A SEARCH FOR LONG-LIVED, CHARGED, SUPERSYMMETRIC PARTICLES USING IONIZATION WITH THE ATLAS DETECTOR

BRADLEY AXEN

September 2016 – Version 0.11

Usually a quotation.

Dedicated to.

ABSTRACT

How to write a good abstract:

https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

PUBLICATIONS

Some ideas and figures have appeared previously in the following publications:

Put your publications from the thesis here. The packages `multibib` or `bibtopic` etc. can be used to handle multiple different bibliographies in your document.

optional quotation

ACKNOWLEDGEMENTS

Put your acknowledgements here.

And potentially a second round.

CONTENTS

I INTRODUCTION 1

1 INTRODUCTION 3

II THEORETICAL CONTEXT 5

2 STANDARD MODEL 7
- 2.1 Particles . . . 7
- 2.2 Interactions . . . 7
- 2.3 Limitations . . . 7

3 SUPERSYMMETRY 9
- 3.1 Motivation . . . 9
- 3.2 Structure . . . 9
- 3.3 Phenomenology . . . 9

4 LONG-LIVED PARTICLES 11
- 4.1 Mechanisms . . . 11
  - 4.1.1 Examples in Supersymmetry . . . 11
- 4.2 Phenomenology . . . 11
  - 4.2.1 Disimilarities to Prompt Decays . . . 11
  - 4.2.2 Characteristic Signatures . . . 11

III EXPERIMENTAL STRUCTURE AND RECONSTRUCTION 13

5 THE LARGE HADRON COLLIDER 15
- 5.1 Injection Chain . . . 15
- 5.2 Design and Parameters . . . 15
- 5.3 Luminosity . . . 15

6 THE ATLAS DETECTOR 17
- 6.1 Coordinate System . . . 17
- 6.2 Magnetic Field . . . 17
- 6.3 Inner Detector . . . 17
  - 6.3.1 Pixel Detector . . . 17
  - 6.3.2 Semiconductor Tracker . . . 17
  - 6.3.3 Transition Radiation Tracker . . . 17
- 6.4 Calorimetry . . . 17
  - 6.4.1 Electromagnetic Calorimeters . . . 17
  - 6.4.2 Hadronic Calorimeters . . . 17
  - 6.4.3 Forward Calorimeters . . . 17
- 6.5 Muon Spectrometer . . . 17
- 6.6 Trigger . . . 17
  - 6.6.1 Trigger Scheme . . . 17
  - 6.6.2 Missing Transverse Energy Triggers . . . 17

7 EVENT RECONSTRUCTION 19
- 7.1 Tracks and Vertices . . . 19

7.1.1 Track Reconstruction 19
7.1.2 Vertex Reconstruction 19
7.2 Jets 19
7.2.1 Topological Clustering 19
7.2.2 Jet Energy Scale 19
7.2.3 Jet Energy Scale Uncertainties 19
7.2.4 Jet Energy Resolution 19
7.3 Electrons 19
7.3.1 Electron Identification 19
7.4 Muons 19
7.4.1 Muon Identification 19
7.5 Missing Transverse Energy 19

IV CALORIMETER RESPONSE 21
8 RESPONSE MEAUREMENT WITH SINGLE HADRONS 23
8.1 Overview and Motivation 23
8.2 Inclusive Hadron Response 23
8.3 Identified Particle Response 23
9 JET ENERGY RESPONSE AND UNCERTAINTY 25
9.1 Jet Energy Response in Simulation 25
9.2 Jet Energy Uncertainty 25

V SEARCH FOR LONG-LIVED PARTICLES 27
10 LONG-LIVED PARTICLES IN ATLAS 29
10.1 Overview and Characteristics 29
10.2 Simulation 29
11 EVENT SELECTION 31
11.1 Trigger 31
11.2 Kinematics and Isolation 31
11.3 Standard Model Rejection 31
11.4 Ionization 31
11.4.1 dE/dx Calibration 31
11.4.2 Mass Estimation 31
12 BACKGROUND ESTIMATION 33
12.1 Background Sources 33
12.2 Prediction Method 33
12.3 Validation and Uncertainty 33
13 SYSTEMATIC UNCERTAINTIES AND RESULTS 35
13.1 Systematic Uncertainties 35
13.2 Final Yields 35
14 INTERPRETATION 37
14.1 Cross Sectional Limits 37
14.2 Mass Limits 37
14.3 Context for Long-Lived Searches 37

VI CONCLUSIONS 39
15 SUMMARY AND OUTLOOK 41
15.1 Summary 41
15.2 Outlook 41

VII APPENDIX 43
A INELASTIC CROSS SECTION 45
B APPENDIX TEST 47
B.1 Appendix Section Test 47
B.1.1 Appendix Subection Test 47
B.2 A Table and Listing 47
B.3 Some Formulas 48

BIBLIOGRAPHY 51

LIST OF TABLES

Table 1 Autem usu id 47

LISTINGS

Listing 1 A floating example (`listings` manual) 48

ACRONYMS

EG Example

PART I

INTRODUCTION

You can put some informational part preamble text here.

1 INTRODUCTION

PART II

THEORETICAL CONTEXT

You can put some informational part preamble text here.

2 STANDARD MODEL

2.1 PARTICLES

2.2 INTERACTIONS

2.3 LIMITATIONS

3

SUPERSYMMETRY

3.1 MOTIVATION

3.2 STRUCTURE

3.3 PHENOMENOLOGY

4

LONG-LIVED PARTICLES

4.1 MECHANISMS

4.1.1 EXAMPLES IN SUPERSYMMETRY

4.2 PHENOMENOLOGY

4.2.1 DISIMILARITIES TO PROMPT DECAYS

4.2.2 CHARACTERISTIC SIGNATURES

PART III

EXPERIMENTAL STRUCTURE AND RECONSTRUCTION

You can put some informational part preamble text here.

5 THE LARGE HADRON COLLIDER

5.1 INJECTION CHAIN

5.2 DESIGN AND PARAMETERS

5.3 LUMINOSITY

6 THE ATLAS DETECTOR

6.1 COORDINATE SYSTEM

6.2 MAGNETIC FIELD

6.3 INNER DETECTOR

6.3.1 PIXEL DETECTOR

6.3.2 SEMICONDUCTOR TRACKER

6.3.3 TRANSITION RADIATION TRACKER

6.4 CALORIMETRY

6.4.1 ELECTROMAGNETIC CALORIMETERS

6.4.2 HADRONIC CALORIMETERS

6.4.3 FORWARD CALORIMETERS

6.5 MUON SPECTROMETER

6.6 TRIGGER

6.6.1 TRIGGER SCHEME

6.6.2 MISSING TRANSVERSE ENERGY TRIGGERS

7 EVENT RECONSTRUCTION

The ATLAS experiment combines measurements in the subdetectors to form a cohesive picture of each physics event.

7.1 TRACKS AND VERTICES

7.1.1 TRACK RECONSTRUCTION

7.1.1.1 NEURAL NETWORK

7.1.1.2 PIXEL DE/DX

7.1.2 VERTEX RECONSTRUCTION

7.2 JETS

7.2.1 TOPOLOGICAL CLUSTERING

7.2.2 JET ENERGY SCALE

7.2.3 JET ENERGY SCALE UNCERTAINTIES

7.2.4 JET ENERGY RESOLUTION

7.3 ELECTRONS

7.3.1 ELECTRON IDENTIFICATION

7.4 MUONS

7.4.1 MUON IDENTIFICATION

7.5 MISSING TRANSVERSE ENERGY

PART IV

CALORIMETER RESPONSE

You can put some informational part preamble text here.

8

RESPONSE MEAUREMENT WITH SINGLE HADRONS

8.1 OVERVIEW AND MOTIVATION

8.2 INCLUSIVE HADRON RESPONSE

8.3 IDENTIFIED PARTICLE RESPONSE

9 Jet energy response and uncertainty

9.1 Jet energy response in simulation

9.2 Jet energy uncertainty

PART V

SEARCH FOR LONG-LIVED PARTICLES

You can put some informational part preamble text here.

10 LONG-LIVED PARTICLES IN ATLAS

10.1 OVERVIEW AND CHARACTERISTICS

10.2 SIMULATION

11 EVENT SELECTION

11.1 TRIGGER

11.2 KINEMATICS AND ISOLATION

11.3 STANDARD MODEL REJECTION

11.4 IONIZATION

11.4.1 DE/DX CALIBRATION

11.4.2 MASS ESTIMATION

12 BACKGROUND ESTIMATION

12.1 BACKGROUND SOURCES

12.2 PREDICTION METHOD

12.3 VALIDATION AND UNCERTAINTY

13 SYSTEMATIC UNCERTAINTIES AND RESULTS

13.1 SYSTEMATIC UNCERTAINTIES

13.2 FINAL YIELDS

14 INTERPRETATION

14.1 CROSS SECTIONAL LIMITS

14.2 MASS LIMITS

14.3 CONTEXT FOR LONG-LIVED SEARCHES

PART VI

CONCLUSIONS

You can put some informational part preamble text here.

15 SUMMARY AND OUTLOOK

15.1 SUMMARY

15.2 OUTLOOK

PART VII

APPENDIX

A

INELASTIC CROSS SECTION

B

APPENDIX TEST

Examples: *Italics*, Small Caps, ALL CAPS [1]. Acronym testing: **UML!** (**UML!**) – **UML!** – **UML!** (**UML!**) – **UML!s**

This appendix is temporary and is here to be used to check the style of the document.

B.1 APPENDIX SECTION TEST

Random text that should take up a few lines. The purpose is to see how sections and subsections flow with some actual context. Without some body copy between each heading it can be difficult to tell if the weight of the fonts, styles, and sizes use work well together.

B.1.1 APPENDIX SUBECTION TEST

Random text that should take up a few lines. The purpose is to see how sections and subsections flow with some actual context. Without some body copy between each heading it can be difficult to tell if the weight of the fonts, styles, and sizes use work well together.

B.2 A TABLE AND LISTING

Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam congue neque id dolor.

There is also a Python listing below Listing 1.

1 Footnote example.

LABITUR BONORUM PRI NO	QUE VISTA	HUMAN
fastidii ea ius	germano	demonstratea
suscipit instructior	titulo	personas
quaestio philosophia	facto	demonstrated

Table 1: Autem usu id.

B.3 SOME FORMULAS

Due to the statistical nature of ionisation energy loss, large fluctuations can occur in the amount of energy deposited by a particle traversing an absorber element[2]. Continuous processes such as multiple scattering and energy loss play a relevant role in the longitudinal and lateral development of electromagnetic and hadronic showers, and in the case of sampling calorimeters the measured resolution can be significantly affected by such fluctuations in their active layers. The description of ionisation fluctuations is characterised by the significance parameter κ, which is proportional to the ratio of mean energy loss to the maximum allowed energy transfer in a single collision with an atomic electron:

You might get unexpected results using math in chapter or section heads. Consider the `pdfspacing` option.

$$\kappa = \frac{\xi}{E_{\mathrm{max}}} \tag{1}$$

E_{max} is the maximum transferable energy in a single collision with an atomic electron.

$$E_{\mathrm{max}} = \frac{2m_{\mathrm{e}}\beta^2\gamma^2}{1 + 2\gamma m_{\mathrm{e}}/m_{\mathrm{x}} + (m_{\mathrm{e}}/m_{\mathrm{x}})^2},$$

where $\gamma = E/m_{\mathrm{x}}$, E is energy and m_{x} the mass of the incident particle, $\beta^2 = 1 - 1/\gamma^2$ and m_{e} is the electron mass. ξ comes from the Rutherford scattering cross section and is defined as:

$$\xi = \frac{2\pi z^2 e^4 N_{\mathrm{Av}} Z\rho\delta x}{m_{\mathrm{e}}\beta^2 c^2 A} = 153.4\frac{z^2}{\beta^2}\frac{Z}{A}\rho\delta x \quad \mathrm{keV},$$

where

z	charge of the incident particle
N_{Av}	Avogadro's number
Z	atomic number of the material
A	atomic weight of the material
ρ	density
δx	thickness of the material

κ measures the contribution of the collisions with energy transfer close to E_{max}. For a given absorber, κ tends towards large values if δx is large and/or if β is small. Likewise, κ tends towards zero if δx is small and/or if β approaches 1.

2 Examples taken from Walter Schmidt's great gallery: `http://home.vrweb.de/~was/mathfonts.html`

Listing 1: A floating example (`listings` manual)

```
for i in xrange(10):
    print i, i*i, i*i*i
print "done"
```

The value of κ distinguishes two regimes which occur in the description of ionisation fluctuations:

1. A large number of collisions involving the loss of all or most of the incident particle energy during the traversal of an absorber.

   As the total energy transfer is composed of a multitude of small energy losses, we can apply the central limit theorem and describe the fluctuations by a Gaussian distribution. This case is applicable to non-relativistic particles and is described by the inequality $\kappa > 10$ (i. e., when the mean energy loss in the absorber is greater than the maximum energy transfer in a single collision).

2. Particles traversing thin counters and incident electrons under any conditions.

   The relevant inequalities and distributions are $0.01 < \kappa < 10$, Vavilov distribution, and $\kappa < 0.01$, Landau distribution.

DECLARATION

Put your declaration here.

Berkeley, CA, September 2016

Bradley Axen

COLOPHON

Not sure that this is necessary.