EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Evaluating Trigger Efficiencies for W Boson to Three Charged Pion Decays

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Abstract

The Compact Muon Solenoid (CMS) detector records, at its peak, around 1 billion interactions per second [4], which, over time, is way too much data to hang on to long-term. This is why CMS utilizes detector components called triggers, which sift through and decide whether or not to keep data. This project focuses on a more detail-oriented trigger, the High-Level Trigger (HLT) looking for an unobserved interaction: W-Boson decays into three charged pions. More specifically, we are analyzing the efficiency of triggers looking for this interaction to see if we can find a replacement for an HLT algorithm based on "DeepTau" [2].

I. Introduction

i. Triggers

The trigger is a detector component that decides whether or not to save events as seen by the detectors based on their content. At CMS, there are two levels of triggers: the level 1 (L1) trigger and the high-level trigger (HLT). Figure 1 depicts how the L1 trigger and HLT are related and how they fit into the grand scheme of data collection. The L1 trigger is hardware-based (FPGAs and other electronic components) and is the most inclusive [5]. Since it is the first layer of data filtering, it makes the simplest of decisions and only looks through data recorded by the calorimeter and muon chamber detectors. It disregards the tracker detectors. This surface-level analysis also means the resolution of data and the analysis time are reduced, saving more effective analysis techniques for the HLT [5]. For example, the L1 reduces the data collection frequency from about 32 MHz (bunch crossing frequency in CMS) to 100 kHz [1]. The HLT takes the data chosen by the L1 trigger and filters them more selectively. The HLT is software-based and runs on a computer farm of commercial processors [1]. This trigger system goes from a data collection frequency of about 100 kHz to O(1) kHz and the processing time between each event is about 400 ms [1]. Trigger Efficiencies are the amount of events that pass the trigger out of all the events the trigger looks through. In other words, the probability that an event passing through all the trigger requirements is a sought-after event [6]. To calculate such an efficiency, one would count the number of detector events that make it through the filters in the trigger menu, count the total number of events the trigger encounters, and divide those values {see Equation 1}. This equation is the basis of our summer project.

ii. W Boson into Three Charged Pion Decays

In this project, the physical process the trigger is seeking is the W boson to three charged pion decay. This decay is unobserved but is theorized to exist by the standard model of particles. See {Figure 2} for the positively charged W boson Feynman diagram decaying into three charged pions. If this interaction is observed, it could be a more direct alternative to measuring the W boson mass compared to the lepton and neutrino decay {See Figure 3}.

iv. Background on DeepTau and ParticleNet

The two HLT algorithms we compared in this project were “DeepTau” and “ParticleNet”. DeepTau is going out of commission because a small number of research groups are using it compared to the vast majority of trigger users. Consequently, DeepTau is taking up processing time in the trigger menu for the benefit of the few, so the CMS Collaboration decided to discard the trigger algorithm in favor of a better-performing one. DeepTau looks for and reconstructs hadronically decaying Tau leptons and is currently the trigger algorithm used for seeking the W

Boson to three charged pion decay. This is why the objective of this project aims to evaluate the efficiency of ParticleNet to see if it is a viable replacement. ParticleNet is a viable candidate to supersede DeepTau because it looks for and reconstructs jets, which are common instances where hadronic tau decays occur [3].

v. Pions, Taus, and Reconstruction

It may seem odd that researchers use a trigger algorithm that looks for hadronically decaying taus instead of charged pions, but really this is an effective strategy. The detector signatures of hadronically decaying taus and the W Boson to three charged pion decay are very similar, especially when it comes to fulfilling trigger requirements {See Figure 4 and 2}. Because the W boson is unstable, it would theoretically decay into three charged pions near the detector center. Similarly, the relatively unstable Tau would decay, close to the center of the detector, into, according to this specific Feynman diagram, a charged pion and a tau neutrino. Given that the filters in the triggers are looking for attributes of the detector signatures, like track patterns and energy deposits in the electromagnetic and hadronic calorimeters, these decays are similar enough to use the DeepTau trigger for the W boson decay we seek.

II. Phases of Project

Prior to CERN, I had a few small research projects and a liberal arts education under my belt, so I definitely wasn't the most equipt intern at CERN this summer. This fact makes this experience all the better. My mentor created this project for the sole purpose of introducing me to the realm of experimental particle physics and to teach me the basic skills one needs to pursue a career in this field. I am very grateful for Riccardo Salvatico's patience and thoughtfulness throughout this whole process. In the following subsections, I will outline the phases I took to evaluate and compare DeepTau to ParticleNet and see if ParticleNet is a viable candidate to replace DeepTau.

i. Project Background

See Figure 5 to see the structure of information we are working with. First, the Monte Carlo simulation data is put in the input file. Then, the trigger algorithm of choice (DeepTau or ParticleNet) is run over the simulated data. An output is created that contains the same initial simulated events, plus information on the relevant trigger algorithm decision. Next, another piece of software henceforth called "analyzer" is run over the trigger output data files in order to gather information on:

- the kinematics of the simulated particles (most notably, the pions from the W boson decay);

- the efficiency for events to fulfill the trigger decision based on the aforementioned particle characteristics.

For DeepTau, the specific trigger used was HLT_DoubleMediumDeepTauPFTauHPS30_L2NN_eta2p1_OneProng_v* and for ParticleNet, the trigger used was HLT_DoublePNetTauhPFJet30_Medium_L2NN_eta2p3_v*. These trigger labels mean that they are High-Level Triggers, they are searching for two Tau's, they have a lower limit transverse momentum threshold of 30 GeV, they are looking within the 2.1 and 2.3 eta range respectively, and the restrictions are graded a level medium restriction (aside from a loose and tight restriction). To gain an understanding of the simulated data we are working with, we made a transverse momentum distribution of the hardest and next-hardest generated pions {See Figure 6}. Given a 30 GeV lower limit of the triggers we used, most of the hardest pions are included in this analysis, and a good portion of the next-to-hardest pions are not included.

ii. Phase 1

For phase one, I learned how to calculate the efficiency of a trigger using the trigger output data. I ran the trigger over the data the Monte Carlo simulation provided. Since the efficiency is the probability of the trigger successfully catching desired events, I simply divided the number of passed events, or events that made it through all of the trigger algorithm's filters, over the total number of events {See Figure 7}.

iii. Phase 2

Using this basic knowledge of efficiency calculations, we took trigger efficiency analysis to the next level and graphed an efficiency for DeepTau in an eta range of eta < 1.0. This process is still considering the ratio of the events that passed the trigger over the total number of events, but it is graphing the efficiency as a function of transverse momentum found in the W boson decay to three charged pions. To graph the efficiency curves, we accessed the data after they were run through the analyzer {see Figure 5} which contains the numerator values (the passed trigger events) and the denominator values (the total number of trigger events). Finally, as a function of transverse momentum, the DeepTau efficiency was plotted {See Figure 8}.

iii. Phase 3

Efficiency analysis grew to be more effective by evolving the code to graph two trigger algorithms to compare and analyze larger data sets to decrease the uncertainty values. We mapped the additional trigger algorithm, ParticleNet, onto our efficiency curves to compare it with DeepTau. Such a comparison would help us decide whether or not ParticleNet would be a sufficient replacement for DeepTau once it goes out of commission. Because the uncertainty bars were too large to obtain conclusive results, we used an external supercomputing resource called HTCondor to increase the computing power and run the trigger over 50 input files rather than one in a short amount of time. We ended up with six graphs, over different domains of eta, phi, and transverse momentum, plotting the efficiency of DeepTau compared to ParticleNet {See Figure 9}.

III. Results

After many efficiency plots, we inputted a counter in the number of events that passed the numerator restrictions (the numerator in this efficiency calculation), a counter for the denominator restrictions (as we only wanted to consider events where the W bosons decay products were within detector acceptance), and used those to calculate the overall efficiencies for DeepTau and ParticleNet. In the end, DeepTau had an overall efficiency of 3.9% and ParticleNet had an overall efficiency of 4.1%. Given how close these overall efficiencies are, ParticleNet would be a viable candidate to replace DeepTau's search for W boson into three charged pion decays.

IV. Next Steps

Given that ParticleNet was a very close comparison to DeepTau, this efficiency analysis shows promise in ParticleNet. The next step in this project would be to use offline data to compare DeepTau and ParticleNet and see if this similar comparison still stands. An additional project to explore could also be to incorporate the prong analysis feature of Hadron Plus Strips (HPS) with ParticleNet to incorporate a tau prong analysis in the online ParticleNet algorithm and potentially be able to lower the transverse momentum filter restrictions to increase the efficiency further.

V. Conclusion

i. Summary of Project

Throughout the summer, my understanding of a trigger and how detectors get the data they need evolved as I compared the two HLT algorithms DeepTau and ParticleNet. I went from understanding the basics of what a trigger efficiency is using the basic efficiency equation {Equation 1}, I turned to code to run an analyzer over the data, I learned how to read into the file, extract the numerator and denominator {of Equation 1} values and graph efficiencies in certain ranges, I learned how to compare two trigger algorithm efficiencies (within those same ranges) on the same graph, and finally how to increase the computing power with HTCondor to increase the data points and consequently reduce the uncertainties. Given that we found DeepTau and ParticleNet to have very similar overall efficiencies, it would be beneficial for future groups to evaluate DeepTau and ParticleNet's efficiencies offline to see if that brings us to the same conclusion.

ii. Reflection of CERN Experience

Working with my mentor on this project in CERN's vibrant environment has been an experience I will cherish forever. I have been exposed to so many different areas of research in the lecture series which has shown me where my interests lie, but also my ignorance. I have talked to many great physicists and gained their insights and wisdom about a career in physics and what it takes. I even had the opportunity to hang out with students around my age from 109 different countries. I have heard tales illustrated in history classes of intellectually lush countries and how they developed because of being in the cross-hairs of many different cultures, but I never realized two things: One, I could actually experience such a thing, and two, CERN alone is one of those places.

References

[1] CMS Collaboration, "Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC", CERN-EP-2020-219, CMS-EGM-17-001, 19. May, 2021. https://arxiv.org/pdf/2012.06888.

[2] CMS Collaboration, "Identification of hadronic tau lepton decays using a deep neural network", CERN-EP-2021-257, CMS-TAU-20-001, 18. July, 2022. https://arxiv.org/pdf/2201.08458.

[3] CMS Open Data Guide (N/A). "Jets". https://cms-opendata-guide.web.cern.ch/analysis/selection/objects/jets/.

[4] CMS Collaboration. (N/A). "Triggering and Data Acquisition". https://cms.cern/detector/triggering-and-data-acquisition.

[5] Foudas, C. (2008). "The CMS Level-1 Trigger at LHC and Super-LHC". https://cds.cern.ch/record/2232067/files/arXiv:0810.4133.pdf.

[6] Mazloum, B. (2023). "Triggers, Efficiencies and Scale Factors". https://cds.cern.ch/record/2871507/files/Trigger%20Efficiency%20Calculation.pdf.

Appendix

$$Efficiency = \frac{\#\ of\ Passed\ Events}{Total\ Events}$$

Equation (1): Equation used to calculate trigger efficiencies. The number of passed events is the number of events that made it through the trigger algorithm filters. The total events are the number of events that interacted with the trigger.

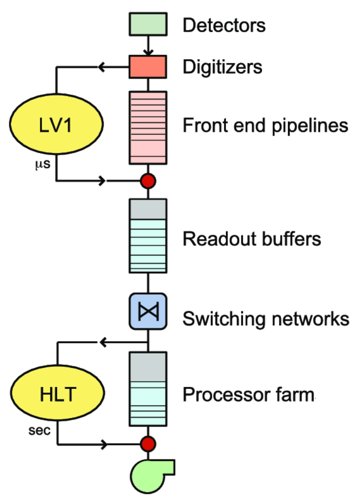

Figure (1): This figure shows the trigger layout and how the Level 1 (L1) trigger is related to the High-Level Trigger (HLT). (https://www.researchgate.net/profile/Ryszard-Romaniuk/publication/236896956/figure/fig1/AS:669073637642257@1536530994803/Schematic-view-of-the-CMS-trigger-system.png)

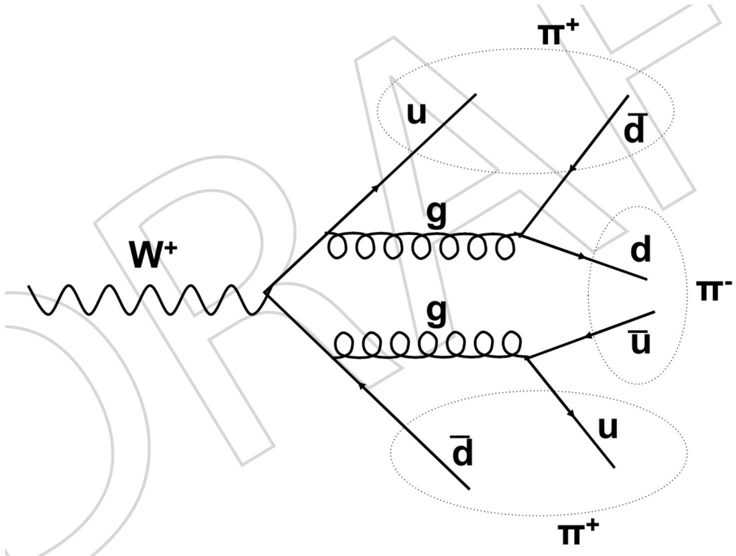

Figure (2): The W+ boson to three charge pion decay Feynman Diagram. (CMS Collaboration)

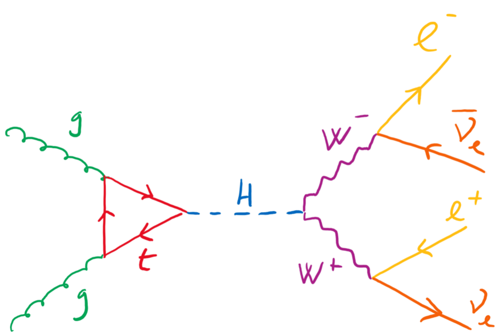

Figure (3): The W boson to lepton and neutrino decay Feynman Diagram. (https://cms.cern/sites/default/files/inline-images/Picture1.png)

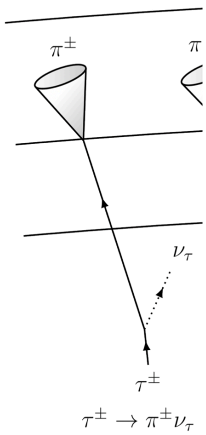

Figure (4): Hadronically decaying Tau lepton Feynman Diagram. (https://tikz.net/tau_decay/)

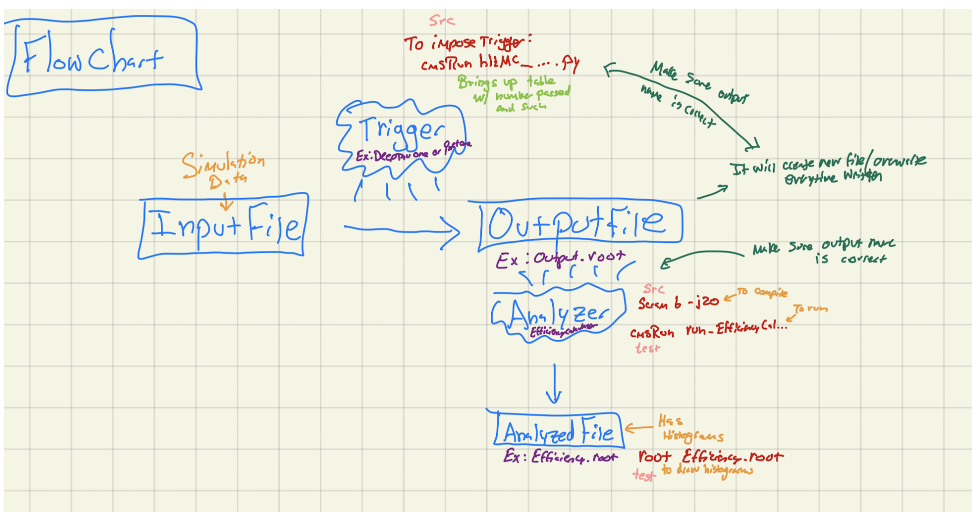

Figure (5): Flow chart that outlines the structure of the files used when carrying out this efficiency evaluation between DeepTau and ParticleNet.

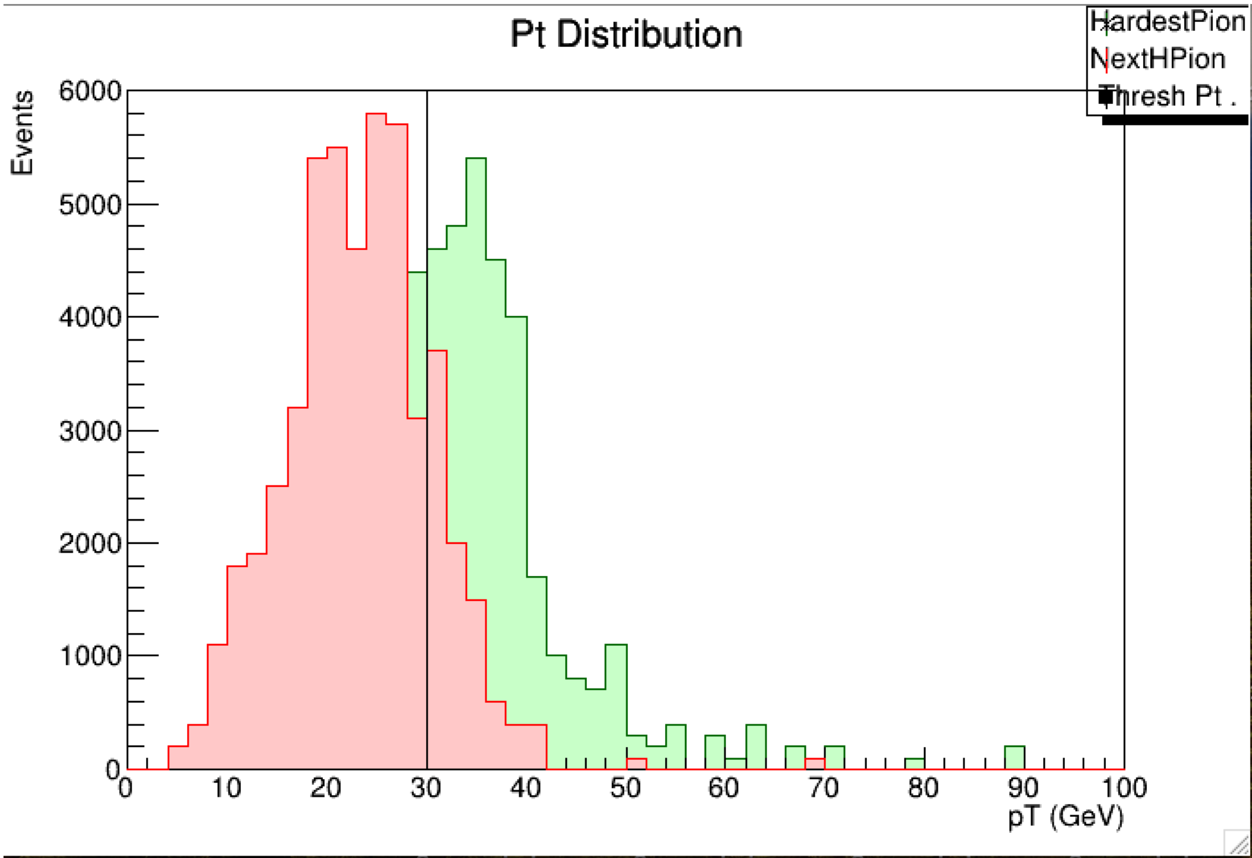

Figure (6): The transverse momentum (pt) distribution of the simulated hardest and next-hardest pions. The hardest pions are green, the next-hardest are red, and the lower limit pt threshold is 30 GeV.

```
TrigReport ---------- Modules in Path: HLT_DoubleMediumDeepTauPFTauHPS30_L2NN_eta2p1_OneProng_v6 ------------
TrigReport  Trig Bit#    Visited     Passed      Failed       Error Name
TrigReport     1    0        500        500           0           0 hltTriggerType
TrigReport     1    1        500        500           0           0 hltGtStage2Digis
TrigReport     1    2        500        500           0           0 hltGtStage2ObjectMap
TrigReport     1    3        500        500           0           0 hltOnlineMetaDataDigis
TrigReport     1    4        500        500           0           0 hltOnlineBeamSpot
TrigReport     1    5        500         33         467           0 hltL1sDoubleTauBigORWithLowMass
TrigReport     1    6         33         33           0           0 hltPreDoubleMediumDeepTauPFTauHPS30L2NNeta2p1OneProng
TrigReport     1    7         33         33           0           0 hltOnlineBeamSpotDevice
TrigReport     1    8         33         33           0           0 hltSiPixelClustersSoA
TrigReport     1    9         33         33           0           0 hltSiPixelClusters
```

```
TrigReport     1  204         29         29           0           0 hltFixedGridRhoProducerFastjetAllTau
TrigReport     1  205         29         29           0           0 hltHpsPFTauBasicDiscriminatorsForDeepTau
TrigReport     1  206         29         29           0           0 hltHpsPFTauBasicDiscriminatorsdR03ForDeepTau
TrigReport     1  207         29         29           0           0 hltHpsPFTauDeepTauProducer
TrigReport     1  208         29         29           0           0 hltPFTau1ProngHPS
TrigReport     1  209         29         29           0           0 hltHpsSelectedPFTausMediumDitauWPDeepTau30
TrigReport     1  210         29         29           0           0 hltHpsL1JetsHLTDoublePFTauMediumDitauWPDeepTauMatch30
TrigReport     1  211         29         13          16           0 hltHpsDoublePFTau30MediumDitauWPDeepTauL1HLTMatched
TrigReport     1  212         13         13           0           0 hltBoolEnd
```

Figure (7): Here is what was outputted after the trigger ran over the simulated data. This table shows the total number of visited events in the top "Visited" column and the total number of passed events in the bottom "Passed" column. The list of names on the right are the trigger filter names and there is a large gap of data between the top and bottom picture.

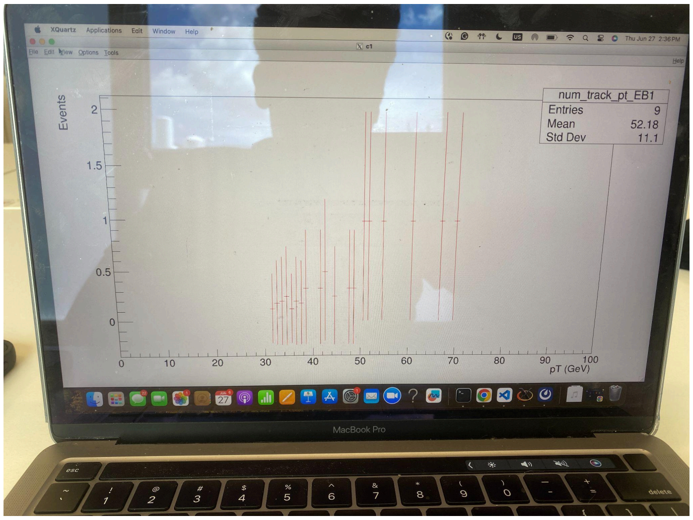

Figure (8): This picture was the first graph we made when analyzing efficiencies. It shows DeepTau's efficiency as a function of transverse momentum (pt). The y-axis should say "Efficiency".

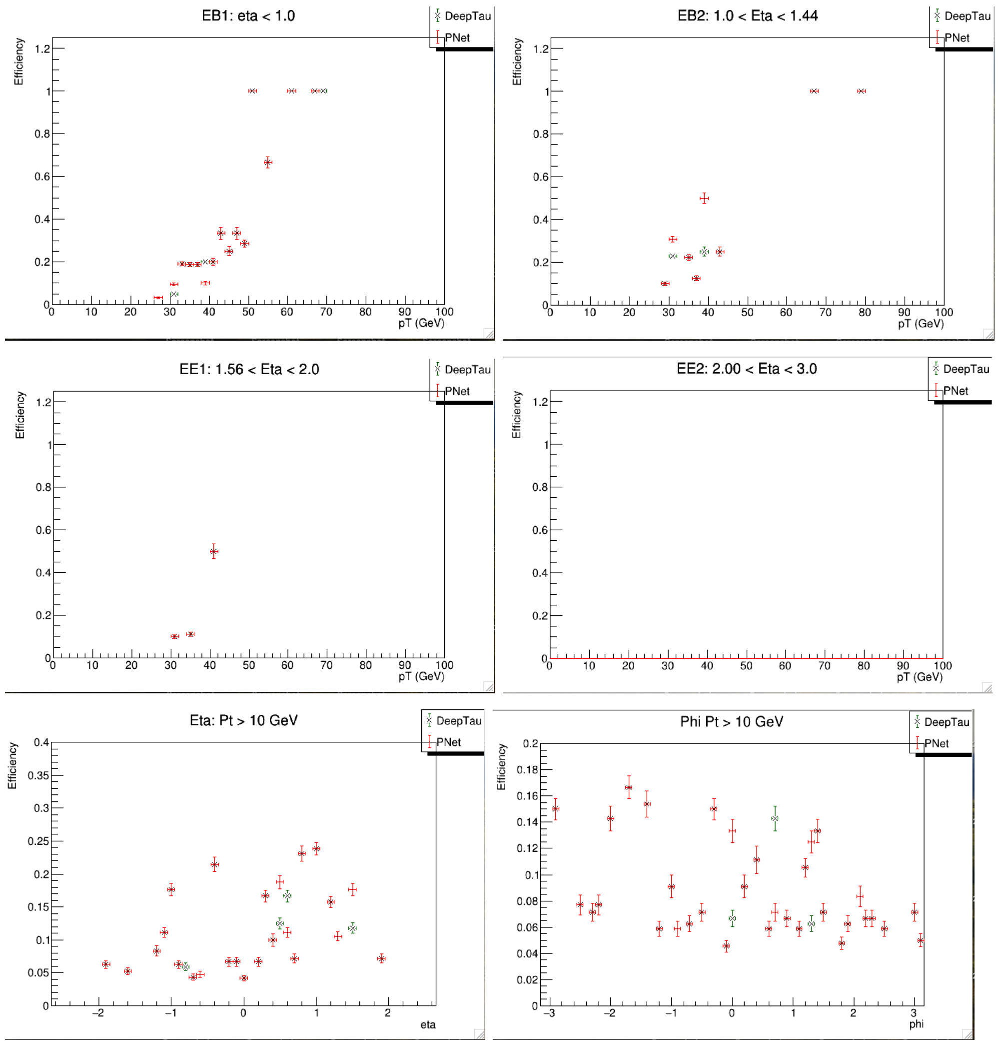

Figure (9): These plots show the efficiencies of DeepTau (green) and ParticleNet (red) as a function of transverse momentum (1-4), eta (5), and phi (6). The first four are broken up into different ranges of eta shown in the graph's title.