Discovery Potential of R-hadrons with the ATLAS Detector at the LHC

Berkeley Workshop on Physics Opportunities with Early LHC Data

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Outline

1. Introduction
    - Motivation
    - R-hadron production and their interactions
2. Analysis
    - MC samples
    - Trigger
    - Final state observables & cuts
    - Results
3. Recent developments
4. Summary & conclusions

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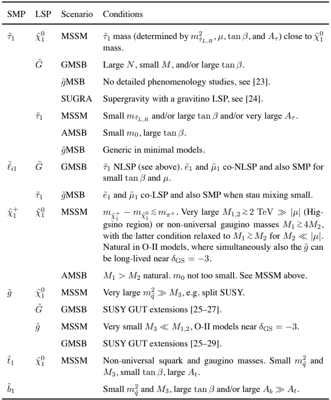
Motivation

- Stable[a] massive particles (SMPs) predicted in a range of SUSY and other BSM scenarios
- Within SUSY: SMPs with different color and electric charges
  - $\tilde{q}$ / $\tilde{g}$ (bound states)
  - $\tilde{\ell}$ or $\tilde{\chi}^+$
- Production processes can have high cross-sections ⇒ important early analysis



SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{\mathrm{GS}} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{\mathrm{GS}} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

Table 1

Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

arXiv:hep-ph/0611040v2

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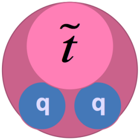
[a] In this context, "stable" means decay lengths ∼ size of ATLAS

Focus of this analysis: R-hadrons

What are they?

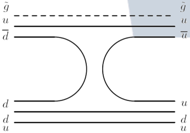
A stable color charged object will hadronize and form R-hadrons

- current mass limits on R-hadrons $\lesssim 250\,\mathrm{GeV}$
- R-hadron is a heavy hadron with
  - one heavy sparticle parton that carries most of the hadron's momentum
  - a light quark system (LQS)

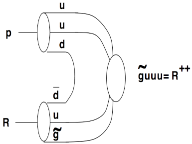


How do they interact?

- heavy parton unlikely to interact (cross-section supressed by $\frac{1}{m^2}$)
- LQS interacting with detector material can cause exchange of
  - electric charge



  - baryon number



(Details of scattering model and GEANT4 implementation: R. Mackeprang, A. Rizzi, Eur. Phys. J. C50 (2007) 353-362)

Focus of this analysis: R-hadrons

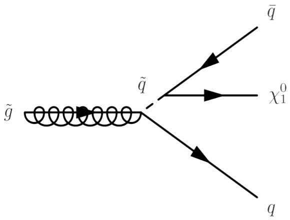
Scenarios giving rise to R-hadrons

Split-SUSY

- gaugino and higgsino masses much smaller than scalar masses
- For high $m_{\tilde{q}}$, the $\tilde{g}$ is long-lived enough to fly out through ATLAS

Models with $\tilde{G}$ LSP and $\tilde{t}_1$ NLSP

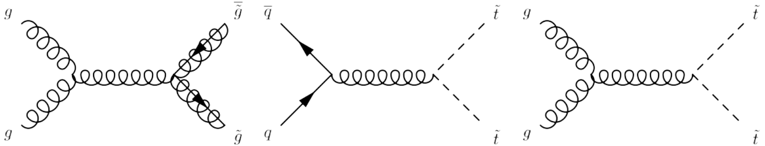
- $\tilde{t}_1$ will hadronize to R-hadron if $m_{\tilde{t}_1} - m_{\tilde{G}}$ sufficiently small



Focus of this analysis: R-hadrons

R-hadron production

- For a conservative estimate, only gg fusion is considered for $R_{\tilde{g}}$-hadrons ($q\bar{q} \rightarrow \tilde{g}\tilde{g}$ also exist, but introduces $m_{\tilde{q}}$ dependence)
- $R_{\tilde{t}}$-hadrons both via gg fusion and $q\bar{q}$ annihilation
- LO diagrams:



Outline

Analysis overview

This analysis was part of the ATLAS *Computing System Commissioning* (CSC) exercise and optimized for 1 fb^{-1} of data at 14 TeV. An analysis is currently being developed for 100 pb^{-1} at 10 TeV.

MC signal samples

Sparticle	**Mass (GeV)**	**Events/fb^{-1}**	**$\mathcal{L}$ (fb^{-1})**
$\tilde{g}$	300	2.69×10^5	3.72×10^{-2}
$\tilde{g}$	600	4.84×10^3	2.07
$\tilde{g}$	1000	138	72.5
$\tilde{g}$	1300	16.4	610
$\tilde{g}$	1600	2.12	4.72×10^3
$\tilde{g}$	2000	0.230	4.35×10^4
$\tilde{t}$	300	7.82×10^3	1.12
$\tilde{t}$	600	1.76×10^2	35.2
$\tilde{t}$	1000	6.4	1.5×10^3

MC background samples

Sample	Gen. Events	Rec. Events	$\mathcal{L}$ (fb^{-1})
QCD: (PYTHIA)			
(140 GeV $< \hat{p}_T <$ 280GeV)	3.125×10^8	2572	0.98
(280GeV $< \hat{p}_T <$ 560 GeV)	2.5×10^7	4800	1.12
(560GeV $< \hat{p}_T <$ 1120 GeV)	3.5×10^5	738	1.01
(1120GeV $< \hat{p}_T <$ 2240GeV)	5×10^4	241	9.46
(2240GeV $< \hat{p}_T$	1×10^4	42	442.29
Electroweak			
ZZ (HERWIG)	2.5×10^4	53	9.82
WW (HERWIG)	2×10^4	50	1.21
WZ (HERWIG)	1.5×10^4	29	2.32
$Z \rightarrow \mu\mu$ (PYTHIA)	1.3×10^4	600	1.29
$Z \rightarrow \tau\tau$ (PYTHIA)	3×10^3	108	9.94
$W \rightarrow \mu\nu$ (PYTHIA)	3×10^4	600	0.94
$W \rightarrow \tau\nu$ (PYTHIA)	3×10^4	120	7.82
Top			
$t\bar{t}$: (MC@NLO)	1×10^6	4065.08	0.98

Trigger

In this analysis

- Low-p_{T} muon trigger chain was used
  - Efficient for R-hadrons with charge in the muon spectrometer
  - Matching of muon spectrometer (MS) and inner detector (ID) tracks at Level-2 rejects large fractions of low mass $R_{\tilde{g}}$-hadrons
  - Performance degrades with R-hadron mass due to rapid drop in efficiency for $\beta < 0.6$
- Total trigger efficiencies for R-hadron samples
  - $\tilde{t}$ samples: 20-30%
  - $\tilde{g}$ samples: 10-15%
  - Varies with m which affects β spectrum

More refined triggers available now, more on that later. . .

Final state observables: p_T

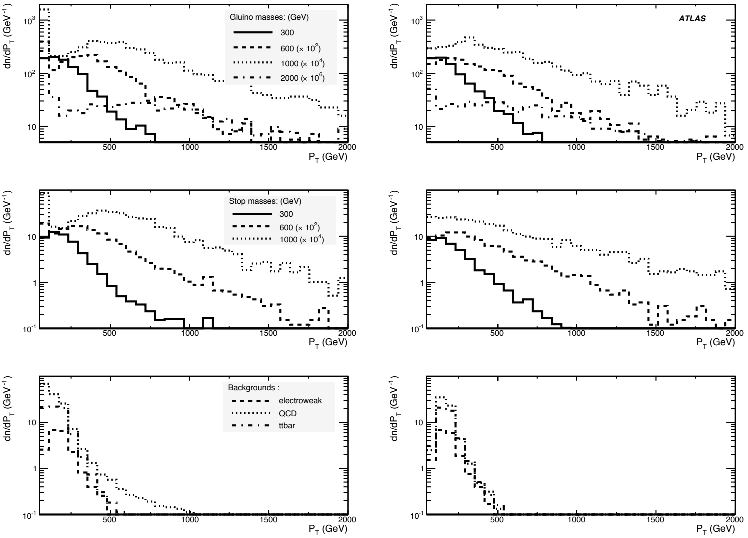
Inner detector

Muon spectrometer

$R_{\tilde{g}}$

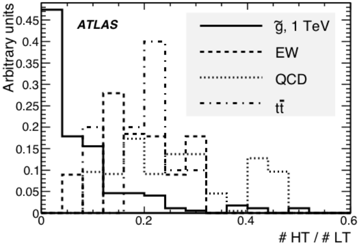
$R_{\tilde{t}}$

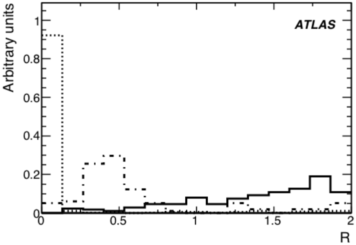
BG



Final state observables: Tracking & ΔR

- Left: ATLAS Transition Radiation Tracker gives the number of High Threshold (HT) and Low Threshold (LT) hits indicating the energy loss of the passing particle. The plot shows the fraction $\frac{HT}{LT}$.
- Right: Distance $\Delta R = \sqrt{\eta^2 + \Phi^2}$ between a high-p_{T} "muon" ($>250\,\mathrm{GeV}$) and the closest jet ($>100\,\mathrm{GeV}$)

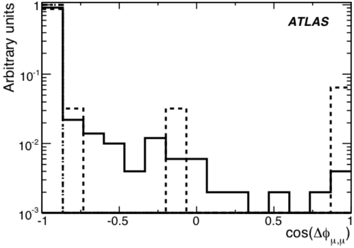




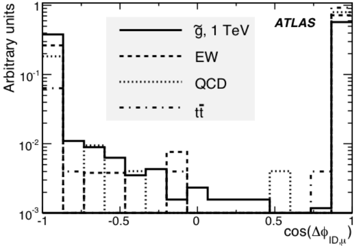
Final state observables: $cos(\Delta\Phi_{\mu,\mu})$

- R-hadrons produced predominantly in back-to-back configuration
- Electroweak background can give collinear muon pairs (boosted Z^0)

$cos(\Delta\Phi_{\mu,\mu})$: Distance between MS tracks



$cos(\Delta\Phi_{ID,\mu})$: Distance between tracks in MS and ID



Analysis cuts

- Require muon track with $p_{\mathrm{T}} > 250\,\mathrm{GeV}$ and $\Delta R < 0.36$ (jet veto)
- Use R-hadron topology: require at least one of
  - Two hard back-to-back ID tracks with $\frac{HT}{LT} < 0.05$ in the Transition Radiation Tracker (TRT)
  - At least one MS track with no matching ID track
  - Two hard back-to-back same sign MS tracks[1]
  - MS track with matching ID track with opposite sign[1]

[1] The last two points are only relevant for $R_{\tilde{g}}$-hadrons, but there is obviously no harm in keeping them for the stable $\tilde{t}$ case

Results

- Number of events selected for the given samples (backgrounds not mentioned are completely rejected)
- $R_{\tilde{g}}$-hadrons up to 1 TeV and low-mass $R_{\tilde{t}}$-hadrons should be within reach with 1 fb^{-1}

Sample	**Accepted events**	**Rate (Events / fb^{-1})**
300 GeV $\tilde{g}$	235	6.44×10^3
600 GeV $\tilde{g}$	551	2.70×10^2
1000 GeV $\tilde{g}$	774	10.7
1300 GeV $\tilde{g}$	732	1.20
1600 GeV $\tilde{g}$	685	0.147
2000 GeV $\tilde{g}$	546	1.26×10^{-2}
300 GeV $\tilde{t}$	78	70.0
600 GeV $\tilde{t}$	134	3.9
1000 GeV $\tilde{t}$	170	0.1
J5	1	0.893
J8	1	2.26×10^{-3}
$Z \rightarrow \mu\mu$	1	0.776

Outline

Recent developments

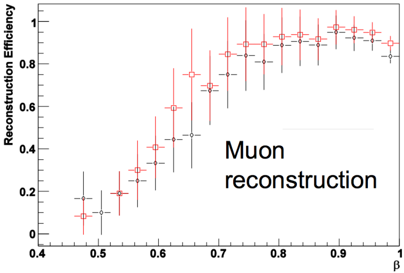
Trigger strategy & offline reconstruction

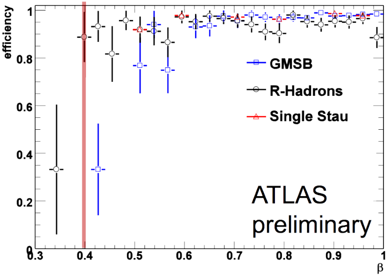
Trigger

- With firming of trigger menu definitions, trigger strategy was refined
- Dedicated Level-2/Event Filter trigger for slow particles in the muon spectrometer (using muon trigger chamber timing)

Offline reconstruction

- Offline muon reconstruction for slow particles (plots presented by S. Vallecorsa at PANIC08 in Israel)





Recent developments

Comlimentary calorimeter based analysis

- Theoretical results suggest lowest lying $R_{\tilde{g}}$-baryon state neutral
  $\Rightarrow$R-hadron always neutral in muon spectrometer
  (Farrar et al., PLB153:311, 1985)
- Developing complementary calorimeter-based search:
  - Jet trigger: PYTHIA suggests $\sim$10% of $R_{\tilde{g}}$ events have FSR jet ($E \gtrsim 100\,\mathrm{GeV}$)
  - Exploitation of calorimeter signature
    - Time-of-Flight measurement using the calorimeters
    - $\frac{dE}{dx}$ as discriminant between muons and R-hadrons

Outline

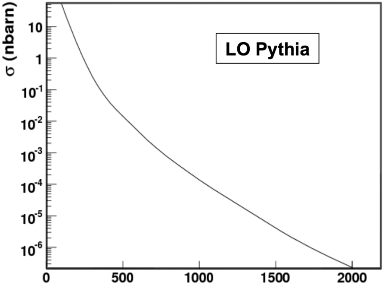
Summary & conclusions

- Stable Massive Particle searches important early analyses
- With the method outlined in this talk, ATLAS is sensitive to $\tilde{g}$ and $\tilde{q}$ masses up to 1 TeV.
- Refined trigger strategies and complementary calorimeter-based search under development and expected to improve sensitivity in low-luminosity (first year) search

Back-up slides

$gg \rightarrow \tilde{g}\tilde{g}$ cross-section @ 14 TeV

- LO cross-section for $gg \rightarrow \tilde{g}\tilde{g}$ at 14 TeV vs. $m_{\tilde{g}}$ according to PYTHIA
- Drops with about $\frac{1}{3}$ for 300 GeV case for $\sqrt{s} = 10$ TeV (bigger drop for higher masses)



Back-up slides

Systematics

The main systematic uncertainties considered in this analysis are

- GEANT4 parameters: 17%
- PDFs + K-factors: 30%
- PYTHIA parameters: 9%

Back-up slides

$\tilde{g}$ lifetime in Split-SUSY

The lifetime of the gluino (in seconds) can be calculated:

$$\tau \simeq 8 \left(\frac{m_S}{10^9\,\mathrm{GeV}}\right)^4 \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \qquad (1)$$

(Details in J. L. Hewett, B. Lillie, M. Masip and T. G. Rizzo, Signatures of long-lived gluinos in split supersymmetry, JHEP 09, 070 (2004), hep-ph/0408248)