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

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ABSTRACT

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Jue Chen

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Table of Contents

List of Figures

List of Tables

Acknowledgments

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Dedication text

Part I

Introduction

Chapter 1

Introduction

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Part II

The standard model and Dark Matter

Chapter 2

The standard model

2.1 Introduction

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The elementary particles defined in the standard model are demonstrated in Fig 2.1.

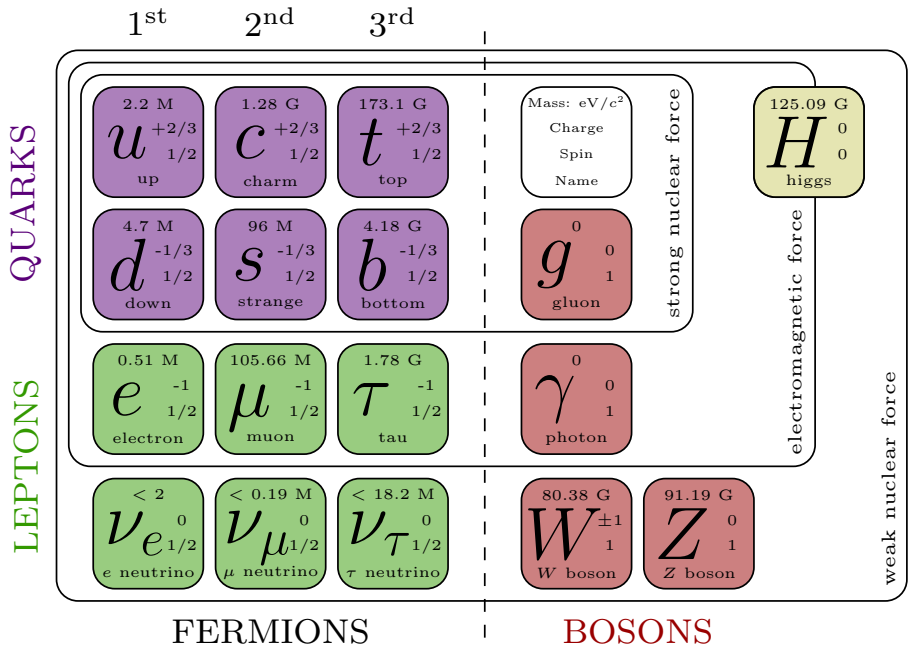

Figure 2.1: Particles of the Standard Model of particle physics

The standard model Lagrangian is shown in Eq 2.1:

$$
\begin{aligned}
L = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(F_{\mu\nu}F^{\mu\nu}) - \frac{1}{2}tr(G_{\mu\nu}G^{\mu\nu}), (Gauge\,terms) \\
& + \begin{pmatrix}\bar{\nu}_L & \bar{e}_L\end{pmatrix}\bar{\sigma}^{\mu}iD_{\mu}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^{\mu}iD_{\mu}e_R + \bar{\nu}_R\sigma^{\mu}iD_{\mu}\nu_R, (Lepton\,dynamical\,terms) \\
& - \frac{\sqrt{2}}{\upsilon}[\begin{pmatrix}\bar{\nu}_L & \bar{e}_L\end{pmatrix}\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}], (Electron, muon, Tau\,mass\,terms) \\
& - \frac{\sqrt{2}}{\upsilon}[\begin{pmatrix}-\bar{e}_L & \bar{\nu}_L\end{pmatrix}\phi^* M^{\nu}\nu_R + \bar{\nu}_R\bar{M}^{\nu}\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}], (Neutrino\,mass\,terms) \\
& + \begin{pmatrix}\bar{u}_L & \bar{d}_L\end{pmatrix}\bar{\sigma}^{\mu}iD_{\mu}\begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^{\mu}iD_{\mu}u_R + \bar{d}_R\sigma^{\mu}iD_{\mu}d_R, (quark\,dynamical\,terms) \\
& - \frac{\sqrt{2}}{\upsilon}[\begin{pmatrix}\bar{u}_L & \bar{d}_L\end{pmatrix}\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}], (Down, strange, bottom\,mass\,terms) \\
& - \frac{\sqrt{2}}{\upsilon}[\begin{pmatrix}-\bar{d}_L & \bar{u}_L\end{pmatrix}\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}], (Up, charm, top\,mass\,terms) \\
& + \bar{D_{\mu}}\phi D^{\mu}\phi - m_h^2[\bar{\phi}\phi - \upsilon^2/2]^2/2\upsilon^2, (Higgs\,dynamical\,and\,mass\,terms)
\end{aligned}
\tag{2.1}
$$

The definition of derivative operators in the Eq 2.1 are:

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

$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - i g_1 B_\mu] e_R$$

$$D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} = [\partial_\mu + \frac{ig_1}{6} B_\mu + \frac{ig_2}{2} W_\mu + i g G_\mu] \begin{pmatrix} u_L \\ d_L \end{pmatrix} \tag{2.3}$$

$$D_\mu u_R = [\partial_\mu + \frac{i2g_1}{3} B_\mu + i g G_\mu] u_R, \quad D_\mu d_R = [\partial_\mu - \frac{ig_1}{3} B_\mu + i g G_\mu] d_R$$

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

2.2 Challenges

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Chapter 3

Dark matter

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3.1 Two-Higgs-doublet model

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3.2 Simplified model

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Part III

The LHC and ATLAS experiment

Chapter 4

The LHC

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4.1 The LHC: Instrument

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4.1.1 Machine layout

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4.1.2 Machine performance

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4.2 The LHC: Operation

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4.2.1 Machine accelerator

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4.2.2 Machine beam

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Chapter 5

The ATLAS experiment

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5.1 ATLAS detector system

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5.1.1 Inner detector

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5.1.1.1 Pixel detector

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5.1.1.2 Semiconductor Tracker

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5.1.1.3 Transition Radiation Tracker

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5.1.2 Calorimeter

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5.1.2.1 Liquid Argon Calorimeter

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5.1.2.2 Tile Calorimeter

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5.1.3 Muon Spectrometer

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5.1.3.1 Thin Gap Chambers

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5.1.3.2 Resistive Plate Chambers

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5.1.3.3 Monitored Drift Tubes

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5.1.3.4 Cathode Strip Chambers

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5.2 Event reconstruction

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5.2.1 Tracks

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5.2.2 Electrons

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5.2.3 Jets

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5.2.4 Missing transverse momentum

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5.2.5 Muons

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5.3 Event simulation

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5.3.1 Event generator

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5.3.2 Detector simulation

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Part IV

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

Chapter 6

Introduction

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6.1 MC samples

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Chapter 7

Boosted Xbb tagging

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7.1 Sample section

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7.1.1 Sample subsection

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7.1.2 Sample subsubsection

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7.2 Sample section

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7.2.1 Sample subsection

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Chapter 8

Signal selection

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8.1 Event Triggers

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8.2 Baseline 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.

8.2.1 Sample subsection

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sample text. Sample text sample text sample text.

8.3 Signal region

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

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8.3.1 Sample subsection

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Chapter 9

Background estimation

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9.1 Backgrounds from top and W decays

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9.1.1 Sample subsection

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9.1.2 Sample subsubsection

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9.2 Backgrounds from neutrinos in Z decays

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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.

9.3 Backgrounds from QCD multi-jet

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Chapter 10

Result

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

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10.1 Sample section

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10.1.1 Sample subsection

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10.1.2 Sample subsubsection

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sample text. Sample text sample text sample text.

10.2 Sample section

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10.2.1 Sample subsection

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Part V

Conclusions

Chapter 11

Conclusions

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Part VI

Appendices

Appendix A

The ATLAS detector service work

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A.1 Sample section

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A.1.1 Sample subsection

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A.2 Sample section

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A.2.1 Sample subsection

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Appendix B

Analysis supplementary materials

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

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B.1.1 Sample subsection

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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

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Part VII

Bibliography

Bibliography

[1] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett.*, B716:1–29, 2012.

[2] 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.

[3] R W Assmann. Preliminary Beam-based specifications for the LHC collimators. Technical Report LHC-PROJECT-NOTE-277, CERN, Geneva, Jan 2002.

[4] 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.

[5] Nicola Cabibbo. Unitary symmetry and leptonic decays. *Phys. Rev. Lett.*, 10:531–533, Jun 1963.

[6] Serguei Chatrchyan et al. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett.*, B716:30–61, 2012.

[7] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13:321–323, Aug 1964.

[8] David J. Gross and Frank Wilczek. Ultraviolet behavior of non-abelian gauge theories. *Phys. Rev. Lett.*, 30:1343–1346, Jun 1973.

[9] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13:508–509, Oct 1964.

[10] Makoto Kobayashi and Toshihide Maskawa. CP Violation in the Renormalizable Theory of Weak Interaction. *Prog. Theor. Phys.*, 49:652–657, 1973.

[11] Y. Nambu and G. Jona-Lasinio. Dynamical model of elementary particles based on an analogy with superconductivity. i. *Phys. Rev.*, 122:345–358, Apr 1961.

[12] Y. Nambu and G. Jona-Lasinio. Dynamical model of elementary particles based on an analogy with superconductivity. ii. *Phys. Rev.*, 124:246–254, Oct 1961.

[13] Yoichiro Nambu. Axial vector current conservation in weak interactions. *Phys. Rev. Lett.*, 4:380–382, Apr 1960.

[14] H. David Politzer. Reliable perturbative results for strong interactions? *Phys. Rev. Lett.*, 30:1346–1349, Jun 1973.

[15] Martin Schmaltz and David Tucker-Smith. Little Higgs review. *Ann. Rev. Nucl. Part. Sci.*, 55:229–270, 2005.

[16] Steven Weinberg. A model of leptons. *Phys. Rev. Lett.*, 19:1264–1266, Nov 1967.

[17] C. N. Yang and R. L. Mills. Conservation of isotopic spin and isotopic gauge invariance. *Phys. Rev.*, 96:191–195, Oct 1954.