Current Status of Particle Theory Models

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February 5, 2016
Some Outstanding Issues of High Energy Theory

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

2. Electroweak Scale

3. Ordinary Matter (baryon) Content ($\Omega_b$ is 5%)

4. Rapid Expansion of the Early Universe

5. Neutrino Mass

Need: Theory, Experiment and Observation
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<td><strong>Collider Experiments:</strong></td>
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<td><strong>Direct Detection Experiments:</strong></td>
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<td><strong>Indirect Detection Experiments:</strong></td>
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<td><strong>Cosmic Microwave Sky:</strong></td>
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<td><strong>Neutrino Experiments:</strong></td>
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- 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: History

(iii) Dark Matter and Ordinary Matter Contents

(iv) Dark Matter at the LHC

(v) Concluding Insights
Large Hadron Collider (LHC)

Proton-Proton Collision
LHC: Higgs

Higgs Boson has been found (Mass ($m_h$) 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

$M_z=91.18$ GeV, $M_w=80.22$ 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

LHC: Supersymmetrized SM

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

Minimal Supersymmetric Standard Model (MSSM)

New colored particles: Squarks, gluinos
New non-colored particles: Sleptons, Neutralinos, Charginos etc
Motivation: supersymmetry (SUSY) or beyond the SM
SM does not provide solutions to any of the outstanding issues

e.g.,
- 27% of the Universe (DM)
- Higgs mass divergence problem
- Baryon content
- Origin of Electroweak scale (associated with Higgs Boson)
- Inflation
- Neutrino mass

SUSY is very useful in explaining some of these issues

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

New Excess at the LHC?
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: Fermi

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

Large cross-section is constrained

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

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 $3 \times 10^{-26}$ cm$^3$/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
Latest result from Planck

Probing Dark Matter

DM content (CMB) + overlapping region:

Thermal history, particle physics models, astrophysics
Planck Measurements

- Accurate measurement of cosmic microwave background ➔ Precision cosmology

- Number of relativistic degrees of freedom: \( N_{\text{eff}} = 3.04 \pm 0.18 \) (neutrinos)

- 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

<table>
<thead>
<tr>
<th>$\Delta m_{\text{sun}}^2$ (10^{-5} \text{ eV}^2)</th>
<th>$\Delta m_{\text{atm}}^2$ (10^{-3} \text{ eV}^2)</th>
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<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$7.54 \pm 0.26$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.307 \pm 0.018$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.0241 \pm 0.025$</td>
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Questions:
Dirac or Majorana type? Charge-Parity violation?
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?

- Indirect Detection and LHC: 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:

$$DM + DM \leftrightarrow SM \text{ particles}$$

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

$$DM + DM \Rightarrow SM \text{ particles}$$

$$DM + DM \nleftrightarrow SM \text{ particles}$$

Boltzmann equation

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

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

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

Increasing $\langle \sigma v \rangle$

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

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

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

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

\( \Rightarrow \quad \langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s} \)

Assuming: \( \langle \sigma v \rangle_f \sim \frac{s}{\alpha_{\chi}^2} \frac{1}{m_{\chi}^2} \)

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

leads to the correct relic abundance

\( Y \sim 10^{-11} \) for \( m_{\chi} \sim 100 \) GeV

to satisfy the DM content

\( \frac{m}{T} \rightarrow \quad Y \) becomes constant for \( T > T_f \)
Thermal Dark Matter

DM particle + DM Particle $\rightarrow$ SM particles

Annihilation Cross-section Rate: $<\sigma_{ann}v>$

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

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

Note: All the particles in the diagram are colorless

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

Neutralino can give rise to larger/smaller annihilation rate

Larger/Smaller Annihilation $\Rightarrow$ Non-thermal Models
**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
Status of Thermal DM

Thermal equilibrium above $T_f$ is an assumption.

Non-standard thermal history at $T_f$ is generic in some explicit high Scale theories.

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

Barrow’82, Kamionkowski, Turner’90

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

$<\sigma_{ann}v>$: different from thermal average, $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$ is not 27%

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:

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

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

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

Decay of moduli produce both DM and ordinary matter
Non-thermal DM Production from moduli decay

Ordinary Matter and DM from moduli decay

⇒ Cladogenesis of DM and Ordinary Matter (Baryons)

[Allaverdi, Dutta, Sinha’11]

Cladogenesis: is an evolutionary splitting event in a species in which each branch and its smaller branches forms a "clade", an evolutionary mechanism and a process of adaptive evolution that leads to the development of a greater variety of sister species.
Large $\langle \sigma_{\text{ann}} \nu \rangle \rightarrow$

multicomponent/non-thermal;

Small $\rightarrow$ Non-thermal

Probe $\langle \sigma_{\text{ann}} \nu \rangle$ directly at Indirect and Collider experiments

$\sim$ WIMP freeze-out
Annihilation of lightest neutralinos (DM particles)

$\rightarrow$ 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 $< \sigma_{ann} \nu >$?

1. Cascade decays of squarks and gluinos
2. Vector Boson fusion
The signal:
SM particles + DM particle (Missing energy)
DM at the LHC Via VBF

- LHC has a blind spot for productions of non-colored particles.
- The W boson (colorless) coming out of high energy protons can produce colorless particles → Vector Boson Fusion (VBF).
- Special search strategy needed to extract the signal.
- New way of understanding DM or new physics sector at the LHC.

Refs (For example):
A. Datta, P. Konar, and B. Mukhopadhyaya, 02.
G. Giudice, T. Han, K. Wang, and L.T. Wang, 13
Dutta, Gurrola, Kamon, John, Sinha, Shledon; ‘13
DM Via W at the LHC

\[ pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj \]
How to check that LHC observations lead to correct dark matter content? Measure $\Omega$ at the LHC ($\Omega$ is 27%: Planck Measurement)

Simultaneous fit of various observables:
New particle at the LHC?

- In the NWA search, an excess of 3.6σ (local) observed at a mass hypothesis of minimal $p_0$ of 750 GeV

New Quarks: Q, New Leptons: L
New scalar particles: X

Do we need dark matter particles to explain the data?

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 Non-thermal DM
- Non-thermal scenarios can allow us to understand the Ordinary Matter-Dark Matter coincidence puzzle

- Determination of the property of DM is crucial: LHC and Indirect detections $\Rightarrow$ identify DM model

- Need to investigate colorless particles (suitable for DM calculation) at the LHC
Acknowledgement

Students/Post-Doctoral Fellow:
Kechen Wang (PhD 2014), Tathagata Ghosh, Sean Wu, Yu Gao

Faculty from TAMU and other places:
Rouzbeh Allahverdi, Richard Arnowitt, Michele Cicoli, James Dent, Ricardo Eusebi, Ilia Gogoladze, Alfredo Gurrola, Teruki Kamon, Tainjun Li, Rabindra Mohapatra, Dimitri Nanopoulos, Farinaldo Queirez, Fernando Quevedo, Qaisar Shafi, Kuver Sinha, Louis Strigari, David Toback, Joel Walker

Research Funded by Department of Energy (DOE)