Graph Neural Network Triggers for Tau3Mu Decays at the HL-LHC

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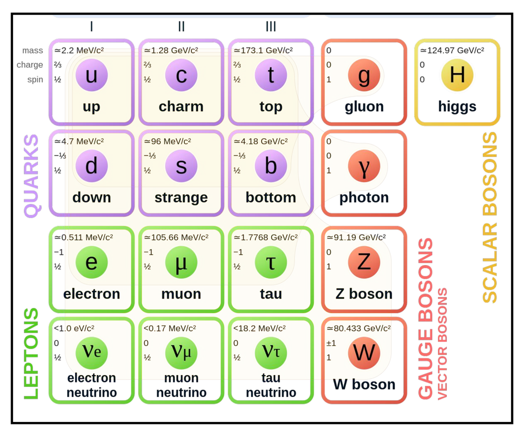
The $\tau\rightarrow3\mu$ Decay: New Physics?

Why is it Important?

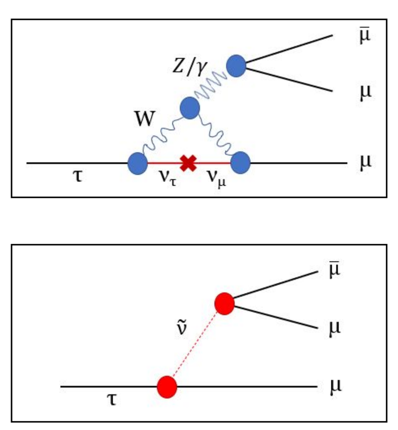
The $\tau\rightarrow3\mu$ decay is an exceedingly rare event due to its violation of charged lepton flavor conservation. Under Standard Model calculations utilizing neutrino oscillation, this decay has a branching ratio on the order of 10^{-55}. A precise measurement of its branching ratio at the HL-LHC may give evidence for new physics.



Standard Model of Particle Physics

Challenges

This decay is challenging to reconstruct in the L1-Trigger due to its collimated muons close to the beamline. The coming upgrades to the CMS detector will improve data-taking, but new strategies must be used in the trigger system for accurate and efficient reconstruction.

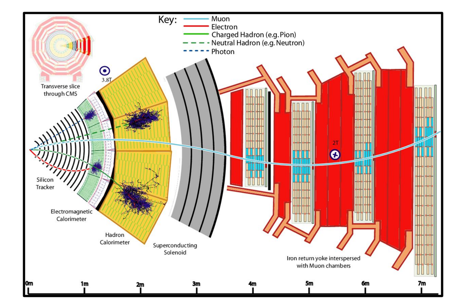


τ→3μ Feynman Diagrams

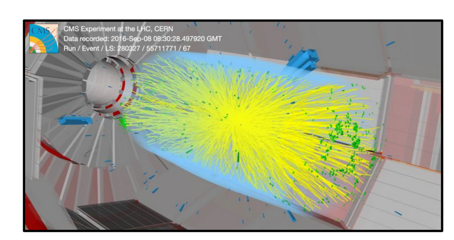
Pileup at the HL-LHC

The High Luminosity LHC

The Large Hadron Collider, located in Geneva, Switzerland, has been the primary tool with which the breaking points of physics have been studied. By 2029, it will have been upgraded to the High Luminosity LHC. With this upgrade, the integrated luminosity will be increased to a maximum of 3000 fb^{-1}, providing roughly 10x more data than the LHC. This will greatly increase its discovery potential for new physics.



Cross-sectional diagram of the CMS detector.



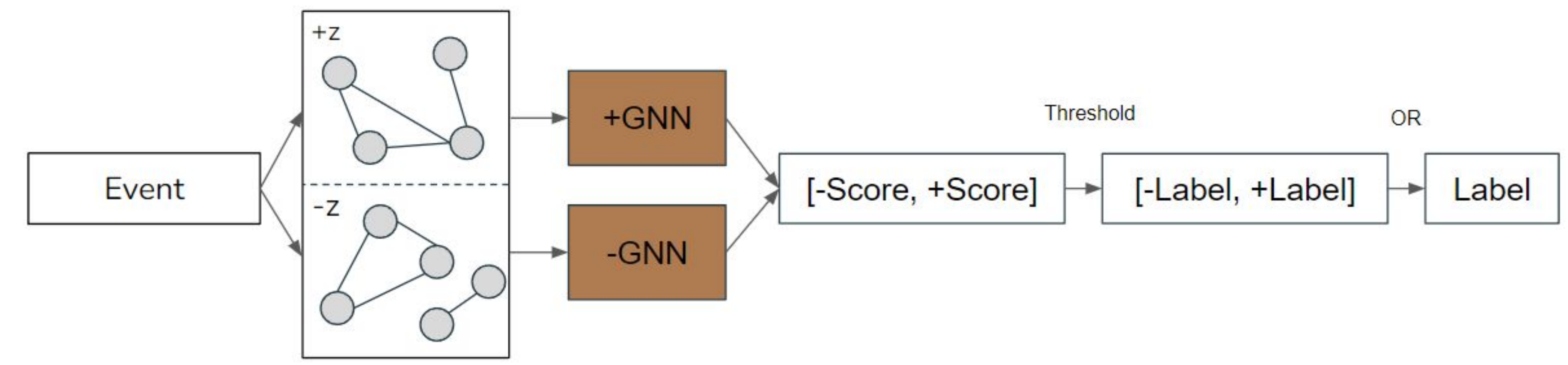
Demonstration of CMS event with high pileup.

Pileup

The tradeoff for this, however, is an increase in "pileup": the number of proton-proton collisions per bunch crossing. The upgrade is expected to increase the average pileup from 30 to 200. Sophisticated trigger methods must be implemented to properly treat this intense background.

The GNN Trigger for $\tau\rightarrow3\mu$ Decays

GNN Trigger Feedforward Diagram



2-GNN Setup

We only consider signal events with exactly one tau particle produced, which will decay into one of the two endcaps of the CMS detector. With this in mind, we train two GNNs independently: one only seeing hits in the positive endcap, one only the negative endcap. To further decrease trigger rate, a preselection is made on the number of hits in the event.

The GNN Trigger

We construct our $\tau\rightarrow3\mu$ trigger out of this 2-GNN setup. To replicate a realistic trigger scenario, each event is assigned a pair of scores from our two GNNs, as we do not know which endcap the tau decayed into if one is present. We then apply a classification threshold to both scores, obtaining a pair of labels. The logical OR operation is then applied for the event's final label. The threshold is chosen such that the rate of background acceptance meets the trigger rate requirements of the L1 trigger system.

The CMS Trigger System

The Level-1 Trigger

The CMS trigger system serves to greatly reduce the rate of data collection during runs of the LHC. The greatest reduction happens in the Level-1 Trigger, where the rate is cut from 400 MHz to 100 kHz in roughly 4μs.

The L1-Trigger is hardware-based, and its electronics will be upgraded along with the CMS detector, allowing complex algorithms, such as machine-learning methods, to be implemented on FPGAs.

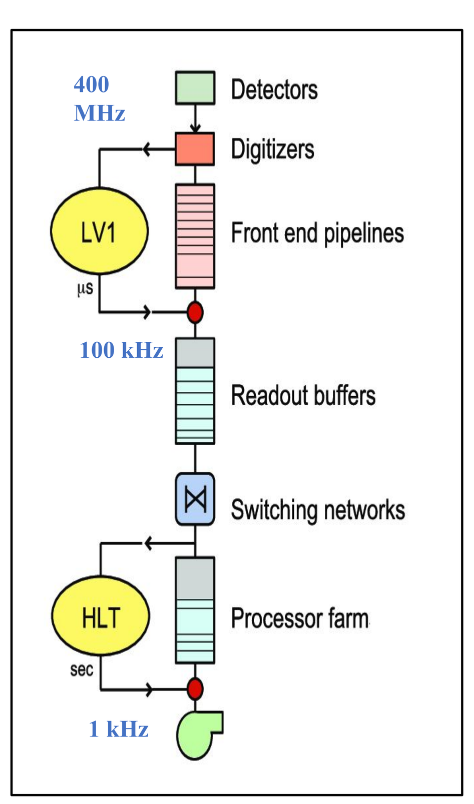


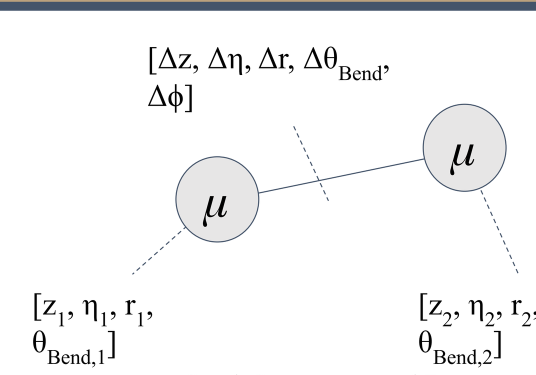
Diagram of CMS Trigger System

Graph neural network methods are being considered to make use of this upgrade as they will be able to exploit the inherently geometric nature of CMS data, capturing the positional correlations between particles.

Graph Neural Networks

GNNs

Graph neural networks are designed to perform inference on data that is structured into a graph: a set of "nodes" connected by "edges" that represent relations between nodes.



Graph Construction and Features

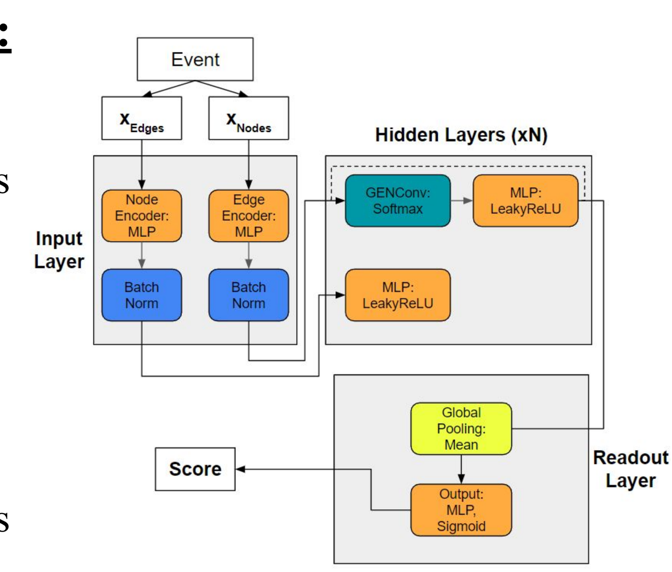
Graph Construction:

Nodes

- Muon hits
- Feature-vector encodes position and bending angle

Intra-Station Edges

- Formed if the distance between nodes in η-ϕ space is ≤ 1
- Feature-vector encodes hit differences



GNN Feedforward Diagram

Results: Projected Yield of $\tau\rightarrow3\mu$ Events at the HL-LHC

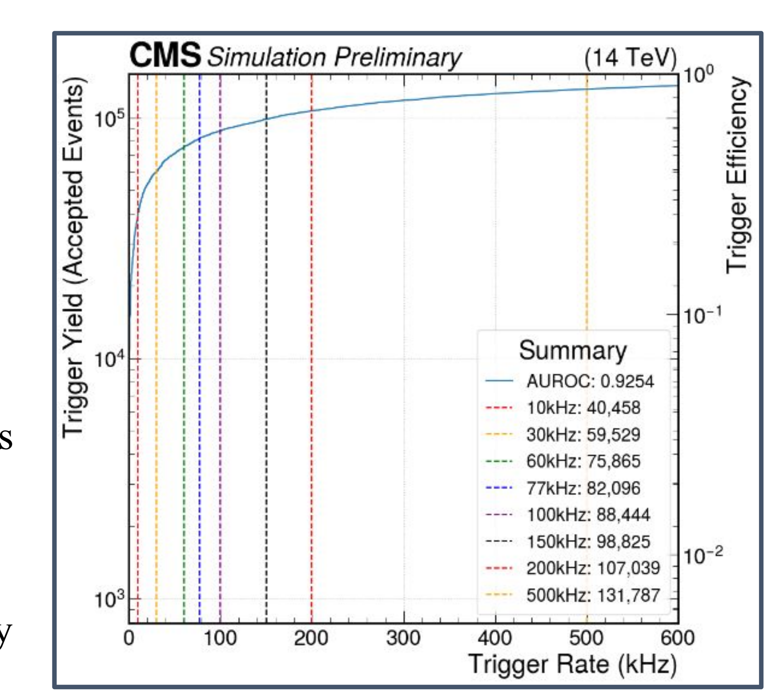
Trigger Yield

To compare this trigger's performance to currently accepted methods, we calculate the projected number of $\tau\rightarrow3\mu$ events triggered over the course of the HL-LHC's lifetime (3000 fb^{-1}), assuming current best limits on the $\tau\rightarrow3\mu$ branching ratio $B_{\tau\rightarrow3\mu}$~2.1*10^{-8} [Belle].

Improvement over Current Methods

We then compare our results to the yield reported in the CMS L1-Trigger Technical Design Report (TDR) at the same trigger rate (77 kHz). The TDR projection was made in a more restrictive phase space, so a separate GNN trigger was trained and evaluated in this phase space for a fair comparison and denoted "GNN (TDR)".

We find that the GNN trigger method with multiplicity preselections will be able to accept far more events than the currently accepted method, improving the statistics by nearly a factor of 5.



GNN Trigger Yield vs Trigger Rate

Trigger	Yield
TDR	15,890
GNN (TDR)	53,213
GNN	**82,096**

Table of Trigger Performances