Searches for R-hadrons at ATLAS

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Heavy exotic hadrons – why bother ?

New energy regime must be probed for new particles with various colours, spins, lifetime.

Hierarchy problem -> TeV solutions

Metastable coloured particles (R-hadrons) in many/most commonly studied BSM theories, eg Split-SUSY.

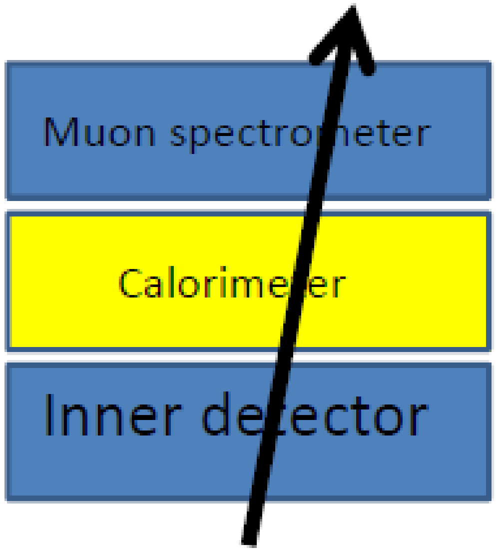
Focus on stable R-hadrons (ctau~detector)

Still lead to dark matter candidates.

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 $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		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 $\delta_{GS} = -3$.
		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. See text for details.

Previous searches for long-lived particles



Typically "generic" searches for long-lived particles mostly sensitive to heavy lepton-like objects.

$\sqrt{s}$ (GeV)	Collision	Experiment	Mass range (GeV)	Charge (e)	Cross-section limit (pb)	CL (%)	Ref.
1800	$p\bar{p}$	CDF	100-270	± 1	0.3-2	95	[340]
1800	$p\bar{p}$	CDF	50-500	$\pm \frac{2}{3}$	10-100	95	[339]
				± 1	5-50		
				$\pm \frac{4}{3}$	5-70		
300	ep	H1	< 100	± 1	190	95	[275]
130-209	e^+e^-	OPAL	45-102	$\pm \frac{2}{3}$	0.005-0.02	95	[280, 319]
			45-102	± 1	0.005-0.03		
			45-100	$\pm \frac{4}{3}$	0.005-0.02		
			45-98	$\pm \frac{5}{3}$	0.005-0.02		
189	e^+e^-	DELPHI	68-93	± 1	0.02-0.04	95	[292]
130-183	e^+e^-	DELPHI	2-91	± 1	0.05-0.3	95	[293]
130-183	e^+e^-	DELPHI	2-91	$\pm \frac{2}{3}$	0.04-0.6	95	[293]
130-172	e^+e^-	ALEPH	45-86	± 1	0.2-0.5	95	[276]
91.2	e^+e^-	ALEPH	5-45	$\pm \frac{1}{3}$	$3 - 10$	90	[279]
				$\pm \frac{2}{3}$	$1 - 12$		
			10-72	$\pm 1^*$	1.6 - 140		
				$\pm \frac{4}{3}$	$1.4 - 4$		
91.2	e^+e^-	OPAL	3-45	$\pm \frac{2}{3}$	0.2-1.0	90	[318]
				$\pm \frac{2}{3}^*$	0.15-0.9	95	
				$\pm 1^*$	0.15-3.0		
				$\pm \frac{4}{3}^*$	0.18-0.21		
				$\pm 2^*$	0.27-0.3		
91.2	e^+e^-	Kinoshita *et al.*	1-45	$\lesssim \lvert 240e \rvert$	70	95	[286]

Table 4

A summary of selected direct searches for electrically charged SMPs belonging to class 1. The searches are categorised according to centre-of-mass energy, colliding particles, and experiment. A range in cross-section limit is provided for an SMP with a given charge. The mass range corresponds to the region for which the upper cross-section limit is quoted. The limits were derived under the assumption of a pair-production mechanism, with the exception of those results marked with the symbol *. For these limits, a single SMP inclusive production mechanism was assumed. The confidence level to which the limits were extracted is also shown.

hep-ph/0611040

Special challenges for R-hadron searches

(1) Charge states

Mass hierarchy and charge composition of stable states

Eg ~g-g state

R-hadron	PYTHIA Fraction (%)	HERWIG Fraction (%)
$R^{+}_{\tilde{g}u\bar{d}}$, $R^{-}_{\tilde{g}d\bar{u}}$	34.2	28.2
$R^{0}_{\tilde{g}u\bar{u}}$, $R^{0}_{\tilde{g}d\bar{d}}$	34.2	28.2
$R^{+}_{\tilde{g}u\bar{s}}$, $R^{-}_{\tilde{g}s\bar{u}}$	9.7	17.5
$R^{0}_{\tilde{g}d\bar{s}}$, $R^{0}_{\tilde{g}s\bar{d}}$, $R^{0}_{\tilde{g}s\bar{s}}$	10.4	26.1
$R^{0}_{\tilde{g}g}$	9.9	—
$R^{++}_{\tilde{g}}$, $R^{--}_{\tilde{g}}$ (anti)baryons	0.1	—
$R^{+}_{\tilde{g}}$, $R^{-}_{\tilde{g}}$ (anti)baryons	0.8	—
$R^{0}_{\tilde{g}}$ (anti)baryons	0.7	—

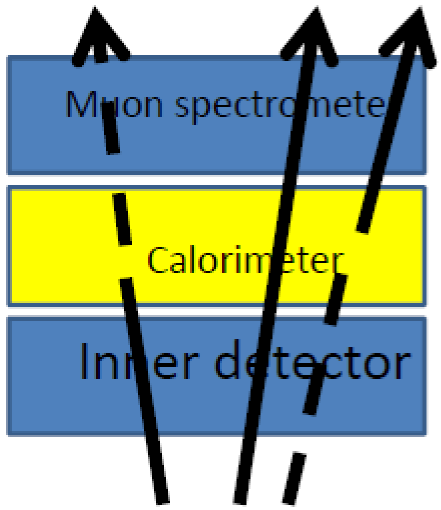
(2) Scattering in matter

Charge exchange

Dominant baryon production (hep-ex/0404001)

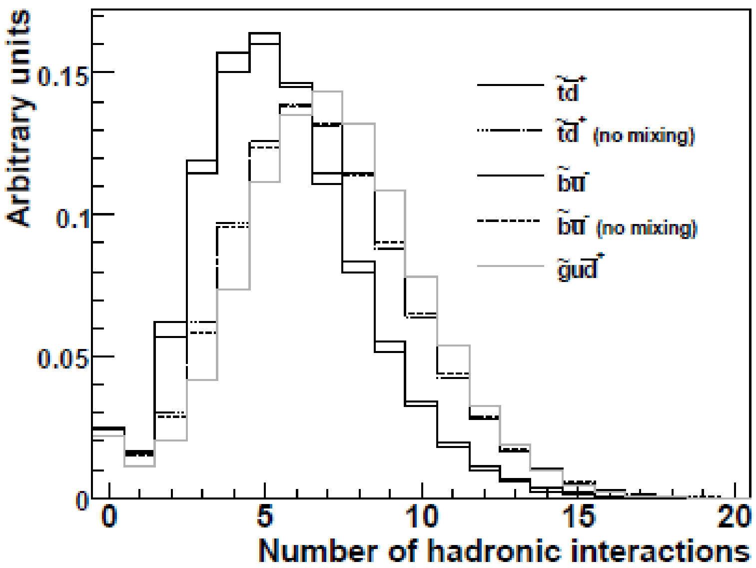
Unknown x-section

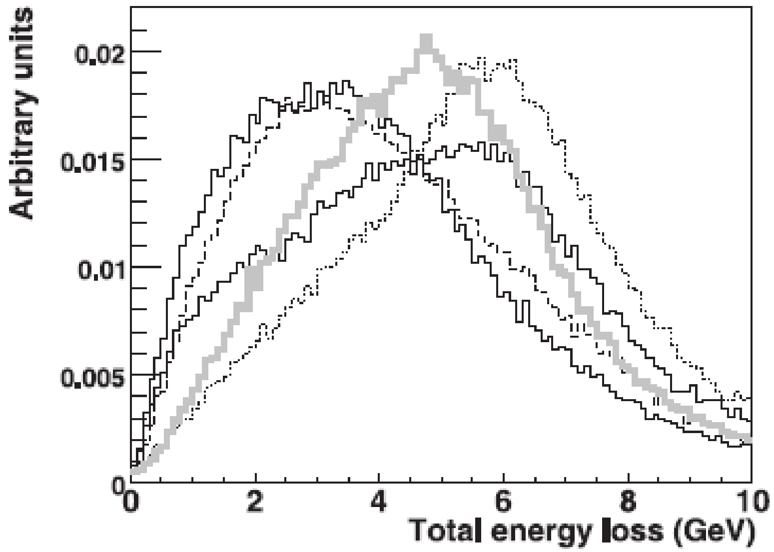
Pheno models

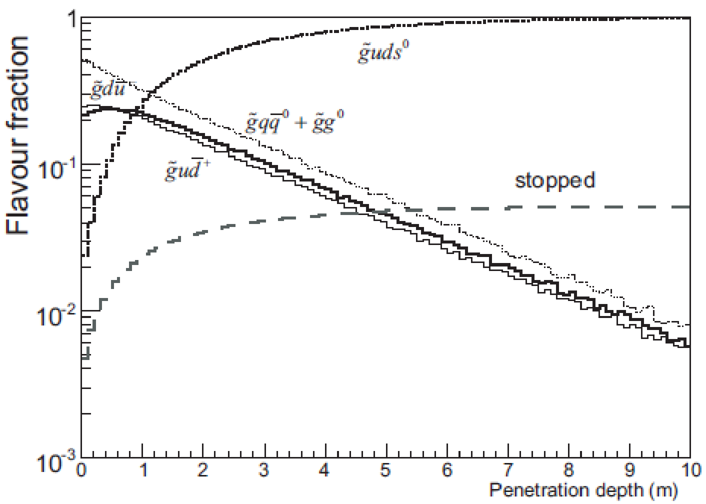


Issues particularly acute for R-hadrons with colour octets

R-hadron hadronisation and scattering effects







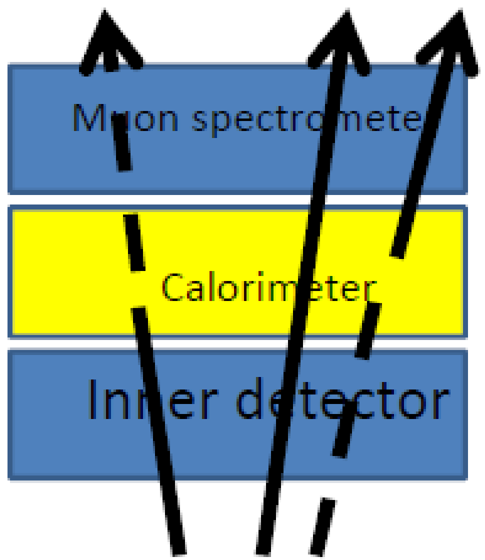
(a) Gluinos

Typically ~5 interactions in calorimeter
LArge charge exchange effects

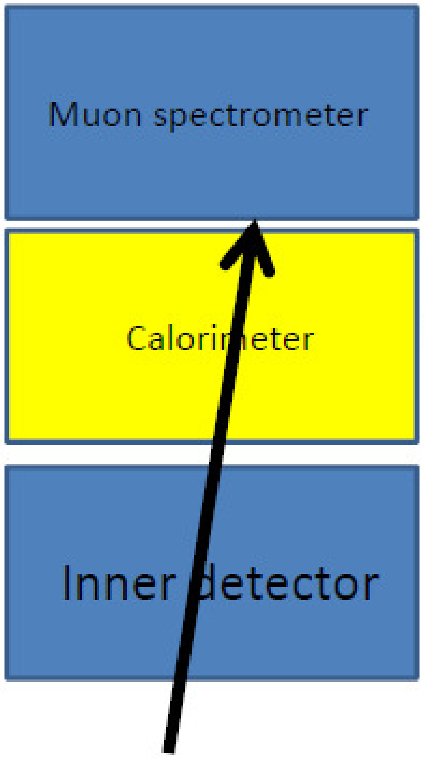
hep-ph/0908.1868

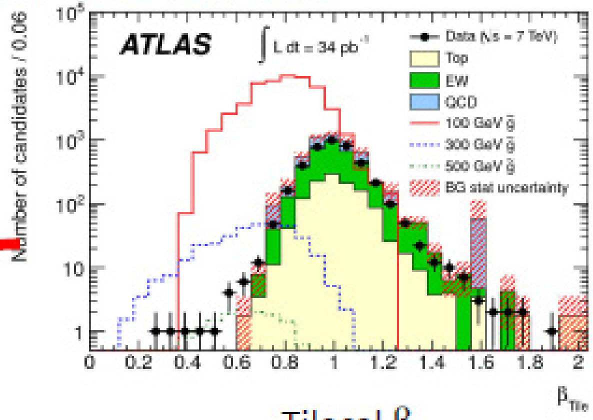
R-hadron search strategy at ATLAS

- A priori unknown fraction of charged R-hadrons will penetrate into muon system (expected large neutrals for sbottom, gluino)
- A prior unknown fraction of gluino R-hadrons will be produced with electric charge
- Consider muon-agnostic and muon-based searches

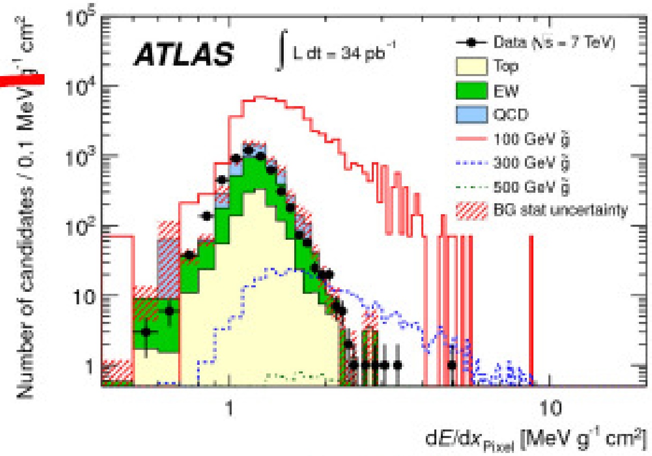


Muon-agnostic search





Tilecal β



Pixel dE/dx

34pb-1

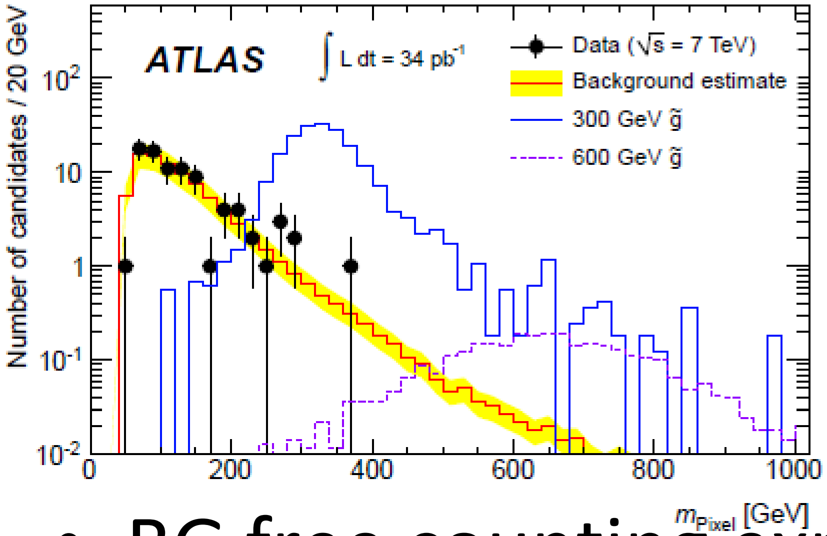
Use TileCal and pixel detector as timing-sensitive detectors

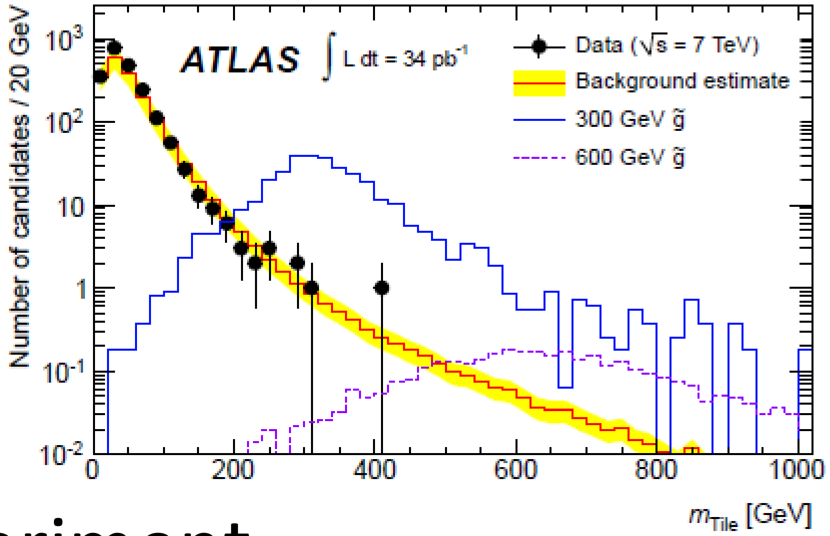
High pt (pt>50 GeV) candidates with MET

Data-driven BG approach.

Muon agnostic search

- Data-driven bg estimates from dE/dx and Tile-speed spectra

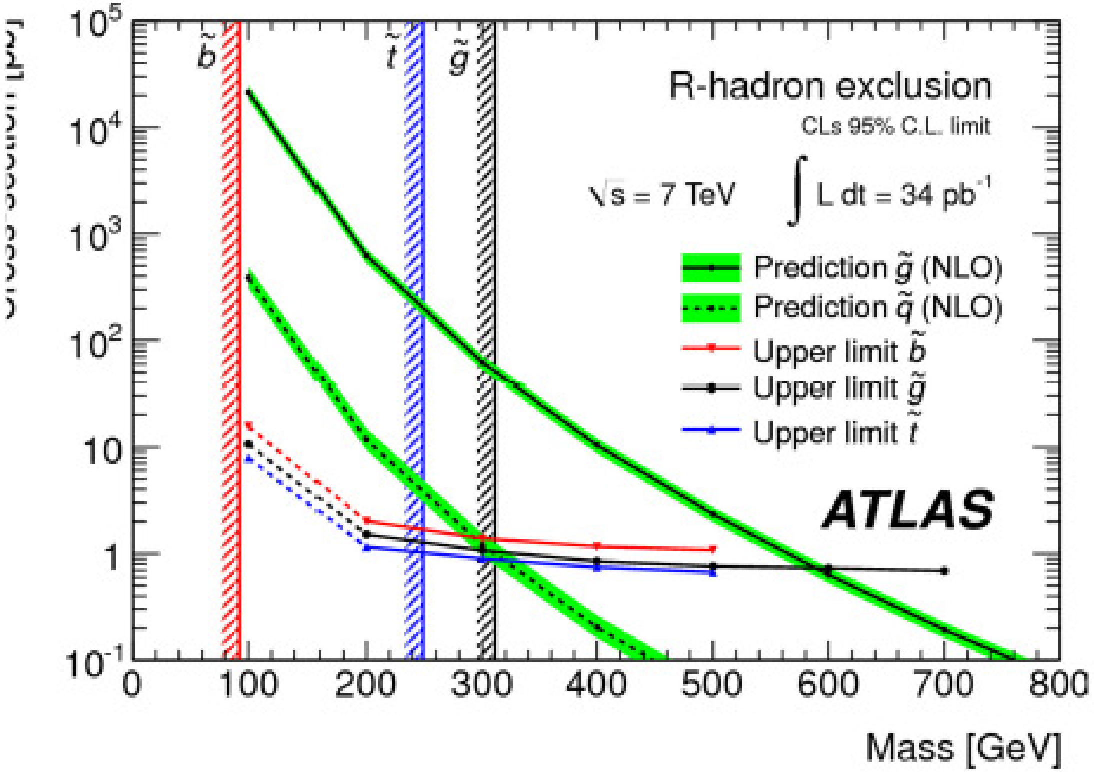




- BG free counting experiment

Cut level	Data	Background	300 GeV $\tilde{g}$	500 GeV $\tilde{g}$	600 GeV $\tilde{g}$	200 GeV $\tilde{t}$	200 GeV $\tilde{b}$
No cuts	-	-	2.13×10^3	80.4	21.8	405	405
Trigger	-	-	616	25.6	6.96	109	108
Candidate	75466	68.0×10^3	416	17.6	4.80	87.4	67.9
Vertex	75461	68.0×10^3	416	17.6	4.80	87.4	67.9
$\lvert\eta\rvert < 1.7$	64618	60.5×10^3	364	15.7	4.32	75.2	56.8
Track quality	59872	58.1×10^3	355	15.3	4.20	73.3	54.9
$\Delta R > 0.5$	49205	49.4×10^3	349	15.1	4.13	72.7	54.5
$p_T > 50$ GeV	5116	6.56×10^3	330	14.5	3.95	68.9	50.0
Mass preselection	36	56.0	184	9.70	2.75	32.6	18.9
Final selection	-	-	173	9.17	2.62	30.6	17.5

Muon-agnostic search



Mass limits (95% CL)

$\tilde{g}$ 562-586

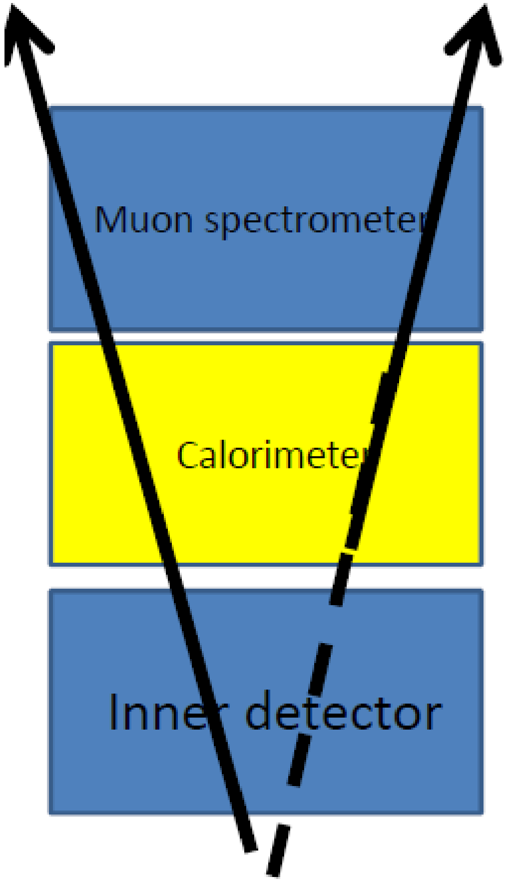
$\tilde{t}$ ($\tilde{b}$) 309 (294) GeV

Direct pair production assumed.

arXiv:1103.1984 [hep-ex]

Sensitive to any production mechanism leading to charged R-hadrons after hadronisation

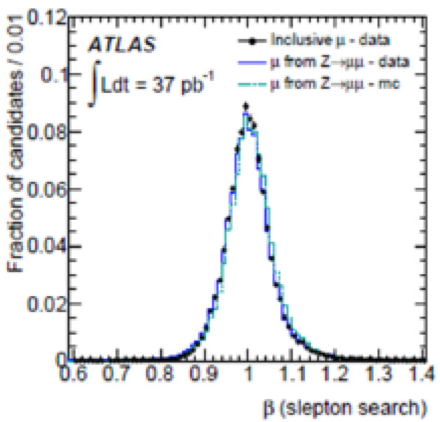
Muon-based R-hadron search

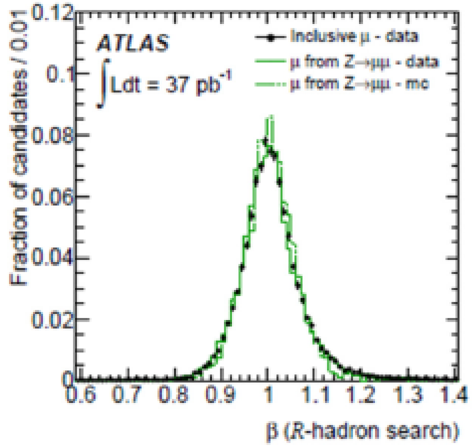


Heavy lepton-like object
Penetrating slow muon

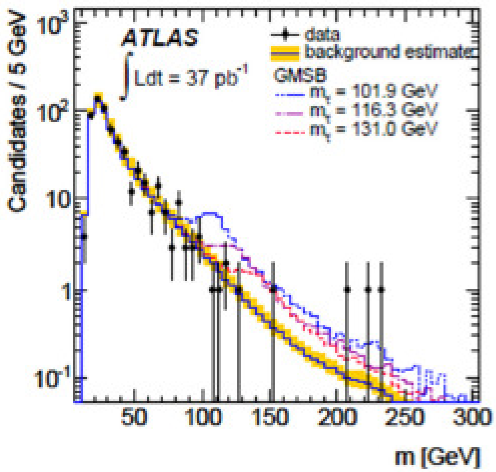
Muon-like SMPs
Two analyses:

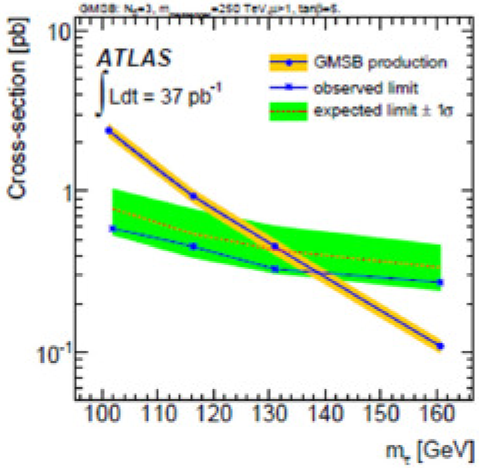
- Slepton-like object visible throughout detector
  - MS+ID : β from MS+Tile
- R-hadron (visible in whole detector or appearing only in MS)
  - MS





Muon-based R-hadron search



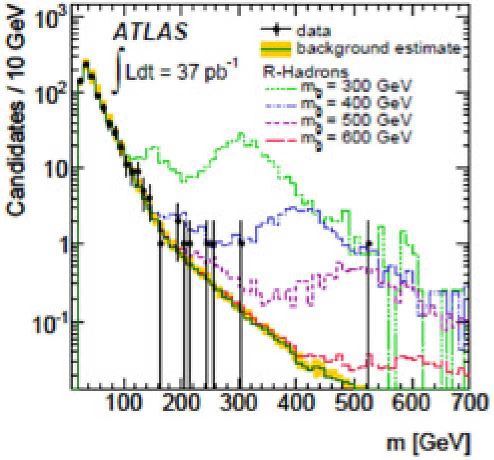


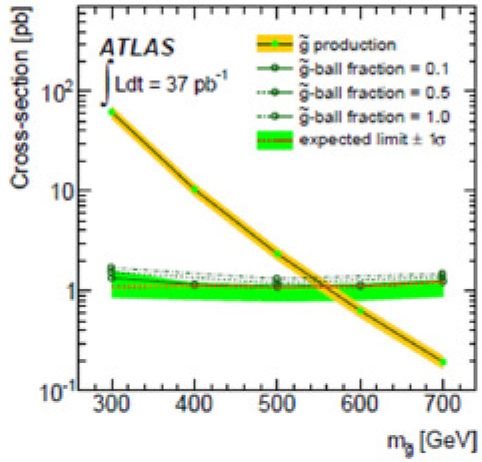
GMSB scenario

$\tilde{\ell}$ mass (95 % CL)

>136 GeV (all prod.)

> 110 GeV (EW prod.)





$\tilde{g}$ mass (95% CL)

> 544 GeV ($f_{\tilde{g}g} = 0.1$)

> 537 GeV ($f_{\tilde{g}g} = 0.5$)

> 530 GeV ($f_{\tilde{g}g} = 1.0$)

arXiv:1106.4495 [hep-ex]

Sensitive to scenarios in which the R-hadron appears as charged after hadronic scattering even if it was produced as a neutral object.

Stopped gluinos

LLP can be stopped in dense calorimeter material by electromagnetic (and hadronic) interactions

Consider Split-SUSY, eg meta-stable gluino in R hadron.

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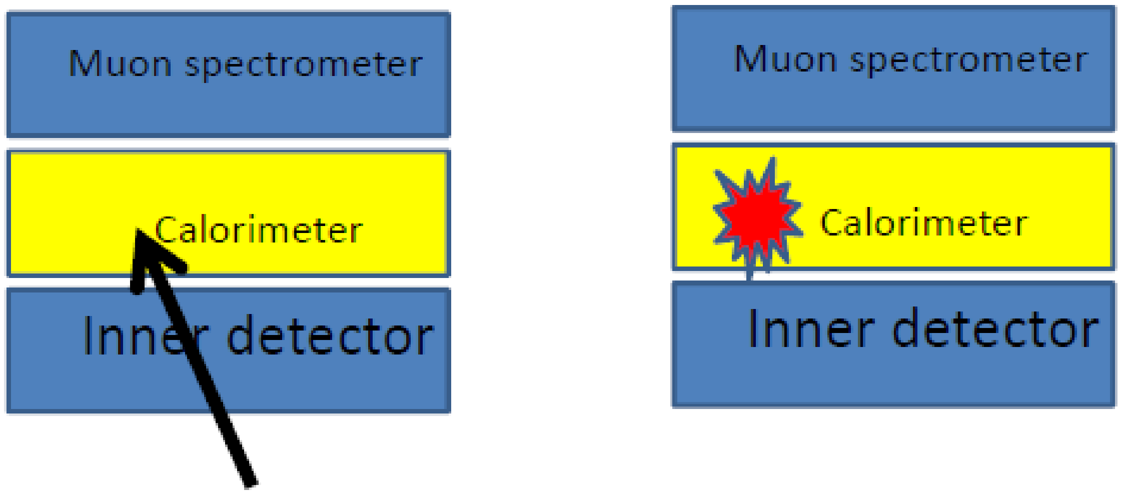
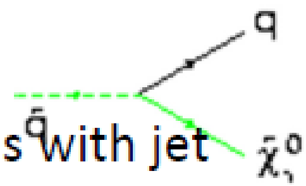
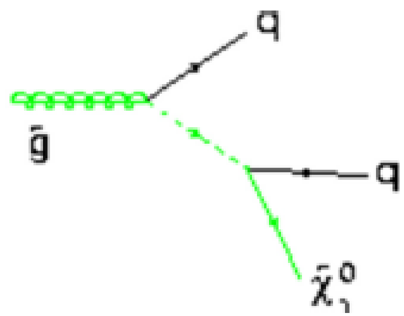


Stopped R-hadron subsequently decays.

Observe decays in empty bunches with jet trigger (E_T> 10GeV, HLT: E_T> 25 GeV)

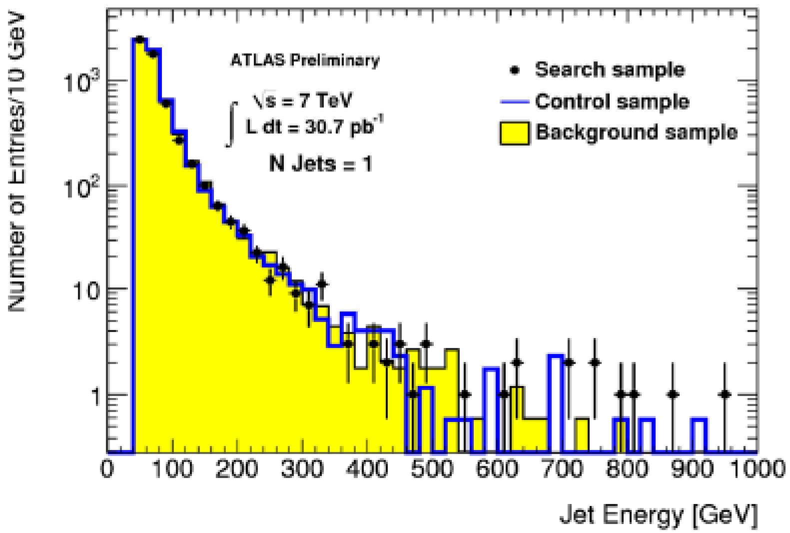
Lifetime range ~ 10^{-5}-10^{3}s



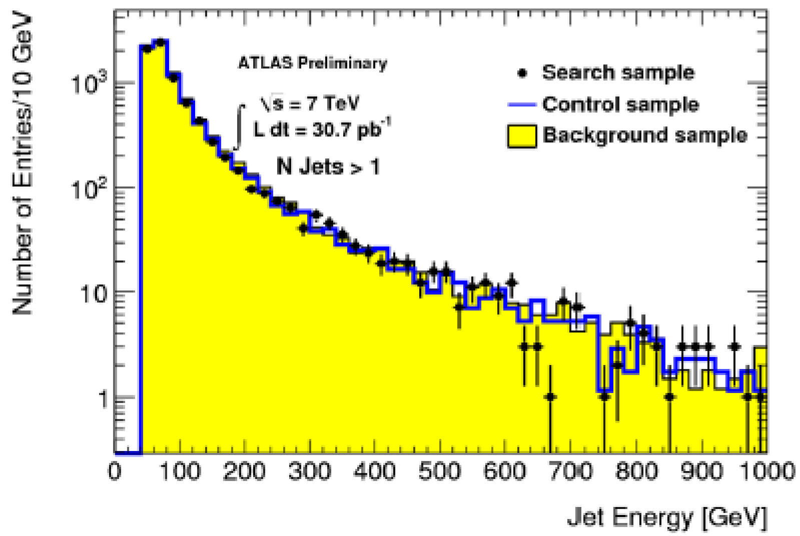


Stopped gluinos

- 3 samples : bg (low inst lum.), control sample ,signal sample
- 31pb-1
- Beam, detector and DQ selections
- Muon veto and jet cleaning selections.
- 1 jet and > 1jet samples (E_T> 50GeV)
- BG from cosmic muons, halo muons, calo noise .

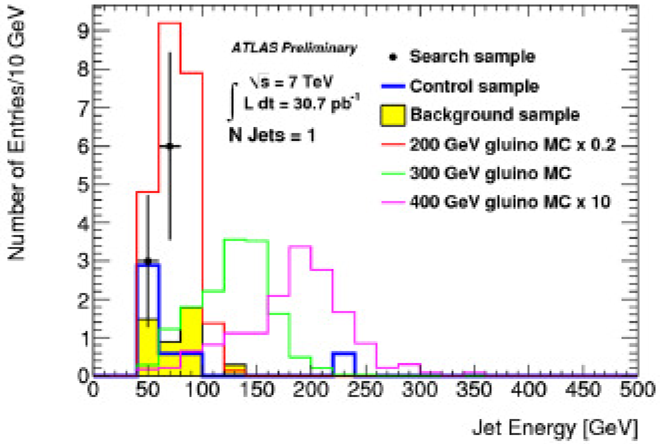


Singlet jet energy (no muon veto)

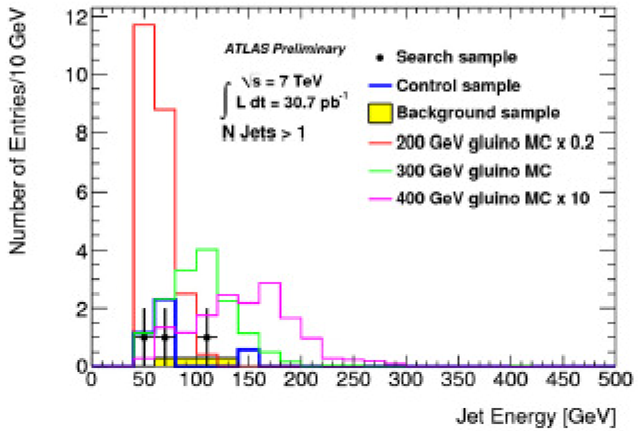


Leading jet energy (no muon veto) in multijet sample

Jet energy after all selections



Single jet energy



Leading jet energy
(multijet sample)

Sensitivity to gluino masses in 300-400 GeV range.

Assuming the handle is turned with more data and no changes are made, we'll see R-hadrons IF they exist in nature at the TeV-scale AND

Hadronic scattering is very roughly as we expect it to be

•AND

ctau ~>detector AND charged in muon chamber

•OR

ctau ~>detector AND charged in inner detector AND Jet/MET above certain thresholds

•OR

ctau ~> detector AND decays in a jetty way.

•OR

ctau << detector AND decays in a way to satisify standard SUSY/exotics searches

How could we miss seeing R-hadrons ?

- Hadronic scattering is eccentric eg cross section ridiculously higher than expected
  - short, split tracks etc.
- R-hadron is dominantly neutral and associated jet/MET too low for high lumi triggers (assuming pair production) . Missed by monojet + MET inclusive analyses.
- R-hadron has ctau>~detector size and decays in a way not expected in current ”stopped searches”
- R-hadron has ctau<<detector size and decays in a way missed by other displaced vertex searches.
  - Trigger objects (associated production)

Summary

- ATLAS has a set of complementary search strategies for R-hadrons
- Guided by extreme cases of ”what can happen” but results are largely independent of non-perturbative QCD phenomenology
- Searches for non-decaying and decaying R-hadrons
- Published mass limits up to ~600 GeV.