Early Searches for Exotic Particles at ATLAS

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Introduction and The ATLAS Detector

Introduction

Limitations of the Standard Model, such as the hierarchy problem related to the Higgs mass, point to the need for new physics at the TeV scale. Furthermore, the SM does not explain the pattern of 3 generations of quarks and leptons, or the origin of baryogenesis. The ATLAS detector (Fig. 1) has been specially designed to reconstruct high p_T particles in anticipation of new physics at the TeV scale.

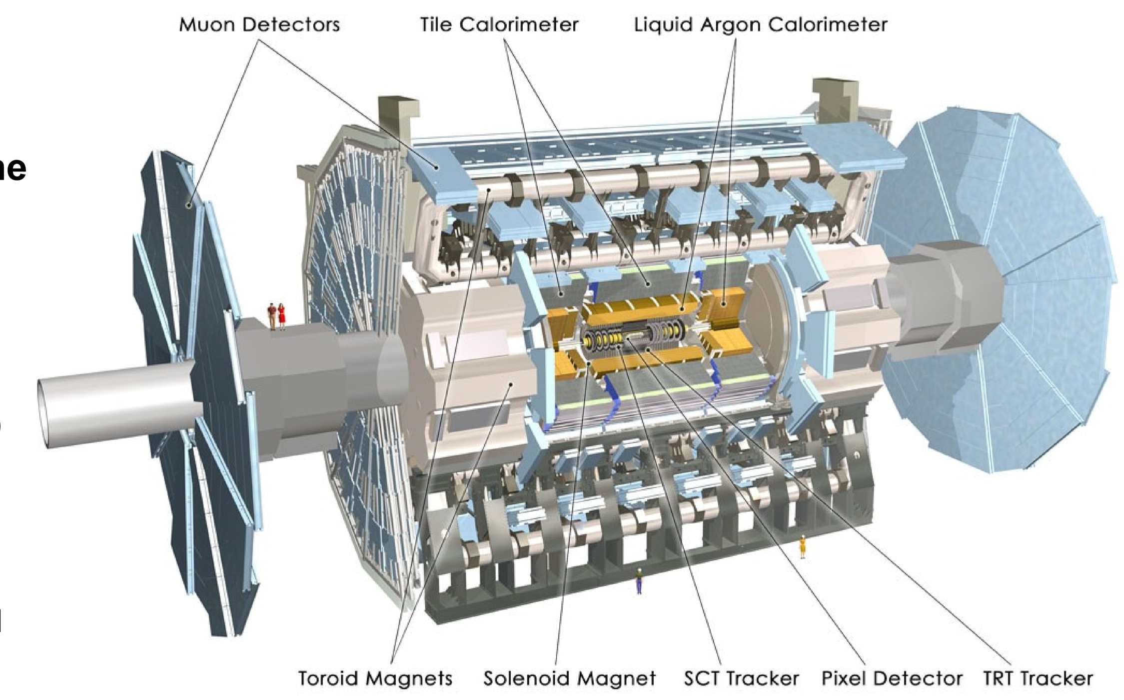


Figure 1: The ATLAS detector [1].

Detector Overview

Resolution and coverage for the various detector components are given in Table 1.

Inner Detector:
- Pixel detectors
- Semiconductor Tracker (SCT)
- Transition Radiation Tracker (TRT)

Electromagnetic Calorimeter:
- Liquid Argon (LAr) calorimeter

Hadronic Calorimeter:
- Scintillating tiles (TileCal) in barrel
- LAr calorimetry in endcaps

Muon Spectrometer:

Precision Chambers:
- Monitored Drift Tubes (MDT)
- Cathode Strip Chambers (CSC)

Trigger Chambers:
- Resistive Plate Chambers (RPC) in barrel
- Thin Gap Chambers (TGC) in endcaps

Detector Component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	$\lvert\eta\rvert < 2.5$	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$\lvert\eta\rvert < 3.2$	$\lvert\eta\rvert < 2.5$
Hadronic calorimetry (jets)			
barrel and endcap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\lvert\eta\rvert < 3.2$	$\lvert\eta\rvert < 3.2$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$TeV	$\lvert\eta\rvert < 2.7$	$\lvert\eta\rvert < 2.4$

Table 1: Expected performance and geometrical acceptance of the ATLAS detector [1].

Baseline Event Selection

Trigger
- electron channel: single e trigger with p_T > 60 GeV OR single isolated e with p_T > 25 GeV (overall ε ~97.0%)
- muon channel: single muon trigger with p_T > 20 GeV (overall ε ~96.5%)

Dilepton:
- "Medium" electron with p_T > 20 GeV and |η| < 2.5
- Combined muon with p_T > 20 GeV, |η| < 2.5 and $E_T^{iso} / p_T < 0.3$ where E_T^{iso} = calorimeter energy inside a ΔR < 0.2 cone around muon
- M_{ee} > 120 GeV and $M_{\mu\mu}$ > 110 GeV

Jets:
- Cone algorithm ΔR < 0.4 with p_T > 20 GeV and |η| < 4.5

Leptoquarks

Motivation

Symmetry between 3 generations of leptons and quarks leads to the hypothesis of leptoquarks which possess both lepton and quark quantum numbers and are sensitive to all interactions.

Experimental constraints suggest that different leptoquarks would couple to 1st, 2nd, and 3rd generation fermions.

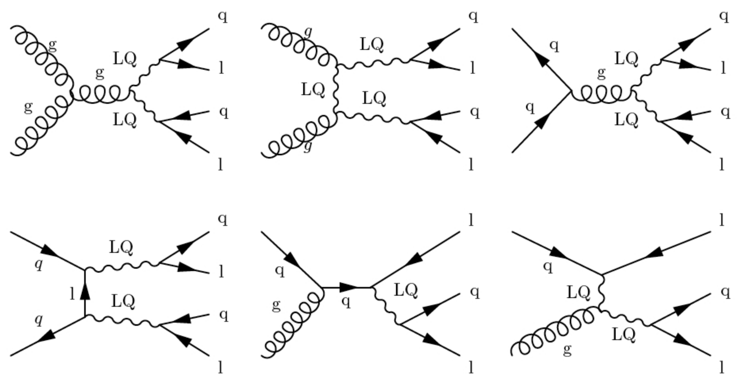


Figure 2: Representative diagrams of leptoquark production at the LHC [2]

Production at the LHC

Leptoquarks can be both single- or pair-produced.

Cross sections calculated with leptoquark-lepton-quark coupling λ = 0.8 (Table 2).

m_{LQ} in GeV	$\sigma(pp \to LQLQ)$ (NLO) in pb
300	10.1 ± 1.5
400	2.24 ± 0.38
600	0.225 ± 0.048
800	0.0378 ± 0.0105

Table 2: NLO cross-sections for leptoquark pair production [3]

Signal vs. Background

Primary background comes from pp → γ/Z + jets and t tbar

Suppressed with requirement on S_T and dilepton mass

Resolve ambiguity in lepton-jet association by minimizing $| m_{\ell j}^1 - m_{\ell j}^2 |$

Selection (Figure 3):
- $S_T = \Sigma\ |p_T|_{jet} + \Sigma\ |p_T|_{lep}$ > 490 GeV (600 GeV) for e (μ)
- Muon channel: $p_T(\mu)$ > 60 GeV and p_T(jet) > 25 GeV

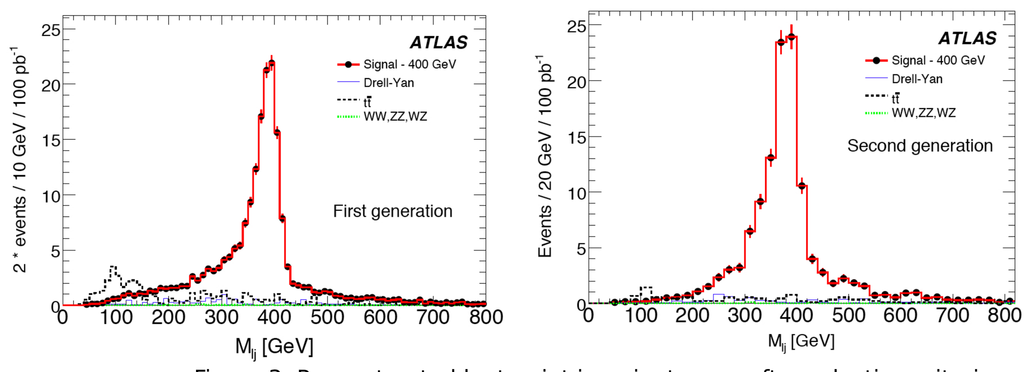


Figure 3: Reconstructed lepton-jet invariant mass after selection criteria for first- (left) and second- (right) generation leptons.

Discovery Reach

- Signal extracted inside a sliding mass window
- Significance calculated based on $CL_b(N_s + N_b)$

Leptoquark mass	Expected luminosity needed for a 5σ discovery	
	1st gen.	2nd gen.
300 GeV	2.8 pb^{-1}	1.6 pb^{-1}
400 GeV	11.8 pb^{-1}	7.7 pb^{-1}
600 GeV	123 pb^{-1}	103 pb^{-1}
800 GeV	1094 pb^{-1}	664 pb^{-1}

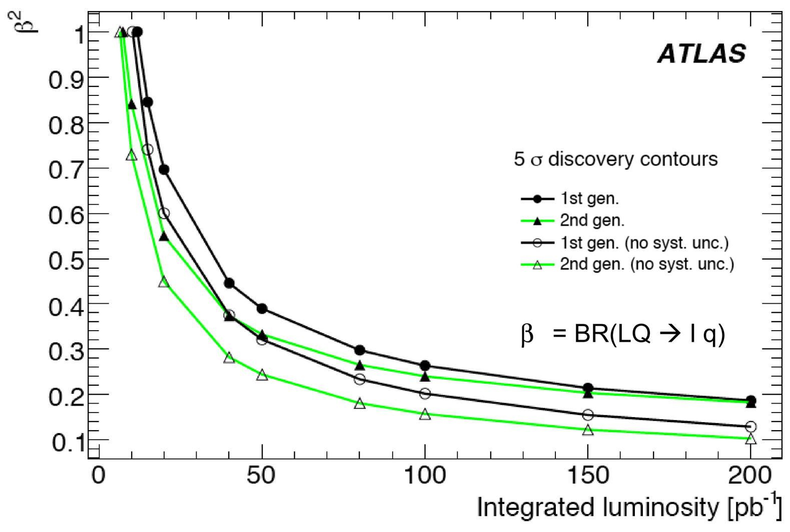


Figure 4: Leptoquark branching fraction versus integrated luminosity. We expect sensitivity up to 500-600 GeV with 100pb⁻¹.

Main systematics originate from:
- Background modeling: 12% for tt and 10% for γ/Z
- Integrated luminosity: 20%
- Jet energy scale: 16% to 35%
- Jet energy resolution: 6% to 28%
- MC statistics for background samples 15% to 30%

Left-Right Symmetric Model and Majorana Neutrinos

Motivation

Another model inspired by higher symmetries is the Left-Right Symmetric Model (LRSM). Most notably, it addresses:
- The non-zero masses of the three SM neutrinos
- Baryogenesis

Left-Right symmetry is broken at lower energies. While baryon and lepton number are not conserved above the energy threshold, the B – L is conserved [4].

$$SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$$

$$q\,\bar{q} \to W_R \to l\,N_l \to lljj$$

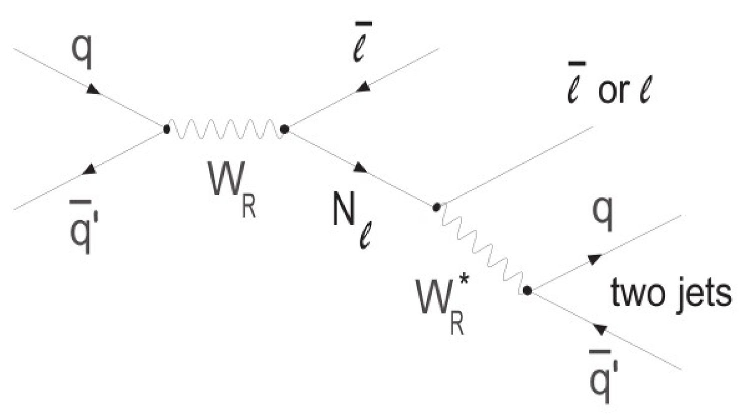


Figure 5: WR and heavy Majorana neutrino production at the LHC.

A consequence of the LRSM is the addition of 3 heavy Majorana neutrinos: N_e, N_μ, N_τ.

Signal

Two samples studied:
- $m(W_R)$ = 1.8 TeV, $m(N_{e,\mu})$ = 300 GeV
- $m(W_R)$ = 1.5 TeV, $m(N_{e,\mu})$ = 500 GeV

LO cross-section times BF for the two samples are 24.8 and 47.0 pb, respectively.

- 2 leading lepton and 2 leading jet candidates are assumed decay products of W_R
- Signal jets are combined with each lepton, and combination with smallest invariant mass is assumed to be $N_{e,\mu}$

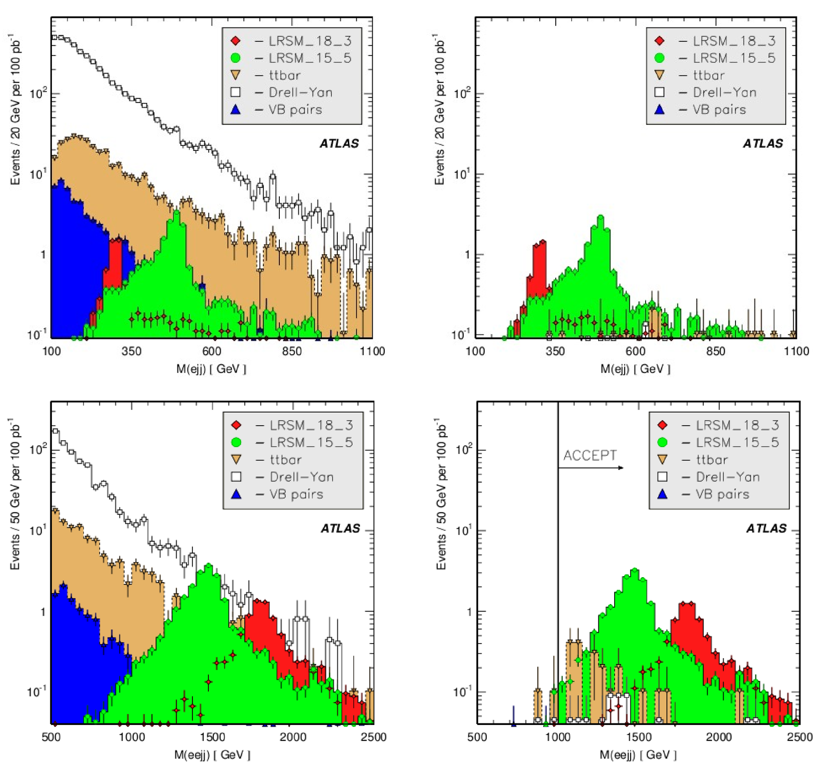


Figure 6: Invariant mass distributions before (left) and after (right) selection cuts for N_e (top) and $W_R \to eN_e$ (bottom)

Background

Primary background for this process is the same for leptoquarks. Figure 6 shows $m(W_R)$ and $m(N_e)$ distributions before and after background suppression using the baseline selection criteria and:
- S_T > 700 GeV
- $m_{\ell\ell}$ > 300 GeV

Discovery Reach

Discovery of W_R and N_ℓ would require an integrated luminosity of 150 pb^{-1} (40 pb^{-1}) for LRSM_18_3 (LRSM_15_5), as shown in Figure 7.

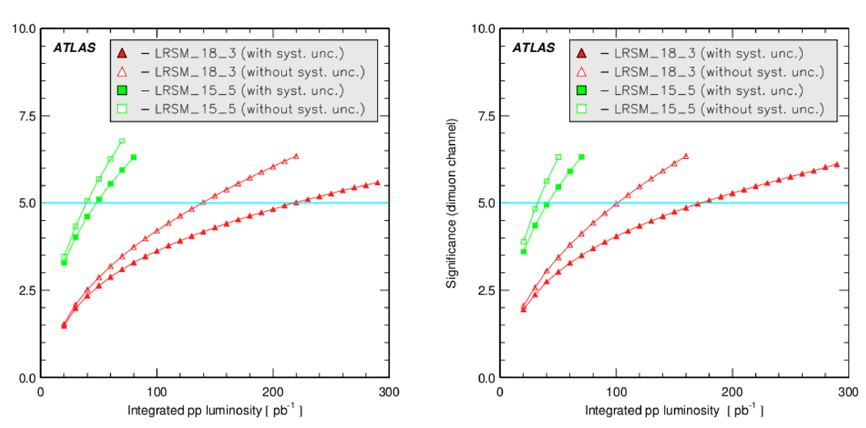


Figure 7: Significance versus luminosity for LRSM in electron (left) and muon (right) channels

Contact Interactions

Motivation

New interactions may exist at an energy scale higher than we are able to reach at the LHC, but they may still be detected through interference with the SM Drell-Yan process (Fig. 8, 9):
- Quark/Lepton Compositeness [5]
- Large Extra Dimensions in the ADD model [6]

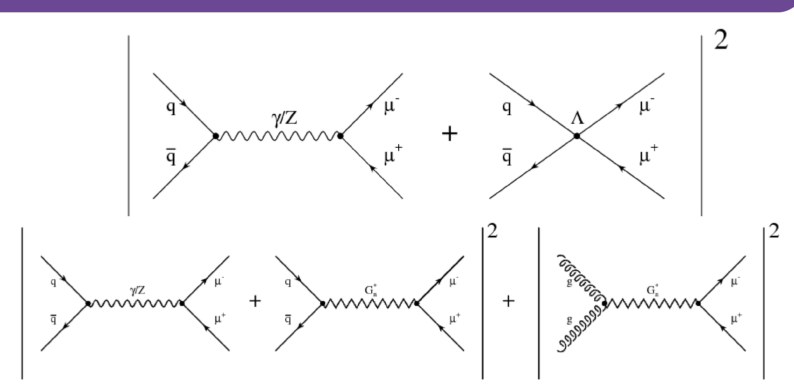


Figure 8: Representative diagrams for Drell-Yan cross-section enhancement including a contact interaction (top) or LED (bottom), where the enhancement comes as a tower of states.

Event Generation

- 2 or more final state muons from the hard scattering
- $M_{\mu\mu}$ > 120 GeV
- Muon p_T > 5 GeV and acceptance |η| < 2.8

Modified cross-section with Contact Interaction: $\sigma = DY + \frac{I}{\Lambda^2} + \frac{C}{\Lambda^4}$

Limit Setting with the Ratio Method

- Count number of events above and below mass threshold and take ratio: R_Λ = N(above M_0)/N(below M_0)
- Compare ratio from data with ratio for signal (Fig. 10)

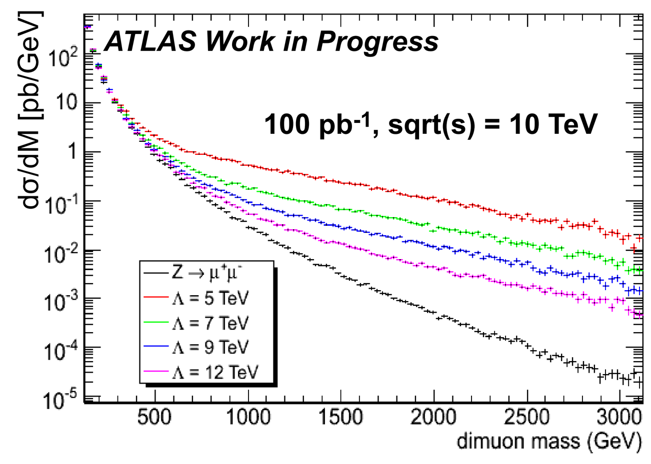


Figure 9: Differential cross section for various Λ values. Note the distribution approaches the Standard Model as Λ → ∞.

Statistical and Systematic Uncertainties

- Statisitcal uncertainty determined using Toy Monte Carlo (Fig. 10)
- Main systematics: resolution and PDF uncertainties
- Ratio method is advantageous for systematics, as only momentum- or mass-dependent uncertainties play a role

Expected Limit

After fitting the significance for Λ = 5, 7, 9, 12, expect Λ > 7.5 TeV (8.7 TeV) for 100pb^{-1} (200 pb^{-1}) at 95% C.L. Systematic effects are negligible in first-year data (less than 200 pb^{-1}), where statistical uncertainty dominates (Fig. 11).

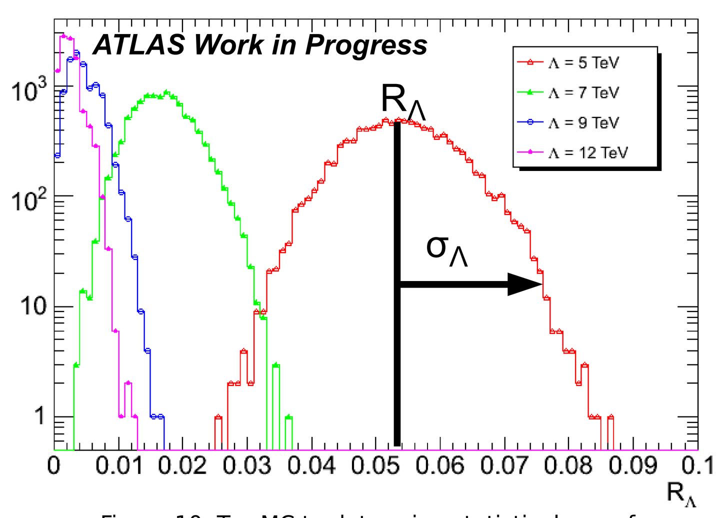
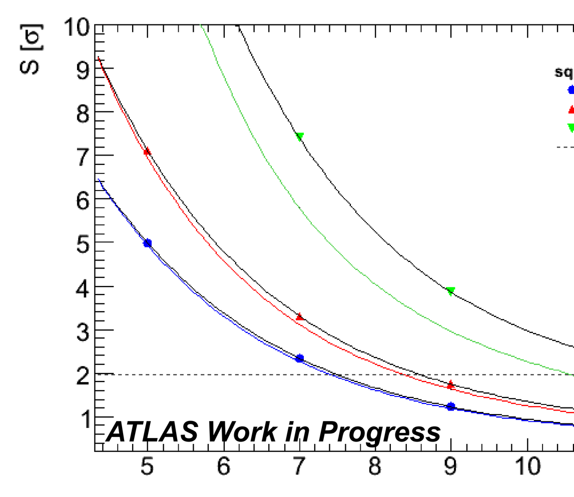


Figure 10: Toy MC to determine statistical error for various Λ values in 100pb⁻¹.



$$S_{lim} = \frac{R_\Lambda - R_{SM}}{\sqrt{\sigma_\Lambda^2 + \sigma_{SM}^2}}$$

Figure 11: The expected 95% C.L. corresponds to a significance of 1.96σ, shown here for various luminosities. Corresponding significance with systematic uncertainty is shown in solid color for comparison.

References

[1] ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider" submitted to JINST. (2008)

[2] M. Kramer et al., Phys. Rev. D71, 057503 (2005)

[3] ATLAS Collaboration, "Search for Leptoquark Pairs, and Majorana Neutrinos from Right-Handed W Boson Decays in Dilepton-Jets Final States", ATLAS PUB (2009)

[4] K. Huitu, J. Maalampi, A. Pietila, and M. Raidal, *Nucl. Phys.* **B487** (1997) 27-42, arXiv:hep-ph/9606311

[5] See, for example, H. Harari, N. Seidberg, *Nucl. Phys.* **B204** (1982) 141-167

[6] For a review, see C. Amsler, et al. (Particle Data Group), *Physics Letters* **B667** (2008) 1.