Searches for Long-Lived Particles in ATLAS: challenges and opportunities of HL-LHC

Simone Pagan Griso
Lawrence Berkeley National Lab.
on behalf of the ATLAS Collaboration

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Introduction

Most common theoretical sources of Long-Lived Particles (LLPs)

- Approximate symmetries
- Small couplings
- Decays through heavy off-shell particles
- Phase space suppression

$$m(\chi^\pm) - m(\chi^0) \approx m(\pi)$$
$$c\tau(\chi^\pm) \approx 10 \text{ cm}$$

$$c\tau_{GMSB} \approx 0.1 mm \left( \frac{m_\tilde{g}}{1000 \text{ TeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_\tilde{g}} \right)^5$$
Experimental strategy

- Best experimental strategy depends on the properties of the particle

- **Electric charge**
  - charged
  - neutral

- **Mass**

- **Lifetime**

- **Decay products**
  - weakly interacting
  - hadrons
  - leptons

- **Direct** detection
  - Direct interaction with detector
  - If LLP minimally interacting and escapes detector $\rightarrow E_T$

- **Indirect** detection
  - SM or invisible decay products
  - “Isolated” activity inconsistent with expected prompt or instrumental background
## Current analyses

### Primary measurement:

<table>
<thead>
<tr>
<th></th>
<th>ID</th>
<th>Calo</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt analysis (jets+$\not{E}_T$)</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Displaced vertices</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>“Isolated” jets</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>“Lepton”-jets</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stopped gluinos</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Delayed photons</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Time-of-flight measurements</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Disappearing track</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large ionization deposits</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Indirect detection

- Dedicated trigger strategies or “collateral” event features (e.g. MET, …)
- Dedicated reconstruction algorithms or calibrations
- Instrumental or “unusual” backgrounds (cosmics, hadronic interactions, …) require data-driven techniques
- Creative use of the ATLAS detector
• New all-Silicon tracker (ITk): 5 pixel and 4 strip barrel layers

• ATLAS Phase-II inner tracker has non-trivial implications for LLPs:
  
  - “Expanded” (in radius) barrel layers
  - Extended coverage $|\eta| < 2.5 \rightarrow 4.0$
  - Reduced material budget
  - Coarser charge measurement in pixels
Displaced Vertices in the ID

- Explicit displaced vertex reconstruction (hadrons and/or leptons)
- Tiny background after selections from:
  - hadronic interactions  — accidental crossing
- Dedicated tracking and vertexing setup
  - Tacking efficiency driven by geometric acceptance and interactions with material

Opportunities
- Layout design
  - Access to longer lifetime
  - Geometric coverage
- Lower material budget
- Better track parameter resolutions

Challenges
- Keep tracking and vertexing efficiency high with large combinatorics

Denominator: LLP decay products with

| $|\eta| < 5$ | $p_T > 1$ GeV |
| Number of silicon hits $\geq 7$ |
"Short" tracks

- Meta-stable charged LLPs with short lifetime
  - reconstructed as “short” (disappearing) tracks
  - main background from mis-measured and fake tracks
- Can also require large ionization loss if $\beta\gamma < 1$
  - measured using pixel detector

**Opportunities**
- Lower fake rate and better accuracy
- Low x-section → profit from large luminosity

**Challenges**
- Only 2-pixel layers in first 12 cm (Run-2: 4!)
  - will need aggressive R&D and creativity
- Impact of coarser pixel charge measurements can be minor
Triggering considerations

- Ensure we retain high efficiency for triggering non-prompt leptons
  - can easily lose efficiency when fighting against pile-up combinatorics

- MET is a critical trigger, but very sensitive to pile-up
  - need upgraded trigger setup to maintain similar thresholds as now

- Track-based triggers can potentially offer a huge boost in sensitivity
  - but need re-optimization and clever solutions for short / non-prompt tracks!

- Flexibility to implement custom triggers for dedicated signatures
Time of flight measurements

- TOF measurements can reveal massive particles traveling with $\beta << 1$
  - resolution tails as main backgrounds
  - detailed calibration needed
- Calorimeter timing resolution $\sim$ ns
  - Proposed High-Granularity Timing Detector ($2.4 < |\eta| < 4.2$) with $\sim30$ ps resolution
    - only sensitive to moderately forward objects
- Trigger strategies that allow objects to be delayed by $> 25$ ns (1 bunch x-ing)
  - already implemented now w/ L1-Topological triggers using a late muon and MET or Jets
Isolated jets

- Neutral particles decaying in the ATLAS calorimeter

- Dedicated trigger strategies
  - “isolated” and narrow energy deposits in Tile calorimeter vetoing other activity
  - very delayed signature on non-colliding bunch crossings and no-beam periods are sensitive to lifetimes up to ~years

- Need to ensure pile-up robustness and high efficiency in rejecting non-collision backgrounds
  - take advantage of calorimeter segmentation

- Upgraded L1 Trigger L1 with increased granularity will help in background rejection
Decays in the Muon system

- Dedicated trigger to select decays of neutral particles in the MS
- Benefit from usage of high-resolution MDT measurement already at L0/L1 trigger
- Main backgrounds for multijets, cosmics and beam-induced backgrounds

- Unpaired and empty bunches provide unique source for data-driven background estimate
- Dedicated reconstruction of displaced vertices in the Muon Spectrometer may suffer larger combinatorics
Theory benchmarks

- Common simplified benchmarks
  - identify overlaps and gaps
  - show interplay of various techniques

- More common and comprehensive set of simplified models will help to better characterize our future reach

- Complete models scans including long-lived particles can direct our efforts and help summarizing the full potential of HL-LHC
  - e.g. pMSSM scan performed on 8 TeV results

<table>
<thead>
<tr>
<th>Long-lived Particle</th>
<th>Bino LSP</th>
<th>Wino LSP</th>
<th>Higgsino LSP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Models</td>
<td>Excluded</td>
<td>Models</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>899 (5.2%)</td>
<td>5.1%</td>
<td>58 (3.4%)</td>
</tr>
<tr>
<td>$\tilde{b}_l$</td>
<td>1252 (99.6%)</td>
<td>76.4%</td>
<td>51 (100.0%)</td>
</tr>
<tr>
<td>$\tilde{t}_l$</td>
<td>345 (56.8%)</td>
<td>36.5%</td>
<td>6 (100.0%)</td>
</tr>
<tr>
<td>$\tilde{\tau}_l$</td>
<td>406 (100.0%)</td>
<td>37.4%</td>
<td>2 (100.0%)</td>
</tr>
</tbody>
</table>

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Conclusions and Prospects

- Current effort in the context of TDR preparations
  - address challenges posed by HL-LHC conditions
  - exploit the new opportunities of a large detector upgrade

- Not everything will be answered by the TDR, and physics ↔ detector interplay will be crucial in defining the best strategy in this process

- Not yet assessed the full physics potential of HL-LHC for LLP searches
  - common benchmarks and scans of more complete models can provide very useful insights and highlight the complementarity of various approaches

- Leveraging re-interpretation efforts of current analyses, together with dedicated full-simulation studies, can be a key to effectively maximize the output of HL and HE-LHC for long-lived particle searches