Particle Theory in the Age of Data

Matthew Buckley
My Research Interests

• I work on particle phenomenology and astrophysics
  • My major interests right now are improving LHC search strategies, dark matter theory and searches, and model-building motivated by experimental results.

• We’re living in interesting times right now, and in my opinion, the way forward in theoretical physics is to pay very close attention to the experiments.

• (Please interrupt with questions if you have them)
The Story Thus Far

- Since the 1970’s we’ve been filling out the particle content of the Standard Model.
The Story Thus Far

- Standard Model both simple and much more complicated than it needs to be.

- Three gauge forces: $U(1)_Y$, $SU(2)_L$, $SU(3)_C$

- A scalar $SU(2)_L$-doublet with a non-zero vacuum expectation value that breaks $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

- Three families of chiral fermions:

$$
\begin{align*}
Q_L & = \left( \begin{array}{c}
\bar{u}_L \\
\bar{d}_L
\end{array} \right) \\
\bar{Q}_L & = \left( \begin{array}{c}
\bar{u}_L \\
\bar{d}_L
\end{array} \right)
\end{align*}
$$

- up, down, charm, strange, top, bottom

- electron, muon, tau, + neutrinos
Finding the Higgs

• The Higgs is the lynchpin of the Standard Model
• Need something to drive electroweak symmetry breaking
• Need something to allow left- and right-handed fermion fields to unite and give fermions mass.

\[ y H Q_L \bar{u}_R \rightarrow y \begin{pmatrix} v & 0 \end{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \bar{u}_R = y v \times u_L \bar{u}_R \]

\[ \langle H \rangle = v \]
July 4, 2012: Higgssmas

- Discovered in both CMS & ATLAS, primarily in

\[ h \rightarrow \gamma\gamma, \ h \rightarrow ZZ^* \rightarrow 4\ell \]
Properties of the Higgs

• With data from 7 & 8 TeV runs, now have reasonably accurate measurements for Higgs production and branching ratios

• Experimental results:
Where to go from here?

• Though we’ve long known something like the Higgs must exist, the Higgs alone presents a bit of a problem to theorists.

• All particles get mass corrections due to high energy loops:

\[ m_f \propto m_f \log(\Lambda/m_f) \]

• But fundamental scalars get quadratic corrections

\[ m_h^2 \propto \frac{3y_t^2}{8\pi} \Lambda^2 \]
Where to go from here?

- One easy solution: cancel loop corrections.

- Can’t be perfect cancellation.
  - But the new physics can’t be that far away.

- Other possibilities. Higgs could not be fundamental scalar, but this is disfavored by data if composite scale low
Where’s the New Physics?

• Supersymmetry the “canonical” new physics scenario.
• Has a wide range of phenomenology, so a convenient stand-in for many possible searches.
• Typically look for the new colored particles.
Missing Supersymmetry

• If supersymmetry, or something like it, exists at TeV-scale, it does not have the properties we expected pre-LHC.

• Gaps in our experimental sensitivity near mass degeneracies.

• From low missing transverse momentum
The Annoying Higgs Mass

- A SM Higgs with mass at 125 GeV lives in an interesting region of parameter space
  \[ V(H) = -\mu^2 H^2 + \lambda H^4 \]
- Quadratic coupling evolves at high energies
- If \( \lambda \) runs negative, our vacuum becomes unstable. Eventually, Universe should decay into true vacuum.

- Ignoring naturalness, do we need New Physics?
Motivations from Data

• Yes!

• Problems remain that the SM doesn’t have answers to:
  • Neutrino Masses
  • Baryogenesis
  • Dark Matter
  • Flavor

• Early Universe cosmology/Inflation
Dark Matter is New Physics

- Multiple lines of evidence stretching from Early Universe to today, all consistent with $\Omega_\chi = 0.1198h^{-2} = 0.265$

A Problem of Gravity

- All evidence for dark matter is purely gravitational.
- Few positive statements we can make:
  - Exists today
  - Existed prior to CMB
  - Non-relativistic at structure formation
- Everything else is what we know dark matter isn’t:
  - Non-EM interacting
  - Non-QCD interacting
  - Sub-Z interaction with nucleons
  - Doesn’t interact with itself
  - Doesn’t decay
    (… upper limits only)
- Why should I expect non-gravitational interactions?
What Could Dark Matter Be?

• Running Universe “backwards” eventually temperature is high enough that massive (~100 GeV) particles will be in thermal equilibrium.
  • Assuming processes like exist
  • As Universe cools, SM particles can’t produce heavy X’s.
  • And rate of X annihilation drops.

\[
\Omega h^2 = \frac{1.04 \times 10^9 \text{ GeV}^{-1}}{M_{Pl}} \times \frac{x_f}{\sqrt{g^*}} \langle \sigma v \rangle^{-1} = 0.12
\]

\[
\Rightarrow \langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2}
\]

Jungman et al hep-ph/9506380
A Miracle with Footnotes

• “Pure” $SU(2)_L$ doublet fermions have extremely large direct detection rates: $\sigma \sim 10^{-35} - 10^{-36}$ cm$^2$

• Models with $m_\chi \sim 100$ GeV often require particles beyond DM to annihilate with or through.
  • Pure thermal bino DM requires sfermions to annihilate away
  • Pure Wino/Higgsino DM requires $m_\chi \sim 1 - 2$ TeV

• Thermal relics can be obtained with new non-$SU(2)_L$ forces

  e.g. Buckley & Neil 1209.6054

Figure 2 – Left: 90% CL spin-independent WIMP exclusion limits shown the LUX 85.3 live-day result (solid blue) and the 300-day projection (dashed blue). Right: Close-up view of exclusion plot in the low-mass regime showing the tension between the LUX result and previous hints of low-mass WIMP signals.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>WIMP−nucleon cross section (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMSLite</td>
<td>$10^{-44}$</td>
</tr>
<tr>
<td>XENON10 S2-only</td>
<td>$10^{-43}$</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>$10^{-42}$</td>
</tr>
<tr>
<td>CoGeNT</td>
<td>$10^{-41}$</td>
</tr>
<tr>
<td>CRESST II</td>
<td>$10^{-40}$</td>
</tr>
<tr>
<td>CDMS II Si</td>
<td>$10^{-39}$</td>
</tr>
<tr>
<td>DAMA/LIBRA (this work)</td>
<td>$10^{-38}$</td>
</tr>
<tr>
<td>LUX 85.3 live-days</td>
<td>$10^{-37}$</td>
</tr>
<tr>
<td>LUX 300 live-days (projection)</td>
<td>$10^{-36}$</td>
</tr>
</tbody>
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<tr>
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<tr>
<td>LUX 88.3 live-days</td>
<td>$5 - 10^{-46}$</td>
</tr>
<tr>
<td>LUX 300 live-days</td>
<td>$5 - 10^{-45}$</td>
</tr>
</tbody>
</table>

b For the same energy, a NR produces less signal than an ER due to the fact that the former has a large energy loss fraction in the form of heat, which produces no photons or electrons.

e.g. Buckley & Neil 1209.6054
Weak-Scale Dark Matter

• We don’t know DM a thermal relic
• If DM not thermal, why expect significant interactions?
• If ever in thermal equilibrium, need to annihilate away the thermal component.
  • Requires \( \langle \sigma v \rangle \gtrsim \langle \sigma v \rangle_{\text{thermal}} \sim 1 \text{ pb} \)
  • Again: DM with “significant” interactions

Example: Asymmetric DM

Buckley & Profumo 1109.2164
Accessible Dark Matter

- If dark matter was in thermal equilibrium, then it needs to be able to annihilate into something. Caveats abound:
  - Dark matter might have never been in equilibrium (e.g. axions)
  - It might annihilate into non-Standard Model particles (have to prevent those from over-closing Universe…)
- But: *Reasonable* to consider dark matter with significant interactions with Standard Model ( ≥ SU(2)_L).

\[ \chi \to \text{SM?} \]

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The Age of Data

- We live in Interesting Times.
  - Major experiments testing theories at the weak scale.
  - Sensitive to dark matter with $\gtrsim \langle \sigma v \rangle_{\text{thermal}}$

![Diagram](image-url)
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![Diagram showing Early Universe Annihilation and Direct Detection](image)
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![Diagram showing different detection methods: Collider Production, Indirect Detection, Direct Detection, Early Universe Annihilation]
Hints from Space

- If dark matter depleted by thermal processes in early Universe, than that annihilation can continue today.
- *Fermi*-LAT capable of probing LHC-accessible dark matter annihilating into Standard Model particles with cross sections approaching $\langle \sigma v \rangle_{\text{thermal}}$
  - Note: if your model has $\langle \sigma v \rangle \propto v^2$, no annihilation today

Fermi 5-year All Sky
Indirect Detection

\[ \frac{d\phi}{dE_\gamma} = \left( \frac{x\langle \sigma v \rangle}{8\pi} \frac{dN_\gamma}{dE_\gamma} \frac{1}{m_\chi^2} \right) \left( \int_{\Delta \Omega} \int_{\text{l.o.s.}} \rho_\chi^2(\vec{\ell}) d\ell d\Omega \right) \]

• Annihilation flux proportional to \textbf{J-factor}
• High density, nearby targets the best:
  • dwarf spheroidal galaxies
  \[ J \sim 10^{18} - 10^{19.5} \text{ GeV}^2/\text{cm}^5 \]
  • Galactic Center
  \[ J \sim 10^{21} - 10^{23} \text{ GeV}^2/\text{cm}^5 \]
Indirect Detection

- Excess of gamma-rays from Galactic Center.
  - Morphology consistent with expected dark matter profile
  - Found by multiple groups
  - Could be dark matter, but can’t rule out “baryonic” backgrounds yet.
- Pulsars etc.
- Need to find signal in multiple locations.

Daylan et al 1402.6703
Indirect Detection

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Daylan et al 1402.6703
The Magellanic Clouds

• Realized that there promising targets nearby:
  • The Large and Small Magellanic Clouds
    \[ J_{\text{LMC}} \sim J_{\text{SMC}} \sim 10^{20} \text{ GeV}^2/\text{cm}^5 \]
  • Complicated objects, no search done before ours.
Large Magellanic Cloud

- Worked with Fermi-LAT to analyze the LMC.
- Larger angular extent: more handles on background.
- Observations & N-body simulation to find J-factor
Large Magellanic Cloud

- Even with uncertainties on background, LMC places competitive bounds on dark matter annihilation.
Large Magellanic Cloud

- Even with uncertainties on background, LMC places competitive bounds on dark matter annihilation.
Small Magellanic Cloud

- SMC has $1/10^{\text{th}}$ the DM mass of the LMC
- But $1/6^{\text{th}}$ the gamma-ray flux
- A similar $J$-factor as the LMC

![Graph demonstrating the relationship between mass and cross-section for different datasets.](Buckley et al. In progress)
If True then What?

- GC anomaly remains unresolved.
- The spectrum is similar to what you find from injected $\pi$'s or pulsars.
- ...or $\mathcal{O}(10 - 100$ GeV) dark matter
- If it is true? What then?
  - Or, can we demonstrate it isn’t DM?
  - Light enough to be produced at LHC
  - Where else should we have seen this?

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Daylan et al 1402.6703
Model Building

• What does the GC anomaly need to do?
  • “Light” DM $\mathcal{O}(10 - 100$ GeV)
  • Annihilation today $\langle \sigma v \rangle \propto v^0$
  • Well fit by annihilation into heavy fermions: $b'$s, $\tau'$s
  • Avoid direct detection constraints.
  • Not seen in LHC (yet)
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- Couplings to heavy fermions suggestive of Higgs-related physics
- Needs to have a new pseudoscalar mediator for present-day annihilation.

(work in progress with David Feld)
Model Building

- Minimum model: add dark matter and new pseudoscalar.
  - Motivates improvements to relevant LHC searches.
  - New $\mathcal{O}(100 \text{ GeV})$ spin-0 particles hard to find.
- Constrained MSSM/NMSSM parameters.
- Motivation for new theories:
  - Leptophilic Higgs models?
  - Supersymmetric versions?

Buckley, Feld, Gonçalves 1410.6497
Direct Detection

- Major stumbling block for many 30-50 GeV dark matter interpretation of Galactic Center excess appears to be strong constraints from direct detection.
- Specifically, LUX
Velocity Distributions

- Assuming elastic scattering, direct detection rate is

\[ \frac{dR}{dE_R} = (\text{Exp}) \frac{\sigma_{\text{nuclei}} |F(E_R)|^2}{2\mu^2} \frac{\rho_X}{m_X} \int_{v_{\text{min}}}^{\infty} \frac{f(v)}{v} dv \]

\[ v_{\text{min}} = c \sqrt{E_R m_N / 2\mu^2} \]

- Maxwell-Boltzmann assumption incompatible with NFW profiles.

- $N$-body simulations of dark matter halos allow us to look at velocity distributions of realistic dark matter halos.
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Looking to the Future

• The next decade will be an era of data:
  • LHC restarts this spring. Luminosity of $\sim 40 \text{ fb}^{-1}/\text{year}$
  • With $300 \text{ fb}^{-1}$ will measure Higgs width $< \text{GeV}$
  • Unprecedented energy and luminosity.
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Looking to the Future

- Direct detection experiments will reach solar neutrino background (est. 3 years after 2018 completion).
- Probe much of the MSSM neutralino parameter space
Looking to the Future

- *Fermi*-LAT has 5 years of data, will collect 10+
- Air-shower Cherenkov telescopes, AMS-2 anti-protons…
- Aided by improved data analysis, simulations of Milky Way-type galaxies, astronomical surveys identifying new dwarfs, GAIA data…
If Nothing Else…

• We know the Higgs exists.
• We know dark matter exists.

• Are they related?

• Next few years of experimental results and theoretical work will be critical.
  • Optimistically, we get an answer to 25% of the Universe