LLP UBIQUITY

New Physics with Exotic and Long-Lived Particles
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INTRODUCTION

• We have already discovered many Long-Lived Particles

In fact, LLPs have played an essential role in many of the conceptual breakthroughs that established the standard model of particle physics: \(e, \rho, n, \mu, K, \nu, \ldots\)

Similarly, models beyond the SM (BSM) typically predict new particles with a variety of lifetimes. In particular, new weak-scale particles can easily have long lifetimes for several reasons, including approximate symmetries that stabilize the long-lived particle (LLP), small couplings between the LLP and lighter states, and suppressed phase space available for decays. For particles moving close to the speed of light, this can lead to macroscopic, detectable displacements between the production and decay points of an unstable particle for \(c\tau & \lesssim 10^{-10}\) m.

The experimental signatures of LLPs at the LHC are varied and, by nature, are often very different from signals of SM processes. For example, LLP signatures can include tracks with unusual ionization and propagation properties; small, localized deposits of energy inside of the calorimeters without associated tracks; stopped particles that decay out of time with collisions; displaced vertices in the inner...
INTRODUCTION

• The next breakthrough in particle physics is likely to involve LLPs
  – LLPs are ubiquitous in BSM theories, especially those with cosmological significance
  – LLPs can be detected through a huge variety of signatures
  – Many of these signals are truly spectacular – a few events can be a discovery
  – For existing experiments, we have not yet reached the full LLP discovery potential
  – And LLPs present many opportunities for new and clever experiments (and new and clever experimentalists!)
INTRODUCTION

• This is by now a huge field and it is impossible to give a proper theory overview. Here I will present a small sampling of theoretical ideas that have led to my personal optimism about LLPs.

• In many cases, LLPs scenarios are “too flexible”; couplings, mass splittings can be tuned to be arbitrarily small and voila – LLP! This is fine (we should look where we can look at this point), but for a short talk…

• Also cosmology provides both a motivation for LLPs and a way to focus the discussion.

• So here I will attempt to highlight scenarios in which LLPs have some independent reason to be long-lived and have some interesting cosmological implications.
THE NEW PARTICLE LANDSCAPE

Mass

Already Discovered

Strongly Interacting Heavy Particles

Weakly Interacting Light Particles

Impossible to Discover

Interaction Strength

Power

Particle Colliders

1

10^-3

10^-6

LLPs from Light Physics

LLPs from Weak-Scale Physics
LLPs FROM WEAK-SCALE PHYSICS
WEAK-SCALE PHYSICS AND LLPs

• Why should there be LLPs at the weak scale? After all, the natural decay length is $c\tau \sim c/m_W \sim 10^{-17}$ m!

• But hierarchy problem $\rightarrow$ new physics at 100 GeV, and precision EW $\rightarrow$ no new physics below few TeV in 4-pt ints.

• Simple solution: impose a discrete parity, so all interactions require pairs of new particles.

• This makes the lightest new particle stable. This is a general argument. It may be augmented in specific contexts, e.g., in SUSY, $p$ decay $\rightarrow$ R-parity $\rightarrow$ stable LSP.

Cheng, Low (2003); Wudka (2003); Farrar, Fayet (1974)
• What good is a stable weak-scale state? Dark matter!

• The resulting relic density is
  \[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

• For a WIMP, \( m_X \sim 100 \text{ GeV} \) and \( g_X \sim 0.6 \) \( \rightarrow \) \( \Omega_X \sim 0.1 \)

• This simple coincidence, the WIMP Miracle, ties together weak-scale physics, LLPs, and cosmology, and has led to the prominence of missing \( E_T \) searches and DM at colliders.
LLPs IN STANDARD SUSY

• But this focus on missing $E_T$ is a vast oversimplification.

• Consider standard (gravity-mediated) supersymmetry. The gravitino has mass $\sim 100$ GeV, couplings $\sim M_W/M_{Pl} \sim 10^{-16}$.

• $\tilde{G}$ not LSP

• Assumption of most of literature

• $\tilde{G}$ LSP

• Completely different cosmology and particle physics
LLPs IN SUPERWIMP SCENARIOS

• In the $\tilde{G}$ LSP scenario, WIMPs freeze out as usual, but then decay to $\tilde{G}$ after $M_{Pl}^2/M_W^3 \sim$ seconds to months.

• The gravitino is superWIMP DM, naturally has the right relic density. But now the WIMP can be charged, implying metastable charged LLPs at colliders.

Feng, Rajaraman, Takayama (2003)
LLPs AND BBN

- Decays to superWIMPs can impact light element abundances

- BBN excludes $\chi \rightarrow Z\tilde{G}$, but $\tilde{I} \rightarrow I\tilde{G}$ may be ok and may even fix the longstanding lithium anomaly! It is not true that BBN categorically excludes LLP lifetimes $> 1$ s.

- Late decays may also distort the CMB, resolve small-scale structure: many interesting cosmological imprints.

Feng, Rajaraman, Takayama (2003); Kaplinghat (2004); Cembranos et al. (2004); …
If we see metastable charged LLPs, we know they must decay.

We can collect these particles and study their decays.

Several ideas have been proposed:

- Catch sleptons in a 1m thick water tank (up to 1000/year) and then move them to a quiet place to observe their decays.
  - Feng, Smith (2004)

- Catch sleptons in LHC detectors

- Dig sleptons out of detector hall walls
  - De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape (2005)
LLPs IN GAUGE-MEDIATED SUSY

• Scenarios with gauge-mediated SUSY breaking are among the most famous of those predicting LLPs.
  
  Dine, Nelson, Nir, Shirman (1994, 1995); Dimopoulos, Dine, Raby, Thomas (1996); …

• NLSPs decay to light \( \tilde{G} \) LSPs. The \( \tilde{G} \) mass and the NLSP decay length are correlated. For \( \tilde{G} \) masses \( \sim \) keV (motivated, with caveats, by \( \tilde{G} \) DM), the decay lengths are macroscopic

\[
cT_{\text{NLSP}} \approx 50 \text{ cm} \left( \frac{200 \text{ GeV}}{m_{\text{NLSP}}} \right)^5 \left( \frac{m_{\tilde{G}}}{\text{keV}} \right)^2
\]

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<thead>
<tr>
<th></th>
<th>Neutralino NLSP</th>
<th>Slepton NLSP</th>
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<tbody>
<tr>
<td>Prompt</td>
<td>Prompt photons</td>
<td>Multi-leptons</td>
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<tr>
<td>Intermediate</td>
<td>Displaced photons</td>
<td>Displaced lepton</td>
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<td>Displaced conversion</td>
<td>Track kinks</td>
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<td>Long-Lived</td>
<td>Missing ( E_T )</td>
<td>Time-of-flight</td>
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<td>High ( dE/dx )</td>
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Scenarios with anomaly-mediated SUSY breaking give additional interesting LLPs signals

Randall, Sundrum (1998); Giudice, Luty, Murayama, Rattazzi (1998); …

The LSPs are a highly degenerate Wino triplet with $\Delta m_{\text{loop}} \gg \Delta m_{\text{tree}}$

Typically, there are 2-body decays $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ and disappearing tracks after $\sim 10\text{cm}$

In exotic cases, there can be even greater degeneracy, leading to very long decay lengths and 3-body decays $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 (e^+ \nu_e, \mu^+ \nu_\mu)$
LLPs IN OTHER WEAK-SCALE MODELS

• By considering a few standard models of weak-scale physics, we have motivated a plethora of possible LLP signatures.

• Of course, there are many other motivated weak-scale models with LLPs.

• In SUSY: e.g., R-parity violating SUSY and compressed SUSY, which have become more motivated as generic, sub-TeV SUSY becomes excluded.

• Extra dimensional scenarios typically have similar possibilities (e.g., viewing universal extra dimensions as bosonic supersymmetry), and naturally compressed spectra.

• Many other motivations and cosmological connections: leptogenesis, neutrino masses, etc.
LLPs FROM LIGHT PHYSICS
DARK SECTORS

• In recent years, dark matter → dark sectors. What do we know about its properties?

• In general, nothing. But suppose DM freezes out in the dark sector just as we discussed above for WIMPs in the visible sector:

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

• WIMP Miracle: \( g_X \sim 1, \ m_X \sim 100 \text{ GeV} \rightarrow \) right abundance.

• WIMPless Miracle: But with a dark sector, we don’t need to fix \( g_X \sim 1 \). The dark sector can have lighter particles and weaker interactions and still have the right abundance.

Boehm, Fayet (2003); Feng, Kumar (2008)
THE NEW PARTICLE LANDSCAPE

Mass

Interaction Strength

Particle Colliders

MeV

GeV

TeV

10^{-6}

10^{-3}

1

Too Attuned to be Dark Matter

Already Discovered

Weakly Interacting Light Particles

Strongly Interacting Heavy Particles

Impossible to Discover

Just Right to be Dark Matter

Too Much to be Dark Matter
PORTALS

• Dark sectors need not talk with us. But if they do, what are the most likely non-gravitational interactions?

• Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is induced by arbitrarily heavy mediators:

\[ F_{\mu\nu} F_{D}^{\mu\nu} \]

• It is "most likely" because it is non-decoupling. Cf.

\[ \frac{F_{\mu\nu} F_{D}^{\nu\alpha} F_{\alpha}^{\mu}}{M^2} \]

• It is also naturally small, since it is induced by a loop.

This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- **Spin 1**
  - Dark photon, couples to SM fermions with suppressed couplings proportional to charge: $\varepsilon q_f$. Holdom (1986)

- **Spin 0**
  - Dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin \theta m_f$. Patt, Wilczek (2006)

- **Spin 1/2**
  - Sterile neutrino, mixes with SM neutrinos with suppressed mixing $\sin \theta$. SM Dark Force

\[ F_{\mu\nu} F^{\mu\nu}_D \]

\[ h^\dagger h \phi^\dagger_D \phi_D \]

\[ h L \psi_D \]
The advent of dark sectors, along with axion-like particles, light gauge bosons, etc., has highlighted a new class of LLPs. Consider a neutral particle with energy $E \sim \text{TeV}$, mass $m \sim 100 \text{ MeV}$, coupling $\varepsilon \sim 10^{-5}$.

- It passes through matter essentially without interacting: radiation length is $(10 \text{ cm}) \varepsilon^{-2} \sim 10^9 \text{ m}$, the distance to the moon!
- It may decay to visible particles, but only after traveling a long distance.

Velocity near the speed of light

Rest lifetime enhanced by small mass, small $\varepsilon$

Lifetime further enhanced by time dilation

\[
L = \nu \tau \gamma \sim (100 \text{ m}) \left[ \frac{10^{-5}}{\varepsilon} \right]^2 \left[ \frac{100 \text{ MeV}}{m} \right]^2 \left[ \frac{E}{\text{TeV}} \right]
\]
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\[ L \propto \frac{1}{\epsilon^2 m^2} \]

MUCH LONGER LIFETIMES
LIGHT LLP PRODUCTION

• The advent of light and weakly interacting particles greatly increases the possible modes of production.

• Production in weak-scale processes remains interesting.

• But now production through light SM particle decays is also possible, opening up the floodgates to experiments at both the energy frontier and the intensity frontier.
THERMAL TARGETS: VISIBLE DECAYS

- If $m_{\text{LLP}} < 2m_{\text{DM}}$, the LLP will decay to the SM, and the most promising signal is visible particle-anti-particle pairs.

- The introduction of dark sector-SM interactions modifies DM freeze out, since the DM can annihilate to the SM.

- To determine the thermal relic targets, must work in a definite model.

- E.g., for dark photons decaying visibly to SM particles, the thermal targets focus attention on
  masses $m \sim 10 \text{ MeV} – \text{many GeV}$
  couplings $\varepsilon \sim 10^{-5} – 10^{-3}$
THERMAL TARGETS: VISIBLE DECAYS

- If $m_{LLP} > 2m_{DM}$, the LLP will typically decay invisibly to DM, and the most promising signal is missing mass or missing energy.

- Again freeze out sets some thermal relic targets, but there is a new possibility: resonant annihilation for $m_{LLP} \sim 2m_{DM}$.

- For dark photons decaying invisibly to DM, the thermal targets are again typically around masses $m \sim 10$ MeV – manu GeV couplings $\varepsilon \sim 10^{-5} – 10^{-3}$

- But for even 10% fine-tuning, e.g., $m_{LLP} \sim 2.2 m_{DM}$, the thermal targets can shift down to couplings $\varepsilon \sim 10^{-7} – 10^{-5}$, beyond any proposed experiment.
SUMMARY

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