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Detector Development and Performance: A Brief and Biased Excerpt

Vivian O'Dell[1]
Fermilab
Batavia, IL, USA
E-mail: odell@fnal.gov

This paper briefly summarizes a few of the developments described during this conference and in the following proceeding papers. As both generic and directed detector development is an extremely prolific and productive field, this paper is not exhaustive and represents the author's bias. The author notes that collaborations for general detector R&D have been extraordinarily successful in developing designs that will be used for upcoming high priority experiments and facilities.

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[1]Speaker

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1.Introduction

The report of the Particle Physics Project Prioritization Panel (P5), "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context"[1] outlines the particle physics priorities over the next decade. Figure 1 shows the timescale for the current experimental program priorities, as well as some more speculative future possibilities (marked with a ?). In order to support new discoveries at new or upgraded facilities, a robust detector research and development program is paramount. This program should be a broad mix of directed research supporting high priority facilities and more speculative R&D that could lead to transformative developments supporting future facilities.

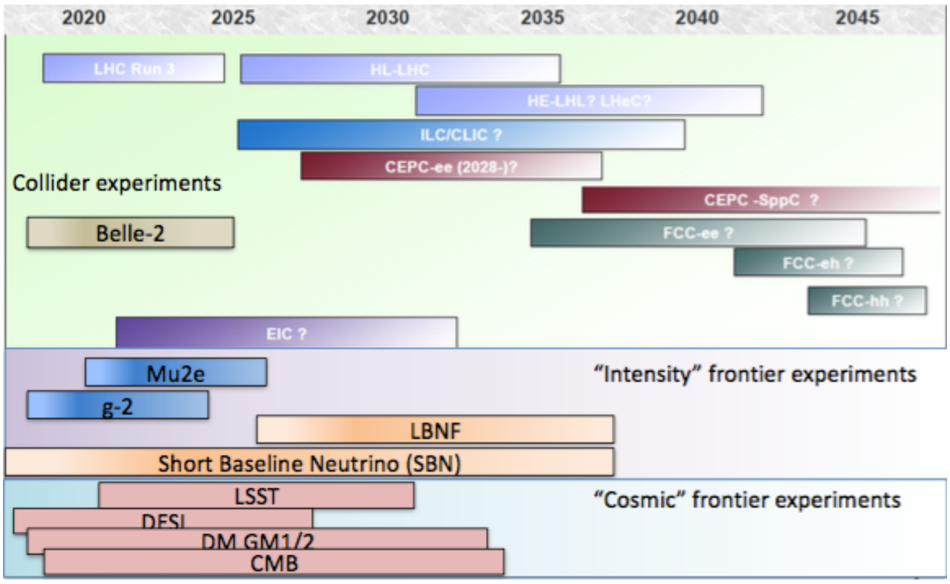

Figure 1 Time scale for future experiments

During the detector development and performance sessions in this conference, there were more than ninety talks outlining active detector developments both in directed and "blue-sky" technologies. This paper highlights some interesting developments, with an emphasis on ongoing research supporting high priority facilities, but is not exhaustive.

1.1 Detectors for Future Hadron Collider Experiments

Detectors for future hadron colliders such as the High Luminosity upgrades to the LHC and a ~100 TeV Future Circular (hadron) Collider, must be radiation hard and be able to collect and analyze high occupancy, complicated events. For example, pileup in the HL-LHC era (2026-2035) is predicted to reach about 200 collisions in each bunch crossing, stressing both real time trigger and data acquisition systems, as well as offline event reconstruction.

In order to mitigate the effects of high pileup, detectors need to be have excellent particle measurements and resolutions for electrons, photons muons, jets, missing transverse energy and bottom / top tagging, especially at high energy, to support precision Higgs measurements and discovery potential. Innovative triggers are needed at an early stage to reduce the flood of data. Detector readout must be radiation hard, with deep buffering to support a large dynamic range, high occupancies, and the latency needed to formulate complex triggers.

1.2 Considerations for Neutrino Experiments

Neutrino and Dark Matter experiments are typically background limited, and thus require high sensitivities to signal events while having the ability to reject background. Because signal rates are low, the detectors must also have large active areas. Conventional neutrino experiments using water Cherenkov or scintillator techniques are background limited, since they cannot distinguish single photons from the single electrons emitted in neutrino charged current interactions. Liquid Argon Time Projection Chambers allows higher overall detection efficiency and particle identification using *dE/dx* – basically bubble chamber quality event images, allowing for excellent resolutions and background rejection.

Liquid Xenon is another avenue being studied, specifically for Dark Matter searches, as the larger atomic number of Xe implies a much higher WIMP-nucleus cross section.

1.3 General Considerations

Precision timing information is an important development accross experiments. For LHC experiments, precision timing is key to maintaining high efficiency in busy events: being able to associate photons and jets unambiguously to a primary vertex in an event with over a hundred vertices will be challenging, and precision timing on the order of ~20-30ps reduces the problem by factors of 4 or 5, which would be equivalent to the level of pileup in the current LHC run. Precision timing for heavy flavor and neutrino experiments is important for particle identification and for rejecting cosmic ray events.

Future trigger and data acquisition systems for neutrino experiments demand excellent timing synchronization over long baselines, while hadron colliders need fast hardware trigger and online reconstruction in events with large occupancy.

Of course, overall, detectors (and their electronics) must be buildable, low cost, and maintainable.

2. Detector technologies

2.1 Silicon Detectors ([2])

Silicon detectors, in general, have been shown to be radiation hard, especially when operated in a cold environment. This observation is being exploited for HL-LHC in both major general detectors, the Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS).

2.1.1 Silicon-based tracking detectors

2.1.1.1 Silicon sensors

Silicon-based tracking detectors combine advantages of high precision, high speed, and radiation hardness. The precision implies multiple readout channels (~600 million in CMS) with associated electronics mass and power consumption. Silicon tracking detectors used in a radiation environment must be made thin and kept cold to control leakage currents and increase of bias voltage. As a result, the current generation of trackers in collider detectors constitute well over a radiation length in material.

There have been a number of recent developments that attack these problems. The large channel counts require significant power: CMS [5] expects to need 110kW to power the HL-LHC tracker. CO_2 cooling, pioneered by the LHC b-physics detector, LHCb, uses two-phase CO_2 to lower the coolant temperature to -30^0 to -50^{0}C and deliver cooling more efficiently, with lower mass then previous systems. In addition, power will be delivered more efficiently utilizing high efficiency radiation hard DC-DC conversion or serial powering technology.

Thinner detectors, integrating electronics with sensors are being developed by integrating CMOS electronic readout and radiation sensors on the same wafer in a standard (preferably high voltage) process. The first large scale use of these devices are in the Solenoid Tracker at RHIC (STAR) detector for the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory and the upgrade of A Large Ion Collider Experiment (ALICE) detector at CERN, both low luminosity Nuclear Physics applications. Development work is ongoing to improve the speed and radiation hardness of these devices to allow application to high luminosity hadron colliders. 3D detectors collect charge using electrodes etched into the detector bulk, reducing the charge collection distance and improving charge collection efficiency. Radiation hard thin planar detectors use a variety of thinning techniques borrowed from the mobile electronics industry. These thin sensors limit the collection distance at the cost of a smaller signal than the thicker 3D sensors. The 3D integration technologies from the electronics energy can replace current bump bonding hybridization techniques with much finer pitch, lower mass and thickness, and radiation hardness equal to hybrid assemblies.

For lepton colliders silicon tracker design is driven by the very low mass required to maintain vertex and momentum resolution for precision measurements such as the Higgs recoil mass. Techniques used for hadron colliders can be borrowed for this very different environment, with low data rates and small beam duty factors. CMOS sensors and 3D integrated electronics are strong candidates, providing the ability to fabricate sensors of <50 μm thickness with single crossing readout. In addition the DEPFET sensors, like those currently being built for the Belle experiment at the KEK B-factory in Japan, can provide low mass, highly integrated sensors with excellent signal/noise.

2.1.1.2 General Tracker Designs for HL-LHC

Both CMS and ATLAS will be replacing their tracking detectors for HL-LHC with detectors designed to withstand the planned CERN ten year run at high luminosities ([5] and [7]). As shown in Figure 2, the detectors are similar in design; in both cases there are inner pixel layers and outer strip layers, however the layouts are slightly different: the CMS pixel detector comprises four barrel layers and eleven forward pixel disks, and the CMS outer tracker has six layers, where the inner three are mixed pixel / strip detectors and the outer three are pure strip detectors. In contrast the ATLAS detector has five inner pixel layers and roughly sixteen pixel layers in the forward direction, and the ATLAS outer tracker comprises four layers of silicon strip detectors. Note that these layouts are still being optimized and will be finalized during 2017 with the planned Technical Design Reports from both experiments.

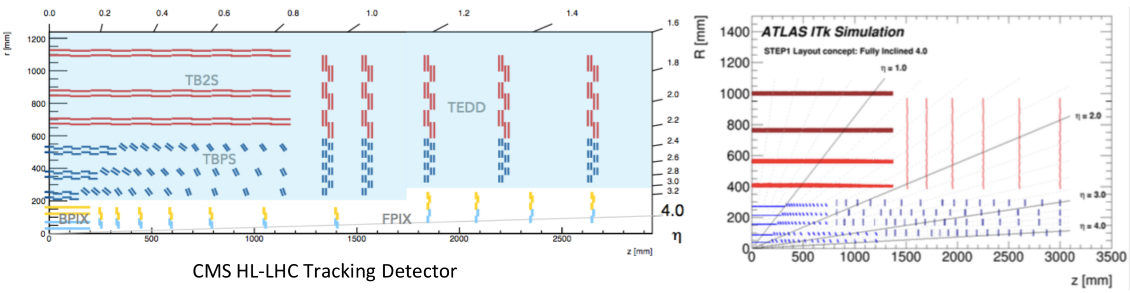

Figure 2 The current proposed HL-LHC tracking detectors for CMS (left) and ATLAS (right).

The CMS detector uses the concept of "p_T" modules, where each module of the six Outer Tracker layers is made up of either two layers of strip detectors (TB2S) or one layer of pixels and one of strips (TBPS). The layers are separated by ~ a few mm, so that tracks bending in the four Tesla magnetic field of CMS will have distinct signatures depending on their momentum, allowing for a fast rejection of low p_T tracks (< 2 GeV), and sending along high p_T track candidates (stubs) to a new Level 1 track trigger, capable of forming tracks within a few microseconds so that track finding can be integrated within the Level 1 trigger. The ATLAS detector will also incorporate tracks into their trigger: however in the ATLAS case, the track trigger will be a "level 1.5" trigger allowing more time to form the online tracks. In both cases, track finding early in the trigger stage allows for efficient triggering on leptons.

2.1.1.3 Readout chips

Pixel readout chips are under active development by RD53 ([3]). These chips are challenging due to the high interaction and data rates, especially in inner layers close to the beam line. RD53 is focussed on demonstrating radiation tolerance for 65nm CMOS, and developing circuit elements necessary for the HL-LHC pixel detectors. More than twenty circuits have been developed (such as DACs, ADCs, PLL, serializers, SEU-tolerent memory and latches, etc.), and the first demonstrator readout chip will be submitted in Spring, 2017.

2.1.2 Silicon-based calorimetry

Silicon sensors enable the fabrication of dense, radiation hard, sampling calorimeters with excellent pattern recognition capability. Sensors in the high radiation areas must have thin active regions to maintain charge collection efficiency at the highest fluence. Modules of sensors, readout chips, and data transmission must also be kept thin to maintain a small Moliere radius for the electromagnetic showers. The major challenges are cost and integration. The cost driver is the silicon sensors – the CMS High Granularity Calorimeter will require 600 m^2 of silicon. The system integration is challenging, as these very large systems must be assembled with low noise and high data bandwidth. The experiments depend on evolution of sensor technology from 6" to 8" wafers for a significant cost saving, and additional economies of scale by the manufacturers.

CALICE ([2]) has been studying silicon based calorimetry for many years. CMS, drawing on the CALICE experience, is proposing a silicon based calorimeter for HL-LHC running, replacing its current endcap calorimeter that covers the $1.5<|\eta|<3.0$ region. By using such a highly segmented "imaging" calorimeter, energy deposits from different interactions can be more easily untangled, thus alleviating pileup background in the forward direction (see Figure 3 and [5]). For sufficiently energetic clusters (~10 GeV), the time resolution is on the order of 20 ps [6]. This highly segmented calorimeter contains about 6M readout channels and presents a challenge both in readout and in triggering. Test beam results of a prototype CMS calorimeter show good agreement with simulations.

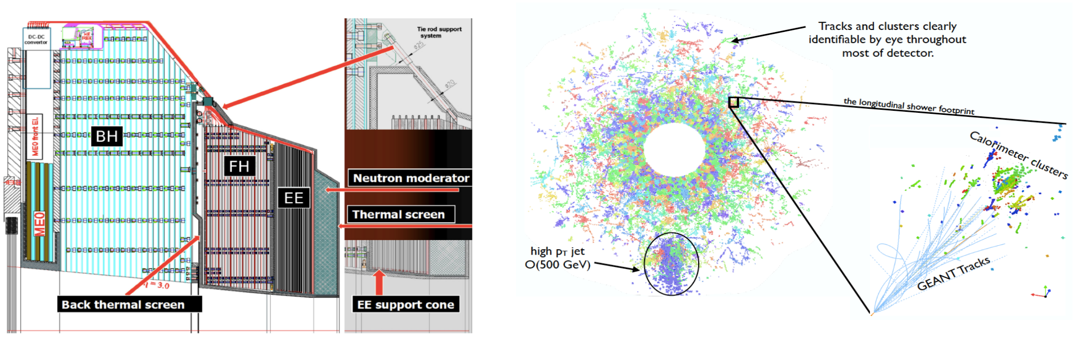

Figure 3 The CMS HL-LHC Endcap Calorimeter (left). An example of simulated event reconstruction (right).

2.2 Noble-Gas Based Detectors

As discussed above, liquid Argon and liquid Xenon afford advantages for low energy and low rate experiments. The Deep Underground Neutrino Experiment (DUNE) [8] has chosen liquid Argon for its active material. The DUNE detector will have a 40 kiloton fiducial area and be located 1.5 kilometers underground, 1300 kilometers from Fermilab in Sanford, South Dakota. Fermilab will host a 1.2 megawatt, 120 GeV neutrino beam, as well as a near detector to characterize the neutrino beam (see Figure 4).

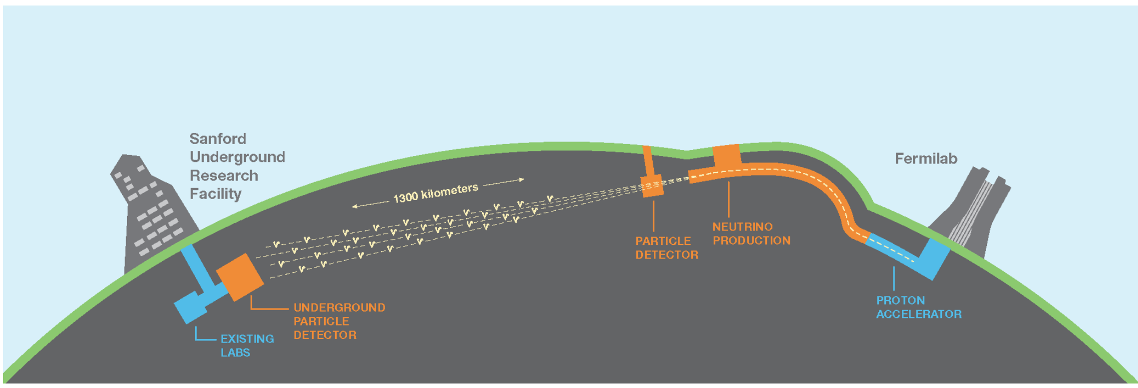

Figure 4 The DUNE experiment. Neutrino beams from Fermilab are aimed at the DUNE far detector in Sanford, ND.

Among the open design questions for DUNE, is whether to use single or dual phase liquid argon. The advantage of single phase is that the electronics would be kept cold, keeping noise levels low, however a big disadvantage is that maintenance is more difficult. For a dual phase system, the electronics and services are easier to route, and the electronics are partially cold but still accessible for maintence. Full scale engineering prototypes, protoDUNE, are being built and will be operational in 2018. ProtoDUNE will contain both single and double-phase detectors (see Figure 5).

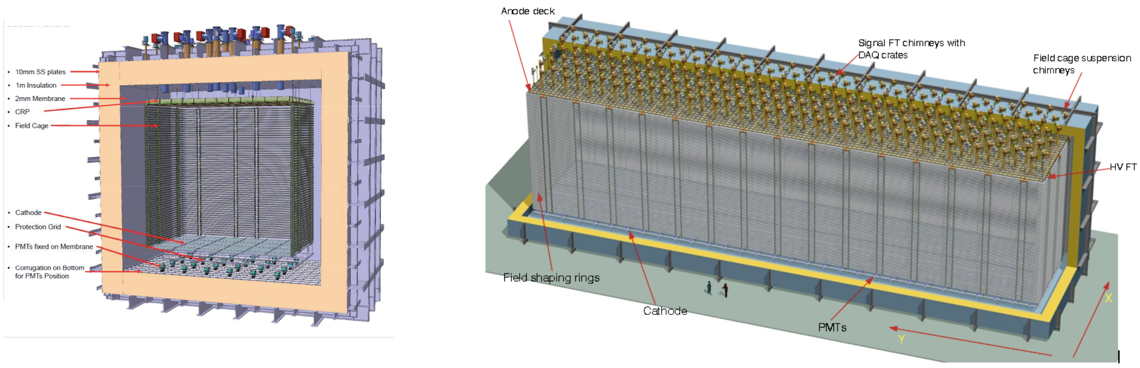

Figure 5 ProtoDUNE (right) and the DUNE detector (right).

A vigorous R&D program on liquid argon is needed in order to optimize the design for DUNE. The LArIAT (Liquid Argon In A Test Beam) [9] experiment at FNAL is currently running and analyzing data with the goal of fully characterizing a liquid argon TPC response to a known beam of charged particles in the energy range relevant for neutrino experiments. Additionally LArIAT will measure hadron-argon interaction cross sections and directly measure electron/photon discrimination capabilities. Figure 6 shows an event reconstructed in LArIAT and the first preliminary π^{-}Ar cross section.

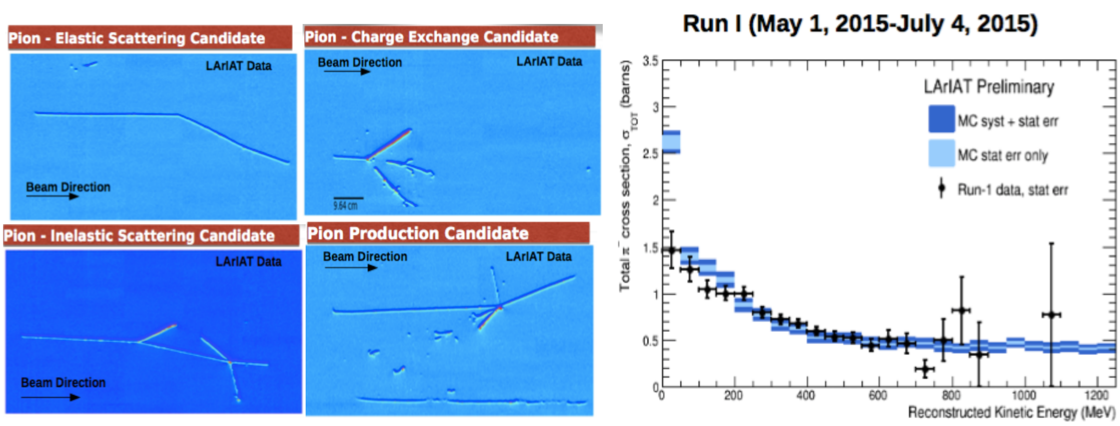

Figure 6 On the right shows reconstructed events from the first run of LAriAT. and on the right is a preliminary measurement of the total π^{-}Ar cross section.

2.3 Precision Timing detectors

Precision timing for minimum ionizing particles can play a critical role in reducing the effects of pileup in hadron collider experiments. There are several candidates for cost effective precision timing layers suitable for HL-LHC experiments. In the barrel regions, scintillating crystals with fast photosensors, such as LYSO +

Silicon Photo Multiplyers (SiPMs), have been shown in test beams to give O(10ps) resolutions for MIP signals. This technology is not suitable for the endcap regions, however, due to high occupancies and radiation levels.

Silicon timing detectors can work well in high occupancy, high radiation areas such as the endcap calorimeter region of HL-LHC experiments, however in order to be efficient for MIP signals, they must be run at high gains. Several options for silicon timing devices include silicon sensors with internal gain, using high gain Avalanche Photo Diodes (APDs), and low gain APDs. All of these options are expected to have time resolutions for MIP signals on the order of ~20-50 ps.

Micro Channel Plate timing detectors have been the subject of an active R&D program [11] in conjunction with industry to develop low cost, high surface area detectors. Small devices have been shown to have 20-30ps resolution with a 70% efficiency for MIP signals. While originally developed as a replacement for traditional PMTs in large volume neutrino experiments, they have the potential to be used in a wide range of experiments.

The Jiangmen Underground Neutrino Observatory (JUNO) [12] uses a 20 kiloton liquid scintillator detector to measure reactor anti-neutrinos, with a goal to measure the neutrino mass hierarchy to 3-4 sigma during a data run of six years. For photodetection, they have developed an elegant 20" PMT which uses at its heart an MCP module (see Figure 7).

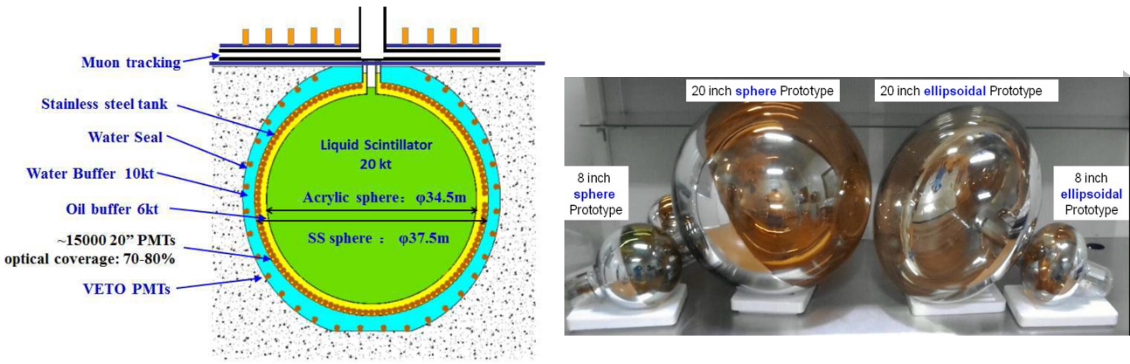

Figure 7 The JUNO detctor (left). On the right, the 20"PMTs are shown.

3. Conclusions and Outlook

The field of detector development has benefitted quite a bit from general R&D and collaborations studying particular problems. Of note are the various research and development collaborations at CERN, the CALICE collaboration which has led studies for new calorimetry methods and the LAPPD collaboration which has studied Large Area Picosecond (blah blah) detectors. These collaborations benefit from generic research and development interests and funding, and many of the ideas from these collaborations are being encorporated into detectors for upcoming high priority experiments and facilities.

As a final note, many areas of active R&D were presented at this conference, and not covered in this overview. The author urges the interested reader to read through these proceedings to get a flavor of the wide range of activities.

References

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[2] The author is indebted to R. Lipton for his help in crafting this section.

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[4] See https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome and references therein, as well as proceedings from this conference.

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