Search for Dark Matter in Proton-Proton Collisions at a Center-of-Mass Energy of 13 TeV in the Higgs Boson associated b-anti-b quark channel

Jue Chen

Submitted in partial fulfillment of the
requirements for the degree
of Doctor of Philosophy
in the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2019

©2019

Jue Chen

All Rights Reserved

ABSTRACT

Search for Dark Matter in Proton-Proton Collisions at a Center-of-Mass Energy of 13 TeV in the Higgs Boson associated b-anti-b quark channel

Jue Chen

The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here. The abstract goes here.

Table of Contents

List of Figures

List of Tables

Acknowledgments

The acknowledgments go here. The acknowledgments go here. The acknowledgments go here. The acknowledgments go here. The acknowledgments go here. The acknowledgments go here. The acknowledgments go here.

Dedication text

Part I

Introduction

Chapter 1

Introduction

The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here. The introduction goes here.

Part II

The standard model and Dark Matter

Chapter 2

The standard model

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

2.1 Introduction

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

2.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

2.2 Challenges

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text

sample text. Sample text sample text sample text.

2.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 3

The Dark Matter

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. [Berlin *et al.*, 2014]

3.1 Two-Higgs-doublet model

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

3.2 Simplified model

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. [Alves *et al.*, 2012]

Part III

The LHC and ATLAS experiment

Chapter 4

The LHC

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.1 The LHC: Instrument

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.1.1 Machine layout

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.1.2 Machine performance

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.2 The LHC: Operation

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.2.1 Machine accelerator

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

4.2.2 Machine beam

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 5

The ATLAS experiment

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1 ATLAS detector system

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.1 Inner detector

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.1.1 Pixel detector

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.1.2 Semiconductor Tracker

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.1.3 Transition Radiation Tracker

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.2 Calorimeter

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.2.1 Liquid Argon Calorimeter

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.2.2 Tile Calorimeter

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.3 Muon Spectrometer

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.3.1 Thin Gap Chambers

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.3.2 Resistive Plate Chambers

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.3.3 Monitored Drift Tubes

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.1.3.4 Cathode Strip Chambers

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2 Event reconstruction

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2.1 Tracks

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2.2 Electrons

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2.3 Jets

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2.4 Missing transverse momentum

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.2.5 Muons

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.3 Event simulation

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.3.1 Event generator

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

5.3.2 Detector simulation

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Part IV

Dark Matter search in the Higgs Boson associated $b\bar{b}$ decay

Chapter 6

Introduction

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 7

Boosted Xbb tagging

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

7.1 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

7.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

7.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

7.2 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

7.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 8

Signal selection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

8.1 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

8.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

8.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

8.2 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

8.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 9

Background estimation

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

9.1 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

9.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

9.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

9.2 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

9.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Chapter 10

Result

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

10.1 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

10.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

10.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

10.2 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

10.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Part V

Conclusions

Chapter 11

Conclusions

The general conclusions go here. The general conclusions go here.

Part VI

Appendices

Appendix A

The ATLAS detector service work

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

A.1 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

A.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

A.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

A.2 Sample section

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

A.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Appendix B

Analysis supplementary materials

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

B.1 $pp \to Hb\bar{b}$

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

B.1.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

B.1.2 Sample subsubsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

B.2 $pp \to q\bar{q}b\bar{b}$

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

B.2.1 Sample subsection

Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text. Sample text sample text sample text.

Part VII

Bibliography

Bibliography

[Alves *et al.*, 2012] Daniele Alves, Nima Arkani-Hamed, Sanjay Arora, Yang Bai, Matthew Baumgart, Joshua Berger, Matthew Buckley, Bart Butler, Spencer Chang, Hsin-Chia Cheng, Clifford Cheung, R Sekhar Chivukula, Won Sang Cho, Randy Cotta, Mariarosaria D'Alfonso, Sonia El Hedri, Rouven Essig, Jared A Evans, Liam Fitzpatrick, Patrick Fox, Roberto Franceschini, Ayres Freitas, James S Gainer, Yuri Gershtein, Richard Gray, Thomas Gregoire, Ben Gripaios, Jack Gunion, Tao Han, Andy Haas, Per Hansson, JoAnne Hewett, Dmitry Hits, Jay Hubisz, Eder Izaguirre, Jared Kaplan, Emanuel Katz, Can Kilic, Hyung-Do Kim, Ryuichiro Kitano, Sue Ann Koay, Pyungwon Ko, David Krohn, Eric Kuflik, Ian Lewis, Mariangela Lisanti, Tao Liu, Zhen Liu, Ran Lu, Markus Luty, Patrick Meade, David Morrissey, Stephen Mrenna, Mihoko Nojiri, Takemichi Okui, Sanjay Padhi, Michele Papucci, Michael Park, Myeonghun Park, Maxim Perelstein, Michael Peskin, Daniel Phalen, Keith Rehermann, Vikram Rentala, Tuhin Roy, Joshua T Ruderman, Veronica Sanz, Martin Schmaltz, Stephen Schnetzer, Philip Schuster, Pedro Schwaller, Matthew D Schwartz, Ariel Schwartzman, Jing Shao, Jessie Shelton, David Shih, Jing Shu, Daniel Silverstein, Elizabeth Simmons, Sunil Somalwar, Michael Spannowsky, Christian Spethmann, Matthew Strassler, Shufang Su, Tim Tait, Brooks Thomas, Scott Thomas, Natalia Toro, Tomer Volansky, Jay Wacker, Wolfgang Waltenberger, Itay Yavin, Felix Yu, Yue Zhao, and Kathryn Zurek and. Simplified models for LHC new physics searches. *Journal of Physics G: Nuclear and Particle Physics*, 39(10):105005, sep 2012.

[Berlin *et al.*, 2014] Asher Berlin, Tongyan Lin, and Lian-Tao Wang. Mono-higgs detection of dark matter at the lhc. *Journal of High Energy Physics*, 2014(6):78, Jun 2014.