Precision Timing in High Pile-Up and Time-Based Vertex Reconstruction

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Abstract

For the High Luminosity upgrade of the Large Hadron Collider (HL-LHC), the Compact Muon Solenoid Experiment (CMS) is currently studying various upgrade options (CMS Phase II Upgrade). HL-LHC involves raising the rate of collisions (luminosity) by a factor of 10 beyond the LHC's original design value, posing the challenge of an increased rate of collisions per bunch-crossing (pile-up). In high pile-up conditions, it is difficult to assign final state particles to individual collisions, and complicated to separate jets. Studies have been conducted on the use of time of flight measurements in the electromagnetic calorimeter (ECAL) of CMS in regards to time cleaning of pile-up jets and vertexing through triangulation of rechits. This project verifies a few applications of ECAL timing within the recently updated timing portion of the CMSSW framework.

1 Introduction

In order to discover new physics, CERN has scheduled the Compact Muon Solenoid Experiment (CMS) Phase II upgrade for the High Luminosity Large Hadron Collider (HL-LHC). The HL-LHC is CERN's planned upgrade to the current LHC. The high luminosity upgrade will maintain scientific progress and ensure that the LHC is being used to the maximum of its capacity. This upgrade involves raising the rate of collisions by a factor of 10 beyond the original design value, which is an involved task given how complex and optimized the LHC is.

One challenge brought about by the increased collision rate is the increase in pile-up, which is the term used to describe collisions that happen very near each other in time. In high pile-up detections, it is difficult to associate final state particle detections with the collisions they originated from. The increase in pile-up calls for improved detectors and algorithms in order to interpret the collected data.

The focus of this project is to verify some of the applications of precision timing in the ECAL. Specifically, I investigated the application of simulated CMSSW ECAL time information to the identification of forward jets in Vector Boson Fusion (VBF) Higgs production, and to time-based vertex reconstruction (tVertexing).

Furthermore, these studies use the current CMSSW ECAL detailed time framework. At the moment, ECAL timing in CMSSW is handled by a stand-in (placeholder) virtual detector located 7 cm deep within each ECAL crystal. The detector is not an actual geometry added to the simulation; rather, it is simply a thin volume defined within the scintillating crystal. All shower particles passing through this volume have their times averaged with a weighting on energy. Essentially, this is a crude mock-up of a time-sensitive layer embedded in the ECAL crystals. Each rechit is assigned a time corresponding to the result of this time averaging, and further down the reconstruction process, reco objects and particle-flow candidates are then assigned a seed rechit, typically the highest-energy rechit within the particle-flow cluster, which gives the object its time.

Lastly, timing in the ECAL is inherently challenging. If we want a position resolution of 1 cm upon tVertexing, we require a time precision of about 30 ps. Conversely, considering that the dimensions of a photon's shower in the ECAL are greater than 1 cm, one has to be careful in how the photon's arrival time is measured in order to get a time precision better than 30 ps.

2 Corrected Time

Supposing one has identified the time and position of the most physically interesting collision (the primary vertex), it is possible to compute a quantity called a corrected time at the rechit level for all reconstructed objects. The corrected time is calculated for a given rechit by subtracting both the time-of-flight and the creation time of the primary vertex from the original time associated with the rechit. The time-of-flight for each rechit is computed by calculating the path length from the primary vertex to the center of the rechit's virtual timing layer, and then dividing by the speed of light. The logic behind correcting times in this way lies in the difference in what this transformation does to a rechit associated with the primary vertex and to a pile-up rechit. Consider a rechit created by a photon from the primary vertex. It is created at the primary vertex time and then travels in a straight line to the timing layer, leaving an arrival time in this detector. Upon correcting this arrival time, we see that if the photon were to not convert before encountering the timing layer, we obtain 0 for the corrected time. Of course, the photon's shower, created in the ECAL crystal, propagates slower than c as a whole (due in part to lateral shower development), and hence the speed of light assumption is not exactly valid for the last 7 cm before detection by the timing layer. This, and other imperfections in the assumptions such as a rechit's position being defined as the center of the timing layer, and the fact that charged particles have increased path length due to bending by the magnetic field, result in most rechits not correcting back to exactly 0. However, overall, we expect to see (and do see) a peak near zero due to rechits associated with the primary vertex. Now, considering a rechit associated with a pile-up vertex, we find that the correction to the primary vertex does not lead to the build up of a specific pattern. As such, the pile-up rechits simply create a diffuse background to the peak at zero (fig. 1).

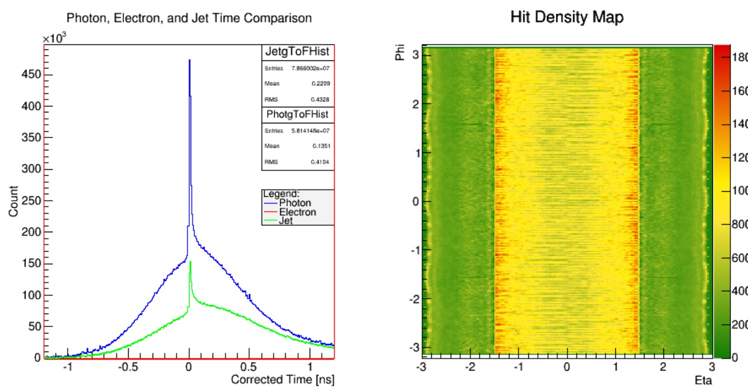

Figure 1: Corrected time at 140 pile-up.

Hypothetically, after time correction, one could select a window near zero and cut out a significant portion of the pile-up under the assumption that most of the objects due to the pile-up are located in the tails. This is one of the current studies of the CMS jetMET group, since such a method would prove useful in cleaning away pile-up jets.

3 VBF Efficiency Table

Using the corrected time, I studied Vector Boson Fusion Higgs production jet identification efficiency. If the corrected time is to be used in identifying primary-vertex jets in VBF Higgs production, we need to know how often this event passes the cuts we impose in order to separate pile-up jets from interesting ones. Also, by applying the same cuts to a VBF sample and to a gluon-fusion Higgs sample in 140 pile-up, we can see how effective timing cuts are in differentiating the two production processes. For example, suppose that the application of certain pT and dijet mass cuts produce similar efficiencies in the VBF and gluon fusion samples. If the application of time cuts decreases the efficiency in gluon fusion samples more than it decreases the efficiency in VBF samples, then the time cut is useful in better differentiating the two types of Higgs production.

The VBF efficiency table for this project is seen in fig. 2. In this table, TCT refers to the Time Cut Tight method written by the jetMET group while TPC refers to the Time Post Cut method I implemented for this project. The Time Cut Tight method supposedly eliminates particle-flow photons (PFPhotons) outside of a 0-150 ps corrected time window and then attempts to cluster jets. The Time Post Cut method waits until all objects are clustered and then cuts any reco object with a corrected time outside the 0-150 ps window. The detailed setup of this table will be included elsewhere as this document is merely a summary of the project. We may note in passing that the ratio of the VBF to GG efficiency in 140 pile-up improves in the dijet mass cuts upon application of Time Post Cut. This can be interpreted as follows: if an event passes the dijet mass cuts and TPC, it becomes more likely that it is a VBF event rather than gluon-fusion.

	Photons Reconstruct Higgs Mass	Photons Reconstruct Higgs Mass (TCT, TPC)	Jets found passing pT cuts	Jets found passing pT cuts (TCT, TPC)	Loose Jet Mass cut	Loose Jet Mass cut (TCT, TPC)	Tight Jet Mass cut	Tight Jet Mass cut (TCT, TPC)
VBF 140 PU	45.516%	44.413% 15.907%	98.826%	100.00% 70.498%	53.238%	58.577% 22.847%	31.957%	35.658% 8.577%
VBF No PU	72.773%	72.602% 69.898%	75.727%	76.159% 46.739%	50.500%	50.739% 23.102%	31.864%	31.864% 11.522%
GG 140 PU	43.409%	43.036% 15.793%	90.652%	99.814% 54.780%	23.089%	31.824% 7.403%	9.294%	13.289% 1.891%
GG No PU	71.186%	71.044% 68.357%	27.752%	28.814% 19.988%	5.936%	6.035% 3.657%	1.841%	1.890% 0.852%

*The mass cuts include the pT cut.

Figure 2: VBF Efficiency Table. In the orange columns, the first efficiency corresponds to the Time Cut Tight method while the second corresponds to the Time Post Cut method. Note that these results are preliminary and are subject to correction.

4 Time-Based Vertex Reconstruction

Another major part of my project was to show that the timing layer setup implemented in CMSSW still has the capability of time-based vertex reconstruction (tVertexing). In the past I have shown that tVertexing can be done for a VBF Higgs to gamma gamma event in no pile-up and with gen-level information about the simulation steps (fig. 3). However, this is an idealistic situation considering the lack of pile-up and the assumption of a perfect timing detector in the ECAL.

In my current project I studied tVertexing in a more realistic setting using the detailed timing implemented in CMSSW (fig 4). The averaging behavior and low granularity of the timing layers implemented in the framework are closer to a real detector, and the use of particle-flow reconstruction as opposed to referencing gen-level information also brings the simulation closer to reality. Furthermore, the event was simulated at 140 pile-up, which is what we would expect following the Phase II upgrade. Overall, the efficiency of successful vertex reconstruction goes down (around 12.5% of the events are successfully vertexed as opposed to the 95% seen in the more idealistic setup), but this is to be expected after making the simulation more realistic. There are many ways to improve the efficiency by using more sophisticated tVertexing algorithms (for example, one could account for the increased path length of converted photons whose electron-positron pairs are deflected by the magnetic field), so the tVertexing concept is definitely not limited to the observed efficiency in these preliminary studies.

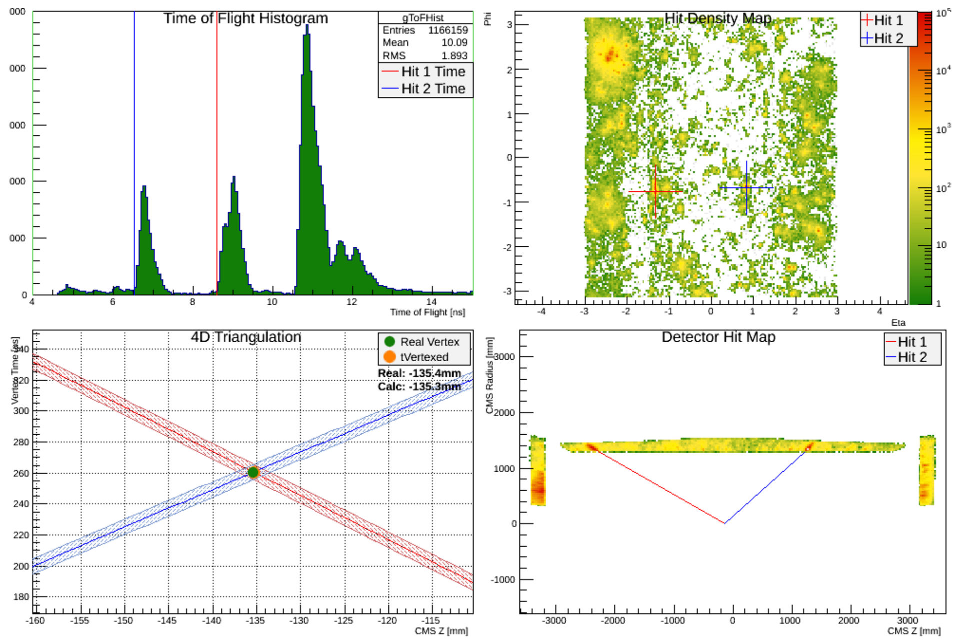

Figure 3: Idealized time-based vertex reconstruction of a pure VBF $H \to \gamma\gamma$ event using the first interaction in a shower as the arrival event definition.

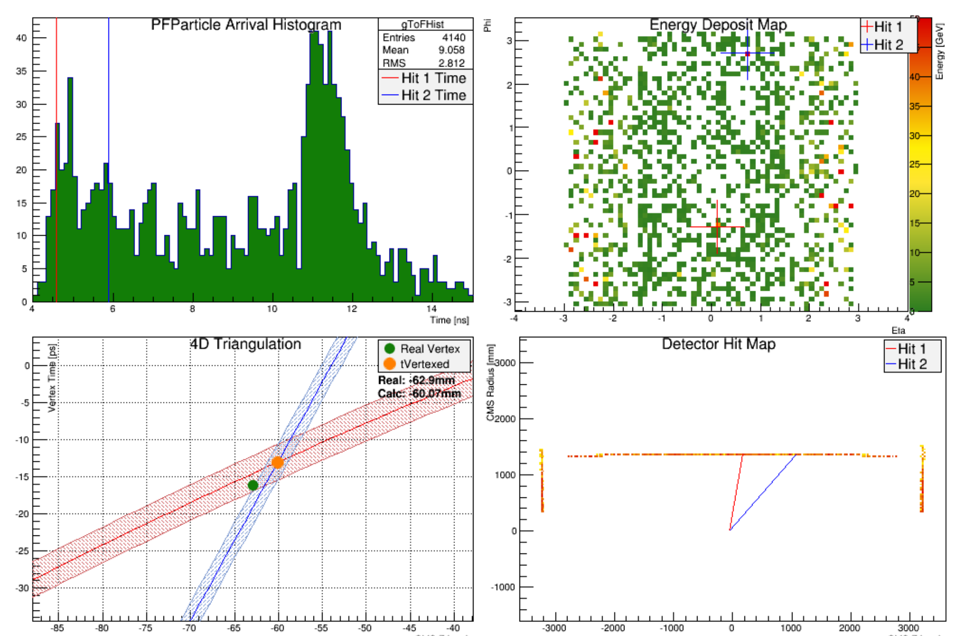

Figure 4: Time-based vertex reconstruction using the timing layer setup in CMSSW.