Searches for new physics with unconventional signatures at ATLAS and CMS

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Rencontres de Moriond
QCD and High Energy Interactions
La Thuile
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Search for New Physics. Where should we look?

- A large number of Beyond the Standard Model (SM) models exist to cover the limitations of the SM
- New particles will either be
  - Prompt decaying
  - Semi-stable Long-Lived Particles (LLPs), decay in the detector
  - Detector-stable, decay outside the detector
  - Stable

- ATLAS and CMS are designed to optimize object identification for (prompt) SM particles
- Standard object ID algorithms don't usually have good efficiency for LLP reconstruction
  - algorithms need to be adjusted for LLPs

- Strategy: organize searches according to final states.
- Searches as model independent as possible

we need to make sure we have sensitivity to these too!
Displaced jets in the ID

Displaced jets in the Calorimeter

Displaced leptonic vertices

Displaced vertices + MET

Displaced jets in the MS

Stopped LLPs
NOT IN FILLED BUNCH CROSSING

Highly ionising particles

(Meta-) Stable Charged LLPs

Late photons

ATLAS, 8 TeV, 20.3fb⁻¹: Phys. Rev. D 90, 112005 (2014)
CMS, 8 TeV, 19.1fb⁻¹: CMS-PAS-EXO-12-035

8TeV result: PRD 93, 052009 (2016)

ATLAS, 13 TeV, 36.1fb⁻¹: SUSY-2016-06
CMS, 13 TeV, 38.4fb⁻¹: CMS-PAS-EXO-16-044

8TeV result: PRD 93, 052009 (2016)

ATLAS, 13 TeV, 3.2fb⁻¹: ATLAS-CONF-2016-103
CMS, 13 TeV, 2.6fb⁻¹: EXO-16-003

13 TeV result, 3.2fb⁻¹:
ATLAS-CONF-2016-042

8TeV result: PRD 92, 012010 (2015)


8TeV result: PRD 92, 012010 (2015)

ATLAS, 13 TeV, 3.2fb⁻¹: ATLAS-CONF-2016-103
CMS, 13 TeV, 2.6fb⁻¹: EXO-16-003

8TeV result: PRD 92, 012010 (2015)


8TeV result: PRD 92, 012010 (2015)
In this talk, focus on searches with full 2016 statistics.
Challenges in LLP searches

- **Trigger**: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger on MET)
    2. Design and develop a new trigger. Need to keep trigger rates under control and within budget

- **Object identification** algorithms assume prompt particles. Need to adapt them

- **Backgrounds**: usually instrumental background such as miss-identified leptons (“fakes”) and non-collision backgrounds (NCB) have to be taken into account

- **Systematic** uncertainties: can’t use standard recommendations for object reconstruction nor trigger
Displaced vertices in the Inner Detector (ID)
Displaced vertices

- **Search for** displaced vertex in the Inner Detector + MET
- **Signature:** Neutral or charged long-lived particles (LLP) decaying in the Inner Detector leading to high-mass, multi-track DV

- **Benchmark model:** simplified model inspired by Split SUSY
  - Decays via a highly virtual intermediate state resulting in long lifetimes

- **LLP decays occurring at** $4 \text{ mm} < r < 300 \text{ mm}$ from the PV

- **Basic Selection:**
  - Trigger on MET
  - $N_{\text{trk}} \geq 5$ (vertices with lower mass and 3–4 tracks for building and validating background estimates)
  - $m_{\text{DV}} > 10$ GeV

- $m_{\tilde{g}} = 400 - 2000$ GeV,

- $c\tau = 0.01 - 50$ ns,

- $m_{\tilde{\chi}_1^0}$ ranges from 100 GeV to $m(\tilde{g}) - 30$ GeV.
Displaced vertices reconstruction

- Standard ATLAS algorithms for tracking and vertexing have low efficiency for displaced vertices

  - Standard tracking
    - tight requirements in number of silicon hits and impact parameter
    - 1. Reconstruct track from pixel to TRT
    - 2. Reconstruct track from TRT to pixel

  - Large-Radius tracking (LRT)
    - Relax requirements in number of silicon hits and impact parameter
    - Re-run 1 only with hits not associated with existing standard tracks

- Secondary vertex
  - Using standard tracks and LRT tracks, form multi-track DVs
  - Apply hit quality criteria:
    - Remove tracks with hits before the DV
    - Hit required in the nearest pixel or SCT layer at larger radius
Displaced vertices backgrounds

- SM backgrounds are negligible
- All dominant (but still very small!) sources of background are instrumental
- Estimated with data-driven methods

1. Hadronic interactions with material
   - material veto
   - \( m_{DV} > 10 \text{ GeV} \) (use \( m_{DV} < 10 \text{ GeV} \) region for background estimation)

2. Accidental crossing of low \( m_{DV} \) with an unrelated track
   - Dominant
   - Compare sample with \((n+1)\)-track vertices (constructed by adding a pseudo-track) to \(n\)-track vertices from the data in the \( m_{DV} > 10 \text{ GeV} \) region

3. Combined low-mass vertices form short-lived SM particles decays
   - DV vertices are combined if they are separated by less than 1 mm
   - Close-by low-mass vertices combined \(\rightarrow\) high mass vertex
   - Build template with random combination of vertices
   - Orders of magnitude smaller than the accidental-crossing
Displaced vertices results

- Background prediction agrees with data observation

<table>
<thead>
<tr>
<th>Selection</th>
<th>Subregion</th>
<th>Estimated</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event preselection</td>
<td>n_{trk} = 3, m_{DV} &gt; 10 GeV</td>
<td></td>
<td>3093</td>
</tr>
<tr>
<td>Event preselection</td>
<td>n_{trk} = 4, m_{DV} &gt; 10 GeV</td>
<td>VRLM</td>
<td>9 ± 2</td>
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<td>1 ± 3</td>
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<tr>
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<td>n_{trk} ≥ 5, m_{DV} &gt; 10 GeV</td>
<td>Total</td>
<td>4.2 +4.1</td>
</tr>
<tr>
<td>Full SR selection</td>
<td>Total</td>
<td>0.02 +0.02</td>
<td>0</td>
</tr>
</tbody>
</table>

- Highest gluino mass exclusion amongst all ATLAS SUSY searches including prompt searches thanks to zero-background
Disappearing tracks

ATLAS latest result: SUSY-2016-06
CMS latest result: CMS-PAS-EXO-16-044
Disappearing tracks description

- Search for disappearing track + MET + jets
- Signature: Chargino track “disappears” when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

- Benchmark model: AMSB model with almost degenerate neutralino and chargino
  $\Delta m \sim O(100 \text{ MeV})$

- Search sensitive to LLP
  lifetime of 10ps to 10 ns
Disappearing track: track reconstruction

- Track reconstruction in 2 steps:
  1. standard tracking
  2. second pass using only hits not associated with tracks in 1.

**ATLAS**

- Looser criteria, require ≥ 4 pixel hits, zero holes
- Veto hits on SCT —> identify “pixel tracklets”, disappears between the pixel and the SCT
- Tracklets isolated from jets and MS tracks

**CMS**

- Looser criteria, require ≥ 3 pixel hits, ≥ 7 silicon hits, zero holes
- >=3 missing outer hits
- Tracklets isolated from jets and MS tracks

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- Inclusion of the innermost tracking layer (IBL):
  - significantly improves the sensitivity to short chargino lifetimes
  - essential to eliminate fakes

- 10x larger acceptance for 400 GeV AMSB chargino decaying before the SCT
Disappearing track: backgrounds

Hadron with hard scattering

Lepton emitting hard photon

Random combination of hits

- Main backgrounds: ttbar, W+jets where e bremsstrahlungs or pion coming form tau lepton, scatters
- Random combination of unrelated particles tracks

Selection:
- high MET, ≥1 high pT jet (ISR)
- high quality tracklet
- lepton veto (ATLAS) or lepton isolation (CMS) to suppress contributions from ttbar and W/Z+jets

- Templates for background components are estimated from data.
Disappearing track Results

- Background prediction agrees with data observation

- Extended limits to lower lifetimes

- Reinterpretation of ATLAS analysis in further EW production modes: ATL-PHYS-PUB-2017-019
  - see details in talk by Teng Jian Khoo on Friday
Stopped LLPs
Stopped LLPs

- Search for stopped LLPs decaying during non-collision bunch crossings (BX)

- **Signature**: LLPs come to rest in the detector and decays after the current BX
  - most likely to stop in the densest detector materials:
    - **Calorimeters** (ECAL, HCAL):
      a) Split SUSY: two-body and three-body decays of a gluino
      b) top squark decay
    - Steel yoke in the muon system:
      a) three-body decay of the gluino (g → qqχ₂, χ₂ → μ μ χ₁)
      b) MCHAMPs, with charge |Q| = 2e decays into two same-sign muons (MCHAMP → μ±μ±)

- Search sensitive to wide range of LLP lifetime: $10^{-5}$ to $10^6$ s
Stopped LLPs: Calorimeter search

- **Trigger:** jet with $p_T > 50$ GeV and $|\eta| < 3$ that are at least two BXs away from pp collisions.

- **Backgrounds:**
  - SM background are negligible.
  - Instrumental and NCB backgrounds estimated with data driven methods:
    - **cosmic rays:**
      - cosmics: DT segments in all layers of the muon system
      - signal: DT segments only in the inner layers, clustered near the jet
      - reject events with DT segments in the outermost barrel layers of the muon system or large separation between segments ($|\Delta \phi| > \pi/2$)
    - **beam halo particles:**
      - veto events with any CSC segments having at least five reconstructed hits
    - **random electronic noise in the HCAL:**
      - use time response and topological information of energy deposits
Stopped LLPs: Muon search

- **Trigger:** at least one muon reconstructed in the muon system with $p_T > 40$ GeV, at least two BXs away from the pp collision

- **Signature:** pair of muons originating anywhere in the detector material, displaced from the IP
  - Standalone tracks (MS only hits) not requiring pointing to the IP
  - Require one displaced standalone muon track in the upper hemisphere and one in the lower hemisphere

- **Backgrounds:**
  - **cosmic rays** (dominant)
    - incoming in the upper hemisphere, outgoing in the lower hemisphere but signal is always outgoing
    - $t_{DT}$: time at the point of closest approach to the IP, assuming the muon is outgoing
  - beam halo particles (negligible)
  - random electronic noise (negligible)
Stopped LLPs: Results

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
</tr>
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<tbody>
<tr>
<td>Calorimeter search</td>
<td>4.1$^{+3.0}_{-1.0}$</td>
<td>11.4$^{+10.3}_{-3.1}$</td>
</tr>
<tr>
<td>Expected</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Observed</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon search</td>
<td>0.04 ± 0.03</td>
<td>0.50 ± 0.40</td>
</tr>
<tr>
<td>Expected</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Observed</td>
<td>0</td>
<td>0</td>
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</table>
Re-interpretation

- Searches for prompt objects can have some sensitivity to longer decay lengths
- New efforts to interpret searches for prompt objects in scenarios involving LLPs

**CMS Preliminary**

13–39 fb\(^{-1}\) (13 TeV)

\[ \tilde{g} \rightarrow q\bar{q}\chi^0 \text{ (BR=100\%)} \]

(R-hadron cloud model)

Status: February 2018

- Jets + \(p_T^{\text{miss}}\), arXiv:1802.02110
- \(m_{\chi^0} = 100\) GeV, charge suppressed
- Jets + \(p_T^{\text{miss}}\), arXiv:1802.02110
- \(m_{\tilde{g}} - m_{\chi^0} = 100\) GeV, charge suppressed
- Stopped gluino, arXiv:1801.00359
- \(m_{\tilde{g}} - m_{\chi^0} > 160\) GeV, \(f_{\tilde{g}} = 0.1\)
- HSCP, CMS-PAS-EXO-16-036
- \(f_{\tilde{g}} = 0.1\)

<table>
<thead>
<tr>
<th>Lower limit (95% CL) on (m_{\tilde{g}}) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
</tr>
<tr>
<td>(10^{-14})</td>
</tr>
</tbody>
</table>

**Re-interpretation:**

SUS-16-038

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**ATLAS Preliminary**

\[ \tilde{g} \rightarrow q\bar{q}\chi^0 : m(\chi^0) = 100\text{ GeV} \]

(R-hadron) \(m(\chi^0) = 100\) GeV

- March 2018

- Expected
- Observed
- Lower limit (95\% CL)

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</table>

**Re-interpretation:**

ATLAS-CONF-2018-003

See details in talk by Dario Barberis at Moriond EW on prompt-to-long-lived SUSY searches in R-hadron and RPV models

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E. Torró 20 March 2018
Conclusions

- Lacking any evidence for New Physics in any of the searched finalized so far, unconventional signatures are gaining in popularity

- ATLAS and CMS have a complete program to search for long-lived particles in many different signatures
  - Wide variety of searches
  - Very challenging, pushing the detector for searches it was not designed to perform
  - Many analysis working on improvements with the full 13 TeV dataset

- No discovery so far but…

- 2017 dataset to be studied yet!

- Looking forward to seeing first significant deviations from the SM predictions!!

Data analysed in the searches at 13 TeV shown in this talk.
Backup
ATLAS and CMS public results

- All ATLAS public results:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome

- EXOTICS specific results:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

- SUSY specific results:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Summary plots

ATLAS Long-lived Particle Searches - 95% CL Exclusion

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>Life time limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV SUSY, m(χ) = 100 GeV</td>
<td>disappeared tracks</td>
<td>&lt; 1.5 TeV</td>
</tr>
<tr>
<td>GMSB, m(χ) = 20 GeV</td>
<td>disappeared tracks</td>
<td>&lt; 1.5 TeV</td>
</tr>
<tr>
<td>AMSB, m(χ) = 500 GeV</td>
<td>disappeared tracks</td>
<td>&lt; 1.5 TeV</td>
</tr>
<tr>
<td>Hidden Valley 1</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
</tr>
<tr>
<td>Hidden Valley 2</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
</tr>
<tr>
<td>Hidden Valley 3</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
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<tr>
<td>Hidden Valley 4</td>
<td>2 D E 05000 cm</td>
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<td>500 mm</td>
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</tr>
<tr>
<td>Hidden Valley 9</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
</tr>
<tr>
<td>g' \rightarrow q \bar{q}</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
</tr>
<tr>
<td>g' \rightarrow q \bar{q}</td>
<td>2 D E 05000 cm</td>
<td>500 mm</td>
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ATLAS Preliminary

<table>
<thead>
<tr>
<th>c.r. (m)</th>
<th>σ fb</th>
</tr>
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<tbody>
<tr>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
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</table>

CMS long-lived particle searches, lifetime exclusions at 95% CL


E. Torró 20 March 2018