THEORY OVERVIEW OF LONG-LIVED PARTICLES

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LHC-LLP Workshop
CERN 2018
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

• Reinterpretation of LLP Searches
LLP Models: Supersymmetry

R-parity-violating SUSY:

- Off-shell decay
- Small splitting (phase space)
- Small coupling

Pure weak-ino states:

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

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

\[ cT \approx 0.7 \text{ cm} \times \left( \frac{\Delta m}{340 \text{ MeV}} \right)^3 \]
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

Craig et al., arXiv:1501.05310; Curtin, Verhaaren, arXiv:1506.06141…
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

*** see Matt’s talk; also dark showers breakout session! ***

e.g., Strassler, Zurek 2006; Han et al., 2007; Juknevich, Melnikov, Strassler, 2009; Schwaller, Stolarski, Weiler 2015; Cohen, Lisanti, Lou 2015; Pierce et al., 2017; ....
The Higgs Portal

- Higgs associated production mechanisms give additional prompt objects
- Can be useful for trigger and reconstruction
The Higgs Portal

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

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

*** HNL Breakout Session!! ***

- Get 1 low mass LLP (lepton-only or semileptonic) from $W/Z$ decay
  Helo, Hirsch, Kovalenko 2013; Izaguirre, BS 2015; see talks by G. Popara, G. Cottin, O. Fischer
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

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

• Examples of Models with Long-Lived Particles

• Reinterpretation of LLP Searches
Reinterpretation Challenges

- One model can generate many different signatures
- One signature can come from many models

neutral LLP channels

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>$\gamma\gamma(+\text{inv.})$</th>
<th>$\gamma + \text{inv.}$</th>
<th>$jj(+\text{inv.})$</th>
<th>$jj\ell$</th>
<th>$\ell^+\ell^-(+\text{inv.})$</th>
<th>$\ell^+\ell^-_{\beta\neq\alpha}(+\text{inv.})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPP: sneutrino pair</td>
<td>$\tilde{\nu}$ or gluino pair $\tilde{g} \rightarrow jjX$</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
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<td>SUSY</td>
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<tr>
<td>HP: squark pair, $\tilde{q} \rightarrow jX$ or gluino pair $\tilde{g} \rightarrow jjX$</td>
<td>$\tilde{\nu}$</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
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<tr>
<td>HP: slepton pair, $\tilde{\ell} \rightarrow \ell X$ or chargino pair, $\tilde{\chi} \rightarrow W X$</td>
<td>$\tilde{\nu}$</td>
<td>SUSY</td>
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<td>SUSY</td>
</tr>
<tr>
<td>HIG: $h \rightarrow XX$ or $\rightarrow XX + \text{inv.}$</td>
<td>Higgs, DM*</td>
<td>$\tilde{\nu}$</td>
<td>Higgs, DM*</td>
<td>RH$\nu$</td>
<td>Higgs, DM*</td>
<td>RH$\nu^*$</td>
<td>RH$\nu^*$</td>
</tr>
<tr>
<td>HIG: $h \rightarrow X + \text{inv.}$</td>
<td>DM*, RH$\nu$</td>
<td>$\tilde{\nu}$</td>
<td>DM*</td>
<td>RH$\nu$</td>
<td>DM*</td>
<td>$\tilde{\nu}$</td>
<td>$\tilde{\nu}$</td>
</tr>
<tr>
<td>RES: $Z(Z') \rightarrow XX$ or $\rightarrow XX + \text{inv.}$</td>
<td>$Z'$, DM*</td>
<td>$\tilde{\nu}$</td>
<td>$Z'$, DM*</td>
<td>RH$\nu$</td>
<td>$Z'$, DM*</td>
<td>$\tilde{\nu}$</td>
<td>$\tilde{\nu}$</td>
</tr>
<tr>
<td>RES: $Z(Z') \rightarrow X + \text{inv.}$</td>
<td>DM</td>
<td>$\tilde{\nu}$</td>
<td>DM</td>
<td>RH$\nu$</td>
<td>DM</td>
<td>$\tilde{\nu}$</td>
<td>$\tilde{\nu}$</td>
</tr>
<tr>
<td>CC: $W(W') \rightarrow \ell X$</td>
<td>$\tilde{\nu}$</td>
<td>$\tilde{\nu}$</td>
<td>RH$\nu^*$</td>
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Reinterpretation Challenges

- We want searches to cover as much phase space as possible

- We want results presented so they are as broadly applicable as possible

- LLP searches are challenging because:
  - “Standard” objects (electrons, muons, tracks) are not so standard if they come from LLP decay or stable LLP
  - Signal efficiencies hard to model with publicly available simulation
  - Efficiencies can have strong dependence on kinematics, LLP decay position, etc.
Reinterpretation Challenges

• Some possible approaches:
  • Cut flow efficiencies
    • But need reliable public tools to simulate signals!
  • Detailed efficiency maps
    • Huge effort to generate!
    • Efficiencies…of what? “Theory” object? “Detector” object?
  • Efficiencies for simplified models
    • Which simplified models? What parameter points?

MUCH MORE on this in Nishita’s reinterpretations overview and in every talk today!
Reinterpretation Challenges

- Challenges multiply for more exotic signatures, charged/color-charged LLPs, quirks, etc.

Event displays by M. Strassler

*** Matt's talk, Dark Showers & G4 Breakout Sessions!! ***
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?
Back-up slides