THEORY OVERVIEW OF
LONG-LIVED PARTICLES

Brian Shuve — SLAC
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Long-Lived Particles in the SM

- The world is full of long-lived particles
Long-Lived Particles in the SM

- Why are SM particle lifetimes long?
- Example 1: charged pion

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

- Quark flavour conserved by all but weak interactions

- Decay highly off-shell:
  \[ \Gamma_{\pi^+} \sim g_W^2 \left( \frac{M_\pi}{M_W} \right)^4 M_\pi \]

See M. Strassler, various talks; S. Knapen, LBL ATLAS trigger workshop
Long-Lived Particles in the SM

• Why are SM particle lifetimes long?
• Example 2: neutron

Isospin ensures that proton and neutron are nearly degenerate

Decay highly off-shell:

\[ \Gamma_{\pi^+} \sim g_W^2 \left( \frac{M_n - M_p}{M_W} \right)^4 (M_n - M_p) \]
Long-Lived Particles in the SM

- Why are SM particle lifetimes long?
- Example 3: flavour-changing neutral currents

- Lepton flavour only violated by tiny neutrino Yukawa couplings / neutrino masses

\[ \text{Br}(\mu \rightarrow e\gamma) \sim 10^{-54} \]
Long-Lived Particles in the SM

- SM particle lifetimes can be long if an approximate symmetry makes the particle stable
  - Typically has to do with “weakness” of weak interactions
  - This in turn arises from hierarchies of scale such as \( \Lambda_{\text{QCD}} \ll M_W \)

- Electroweak symmetry can lead to mass degeneracies, which suppress decay rates

- Small symmetry-breaking parameters can suppress decay rates
Long-Lived Particles Beyond the SM

• Same principles apply to BSM particles!

• Feeble couplings, no definite mass scale: easily get LLPs!
Outline of Talk

• Examples of Models with Long-Lived Particles

• A Theorist’s Take on the Road Ahead
  • A Systematic Approach to Searches
  • Backgrounds at the LLP frontiers
  • Towards a comprehensive search strategy
  • Taming wild signatures
LLP Models: Supersymmetry

R-parity-violating SUSY:

Pure weak-ino states:

- Electroweak symmetry gives degeneracy of NLSP-LSP masses if little mixing between Higgsino/gauginos

\[ |\lambda| \lesssim 10^{-8} \]

\[ c\tau \approx 0.7 \text{ cm} \times \left( \frac{\Delta m}{340 \text{ MeV}} \right)^3 \]
LLP Models: Supersymmetry

Split SUSY:
- Models with decoupled supersymmetric scalars

\[ c\tau \approx 100\mu m \times \left( \frac{m_\tilde{q}}{10^3 \text{ TeV}} \right)^4 \times \left( \frac{\text{TeV}}{m_\tilde{g}} \right)^5 \]

Gauge mediation:
- Decays to gravitino suppressed by SUSY-breaking scale

\[ c\tau \approx 100\mu m \times \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \times \left( \frac{100 \text{ GeV}}{m_\tilde{\tau}} \right)^5 \]
LLP Models: Supersymmetry

Lessons from SUSY:

• Production typically through new particles charged under SM gauge interactions (gluinos, stops, Higgsinos, etc.)
  • Some new, **heavy** particles in spectrum
  • Can have prompt production of jets, leptons, MET, …
  • Often LLP pairs

• LLP decays give jets, leptons, MET, or could be **stable & charged**

• Sometimes spectra are compressed, so there is still benefit in looking at searches for softer objects
LLP Models: Hidden Sectors

- New particles may (likely) be SM singlets
- Could be any mass! Want to look for low-mass LLPs in addition to > weak scale
- Could have own hidden-sector confinement, multiple states, … hidden valleys: Strassler, Zurek 2006
- Rich phenomenology, need comprehensive search strategies to cover all bases
Hidden-Sector Portals

- Singlets dominantly couple to SM via singlet portals

HIGGS PORTAL

VECTOR PORTAL

NEUTRINO PORTAL

AXION PORTAL
The Higgs Portal

- Probably the best motivated portal due to small Higgs width
- Easy to have large beyond-SM branching fractions!

Example: Higgs portal to confining hidden sector

- Seen resurgence in interest due to connection w/ hierarchy problem in Twin Higgs models

\[ c \tau \sim 18 \text{ m} \times \left( \frac{10 \text{ GeV}}{m_0} \right)^7 \]
The Higgs Portal

• Can have variety of signatures based on whether pure-glue or quarks

• Different, long lifetimes for each type of hidden-sector particle
  • Scalar states can mix with SM Higgs, decay to bb, taus, etc
  • Vector mesons can mix with SM photon, decay to leptons
  • Some could be absolutely stable (giving rise to MET)

• Can also have mix of all of the above
  e.g., “semi-visible jets”, Cohen, Lisanti, Lou 2015
The Higgs Portal

• Higgs associated production mechanisms give additional prompt objects

• Can be useful for trigger and reconstruction

VBF + LLP(s)  
VH + LLP(s)

(jets, leptons, MET, …)
The Higgs Portal

- Complementarity between different experiments
- Particularly important for all-hadronic channels

Figure 1.8: Illustration of the parameter space regions probed by different experiments, assuming pair-production of $\pi v$ particles in the decay of a Brout-Englert-Higgs boson, whose assumed mass range (in GeV/c$^2$) is indicated in each region. The vertical dotted lines indicate the proper lifetime where each search is the most sensitive. For a full comparison, also the sensitivity of each search and the experimental signature, one or two vertices, should be taken into account.

(assuming only pair production, hadronic decays)

Pieter David thesis (LHCb), 2016

- In all cases, should push to more aggressive limits on Higgs mixing
The Neutrino Portal

- Heavy, right-handed neutrino mixes with SM neutrino
- Naturally long lifetime due to off-shell decay

$W^\mp \rightarrow N \rightarrow \mu^\pm + N\mu + \bar{\nu}_e$

$M_N \ll M_W$

- Get 1 low mass LLP (lepton-only or semileptonic) from $W/Z$ decay

Helo, Hirsch, Kovalenko 2013; Izaguirre, BS 2015
The Neutrino Portal

• Complementary forward/low-E experiments

\[ B^\pm \to \mu^\pm N \to \mu^\pm \mu^\pm \pi^\pm \]

\[ B \to D^{(*)\pm} \ell^\pm N \to \ell^\pm \ell^\pm \pi^\mp \] \( m_N \) (GeV)

LHCb: 1401.5361; Belle: 1301.1105

• Not yet leading constraint, more inclusive searches (including more initial states) could do better
Decays of Hidden-Sector LLPs

- LLP widths are, by definition, small
  - Easily modified by new couplings
  - Usually, lifetime best treated as free parameter

- Decays often motivated by particular portal, but sometimes uncorrelated

- From theory point of view, decays at different distances classified in same manner (hadrons, leptons,…) while totally different for experimental reconstruction
Summary of Hidden-Sector Portals

- Can have many different:
  - Masses
  - Lifetimes
  - Associated objects
  - Decay modes/stable exotic particle states
  - LLP multiplicities

- When lifetime arises due to a hierarchy of scales, can get large boosts
  
  *e.g.*, Falkowski *et al.*, 2010

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Table 11: Ranges of lifetime ($\tau$) excluded at 95% CL for $H \rightarrow d + X$ and $H \rightarrow 4d + X$, assuming 10% BR and the Higgs boson SM gluon fusion production cross section. TYPE2-TYPE2 events are not used.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$\tau$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-2}</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>10^{-1}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>10^{0}</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>10^{1}</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>10^{2}</td>
<td>10^{-1}</td>
</tr>
</tbody>
</table>

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Figure 17: Parameters space exclusion plot for dark photons as a function of the mass and of the kinetic mixing parameter $\varepsilon$, from figure 6 of ref. [60]. Shown are existing 90% CL exclusion regions from beam dump experiments E137, E141, and E774 [16–18], Orsay [23], U70 [24], CHERM [25], LSND [26], A1 [20], the electron and muon anomalous magnetic moment [33–35], HADES [30], KLOE [28, 29], the test run results reported by APEX [19], an estimate using a BaBar result [22, 31, 32], and constraints from astrophysical observations [36, 37]. The 90% CL exclusion limits from the present search, assuming the FRVZ model $H \rightarrow 2d + X$ with decay branching fraction to $d$ of 5/10/20/40% and the NNLO gluon fusion Higgs production cross section, are shown.
Outline of Talk

• Examples of Models with Long-Lived Particles

• A Theorist’s Take on the Road Ahead
  • Developing a systematic approach to searches
  • Ensuring that needed searches can be done
  • Backgrounds at the LLP frontier
  • Taming wild signatures
A Systematic Approach to Searches

• Searches often target/are optimized for particular model

• However, LLP searches can be inclusive enough to have excellent sensitivity to a range of scenarios
  Liu, Tweedie 2015; CMS & ATLAS displaced jets; HSCP searches; ATLAS displaced multitrack; CMS “displaced SUSY”; …

• Want to identify a minimal set of motivated searches that covers as many scenarios as possible while being reasonably achievable

• Identify motivated, non-redundant list of simplified models
  • Searches should be (reasonably) easily re-interpretatable
A Systematic Approach to Searches

WORKING GROUP: Simplified Models/Monte Carlo/RECASTING and Reinterpretation

• Choose set of models, cross-reference to searches
  • Low-mass and/or high-multiplicity searches are most under-developed, need most work

• Ensure adequate tools exist for smooth interface between theory and experiment

• Recommendations for presentation of results so that searches can be easily applied to other models
  • Most important for signal efficiency?
Ensuring That Searches are Possible

• In order to do search, data must be on tape!
  • New triggers needed (especially for soft and/or high-multiplicity objects)?

• Can existing triggers be doing more?
  • Seeding LLP analyses with multiple triggers
  • Using associated objects where possible

• As we head into Phase 2, concerned that trigger sensitivity to LLP will degrade
  • Strategies to mitigate pile-up? Best ways to use upgrades?
Ensuring That Searches are Possible

WORKING GROUP: Triggering Strategies and Recommended Studies for LLP Searches

• Discuss new uses of existing triggers, as well as brand new ideas

• Complementarity between ATLAS/CMS/LHCb/auxiliary detectors, especially for low-mass or unusual signatures

• Preparing for new challenges in future running
  • Soft displaced leptons (once iso/track requirements start coming in)
  • Ways to use FTK/track trigger technologies?
  • Impact of timing and other improvements on LLP reconstruction
Backgrounds for LLP Searches

- Unique non-prompt and non-collision backgrounds for LLPs
- Many searches are bkd-free
  - But, selections also limit sensitivity to low-mass regime
  - This may no longer be true as we push into low-mass regime or to other signatures
  e.g., Coccaro et al., 2016
- For theorists (and experimentalists on other expts), helpful to know where limitations are & what could be possible
- Connects with earlier discussion on upgrades
### Backgrounds for LLP Searches

**WORKING GROUP: Backgrounds for LLP Searches**

- Summarize important backgrounds for LLP searches
- Better methods for characterizing such backgrounds and identifying signal vs. background
- Helps theorists (and others!) think of ideas to suppress backgrounds & models that give distinctive signatures
Taming Wild Signatures

- Showers can occur in hidden sectors with large couplings & hierarchies of scales

Schwallier, Stolarski, Weiler 2015

Knapen et al., 2016

Event displays by M. Strassler
Taming Wild Signatures

• Ever more interest in these models thanks to neutral naturalness, Hidden Valleys, etc.

• But there are many unknowns:
  • Radiation patterns (details of shower)
  • Multiplicities (details of hadronization)
  • Fraction of visible vs. invisible particles
  • Fraction of particles with a given lifetime

• Not well covered by existing searches, in part because it’s hard to design a search that isn’t overly optimized to a particular model
Taming Wild Signatures

WORKING GROUP: Dark Showers

- Work systematically to identify most relevant parameters affecting the phenomenology (simplified model framework?)

- What are the challenges with robustly dealing with variable numbers of particles, overlapping states, etc.?

- Identify search strategies to fill the major gaps AND assure experimentalists that the searches are broadly applicable
Summary

• For decades, LLPs predicted in theoretical models & today receiving a resurgence in interest

• Amazing progress in the past few years on the theory & experiment fronts, but a long way to go

• One day, we hope to move from constraints to discovery. Are we ready for when that time comes?