Long-lived and compressed SUSY searches at CMS and ATLAS

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(on behalf of the ATLAS and CMS collaborations)
Motivation

- Searches at ATLAS and CMS are doing a great job of excluding huge swathes of SUSY parameter space, but no signs of SUSY have been seen so far.

- Two possible hard-to-reach corners of parameter space where SUSY could have been hiding:
  1. “Compressed spectra” - small mass differences in decay chain, soft leptons or jets might fail analysis cuts.
  2. Long-lived particles - some analyses have quality cuts that reject jets or leptons with “non-prompt” tracks.

- ATLAS and CMS have conducted numerous searches to cover these challenging scenarios as well as we possibly can.
Compressed signatures

- Two general strategies used in several ATLAS and CMS analyses for searching for scenarios with small mass differences somewhere in the decay chain:
  - Push pT thresholds as low as possible to allow for softer objects.
  - Look in events with hard Initial State Radiation (ISR)
    - Presence of high-pT ISR jet (or photon, or W, or Z) means we are more likely to have triggered on the event.
    - The recoil against the ISR object will boost the rest of the system in the opposite direction, increasing the chances that jets or leptons will pass pT thresholds, or that “invisible” objects will give rise to large missing transverse energy (ETmiss).
CMS search for SUSY with soft leptons, low jet multiplicity, and ETmiss

- Select events containing high-pT jet from ISR, and a soft muon (pT>5 GeV).
- Soft muon is required to be the only lepton in the event (single lepton channel) or to have an electron or muon of opposite charge (dilepton channel).

ATLAS have performed a similar analysis, arXiv: 1407.0583 and arXiv:1501.03555.
ATLAS searches with monojets and c-tagged jets

- If mass difference between stop and neutralino is small, stop can decay to charm+neutralino.
- Two search strategies:
  - Monojet-like: require high-pT jet (from ISR) back-to-back with large ETmiss (stop pair system is not reconstructed).
  - C-tagged: require at least one of the three subleading jets to be tagged as a charm jet using multivariate tagger.
- Monojet search has also been reinterpreted in context of light squark production:
  - Dominates exclusion limits close to diagonal m(squark)~m(neutralino).
CMS search for electroweak SUSY in Vector Boson Fusion events

- Vector Boson Fusion (VBF) events are characterized by two forward jets, in opposite hemispheres, with large invariant mass $m_{jj}$.

- Use this topology to select events in which to search for electroweak production of charginos and neutralinos.

- Require two same-sign or opposite-sign leptons (e, mu, or tau) in the event, eight final states considered:
  
  - $e^\pm \mu^\pm jj$, $e^\pm \mu^\mp jj$, $\mu^\pm \mu^\pm jj$, $\mu^\pm \mu^\mp jj$, $\mu^\pm \tau^\pm jj$, $\mu^\pm \tau^\mp jj$, $\tau^\pm \tau^\pm jj$, $\tau^\pm \tau^\mp jj$

- Use $m_{jj}$ spectrum to estimate signal and background contributions.

Exclude $m$(chargino)$<175$ GeV at 95% C.L. for compressed scenario.
Long-lived signatures

• Long-lived particles can easily arise in a model if there are:
  • Small couplings in a decay chain.
    • e.g. R-Parity violating SUSY, Gauge-Mediated SUSY breaking.
  • Decays proceeding via highly off-shell propagators.
    • e.g. gluinos decaying via virtual squarks in “Split SUSY”.
  • Very small mass differences in a decay chain (extremely compressed) leading to small kinematic phase space.
    • e.g. nearly-mass-degenerate chargino and neutralino in Anomaly-Mediated SUSY Breaking.

• One or more of these can occur in a wide variety of SUSY and other New Physics models, and depending on lifetime and decay channels, can give various detector signatures at the LHC…..
# Long-lived SUSY searches: signatures and models

<table>
<thead>
<tr>
<th>Multi-track displaced vertices</th>
<th>Displaced dileptons</th>
<th>Kinked/Disappearing tracks</th>
<th>Non-pointing photons</th>
<th>Non-pointing leptons</th>
<th>Slow/highly-ionizing charged particles</th>
<th>Decays in empty bunch crossings</th>
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- **Green** = Search should be possible in principle.
- **Red** = Model is unlikely to give rise to this signature.

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**Note 1:** These lists are not exhaustive! Other models are available.
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**Note 1:** These lists are not exhaustive! Other models are available. Many searches also have non-SUSY interpretations.

**Note 2:** Refs shown on final slide.

[1],[10] = ATLAS, CMS publication.
ATLAS displaced vertex search

- Particles with average decay lengths of a few cm could decay within the tracking detector to give rise to displaced vertices.

- Look for high-mass, high-track multiplicity vertices in events with multiple hard jets, large ETmiss, or a high-pT lepton, or for dilepton pairs (ee, emu, mumu) forming a high-mass vertex.

Veto vertices in dense material regions
CMS Displaced SUSY search

- Look for events containing an electron and a muon of opposite sign, both with large transverse impact parameters.

- Set limits on R-Parity Violating SUSY, with long-lived top squarks decaying to $b\bar{t}$.
ATLAS and CMS non-pointing photon searches

- Motivated by Gauge-Mediated SUSY Breaking (GMSB) model, where long-lived neutralino NLSP decays to photon+gravitino.

- ATLAS makes use of two features of its ElectroMagnetic Calorimeter:
  - Longitudinal segmentation enables measurement of “pointing direction”.
  - Excellent time resolution allows identification of late-arriving photons.

- CMS look at photon conversions.
  - Make use of excellent tracking for large-impact-parameter tracks.
Gluino R-hadrons, produced when a long-lived gluino hadronizes with standard model partons.

Long-lived wino-like charginos, decaying to a neutralino and a soft pion.
Conclusions

• Huge amount of work has gone into “filling in the gaps” in coverage of SUSY parameter space from Run 1 searches.

• These searches are challenging - push the boundaries of our detector performance (and our understanding of it).

• Many situations where ATLAS and CMS searches complement one another, due to different detector technologies and analysis strategies.

• Run 2 is under way, and mass reach of searches is greatly extended.

  • More opportunities for us to take full advantage of our wonderful detectors, and explore all the parameter space as thoroughly as we can!
References (1)

[1]: Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $s\sqrt{s}=8$ TeV with the ATLAS detector, arXiv:1504.05162, submitted to PRD.

[2]: Search for metastable heavy charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS experiment, arXiv:1506.05332, submitted to EPJC.

[3]: Searches for heavy long-lived particles with the ATLAS detector in proton-proton collisions at $\sqrt{s}=8$ TeV, JHEP01(2015)068.


[9]: Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D 91 (2015) 052012.

[10]: Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D 91 (2015) 012007.


[12]: Searches for long-lived charged particles in pp collisions at $\sqrt{s} = 7$ and 8 TeV, JHEP 07 (2013) 122.

[14]: Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters, CMS

[15]: Search for supersymmetry in events with soft leptons, low jet multiplicity, and missing transverse momentum in proton-
proton collisions at √s = 8 TeV, CMS-PAS-SUS-14-021).

[16]: Summary of the searches for squarks and gluinos using √s= 8 TeV pp collisions with the ATLAS experiment at the LHC,

[17]: ‘Search for pair-produced third-generation squarks decaying via charm quarks or in compressed supersymmetric

[18]: Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at
Backup
ATLAS and CMS Stable Massive Charged Particle searches

- Charged particles will leave tracks in the inner tracking detector, and the muon spectrometer.

- If they are heavy, they will be more highly-ionizing, and slower, than any Standard Model particles.

- ATLAS searches use:
  - Only dE/dx measurement in Pixel detector (new result!)
  - Pixel dE/dx and also time-of-flight in the calorimeters and muon spectrometer.

- CMS searches use:
  - dE/dx measurement in silicon strip tracking detector.
  - AND/OR time-of-flight measured in the muon spectrometer.

Both ATLAS and CMS interpret results in terms of strongly interacting sparticles ("Rhadrons") and lepton-like (sleptons).
ATLAS and CMS stopped particle searches

- Strongly interacting sparticles with very-long lifetimes will form R-hadrons, and could potentially stop in dense material of ATLAS calorimeters.

- Could potentially decay at a later time, perhaps when there is no collision going on.
  - Look for calorimeter activity in empty bunch crossings.

- Potential backgrounds come from beam halo, cosmics, and instrumental effects.
  - Cosmics and beam halo dramatically reduced by vetoing events with any reconstructed muon segments (ATLAS) or certain combinations of muon spectrometer hits (CMS). Instrumental effects eliminated by “cleaning” cuts.
ATLAS and CMS disappearing track searches

- If mass difference between chargino NLSP and neutralino LSP is very small, chargino will be long-lived, and could decay to neutralino+soft-pion inside the tracking detector.
- Select events with hard jet and large ETmiss (likely ISR events).
- Require high-pT, isolated, charged track, without hits in outermost part of tracking detector.
Another summary of ATLAS searches