In-Time Pileup Mitigation at HL-LHC with Fast Timing

Introduction

When the mean number of interactions per LHC bunch crossing(mu) grows beyond that of the original design value (mu~25) to that projected for HL-LHC operation (mu~140) a significant background develops in analyses that combine physics objects from different regions of the detector.
One area of interest is processes (ie Higgs production and WW scattering) involving Vector Boson Fusion(VBF). The forward jet fragments from VBF emission are not kinematically distinct from those occuring opportunistically in minimum bias events during the same crossing.
However this background can be suppressed by proper association with the vertex of interest among the 140 or so randomly distributed (in time of occurrence and vertex position along the beam direction) within the same crossing.
CMS has significant experience in reducing these backgrounds through kinematical trimming of jets (in both Pb-Pb and pp running) and z-vertex association using the tracker (primarily in pp running).
Projecting to HL-LHC pileup conditions however there is growing concern that other tools may be needed to reach an acceptable reduction in background due to pileup.
One area receiving attention concerns precision timing of physics objects. This is a so-far unexploited tool for correct vertex association of physics objects. It has the potential to reduce both jet mis-association and vertex merging in track reconstruction.
Up to now this activity has primarily focused on time reconstruction of physics objects (photon showers and jets) in the existing or planned calorimeters of CMS assuming an ideal knowledge of the time of occurrence of event vertices to which they can be associated.{Footnote: there is also an emerging physics simulation of the timing benefits to muon objects in the endcap region-Piet Verwilligen, private communication.}As we will see, this study for the case of a silicon based sampling calorimeter (HGCAL) indicates that a time resolution for high energy photon showers (E~>100 GeV) could reach of order 30 picoseconds with proper attention to timing aspects of the Si readout. However analysis of charged hadron showers, up to now, shows that fluctuations in hadron shower development limit charged hadron objects to a time jitter of order 200 picoseconds independent of the sensor intrinsic time jitter.
Since the time spread of interactions occurring within a bunch crossing is of order 200 picoseconds or less for most bunch crossing schemes (ie 170 picoseconds for LHC design book) the charged hadron timing is an unresolved problem for pileup mitigation.
Given that studies showing performance benefit to CMS from calorimeter timing, in any case, assume ideal knowledge of the vertex time there is a strong case for a dedicated fast timing tool to time stamp both the interaction vertices and the calorimeter physics objects.

Such a system will require single MIP sensitivity and should be located before, or in an early layer, of the calorimeter due to jitter due to shower development noted above.

Calorimeter Object Timing Limitations.

This section refers to physics performance studies of the HGCAL endcap calorimeter option, which appears elsewhere in the proposal. Here we reproduce the projected performance plots with various assumptions about the intrinsic jitter due to the sensors themselves (for which, at this writing, CMS does not yet have direct measurements).

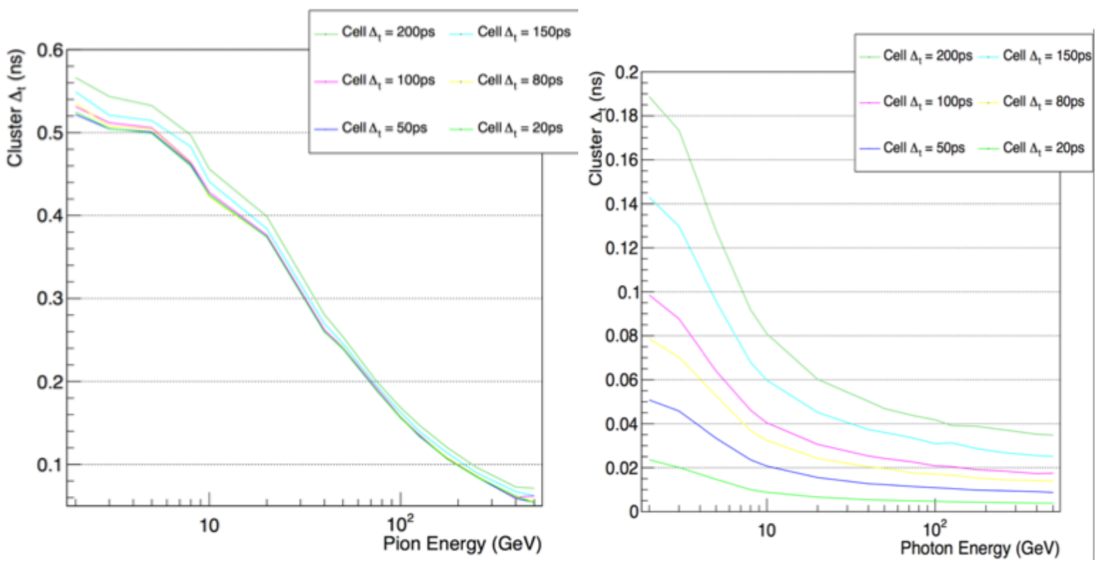

Figure Caption: HGCAL simulation of calorimeter timing of physics objects for various assumptions of intrinsic sensor (of individual Si sampling elements) timing resolution. These calculations employ a "naïve" energy-weighted average to calculate the resolution vs. energy. For reference, an existence case in a similar sensor with the same proposed electronics (NA62 Gigatracker) would correspond to the ~150 picosecond curves.

Performance Requirements for a Dedicated Fast Timing Layer

In Fig.2 we display a simulated bunch crossing with the location of event vertices in time and space during the bunch crossing. For this simulation we assume the LHC "design book" bunch crossing parameters and mu=140, as projected for HL-LHC.

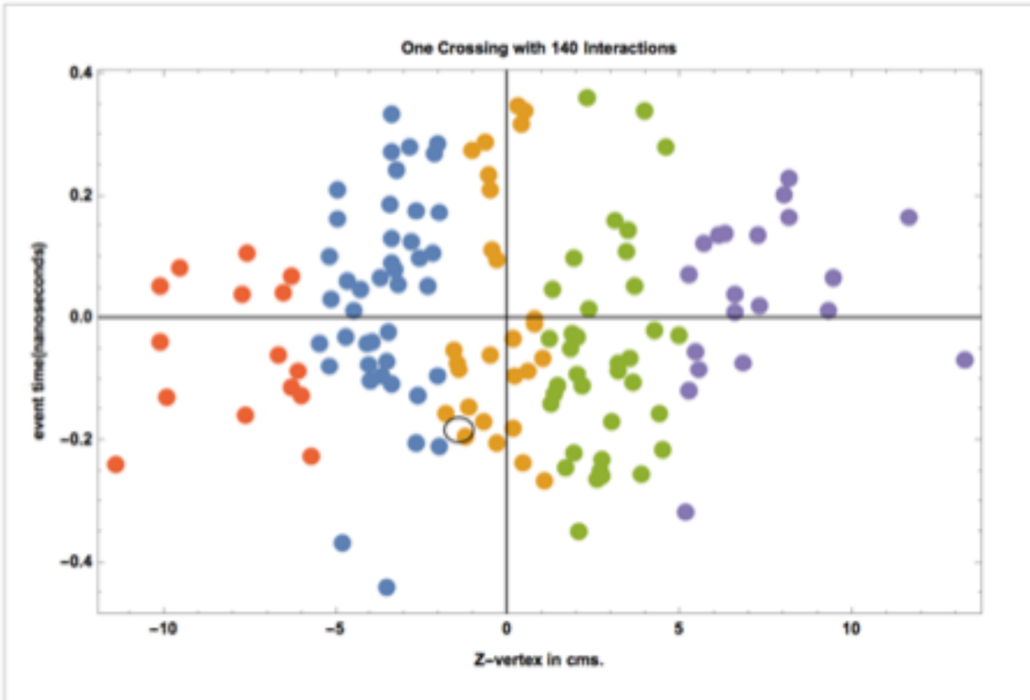

Fig. 1. Simulation of the space(z-vertex) and time distribution of interactions within a single bunch crossing in CMS at a pileup of 140 events- using LHC design book for crossing angle, emittance, etc. Typically events are distributed with an rms-in time- of 170 picoseconds, independent of vertex position.

The "error ellipse" on a vertex of interest (at z~-3mms. and t_0~-0.2, in this case) assumes a time resolution on vertices of ~15 picoseconds. It is clear that the additional "time stamp" on vertex time would reduce the potential for pileup in event reconstruction- distinguishing from other physics objects which point back to z-vertices in the -3mm part of the distribution.

What strategy is appropriate for obtaining such a time resolution?

Any track, for which there is a time stamp (derived from a MIP sensitive detector element) can be associated with the correct vertex (in time and z-vertex). Several tracks which are so tagged will then contribute to reducing the error ellipse around the vertex of interest.

For objects where tracking resolution is limited but a good time stamp is available a quality of fit (chi^2) can be calculated for the any vertex association. Early simulation studies in CMS have shown that early photon conversions, detected in a preshower layer of the calorimeter provide an excellent time stamp.