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Daiki Yamaguchi

Search for New Phenomena in Top-Antitop Quarks Final States with Additional Heavy-Flavour Jets with the ATLAS Detector

Doctoral Thesis accepted by
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Supervisor's Foreword

For the last half a century, the growth of science has been so rapid. We have witnessed magnificent discoveries each year over the diverse fields. Among all, the discovery in particle physics is distinguished from the others and has a special and profound meaning. Why is that? Because the elementary particles are so fundamental, and not known no more than seventeen species. In addition, only three fundamental forces are hitherto acknowledged and theoretically/experimentally confirmed. Therefore, adding a new element to the list of the particles, or finding a basic law of the fundamental forces, has an enormous impact on our current understanding of the universe.

The discovery of the new particle, i.e., Higgs boson, which were announced to be found at LHC in 2012, has a further unique meaning in its relation to the mass of the other elementary particles. Its discovery opened a new window to examine and explore the vacuum state and the space-time structure of our universe. A number of acknowledged elementary particle species turn out to be 17, and the interactions between them are described by the theoretical framework called the Gauge theory, or including all these together, the Standard Model. This is not a story of the past. After 6 years from the discovery, the precision measurements on the Higgs boson properties are in full swing at the LHC experiments now. The experimental confirmations over the correctness of the SM have been updated every moment ever since the start of LHC. Nonetheless, cracks of the SM are not yet seen.

This is a victory of the SM and the Quantum Field Theory which is a basis of the SM framework. The cross section calculations of the particle processes including the higher order quantum corrections are confirmed to be correct from the major processes like inclusive inelastic scattering of the protons, to the very minor processes like double gauge boson production, over a span of 14th orders of magnitude. Hence, it looks as if we have established the ultimate theory of everything.

The SM is correct and precise to every corner of phase space; however, it is beset by intrinsic problems. It has no components corresponding to Dark Matter. Also, the calculated Higgs boson mass with the quantum corrections is supposed to be extremely heavy, should the quantum theory is correct, which clearly contradicts to the experimental observation. We know the SM is correct with an outstanding precision and that renders these issues even more problematic. This brings us to believe there must be a physics beyond the SM (BSM).

Many varieties of BSM models are proposed. Majorities of them predict an existence of massive new particles. A most effective way to search for such particles is to perform the proton-proton collisions at the energy frontier experiments such as LHC-ATLAS. Thoroughness and prudent systematic studies are required in searching for the BSM. Dr. Daiki Yamaguchi is an excellent researcher, who can conduct such exhaustive studies.

He performed the data qualifications of the Pixel detector in ATLAS, which is the core detector for the precision of the charged particle tracking, during the LHC Run-2 after the increased collision energy to 13 TeV. During 2015–2016, he contributed to the ATLAS Pixel detector operations and studies on the tracking performance in the high pile-up conditions.

Using the data from the LHC-ATLAS in the same period of time, Dr. Yamaguchi searched for the cracks of the SM. He performed studies on the search for the vector-like quarks (VLQ), which are predicted in the models, like composite Higgs model, RS-Extra dimension model. He summarized them in this thesis.

VLQs would manifest themselves in various signatures. Systematical and thorough works in various categories of signal spaces are needed in completing of these searches. Dr. Yamaguchi developed and introduced a new method for this thesis, namely, the jet tagger to distinguish the QCD jets from Higgs boson and top quark. He also optimized the categorization of the signal-like events using this tagger. Largely owing to the new tagger's performance, he obtained the better sensitivities for VLQ than the previous works.

In the thesis, he started from the introduction to the Standard Model and the target BSM models he pursuits, then he proceeds to the LHC and the ATLAS detector, followed by the deep explanations on his search for the VLQs. Each step of the analysis procedure is laid out in detail from the initial design of the analysis strategy to the final decisions of the systematic error treatments. Statistical treatment of the data is an important key for this analysis and is described in detail in this thesis.

I believe the value of this thesis grows and would not fade as long as the LHC continues its endeavors.

Tokyo, Japan Prof. Osamu Jinnouchi
November 2019

Parts of this thesis have been published in the following journal articles

M. Aaboud et al., *Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector*, JHEP **07** (2018) 089, arXiv:1803.09678[hep-ex].

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Acronyms

2UED-RPP	2 Universal Extra Dimensions on the Real Projective Plane
AD	Antiproton Decelerator
ADD	Arkani-Hamed, Dimopoulos, and Dvali
AdS	Anti-de Sitter
ALFA	Absolute Luminosity for ATLAS
ATLAS	A Toroidal LHC Apparatus
BDT	Boosted Decision Tree
BR	Branching Ratio
BSM	Beyond the Standard Model
Cal	Calorimeter
CERN	European Organization for Nuclear Research
CL	Confidence Level
CMS	Compact Muon Solenoid
CSC	Cathode Strip Chamber
DT	Direct Tagging
ED	Extra-Dimensional models
EFT	Effective Field Theory
EM	Electromagnetic
EW	Electroweak
FCal	Forward Calorimeter
GUT	Grand Unified Theory
GWS	Glashow-Weinberg-Salam theory
HLT	High Level Trigger
IBL	Insertable B-Layer
ID	Inner Detector
JVT	Jet Vertex Tagger
KK	Kaluza-Klein
L1	Level-1
LAr	Liquid Argon
LEP	Large Electron-Positron Collider

LHC	Large Hadron Collider
LINAC2	Linear Accelerator 2
LINAC3	Linear Accelerator 3
LS1	Long Shutdown 1
LUCID	Luminosity measurement using Cerenkov Integrating Detector
MBST	Minimum Bias Trigger Scintillators
MC	Monte Carlo
MCC	Module Controller Chip
MDT	Monitored Drift Tube chamber
MIP	Minimum Ionizing Particle
MPI	Multiparton Interaction
MS	Muon Spectrometer
NGB	Nambu-Goldstone bosons
NLO	Next-to-Leading Order
NNLL	Next-to-Next-to Leading Logarithm
NNLO	Next-to-Next-to Leading Order
NP	Nuisance Parameter
PDF	Parton Density Function
pdf	Probability Density Function
PMT	Photomultiplier tube
pp	Proton-Proton
PS	Proton Synchrotron
PV	Primary Vertex
QCD	Quantum Chromo-Dynamics
RF	Radio-Frequency
RMS	Root-Mean Square
ROD	Read Out Driver
RPC	Resistive Plate Chamber
RS	Randall and Sundrum
SCT	Semiconductor Tracker
SM	Standard Model
SPS	Super Proton Synchrotron
SR	Search Regions
SSB	Spontaneous Symmetry Breaking
TGC	Thin Gap Chamber
ToT	Time over Threshold
TRF	Tag-Rate-Function
TRT	Transition Radiation Tracker
UED	Universal Extra Dimensions
vdM	van der Meer
VEV	Vacuum Expectation Value
VLQ	Vector-Like quark
VLT	Vector-Like top quark
VR	Validation Regions
ZDC	Zero-Degree Calorimeter