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

BRADLEY AXEN

September 2016 – Version 0.16

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

LIST OF FIGURES

LIST OF TABLES

LISTINGS

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

The Standard Modelof particle physics seeks to explain the symmetries and interactions of all currently discovered fundamental particles. It has been tested by several generations of experiments and has been remarkably succesful, no significant deviations have been found. The Standard Modelprovides predictions in particle physics for interactions up to the Planck scale (10^{15}-10^{19} GeV).

The theory itself is a quantum field theory grown from an underlying $SU(3) \times SU(2) \times U(1)$ that requires the particle content and quantum numbers consistent with experimental observations (see Section 2.1). Each postulated symmetry is accompanied by an interaction between particles through gauge invariance. These interactions are referred to as the Strong, Weak, and Electromagnetic forces, which are discussed in Section 2.2.

Although this model has been very predictive, the theory is incomplete; for example, it is not able to describe gravity or astronomically observed dark matter. These limitations are discussed in more detail in Section 2.3.

2.1 PARTICLES

The most familiar matter in the universe is made up of protons, neutrons, and electrons. Protons and neutrons are composite particles, however, and are made up in turn by particles called quarks. Quarks carry both electric charge and color charge, and are bound in color-neutral combinations called baryons. The electron is an example of a lepton, and carries only electric charge. Another type of particle, the neutrino, does not form atomic structures in the same way that quarks and leptons do because it carries no color or electric charge. Collectively, these types of particles are known as fermions, the group of particles with half-integer spin.

There are three generations of fermions, although familiar matter is formed predominantly by the first generation. The generations are identical except for their masses, which increase in each generation by convention. In addition, each of these particles is accompanied by an antiparticle, with opposite-sign quantum numbers but the same mass.

The fermions compromise what is typically considered matter, but there are additional particles that are mediators of interactions between those fermions. These mediators are known as the gauge bosons, gauge in that their existance is required by gauge invariance (discussed further in Section 2.2) and bosons in that they have integer spin. The boson which mediates the electromagnetic force is the photon, the first boson to be discovered; it has no electric charge, no mass, and a spin of 1. There are three spin-1 mediators of the weak force, the two W bosons and the Z boson. The W bosons have electric charge of $\pm$ 1 and a mass of 80.385 ± 0.015 GeV, while the Z boson is neutral and has a mass of $91.1876 \pm$

0.0021 GeV. The strong force is mediated by eight particles called gluons, which are massless and electrically neutral but do carry color charge.

The final particle present in the Standard Modelis the Higgs boson, which was recently observed for the first time by experiments at CERN in 2012. It is electrically neutral, has a mass of 125.7 ± 0.4 Gev, and is the only spin-0 particle yet to be observed. The Higgs boson is the gauge boson associated with the mechanism that gives a mass to the W and Z bosons.

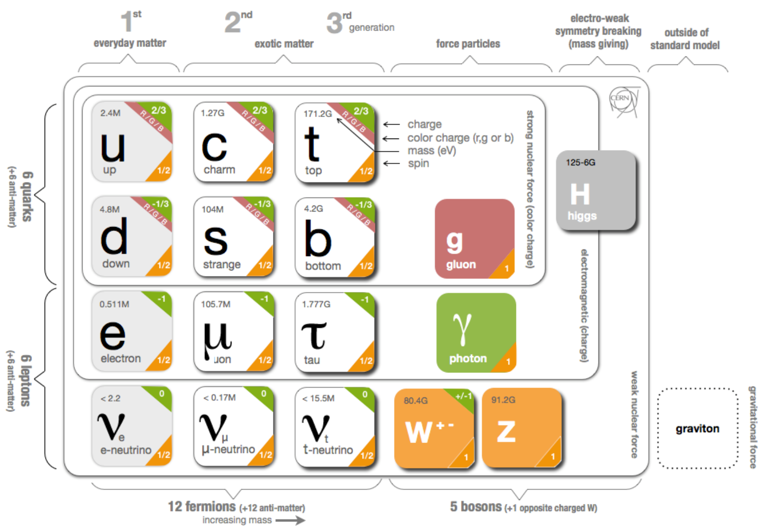

Figure 1: The particle content of the Standard Model.

Together these particles form the entire content of the Standard Model, and are summarized in Figure 1. These are the particles that constitute the observable universe and all the so-far-observed interactions within it.

2.2 INTERACTIONS

The interactions predicted and described by the Standard Modelare fundamentally tied to the particles within it, both in that they describe the way those particles can influence each other and also in that the existence of the interactions requires the existence of some particles (the gauge bosons).

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

As discussed in Section 7.2, colored particles produced in collisions hadronize into jets of multiple individual hadrons. As jets form a major component of many physics analyses at ATLAS, it is crucial to carefully calibrate the measurement of jet energies and to derive an uncertainty on that measurement. These uncertainties have often been the dominant systematic uncertainty in high-energy analyses at the LHC.

One approach to understanding jet physics in the ATLAS calorimetry is to evaluate the calorimeter response to individual hadrons; measurements of individual hadrons can be used to build up an understanding of the jets that they form. The redundancy of the momentum provided by the tracking system and the energy provided by the calorimeter provides an opportunity to study calorimeter response using real collisions, as described further in Section 8.2.

A number of interesting factors compromise calorimeter respose, and extracting these separately provides insight into many aspects of jet modelling. First, many charged hadrons interact with the material of the detector prior to reaching the calorimeters and thus do not deposit any energy. Comparing this effect in data and simulation is a powerful tool in validating the interactions of particles with the material of the detector as well as the model of the detector geometry in simulation, see Section 8.2.1. The particles which do reach the calorimeter deposit their energy into individual cells, which are then clustered to measure full energy deposits. Comparing the response in data to simulated hadrons provides a direct evaluation of several aspects of simulation: noise in the calorimeters, the showering of hadronic particles, and the energy deposited by particles in matter, among others (Section 8.2.2). Additionally, comparing the effect of clustering in data and simulation can indirectly test the simulation's modelling of the shape of hadronic showers, see Section 8.2.2.1. These measurements are extended to explore several additional effects, such as the dependence on charge or the individual calorimeter layer in Section 8.2.2.2.

The above studies all use an inclusive selection of charged particles, which are compromised predominantly of pions, kaons, and (anti)protons. It is also interesting to measure the particle types separately to evaluate the simulated interactions of each particle, particularly at low energies where differences between species are very relevant. Pions and (anti)protons can be identified through decays of long-lived particles, in particular Λ, $\overline{\Lambda}$, and K_S^0, and then used to measure response as described above. This is discussed in detail in Section 8.3.

Together, these measurements in data provide a thorough understanding of the way hadrons interact with the ATLAS detector and can be used to build up a description of jets, as seen in Chapter 9. The results in this chapter use data collected at 7 and 8 TeV collected in 2010 and 2012, respectively. Both are included as the calorimeter was repaired and recalibrated between those two data-taking periods. Both sets of data are compared to an updated simulation that includes new physics models provided by `Geant4` [5] and improvements in the detector description [2, 4]. These results can be compared to a similar measurement performed in 2009 and 2010 [3], which used the previous version of the simulation framework [1].

8.2 INCLUSIVE HADRON RESPONSE

8.2.1 ZERO FRACTION

8.2.2 CALORIMETER RESPONSE

8.2.2.1 CLUSTERING

8.2.2.2 ADDITIONAL STUDIES

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

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

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

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.

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

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

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

where $\gamma = E/m_{\text{x}}$, 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:

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

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.

BIBLIOGRAPHY

[1] ATLAS Collaboration. “The ATLAS Simulation Infrastructure”. In: *Eur. Phys. J. C* 70 (2010), p. 823. doi: 10.1140/epjc/s10052-010-1429-9. arXiv: 1005.4568 [hep-ex].

[2] ATLAS Collaboration. “A study of the material in the ATLAS inner detector using secondary hadronic interactions”. In: *JINST* 7 (2012), P01013. doi: 10.1088/1748-0221/7/01/P01013. arXiv: 1110.6191 [hep-ex].

[3] ATLAS Collaboration. “Single hadron response measurement and calorimeter jet energy scale uncertainty with the ATLAS detector at the LHC”. In: *Eur. Phys. J. C* 73 (2013), p. 2305. doi: 10.1140/epjc/s10052-013-2305-1. arXiv: 1203.1302 [hep-ex].

[4] ATLAS Collaboration. “Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data”. In: *Eur. Phys. J. C* 74 (2014), p. 3071. doi: 10.1140/epjc/s10052-014-3071-4. arXiv: 1407.5063 [hep-ex].

[5] S. Agostinelli et al. “GEANT4: A simulation toolkit”. In: *Nucl. Instrum. Meth. A* 506 (2003), pp. 250–303. doi: 10.1016/S0168-9002(03)01368-8.

DECLARATION

Put your declaration here.

Berkeley, CA, September 2016

Bradley Axen

COLOPHON

Not sure that this is necessary.