Accelerating End-to-End Deep Learning Reconstruction using Graph Neural Networks

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**(Additional interested IRIS-HEP co-supervisors are welcome)*

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1. Background:

Most of the existing work on high energy particle reconstruction relies on the inputs provided by the Particle Flow (PF) algorithm used to convert detector level information to physics objects which sometimes fail to reconstruct or reconstruct with defects using this approach [1]. The end-to-end deep learning technique unites deep learning algorithms and low level detector representation of collision events [2-5]. To maximize the information content of the end-to-end detector reconstruction, it becomes necessary to combine information from multiple subdetectors to maintain a high energy efficiency of the signal and low rate of misidentification, for example to reconstruct jets or semi-leptonic or hadronic taus.

At the same time, machine learning algorithms are advancing in high energy physics owing to their applications in particle and event identification, physics analysis, detector reconstruction, simulation and trigger. However, the integration of these computational tools with the experimental framework is faced with several new challenges. As a student of the Google Summer of Code 2020 program, I developed an end-to-end deep learning framework (`E2EFW`) within the CMS Software (CMSSW) framework with the objective of addressing the aforementioned concerns under the mentorship of Dr. Sergei Gleyzer. During the tenure of the IRIS-HEP fellowship program, this project aims to extend the previously developed CMSSW based interface, `E2EFW` for end-to-end deep learning based tau reconstruction.

2. Project Proposal

The `E2EFW` is designed to be highly modular and flexible to support customizable workflows relevant for end-to-end machine learning training and inference. `E2EFW` is built upon C++ based CMSSW framework and extends the CMSSW base classes (`edm::EDProducers`). It can optionally be run to produce EDM-format files for further downstream processing by other CMSSW modules. `E2EFW` enables a user to configure the end-to-end pipeline by choosing which subdetectors to include, selecting the jet clustering algorithms to use for determining the centers of the jets or defining an altogether new algorithm for the same. In [7] we have described the detailed implementation of `E2EFW` for end-to-end reconstruction of electrons, photons, quarks, gluons and top jets.

In this project I propose to develop a Graph Neural Network based approach for tau identification, compare and study its performance with the Convolutional Neural Network benchmark for the same and extend the integration of `E2EFW` with CMSSW for end-to-end tau reconstruction and identification. This project aims to explore various GNN based approaches with attention mechanisms to develop highly efficient tau reconstruction algorithms. The proposed work will be mentored by Dr. Sergei Gleyzer (The University of Alabama) and Dr. Davide DiCroce (The University of Alabama). Additional interested IRIS-HEP co-supervisors are also welcome.

3. Deliverables

The major deliverables of this project include the algorithms and codes for end-to-end deep learning tau reconstruction with GPU support along with the detailed analysis and study of GNN based approaches as compared to CNNs for the same task. The entire code will be combined with the existing `E2EFW` and a pull request against the official CMSSW repository will be generated with the objective of merging the `E2EFW` with CMSSW. All the codes will be publicly available on the GitHub. We will use CMS Open Data to benchmark the algorithms and corresponding codes in a realistic scenario. The results of this work will be relevant for other end-to-end particle and event identification tasks at the LHC.

4. Timeline (May 2021 - July 2021)

Week(s)	Tasks
1 - 2	● Project setup. Review the existing implementations of GNN based tau identification.
3 - 4	● Use these implementations to define a few baseline models along with their deployment on the CMSSW inference engine using `E2EFW`. Investigate the performance of these models on the CMSSW inference engine in terms of memory, timing and efficiency.
5 - 8	● Improvise the performance by exploring and experimenting with various GNN based approaches. ● Experiment with various graph convolution methods, attention mechanisms, graph pooling and node clustering techniques to effectively define graphs.
8 - 9	● Finalize the final GNN implementation to deploy for the identification task and benchmark the existing potential CNN implementations. ● Scale the implementation to multiple GPUs and larger datasets.
9 - 10	● Implement end-to-end tau identification using GNNs on the `E2EFW` and comparing the performance on the CMSSW inference engine with the CNN benchmarks.
10 - 12	● Prepare the results, documentations for the code and present the final analysis.

5. Student Background

I am an undergraduate student pursuing (Hons.) Bachelors of Engineering in Electronics and Instrumentation at BITS Pilani, India. Currently, I am pursuing my bachelor's thesis under the supervision of Dr. Sergei Gleyzer at the University of Alabama. The focus of my bachelor's thesis is developing graph based deep learning approaches for boosted top jets identification and reconstruction. Starting from Fall 2021, I will be joining a graduate school in the USA (I have received a few admits from the University of Alabama, New York University, etc.) for a Masters program in Computer Science with a major focus in data science and applied machine learning. I would like to continue being involved in high energy physics research and will continue contributing this summer and throughout the graduate studies.

The proposed project will provide me the opportunity to continue the current research and software development in the end-to-end deep learning learning domain for high energy physics during the summer.

It will enable me to expand my skill set and study graph neural networks in depth with their impact on various particle reconstruction tasks. I initiated my work on this project as a student of the Google Summer of Code 2020 program and have been making contributions to the project for more than a year. The details about the GSoC work done can be found here. You may refer to my CV for more details about my past research experience.

6. References

[1] The CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, European Organisation for Nuclear Research (CERN), arXiv:1706.04965v2 [physics.ins-det] 9 Oct 2017

[2] M. Andrews, M. Paulini, S. Gleyzer, B. Poczos, End-to-End Event Classification of High-Energy Physics Data, J. Phys. Conf. Ser. 1085 (4) (2018) 042022. doi:10.1088/1742-6596/1085/4/042022.

[3] M. Andrews, M. Paulini, S. Gleyzer, B. Poczos, End-to-End Physics Event Classification with CMS Open Data: Applying Image-Based Deep Learning to Detector Data for the Direct Classification of Collision Events at the LHC, Comput. Softw. Big Sci. 4 (1) (2020) 6. arXiv:1807.11916, doi:10.1007/s41781-020-00038-8.

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[5] M. Andrews, M. Paulini, S. Gleyzer, B. Poczos, Exploring End-to-end Deep Learning Deep Learning Applications for Event Classification at CMS, EPJ Web of Conferences 214, 06031 (2019), CHEP 2018, https://doi.org/10.1051/epjconf/201921406031

[6] Androsov, K. (2019). Identification of tau lepton using deep learning techniques at CMS. 27th International Symposium on Nuclear Electronics and Computing (NEC'2019) Book of Abstracts, (p. 152). Joint Institute for Nuclear Research (JINR): JINR.

[7] Michael Andrews, Bjorn Burkle, Shravan Chaudhari, Davide DiCroce, Sergei Gleyzer, Ulrich Heintz, Meenakshi Narain, Manfred Paulini, Emanuele Usai, Accelerating End-to-End Deep Learning for Particle Reconstruction at CMS, CHEP Conference 2021.

[8] Michael Andrews, Bjorn Burkle, Shravan Chaudhari, Davide DiCroce, Sergei Gleyzer, Ulrich Heintz, Meenakshi Narain, Manfred Paulini, Emanuele Usai, End-to-End Jet Classification of Boosted Top Quarks with CMS Open Data, CHEP Conference 2021.