Long-lived Particles
motivations, models and gaps

Nishita Desai • Snowmass Meeting • 7 July 2020
What does long lifetime signify?

Three ways to get a long-lived particle:

1. Small couplings
2. Heavy intermediate particle (e.g. most meson decays in SM)
3. Compressed spectrum (e.g. new SU(2) Triplet fermion)

Ways to produce a particle at the LHC:

1. Needs to have colour/EW-charge to be produced directly
2. Can be produced in decays of a “mediator” if it does not have SM charges
Instructions from EF09 convenors (last Tuesday):

‘point to some of these existing … studies …; this would give the audience a good idea of … studies that are coming up for this snowmass exercise’

Not a review, apologies if I missed your paper.
Most of these ideas have been around a long time.

‘focus on charged, *not* light [LLPs] … with the idea of connection with SUSY and in relevant DM’

The number of models selected here is limited, see LLP Community white paper (1903.04497) for a comprehensive list of simplified models.
LLP Signature vocabulary

Displaced
Leptons  eµ, µµ
Vertices with muons, lepton veto (n_trk ≥ 5), dimuon
Jets (emerging, lepton, trackless)

“Prompt”
Heavy charged track
Disappearing track

One-off SUEP
Motivation for LLPs: Dark Matter

Dark Matter model building relies on obtaining the right observed DM density

Ways to get LLPs:

1. Large couplings but high compression (thermal co-annihilation)
2. Small couplings with heavy mediators + medium compression (thermal co-scattering)
3. Feeble couplings with heavy mediators (non-thermal Freeze-in)
Particle naming : SUSY/non-SUSY

Warning: Particles with same quantum numbers as those predicted by SUSY are named with SUSY conventions even when not talking about SUSY.

squarks or sleptons = spin-0 with same SM charges as quarks or charged leptons; but NOT necessarily with Yukawa coupling determined by gauge couplings like SUSY

E.g. stau, sbottom

Wino = vector-like fermion, triplet under SU(2)

Bino or singlino = Majorana fermion, scalar under SM
Motivation for LLPs: Dark Matter

Co-annihilation + extreme compression: slepton/squark co-annihilation, pure-Wino

Early Universe  |  LHC
Motivation for LLPs: Dark Matter

Co-annihilation + extreme compression : stau co-annihilation

\[ \mathcal{L} \supset \tilde{\tau}^*(\chi \tau_R) + h.c. \]

Disappearing track

\[ \tilde{\tau}_1^- \rightarrow a_1^- \nu_\tau \chi \]
\[ \tilde{\tau}_1^- \rightarrow \rho^- \nu_\tau \chi \]
\[ \tilde{\tau}_1^- \rightarrow \pi^- \nu_\tau \chi \]

Heavy charged track

\[ \tilde{\tau}_1^- \rightarrow e^- \bar{\nu}_e \nu_\tau \chi \]
\[ \tilde{\tau}_1^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \chi \]

(non-SUSY) Khose et al. 1702.00750
(SUSY) Desai et al. 1404.5061
Motivation for LLPs: Dark Matter

Co-annihilation + extreme compression : pure Wino

CMS Preliminary

CMS-PAS-EXO-19-010

Pure Wino from DM: 2.7 TeV

Bramante, ND, et al 1510.03460
Cirelli et al 1407.7058
Low and Wang 1404.0682
Motivation for LLPs: Dark Matter

Co-scattering = small coupling + some compression:

D’Agnolo et al. 1705.08450
Garny et al. 1705.09292
Motivation for LLPs: Dark Matter

Co-scattering = small coupling + some compression: **singlet-triplet (Bino-Wino) model**

\[
\psi_L = \cos \theta \, \psi_1 + \sin \theta \, \psi_2 \\
\psi_H = -\sin \theta \, \psi_1 + \cos \theta \, \psi_2
\]

$mc$

\[
\Delta m \quad m_L
\]

$\psi_C \to \psi_L + W^*$  
Long-lived because $\theta$ is small

$\psi_C \to \psi_H + \pi^+$  
Long-lived because compressed

Bharucha et al. 1703.00370
Filimonova, Westhoff 1812.04628
Gaps in coverage: example of displaced leptons

CMS-PAS-EXO-16-022

No disappearing track limit from 13 TeV search for $\Delta m < 40$ GeV
Gaps can be fixed with dedicated searches

SR III
\( p_T(e, \mu) = 20 \text{ GeV} \)
\( L = 140 \text{ fb}^{-1} \), \( \sqrt{s} = 13 \text{ TeV} \)

CMS Run 1

95% CL excl.

Blekman, ND, et al. to appear 2007.xxxx
Motivation for LLPs: Dark Matter

Freeze-in: start with zero DM density, populate later via mediator decay/interactions

Hall et al. 0911.1120
Complementarity of different searches: freeze-in

Scalar DM (S) + Vector-like fermion (F)

\[ \mathcal{L} \supset -y_L S F \ell_R + \text{h.c.} \]

Belanger, ND, et al. 1811.05478
Motivation for LLPs: Naturalness (NMSSM)

(1) NMSSM for Higgs mass, (2) GMSB for SUSY breaking

Main ingredient: NLSP is Bino which decays into gravitino + singlet scalar a; a is long-lived and decays via $a \rightarrow bb$

Displaced vertex searches are potentially sensitive, but current cuts too strong.

 Loose cuts = more background $\Rightarrow$ cuts on other objects.

Less “model independent” but more sensitive for this model.
Motivation for LLPs: Naturalness + DM (hidden SU(N)s)

Emerging jets: Schwaller et al, 1502.05409

A lot of very recent work:

NN for dark jets: Bernreuther et al 2006.08639

Dark jet substructure: Cohen et al 2004.00631
Motivation for LLPs: Neutrino mass

Deppisch et al. 1905.11889

ATLAS 1905.09787

B-L model

Deppisch et al. 1905.11889
Top-down or bottom-up

(Also mentioned in Simon Knapen’s talk)

**Top-down**

Good physics motivation

New signatures no one has thought of

Covers “weird” pockets of phase space that behave differently from typical expectations

May bias search strategies

**Bottom-up**

Less prejudiced by “theory”

Good for coverage/overlaps of different signatures (simplified models)

May not be sensitive to “weird” pockets because model is too simple.

Better for future reinterpretation
Avenues for exploration

Pick a (simplified) model, investigate sensitivity in multiple searches.
**Avenues for exploration**

No specific b-tagged searches so far only search I found was

![Graph showing upper limits on number of $R^2$ decays](Image)

Displaced tau tagging would be useful e.g. low mass scalars that decay to tau pair, say $h \rightarrow aa \rightarrow 4\tau$

**Coverage gaps: displaced b/tau**

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<th>$\sqrt{s} = 8$ TeV</th>
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</table>

"[T]he primary cause for this is failure to satisfy the requirements $N_{trk} \geq 5$ and the vertex mass cut $mDV > 10$ GeV … is due to the fact that the displaced jets are mainly $b$-jets."

Allanach, ND et al. [1606.03099](https://arxiv.org/abs/1606.03099)
Avenues for exploration

More ideas:

• Kink tracks: predicted for charged mediator that decays to lepton/pion
• Soft decay products from displaced decays (e.g. soft emerging jets, soft leptons)
• Special triggers for signatures other than mono-jet or MET; maybe use multiple objects in trigger to lower thresholds
• …
Another important hurdle for theorists: reinterpretation

Over the years, we have identified all information required to re-interpret SUSY searches. Jet algorithms are standard, smearing functions are published, lepton efficiency is given in terms of momentum, cut flow tables, …

LLP searches are fairly new and there isn’t a standard list of objects or an agreed-upon method of communicating efficiencies etc. that can be used for reinterpretation.

Even when efficiencies are available, they do not always work.
Summary

• Multiple motivations to look for LLPs, studies ongoing at least since 2013.

• Dark Matter models with LLPs typically predict charged, long-lived mediators, which can be seen in track searches and in displaced lepton/jet searches.

• Neutrino mass motivations give Heavy Neutral Leptons, signatures can be displaced di-leptons, displaced vertices.

• Lots of new activity in dark showers/emerging jets (Hidden valley, twin higgs, etc.).

• Many gaps remain, in signatures as well in lifetime coverage.

• We need to work out how to best preserve the result for future use (reinterpretation).