Searches for Long-Lived Particles at High-Energy and High-Intensity Experiments

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Motivation

• Long-lived particles are ubiquitous in the Standard Model and its extensions.
  • LLPs appear due to approximate symmetries, mass hierarchies, weak couplings, …
  • Arise in top-down models addressing dark matter, baryogenesis, naturalness, …
  • Light particles are necessarily weakly coupled to SM; naturally long lived

• LLPs feature a rich phenomenology, requiring multiple novel search strategies, experiments, and facilities to probe a broad range of models and signatures:
  • Calls for dedicated strategies for triggering, reconstruction, background mitigation
  • Motivates new dedicated LLP detectors at existing facilities

• There is still much work to be done and many exciting results ahead!

See S. Knapen’s previous talk
A Rich Experimental Landscape!

Modest upgrades enable transformative physics

Significant US contribution
International effort

Present

Future high energy colliders…

+ ATLAS and CMS

Figure from RF6 Experiments & Facilities Whitepaper, 2206.04220
LLPs at the LHC: ATLAS and CMS

- Variety of signatures of LLPs (e.g., displaced and delayed leptons, photons, and jets; displaced vertices, disappearing tracks; nonstandard tracks, …)

- Striking signatures, but often require custom trigger, reconstruction, background mitigation strategies

- Substantial work needed both from the phenomenology and experimental communities to realize the full potential of LHC LLP physics program

- Unique sensitivity to heavy LLPs and low mass LLPs produced through heavy particle decays

Figure from J. Antonelli
LLPs at the LHC: LHCb

- Designed to detect long lived $b$, $c$ hadrons; this capability extends to BSM LLPs

- Advantages include unique forward acceptance, low pile-up, precise mass and time resolution, excellent tracking

- Powerful sensitivity to low mass LLPs with moderate lifetimes
Probing LLPs with LHC Auxiliary Detectors

- **Basic idea:** use primary high energy LHC $pp$ collisions as the production source of LLPs, and place a detector nearby the interaction point to detect them.

See for example:
- [Haas, Hill, Izaguirre, Yavin]
- [Feng, Galon, Kling, Trojanowski]
- [Chou, Curtin, Lubatti]
- [Gligorov, Knapen, Papucci, Robinson]

See J. Feng’s talk next on Forward Physics Facility.
Central LHC shielded detectors

- Transverse location offers sensitivity to LLPs produced through both exotic light (e.g., meson) and heavy (e.g., Higgs) particle decays
- Backgrounds substantially mitigated by additional shielding / dirt

- Medium-scale, modest cost detector located 25 m from LHCb IP for HL-LHC
- Smaller CODEX-β demonstrator will operate during Run 3

- Large-scale surface detector near CMS for the HL-LHC era
Other proposed auxiliary detectors:

Figure from EF8, EF9, EF10 BSM draft report
**B factories (Belle II)**

- Medium energy ($E_{CM} \sim 10.5$ GeV), high luminosity $e^+e^-$ collider
- Hermetic detector, full reconstruction of event kinematics
- Direct production of mediator through electron, photon couplings, or through $B$ meson decays
- Sensitive to a variety of signatures of prompt, displaced, and long-lived mediators

Fig from L. Corona
Probing LLPs with Fixed Target Experiments

Advantages:
• high collision luminosity
• forward kinematics
• large production rates

• Basic experimental setup entails a detector located downstream of the target
• Produce LLP via rare meson decays, bremsstrahlung, secondary collisions (e.g. photon induced Primakoff process, muon induced bremsstrahlung)
• A variety of search strategies may be employed depending on the properties of the LLP:
  • mass, lifetime, couplings to SM particles, interactions with other states (e.g., dark matter, neutrinos, etc.)
Beam Dumps

- Leverage relatively higher intensities, longer baselines to probe long mediator lifetimes, small couplings

- Experiments include MicroBooNE, ICARUS, SBND, T2K-ND280, BDX, DUNE, SBN-Beam Dump, PIP-II Beam Dump, ...
Short Baseline Neutrino Experiments @ FNAL

- MicroBooNE, SBND, ICARUS LArTPC detectors
- Situated along 8 GeV Booster beam line and slightly off axis from 120 GeV NuMi beam line
- Will collect $\sim 10^{21}$ POT over next several years
- LArTPC detectors have excellent particle ID, reconstruction capabilities

DUNE Near Detector @ FNAL

- 120 GeV proton beam, $\sim 10^{22}$ POT
- Multi-Purpose Near Detector (MPD): 1 ton gaseous Argon TPC, surrounded by ECAL, located 574m downstream of target
- Gaseous near detector leads to relatively low beam-related neutrino background rates
• Compact detector geometry, relatively short baseline allows for sensitive probes of moderate mediator lifetimes

• Experiments include HPS, DarkQuest, …

• Dedicated missing energy/momentum experiments (NA64, LDMX, M$^3$) can also search for visibly decaying particles in a similar manner
DarkQuest @ FNAL

- DarkQuest is a proposed upgrade of the SeaQuest nuclear physics experiment
- 120 GeV protons impinge on ~ 5m iron beam dump, $10^{18} - 10^{20}$ POT
- 4 tracking stations, muon ID system, EM calorimeter (proposed upgrade)

HPS @ JLAB

- Multi-GeV electron beam on high Z thin target
- Silicon vertex tracker + ECAL
- Both prompt and displaced dark photon searches are possible
Kaon Factories (e.g., NA62, KOTO)

- Produce mediator via rare kaon decays
- Long lived mediators detected via missing mass technique (as above)
- Short lived mediators can be searched for directly by detecting their decay products
- The approach benefits from the narrowness of the Kaons, as well as large datasets
- Other dedicated meson and lepton facilities can also probe LLPs (PIONEER, Mu3e, REDTOP, …)

See 2201.07805 for a recent review article
Very Long Lived / Stable Particles (e.g., Dark Matter)

- Missing pT searches at the LHC

- Fixed target missing energy / momentum (NA64, LDMX, M^3…)

- Fixed target production and re-scattering (CCM, COHERENT, BDX, DUNE, …)
Benchmark Studies
Long-lived chargino
(disappearing track signature)

Higgs decay to LLPs
($h \rightarrow SS$, $S$ long lived)
Muon-philic Scalar for \((g - 2)_\mu\)

Experimental Approach
- Line/Shading types
  - excluded
  - operating exp.
  - Proposed US
  - Proposed (US Lead.)
  - Proposed (Int'l)
  - Post-2032 Proposed

- g-2 best fit
  - e^+e^- collider
  - secondary \(\mu\) from p
  - Fixed Target
  - pp collider

- Muon 3 TeV
- Muon 500 GeV
- Fixed Target
- DarkQuest
- FASER
- FASER2
- pp collider
- pp LLP
- SpinQuest
- Belle 4\(\mu\)
- Belle 4\(\mu\) (2026)

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RF6 Big Idea 3 whitepaper, 2207.08990
Inelastic Dark Matter

Fermionic IDM, $m_\chi = 3 m_1$, $\Delta = 0.1, \alpha_D = 0.1$

Experimental Approach
- $e^- e^+$ collider
- $e^- e^+$ experiment
- $p p$ LSP
- $p p$ LL Detector
- $p$ Fixed Target
- Proposed US
- Proposed/US Lead
- Proposed/US

Line/Shading types
- excluded
- operating exp.
- proposed US

RF6 Big Idea 3 whitepaper, 2207.00597
Summary and Outlook

• Long-lived particles are ubiquitous in nature and in BSM theories. They and appear in a variety of solutions to the outstanding puzzles in particle physics and cosmology.

• An expansive worldwide program of experiments will provide a fertile ground for LLP searches in the coming years.

• New auxiliary detectors at the LHC as well as intensity frontier experiments provide powerful sensitivity to a variety of LLPs, complementing searches at the main LHC experiments.

• Many exciting experiments and results on the horizon!