Hidden sector searches using displaced decays in ATLAS

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Where to look for new physics?

- High-energy experiments
  - Electron fixed target
  - Proton fixed target
  - B factories

- High-intensity experiments

- Known physics

- LHC

Unknown physics
Where to look for new physics?

- High-energy experiments
  - Portal to hidden sector through postulated new massive scalar or vector particle
- High-intensity experiments
  - Neutrino portal: can the LHC be used as an intensity frontier machine?

- Electron fixed target
- Proton fixed target
- B factories

- LHC

Known physics

Interaction strength

Energy
• $g$-2, dark matter, positron excess, parity (mirror world), ...

• Production via kinetic mixing with the photon
  – Coupling to charged particles suppressed by $\varepsilon$

• Decay to fermion pairs
  – Search for resonances
Dark photons in the lab

• Need to produce MANY photons and look for LIGHT resonance
  – B factories
  – Electron fixed-target experiments

• The LHC is NOT ideal!
  – Not so many photons
  – Large backgrounds at low mass

• Strategy at ATLAS: assume production via Higgs decay
  – Hidden fermions $f_d$ coupling to Higgs (assume also $H \rightarrow f_d f_d$ BR) and decaying $e g$ into dark photons
  – No longer a simple scenario of new physics – need a couple new parameters in addition to $\epsilon$ and $m_{\gamma d}$
• Dark photon through Higgs portal
• Triggers: either three muons, or special “calorimeter ratio”
• Search for events with two “displaced lepton-jets”
  – definition: at least two collimated tracks in muon spectrometer with no matching track in inner detector, or a narrow trackless calorimeter deposit with low electromagnetic fraction
Dark photon limits

This range probed with prompt lepton-jet analysis (paper coming very soon)

Remember: ATLAS limits rely on more assumptions
Displaced hadronic jets with ATLAS

• **Triggers**: special “calorimeter ratio”, or special “muon RoI cluster”, or jet+MET

• Select events with **two displaced jets** in hadronic calorimeter (with low EM fraction), in inner tracking detector, or in muon spectrometer

• Interpretation in “Hidden valley” models
  – **Scalar and vector portals**: assumes heavy mediator and hidden pions decaying back into jets after some distance
Heavy neutral lepton (HNL)

- Neutrino masses, dark matter, X-ray astronomy, matter-antimatter asymmetry
- Production via mixing to neutrinos (neutrino portal)
- Decay to $l\nu$ or $l+$hadron(s)

$N_1$ stable dark matter
$N_{2,3}$ long-lived, mass in 0.2-100 GeV range
HNLs from W and Z decays at colliders

- Probing masses up to 90 GeV
- **LEP1 (Z resonance)**
  - \( \sim 10^6 \) vs from Z decays
  - Displaced decays for masses up to 4 GeV
- **Tevatron (2 TeV)**
  - \( \sim 10^7 \) vs from W decays
  - Low mass or prompt \( \rightarrow \) large backgrounds, no search made
- **LHC Run1 (8 TeV)**
  - \( \sim 10^9 \) vs from W decays in ATLAS and CMS
  - Displaced decays for masses up to \( \sim 25 \) GeV
- **LHC Run2 (14 TeV)**
  - \( \sim 10^9 \) vs for each 25 fb\(^{-1}\) from W decays in each experiment
  - The LHC is indeed an intensity frontier machine!
Quick comment on displaced vs. prompt HNL signatures

- Here we consider HNLs with masses below W mass
  - Favoured by cosmology
  - Realm of SHiP physics
  - Displaced vertex signature
- HNLs with masses $\gtrsim 100$ GeV can also be probed at ATLAS (eg JHEP 07, 162 (2015))
  - Off-shell $W \to$ can probe only large mixing
  - That leads to prompt decays $\to$ to suppress backgrounds, need stringent cuts (high-pT jets, same-sign leptons...)
  - This is not discussed in this talk
ATLAS search for HNLs from W decays

- **Run-1 searches for displaced vertices in inner detector** (PLB 707, 478; PLB 719, 280; JHEP 11, 088; PLB 743, 15; PRD 92, 012010; arXiv:1504.05162)
  - Not sensitive to HNLs due to high pT thresholds, or requirement of two displaced vertices
  - Adequate track and vertex reconstruction tools, similar backgrounds

- **Dedicated HNL search possible and needed**
HNL signature in ATLAS
HNL signature in ATLAS

Essential for triggering

$W^\pm$

$\nu$

$N_{2,3}$ (macroscopic distance)

$\nu$

$W^\pm$

$\nu$, $\bar{q}$

$\nu$, $l^\pm$

$\nu$, $l^\pm$, $q$
HNL signature in ATLAS

- Prompt lepton
- Essential for background rejection

Diagram:
- $W^\pm$ decays to $v$, $N_{2,3}$
- $N_{2,3}$ has a macroscopic distance
- $W^\pm$ decays to $l^\pm$, $l^\pm$, $q$, $\bar{q}$
- Displaced vertex
HNL signature in ATLAS

$W^\pm$

$N_{2,3}$ (macroscopic distance)

Prompt lepton

W invariant mass

Displaced vertex

$W^\pm$

$\nu$

$\nu$, $\bar{q}$

$\nu$, $q$

$1^\pm$

$1^\pm$, $q$

$1^\pm$, $\bar{q}$
HNL signature in ATLAS

W invariant mass

Flavour analysis possible!

Prompt lepton

Displaced vertex

\( W^\pm \)
Challenge 1: low-pT signal

- **Prompt lepton used for triggering** (~45% efficiency)
- **Backgrounds can still be reduced to negligible levels**
  - Requirement on vertex distance
  - Lepton identification among particles forming the vertex
  - Requirement on vertex mass
  - Material veto to reduce hadronic-interaction backgrounds
  - Kinematic fit using W mass constraint
Challenge 2: need for “retracking”

- Standard ATLAS tracking requires low impact parameter (D0), inefficient for displaced tracks
- The data therefore needs processing with special tracking. This is consuming in terms of data storage and CPU and thus a smart filter is needed to reduce event rate/size while retaining signal events.
- Such a filter was implemented for ATLAS HNL analysis in the muon final state
  - One prompt isolated muon with pT > 28 GeV
  - Another muon with pT > 5 GeV and D0 > 1 mm if it is matched with inner detector track
- Will later reprocess the data for retracking with electron final state (more challenging)
Approximate expected sensitivity to HNL observing 1 event assuming 100 fb$^{-1}$ @ 14 TeV in ATLAS
Summary

• Complementary searches for hidden sectors can be made at dedicated fixed-target experiments and colliders
• New massive particles that couple to both sectors could be accessed by the LHC – but that requires extra assumptions
• The LHC is a $W$ factory, providing access to the neutrino portal at high mass
• Using the unique signature of a displaced vertex, ATLAS can probe unexplored regions of the parameter space for HNL masses between 2 and 30 GeV
(extra slides)
Search for heavy neutral leptons in Z decays

- $3 \cdot 10^6$ Zs
- Both prompt and displaced decays to lW and νZ
HNLs at future circular colliders

- **CERN Future Circular Collider (FCC) design study**
  - ~100 km ring
  - Conceptual design report to be prepared for 2018
- **FCC-ee**: $10^{13}$ Zs, Higgs factory...
- **FCC-hh**: 100 TeV pp collisions

- Dedicated displaced vertex analyses at FCC can achieve several orders of magnitude improvement in sensitivities to HNLs in mass range 2–90 GeV
  - [arXiv:1411.5230](http://arxiv.org/abs/1411.5230)
The (approximate) big picture assumes $50 \text{ fb}^{-1} @ 14 \text{ TeV}$ in both ATLAS and CMS assumes $10^{13}$ Zs for FCC-ee with LHC-sized detector.