PoS PROCEEDINGS OF SCIENCE

Recent activities in HEP detector R&D

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Detector R&D for better measurement with higher precision is another key activity in and even beyond the HEP field. Thanks to the recent progresses, our measurements are about to reach the level of precision of sub-micro-meter or sub-pico-second. Besides the precisions, there happens in the position measurement the transition from "1D" to "2D" array of sensors partly due to higher luminosity/more intensity of the accelerator. The natural step coming next is "3D" where highly integrated electronics with sophisticated functions could be realized in a very compact pixel.

In the future higher energy collider experiment, energy measurement of parton is so important that the R&D for calorimetry is the hottest issue. In the other extreme, the R&D for the measurement at low energy with ultra high sensitivity /resolution is another active field where dark matter or neutrinoless double beta decay are searched for.

In these days R&D activity in HEP can not and should not be independent of the applications in the other sectors like industrial inspection, medical diagnose or security related equipments. .

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1. Introduction

In recent years, the field of detector R&D in HEP (High Energy Physics) is so active that more than 100 regular international conferences/workshops/symposia are held in the related field a year. Thus it is almost impossible to summarize this field in a short review. The newly established IUPAP conference, TIPP (Technology and Instrumentation in Particle Physics) , which was first held in Tsukaba, Japan in 2009 and will be held at 9-14 June in Chicago, US, is a good opportunity to overview the field [1].

In this article recent developments of detector technologies are reviewed in terms of Lorenz four vectors of space-time (x_μ) and momentum (p_μ).

2. Space coordinate measurement

Position measurement is a basic tool to identify the decay of long lived particles. Nuclear emulsion technique still provides the best measurement, which recently enabled the OPERA experiment to find a direct evidence of ν_τ appearance for the first time [2].

Since a real time measurement recorded on-line is essential at a high luminosity accelerator, multi wire chambers invented by George Charpak [3] have been adapted in almost all HEP experiments for more than 40 years. (It is our great loss that the genius inventor has passed away in September 2010.)

At the end of the last century, new types of structure were introduced in the chambers. They are called as MPGD (Micro Pattern Gas Detector) which have a special thin planar structure instead of wires. Among several variations introduced so far, one of the most popular is the GEM (Gaseous Electron Multiplier) foil first developed in 1996 by Fabio Sauli [4]. Fig. 1 illustrates the concept of GEM. The foil of 50μm thicnkness has millions of tiny holes (typically 70μm diameter each) with a pitch of 140μm. By applying several hundred volt between two copper layers plated on both sides of the foil, an enough intense electric field is generated inside the tiny holes to initiate electron avalance multiplication in a similar manner under the field around wires in a multi wire chamber. The most important difference is the foil is a two dimensional (2D) object while the wire is one dimensional. Under the environment of very high particle flux, this will cause a significant advantage on the detector system as demonstarated in Fig. 2. The stable performace of GEM up to very high flux can be understood as particle flux is shared by N^2 elements (holes) in a two dimensional structure in constrast with N elements (wires) in multi wire chamber.

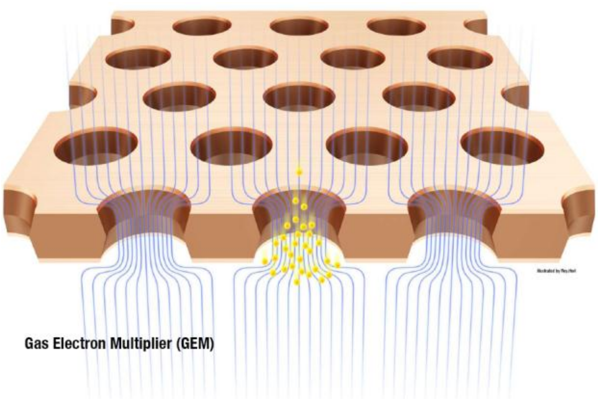

Fig. 1 Schematic illustration of GEM foil.

The movement toward 2D is also important for silicon trackers to date. Those used in the heart of the gigantic LHC detectors are silicon strip detectors (1D) and silicon pixel detectors (2D) where two dimensional array of pixel as small as 100 μm or less are aligned as shown in Fig. 3. As a trade off of the superior performance of 2D device, we have to pay a high price for it. The number of channels to be handled for the silicon trackers in the LHC experiments approaches almost 10^8. The necessary bandwidth of the data acquisition and the output data size become tremendous accordingly.

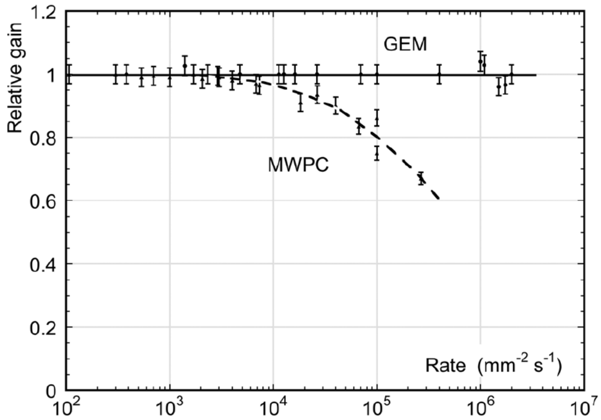

Fig. 2 Rate capability of MWPC and GEM [5].

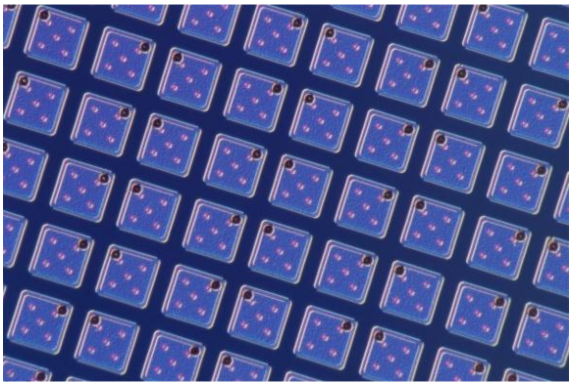

Fig. 3 Picture of typical pixel array [6].

It is interesting to compare the vertex resolutions achieved by the silicon trackers used in various collider experiments. In Fig. 4, one can find that the resolutions of the state-of-the-art LHC detectors do not always show better performances especially in a low momentum region. It is rather obvious that the LHC detectors have a significant amount of material integrated together with the sophisticated sensors, which includes complicated electronics, cables and mechanical and cooling structures and so on. Future high energy collider experiments like ILD which aim at very ambitious goal should realize very light supporting structure and service utilities. That is another aspect of the challenges for the LC experiments.[1]

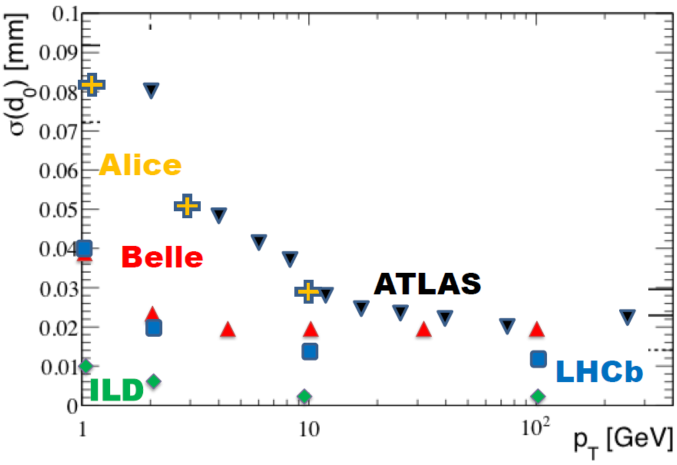

Fig. 4 Impact parameter resolution for various experiments [7].

[1] It might be instructive to recall that the SLD experiment did achieve the resolution of $\sigma = 7.8 \oplus 33/p\ \mu m$ in mid '90 by a CCD device with as little material as possible in the readout [8].

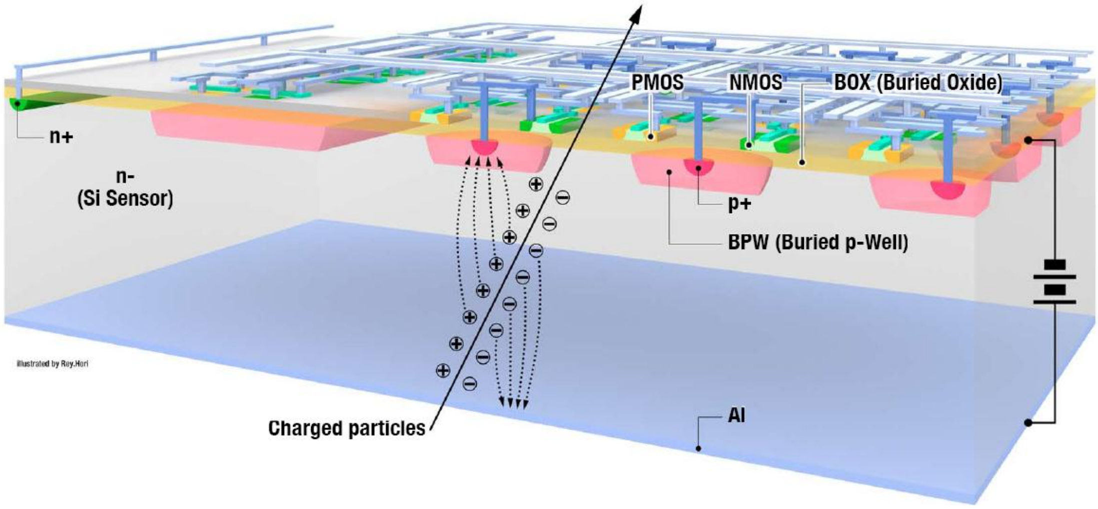

Fig. 5 Structure of SOI pixel sensor.

There are intensive research activities to develop ultra light weight detectors in the world. To minimize the thickness of the electronics, which were bump-bonded on the present LHC pixel detector as an independent chip, several types of monolithic devices are proposed and developed to integrate the electronics and sensors in a single chip. One of the promising candidates is the SOI pixel sensor [9]. SOI is an abbreviation of Silicon-On-Insulator representing an integrated circuit on an insulator layer formed above a bulk silicon substrate. If one uses the bulk silicon layer as a radiation sensor and connected to the LSI electronics (amplifier and functional circuit) formed in the thin silicon layer on the insulator, it can work as a highly functional monolithic pixel detector as illustrated in Fig. 5. The LSI layer can have a full capability of modern sub micron CMOS electronics while its thickness is far less than 1 μm. Various intelligent operation inside the LSI enables us also to reduce heavy interconnections of the detector and the data transaction.

3.Time measurement

The most demanding application of direct time measurement is a Time of Flight (ToF) system for particle identification. The best timing resolution to date in a large scale system is realized in the ALICE [2] and STAR [3] experiments. They use an MRPC (Multigap Resistive Plate Chamber) technology to achieve better than 100 psec timing resolution [10].

At the R&D stage, the best resolution is reported to be better than 10 psec for the Cherenkov

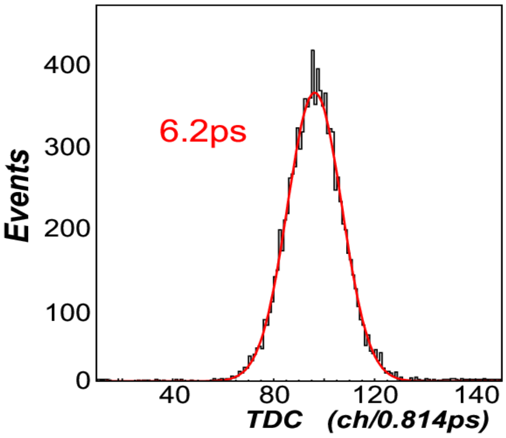

Fig. 6 Best timing resolution for a ToF measurement

[2] Heavy Ion experiment in LHC at CERN..
[3] Heavy Ion experiment in RHIC at BNL.

counter with a glass radiator viewed by a MCP (Multi Channel Plate) photo multiplier [11] as shown in Fig. 6.

4. Momentum measurement

Particle momentum is usually measured with its trajectory inside a magnetic field. The momentum resolution achieved in some of the modern collider detectors are summarized in Fig. 7. Although the resolutions of the sophisticated LHC detectors are not superior again in a low momentum region due to their relatively heavy material used in the tracking volume, they demonstrate an excellent performance in a high momentum region thanks to their large tracking volume under a strong magnetic field. The CMS solenoid generating 4T field in a cylinder of 6m diameter 12.5 m long is the strongest ever built for HEP application [13]. Thus R&D in super conducting technology, is also essential for the future high energy collider experiment to provide the satisfactory magnetic field of greater strength in a larger volume.

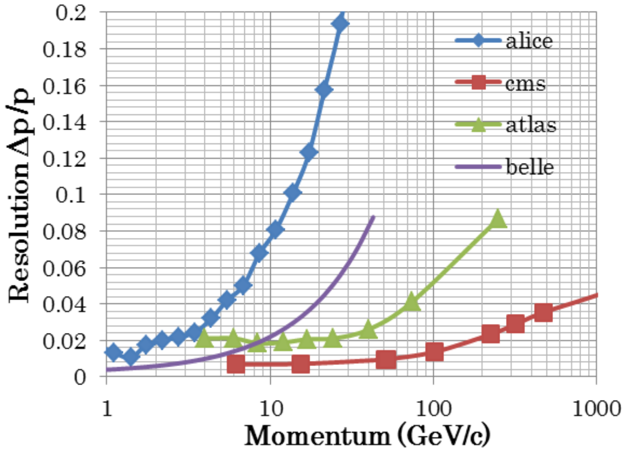

Fig. 7 Momentum resolution of various experiments [12]

5.Energy measurement

Direct measurement of particle energy is usually done by a calorimeter technique. Since the resolution of the calorimeter measurement becomes better for higher energy as an inverse of $\sqrt{E}$, it could be the most useful for the highest energy colliders. "Parton" is reconstructed in rather straightforward way as jet energy evaluated from the sum of the energies of particles inside the jet. Calorimetry is a very convenient way to sum up them easily. Nevertheless the future high energy collider experiment like ILD requires a further better measurement of the jet energy as shown in Fig. 8.

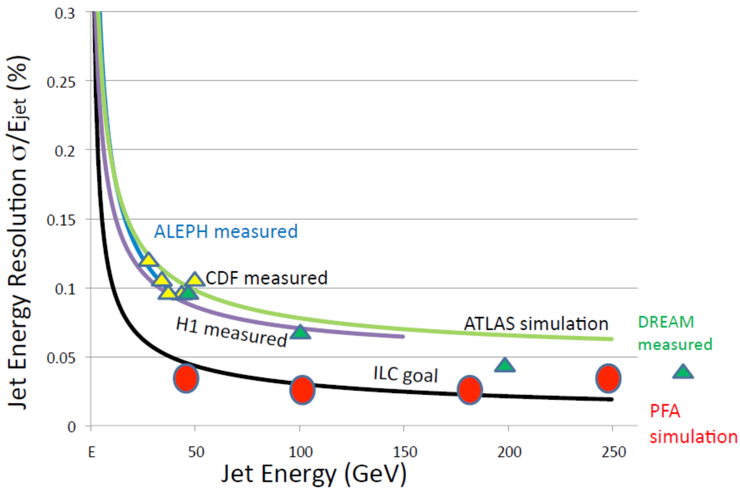

Fig. 8 Energy resolution for calorimeters of various experiments [14]

For the drastic improvement of the measurement, two schemes are proposed these days. One is the Particle Flow Algorithm (PFA) which is adapted as a guiding principle to design the ILC detectors [15]. In this scheme, the energies of charged hadrons are determined by the tracking device and the connected activities in the calorimeter are removed. Thus the calorimeter will add up only for the energies of neutral hadrons and less deteriorate the jet energy resolution. With the intensive simulation study so far, the PFA scheme seems proven to work. Because of its very fine granularity, the PFA calorimeter could require more than 100 million channels. That is thousand times more than the present LHC experiments.

Another approach is the Dual Readout calorimeter [16] where electromagnetic and hadronic components of the energies in the calorimeter are treated separately by using a clever dual readout of quartz and scintillation fibers. Several proof-of-concept beam tests have been made and exhibited some promising improvements over the traditional methods as indicated by "DREAM" in Fig. 8.

6.Another dimension of the detector technology

Micro electronics technology is an essential tool for the detectors using silicon including various silicon sensors or the ASICs for any high performance readout system. The progress in the field for the last decade largely relies solely on the advanced microelectronics technology developed in industry. It is frequently pointed out these days that the current scale of integration circuit does cost too much even for giant companies to afford it. Therefore further integration in plane (2D) may be impossible to continue. One of the alternative directions is to escape to another dimension. This new technology is called as "vertical integration" or simply "3D electronics" as shown in Fig. 9. With this new technology we may be able to have finer pixels with higher functionality like local AD conversion, intelligent triggering, tracking or pattern recognition inside a tiny chip. Since the technology is so promising and important, the global facilitation group (VIPS, Vertically Integrated Pixel Sensor development) has been formed to encourage and arrange the R&D activities in HEP among the world by the initiatives of the three institutes (KEK, FNAL and CERN) [18].

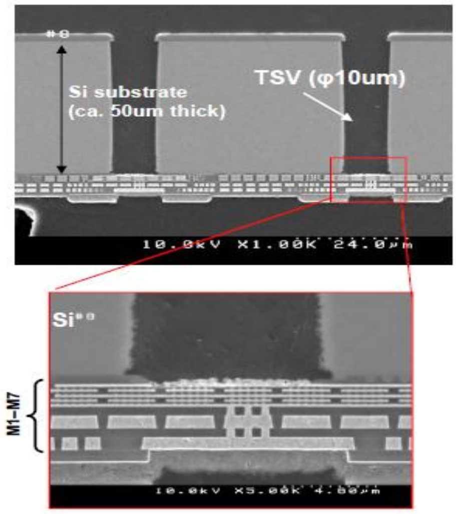

Fig. 9 Image of a vertically integrated circuit [17]

7.Spin-Off to other fields

Another big consideration for the most HEP institutes is to make the R&D outcome useful also for any applications outside HEP. It is strongly encouraged in many HEP institutes to introduce their developed technology to the other sectors like material science (X-ray or neutron) and industrial or medical applications. One of the most successful examples in that direction is the application of the CMS pixel sensor to the high performance X-ray imager (PILATUS) which is adapted in many places of photon science field [19]. Another beautiful example is the Medipix project at CERN [20] where highly functional pixel electronics are developed for a medical application. There are number of research activities in the world to apply the chip to various fields.

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