Roadmap for the Development of a Particle Flow Calorimeter for the CMS Phase 2 Upgrade.

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Introduction

The FDUWG is charged to develop a detailed roadmap for arriving at a viable solution for the forward detectors at the HL-LHC. In this document we describe the initial plans for demonstrating and qualifying the technology required for a Particle-Flow calorimeter (PFCAL) for the forward detector region of CMS.

Particle-flow calorimeters (or Imaging-, or 3D-calorimeters) are calorimeters where individual sampling layers are highly segmented and readout independently, so that a three-dimensional image of the showers inside the calorimeter can be reconstructed. The idea of using Particle-Flow calorimetry at the HL-LHC was inspired by the work that has been carried out for the ILC/CLIC detectors and is now a well developed concept, about which much is understood. There are however several specific questions unique to the application of PFCAL at a hadron collider.

We assume that the current absorber of the HE will be removed and that the ES, EE and HE will all be replaced by a PFCAL. It will be an integrated calorimeter measuring both hadronic and electromagnetic energy depositions. Though it can be built with the parameters, like the pad size or the absorber thickness, varying in depth to match the evolution of the hadronic and electromagnetic showers, for the sake of discussion we consider here a PFCAL divided into two sections, an electromagnetic and hadronic (EM and HCAL) sections with the parameters given in Table[1]. These are, however, preliminary and will change as the R&D plan is executed. The EM section will be constructed as a classical sandwich calorimeter consisting of ~ 28 layers of absorber and active media and will have a thickness of $\sim 28\ X_0$. The HCAL will be constructed with ~ 40 sampling layers for a total depth of 10 λ_I. Each layer will consist of a highly segmented detector that is readout separately. In the EM section the readout will consist of pads ranging in size 7×7 mm^2 to 10×10 mm^2, while in the hadron calorimeter the pad sizes will be larger, ranging form 10×10 mm^2 to 30×30 mm^2. To keep the number of cells to a minimum, the cells will be larger towards the back of the ECAL and HCAL. Furthermore the flexibility in placing detectors with different patterns at different layers allows for the possibility that towards the back a layer can be placed that is optimized for muon tracking, and can act as the first measurement stage of the muon system.

In the PFCAL, each pad will be readout separately with an amplifier coupled to an ADC, with a dynamic range of 9 or more bits effective. A subset of the data will be shipped off-detector at 40 MHz to form the trigger, and the complete data will be transferred off detector on a Level 1 accept. Off-detector the trigger and data signals will be processed before being sent to the DAQ.

Table 1: Assumed Properties of the PF Calorimeter for Cost Evaluation.

	EM Section	Hadronic section
Cell Size	0.5 - 1. 0 cm^2	1.0 - 10 cm^2
Number of layers	28	40
Absorber thickness	28 X_0	10 λ_I
Average detector area/layer	6.6 m^2	19.1 m^2
Total area for two endcaps	370 m^2	1450 m^2

Absorber Options

The choice of absorber is a balance between cost, neutron emission and moderation, and mechanical considerations. For small shower size an EM calorimeter of Tungsten is preferred, which costs much more than lead. For the hadron calorimeter we are currently assuming brass or non-magnetic stainless steel. For now and for our simulations we will assume a tungsten EM absorber and a steel hadronic absorber. The former on the basis of shower spreading, and the latter on the basis of neutron moderation. This selection will need to be confirmed, or changed based on Fluka calculations and detailed cost estimates.

The construction of the absorber, we assume, will be the same as the current absorber of HE, with interleaved absorber and detector volumes. In the design one layer consists of alternating radial sections of detector and absorber and in the next layer the detector and absorber are interchanged. This is repeated for the depth of the calorimeter.

Detector Options

The ILC/CLIC community has investigated several detector options for their calorimeter designs: scintillator and silicon for their EM sections, and RPCs, GEMs and Micromegas for their hadron calorimeters. In CMS at the HL-LHC the single particle crossing average rate in the highest $|\eta|$ regions of the calorimeter will be as high as 50 MHz/cm^2 at shower maximum in the EM section at the $|\eta| = 3.0$, this alone excludes the possibility of using glass RPCs, even those with the new low-resistivity glasses. Silicon would be ideal for the EM calorimeter, as it could be made very thin, but it is expensive, and not necessarily sufficiently radiation hard. For these reasons we are currently examining the use of either GEM or Micromega detectors as the active detector for both the ECAL and the HCAL sections. Both GEM and Micromega detectors have been developed principally for the detection of muons and have been shown to work in high rate environments, but have not been extensively studied for their use in EM calorimeters. However, for the part of the calorimeter that is directly behind the tracker, or at shower maximum at the very highest values of $|\eta|$, silicon could be the best option.

Micromegas consist of a charge collection region separated from an amplification region by a fine mesh. The amplification region is $\sim$ 50 μm thick and on the opposite side there is a resistive material coating a PCB that is the anode. Charge is collected on pads of the PCB and sent to an amplifier stage mounted on the detector. The gas gain inside the amplification region is $10^3 - 10^4$ and the spatial extent of the electron/ion avalanches is $\sim 15 \mu m RMS$. For Micromegas the detector development and the transfer of the manufacturing technology to industry is well advanced since approximately 1000 m^2 of Micromega detectors will be installed in the ATLAS forward muon

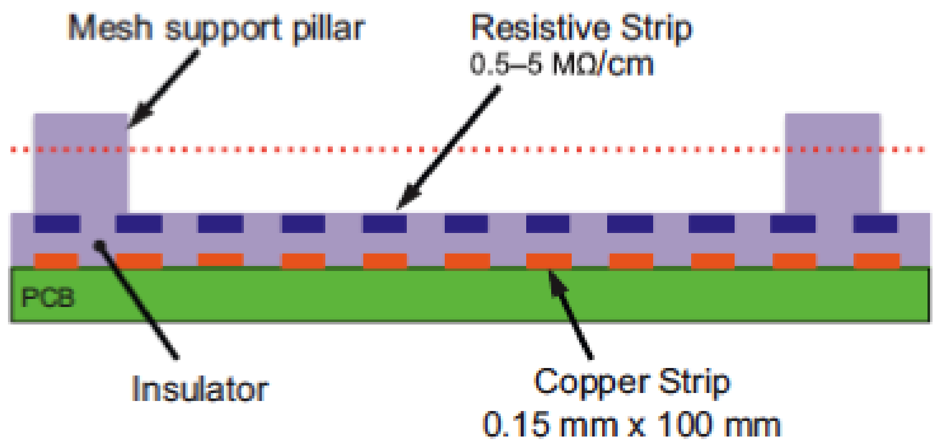

Figure 1: Schematic of a Micromega to be installed in the ATLAS detector. For the application in the upgraded CMS calorimeter instead of the copper strips to detect the charge pads would be used in their place [1].

system in LS2. They are currently undergoing many tests to ensure their continued operation in Phase 2 operations of ATLAS. A schematic of a Micromega is shown in Figure[1]. Full details of the state-of-the-art for Micromegas can be found in the talks given at the FDUWG meeting https://indico.cern.ch/conferenceDisplay.py?confId=258598.

GEM detectors will be installed in CMS during LS2 [2]. A discussion of the current state-of-the-art was given in a FDUWG meeting (https://indico.cern.ch/conferenceDisplay.py?confId=243197.) They operate with three layers of copper-coated kapton perforated with closely-spaced small holes. Across each layer a potential is set up, and gas amplification is achieved as the charges pass through the pores. Each foil operates with a gain of 10 - 20 and the system provides an overall multiplication of $10^3 - 10^4$. These devices have been studied extensively by the RD51 collaboration, and the transfer of the technology to industry has started.

Tracker

A calorimeter built for particle flow does not work alone; it must work with a tracker upstream. It is currently envisaged to add pixel disks to the tracker and to extend the outer layer disks of the strip detector, so that tracker coverage will reach to $|\eta|$ of 4.0. The parameters of this extended tracker have been estimated to be those given in Table[2].

Table 2: Performance of the extended tracker in the high $|\eta|$ regions.

	$\eta = 3.0$	$\eta = 3.0$	$\eta = 3.5$	$\eta = 3.5$	$\eta = 4.0$	$\eta = 4.0$
p (GeV)	10	100	17	170	25	250
$\delta(z0)(mm)$	1.5	0.3	2.0	0.4	4	1.5
$\delta(p)/p$	4%	5%	4%	10%	9%	50%
$\delta(d0)$ (μm)	150	40	150	500	250	150

Research Programme

The major uncertainties with the PFCAL approach that need to be investigated are:

1. The linearity of the gas detectors for the EM section: The number of ionizing particles in a cell at shower maximum of a 50 GeV shower can exceed 200. It has to be demonstrated that a linear response can be obtained from either of the detector options.

2. The operation of the detector in an extremely high rate environment: The rate capabilities of both GEM and Micromega detectors are reported as being capable of operating up to rates of 100 MHz/cm^2. This figure is determined from measurements and is consistent with an estimate based on the charge collection times in the gas amplification stages. However in a calorimeter the rate is not continuous and has large fluctuations as shower are produced in the calorimeter.

3. Heavily ionizing particles: In the CDF gas proportional calorimeter there were a significant number of triggers caused by the heavily ionizing particles in the gas. It needs to be demonstrated in a beam that with this geometry and gas, the effect is either not present or insignificant. The stable operation of both detector technologies under these conditions needs to be demonstrated.

4. The reconstruction of events: Demonstrating that in the HL-LHC environment that a PFCAL can be used to disentangle complex events with a large background is required. The ILC/CLIC community has developed a framework for event reconstruction, Pandora [3], which is now adopted by the ILD, SiD and CLIC communities. This framework needs to be adapted to the LHC environment so that we can investigate the detector's performance with events under HL-LHC conditions.

5. Triggering: It needs to be demonstrated that triggering with a high granularity gas calorimeter at 40 MHz is feasible.

6. Performance and Cost: PFCAL is a highly flexible system. It is possible to have a varying level of granularity throughout the detector. What the optimum configuration that has neither too little, nor too much granularity at every depth, needs to be determined.

Currently work has begun on the estimation of performance and costs, with detailed simulations studies just beginning. The plan for fully investigating this idea is given below and the groups that have expressed interested in participating in them.

Current knowledge

There has been significant work in the development of particle flow calorimetry and the reconstruction of events by the CALICE collaboration. While CALICE has not investigated in detail the performance of GEMs or Micromegas for EM calorimetry, much is nevertheless known about their performance.

The properties of GEM detectors, including tests of their radiation tolerance and lifetime is discussed in reference [4]. One result, already mentioned, discussed in this paper is that the maximum charged particle density is 100 MHz/cm^2. Resistive-anode Micromegas detectors have been studied under several types of irradiations (X-rays, cold neutrons, 60 Co gammas) up to an equivalent HL-LHC time of more than five years in ATLAS Muon System without showing any degradation of the performances in terms of gain and energy resolution [5] and similar results have been obtained with GEM detectors.

The dynamical range of a Micromega detector is given by the spark limit which is about 10^8 electrons. Assuming a multiplication factor of 10^3 and the most probable number of 15 primary electrons from a MIPs (i.e. 350 eV in Ar-based mixtures), the spark limit translates into a dynamic range of up to 5×10^3 MIPs, This is sufficient for measuring EM or hadron showers up to about 1 TeV. It should be noted that the dynamical range is defined by the multiplication factor of the Micromegas.

In Fig. [2] shows a GEANT4 simulation of a 50 GeV shower in an 31 X_0 EM calorimeter with 40 tungsten plates readout with Micromegas and in Fig. [3] the visible energy as a function of depth.

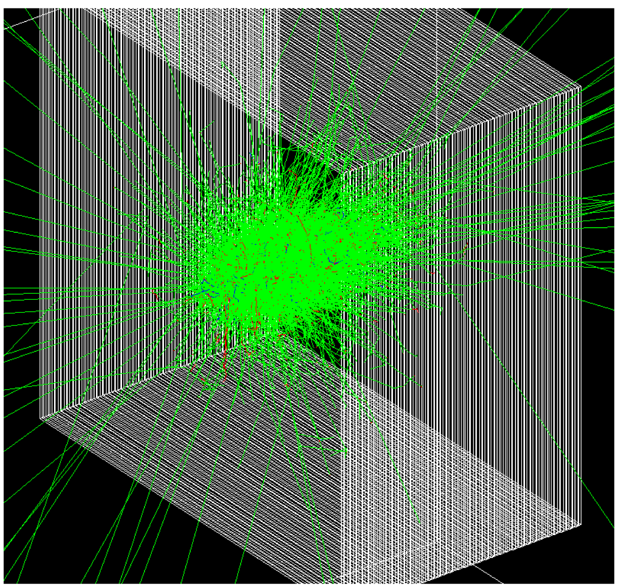

Figure 2: A 50 GeV electron showering in a Ar/W ECAL (Geant4, 40 layers, 31 X_0).

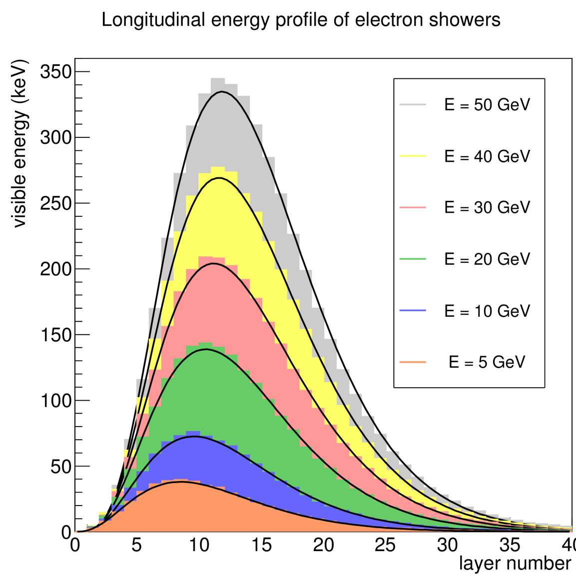

Figure 3: Geant4 simulation of the longitudinal profile of electron showers in an Ar/W ECAL.

Active Detector Development

Much work has already gone into the design and optimization of GEM and Micromega, this work needs to be extended to include the harsh environment of the HL-LHC, in particular the high radiation fields and rates that we expect.

The first step will be to make at CERN, or at some other facility, 30 × 30 cm^2 modules preferably in both types of detectors, with the current state-of-the-art construction, and to use these to build an electromagnetic calorimeter and test it in a test beam. This could be done in early 2014. The proposed parameters of the test calorimeter are given in Table[3].

The readout of the calorimeter will be the 128-channel APV25 chip, coupled to the Scalable Readout System (SRS) developed by the RD51 collaboration [6] [7] [8]. Each detector plane would have 1024 channels readout by 8 APV25s connected to SRS modules, a 30-plane detector would require 15

Table 3: Parameters of the Test EM Calorimeter

Active Area	30 cm $\times$ 30 cm
Number of Layers	10 - 30
Pad size	1 cm $\times$ 1 cm
Channel Count	10,000 - 30,000
Readout	CMS APV Chip
DAQ	5 - 15 CMS FECs $\rightarrow$ Ethernet

SRS modules. The hybrid board that is mounted on the anode board of the Micromega or GEM detectors, is shown in Fig[4] and the SRS ADC and FEC card is shown in Fig [5] from Ref [6].

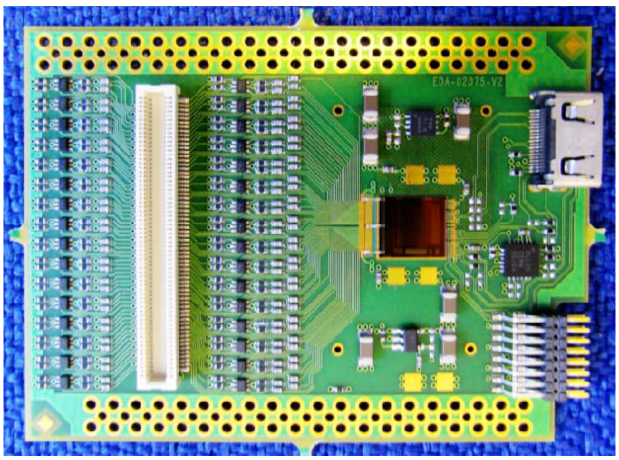

Figure 4: The SRS front-end hybrid with a bonded APV25 ASIC (from ref [6])

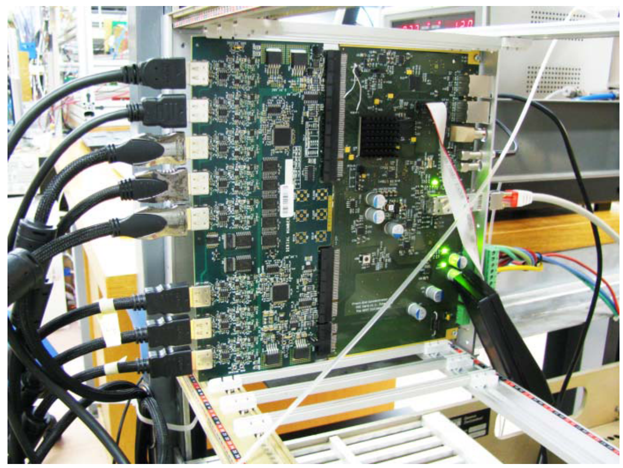

Figure 5: Photo of powered and fully connected SRS ADC adapter card (left) and FEC card (right) in a 6U chassis. (from ref [6])

This will be used to investigate the feasibility of using both Micromegas and GEMs in EM calorimetry, and to identify places where adaptions of the detector technologies are required. This test is the only beam test that can be realistically completed before the Technical Proposal is submitted in the autumn of 2014. In this test we will measure the resolution, linearity and uniformity and the reconstruction of complex events.

In mid-2014 we will start the construction of a large-scale calorimeter with both a ECAL and an HCAL. It will consist of a 1 m^2 calorimeter with the full 10 λ_I. This device will be tested with hadrons in a high-rate beam, most likely the CERN H2 beam line, where large fluxes of high-energy hadrons are available. The purpose of this test is to demonstrate the high rate capability of the calorimeter, to measure hadrons in a high flux environment, and to qualify the GEANT simulations This test should be able to begin when the SPS resumes operation late 2014 or early 2015.

In parallel to this step, we will perform tests of a different prototype system with both HCAL and ECAL modules in a high intensity hadron beam. This will be used to examine the device performance and its triggering capabilities. Data collected at these two test beam efforts and extensive simulations will provide much of the supporting material for the Technical Design Report is written and will therefore need to be completed by 2016. Once these tests are complete an optimized full-scale prototype will need to be constructed in the final configuration for the CMS upgrade.

Other tests of detector design and construction will need to be performed. We envision that these tests will become part of the ongoing GEM and Micromega studies. These stand-alone studies include, among others, chemical compatibility of materials in high radiation environments, the effect of neutrons, gammas and alphas on their long-term performance, and the total integrated charge. To date these tests have been designed for the applications currently foreseen, and will need to be extended to cover the ranges that we expect at the HL-LHC.

One critical technical question is calibration. The average number of pads that will contribute to an 50 GeV electron shower can be estimated as roughly 100, this implies that the required inter-calibration between cells should be on the order of 5% to achieve a constant term of $< 1\%$ ($\frac{\sigma}{\sqrt{N}}$). A method to determine this inter-calibration in a gas calorimeter was developed by the DELPHI and the ALEPH collaborations [9]. It consists of injecting the short-lived isotope of Krypton, ^{84m}Kr, into the detector gas, that is produced by a ^{83}Rb source. The ^{84m}Kr emits, with a half-life of 1.86 hours, a low energy gamma, which is captured releasing a mono-energetic electron. We plan to test this method for GEM and Micromegas before the submission of the Technical Proposal.

Another critical question is the generation of ions in the gas in hadronic showers that propagate a long distance in the calorimeter giving a disproportionately large signal. These can have two very serious negative effects on the calorimeter. The first is that whenever the total charge in the avalanche exceeds a value of 10^8 electronion pairs (the Raether limit), an enhancement of the electric field in front of and behind the primary avalanche induces a fast growth of a filament-like streamer that can damage the readout ASIC.. This effect has been observed in early versions of Micromegas and has been eliminated by placing a resistive coating on the anode's surface which quenches the plasmas. The effect of this resistive coating on the range of linearity needs to be determined. For GEMs this effect is less significant as all the amplification takes place inside the pores. The second effect is that the ions propagate a long way in a low-field region giving very large pulses in the detector that can produce false triggers. This effect was observed in the CDF gas proportional tube calorimeter, and is known as 'Texas Towers.' In CDF they used a hydrogenous gas and rectangular proportional tubes, whose cathode signal was summed together in depth to form towers. In both GEMs and Micromegas there are no low field regions, the gas is Argon-CO_2 and the layers are readout separately for the trigger, and outliers can be ignored. Nevertheless this effect has to be searched for with a full detector in a high-intensity hadron beam and will form part of the beam tests discussed above.

Precision Timing

The reconstruction of the high-p_T objects from hard interactions will be complicated by high pile-up at the HL-LHC. One technique that could mitigate this effect is to introduce a high resolution timing detector as a special layer indie the calorimeter. This could be used to discriminate physics objects originating from the hard scattering from those originating due to PU interactions, and to remove pileup hits at the single channel level in the object reconstruction. In concert with shower tracking, this would improve object identification and energy resolution for electrons and photons. If the detector is placed after sufficient material to ensure conversion, then it could be used to identify the hard scatter vertex for neutral objects and improve the γ/π^0 separation, and to separate spatially overlapping vertices that are time-wise separated. Based on preliminary CMS simulations[10], in such conditions a device capable of $\sim$10 ps resolution can reduce the amount of PU jets in the forward region by a factor of 10 [11] and can provide significant improvement in the reconstruction of the physics object in the HL-LHC environment.

One possible approach to equip the PFCAL with fast timing would be to insert a dedicated layer, or layers of timing devices like, for example, large area MCPs (Micro-Channel Plates). The LAPPD project [12] is developing MCPs that are made by atomic-layer-deposition that will allow coverage of large areas at a fraction of the cost of commercial MCPs. A critical parameter would be the lifetime of these detectors in the HL-LHC environment: the LAPPD-MCPs have been measured to have a larger integrated current than commercial MCPs, and could possibly be developed to survive the fluxes of the HL-LHC environment. The readout of such a system, without compromising the performance of the calorimeter would, however, be a major challenge.

Simulations

A critical part of the programme are full-scale simulations and reconstruction of physics channels within the CMSSW framework. This is a major challenge for the community as this calorimeter structure is a significant deviation from our current structure, with a new geometry description required and optimization of the analysis.

To get to this stage we recently have started with two parallel steps. In one standalone GEANT4 simulations are used to investigate the reconstruction of events in the presence of background, and in the other we are making use of the CLIC/ILC detector simulations and generating events using the CMS generators. In Fig [6] a CMS event generated at 14TeV (pp $\rightarrow$ WH, W $\rightarrow$ lepton ν, H $\rightarrow$ bb) is shown reconstructed in the ILD detector. Three hundred and twenty-two particle flow objects were reconstructed, combined into 8 jets. Our plan is, once these studies have been completed, to move it to the CMSSW framework.

Triggering

To use the PFCAL in the CMS Level-1 trigger information about showers in the calorimeter has to be assembled from layers at different depths to form trigger primitives that are used in the trigger decision. The parameters of the Level-1 trigger are assumed to be that the accept rate is 1 MHz and trigger latency $\leq 10\ \mu$ sec. For both GEM or Micromegas one possible approach would be to derive a signal from each of the 128-channel readout chips, which would cover in the EM (Hadron) section a region of between 12×12 cm^2 to 16×16 cm^2 (16×16 cm^2 to 24×24 cm^2) and send 128 bits of information to an off-detector processor. This information would contain information about amplitude and location of the signal, and possibly timing. With GEM detectors there is also the possibility of electronically segmenting the third GEM foil and combining the signals form these segments to form trigger towers.

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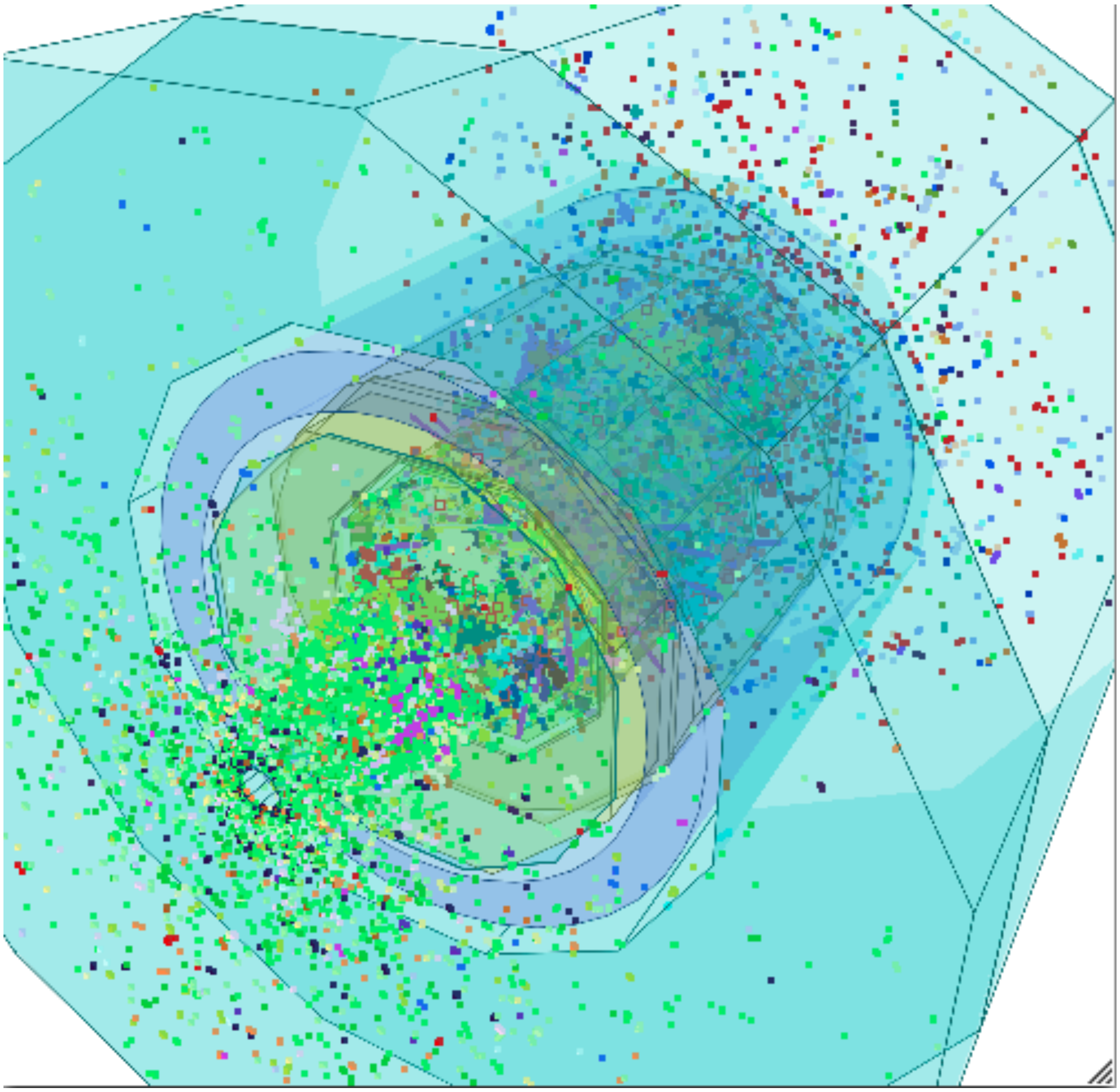

Figure 6: Event display of pp collisions simulated and reconstructed in the ILD detector. This pp→ WH at 14 TeV, W→lepton ν, H→bb event is generated using official CMS production and propagated through the CLIC/ILD framework. 322 particle flow objects reconstructed, combined into 8 jets..

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