SEARCH FOR NEW PHYSICS WITH LONG-LIVED PARTICLES AT THE LHC

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NEW PHYSICS AND LONG-LIVED PARTICLES

Long-lived exotic particles (LLP) with striking signatures predicted by many extensions of the Standard Model

- Heavy, long-lived, charged particles (R-hadrons, Sleptons)
  - speed < c
  - charge not equal to ±1e
  - lifetimes > few ns. Travel distances larger than the typical collider detector and appear stable

- Particles decaying in the detector far from interaction point
  (neutralinos in GMSB, mass-degenerate gauginos, particles of a Hidden Sector)
  - decay in displaced vertexes (jets, leptons, photons)
  - delayed interaction with calorimeters due to extra flight-length
**Typical Long-Lived Analysis**

- **Detector-based exotic signatures** required:
  - $dE/dx$
  - time of flight
  - displaced vertex
  - disappearing tracks
  - stopped particles

- **Possible additional requirements** to identify SUSY-like topology:
  - MET
  - large jet activity ($H_T$, $p_T$(leading jet)>threshold)
  - the less the extra requirements, the smaller the model dependence

- **Specific control samples** to model exotic signature in detector:
  - non-trivial job. LLP signatures look like detector noise
  - deep knowledge of detector performance
**SIGNATURES: dE/dx**

- **Large ionization** left in tracker detectors by high mass R-hadrons or sleptons
- **Enhanced if charge ≠ 1**

\[
I_h = \left( \frac{1}{N} \sum_i \left( \frac{dE}{dx_i} \right)^2 \right)^{1/2}
\]
**Signatures: Time of Flight**

**Neutral particles**
- **produced in flight** (also from slow particles) and far from beam spot
- **time of arrival at calorimeter longer** than for SM contribution coming from beam spot
- tagged looking at measured timing

**Slow moving** high mass stable charged particles identified using **timing** measured in muon system and calorimeter

\[
\beta^{-1} = 1 + \frac{\delta x}{L} \frac{c}{v_{\text{drift}}} \quad \text{averaged over all layers}
\]

example for CMS drift tubes

L=flight distance
\(\beta\) obtained as an average over the detector hits
**Signatures: Displaced Vertexes**

- **Long-lived particles decaying in charged particles** (hadrons, leptons) identified via vertexing
- **Requirement of small activity** along the track in detector sectors closer to the beamspot

\[
\begin{align*}
H^0 \rightarrow XX \rightarrow 4l \text{ MC event with a } H^0 \text{ mass of } 400 \text{ GeV and } X \text{ boson mass of } 150 \text{ GeV/c}^2
\end{align*}
\]
SIGNATURES: DISAPPEARED/STOPPED PARTICLES

Long-lived charged exotic particles decaying in flight within the detector
- identified as truncated tracks
- small activity in the calorimeter along the propagated track direction
- track inefficiency need to be modeled carefully

Stoppers position in r-z view for a 600 GeV gluino

- charged particles with low velocity may stop in detector volume
  - preferentially in the densest detector elements (calorimeters)
- When decaying, energy deposit similar to jet
- Searched when no pp collision (gaps between proton bunches)
First Summary on Long-Lived Searches

- Several striking exotic signatures
  - some searches use more than one

- Very generic searches, driven by signatures
  - open-minded searches
  - models are used as benchmark to report results

- Limits are very model dependent

- Results are limited by detector acceptance and triggers (non-standard signatures)
  - difficult to find good control samples

- Experimentally challenging analyses
  - look where background for SM analyses is
  - implementation of ad-hoc triggers
**Heavy Stable Charged Particles**

- **Sleptons**: massive, charged and metastable in GMSB
- **R-hadrons**: bound states formed by squarks and gluinos hadronizing with a light SM quarks system, several electric charges (and the electric charge can change due to nuclear scattering in the detector)

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<table>
<thead>
<tr>
<th>composition</th>
<th>notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-mesons</td>
<td>$R = \tilde{g}q\bar{q}, (\bar{q}q)$</td>
</tr>
<tr>
<td>R-baryons</td>
<td>$R = \tilde{g}qqq, (\bar{q}qq)$</td>
</tr>
<tr>
<td>R-gluinoballs</td>
<td>$R = \tilde{g}g$</td>
</tr>
</tbody>
</table>

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HSCP: Analysis Technique

- Information from $dE/dx$ and $p_T$ (tracker) used to calculate mass
- Time of flight from muon detector and calorimeters to measure $\beta$
  - calibrated using cosmics and $Z \rightarrow \mu^+\mu^-$
- Background dominated by high $p_T$, mis-reconstructed muons
HSCP RESULTS: ATLAS

- No indication of signal above expected background
- Cross-section limits at 95% confidence level → translating into limits on the R-hadron/slepton mass

http://arxiv.org/abs/1211.1597

<table>
<thead>
<tr>
<th>Limits on rhadron containing</th>
<th>95% CL limits on mass exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino</td>
<td>985 GeV</td>
</tr>
<tr>
<td>stop</td>
<td>683 GeV</td>
</tr>
<tr>
<td>sbottom</td>
<td>612 GeV</td>
</tr>
</tbody>
</table>

sleptons
HSCP RESULTS: CMS

- Results with \(\sim 19\text{fb}^{-1}\). **No excess observed**
- Results for **fractional/multiple charge too**

http://arxiv.org/abs/1305.0491
In scenarios with **mass-degenerate gauginos** (predicted by AMSB) – chargino lifetime $O(0.1 \text{ ns})$, decay to neutralino and low E pion

- Selected as tracks with **missing hits in transition radiation trk (TRT)**
- Triggered with **ISR jet**
- **No excess**

STOPPED PARTICLES

• Dedicated calorimeter trigger to selected events in gaps between LHC beam crossings
  – $p_T^{(\text{jet})} > 50\text{GeV}$

• Search interval of 246 hours

• Selection based on jet $p_T$ ($>70\text{GeV}$) and criteria to reject residual backgrounds
  – beam halo, cosmics, out-of-time pp collisions, detector noise

• Limits presented in a long-lived gluino or stop in R-hadrons scenario

http://arxiv.org/abs/1207.0106
**Displaced Photons: Theory and Analysis**

- In models like **Gauge Mediated Supersymmetry Breaking**, Neutralino decays to Gravitino (lightest susy particle)
  - Missing ET
  - high pT jets and one or two photons
- **Neutralino can be long-lived**
  - displaced/delayed photons
- **Tagged using em calorimeter time and pointing direction**
  - design time resolution: 100 ps or better
  - 1.5 cm pointing resol. with ATLAS calorimeter
- **Topology requirements**
  - >=1 γ p_T>100GeV CMS, 2 γ p_T>50GeV ATLAS
  - large Missing E_T
**DISPLACED PHOTONS: CMS RESULTS**

- Additional requirement of 3 high $p_T$ jets
- No excess observed
- Limits are set varying **Neutralino masses and lifetimes**

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**Additional Details**

- [CMS Simulation](#)
  - $\sqrt{s} = 7$ TeV
  - $\tau = 250$ mm
  - $\tau = 2000$ mm
- **Neutralino Proper Decay Length**
  - $[\text{mm}]$
  - $\tau = 0.25$
- **Neutralino Mass vs. Number of Events**
  - $[\text{GeV}]$
  - $[\text{Events}]$
- [CDF with $\gamma\gamma + E_T + \text{Jets}$](#)
- [D0 with prompt $\gamma\gamma + E_T$](#)
- [ATLAS with prompt $\gamma\gamma + E_T$](#)

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**Displaced photons: ATLAS Results**

- Use of **distance of closest approach** of the projected photon direction – **timing** also as a crosscheck
- Requirement of two high $p_T$ photons
- No excess observed
Displaced Vertexes: Models

• Hidden Sector weakly coupled to SM
  - motivated by \((g-2)_\mu\) and Pamela results
• Communicate through heavy mediator particles (Higgs, \(Z',\) loop of SUSY particles)
• Heavy particles (e.g. Higgs boson) decay to particles of the hidden sector and back to the standard sector via:
  - hadronic jets
  - collimated jets of leptons: lepton-jets
• Hidden particles can be long-lived and neutral
• Identified reconstruction displaced vertexes
**Displaced Heavy Fermions**

- **Pairs of** back-to-back neutral particles decaying in the muon system (2 vertices in muon system, isolation in calorimeter)
- **Signature of** $H \to \pi_v \pi_v$ where $\pi_v$ is a long-lived pseudoscalar from Hidden Sector decaying to heavy fermion pair (mainly $b$-bbar)
- **No excess.** Limits assuming $\pi_v$ assuming 100% BR of $h \to \pi_v \pi_v$
- **Ongoing developments** to use also inner tracking and to search for $\pi_v$ decaying in calorimeters

- \[ \int L dt = 1.94 \text{ fb}^{-1} \]
  \[ \sqrt{s} = 7 \text{ TeV} \]

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**Displaced Leptons: Muon Jets in ATLAS**

- **Signature:** two isolated boosted pairs of muons with displaced vertex (reco’ed only with Muon System)

- **Benchmark model:** $H \rightarrow 2 f_{d2}, f_{d2} \rightarrow \text{LSP} + \gamma_d$
  - $\gamma_d$ is a dark photon (long-lived) and $f_{d2}$ an hidden fermion

- **No excess:** exclusion limit as a function of proper lifetime

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**Model Parameters**
- $m_h = 100/140$ GeV
- $m_{f_{d2}} = 5$ GeV
- $m_{f_{d1}/\text{LSP}} = 2$ GeV
- $m_{\gamma_d} = 400$ MeV
- $\text{BR}(\gamma_d \rightarrow \text{ee}) = 45\%$
- $\text{BR}(\gamma_d \rightarrow \mu\mu) = 45\%$
- $\text{BR}(\gamma_d \rightarrow \pi\pi) = 10\%$
- $c\tau(\gamma_d) = 47 / 36$ mm

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**Ranges of $\gamma_d$ proper decay lengths excluded at 95% CL for both Higgs masses**

<table>
<thead>
<tr>
<th>BR (%)</th>
<th>$c\tau$ (mm) $m_h=100$ GeV</th>
<th>$c\tau$ (mm) $m_h=140$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.1±674</td>
<td>1.2±431</td>
</tr>
<tr>
<td>50</td>
<td>1.5±455</td>
<td>1.6±286</td>
</tr>
<tr>
<td>20</td>
<td>2.4±260</td>
<td>3.3±156</td>
</tr>
<tr>
<td>10</td>
<td>4.5±159</td>
<td>7.3±87</td>
</tr>
</tbody>
</table>

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**Displaced Leptons: CMS**

- Signature of *oppositely charged leptons* originating at a separated secondary vertex within the *inner tracker volume*.
- **Benchmark model:** $Higgs \rightarrow 2X, X \rightarrow l^+l^-$
- Main selection variable: *transverse decay length significance* $L_{xy}/\sigma_{xy}$
- **No excess**

![Graph](http://arxiv.org/abs/1211.2472)
In RPV SUSY, **neutralino can decay in muon + jets**

- muon good for triggering, jets for vertexing
- dedicated vertex reconstruction

**No excess seen**

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**Displaced Vertexes with Track+Muon**

![Diagram](http://arxiv.org/abs/1210.7451)

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**ATLAS**

- **Signal region**
- **Data 2011**
  - \( \int L dt = 4.4 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 7 \text{ TeV} \)
- **ATLAS**
  - **MH**
  - **ML**
  - **HH**
  - \( \int L dt = 4.4 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 7 \text{ TeV} \)

**PROSPINO 700 GeV squark pair production**

**PROSPINO 1.5 TeV squark pair production**

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SUMMARY

• In several SUSY and Exotics Models interesting signatures with long-lived particles
  – extend phase-space of searches

• Searches for long-lived particles very challenging
  – look where background for SM analyses is
  – full understanding of the detectors and “non-standard” analysis techniques needed

• So far, no evidence of new physics

• Most of the analysis being updated and improved with full statistics
  – we still have 20 fb\(^{-1}\) 2012 data to look at

• Lots of space for new ideas
DISCUSSION
## Comparison Between the Two Experiments

<table>
<thead>
<tr>
<th>Analysis</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSCP</td>
<td>4.7 fb⁻¹ (7TeV)</td>
<td>5 fb⁻¹ (7TeV) + 18.8 fb⁻¹ (8TeV)</td>
</tr>
<tr>
<td>Disappearing tracks</td>
<td>4.7 fb⁻¹ (7TeV)</td>
<td>work in progress</td>
</tr>
<tr>
<td>Stopped particles</td>
<td>31 pb⁻¹ (7TeV)</td>
<td>4 fb⁻¹ (7TeV)</td>
</tr>
<tr>
<td>Displaced photons</td>
<td>4.8 fb⁻¹ (7TeV)</td>
<td>4.9 fb⁻¹ (7TeV)</td>
</tr>
<tr>
<td>Displaced heavy fermions</td>
<td>1.9 fb⁻¹ (7TeV)</td>
<td>work in progress</td>
</tr>
<tr>
<td>Displaced leptonjets</td>
<td>1.9 fb⁻¹ (7TeV)</td>
<td>5.1 fb⁻¹ (7TeV)</td>
</tr>
<tr>
<td>Displaced vertices + muon</td>
<td>4.4 fb⁻¹ (7TeV)</td>
<td>-</td>
</tr>
</tbody>
</table>

**ATLAS SUSY Searches - 95% CL Lower Limits**

- Direct $\tilde{\chi}_1$ pair prod. (AMSB): long-lived $\tilde{\chi}_1$
- Stable $\tilde{g}$, R-hadrons: low $\beta$, $\beta_y$
- GMSB, stable $\tilde{\tau}$: low $\beta$
- GMSB, $\tilde{\chi}_0 \rightarrow \gamma \tilde{\gamma}$: non-pointing photons
- GMSB, $\tilde{\chi}_0 \rightarrow q\tilde{\mu}$ (RPV): $\mu +$ heavy displaced vertex

**CMS EXOTICA 95% CL Exclusion Limits (TeV)**

- gluino, Stopped Gluino stop, HSCP stop, Stopped Gluino stau, HSCP, GMSB
- hyper-K, hyper-$\rho$: 1.2 TeV
- neutralino, $c\tau < 50$ cm

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*Long-Lived Particles at the LHC*
Issues for Discussion

- Current activities
  - extend analyses to the full statistics

- Model-independent approach
  - to help theoreticians in the interpretation
  - does it make sense to have a “rivet”-like approach

- Better definition of control samples

- Next LHC run
  - upgrade of the detectors (phase two / sLHC): keep in mind the LL signatures
  - develop more ad-hoc triggers
  - larger use of data parking (delayed data stream)
  - take advantage of a much larger statistics (~100 fb⁻¹)
    - e.g. search for rare Higgs decays

- In general, invest more in these analyses (once most of SUSY/exotica phase space will be explored, investigate LL)
  - lot of space for master degree and PhD theses
## LeptonJets: Current Activity

- Investigate more complex decay modes → higher particle multiplicity in the final state and final states with electrons, muons and pions.
- Extend search to be as more model independent as possible → constrain many theoretical models.

### Table: Lepton Jets Search

<table>
<thead>
<tr>
<th>LJ 1</th>
<th>LJ 2</th>
<th>1st Muons</th>
<th>2nd Muons</th>
<th>1st Hadrons</th>
<th>2nd Hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>only 2 $\mu$ + 2 $\mu$ in 2011</td>
<td>electrons</td>
<td>muons</td>
<td>light hadrons</td>
<td>leptons+light hadrons</td>
</tr>
<tr>
<td>muons</td>
<td></td>
<td>muons</td>
<td>light hadrons</td>
<td>leptons+light hadrons</td>
<td></td>
</tr>
<tr>
<td>electrons + muons</td>
<td></td>
<td>electrons + muons</td>
<td>leptons+light hadrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>light hadrons</td>
<td></td>
<td>light hadrons</td>
<td>leptons+light hadrons</td>
<td></td>
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</tr>
<tr>
<td>leptons+light hadrons</td>
<td></td>
<td>leptons+light hadrons</td>
<td>leptons+light hadrons</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

= work in progress

Very challenging search!
DISPLACED VERTICES/JETS: CURRENT ACTIVITY

- Extend previous analysis to the entire collected statistics
  - Search for displaced vertices in Muon System
  - Search for displaced vertices in Inner Tracker
  - Search for two πν’s decaying both in the Hadronic Calorimeter (well advanced)
- Signature of a πν decaying in the HAD calorimeter:
  - narrow energy deposition in HAD calorimeter
  - anomalous log(E_{HAD}/E_{EM})
  - isolation (no tracks) in ID
HSCP: current activity

• Update of the analysis on the 8 TeV data expected soon

• Interesting planned improvements:

  1. possibility for R-hadrons to decay or to interact with the detector material and to change charge (charged $\rightarrow$ neutral within a certain lifetime $O(\text{ns})$ only detected by ID; neutral $\rightarrow$ charged no track in the ID but detected by MS)

      • for the current analysis, only a simplified study of variation in efficiency with R-hadron lifetime $\rightarrow$ perform the new analysis as lifetime dependent (particularly sensible for ID-only approach)

  2. investigating different triggers, both for muons and for R-hadrons
BACKUP
HSCP: Analysis Technique

Combination of several detector inputs to be sensitive to slepton (slow muon-like) and R-hadrons (maybe with short lifetime)

ATLAS EXAMPLE

- Muon Spectrometer + ID (β,μ-like) (sleptons)
- ID + Calo + Muon Spectrometer (R-hadrons, full-detector analysis)
- Pixel + Tracker + Tile Calorimeter (β) (R-hadrons, μ-agnostic analysis)
- Pixel Detector(dE/dx,p)+SCT(p) (R-hadrons with short lifetimes, ID-only analysis)
**Benchmark Scenario for Stau in HSCP**

<table>
<thead>
<tr>
<th>Par.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>SUSY breaking scale</td>
</tr>
<tr>
<td>$M_m$</td>
<td>Messenger mass scale</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>Ratio of Higgs vev</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Number of SU(5) messenger multiplets</td>
</tr>
<tr>
<td>$\text{sign}(\mu)$</td>
<td>$\mu$ from Higgs sector</td>
</tr>
<tr>
<td>$C_{\text{grav}}$</td>
<td>Sets NLSP lifetime</td>
</tr>
</tbody>
</table>

30-160 GeV depending on stau mass

250 TeV

10

3

positive

$10^4$ (lifetime to avoid slepton decaying in det)