models in particle physics framework?
Neutrinos

Recent Neutrino Data:
Accurate measurements of 2 mass differences and 3 mixing angles

| \( \Delta m_{\text{sun}}^2 \) \((10^{-5} \text{ eV}^2)\) | 7.54\(+\frac{0.26}{-0.22} \) | 7.50 \(\pm 0.185\) |
| \( \Delta m_{\text{atm}}^2 \) \((10^{-3} \text{ eV}^2)\) | 2.43\(+\frac{0.06}{0.10} \) | 2.47\(+\frac{0.032}{0.037} \) |
| \( \sin^2 \theta_{12} \) | 0.307\(+\frac{0.018}{-0.016} \) | 0.30 \(\pm 0.013\) |
| \( \sin^2 \theta_{23} \) | 0.386\(+\frac{0.024}{0.024} \) | 0.41\(+\frac{0.037}{0.022} \) |
| \( \sin^2 \theta_{13} \) | 0.0241 \(\pm 0.025\) | 0.023 \(\pm 0.0023\) |

Questions:
Dirac or Majorana type? Charge-Parity violation? Contribution to baryon content? Exact masses? How many?

Status of GUT (Grand Unified Theory)?

SO(10)?
Summary

- Direct Production at the collider: SUSY lurking around? More Higgs?

- Direct Detection and LHC: Low/high mass DM particle? Seen a signal already at CDMS/Xenon/DAMA?

- Indirect Detection and LHC: $<\sigma_{\text{ann}}\nu>$ DM thermal/non-thermal/multi-component? Seen a signal already at AMS?

- Neutrinos experiments: CP phase? More than 3 neutrinos? Do we have GUT (Grand Unified Theory) model?

- Planck: Model of Inflation?
Dark Matter: When?

Now

~ 0.0000001 seconds
Dark Matter: Thermal

Production of thermal non-relativistic DM:

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

Universe cools (\( T < m_{DM} \))

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

\[ DM + DM \not\iff f + \bar{f} \]

Boltzmann equation

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

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

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

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

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

\[ \Omega_{\text{DM}} = \frac{m_{\text{DM}} n_{\text{DM}}}{\rho_c} \sim \frac{1}{\langle \sigma v \rangle} \]

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

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

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

Assuming: \[ \langle \sigma v \rangle_f \sim \frac{s}{\alpha^2} \frac{1}{m_{\chi}^2} \]

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

leads to the correct relic abundance

Y becomes constant for \( T > T_f \)

\[ Y \sim 10^{-11} \text{ for } m_\chi \sim 100 \text{ GeV} \]

to satisfy the DM content
Thermal Dark Matter

DM particle + DM Particle $\rightarrow$ SM particles

Annihilation Cross-section Rate: $\langle \sigma_{\text{ann}} v \rangle$

DM Abundance:

$$\Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle}$$

$\sigma$: SM particles; $h, H, A$: various Higgs, $\tilde{f}$: SUSY particle

Note: All the particles in the diagram are colorless

$\Rightarrow$ We need $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$ to satisfy thermal DM requirement
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 $\Rightarrow$ Non-thermal Models

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

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

Weak scale physics:
\[ \alpha_{\chi} \sim O(10^{-2}) \quad \text{with} \quad m_{\chi} \sim O(100) \text{ GeV} \]
leads to the correct relic abundance.
SUSY Model - DM

$<\sigma_{ann}\nu>$ can be larger or smaller than the thermal average value depending on the DM type

Thermal DM $\Rightarrow 27\%$

LHC and indirect detection will help us understanding $<\sigma_{ann}\nu>$

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

Large Cross-section is also constrained
Non-standard thermal history at $\varphi$ is generic in some explicit UV completions of the SM.

Thermal equilibrium above $T_f$ is an assumption.

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

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

$< \sigma_{\text{ann}} v >$ : different from thermal average, $\Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle}$ is not 26%

Non-thermal DM can be a solution

DM from the decay of heavy scalar field, e.g., Moduli decay

[Moduli : heavy scalar fields gravitationally coupled to matter]

Decay of moduli/heavy field occurs at:

$$T_r \sim c^{1/2} \left( \frac{m_\phi}{100 \text{TeV}} \right)^{3/2} \text{ (5MeV)}$$

For $T_r < T_f$: Non-thermal dark matter

$T_r \sim \text{MeV}$ : Not allowed by BBN

Abundance of decay products (including DM) $Y_\phi \equiv \frac{3T_r}{4m_\phi}$

DM content: also needs to consider the DM annihilation.
Benefit of Non-Thermal DM

- For $T_r < T_f$, larger annihilation cross-section $\langle \sigma_{\text{ann}} \nu \rangle_f = \langle \sigma_{\text{ann}} \nu \rangle_f^{\text{th}} \frac{T_f}{T_r}$ is needed for $\Omega \rightarrow 26\%$

- For $T_r << T_f$, Yield $Y_\phi \equiv \frac{3T_r}{4m_\phi}$; $Y_{\text{DM}} = Y_\phi BR_{\phi \rightarrow DM}$ is small $\sim 10^{-10}$ DM will be produced without any need of annihilation

[Note: For $m_{\text{DM}} \sim 10$ GeV, $Y_\phi$ is needed to be $\sim 10^{-10}$ to satisfy the DM content]

Outcome:

- Large and small annihilation cross-section from models are okay
- We may not need any annihilation

Since $\phi \rightarrow DM + \text{other particles}$, abundance (for $T_r << T_f$): $10^{-10}$

- The Baryon and the DM abundance are correlated $\sim 10^{-10}$

DM and Baryon Abundance

\[ \frac{\Omega_b}{\Omega_{DM}} = \frac{5}{27} \]

Baryon abundance: \[ \Omega_b = \frac{m_b n_b}{\rho_c} \]

DM abundance: \[ \Omega_{DM} = \frac{m_{DM} n_{DM}}{\rho_c} \]

\( \rho_c = \) critical density
\( n = \) number density

If \( m_{DM} \sim \) few GeV (as claimed by some experiments)
\( \Rightarrow \) \( n_b \sim n_{DM} \) (since \( m_b = 1\) GeV)

Same number densities \( \Rightarrow \) same origin

Heavy field decay to DM and generate Baryon abundance
(without any annihilation cross-section uncertainty)
\( \Rightarrow \) Solves the coincidence problem

Predictive model has been constructed

Thermal vs Non-thermal

Measurement of DM annihilation cross-section is crucial
Large: multicomponent/non-thermal; Small: Non-thermal

- LHC: Determine the model then calculate $<\sigma_{\text{ann}}\nu>$

- DM annihilation from galaxy, extragalactic sources

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

  Annihilation into neutrinos: IceCube

  Neutrinos are better for signal from the galactic center

LHC 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 126 GeV & Cosmological gravitino solution [Allahverdi, Dutta, Sinha’12]

⇒Higgsino dark matter

Higgsino dark matter has larger annihilation cross-section

SUSY Model: Wino DM- Larger annihilation cross-section

Arkani-Hamid, Gupta, Kapla, Weiner, Zorawsky’12
Dark Matter at the LHC

Annihilation of lightest neutralinos $\rightarrow$ quarks, leptons etc.
At the LHC: proton + proton $\rightarrow$ DM particles

DM Annihilation diagrams: mostly non-colored particles
  e.g., sleptons, staus, charginos, neutralinos, etc.

How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section $<\sigma_{\text{ann}}\nu>$?

1. Cascade decays of squarks and gluinos
2. Monojet Searches
3. Via stop squark
4. Vector Boson fusion
1. Via Cascade decays at the LHC

LHC is very complicated

Colored particles are produced and they decay finally into the weakly interacting stable particle

The signal:
jets + leptons+ t’s +W’s+Z’s+H’s + missing $E_T$
1. Via Cascade decays at the LHC

Ambitious Goal:
Final states $\rightarrow$ Masses $\rightarrow$ Model Parameters
$\rightarrow$ Calculate dark matter density

$\tilde{Q} \rightarrow q + l + \tilde{\chi}_1^0 \quad \tilde{L} \rightarrow l + \tilde{\chi}_1^0$

$\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \rightarrow Z, h, l \bar{l} + \tilde{\chi}_1^0$ etc.

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

Problem 2:
Not all the sparticles appear in cascade decays

Problem 1:
Identifying one side is very tricky!

Challenge: Solving for the MSSM with many parameters

Apply:
Bi-Event Subtraction Technique (BEST)
Dutta, Kamon, Krislock, '12
1. Via Cascade decays at the LHC

mSUGRA

Non Universal Higgs Model

$\Omega h^2 = 0.23 \pm 0.13$

Dutta, Kamon, Krislock


Mirage Mediation Model

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Stat.</th>
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</thead>
<tbody>
<tr>
<td>$\tilde{t}$</td>
<td>690</td>
<td>± 6</td>
</tr>
<tr>
<td>$\tilde{b}$</td>
<td>1002</td>
<td>± 126</td>
</tr>
<tr>
<td>$\tilde{\tau}$</td>
<td>717</td>
<td>± 10</td>
</tr>
<tr>
<td>$\tilde{q}$</td>
<td>1133</td>
<td>−132, +167</td>
</tr>
</tbody>
</table>

@ 200 fb^{-1}

Determine DM content at 14 TeV LHC with high luminosity
If squarks are produced
LHC has a blind spot for productions of non-colored particle.

The W boson (colorless) coming out of high energy protons can produce colorless particles \(\rightarrow\) Vector Boson Fusion (VBF).

Special search strategy needed to extract the signal.

New way of understanding DM or new physics sector at the LHC.

Dutta, Gurrola, Kamon, John, Sinha, Shledon; Phys.Rev. D87 (2013) 035029
Baer, Barger, Mickelson, Tata, Phys.Rev. D89 (2014) 11, 115019
4. DM at the LHC Via VBF

- Direct probes of colorless charginos, neutralinos and sleptons do not have strong limits from the LHC

- The weak Bosons from protons can produce

\[ \text{P} + \text{P} \rightarrow \]

Two high \( E_T \) forward jets in opposite hemispheres with large dijet invariant mass
DM via VBFDM at the LHC

\[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]
Simultaneous fit of the observed rate, shape of missing energy distribution:

- 99% Higgsino, $\Omega_{\text{benchmark}} h^2 = 0.0144$
- 99% Wino, $\Omega_{\text{benchmark}} h^2 = 0.000267$

500 fb$^{-1}$, 14 TeV

$\Omega / \Omega_{\text{benchmark}}$

$m(\tilde{\chi}_1^0)$ [GeV]
Concluding Insights

- Model ideas have constraints from LHC, Planck, Neutrino data, direct and indirect detection constraints
- Higgs mass is within the supersymmetry model prediction window
- LHC measurements so far seem to be preferring large DM annihilation cross-section → Non-thermal DM
- Non-thermal scenarios can accommodate both large and small annihilation cross-sections and can allow us to understand the baryon-DM coincidence puzzle
- Determination of the DM Annihilation Cross-section is crucial: LHC and Indirect detections → identify DM model
- Need to investigate colorless particles (suitable for DM calculation) at the LHC using vector Boson technique
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