DARK MATTER AND THE LHC

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INTRODUCTION

• The Higgs discovery at the LHC capped a 50-year saga and completed the particle content of the Standard Model.

• No other new particles have been found.

• But many expect more discoveries, and the Higgs may be just the LHC’s opening act. Why?

Source: AAAS
EVIDENCE FOR DARK MATTER

• Our understanding of the Universe has been transformed in recent years

• There is now strong evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Normal Matter: 4% ± 0.4%
  Neutrinos: 0.2% \(\Sigma m_\nu/0.1\text{eV}\)

• To date, all evidence for dark matter is from its gravitational effects; to identify it, we need to see it in other ways
DARK MATTER

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new physics
WHAT COULD DARK MATTER BE?

Theories of Dark Matter?

These are not mutually exclusive – multi-component DM is certainly possible
DARK MATTER CANDIDATES

- Clearly the observational constraints are no match for the creativity of theorists
- Masses and interaction strengths span many, many orders of magnitude
- Axions, sterile neutrinos, etc. are well-motivated, but focus here on ideas most relevant for particle colliders
THE WEAK MASS SCALE

• Fermi’s constant $G_F$ introduced in 1930s to describe beta decay

$$n \rightarrow p \ e^- \bar{\nu}$$

• $G_F \approx 1.1 \cdot 10^{-5} \text{ GeV}^{-2}$ → a new mass scale in nature

$$m_{\text{weak}} \sim 100 \text{ GeV}$$

• We still don’t understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale
(1) Assume a new heavy particle $X$ is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{qq}$$

(2) Universe cools:

$$XX \rightarrow \bar{qq}$$

(3) Universe expands:

$$XX \rightarrow \bar{qq}$$

Zeldovich et al. (1960s)
• The relation between $\Omega_X$ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$X \rightarrow q$$

$$X \rightarrow \bar{q}$$

• $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

• Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter
WIMPS FROM SUPERSYMMETRY

The classic WIMP: neutralinos predicted by supersymmetry
Goldberg (1983); Ellis et al. (1983)

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle \( \tilde{X} \)

Neutralino \( \chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d) \)

Particle physics alone \( \rightarrow \chi \) is lightest supersymmetric particle, stable, weakly-interacting, mass \( \sim 100 \) GeV. All the right properties for WIMP dark matter!
Correct relic density $\rightarrow$ Efficient annihilation then

Efficient scattering now (Direct detection)

Efficient production now (Particle colliders)
DIRECT DETECTION

- WIMP properties
  - If mass is 100 GeV, local density is ~1 per liter
  - velocity ~ $10^{-3}$ c

Look for normal matter recoiling from WIMP collisions in detectors deep underground

Dark matter elastically scatters off nuclei

Nuclear recoils detected by phonons, scintillation, ionization, ..., ...

Attisha
CURRENT STATUS

There are claimed signals: For example, collision rate should change as Earth’s velocity adds with the Sun’s → annual modulation

Dukier, Freese, Spergel (1986)

DAMA: $9\sigma$ signal with $T \sim 1$ year, max $\sim$ June 2

DAMA signal now supplemented by others
CURRENT STATUS AND FUTURE PROSPECTS

Snowmass Cosmic Frontier Working Group (2013)
MOORE’S LAW FOR DARK MATTER

Evolution of the WIMP–Nucleon $\sigma_{SI}$

$\sigma_{SI}[cm^2] \text{ for a 50 GeV/c}^2 \text{ WIMP}$

- Z-exchange models (hep-ph/0209262)
- Higgs-exchange models (hep-ph/1109.2604)
- Coherent neutrino scattering signals

Year:
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
- 2025
INDIRECT DETECTION

• Dark matter may pair annihilate in our galactic neighborhood to
  • Photons
  • Neutrinos
  • Positrons
  • Antiprotons
  • Antideuterons

• The relic density provides a target annihilation cross section
  \[ \langle \sigma A \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \]
Relative to direct rates, indirect rates have smaller particle physics uncertainties (but larger astrophysical uncertainties)

Roszkowski (2013); See 1307.1567 for details
FOR EXAMPLE: INDIRECT DETECTION BY PHOTONS

Current: Veritas, HESS, MAGIC, Fermi-LAT, HAWC, and others
INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
best sensitivity
in the 100 GeV–10 TeV domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km² area at
multi-TeV energies

Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold
of some 10s of GeV

First Science: ~2016
Completion: ~2019
INDIRECT DETECTION: PHOTONS

- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV
PARTICLE COLLIDERS
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)

Cascades: Produce other particles, which decay to DM

Feng, Kant, Profumo, Sanford (2013)
DARK MATTER AT COLLIDERS

DM Effective Theories

Alternatively, save energy by just producing DM directly

DM pair production is invisible, so must radiate something to “tag” the event

The DM relic density is tied to rates for

Mono-photons at $e^+e^-$ colliders

Birkedal, Matchev, Perelstein (2004)

Mono-jets at the LHC

Feng, Su, Takayama (2005)
DM EFFECTIVE THEORY

- This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses

  Beltran, Hooper, Kolb, Krusberg, Tait (2006)
  Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
  Bai, Fox, Harnik (2010)

- There is now a mono-$\gamma,j,b,t,W,Z,h$ industry, probing dark matter at the LHC one operator at a time

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
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<tbody>
<tr>
<td>D1</td>
<td>$\chi \bar{q} q$</td>
<td>$m_q / M_s^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\chi \gamma^5 \bar{q} q$</td>
<td>$m_q / M_s^3$</td>
</tr>
<tr>
<td>D3</td>
<td>$\chi \bar{q} \gamma^5 q$</td>
<td>$m_q / M_s^3$</td>
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<td>D4</td>
<td>$\chi \gamma^5 \bar{q} \gamma^5 q$</td>
<td>$m_q / M_s^3$</td>
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<tr>
<td>D5</td>
<td>$\chi \bar{q} \gamma \gamma_{\mu} q$</td>
<td>$1 / M_s^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\chi \gamma^\mu \gamma^5 \bar{q} \gamma_\mu q$</td>
<td>$1 / M_s^2$</td>
</tr>
</tbody>
</table>

\[ \int L \, dt = 19.5 \, fb^{-1} \]

CMS Preliminary

\[ \bar{s} = 8 \, TeV \]

$\chi$-Nucleon Cross Section [cm$^2$]

Spin Independent

$M_\chi$ [GeV/c$^2$]
THE FUTURE

If there is a signal, what do we learn?

• Cosmology and dark matter searches can’t prove it’s SUSY

• Particle colliders can’t prove it’s DM

Lifetime > $10^{-7}$ s $\Rightarrow$ $10^{17}$ s ?
DARK MATTER COMPLEMENTARITY

• Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity!

• After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties
COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space

Different expts probe different models, provide cross-checks

Cahill-Rowley et al. (2013)
BEYOND WIMPS

• All evidence for dark matter is gravitational. Perhaps it’s in a hidden sector, composed of particles without EM, weak, strong interactions

![Diagram showing SM and Hidden X]

• *A priori* there are both pros and cons
  – Lots of freedom: interesting astrophysics, …
  – Too much freedom: no connections to known problems, no WIMP miracle to guide experiments, …
THE WIMPLESS MIRACLE

Feng, Kumar (2008); Feng, Tu, Yu (2009); Feng, Shadmi (2011)

- Can we recover the WIMP miracle in a hidden sector?
- Consider SUSY: in fact, in many SUSY models, to avoid unseen flavor effects, superpartner masses satisfy
  \[ m_X \sim g_X^2 \]
- If this holds in a hidden sector, we have a “WIMPless Miracle”: hidden sectors of these theories automatically have DM with the right \( \Omega \) (but they aren’t WIMPs)
- Is this what the new physics flavor problem is telling us?
SELF-INTERACTING DARK MATTER

• If dark matter is completely hidden, can we learn anything about it?

• The Bullet Cluster provided evidence for dark matter. But the fact that dark matter passed through unperturbed →
  \[ \sigma_{\text{T}}/m < 1 \text{ cm}^2/\text{g} \text{ (} \sim 1 \text{ barn/GeV}) \]

• But there are indications that the self-interactions may be near this limit
  – Cusps vs. cores
  – Number of visible dwarf galaxies

Theory: \( N \gg 1000 \)  
Observation: \( N_{\text{bright}} \sim 10 \)
A SIMPlE THEORY OF DARK MATTER

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2014)

- A simple example: pure SU(N) with hidden gluons $g$ and gluinos $\tilde{g}$

- At early times, interaction is weak, $\sim 10$ TeV $\tilde{g}$ freezeout with correct $\Omega$

  At late times, interaction is strong, glueballs $(gg)$ and glueballinos $(g\tilde{g})$ form and self-interact with $\sigma_T/m \sim 1 \text{ cm}^2/\text{g} \sim 1 \text{ barn/GeV}$

- Realizes WIMPless miracle: TeV-masses with correct thermal relic density

- But self-interacting (and predicts a keV line, which may have been seen)
CONCLUSIONS

• Particle Dark Matter
  – Central topic at the interface of cosmology and particles
  – Both cosmology and particle physics $\rightarrow$ new particles at the weak scale $\sim 100$ GeV

• Candidates
  – WIMPs: Many well-motivated candidates
  – Hidden dark matter: Similar motivations, but qualitatively new properties
  – Many others

• LHC is coming back on line in 2015, direct and indirect detection, astrophysical probes are improving rapidly