First Results from the Searches for Stopped Gluinos and Heavy Stable Charged Particles in pp collisions at 7 TeV

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ICHEP 2010, Paris
Motivation & Overview

- Many new physics scenarios predict **heavy long-lived particles**
  - Some flavours of SUSY predict long lived stau, gluino, stop
  - Hidden valley models, certain GUTs
  - Lifetimes around 100-1000s are of particular interest in cosmology
    - **May explain the** $^6\text{Li}, \ ^7\text{Li}$ **abundance discrepancy** between measurement and conventional nucleosynthesis
- These particles may be strongly interacting and form bound states with quarks/gluons - “R-hadrons”

- If charged, these particles will lose energy as they traverse the detector
  - Slow moving heavy particles **will lose energy at a greater rate than a MIP**
  - Some fraction of particles **will stop altogether**

- Results from **two complementary search methods** are presented here
  - Searching for tracks with **anomalously high dE/dx**
  - Searching for **decays of particles that have stopped** in the detector
  - Stopped particle search more sensitive to low $\beta$ ($<0.3$), dE/dx method more sensitive at moderate $\beta$ ($>0.3$)

- Both methods offer **high sensitivity** with the early LHC data
Search for Heavy Stable Charged Particles

- Attempt to identify the HSCP as it moves through the detector
  - Looking for an excess of tracks with high $p_t$, high $dE/dx$

- HSCP will be highly penetrating and identified as a muon
  - R-hadrons undergo nuclear interactions, and may change charge/flavour
  - Some models of R-hadron interactions predict they become neutral and remain so

- Perform two analyses
  - Track+muon - for muon-like HSCP
  - Track-only - for non muon-like HSCP

- Benchmark signals
  - Track+muon => mGMSB stau (100-300 GeV)
  - Track only => stop & gluino R-hadron (130-900 GeV), with “Cloud model” of R-hadron interactions

- Triggers
  - For muon-like HSCP, use muon triggers (muon > 3 GeV, double muon > 0 GeV)
  - For non muon-like HSCP, trigger on other products of the event (jet > 50 GeV, $E_t^{miss} > 45$ GeV)
Select tracks with high $p_t$ and dE/dx
- Use a discriminator for dE/dx based on measured energy loss for MIPs
- Good discrimination, and MC-data agreement in both variables

Analysis is performed in bins of $\eta$ and $N_{\text{hits}}$
- Thresholds set separately for each bin to give a uniform background rejection
- Important for tracks with few hits;
- Important for R-hadrons which may change charge

Improves S/B by factor 2 at current luminosity
Mass Reconstruction

- Mass reconstruction
  - Approximate Bethe-Bloch formula before minimum
    \[ I_h = K \frac{m^2}{p^2} + C \]
  - Extract parameters $K$, $C$ by fitting to the proton line
  - Reverse to compute higher masses

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Search Procedure

- Perform a counting experiment in the mass range 75-1200 GeV/c² using 198 nb⁻¹ data
  - Summing over bins in η, N_{hits}
  - Background for each bin determined from data using an “ABCD” method + (data-determined) correction
- Signal efficiency does not depend strongly on threshold (see right)
  - Optimise thresholds to yield desired background
- Define a tight selection for the search
- And a background enriched selection for cross-checks

<table>
<thead>
<tr>
<th></th>
<th>( \epsilon_{p_T} )</th>
<th>( p_{T}^{cut} )</th>
<th>( \epsilon_I )</th>
<th>( I_{as}^{cut} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tracker+Muon</td>
<td>Tracker only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOOSE</td>
<td>10⁻¹.⁰ 7.7 - 25.9</td>
<td>10⁻².⁰ 7.9 - 67.4</td>
<td>10⁻¹.⁵ 10⁻².⁰</td>
<td>0.0036 - 0.4521</td>
</tr>
<tr>
<td></td>
<td>10⁻².⁰ 7.9 - 67.4</td>
<td></td>
<td>0.0037 - 0.5293</td>
<td></td>
</tr>
<tr>
<td>TIGHT</td>
<td>Tracker+Muon</td>
<td>Tracker only</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10⁻³.⁰ 7.7 - 125.9</td>
<td>10⁻³.⁰ 7.9 - 259.0</td>
<td>10⁻³.⁵ 10⁻³.⁵</td>
<td>0.0036 - 0.6526</td>
</tr>
<tr>
<td></td>
<td>10⁻⁴.⁰ 7.9 - 259.0</td>
<td></td>
<td>0.0037 - 0.8901</td>
<td></td>
</tr>
</tbody>
</table>
Background-Enriched Selection

- Good agreement between expected background and observation
- Both in event counts:

<table>
<thead>
<tr>
<th>LOOSE</th>
<th>Exp.</th>
<th>Obs.</th>
<th>Exp. in full spectrum</th>
<th>Obs. in full spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker+Muon</td>
<td>82 ± 33</td>
<td>77</td>
<td>1007 ± 200</td>
<td>838</td>
</tr>
<tr>
<td>Tracker Only</td>
<td>108 ± 38</td>
<td>122</td>
<td>184 ± 250</td>
<td>260</td>
</tr>
</tbody>
</table>

- And in mass distribution:

![Graphs showing track+muon and track only distributions](image-url)
Search Results

- Null result in signal region and full mass spectrum

<table>
<thead>
<tr>
<th>TIGHT</th>
<th>Exp.</th>
<th>Obs.</th>
<th>Exp. in full spectrum</th>
<th>Obs. in full spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon-like</td>
<td>$0.153 \pm 0.061$</td>
<td>0</td>
<td>$0.249 \pm 0.050$</td>
<td>0</td>
</tr>
<tr>
<td>Tk-only</td>
<td>$0.060 \pm 0.021$</td>
<td>0</td>
<td>$0.060 \pm 0.011$</td>
<td>0</td>
</tr>
</tbody>
</table>

- 95% CL limits on the production cross-section for stau, stop and gluino
  - Track-only analysis => exclude $m_{\tilde{g}} < 271 \text{ GeV/c}^2$
  - Track+muon analysis => exclude $m_{\tilde{g}} < 284 \text{ GeV/c}^2$

![CMS Preliminary 2010 \( \sqrt{s} = 7 \text{TeV} \) 198 nb\(^{-1} \) - Tracking Results](image.png)

![CMS Preliminary 2010 \( \sqrt{s} = 7 \text{TeV} \) 198 nb\(^{-1} \) - Tracking Results](image.png)
Search for Stopped Gluinos

- This is a highly unorthodox search, for the decays of long-lived particles that have stopped in the detector.

- Use a dedicated calorimeter trigger to search during periods when no collisions are expected.
  - In gaps between filled bunches during an LHC fill, and between LHC fills (not used yet).
  - Trigger includes a no-beam condition using beam position and timing monitors (BPTX).

- Observation of a signal during these periods will be an unambiguous sign of BSM physics.

  - CMS-PAS-EXO-09-001.
Simulation

- Solve the problem of simulating long lifetimes by factorising into 3 phases:
  1. R-hadron production, interaction with detector, and map stopping points
  2. Decay stopped R-hadron and simulate interaction of decay products with detector
  3. Simulate time of production (based on *delivered* luminosity profile), time of decay and calculate “time acceptance”

We search in CMS HCAL

~20% probability for an R-hadron to stop somewhere in CMS
Event Selection

- Backgrounds: instrumental effects, cosmic rays, out of time beam triggers
- Cosmic & noise background originally measured with 2008 cosmic data
  - Confirmed with 2009 cosmic data, 2009/2010 collision data
  - Selection to reject these backgrounds unchanged since 2009 public note
- Beam backgrounds observed in 900 GeV and 7 TeV data
  - Mostly early collision triggers (but potentially also beam halo, beam-gas, parasitic collisions)
  - Reject this by vetoing events within +/-1 BX of passage of beam through CMS

### Beam background rejection

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Background Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1+HLT (HB+HE)</td>
<td>3.27</td>
</tr>
<tr>
<td>Calorimeter noise filters</td>
<td>1.12</td>
</tr>
<tr>
<td>BPTX/BX veto</td>
<td>1.11</td>
</tr>
<tr>
<td>muon veto</td>
<td>$6.6 \times 10^{-1}$</td>
</tr>
<tr>
<td>$E_{jet} &gt; 50$ GeV, $</td>
<td>\eta_{jet}</td>
</tr>
<tr>
<td>$n_{60} &lt; 6$</td>
<td>$7.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>$n_{90} &gt; 3$</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$n_{phi} &lt; 5$</td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$R_1 &gt; 0.15$</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$0.1 &lt; R_2 &lt; 0.5$</td>
<td>$8.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$0.4 &lt; R_{peak} &lt; 0.7$</td>
<td>$7.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$R_{outer} &lt; 0.1$</td>
<td>$6.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Rates measured in low lumi 7 TeV collision runs ($2-7 \times 10^{27}$ cm$^{-2}$s$^{-1}$)

Signal efficiency ~17% (of all R-hadrons that stop anywhere in CMS)
Counting Experiment

- Perform a counting experiment in bins of lifetime, $\tau$
  - For small $\tau$, select events in a window $1.256 \times \tau$ after each collision

- We divide the collision data into two sets:
  - The first, low lumi, set is used to measure the background rate
  - Then perform the search in the second, high lumi, set
    - $L_{\text{int}} = 203 \ (232) \text{ nb}^{-1}$ recorded (delivered)

- Observed counts compatible with background expectation

<table>
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<tr>
<th>Lifetime [s]</th>
<th>Expected Background ($\pm$ stat $\pm$ syst)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e-07</td>
<td>$0.15 \pm 0.04 \pm 0.05$</td>
<td>0</td>
</tr>
<tr>
<td>1e-06</td>
<td>$1.8 \pm 0.5 \pm 0.5$</td>
<td>0</td>
</tr>
<tr>
<td>1e-05</td>
<td>$11.7 \pm 3.2 \pm 3.5$</td>
<td>8</td>
</tr>
<tr>
<td>1e-04</td>
<td>$28.3 \pm 7.8 \pm 8.5$</td>
<td>19</td>
</tr>
<tr>
<td>1e-03</td>
<td>$28.3 \pm 7.8 \pm 8.5$</td>
<td>19</td>
</tr>
<tr>
<td>1e+03</td>
<td>$28.3 \pm 7.8 \pm 8.5$</td>
<td>19</td>
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- Can then calculate a cross-section, given the integrated luminosity
  - Potentially **sensitive to lumi delivered when CMS was not running!**
  - Use the delivered lumi profile + Toy MC, to calculate this
Model-Independent Result

- First result is a limit on cross-section x stopping probability
  - Independent of the model for interactions with matter

- $\tau < \text{few 100 ns}$
  - Decays occur during vetoed BXs

- $\tau < T_{\text{orbit}} (\sim 10^{-4} \text{ s})$
  - Decays occur within the orbit, but we optimise the time window

- $T_{\text{orbit}} < \tau < T_{\text{fill}} (\sim 10^4 \text{ s})$
  - Accept events over the full orbit - sensitivity plateau

- $\tau > T_{\text{fill}}$
  - Lose sensitivity as increasing fraction of decays occur post-fill

**Cross-section x stopping probability**

- Steps occur between time-windows as $N_{\text{obs}}$ increments for each observed event

- 14 orders of magnitude!
Time Profile Analysis

- As well as counting expt, we analyse the distribution of observed event times
  - For a given lifetime hypothesis, calculate a PDF for signal event time, using the delivered luminosity profile
  - Background PDF is flat in time
- Fit data and calculate a 95% CL on the signal
- We do this for lifetimes less $\sim 100\ \mu s$
  - Using event time within the orbit, ie. BX

Signal PDF peaks at collision BXs

Background PDF is flat
Cross-section Limit

- Use the stopping probability to obtain a limit on the cross-section
  - For \( m_\tilde{g} = 200 \) GeV, \( M_{\chi^0} = 100 \) GeV

- Stopping probability depends on models of R-hadron interactions
  - Default "Cloud model"
  - "EM only"
  - "Neutral R-Baryon" model

Time profile analysis improves sensitivity to small lifetimes

For \( m_\tilde{g} < 200 \) GeV, exclude lifetimes \( 120 \) ns < \( \tau \) < 6 \( \mu \)s

Extends D0 limit (valid for \( \tau > 30 \) \( \mu \)s)
Mass Exclusion Limit

- Present limit for fixed lifetime, as a function of $m_\tilde{g}$,$M_\tilde{\chi}_0$
  - Fixed $m_\tilde{g}$-$M_\tilde{\chi}_0=100$ GeV

- Trigger/reco/stopping efficiency is roughly flat
  - And valid for mass differences > 100 GeV

- Results not presented for region below $m_\tilde{g}=150$ GeV
  - Being to encroach on LEP neutralino limit
  - And/or trigger/reco efficiency declines

Time profile analysis:
for $\tau=200$ ns,
exclude $m_g < 229$ GeV

Counting experiment:
for $\tau=2.6$ $\mu$s,
exclude $m_g < 225$ GeV
Summary

Search for heavy stable charged particles
- Searched for high-p_t, high dE/dx tracks, with and without muon ID, in 198 nb^{-1} data at \( \sqrt{s} = 7 \) TeV
- For masses 130-900 GeV, \textit{gluino/stop cross-section limited to \sim 100pb}
- Track-only analysis \( \Rightarrow \) exclude gluino below 271 GeV
- Track+muon analysis \( \Rightarrow \) exclude gluino below 284 GeV

\textit{already approaching Tevatron limits}

- CMS-EXO-PAS-10-004 (on CERN CDS soon)

Search for stopped gluinos
- Searched for decays of particles stopped in CMS, in 203-232 nb^{-1} of data at \( \sqrt{s} = 7 \) TeV
- Using a novel calorimeter trigger to record decays during gaps between LHC collisions
- For 120 ns < \( \tau \) < 6 \( \mu \)s, \textit{exclude gluinos of mass up to 200 GeV/c^2}
- For lifetimes of 2.6 \( \mu \)s, \textit{exclude gluinos of mass up to 225 GeV/c^2}
- For lifetimes of 200 ns, \textit{exclude gluinos of mass up to 229 GeV/c^2}

\textit{extending D0 limit for \tau > 30 \mu s}

- CMS-EXO-PAS-10-003 (on CERN CDS soon)
Backup Slides (HSCP)
dE/dx estimators

- Mass reconstruction
  - Harmonic 2 estimator
    \[ I_h = \left( \frac{1}{N} \sum_i c_i^k \right)^{1/k} \text{ with } k = -2 \]

- Event selection
  - Modified Smirnov-Cramer-von Mises estimator
    \[ I_{as} = \frac{3}{N} \times \left( \frac{1}{12N} + \sum_{i=1}^{N} \left[ P_i \times \left( P_i - \frac{2i - 1}{2N} \right) \right]^2 \right) \]
  
  - \( P_i \) = probability for a MIP to produce equal or less charge than that observed, for the observed path length
  
  - The PDFs used to compute \( P_i \) are determined from tracks (\( p_T > 5 \text{ GeV} \)) taken on a minimum bias trigger
Mass Reconstruction

- $I_h$ vs $p$, and reconstructed mass distribution for stop MC samples
- Reconstructed tracks matched to the MC truth stop
- Bias at high mass is due to ADC saturation
  - Does not affect this analysis, which is purely a counting experiment
Background Determination

- Background for each \((N_{\text{hits}}, \eta)\) bin is determined using an “ABCD” method
  - Background in signal region, \(D = BC/A\)
  - This relies on non-correlation of \(p_t\) and \(dE/dx\) measurements
  - Shown above, \(I_{\text{as}}\) distribution for two \(p_t\) ranges
  - This method is extended to also predict the expected background mass spectrum

- Cross-check the background determination by comparing observed with expected background counts for a control region (mass < 75 GeV/c^2)
  - Find that a correction is required, average factor 1.32 (tk+muon), 1.36 (tk only)
  - Also use this to determine the systematic uncertainty on the background
Backup Slides
(Stopped Gluinos)
Know Thy Enemy

Noise events from 2008 cosmic data

Run 63008, Event 329536

Run 68021, Event 17978774, LS 323,

Run 63008, Event 123562

Run 68021, Event 17978761,