Searches for highly ionizing particles in ATLAS and CMS

Antonio Policicchio
INFN Cosenza - CERN
ATLAS Collaboration
Introduction

• High-mass, long-lived charged particles predicted by various extensions of the Standard Model
• If such particles have a mass lighter than a few TeV they could be produced by the CERN LHC
• Massive particles with lifetime greater than $O(1)$ ns could be observed with the ATLAS and CMS detectors as high-momentum tracks with anomalously large rates of energy loss through ionization
• These particles could also be highly penetrating such that the fraction reaching the muon system of the detectors would be sizeable
  • The muon system could therefore be used to help in identification and in the measurement of the time-of-flight (TOF) of the particles
• In this talk results are presented of some specific BSM searches for high-mass, long-lived charged particles. Results are interpreted in terms of
  • the production of new particles with a fractional or multiple value of the charge of the electron
  • the production of high mass stable charged particles (HSCP), also reinterpreted in the context of supersymmetric scenarios that predict stable or pseudo-stable charged particles in the final state
  • the presence of magnetic monopoles
Multi-Charged Particles (MCP) in ATLAS

arXiv:1504.04188 submitted to EPJ C

- Search for long-lived highly ionizing heavy (mass in 50 - 1000 GeV) particles with high electric charges (|q|=2,3,4,5,6 e)
- “Blue-sky” search, but some models predict new particles with charge greater than one
  - Almost Commutative Geometry model (AC-leptons): extends SM by two heavy particles with |q|≥e
  - Walking Technicolor Model (techni-leptons): production of 3 particle pairs with q+e, q, q-e (|q|≥e)

- Analysis features
  - Long-lived particles → high p_T muon trigger or missing E_T trigger
  - Selection
    - muon-like particles with high ionization losses in Pixel, Transition Radiation Tracker (TRT) and muon precision chambers (MDT)
    - high fraction of TRT hits passing the high threshold, f_{HT}
  - Background estimation: ABCD method

- Results: no candidate events observed in data → exclusion limits assuming a Drell-Yan production cross-section

| |q| | Mass limits [GeV] |
|---|---|---|
| 2e | 50-660 |
| 3e | 50-740 |
| 4e | 50-780 |
| 5e | 50-785 |
| 6e | 50-760 |
Stable heavy charged particles in ATLAS

JHEP01 (2015) 068

- Search for heavy, charged, stable, slow-moving ($\beta < 1$) particles
- Analysis strategy
  - High $p_T$ muon trigger or missing $E_T$ trigger
  - Track information is used to calculate the candidate mass
    - $p$ derived from the candidate track
    - $\beta$ calculated from measured ToF (using muon system and calorimeter)
    - $\beta\gamma$ deduced from Pixel $dE/dx$
  - Background: high-$p_T$ muons with large ionization, mis-measured $\beta$
    - Contribution estimated from data
  - Interpretations: stable sleptons, leptoSUSY, charginos, R-hadrons

![](image)

<table>
<thead>
<tr>
<th>Search</th>
<th>Lower mass limit [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMSB sleptons</td>
<td></td>
</tr>
<tr>
<td>$\tan\beta$ = 10, 20, 30, 40, 50</td>
<td>440, 440, 430, 410, 385</td>
</tr>
<tr>
<td>direct $\tilde{\ell}$ production ($m_{\tilde{\ell}} - m_{\ell}$ = 2.7–9.3 GeV)</td>
<td>377–335</td>
</tr>
<tr>
<td>direct $\tilde{\tau}_1$ production</td>
<td>289</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0\tilde{\chi}_1^\pm$ decaying to stable $\tilde{\tau}_1$</td>
<td>537</td>
</tr>
<tr>
<td>LeptoSUSY</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{g}$</td>
<td>1500, 1360</td>
</tr>
<tr>
<td>Charginos</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm$</td>
<td>620</td>
</tr>
<tr>
<td>$R$-hadrons</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{b}, \tilde{t}$ (full-detector)</td>
<td>1270, 845 and 900</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{b}, \tilde{t}$ (MS-agnostic)</td>
<td>1260, 835 and 870</td>
</tr>
</tbody>
</table>
Updated searches using Pixel dE/dx only → extend sensitivity to lower lifetimes
Mass obtained by fitting energy loss and momentum to an empirical Bethe–Bloch distribution
Events selected by missing transverse energy trigger
Offline selection:
- track isolation ($\Delta R$ with respect to any other track > 0.25)
- electron veto
- high (>150 GeV) momentum
- high ionization (>MIP value)
- muon veto if particle is metastable with decay before the muon system

No events observed in data over the estimated background → lower limits on particles mass
Search for monopoles and stable particles with high electric charges in ATLAS

- Massive stable particles with very high electric charge predicted by several new physics models: theories of magnetic monopoles (carry magnetic charge $g$, $g = n \times g_D$, where $g_D = 68.5 e$), strange quark matter, Q-balls, stable microscopic black-hole remnants

- Signature to maximise the acceptance for particles predicted by the models (energy in 100 - 500 GeV): large localised energy deposit in the Electromagnetic calorimeter + a region of high ionisation density in the TRT ($f_{TH}$)

- Event selection
  - dedicated trigger: EM calorimeter energy deposit with no energy after the first calorimeter layer + large $f_{HT}$
  - high $f_{HT}$ matched to EM energy deposit
  - EM energy deposit dispersion (fraction of EM energy contained in the most energetic cells, $w$)
  - ABCD method used to determine the background from data

- Results: no events observed in 7 fb$^{-1}$ @ 8 TeV $\rightarrow$ DY pair production mass limits
High mass Stable Charged Particles (HSCP) in CMS

JHEP07 (2013) 122

- Search for particles with significant lifetime (\(\geq a \) few ns), \(\beta < 1\), and possibly \(|q| \neq 1\)
- High \(p_T\) muon trigger plus missing \(E_T\) trigger
- Use \(dE/dx\) in tracker and TOF to muon system to distinguish HSCP signal
- Five channels: single charge in tracker+TOF, tracker only, muon only, fractional-charge (tracker only), and multiple charge
- Smirnov–Cramer–von Mises discriminator, \(l_{as}\) used to separate SM particle from candidates with large (small) \(dE/dx\)
- Background estimation: ABCD method

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>(\sqrt{s} = 7) TeV</th>
<th>(\sqrt{s} = 8) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_T) (GeV/c)</td>
<td>(l_{as})</td>
<td>1/(\beta)</td>
</tr>
<tr>
<td>Tracker-only</td>
<td>&gt;70</td>
<td>&gt;0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracker+TOF</td>
<td>&gt;70</td>
<td>&gt;0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon-only</td>
<td>&gt;230</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Q &gt; 1e)</td>
<td>–</td>
<td>&gt;0.500</td>
</tr>
</tbody>
</table>
• Limits on cross sections are given for models with the production of gluinos, scalar tops, and staus, and for Drell–Yan like production of fractionally, singly, and multiply charged particles.
## High mass Stable Charged Particles in CMS

- **Summary of exclusion limits**

<table>
<thead>
<tr>
<th>particle</th>
<th>mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino (f = 0.5)</td>
<td>&lt; 1276 GeV</td>
</tr>
<tr>
<td>gluino (f = 1.0)</td>
<td>&lt; 1250 GeV</td>
</tr>
<tr>
<td>gluino (f = 0.1)</td>
<td>&lt; 1322 GeV</td>
</tr>
<tr>
<td>gluino (f = 0.1)</td>
<td>&lt; 1233 GeV</td>
</tr>
<tr>
<td>stop</td>
<td>&lt; 935 GeV</td>
</tr>
<tr>
<td>stop</td>
<td>&lt; 818 GeV</td>
</tr>
<tr>
<td>stau</td>
<td>&lt; 500 GeV</td>
</tr>
<tr>
<td>stau</td>
<td>&lt; 339 GeV</td>
</tr>
</tbody>
</table>

*f* is the fraction of gluinos hadronizing into $g^{-}\text{gluon}$ bound states

- Drell–Yan like signals with $|Q| = e/3, 2e/3, 1e, 2e, 3e, 4e, 5e, 6e, 7e,$ and $8e$ are excluded with masses below $200, 480, 574, 685, 752, 793, 796, 781, 757,$ and $715$ GeV/$c^2$, respectively
In the context of the AMSB model, charginos with lifetimes $\tau > 100$ ns (3 ns) and masses up to about 800 GeV (100 GeV) are excluded at 95% CL.

High mass Stable Charged Particles in CMS

- **Reinterpretation of the search results**
  - Developed a technique to allow anyone to assess CMS sensitivity to any model predicting long-lived lepton-like particles
  - Main principle: measure the efficiency for these particles as a function of $\beta$ and $\eta$ in bins of $p_T$; then one just needs the predicted kinematics from the model
  - Example: reinterpret results in the context of the phenomenological minimal supersymmetric standard model (pMSSM) and the anomaly-mediated supersymmetry breaking (AMSB) model
  - The most stringent limits to date are set on the long-lived sector of the pMSSM sub-space that covers SUSY particle masses up to about 3 TeV: 95.9% (100%) of the points with a chargino lifetime $\tau \geq 10$ ns (1000 ns) are excluded by the present analysis of the results from the CMS search

In the context of the AMSB model, charginos with lifetimes $\tau > 100$ ns (3 ns) and masses up to about 800 GeV (100 GeV) are excluded at 95% CL.
Conclusions

- With no sign of new physics, there has been much speculation that BSM signals could be hiding in stable, meta-stable heavy charged particles
- ATLAS and CMS Run1 searches for highly ionizing particles at the LHC were very successful
- Long list of new physics analyses and results presented in this talk
- New or stronger limits have been established by the two experiments
- While we complete the Run1 program, data at higher energy are being collected
- We are looking forward to the increased discovery potential of Run2
Extra
The ATLAS detector

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Semiconductor tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
The CMS detector

CMS Detector
- Weight: 14,000 tonnes
- Diameter: 15.0 m
- Length: 28.7 m
- Magnetic field: 3.8 T

- Silicon Trackers
- Superconducting Solenoid
- Muon Chambers
- Preshower
- Forward Calorimeter
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Steel Return Yoke
Physics objects

- **Jet**: cluster in EM and hadronic calorimeters (and Inner Detector)
- **Photon**: EM cluster without matching track
- **Electron**: EM cluster with matching track
- **Muon**: matching tracks in inner and muon trackers, or muon standalone
- **Tau**: Narrow jet with matching track(s)
- **MET (missing $E_T$)**: $p_T$ required to balance all of the above (and more)
Physics objects
### ATLAS and CMS: more details

| LTerafe | CMS
|---|---
| **B-field** | 2T solenoid (Inner Tracker inside, HCAL outside of B-field) + toroid: 0.5T (barrel), 1T (endcap)  
→ good for jet resolution, worse for e/γ |
| **Tracker** | 4T solenoid + return yoke (ECAL and part of HCAL inside)  
→ good for e/γ resolution, worse for jet |
| Si pixels and strips + transition radiation tracker  
→ high resolution, granularity, “continuous” tracking at large radii | Si pixels and strips (fully Silicon)  
→ high resolution, granularity |
| σ/pt ~ 5 x 10^-4 pt + 0.01 | σ/pt ~ 1.5 x 10^-4 pt + 0.005 |
| 84% reco efficiency (material budget, B-field) | 80% reco efficiency |
| 90% reco efficiency | 85% reco efficiency |
| **EM calo** | Liquid argon + Pb absorbers  
→ high granularity |
| PbWO₄ crystals  
→ high resolution |
| σ/E ~ 10%/√E + 0.007 | σ/E ~ 3%/√E + 0.003 |
| 1.0 - 1.5% E resolution | 0.8% E resolution |
| 1.3 - 2.3% E resolution | 2.0% E resolution |
| **Had calo** | Fe + scintillator / Cu+Lar (10λ)  
σ/E ~ 50%/√E + 0.03 GeV |
| Brass + scintillator (7λ + catcher) |
| σ/E ~ 100%/√E + 0.05 GeV | 5% |
| 2% |
| 20 GeV |
| **Muon** | σ/pt~2% at 50 GeV to 10% at 1 TeV  
(Inner Tracker + muon system) |
| σ/pt~1% at 50 GeV to 10% at 1 TeV  
(Inner Tracker + muon system) |
Stable Massive Particles (SMPs) predicted by many BSM scenarios, including several different SUSY models

- **Sleptons** are massive, charged and metastable in GMSB

- **R-hadrons** are colored SMPs: 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)

- **Long-lived** for this search

---

<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}qq, (\bar{q}qq) )</td>
</tr>
<tr>
<td>R-gluinoballs</td>
<td>( R = \tilde{g}g )</td>
</tr>
</tbody>
</table>

---

As in Ref. [19], $dE/dx$ for a track is estimated as:

$$I_h = \left( \frac{1}{N} \sum_i c_i^{-2} \right)^{-1/2}$$

where $N$ is the number of measurements in the silicon-strip detectors and $c_i$ is the energy loss per unit path length in the sensitive part of the silicon detector of the $i$th measurement; $I_h$ has units MeV/cm. In addition, two modified versions of the Smirnov–Cramer–von Mises [54, 55] discriminator, $I_{as}$ ($I_{as}'$), are used to separate SM particles from candidates with large (small) $dE/dx$. The discriminator is given by:

$$I_{as}^{(l)} = \frac{3}{N} \times \left( \frac{1}{12N} + \sum_{i=1}^{N} \left[ P_i^{(l)} \times \left( \frac{P_i^{(l)} - \frac{2i - 1}{2N}}{2} \right)^2 \right] \right),$$

where $P_i$ ($P_i'$) is the probability for a minimum ionizing particle (MIP) to produce a charge smaller (larger) or equal to that of the $i$th measurement for the observed path length in the detector, and the sum is over the measurements ordered in terms of increasing $P_i^{(l)}$.

As in Ref. [19], the mass of a $|Q| = 1e$ candidate particle is calculated based on the relationship:

$$I_h = K \frac{m^2}{p^2} + C,$$

where the empirical parameters $K = 2.559 \pm 0.001$ MeV $\cdot$ $c^2$/cm and $C = 2.772 \pm 0.001$ MeV/cm are determined from data using a sample of low-momentum protons in a minimum-bias dataset. The number of silicon-strip measurements associated with a track, 15 on average, is sufficient to ensure good $dE/dx$ and mass resolutions.