Searches for Long Lived Particles at the LHC – Present and Future

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Outline

• Introduction to long lived exotic particles: why do we care?
• Challenges at and results from the LHC
• New experiments for the LHC?
• Other opportunities for LLPs searches
• Summary/Outlook
New Physics Hunters @ the LHC

The ATLAS experiment

The CMS experiment

…And also LHCb and MoEDAL

LHCb
MoEDAL
LHC: So far no new physics!

Classical Searches
- Supersymmetry
- Exotica
- Flavor Universality
- ...

No signal of new physics so far!!
• The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
• But if we still do not see more than a 2 sigma at the end of run 3, the HL-LHC will be likely mostly a precision physics machine, searching for subtle deviations or small couplings
• Are we looking at the right place? Time for more effort in thinking of complementary searches?

Are we looking at the right place?

Leave no stone unturned!!
Long Lived Particles

Long lifetimes arise from a hierarchy of scales or a small coupling

- RP Violating SUSY
- ASMB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Monopoles
- Quirk Models
- Dark Matter Models
- Stable Sexaquarks
- Axion-Like Particles
- ....
Long Lived Particles @ LHC

Some of the Challenges

Triggers: Tracking detectors are powerful but difficult to use in trigger

SM backgrounds often low. But need special studies (punch through, secondary interactions, tails, cosmics...)

Special reconstruction is often needed

Some detector upgrades for High-Luminosity LHC (>2026) address these issues.
Long Lived Searches Overview

- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced leptons & lepton jets
- Displaced photons
- Dark photon decays
- Heavy Stable Charged Particles
- Stopped particles
- Emerging jets
- Monopoles stuck in material
- Heavy Neutral Lepton searches
- Strongly Interaction Massive Particles
- …. (others…new ideas… )
Long Lived Searches: Examples

- Displaced jets
- Displaced leptons
- Disappearing tracks
- Metastable R-hadrons
- Stopped particles
- Hidden Valley searches
Multi Charged Particles

Use central tracker and $\mathrm{d}E/\mathrm{d}x$ measurement to search for particles with electric charges of 2e to 7e.

Exclusion between 50 GeV and 980-1220 GeV.

arXiv:1812.03673
Search for Delayed Jets

- Using the ECAL precision timing ~200 ps
- Search for jets not connected to the primary vertex
- Data driven background estimate

EXO-19-001

GMSB long-lived gluino model search. Mass limits up to 2500 GeV
Heavy Neutral Leptons

Neutrino portal: $\nu$MSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: $N_1$, $N_2$, $N_3$.


First LHC results on prompt studies
Majorana/Dirac? Now studies with displaced jets/lepton analyses. $L \sim 1m$?
Search for Heavy Neutral Leptons

Neutrino portal: $\nu$MSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.

arXiv:1802.02965
Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac ‘31)

\[ \nabla \cdot \mathbf{E} = 4\pi \rho_e \]
\[ \nabla \cdot \mathbf{B} = 4\pi \rho_m \]
\[ -\nabla \times \mathbf{E} = \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c} \mathbf{j}_m \]
\[ \nabla \times \mathbf{B} = \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c} \mathbf{j}_e \]
\[ \mathbf{F} = q_e (\mathbf{E} + \frac{\nabla \times \mathbf{B}}{c}) + q_m (\mathbf{B} - \frac{\nabla \times \mathbf{E}}{c}) \]

\[ e g = n \frac{\hbar c}{2} = n g_D \]

\[ \sigma_D(m) = \left( \frac{g_D}{e} \right)^2 \times \sigma_{\mu\mu} \times (1 - 4 \frac{m^2}{s}) \]

Symmetrizes Maxwell equations
Searched for at all colliders
Tevatron direct limits ~ 400-800 GeV

arXiv: 1112.2999
Monopole Searches: MoEDAL @ 13TeV

2016 data analysis base on 794 kg Aluminium to “stop” the monopoles and search for them with a SQUID precision magnet (4.0fb⁻¹) arXiv:1903.08491

- Limits for different monopole charges
- First monopole search result @LHC at 13 TeV
  No signal yet.
Monopoles Stopped in the Beampipe

Test performed with pieces of material from the LHC from 18 m away from the interaction region.

Faulty connecting “fingers” were removed and scanned in a SQUID in Zurich.

|g| ≥ 4g_D


Want to use the 2012 CMS beampipe! MoEDAL officially got it since 18/2/2019!!

A beampipe analysis effort is put into place in MoEDAL.

-> The analysis preparation effort is starting now.
Proposals for New Experiments @LHC

MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL

MATHUSLA: searches for long lived weakly interacting neutral particles

FASER: searches for long lived dark photons-like particles

New: AL3X ('ALICE' for LLP arXiv.1810.03636)
Particles with Milli-Charges?

“New” idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,1 Jim Brooke,2 Claudio Campagnari,3 Albert De Roeck,1 Brian Francis,4 Martin Gastal,1 Frank Golf,3 Joel Goldstein,2 Andy Haas,5 Christopher S. Hill,4 Eder Izaguirre,6 Benjamin Kaplan,5 Gabriel Magill,7,6 Bennett Marsh,3 David Miller,8 Theo Prins,1 Harry Shakeshaft,1 David Stuart,3 Max Swiatkowski,8 and Itay Yavin7,6

arXiv:1607.04669

MilliQan Experiment

\[ \sqrt{s} = 14 \text{ TeV} \]
A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

Aim to cover the range

\[ cT \lesssim 10^7 \ldots 10^8 \text{ m} \]

\sim \text{ BBN constrained inspired}

Physic case arXiv:1806.07396
An LLP detector in the LHCb area
Re-using the ALICE detector?

A Laboratory for Long-Lived eXotics (AL3X)

Reuse the L3 magnet and (perhaps) the ALICE TPC

For LHC Run 5??

Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636
Physics Reach: Example

For low masses: MATHUSLA, CODEX-b and AL3X have a leading edge...
FASER has significant discovery potential for dark photons, dark Higgs bosons, heavy neutral leptons (sterile neutrinos), ALPs, other gauge bosons, and many other new particles.

Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.
FASTER Approval

Breaking news: the FASER experiment (phase-I) has been approved March 5th.

FASTER: CERN approves new experiment to look for long-lived, exotic particles.

Date Issued
March 5th, 2019
### Status of the Various Projects

**Lifetime frontier**

**Supplementary detectors**

<table>
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<th>Project</th>
<th>Higgs decay</th>
<th>B-meson decay</th>
<th>$\pi,\eta$-decay (dark photon)</th>
<th>Progress</th>
<th>Cost</th>
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<td>✓</td>
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<td>Technical design report</td>
<td>$$$</td>
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**MOEDAL**: monopoles, already running

**MiliQan**: milicharged particles, phase 1 detector in place

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**Similar timelines for**

- MATHUSLA
- MilliQan
- CODEX-b
- FASER

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**Diagram:**

- Run2: 2018
- LS2: 2020
- Run3: 2023
- LS3: 2027
- HL-LHC: 2027

**Legend:**

- Initial BG study
- Mini install
- BG measurements
- install
- run
Approved program at CERN to collect 3-4 ab⁻¹ with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)
CERN High Beam Intensity Initiative

Many studies on long-lived particles

Summary plots of the reach are being completed for the European Strategy Document (November)

Last workshop (January ’19)
https://indico.cern.ch/event/755856/

Next workshop November 5-6

NA62, NA64, SHIP, LHC new experiments...
New Possible Experiments

From the beyond collider study document: arXiv:1902.00260
SHiP is a proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to $O(10)$ GeV and weak couplings, down to $10^{-10}$.

New beam line in the north area at SPS
- Proton beam SPS@400GeV
- Possible to deliver $2 \times 10^{20}$ PoT in ~5 years

arXiv:1504.04956
arXiv:1811.00930
Sensitivity Summaries

Search for dark photons (visible mode)

Search for millicharges

Search for dark scalars

Search for heavy neutral leptons
Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings

- upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams

These experiments can perform searches for low mass New Physics particles eg
- HNL/sterile neutrinos
- dark photons
- ALPs
- mini/millicharges
...

<- Example for millicharges
FerMINI @FNAL?

https://indico.fnal.gov/event/18430/

Near Detector: few 100m away from the dump

> $10^{21}$ POT/Year
Current Neutral LLP Searches

at the LHC

Need a more systematic approach

Shorter lifetimes: identify DV for < ~ mm displacements

Mass gaps in current searches:
- X → leptons: 2 - 20 GeV
- X → hadrons: < 10 GeV

Slide from D. Curtin
LHC Community White Paper

Web page: https://indico.cern.ch/event/649760

Searches for long-lived particles at the LHC: Second workshop of the LLP Community

- 17 Oct 2017, 16:00 → 20 Oct 2017, 18:00 Europe/Zurich
- Giambiagi Lecture Hall (ICTP, Trieste, Italy)
- Albert De Roeck (CERN), Bobby Samir Acharya (Abdus Salam Int. Cent. Theor. Phys. (IT)), Brian Shuve (SLAC National Accelerator Laboratory), James Beacham (Ohio State University (US)), Xabier Cid Vidal (Universidad de Santiago de Compostela)

Next workshop: 27-29 May 2019 CERN

White paper — chapter statuses and roundtable
[ draft here (18 Oct)]

- Simplified models — First draft done!
- Experimental coverage — First draft essentially done!
- Triggers, upgrades, HL- / HE-LHC opportunities — First draft in progress
  — discussion today [ live doc! ]
- Re-interpretations / recommendations — First draft imminent!
- Backgrounds — First draft imminent!
- Dark showers — First draft (summarizing status and advertising for the future) imminent!

White Paper being finalized

Input from ATLAS, CMS, LHCb, proposed specialized experiments and theory
Completed March 2019 (~ 300 pages)

Also meetings with LHC Dark Matter group
Recent Reviews/Reports

White paper of the LHC long-lived particle community

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

Report of the CERN Physics Beyond Colliders Working group

Summary Report of Physics Beyond Colliders at CERN

Collider Searches for Long-Lived Particles Beyond the Standard Model
Summary

• Clearly and increased interest in LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. Many analyses done or in are progress. No signal observed yet, but only top of the iceberg covered so far.
• LLP White Paper released! (LHC). Many ideas for new analyses yet to be analysed for the LHC data.
• New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, MATHUSLA, CODEX-b, FASER, AL3X. Future beam dump experiments (SHiP). LLPs also focus in the Physics Beyond Collider studies.
• Of interest to study in detail the complementarity with LLP searches at Neutrino Near Detectors. Can these be further optimized?
• More opportunities at future projects (FCC…).