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学 位 論 文 題 目　Evidence for the Higgs boson production in association with top-quark pair with $\sqrt{s}$=13 TeV of proton-proton collisions at LHC with the ATLAS detector

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博士論文の要旨

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論文題目

Evidence for the Higgs boson production in association with top-quark pair with $\sqrt{s}$ = 13 TeV of proton-proton collisions at LHC with the ATLAS detector

In the Standard Model of the particle physics, the mass of fermions is generated dynamically through the Yukawa interaction with Higgs field. However, the Yukawa interaction for top-quark (called Top-Yukawa coupling) is not directly observed yet, and could be a portal to the new physics. The direct Top-Yukawa coupling can only be measured with the Large-Hadron-Collider (LHC) which is the proton-proton collider with the highest energy in the world. We use the Higgs production process via Higgs and top-quark pair (called ttH process) to measure the Top-Yukawa coupling. The Higgs decaying into di-photon ($H\rightarrow\gamma\gamma$) is considered since the clear di-photon invariant mass peak can be reconstructed, which indicates the existence of Higgs boson. It is also easy to estimate the number of backgrounds comparing to the other decay channels. Therefore we conduct the search for the ttH ($H\rightarrow\gamma\gamma$) process with 79.8 fb^{-1} of proton-proton collision data at $\sqrt{s}=13$ TeV with the ATLAS detector.

The final state of the ttH ($H\rightarrow\gamma\gamma$) process consists of two photons and decay products from top-quark pair ($t\bar{t}\rightarrow b\bar{b}W^+W^-\rightarrow b\bar{b}q\bar{q}q\bar{q}$, $b\bar{b}q\bar{q}l^+\nu$, $b\bar{b}q\bar{q}l^-\bar{\nu}$ or $b\bar{b}l^\pm l^\mp\nu\bar{\nu}$). The possible backgrounds can be classified into two types of events. One includes di-photon productions together with multi-jets ($\gamma\gamma$) or with top-quark pair ($t\bar{t}+\gamma\gamma$), which make continuum di-photon invariant mass distribution. The other includes non-ttH Higgs productions, which make a peak around 125 GeV in the mass distribution. The continuum backgrounds are dominated because of their large cross section. In order to separate the signal from the continuum backgrounds, the ATLAS detector is needed to have a good di-photon invariant mass resolution.

The ATLAS is the general purpose detector built in one of the collision points of the LHC. The ATLAS detector consists of four systems; the Inner detector, the solenoid magnet, the electro-magnetic (EM) and hadronic calorimeters, and the muon spectrometer. Photons are detected by the EM calorimeter which is finely segmented and has good energy resolution of $\sigma_E/E = 10/\sqrt{E(\mathrm{GeV})}\oplus 0.17$ %. The di-photon invariant mass resolution is suppressed to be $\sigma_{m_{\gamma\gamma}} = 1.7$ - 1.3 GeV estimated by the signal Monte-Carlo simulation, depending on the photon kinematics.

In this analysis, the deep understanding of the photon selection efficiency is crucial. We studied the photon selection efficiency in detail using two event samples. One is $Z\rightarrow ll\gamma$ sample where photon comes from the final state radiation. High purity photons can be obtained but the statistics of high momentum photon is not sufficient. The other is $Z\rightarrow ee$ sample where electrons are used to measure photon efficiency with some correction by making use of the similarities of the shower shape between electron and photons. These two data-driven measurements give the consistent result. The efficiency is measured to be >90%.

For the event selection, two photons and at least one b-jet are required to exist. The selected events are still suffered from $\gamma\gamma$ backgrounds. In order to separate signals from $\gamma\gamma$ backgrounds, kinematic variables (energy, momentum and position) for all objects in the final state are used as inputs of the multivariate analysis (MVA) with machine learning. To improve the signal sensitivity, events are categorized into some groups with different signal to background ratio based on the MVA output.

After the selection and categorization, the number of signal events is extracted using unbinned maximum likelihood fit with analytic functions for the $H\rightarrow\gamma\gamma$ peak and continuum background. The systematic uncertainty is dominated by the signal simulation modeling, photon-related uncertainties (photon energy scale, energy resolution and selection efficiency) and jet-related uncertainties (jet energy scale and resolution).

From the fitting, we found the di-photon invariant mass peak at 125 GeV, which represents the existence of the Higgs boson. The statistical significance is estimated to be 4.2 standard deviations relative to the background-only hypothesis while the expected significance is 3.6 standard deviations. This result provides the evidence of the coupling between top-quark and Higgs boson. The cross section of the ttH production process is measured to be

$$\sigma_{ttH} = [694.9\ ^{+198.0}_{-179.3}\ (\text{stat.})\ ^{+141.7}_{-108.2}\ (\text{syst.})\ ]\ \text{fb} = 694.9\ ^{+243.1}_{-207.7}\ \text{fb},$$

which is slightly larger than Standard Model prediction with the NLO calculation, $\sigma_{ttH}^{SM} = 506.5\ ^{+34.6}_{-50.0}$ fb although the uncertainty in the measurement is not small enough to judge whether the deviation is significant or not. The further study with better precision is important program in the high energy physics in future.

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博士論文審査結果

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Title
論文題目　Evidence for the Higgs boson production in association with top-quark pair with $\sqrt{s} = 13$ TeV of proton-proton collisions at LHC with the ATLAS detector

本論文は、LHC ATLAS 実験において世界で初めて観測された、重心系エネルギー13 TeV 陽子衝突による、トップクォーク対と随伴生成するヒッグス粒子についての論文である。トップクォークとヒッグス粒子の結合定数を初めて直接検証した測定であり、投稿論文としても ATLAS 実験共著として Physics Letters B に発表されている。

東野氏はこの解析で肝となる、トップクォーク対とヒッグス粒子の崩壊粒子群を考慮したイベントのカテゴリ分け、運動学を考慮した機械学習によるイベント選択の評価に特に取り組み、生成断面積$\sigma_{ttH} \to 694.9^{+243.1}_{-207.7}$ fb と結論づけ、本崩壊モードを統計的に有意に観測した事を示した。得られた生成断面積は NLO QCD 計算による計算、$\sigma^{SM}_{ttH} \to 506.5^{+34.6}_{-50.5}$ fb と統計の範囲内では一致しているが少し高い値が観測され、今後の LHC ATLAS 実験で期待される更なる高統計による検証に向けた系統誤差の削減についての考察を行っている。また、投稿論文では割愛されたが、ヒッグス粒子崩壊で生成する光子を測定するための電磁カロリメータについて、エネルギー分解能、検出効率など、その基礎性能評価を行い、本結果の信頼性を裏付けている。

公開発表会では、本解析の物理背景、解析に関わる検出器群、イベント選択、結果の導出から考察について段階的に説明した。説明は丁寧でわかりやすく、質問の際には議論が行われる場面があったが、十分的確に答えていた。

本研究を行うにあたって、東野氏は CERN に長期滞在しており、現地研究者と共同で密な議論、会議での発表を行い、研究を進めてきた。英語による研究遂行能力を十分に持っていると判断する。

以上の理由により、本審査委員会は、東野聡氏が学位の授与に値すると全員一致で判断した。