Search for long-lived massive particles with the ATLAS detector

Orin Harris (UW/Seattle)

On behalf of the ATLAS collaboration

Standard Model object IDs

- ✓ electrons
- ✓ photons
- ✓ muons
- ✓ jets
- ✓ b-jets
- ✓ E_T^{miss}
- ...

New particle searches

- New particle searches typically search for rare combinations of Standard Model objects:

- New *long-lived* particles*

- Neutral
 - Displaced vertices/jets
- Massive charged
 - Slow $\rightarrow$ highly ionizing
 - Really slow $\rightarrow$ stop (decay out-of-time)
 - Decay $\rightarrow$ kinked or disappearing track

} need new object IDs!

Long-lived particle ATLAS Analyses

- Neutral massive particles
 - Hidden Valley: displaced vertex [arXiv:1203.1303v2](#)
 - RPV LSP decay: displaced vertex [arXiv:1109.2242v2](#)
- Charged massive particles
 - R-hadrons: dE/dx , β [ATLAS-CONF-2012-022](#)
[arXiv:1103.1984v1](#)
[arXiv:1106.4495v2](#)
 - Stable stau: β
 - HIP: high-threshold TRT hits [arXiv:1102.0459v3](#)
- Stopped R-hadron
 - Jets in empty/unpaired bunch crossings [arXiv:1201.5595v2](#)
- Anomaly-Mediated SUSY-breaking
 - Truncated tracks: missing TRT hits [ATLAS-CONF-2012-034](#)

This talk: recent ATLAS analyses

- Neutral massive particles
 - Hidden Valley: displaced vertex
 - RPV LSP decay: displaced vertex
- Charged massive particles
 - R-hadrons: dE/dx , β
 - Stable stau: β
 - HIP: high-threshold TRT hits
- Stopped R-hadron
 - Jets in empty/unpaired bunch crossings
- Anomaly-Mediated SUSY-breaking
 - Truncated tracks: missing TRT hits

Neutral massive: hidden valley

4 models: $m_h=120,140$ GeV, $m(\pi_v^0)=20,40$ GeV

Chose π_v^0 proper lifetime ($c\tau$) to give decays through out the detector

calorimeter

Different techniques
are required for each
section of the
detector

muon spectrometer

3 triggers

trackless jet trigger

Jet $E_T > 35$ GeV

No tracks with $p_T > 1$ GeV near jet

Muon spectrometer activity

Low efficiency

decays late in inner detector

$\text{Log}(E_{\text{had}}/E_{\text{EM}})$

Jet $E_T > 35$ GeV

No tracks with $p_T > 1$ GeV near jet

$\text{Log}(E_{\text{had}}/E_{\text{EM}}) > 1.0$

Very good efficiency

decays beyond the EM calorimeter

muon spectrometer cluster trigger

three muon clusters all close by
no jets

no tracks

Very good efficiency

decays beyond the calorimeter

muon spectrometer vertex

The ATLAS muon spectrometer is designed to reconstruct muon tracks stand alone

It can do more than particle ID!

Efficiency x-
checked with
punch-thru jets

Analysis Strategy

Muon Cluster Trigger
2 back-to-back vertices
in the muon spectrometer
No Jet or Track activity
near the vertex

0 events
seen in
 1.94 fb^{-1}

Expected signal in 1.94 fb^{-1}

Expected Backgrounds:

P calculated on zero bias data

limits

equal systematic error contributions from theory and efficiency verification for our signals.

Quantity	Systematic uncertainty
Higgs cross section	
$m_{h^0} = 140 \text{ GeV}$	+18.8% -14.9%
$m_{h^0} = 120 \text{ GeV}$	+19.7% -15.1%
RoI cluster trigger	14%
MS vertex (per vertex)	16%
Luminosity	3.7%

List of the systematic uncertainties.

$m_{h^0} \text{ (GeV)}$	$m_{\pi_v} \text{ (GeV)}$	Excluded Region
120	20	$0.50 < c\tau < 20.65 \text{ m}$
120	40	$1.60 < c\tau < 24.65 \text{ m}$
140	20	$0.45 < c\tau < 15.8 \text{ m}$
140	40	$1.10 < c\tau < 26.75 \text{ m}$

Charged massive: decaying

anomaly-mediated SUSY breaking

compressed mass spectra

Mass difference between $X_1^\pm$ and X_1^0 so small it has a long lifetime

analysis is sensitive to decays occurring somewhere in ATLAS inner tracker

Chargino leaves hits in tracker until it decays!

Looked at mass $X_1^\pm = 90.2, 117.8, 147.7$ GeV, $\text{BR}(\chi_1^\pm \rightarrow \chi_1^0 \pi^\pm) = 1.0$

detector signature, backgrounds

the analysis

Transition Radiation Tracker

- $0.5\text{m} < r < 1.1\text{m}$
- average of 15 hits for a charged track in the outer TRT ($N_{\text{TRT}}^{\text{outer}}$)

trigger

1 jet, $p_{\text{T}} > 75\text{ GeV}$
 $E_{\text{T}}^{\text{miss}} > 55\text{ GeV}$

offline

3 jets, $p_{\text{T}} > 130, 60, 60\text{ GeV}$
 $E_{\text{T}}^{\text{miss}} > 130\text{ GeV}$

lepton veto

track: $p_{\text{T}} > 10\text{ GeV}$

isolated

less than 5 hits in the TRT

304 events remain in 4.7 fb^{-1} of data

the shape of the track p_{T} spectra
differentiates signal and backgrounds

Background track p_T shapes

shape for high p_T tracks that interact
 Sample is signal-free:
 $N_{\text{TRT}}^{\text{outer}} > 10$.

shape for mismeasured low p_T tracks
 Sample is signal-free:
 $E_T^{\text{miss}} < 100 \text{ GeV}$
 no pixel hits

Fit track p_T shape

The 3 templates are fit to data:

- The two background templates are fit for $p_T > 10$ GeV
- The signal template is included in the fit for $p_T > 50$ GeV

data and background fit
best fit has zero contribution from
signal template

Fit prefers zero signal contribution!

limits

Limit for the mass

Previous LEP2 limit: $X_1^\pm > 92 \text{ GeV}$ (for any lifetime)

limit on production of truncated tracks

primary uncertainty is the theoretical cross section (27%)

backgrounds are data driven and so have very small uncertainty

Charged massive: R-hadrons

SUSY LSP is gluino (colored)

Hadronizes $\rightarrow \tilde{g}g, \tilde{g}qq, \tilde{g}qqq\dots$

“R-Hadron”: unlike a normal neutral LSP, can interact with the ATLAS detector!

Travels slowly through detector
 $\Rightarrow$ large dE/dx

$Mass(p, dE/dx)$

Pixel detector fires if $> 3100e^-$ deposited
Measures time-above-threshold $\Rightarrow dE/dx$
Bethe-Bloch to infer mass

analysis

trigger

No dE/dx information available

MIP in Calorimeter + **ISR** means $E_{\text{T}}^{\text{miss}}$

$E_{\text{T}}^{\text{miss}} > 70 \text{ GeV}$

20% efficient

offline

$E_{\text{T}}^{\text{miss}} > 85 \text{ GeV}$

isolated track, $p_{\text{T}} > 50 \text{ GeV}$, $p > 100 \text{ GeV}$

$\Delta R(\text{track}, p_{\text{T}} > 5 \text{ GeV track}) > 0.25$

dE/dx cut depends on η .

data driven background

results

Gluino R-hadron mass $< 810 \text{ GeV}$

conclusions

- three analyses presented
 - Hidden Valley search, AMSB search, R-hadron search
 - New limits on masses/lifetimes
 - More analyses and updates are ongoing
- non standard object ID
 - late appearance of jets, truncated tracks, high dE/dx , out-of-time energy, displaced vertices
- lots of information from the these detectors!!
 - how else can we combine this information to search for new things!?

backup

analyses on 2010 data

Analysis	
stopped gluinos	Particles come to rest in the ATLAS detector volume, and decay out-of-time. (1201.5595, submitted to EPJC)
displaced vertices	R-parity violating SUSY. Displaced vertices with $r > 4\text{mm}$ (1109.2242, PLB 707 (2012) 478-496)
R-Hadron	Neutral R-hadron becomes charged in calorimeter and leaves track in muon system (1103.1984, PLB 701 (2011) 1)
HIP search	Massive long lived highly ionizing particles with large electric charge (q-balls, stable micro black holes, etc.). Energy loss in calorimeter and tracker used (arxiv:1102.0459; PLB698:353-370,2011)

Hidden valley backup: the models

$m_h = 120 \text{ GeV}, 140 \text{ GeV}$
 $m(\pi_v^0) = 20 \text{ GeV}, 40 \text{ GeV}$

allow proper lifetime ($c\tau$) to vary to give
decays through out the detector

Backup: hidden valley long-lived particle triggers

- ATLAS has only so much bandwidth, drive space, cpu
 - Triggering means throwing away “less important” data
- Single-objects unprescaled @ end of 2011
 - 1e@22, 1 μ @18, 1j@250...
 - single medium- p_T objects not an option
- b-tagging triggers
 - good for a decay a few millimeters from primary vertex
 - huge backgrounds from QCD $b\bar{b}$ production
- Specially designed triggers
 - L1 is hardware-based (nothing can be done)
 - Room for innovation at L2/HLT
- Long-lived neutral particle triggers
 - neutral particle decays mid-detector
 - run for full 2011 dataset (5 fb⁻¹)

Hidden Valley backup

Muon Rol trigger efficiency

backup: AMSB model parameters

Table 1: Parameters of AMSB signal points, chargino masses and their NLO+NLL cross sections. The parameters $\tan \beta$ and $\text{sgn}(\mu)$ are set to 5 and +1. The cross sections only include $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}$ production processes.

Sample	$m_0[\text{TeV}]$	$m_{3/2}[\text{TeV}]$	$m_{\tilde{\chi}_1^\pm}[\text{GeV}]$	Cross section[pb]
LL01	1.5	32	90.2	6.79×10^{-2}
LL02	1.8	41	117.8	8.66×10^{-3}
LL03	2.0	51	147.7	1.16×10^{-3}

backup: AMSB cut flow

Requirement	Observed events	Signal efficiency (purity) [%]		
		LL01	LL02	LL03
Trigger selection and non-collision rejection	7141026	87.3	89.1	90.1
Lepton veto	6644394	72.8	72.5	72.6
$E_T^{\text{miss}} > 130 \text{ GeV}$	321412	66.5	68.2	69.6
Jet requirements	73433	64.9	67.4	69.0
High- p_T isolated track selection	8458	24.8 (67.6)	26.2 (66.8)	27.2 (66.7)
Disappearing track selection	304	6.1 (94.6)	6.6 (94.5)	7.3 (94.7)

Note: purity is only for tracks in the signal sample – it is not S/B!

Backup: R-Hadron models

SUSY, but the LSP is colored

→ hadronizes into colored hadrons

$\tilde{g}g, \tilde{g}qq, \tilde{q}\bar{q}, \tilde{g}qqq, \tilde{q}qq, \text{etc.}$

R-Hadrons

← “they carry one unit of R-Parity”

the R-Hadron will, unlike a normal neutral LSP, have interactions in the ATLAS detector!

three models are used (regge, generic, and “intermediate”)

the generic is used for limits, the other models are taken as a systematic error

Generic model

backup: R-hadron model details

The first model assumes that R -hadrons containing gluinos are simulated according to [19]. This model employs a triple-Regge formalism to describe hadronic scattering, and will henceforth be referred to as *Regge*.

The second physics model described in [30, 31] and hereafter referred to as *generic* has been used in other publications [32–34] and it imposes few constraints on allowed stable states. Doubly charged R -hadrons and a wide variety of “charge reversal” signatures in the detector are possible. Hadronic scattering is described through a purely phase space driven approach.

More recent models for the hadronic scattering of gluino R -hadrons predict that the majority of all produced R -hadrons will be electrically neutral after just a few hadronic interactions. The third model belongs to this family, is based on the bag-model calculations presented in [35] and is referred to as *intermediate*.

Backup: r-hadron mass resolution

backup: R-hadron cut flow

Table 1: Observed event yields at different steps of the selection procedure. The total efficiency is computed with respect to the events that passed the trigger and the data quality decision. *Trigger* selects only those events which satisfy the calorimetric ($E_T^{\text{miss}} > 70$ GeV) online trigger. *Offline* E_T^{miss} should exceed 85 GeV. *Primary vtx* requires a primary vertex with at least five tracks. Next cuts require in the event at least one track with: *High- p_T* corresponds to the request on high p_T , cuts on the impact parameters and Pixel/SCT clusters; *Isolation* refers to the requirement that the track satisfies $\Delta R_{\text{track, othertrack}} > 0.25$ from any other track with $p_T > 5$ GeV; *High- p* corresponds to the request on $p > 100$ GeV, *ionization* is the request on the Pixel dE/dx as explained in the text.

Cut level	# Events	Cut Eff.	Total Eff.
Trigger	2,413,863		
Offline E_T^{miss}	1,421,497	0.589	0.589
Primary vtx	1,368,821	0.963	0.567
High- p_T	212,464	0.155	0.0880
Isolation	32,188	0.151	0.0133
High- p	21,040	0.654	8.7E-03
ionization	333	0.016	1.4E-04

Cut level	Gluino 400 GeV		Gluino 700 GeV		Gluino 1000 GeV	
	Cut Eff.	Total Eff.	Cut Eff.	Total Eff.	Cut Eff.	Total Eff.
Trigger	0.205 ± 0.013	0.205 ± 0.013	0.219 ± 0.009	0.219 ± 0.009	0.177 ± 0.009	0.177 ± 0.009
Offline E_T^{miss}	0.98 ± 0.08	0.200 ± 0.013	0.99 ± 0.05	0.216 ± 0.009	0.98 ± 0.07	0.175 ± 0.009
Primary vtx	1.00 ± 0.09	0.200 ± 0.013	1.00 ± 0.05	0.216 ± 0.009	1.00 ± 0.07	0.175 ± 0.009
High- p_T	0.59 ± 0.06	0.120 ± 0.010	0.58 ± 0.04	0.129 ± 0.007	0.59 ± 0.05	0.108 ± 0.008
Isolation	0.84 ± 0.10	0.100 ± 0.009	0.84 ± 0.06	0.105 ± 0.006	0.88 ± 0.09	0.091 ± 0.007
High- p	0.99 ± 0.12	0.099 ± 0.009	0.99 ± 0.08	0.104 ± 0.006	1.00 ± 0.10	0.091 ± 0.007
Ionization	0.66 ± 0.09	0.067 ± 0.008	0.80 ± 0.07	0.085 ± 0.005	0.92 ± 0.09	0.084 ± 0.006

stopped particles

- Long-lived particles produced with low β can stop in detector material and decay much later.
- Most likely to stop in densest part of ATLAS $\Rightarrow$ calorimeters.
- Look for events with large energy deposits in calorimeter in “empty” bunches.

backgrounds: calorimeter noise, cosmics, beam-halo

stopped particles

stopped particles

LONG-LIVED CHARGED PARTICLES

(previous 2010-data analysis)

- Long lived particles (LLPs) are allowed by many BSM theories
- If produced at LHC they would travel with $\beta < 1$
- $m = p/\beta\gamma$ would produce a peak at the LLP mass
- GMSB:
 - The LSP is the gravitino
 - Small coupling to gravitino $\rightarrow$ NLSP is long lived
 - 2 $\tilde{\tau}$ LLPs and additional leptons in each event
- R-hadrons
 - Gluino NLSP hadronizes to long lived R-hadron
 - 2 gluinos produced directly – low β
 - R-hadron may change charge from ID to MS – how often is model dependent
- β measurements from ToF
 - Calo, RPC, MDT combined
- Background are muons with mismeasured β

LONG-LIVED CHARGED PARTICLES

(previous 2010-data analysis)

- Background estimation from data
 - Convolute p with β to get bkg mass spectrum
- No deviation of data from the background estimate is observed
- Limits are set using the CLs method

$m(\tilde{\tau}) > 136 \text{ GeV}$

EW produced LLPs:

$m(\tilde{l}) > 110 \text{ GeV}$

Previous limits: $m > 98 \text{ GeV}$

scale [2]. Additional scenarios allowing for such a signature include split-supersymmetry [3], hidden-valley [4], dark-sector gauge bosons [5], stealth supersymmetry [6], or a meta-stable supersymmetry-breaking sector [7].

displaced vertices

displaced vertex

SUSY++

$\mathcal{L}=33\text{ pb}^{-1}$

vertex reconstruction

standard

use tracks that have no pixel hits

reject vertices near material

sensitive starting at 4mm from PV

displaced vertices

displaced vertices

ATLAS