## 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** 

## **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.

# Table of Contents

I	Int	Introduction										
1	Intr	oduction	2									
II	Tl	ne standard model and Dark Matter	3									
2	The	The standard model										
	2.1	Introduction	4									
		2.1.1 Sample subsection	6									
	2.2	Challenges	6									
		2.2.1 Sample subsection	6									
3	The	Dark Matter	7									
	3.1	Two-Higgs-doublet model	7									
	3.2	Simplified model	7									
II	I I	The LHC and ATLAS experiment	8									
4	The LHC											
	4.1	The LHC: Instrument	9									
		4.1.1 Machine layout	9									
		4.1.2 Machine performance	9									
	4.2	The LHC: Operation	10									
		4.2.1 Machine accelerator	10									

	4.2.2	Machine beam	10
The	ATL	AS experiment	11
5.1	ATLA	S detector system	11
	5.1.1	Inner detector	11
		5.1.1.1 Pixel detector	11
		5.1.1.2 Semiconductor Tracker	12
		5.1.1.3 Transition Radiation Tracker	12
	5.1.2	Calorimeter	12
		5.1.2.1 Liquid Argon Calorimeter	12
		5.1.2.2 Tile Calorimeter	12
	5.1.3	Muon Spectrometer	12
		5.1.3.1 Thin Gap Chambers	13
		5.1.3.2 Resistive Plate Chambers	13
		5.1.3.3 Monitored Drift Tubes	13
		5.1.3.4 Cathode Strip Chambers	13
5.2	Event	reconstruction	13
	5.2.1	Tracks	13
	5.2.2	Electrons	14
	5.2.3	Jets	14
	5.2.4	Missing transverse momentum	14
	5.2.5	Muons	14
5.3	Event	simulation	14
	5.3.1	Event generator	14
	5.3.2	Detector simulation	15
D	ark M	Matter search in the Higgs Boson associated $b\bar{b}$ decay	16
Intr	oducti	ion	17
6.1			17
	5.1 5.2 5.3	The ATLA 5.1 ATLA 5.1.1  5.1.2  5.1.2  5.1.3  5.2.1 5.2.2 5.2.3 5.2.4 5.2.5 5.3 Event 5.3.1 5.3.2  Dark M  Introduct	The ATLAS experiment  5.1 ATLAS detector system  5.1.1 Inner detector  5.1.1.1 Pixel detector  5.1.1.2 Semiconductor Tracker  5.1.2.1 Semiconductor Tracker  5.1.2.1 Liquid Argon Calorimeter  5.1.2.2 Tile Calorimeter  5.1.3 Muon Spectrometer  5.1.3.1 Thin Gap Chambers  5.1.3.2 Resistive Plate Chambers  5.1.3.3 Monitored Drift Tubes  5.1.3.4 Cathode Strip Chambers  5.1.3.4 Cathode Strip Chambers  5.2.1 Tracks  5.2.2 Electrons  5.2.3 Jets  5.2.4 Missing transverse momentum  5.2.5 Muons  5.3 Event simulation  5.3.1 Event generator  5.3.2 Detector simulation  5.3.3 Dark Matter search in the Higgs Boson associated bb decay  Introduction

7	Boo	osted Xbb tagging	18
	7.1	Sample section	18
		7.1.1 Sample subsection	18
		7.1.2 Sample subsubsection	18
	7.2	Sample section	19
		7.2.1 Sample subsection	19
8	Sign	nal selection	20
	8.1	Event Triggers	20
	8.2	Baseline selection	20
		8.2.1 Sample subsection	20
	8.3	Signal region	21
		8.3.1 Sample subsection	21
9	Bac	ckground estimation	22
	9.1	Backgrounds from top and W decays	22
		9.1.1 Sample subsection	22
		9.1.2 Sample subsubsection	22
	9.2	Backgrounds from neutrinos in Z decays	23
		9.2.1 Sample subsection	23
	9.3	Backgrounds from QCD multi-jet	23
10	Res	$\mathrm{sult}$	24
	10.1	Sample section	24
		10.1.1 Sample subsection	24
		10.1.2 Sample subsubsection	24
	10.2	Sample section	25
		10.2.1 Sample subsection	25
$\mathbf{V}$	C	onclusions	<b>26</b>
11	Cor	nclusions	27
		ACA GROAD CARD	

V.	I A	Appendices	<b>28</b>
$\mathbf{A}$	The	e ATLAS detector service work	<b>29</b>
	A.1	Sample section	29
		A.1.1 Sample subsection	29
	A.2	Sample section	29
		A.2.1 Sample subsection	30
В	alysis supplementary materials	31	
	B.1	$pp  o Hbar{b}$	31
		B.1.1 Sample subsection	31
	B.2	$pp  o qar{q}bar{b}$	32
		B.2.1 Sample subsection	32
V	II I	Bibliography	33
Bi	bliog	graphy	34

# List of Figures

0 1	Dartialog of	f the Stand	ard Model of	partiala r	hygieg				5
4.1	Particles of	i ine Standa	ard Model of	particle t	mysics .	 	 		$\mathbf{o}$

# List of Tables

# Acknowledgments

The acknowledgments go here. The acknowledgments go here.

Dedication text

# Part I

# Introduction

## Introduction

The introduction goes here. The introduction goes here.

## Part II

# The standard model and Dark Matter

## 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.

## 2.1 Introduction

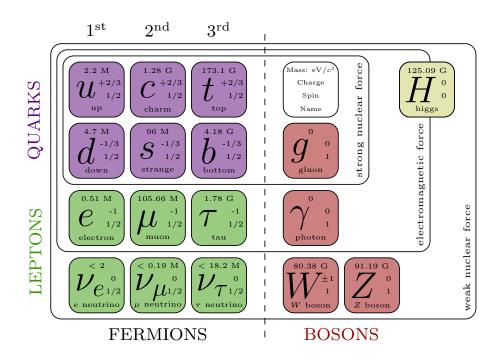


Figure 2.1: Particles of the Standard Model of particle physics

$$L = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(F_{\mu\nu}F^{\mu\nu}) - \frac{1}{2}tr(G_{\mu\nu}G^{\mu\nu}), (Gauge \, terms)$$

$$+ \left(\bar{\nu}_L \quad \bar{e}_L\right)\bar{\sigma}^{\mu}iD_{\mu}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^{\mu}iD_{\mu}e_R + \bar{\nu}_R\sigma^{\mu}iD_{\mu}\nu_R, (Lepton \, dynamical \, terms)$$

$$- \frac{\sqrt{2}}{v}\left[\left(\bar{\nu}_L \quad \bar{e}_L\right)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right], (Electron, muon, Tau \, mass \, terms)$$

$$- \frac{\sqrt{2}}{v}\left[\left(-\bar{e}_L \quad \bar{\nu}_L\right)\phi^*M^{\nu}\nu_R + \bar{\nu}_R\bar{M}^{\nu}\phi^T\begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right], (Neutrino \, mass \, terms)$$

$$+ \left(\bar{u}_L \quad \bar{d}_L\right)\bar{\sigma}^{\mu}iD_{\mu}\begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^{\mu}iD_{\mu}u_R + \bar{d}_R\sigma^{\mu}iD_{\mu}d_R, (quark \, dynamical \, terms)$$

$$- \frac{\sqrt{2}}{v}\left[\left(\bar{u}_L \quad \bar{d}_L\right)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right], (Down, strange, bottom \, mass \, terms)$$

$$- \frac{\sqrt{2}}{v}\left[\left(-\bar{d}_L \quad \bar{u}_L\right)\phi^*M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right], (Up, charm, top \, mass \, terms)$$

$$+ D_{\mu}\bar{\phi}D^{\mu}\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2, (Higgs \, dynamical \, and \, mass \, terms)$$

$$(2.1)$$

The definition of derivative operators in the Eq 2.1 is:

$$D_{\mu} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \left[ \partial_{\mu} - \frac{ig_1}{2} B_{\mu} + \frac{ig_2}{2} W_{\mu} \right] \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \tag{2.2}$$

$$D_{\mu}\nu_{R} = \partial_{\mu}\nu_{R}, \quad D_{\mu}e_{R} = [\partial_{\mu} - ig_{1}B_{\mu}]e_{R}$$

$$D_{\mu} \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \left[ \partial_{\mu} + \frac{ig_1}{6} B_{\mu} + \frac{ig_2}{2} W_{\mu} + igG_{\mu} \right] \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$D_{\mu} u_R = \left[ \partial_{\mu} + \frac{i2g_1}{3} B_{\mu} + igG_{\mu} \right] u_R, \quad D_{\mu} d_R = \left[ \partial_{\mu} - \frac{ig_1}{3} B_{\mu} + igG_{\mu} \right] d_R$$

$$(2.3)$$

$$D_{\mu}\phi = \left[\partial_{\mu} + \frac{ig_1}{2}B_{\mu} + \frac{ig_2}{2}W_{\mu}\right]\phi \tag{2.4}$$

#### Sample subsection 2.1.1

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

#### 2.2Challenges

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

#### 2.2.1Sample 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.

## 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. [Berlin et al., 2014]

## 3.1 Two-Higgs-doublet model

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

## 3.2 Simplified model

## Part III

The LHC and ATLAS experiment

## 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.

#### 4.1 The LHC: Instrument

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.

#### 4.1.2 Machine performance

## 4.2 The LHC: Operation

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.

## 4.2.2 Machine beam

## 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.

## 5.1 ATLAS detector system

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.

### 5.1.1.1 Pixel detector

#### 5.1.1.2 Semiconductor Tracker

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.

#### 5.1.2 Calorimeter

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.

#### 5.1.2.2 Tile Calorimeter

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

#### 5.1.3 Muon Spectrometer

#### 5.1.3.1 Thin Gap Chambers

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.

#### 5.1.3.3 Monitored Drift Tubes

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.

## 5.2 Event reconstruction

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

#### 5.2.1 Tracks

#### 5.2.2 Electrons

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.

#### 5.2.4 Missing transverse momentum

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.

## 5.3 Event simulation

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

#### 5.3.1 Event generator

## 5.3.2 Detector simulation

## Part IV

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

## 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.

## 6.1 MC samples

# 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.

## 7.1 Sample section

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.

### 7.1.2 Sample subsubsection

## 7.2 Sample section

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

## 7.2.1 Sample subsection

# 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.

## 8.1 Event Triggers

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

#### 8.2 Baseline selection

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 samp

sample text. Sample text sample text.

## 8.3 Signal region

TODO, MC simulation in signal region, Pie chart + table. No data.

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

## 8.3.1 Sample subsection

# 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.

## 9.1 Backgrounds from top and W decays

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.

#### 9.1.2 Sample subsubsection

## 9.2 Backgrounds from neutrinos in Z decays

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.

## 9.3 Backgrounds from QCD multi-jet

## Result

TODO, background predictions in signal region, stack chart and table.

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.

#### 10.1.1 Sample subsection

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 sampl

sample text. Sample text sample text.

## 10.2 Sample section

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

## 10.2.1 Sample subsection

# $\mathbf{Part}\ \mathbf{V}$

# Conclusions

## 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.

## A.1 Sample section

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.

## A.2 Sample section

## A.2.1 Sample subsection

## Appendix B

## Analysis supplementary materials

Sample text sample text sample text. Sample text sampl

## **B.1** $pp \rightarrow Hb\bar{b}$

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

## B.1.1 Sample subsection

## **B.2** $pp \rightarrow q\bar{q}b\bar{b}$

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

## **B.2.1** Sample subsection

# Part VII

Bibliography

BIBLIOGRAPHY 34

## **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.