Long Lived Particles

Sarah ben Abdesselem
Advanced Particle Physics VT25

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01 Introduction

What are LLPs and their signatures

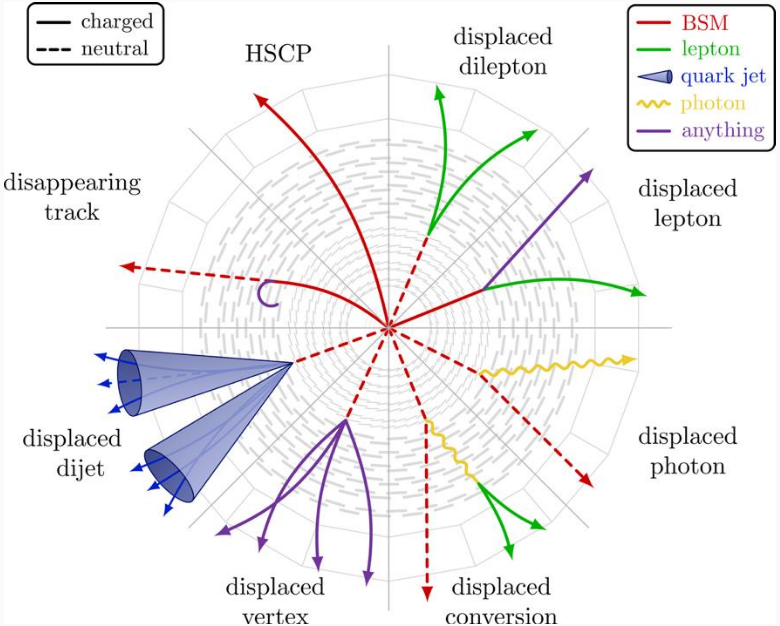
What are LLPs?

Unstable particles with a sizeable lifetime
→ travel macroscopic distances before decay

BSM particles could easily reach long lifetimes:

- Approximate symmetries
- Small coupling between LLP and lighter state
- Suppressed phase space of available decays

Unusual signatures ≠ SM processes



Unusual signatures

Unusual ionization + abnormal tracks

Energy deposit without associated track

Stopped particles with out of time decay

Displaced vertices in ID or MS

Disappearing and appearing tracks

Knicked tracks

Consequences

..Positive

Promising to discover new physics!

..Negative

Might..

- not pass trigger
- get rejected by algorithms
- get considered as noise or pile up

→ **We need dedicated detectors, specific reconstruction algorithms and background models**

02

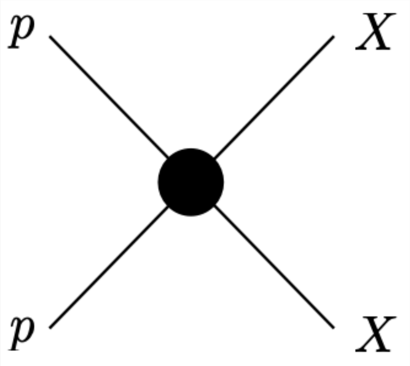
Simplified Models

Production modes and decay channels

Production modes

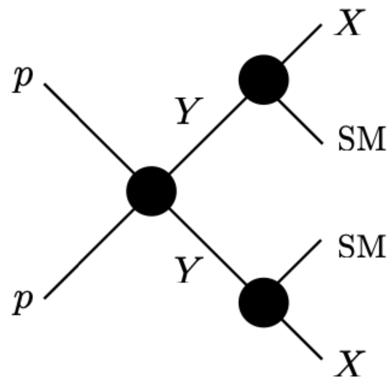
Direct Pair Production

Produced from a SM final
No intermediate particle



Heavy Parent

Produced from decay of
- heavy
- pair produced
- on shell parent

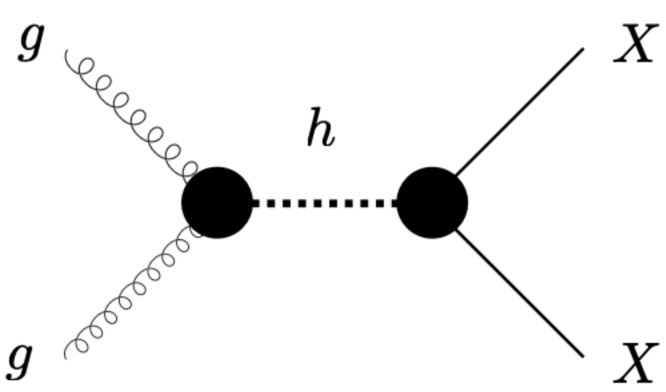


Production modes

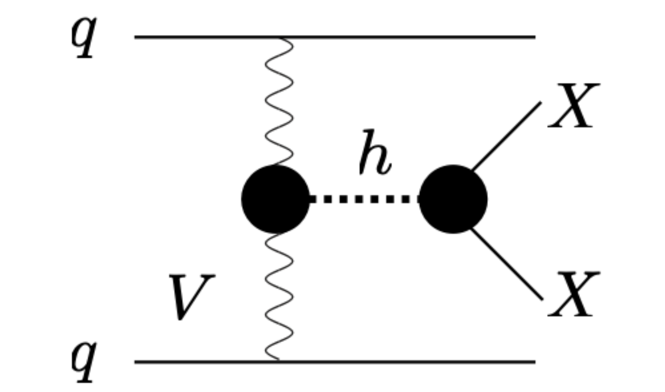
Higgs (HIG)

Produced through coupling with SM Higgs boson, both pair or single production

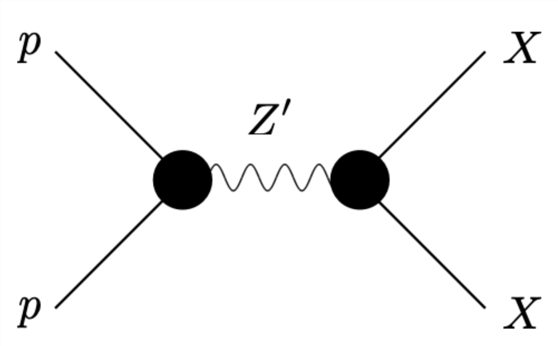
Gluon fusion

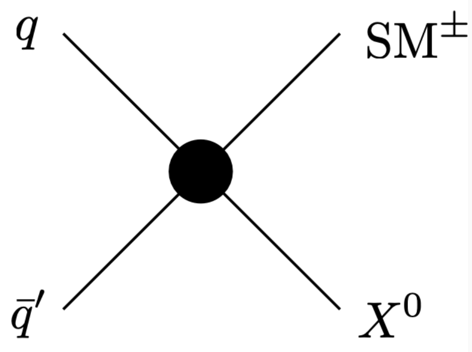


Vector boson fusion



Production modes





Reasonance (RES)

Decay of on shell Z’ boson
Pair production

Charged current (CC)

Leptonic decay of W’ boson
Single production

Decay channels

1 **Di-photon**

- Resonant decay (Higgs model) or ɣɣ+ invisible (DM model)

2 **Single photon**

- ɣ + invisible (SUSY)

3 **Hadronic**

- jj (Higgs), jj+invisible (SUSY, DM, neutrino), j+invisible (SUSY)

4 **Semi-leptonic**

- l+jet, jj (SUSY)

5 **Leptonic**

- l+l- (+invisible) (SUSY, neutrino)

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*

Alimena et al., *J. Phys. G* 47, 090501 (2020), https://doi.org/10.1088/1361-6471/ab4574.

03 Experimental coverage

Existing LLP research at ATLAS

Searches at ATLAS

Hadronic

In ID or HCAL/MS

Leptonic

Photonic

Semi-leptonic

Hadronic LLP decay

In inner detector

Large Radius Tracking algorithm (LRT)

1. Default track algorithm
2. 2nd run with looser requirements

CPU intensive: only on requested events

- $\not{E}_t$ > 250 GeV
- M_{DV} > 10 GeV
- High P_t jets
- 5 tracks

In HCAL or MS

- CalRatio in HCAL

1 trackless jet, low E deposit in ECAL

- MuonRoI in MS

Isolated clusters of L1 RoI in MS

Requires 2 DV:

- 1in ID and 1 in MS
- 2 in MS

→ Due to high P_t requirement: no sensitivity to low mass LLP

→ Due to 2 DV requirement: only sensitive to DPP and HP production modes

Leptonic and Semi-leptonic decays

Leptonic

Search for displaced leptons

Triggered by: $e^-, \mu,\ \gamma$ without track

- μ > 50 GeV
- e^- > 110 GeV
- γ > 130 GeV
- 2 e^- in range 38-48 GeV
- 1 e^- 1 γ in range 38-48 GeV
- DV at 4mm from PV

Semi-leptonic

Identical to leptonic search

Except:

⇽ 2 opposite sign leptons

⇾ 1 lepton and 4 displaced tracks

Photonic decay

Delayed photons

→ Arrive later at ECAL

Non-pointing photons

→ Cannot be traced back to PV

Liquid argon ECAL to measure flight time and direction → 15mm on Δz, 0.25ns on Δt.
Based on theories of decay of neutralino into gravitinos and photons → Requires $\not{E}_t$!

→ Searches don't cover any processes without $\not{E}_t$

04 Background sources

Background sources

Real particles produced in detector

Real particles originating from outside the detector

Fake particles

Algorithmically induces fakes

Real particles produced in detector

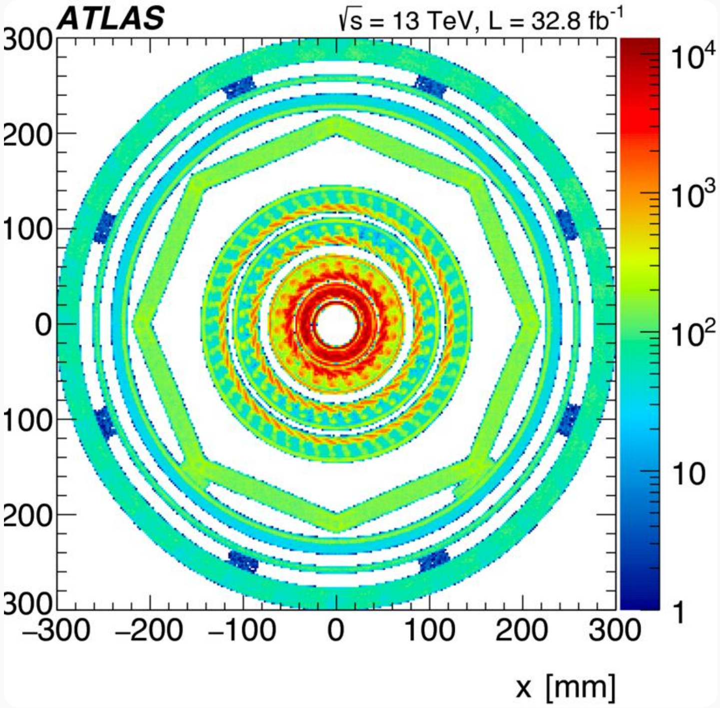
pp-collisions produce particles

→ Interact with nuclei in detector

→ Displaced vertex that mimic LLP signals

→ Located in high density regions

→ Effectively rejected by using material maps



Real particles originating from outside the detector: cosmic muons

Cosmic rays enter detector as **cosmic ray muons**

→ rate of 500 Hz at L1, less in LLP searches (high level trigger and offline selection)

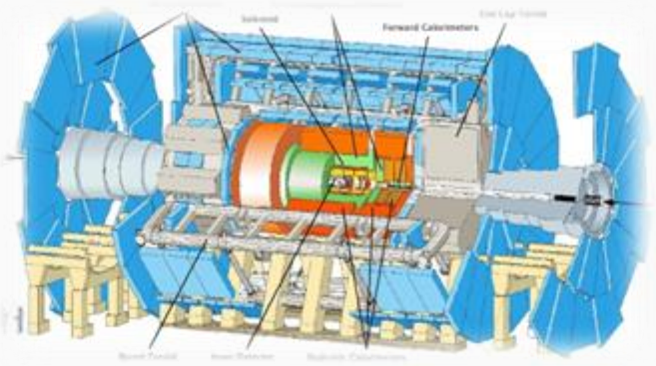
In many cases: back to back di-muon signal can be rejected

= one muon traveling from one side to the other,

reconstructed as two back to back muon tracks

High Pt trigger

= cosmic muos have rapidly falling Pt spectra

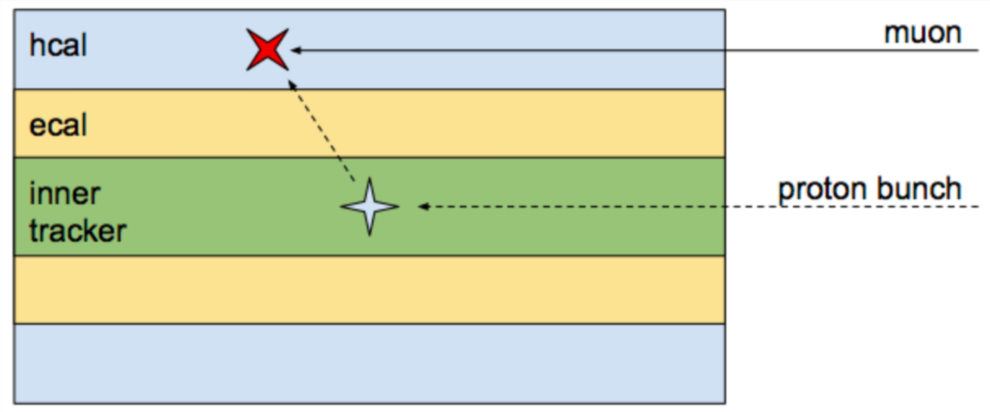


Real particles originating from outside the detector: Beam halo

Particles not centered in the beam (EM effects, scattering)

Travel shorter distances → faster signal
= LLP signature!

Filter out:
- Check timing
- Track origin
- High P_t or E



Real particles originating from outside the detector: Cavern radiation

pp-collisions produce neutral, long lived SM particles (n, γ)
→ accumulate in LHC caverns
→ wander around and create off timing hits in detector (mostly MS)
= LLP signature!

Hard to simulate
→ Measure detector activity when no collisions are expected

Signals that mimic real particles, but are not

Actually from detector noise: usually single concentrated energy deposit

⇾ out of time and space!

⇾ Reject single concentrated energy deposits associated to no tracks

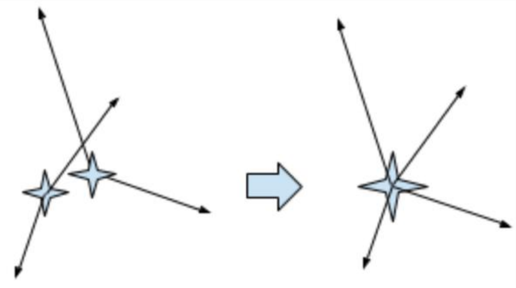
Fake particle signatures

Algorithmically induced fakes

Random merged vertices

2 low mass merged into 1 high mass DV

Important in region with high track density

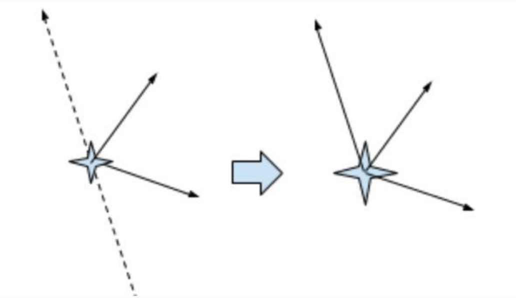


Randomly crossing tracks

2 tracks that cross each other → DV

More relevant that RMv

Reject: removing 1 track significantly decrease mass of DV



05 Detector Upgrades

ATLAS and the HL LHC

Detector upgrades

Current experimental searches for LLPs: limited by the abilities of ATLAS, CMS and LHCb

LHC upgrade to the HL LHC → detectors upgrade accordingly (deal with high pile-up)
→ improve LLP searches significantly

06 Conclusions

And summary

Conclusions

- SM is incomplete → we need BSM. Particles mostly assumed to decay promptly
- SM particles have big range of lifetimes... Why not BSM particles?
- Long lifetime → unusual signatures → we need dedicated analysis

- Theoretical overview of simplified models
- Existing searches, need to be improved (sensitivity to low mass LLP, singly produced)
- Specific background: usually negligible, not in LLP searches
- HL LHC offers good prospects for LLP searches!