CMS Analysis 2025

Youn Jung Roh (노연정)

자연과학연구소 워크샵 2026.1.13~2026.1.16

CMS Analysis Group (2025)

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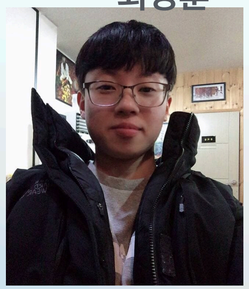
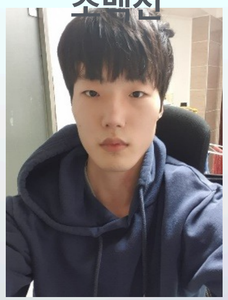




CMS Experiment

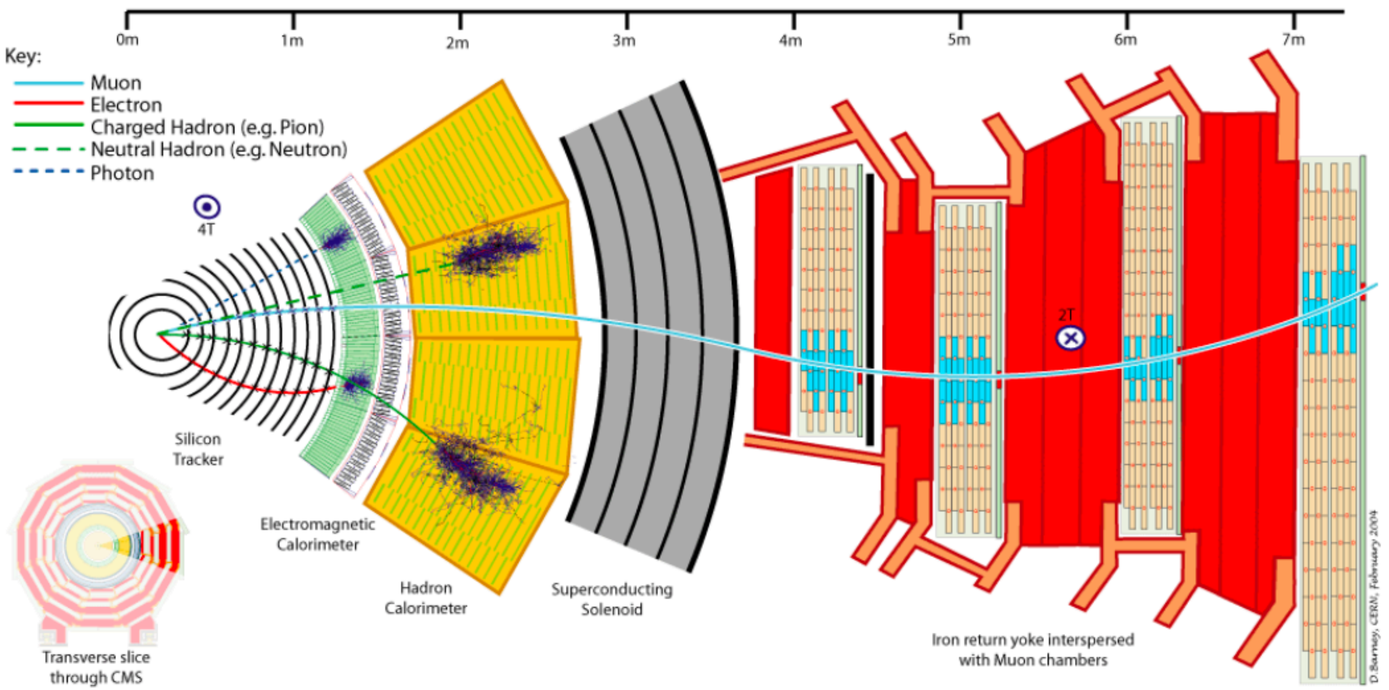


Figure 3.1: Slice of the CMS detector. [1]

- The Compact Muon Solenoid(CMS) is one of two large general-purpose detectors at the LHC.
- The CMS consists of : Tracker, Electromagnetic Calorimeter (ECAL), Hadronic Calorimeter (HCAL), Muon system, and Superconducting Solenoid.
- The trigger system operates in two stages: Level-1 Trigger (L1, ~100Hz) and High-Level Trigger (HLT, ~1kHz)

CMS Muon System

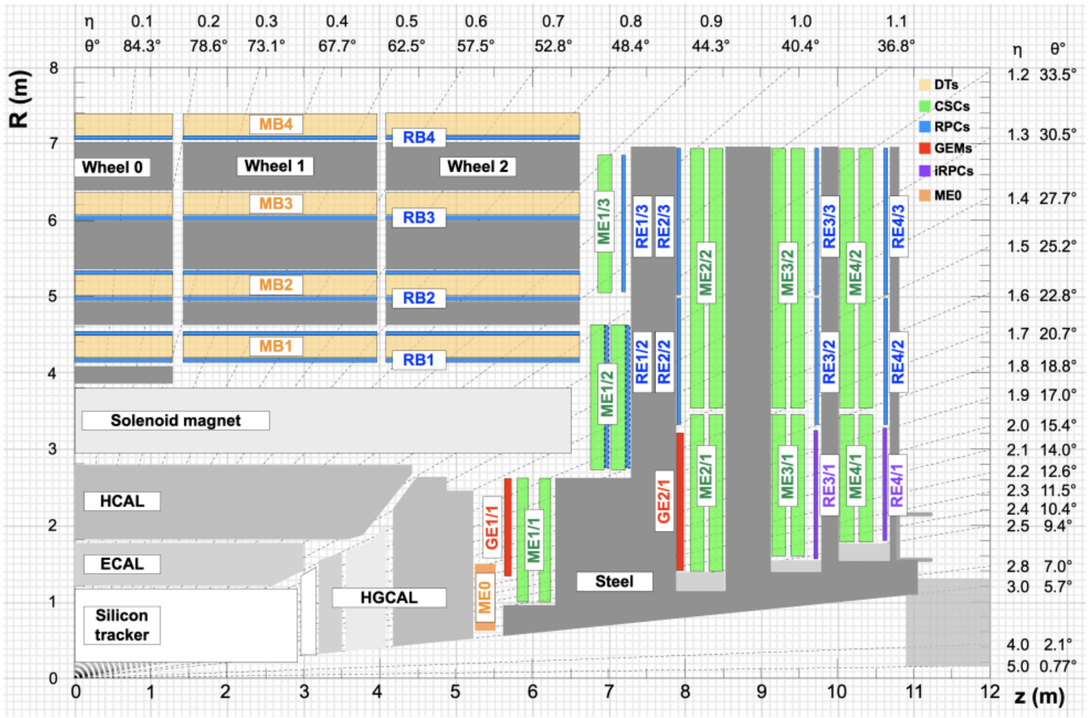
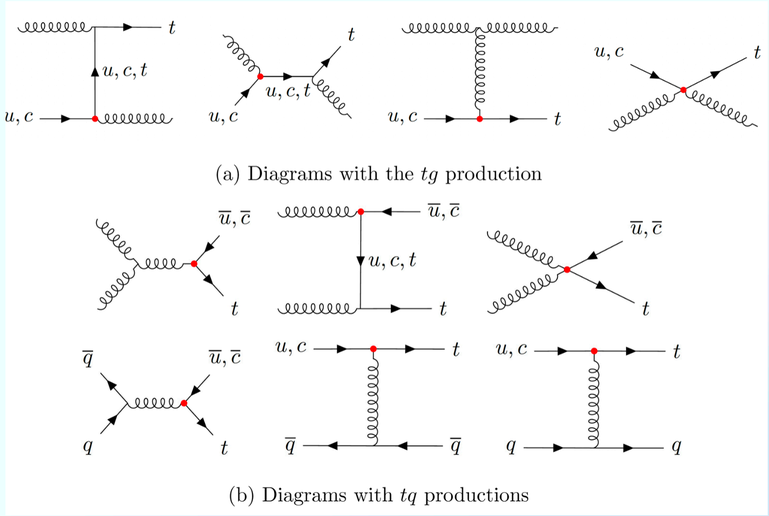


Figure 3.3: An *R-z* cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0) [29].

- UOS members are highly involved GEM detector study.
  - 이상훈 GEM PM Deputy
  - 이안 제임스 왓슨 GEM DPG L2
  - 김슬기 GEM Production L2
  - 장우진 GEM DPG PPD L3

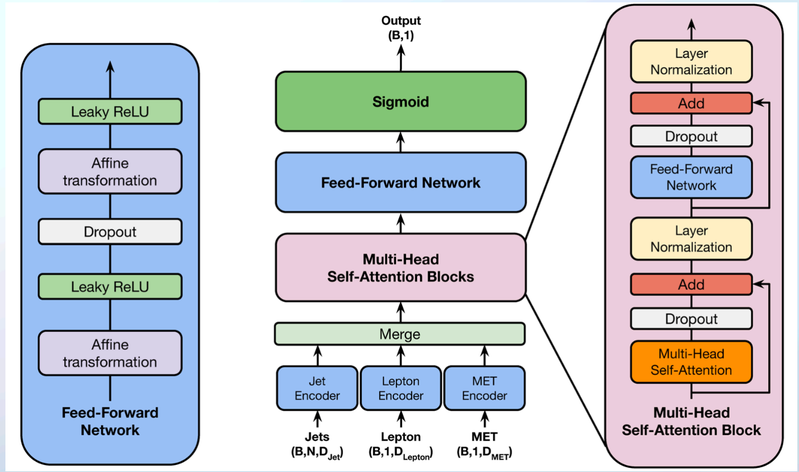
Flavor-changing neutral current (FCNC)

- At the Standard Model (SM), top quark FCNC branching ratios Br(t → ug) (respectively, Br(t → cg)) are of the order of 10^−14 (10^−12).
- However, FCNC interactions may enhance these branching ratios to up to 10^−4 in scenarios including physics Beyond the Standard Model (BSM).
- The tq production resembles SM events, while the tg production is forbidden at the tree level in the SM.
- The proportion of tg production is significantly higher than that of tq production, enabling us to distinguish tqg FCNC events from the SM.



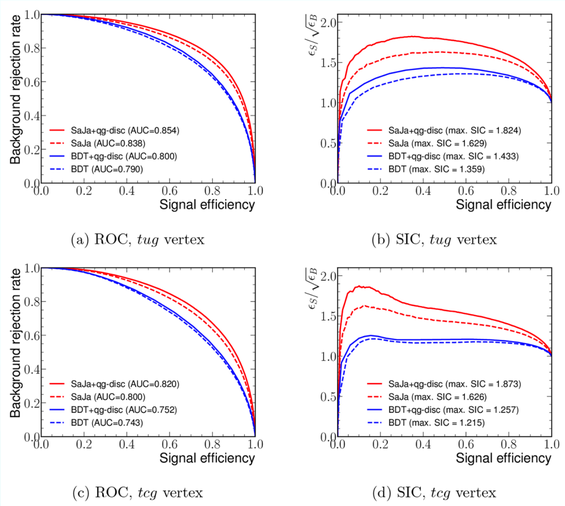
Flavor-changing neutral current (FCNC)

- We identify tqg flavor-changing neutral current interactions using machine learning techniques.
- The Boosted Decision Tree (BDT) method set as a baseline classifier.
- We compare with a transformer-based deep learning method known as the Self-Attention for Jet-parton Assignment (SaJa) network, which allows us to include information from all jets in the event, regardless of their number, eliminating the necessity to match the associated parton to the leading jet.



Flavor-changing neutral current (FCNC)

- The SaJa network with qg-discrimination variables has the best performance.



(a) ROC, tug vertex (b) SIC, tug vertex

(c) ROC, tcg vertex (d) SIC, tcg vertex

- Identification of tqg flavor-changing neutral current interactions using machine learning techniques (JKPS, 2025.1)

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RESEARCH - PARTICLES AND NUCLEI

Identification of *tqg* flavor-changing neutral current interactions using machine learning techniques

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Abstract
Flavor-changing neutral currents (FCNCs) are forbidden at tree level in the standard model (SM), but they can be enhanced in physics beyond the standard model (BSM) scenarios. In this paper, we investigate the effectiveness of deep learning techniques to enhance the sensitivity of current and future collider experiments to the production of a top quark and an associated parton through the *tqg* FCNC process, which originates from the *tug* and *tcg* vertices. The *tqg* FCNC events can be produced with a top quark and either an associated gluon or quark, while SM only has events with a top quark and an associated quark. We apply machine learning techniques to distinguish the *tqg* FCNC events from the SM backgrounds, including *qg*-discrimination variables. We use the Boosted Decision Tree (BDT) method as a baseline classifier, assuming that the leading jet originates from the associated parton. We compare with a transformer-based deep learning method known as the Self-Attention for Jet-parton Assignment (SaJa) network, which allows us to include information from all jets in the event, regardless of their number, eliminating the necessity to match the associated parton to the leading jet. The SaJa network with qg-discrimination variables has the best performance, giving expected upper limits on the branching ratios $Br(t \to qg)$ that are 25–35% lower than those from the BDT method.

Keywords FCNC · Top quark · Transformer-based · Deep learning · Self-attention · Machine learning

1 Introduction

Flavor-changing neutral currents (FCNCs) in the Standard Model (SM) are forbidden at the tree level and suppressed at higher orders through the Glashow–Iliopoulos–Maiani mechanism [1]. At the one-loop level of the SM, top quark FCNC branching ratios $Br(t \to ug)$ (respectively, $Br(t \to cg)$) are of the order of 10^{-14} (10^{-12}) [2]. However, FCNC interactions may enhance these branching ratios to up to 10^{-4} in scenarios including physics Beyond the Standard Model (BSM), such as the $Q = 2/3$ quark singlet model [3], the two Higgs doublet model [4], and the minimal supersymmetric Standard Model [5].

In this study, we focus on *tqg* FCNCs, where *q* is *u* or *c*, in proton–proton (pp) collisions at a center-of-mass energy of 13TeV to probe BSM physics. The tree-level Feynman diagrams for the *tqg* FCNCs are shown in Fig. 1, where the red dots indicate the *tug* and *tcg* vertices for *tg* production (Fig. 1a) and *tq* production (Fig. 1b). The *tq* production resembles SM events, while the *tg* production is forbidden at the tree level in the SM due to the conservation of charge and quark numbers. However, the proportion of *tg* production is significantly higher than that of *tq* production, enabling us to distinguish *tqg* FCNC events from the SM.

Searches for *tqg* FCNCs have been performed by the ATLAS [6–8] and CMS [9] Collaborations in pp collisions at center-of-mass energies of 7, 8, and 13 TeV, and there is also a feasibility study to search for the *tqg* FCNC interactions in future colliders [10]. These studies used machine learning techniques with high-level features as inputs to produce their final results. However, they did not utilize gluon discrimination to enhance their sensitivity to the *tqg* FCNC interactions. In this study, we employ jet-based

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|Vts| measurement in ttbar

- The Cabibbo-Kobayashi-Maskawa (CKM) matrix component, |Vts|, is directly measured in the top pair production.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

$$|V_{ts}|^2 = \frac{BR(t \to s)}{BR(t \to q)}$$

- The main challenge is improving the discrimination performance between strange jets from top decays and other jets.

- We develop novel jet discriminators, called DiSaJa, using a Transformer-based deep learning method.

|Vts| measurement in ttbar

- The DiSaJa-H model utilizes multidomain inputs (jets, leptons, and missing transverse momentum).
- The DiSaJa-L is a novel model that combines low-level jet constituent analysis with event classification using multidomain inputs.
- The model performance is evaluated by comparing various statistical test results to those from a Transformer-based jet classifier which considers only the individual jets.

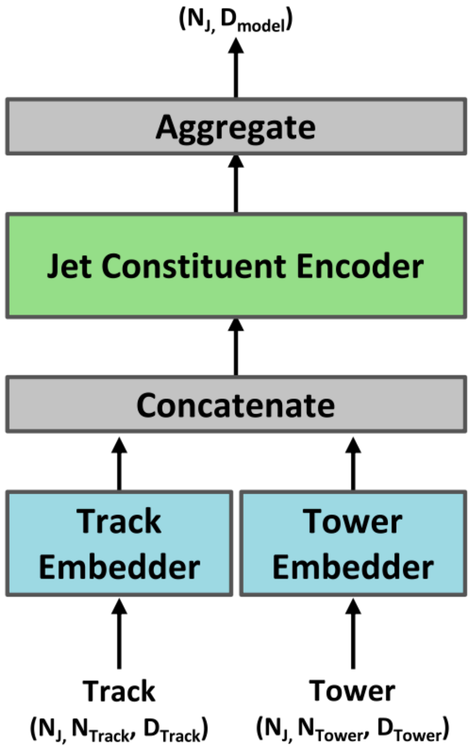
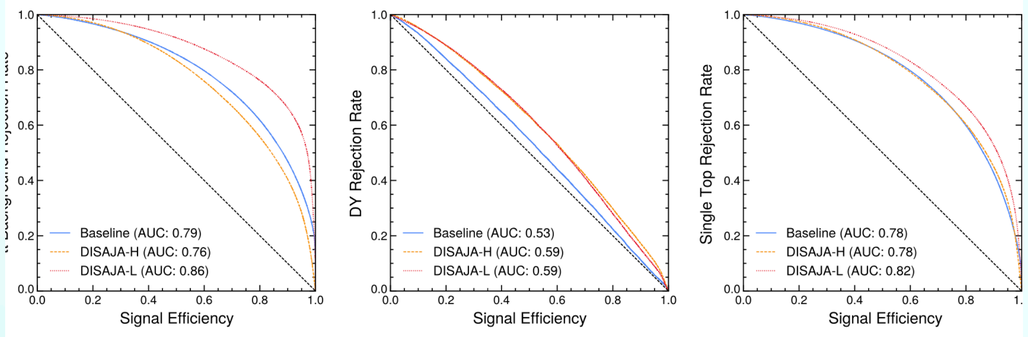


FIG. 4. Architecture of the jet constituent encoder, which can replace the jet high-level feature encoder. Track and tower features are fed into encoders and the jet constituent encoder learns jet representation.

|Vts| measurement in ttbar

- The DiSaJa models have significant performance gains over the individual jet classifier.



- This study show the potential of the measurement during Run 3 of the LHC and the High-Luminosity LHC.

- Improving the direct determination of |Vts| using deep learning (PRD, 2025.9)

PHYSICAL REVIEW D **112,** 052003 (2025)

Improving the direct determination of $|V_{tx}|$ using deep learning

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An s-jet tagging approach to determine the Cabibbo-Kobayashi-Maskawa matrix component $|V_{ts}|$ directly in the dileptonic final state events of the top pair production in proton-proton collisions has been previously studied by measuring the branching fraction of the decay of one of the top quarks by $t \to sW$. The main challenge is improving the discrimination performance between strange jets from top decays and other jets. This study proposes novel jet discriminators, called DiSaJa, using a Transformer-based deep learning method. The first model, DiSaJa-H, utilizes multidomain inputs (jets, leptons, and missing transverse momentum). An additional model, DiSaJa-L, further improves the setup by using lower-level jet constituent information, rather than the high-level clustered information. DiSaJa-L is a novel model that combines low-level jet constituent analysis with event classification using multidomain inputs. The model performance is evaluated via a CMS-like LHC Run 2 fast simulation by comparing various statistical test results to those from a Transformer-based jet classifier which considers only the individual jets. This study shows that the DiSaJa models have significant performance gains over the individual jet classifier, and we show the potential of the measurement during Run 3 of the LHC and the High-Luminosity LHC.

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I. INTRODUCTION

The Cabibbo-Kobayashi-Maskawa (CKM) matrix is the 3×3 unitary complex matrix that gives the strength of the charged-current weak interaction between the quark generations in the Standard Model (SM) [1]. A global fit has been performed to constrain its components using measurements of various aspects of the CKM matrix and by imposing the SM condition of unitarity [2]. Although the fit gives precise values for each CKM component, further measurements are necessary to test the validity of the unitarity condition. In particular, the unitarity is no longer valid in several beyond the SM (BSM) theories [3]. Therefore, direct measurement of the components should be performed to test the SM consistency and constrain BSM scenarios.

In this paper, we focus on the measurement potential of the third-row component $|V_{ts}|$, whose squared value gives the branching ratio of the decay of the top quark to the strange quark and a W boson in the SM. In the global fit of the CKM under the SM conditions, the value of $|V_{ts}|$ is $4.110^{+0.083}_{-0.072} \times 10^{-2}$ [2]. There have been several studies for measuring the component indirectly, which are used in the global fit. For example, $|V_{ts}|$ is determined indirectly using the $B_s^0 - \bar{B}_s^0$ oscillation frequency [4–6] and decay constant parameters from lattice QCD results [7], which results in $|V_{ts}| = 4.15 \pm 0.09 \times 10^{-2}$ [2]. However, as the indirect measurements rely on loop processes, there could be BSM contributions and therefore these measurements could yield results that differ from the true value of $|V_{ts}|$. For example, BSM models with additional quark generations allow $|V_{ts}|$ to be as large as 0.2 [3].

There are several measurements for the model-independent direct determination of the V_{tx} components, where x is d, s, and b. For instance, there are recent analyses with the ATLAS and CMS detectors using 13 TeV data where the single top process probes the tWq vertices in production and decay in the t-channel. The CMS study gives limits of $|V_{ts}|^2 + |V_{td}|^2 < 0.057$ and $|V_{ts}|^2 + |V_{td}|^2 < 0.06$ at the 95% confidence level (CL) under SM CKM unitarity and after relaxing the SM constraint, respectively [8]. The ATLAS study uses the fact that the d-quark is a valence quark of the proton while the s-quark is a sea quark to give the separate limits $f_{LV}|V_{ts}| < 0.58$ and $f_{LV}|V_{td}| < 0.23$ at the 95% CL, where f_{LV} is the left-handed form factor [9]. Additionally, previous studies have proposed the direct determination using a light-flavor jet tagging approach to discriminate strange jets from the $t \to sW$ decay in the top pair production process for $|V_{ts}|$ [10,11] or the b-jets from $t \to bW$ for $|V_{tb}|$ [12].

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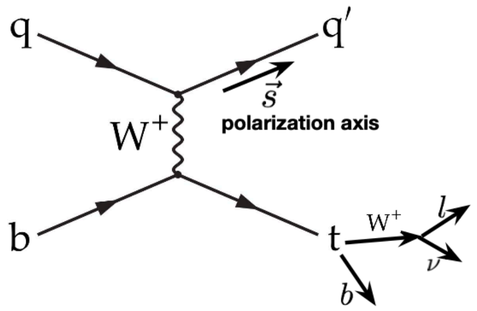
Measurement of CP violation in single top t-channel

- A violation of the charge-parity (CP) symmetry can explain the paradox of the baryon asymmetry of the universe.
- A forward-backward asymmetry of an angular distribution defined in the top quark sector, which is strongly related to the CP violation.
- The measurement is performed in the t-channel production of single top quark in proton-proton collisions, at center-of-mass energy of 13 TeV.

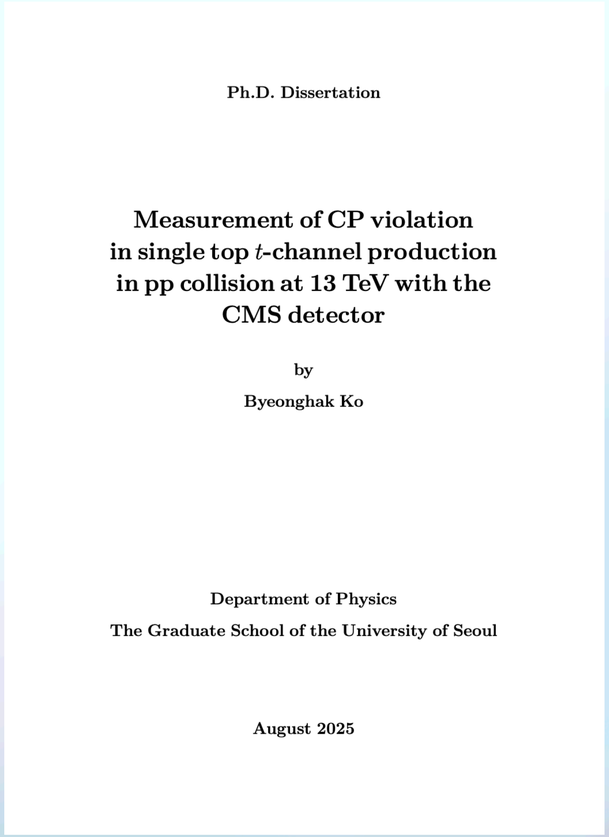


Target variable

$$A_{FB}^{N} = \frac{N(\cos\theta^{N} > 0) - N(\cos\theta^{N} < 0)}{N(\cos\theta^{N} > 0) + N(\cos\theta^{N} < 0)}$$

Measurement of CP violation in single top t-channel

- 고병학 박사 학위 (2025.8, Measurement of CP violation in single top t-channel production in pp collision at 13 TeV with the CMS detector)
- CMS internal review for publication is on-going.
- UOS members (노연정, 이안 왓슨, 이상훈) are co-work with Sejong Univ. members (김현수, 고병학).



Ph.D. Dissertation

Measurement of CP violation in single top *t*-channel production in pp collision at 13 TeV with the CMS detector

by

Byeonghak Ko

Department of Physics

The Graduate School of the University of Seoul

August 2025

Supersymmetry in the VBF 0-lepton channel

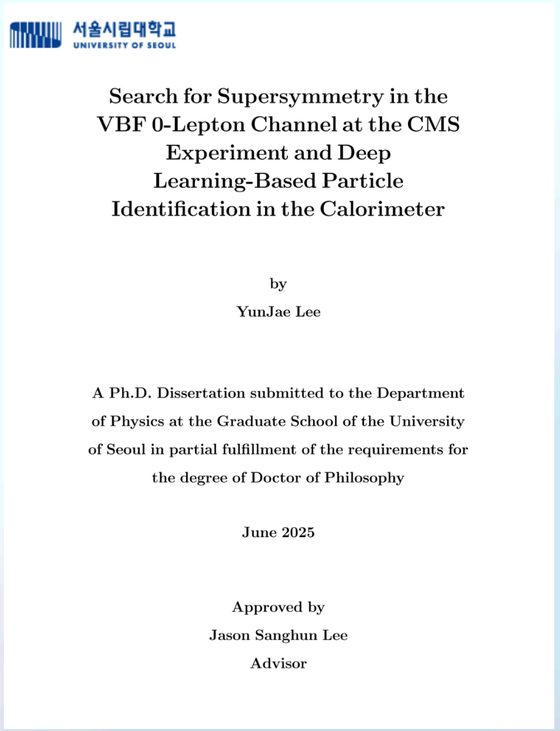
- Supersymmetry (SUSY) is a compelling extension of the Standard Model of particle physics, postulating a symmetry between fermions and bosons to address key issues of the Standard Model such as the hierarchy problem and dark matter.
- A search for SUSY in the vector boson fusion (VBF) 0-lepton channel using CMS data is presented.
- The VBF topology, characterized by two forward jets with large rapidity separation and minimal central hadronic activity, offers a distinctive environment to probe SUSY scenarios while suppressing Standard Model backgrounds.
- The analysis targets events with no isolated leptons and significant missing transverse energy, consistent with the production of very soft lepton below measurement threshold and neutral SUSY particles escaping detection.

Supersymmetry in the VBF 0-lepton channel

- The results are interpreted with constraints on superpartner masses and production cross sections of SUSY models.
- The analysis places upper limits on SUSY production cross sections within simplified models.
- Results demonstrate the effectiveness of VBF selections in enhancing sensitivity to electroweak SUSY production, especially in compressed spectra scenarios.
- This complements existing searches focused on lepton-rich final states.

Supersymmetry in the VBF 0-lepton channel

- 이윤재 박사 학위 (2025.8, Search for supersymmetry in the VBF 0-lepton channel at the CMS experiment and deep learning-based particle identification in the calorimeter)
- 이윤재 박사 - 중앙대학교 박사후연구원


서울시립대학교
UNIVERSITY OF SEOUL

Search for Supersymmetry in the VBF 0-Lepton Channel at the CMS Experiment and Deep Learning-Based Particle Identification in the Calorimeter

by

YunJae Lee

A Ph.D. Dissertation submitted to the Department of Physics at the Graduate School of the University of Seoul in partial fulfillment of the requirements for the degree of Doctor of Philosophy

June 2025

Approved by

Jason Sanghun Lee

Advisor

Muon Track Reconstruction for ME0

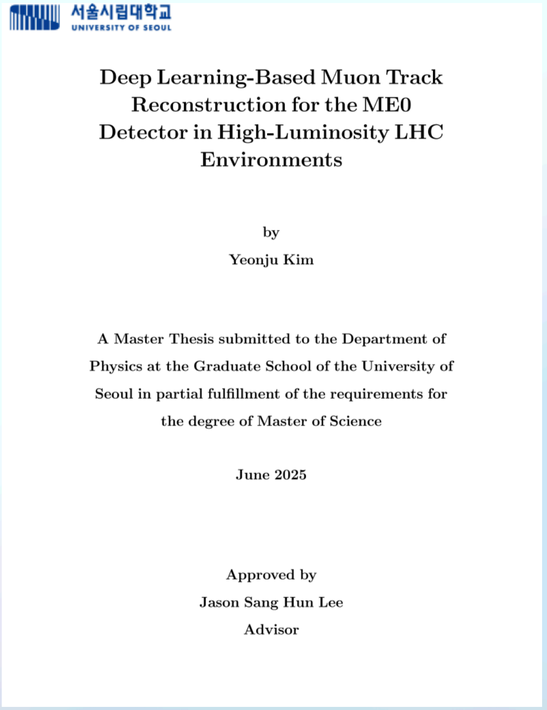
- As part of the CMS muon system upgrade for the HL-LHC, the ME0 detector, a new triple GEM station, is planned to be installed to extend muon coverage in the forward region.
- Triple GEM detectors are known for their robustness in high radiation environments, making them well-suited for deployment in such regions.
- However, the ME0 detector also presents challenges for segment reconstruction due to the high rate of pileup interactions, due to the inherently high pileup rates in the forward region where it is located.

Muon Track Reconstruction for ME0

- This study investigates two deep learning-based models for muon segment reconstruction in the ME0 detector: a 3D convolutional neural network (ME0SegCNN3d) and a Transformer-based architecture (ME0Transformer).
- The models are trained on simulated ME0 data and evaluated under HL-LHC conditions using hit- and segment-level metrics, and compared against a rule based baseline derived from the CSC road usage algorithm.
- Both deep learning models substantially reduce the segment fake fraction compared to the baseline, which reaches 35.5%. The ME0SegCNN3d achieves a fake fraction of 3.4%, while the ME0Transformer achieves the lowest at 2.1%.
- All models maintain comparable segment reconstruction efficien- cies above 99.2%, with the baseline at 99.38%, the CNN model at 99.30% and the Transformer model at 99.27%.

Muon Track Reconstruction for ME0

- The results demonstrate the viability of deep learning approaches for muon reconstruction under realistic detector conditions. These findings motivate further research into flexible, data-driven alternatives to traditional reconstruction logic.
- 김연주 석사 학위 (2025.8) Deep Learning-Based Muon Track Reconstruction for the ME0 Detector in High-Luminosity LHC Environments



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Deep Learning-Based Muon Track Reconstruction for the ME0 Detector in High-Luminosity LHC Environments

by

Yeonju Kim

A Master Thesis submitted to the Department of Physics at the Graduate School of the University of Seoul in partial fulfillment of the requirements for the degree of Master of Science

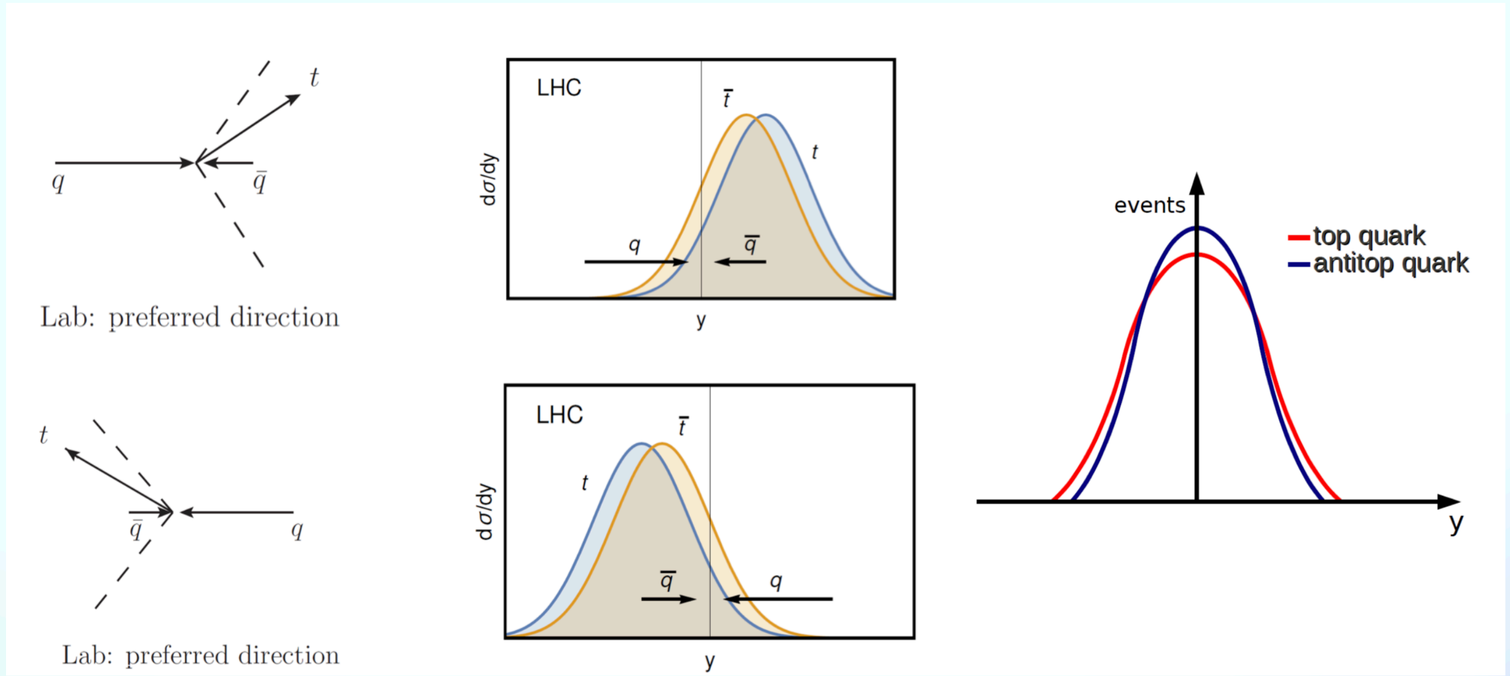
June 2025

Approved by

Jason Sang Hun Lee

Advisor

Charge Asymmetry in ttbar production



- The valence quarks in protons have larger energy than other quarks. The charge asymmetry (CA) is expected in the top pair production at LHC.
- The CA is suppressed by gg-> ttbar in LHC. Very small amount of the asymmetry is measurable.

Charge Asymmetry in ttbar production

- RUN2 and RUN3 studies are on-going.
- RUN2 study : UOS members (노연정, 이안 왓슨) are co-work with Sejong Univ. members (강예찬, 김현수) and UIC group.
- RUN3 study: 권도훈, 노연정

CMS Analysis Achievements 2025

- **논문**
  - Identification of tqg flavor-changing neutral current interactions using machine learning techniques (JKPS, 2025.1)
  - Improving the direct determination of $|Vts|$ using deep learning (PRD, 2025.9)

- **인력배출**
  - 고병학 박사 (2025.8, Measurement of CP violation in single top t-channel production in pp collision at 13 TeV with the CMS detector)
  - 이윤재 박사 (2025.8, Search for supersymmetry in the VBF 0-lepton channel at the CMS experiment and deep learning-based particle identification in the calorimeter)
  - 김연주 석사 (2025.8, Deep Learning-Based Muon Track Reconstruction for the ME0 Detector in High-Luminosity LHC Environments)

CMS Analysis Achievements 2025

- **학회 발표**
  - 고병학: 한국물리학회 (대전, 2025.4) Identification of tqg flavor-changing neutral current interactions using machine learning techniques
  - 허우현: 한국물리학회 (대전, 2025.4) Enhancing the ME0 Level-1 Trigger in the CMS Experiment Using Machine Learning
  - 허지원: 한국물리학회 (대전, 2025.4) Background Rate Measurement of the GE1/1 Detector in the CMS Experiment
  - 김연주: LHCP (대만, 2025.6) Deep Learning Approaches to Muon Reconstruction in the ME0 Detector
  - 허지원: LHCP (대만, 2025.6) Background Rate of the GE1/1 Detector in the CMS Experiment
  - 김우종: 한국물리학회 (광주, 2025.10) Efficiency and Imaging Performance of a Boron-10 Coated Double-GEM Detector for Cold Neutrons
  - 허우현: 한국물리학회 (광주, 2025.10) Enhancing the ME0 Level-1 Trigger in the CMS Experiment Using Machine Learning
  - 허지원: 한국물리학회 (광주, 2025.10) Improving the Direct Determination of |Vts| using Deep Learnin

CMS Analysis Achievements 2025

- **수상**
  - 우수 발표상: 허지원, 한국물리학회 (대전, 2025.4) Background Rate Measurement of the GE1/1 Detector in the CMS Experiment
  - LHCP 2025 Poster Award: 허지원, LHCP (대만, 2025.6) Background Rate of the GE1/1 Detector in the CMS Experiment