PROCEEDINGS OF SCIENCE

Highlights of the Pixel 2016 workshop

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The Pixel 2016 workshop was held in Sestri Levante, a renowned touristic resort on the Ligurian coast, in early September. It is the 8th of a series that initiated in the year 2000 in Genoa and travelled, with bi-annual frequency, to US, Europe and Asia. It is the only workshop entirely dedicated to the technology of the pixel detectors and all the applications in particle and x-ray physics. In this report I will illustrate a personal view of the most significant advances which have been presented and discussed at the workshop.

The 25th International workshop on vertex detectors
September 26-30, 2016
La Biodola, Isola d'Elba, ITALY

PoS(Vertex 2016)001

1. Introduction

The Pixel 2016 workshop is the 8th of a serie initiated in the year 2000 and dedicated to the pixel detector technology and applications. It is held each two years in locations close to laboratories which play major roles in the development of pixel detectors either in high energy physics (HEP) or in photon detection applications. About 100 scientists meet, present the most recent results and discuss them together with the emerging trends. Contributions are subdivided in

- review talks, deemed to give an overview of a given item by an authority in the field
- invited talks, where experiments (or individuals) active in the field are requested to present the most recent results and plans
- contributions, which are solicited from individuals or collaborations and can either be orally presented or discussed in a poster session

The participation to the workshop is free and about 20% of the participants typically come only to listen to the workshop and participate in the discussion sessions. In Pixel 2016 we had 7 review talks, 13 invited talks, 35 oral presentations and 23 posters. To leave a trace of the workshop the proceedings will be published in a special issue of JINST.

The evolution of HEP toward high luminosity experiments and the study of complex topologies has imposed the use of pixel detectors in the innermost part of the tracking systems [1, 2, 3, 4]. The tracking volume covered by these detectors tends to substantially increase in the generation of experiments under construction [5, 6, 7] or planned [8, 9]. This is due both to the success of the pixel technology in the current experiments and to the further increase of luminosity planned by the next generation of accelerators. This fact has increased the overlap between the Pixel and the Vertex workshops and demands for some adjustment of the respective scientific programs. This issue will be briefly discussed in the conclusions of this report.

2. Highlights of Pixel 2016

Only two weeks have passed from the end of Pixel 2016 and the beginning of this conference. This short period of time still does not permit a perspective view of the new results and does not allow them to pass through a peer review, a step which will only be done for the proceedings publication. All the information presented is therefore uniquely based on the slides presented at Pixel 2016. The figures are extracted from the workshop slides and their quality is not always very high. The name of the speaker who presented the results reported here will always be quoted in such a way that the interested reader can obtain additional information going to the workshop agenda page [10] or later, when available, to the JINST publication.

Very many results have been presented at Pixel 2016 and several of them will be repeated in this workshop. I have then decided to limit this report to a small number of results avoiding, as far as possible, those which are planned to be presented here. I recognise this represents a bias and and I apologise here for the possible mistakes and the omissions.

The accent of each Pixel workshop depends on the interests of the local organisers and on the novelties emerging in the last two years. The items stressed in the Pixel 2016 workshop were:

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- the importance of pixel detectors in past, present and future HEP measurements
- the rise of monolithic pixels (and CMOS pixel in general)
- the possible role of fast timing

2.1 High Energy Physics applications

The miniaturisation trend in microelectronics has allowed to integrate in each pixel read-out cell an increasing number of functions. Pixel detectors became more difficult to design and build, but, thanks to all the sophisticated control circuitry, they turned out to operate very stably in all experiments and contributed significantly to improve their physics reach. An example is shown in Figure 1 that illustrates that 2/3 of the ATLAS measurements presented at ICHEP2016 [11] uses b-tagging identification criteria. Those criteria are based on tracks missing the primary vertex by an impact parameter of O[0.1mm]. The impact parameter accuracy heavily depends on the space point accuracy of the tracking detectors closest to the interaction point i.e. the pixel detectors in the case of ATLAS.

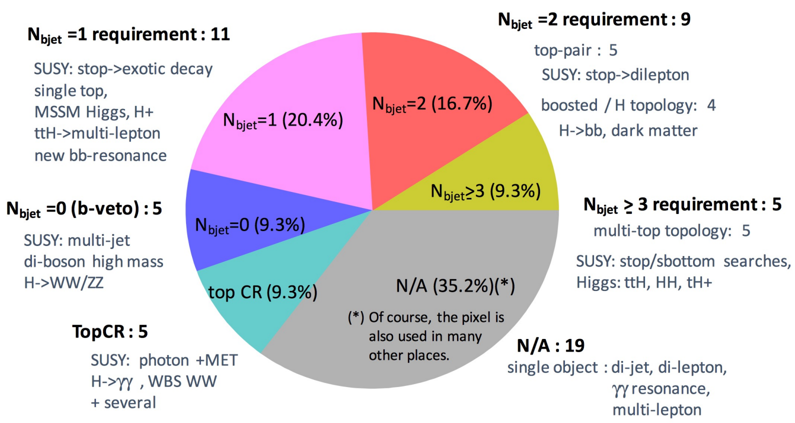

Figure 1: Number of papers presented by the ATLAS experiment at the ICHEP 2016 conference in Chicago [11], with indications of those where the b-tagging has been used. The top control region (top CR) is enhanced in top-pair events (selected through b-tagging) and is used to control the top-pair background in searches for supersymmetric signals. The fraction of papers not using b-tagging (N/A) addresses primarily the study of channels with two (or many) leptons or with two photons and amounts to only 35.2%. Compilation presented by Soshi Tsuno.

Pixel detectors allow track position measurements very close to the interaction point in high luminosity HEP experiments and cover spatial regions which, otherwise, would remain unmeasurable. The success in the very challenging LHC environment has pushed also the experiments dedicated to beauty related searches to include, in the next generation spectrometers, pixel detectors to cover the vertex regions. This should allow both BELLE II [7] and LHCb [6] to improve their beauty identification capabilities even with the foreseen one order of magnitude increase of interaction rate. This is particularly important to investigate beauty decay modes where there is significant disagreement with the Standard Model expectations, like, for instance, in the ratio of branching fractions (BF) for $\overline{B}$ semileptonic decays into D^* mesons as defined in Eq.2.1

$$R(D^*) = \frac{BF(\overline{B} \to D^* \tau^- \overline{\nu}_\tau)}{BF(\overline{B} \to D^* \ell^- \overline{\nu}_\ell)} \tag{2.1}$$

The tension between the current measurements of R(D^*) and the Standard Model expectations is at 4σ level (see Figure 2). The pixel detectors of BELLE II and LHCb are designed to provide the measurement accuracy necessary to find out if this mismatch is real or not. The different environment of the two experiments, in particular the very different momentum spectra of the particles to be measured and their track density, has pushed toward different solutions. BELLE II privileges material minimisation and has therefore adopted the more challenging monolithic solution (sensor and read-out electronics on the same high resistivity silicon substrate), while LHCb privileges speed and on-chip computing power and has therefore adopted the more standard hybrid solution (sensor and electronics on different substrates, each optimised, and connected together through bump-bonding).

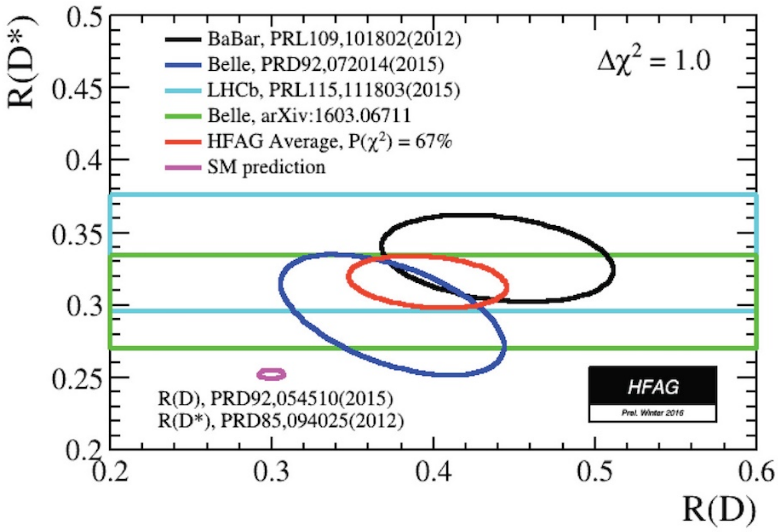

Figure 2: Ratio of semileptonic B decays to a τ versus the same decay to lighter leptons. The Standard Model expectation is the small purple ellipse and the measurements show a 4σ disagreement with expectations. References for the measurements are given in the figure (shown by Abe Seiden).

Thanks to the very high granularity, pixel are the ideal detector to cope with tracking in dense environment. Highly boosted systems, together with b-tagging and τ reconstruction, are the physics cases requiring the best performance in this environment. While smaller size pixel could help, it may always happen that more than one track cross the same pixel cluster. An interesting method to optimise pattern recognition in dense environment has been presented by Jason Mansour. This is based on the specific ionisation of each cluster and is illustrated in Figure 3 where the specific ionisation distributions generated by one minimum ionising particle or by multiple tracks are shown. Once the template for the single and multiple case are derived from data, the specific information of a given cluster can be used to assign a probability for single or multiple tracks crossing this cluster. This information is then used by the pattern recognition algorithm to look harder for close tracks. The fraction of lost tracks inside the core of jets at 13 TeV pp collisions decreases significantly using this algorithm. The improvement has been estimated with Pythia8 simulation in the range of jet p_T from 200 to 1200 GeV. The fraction of lost tracks inside the jet core increases with the jet p_T and ranges from 6% to 12% without using the ionisation information and from 1% to 3% using it.

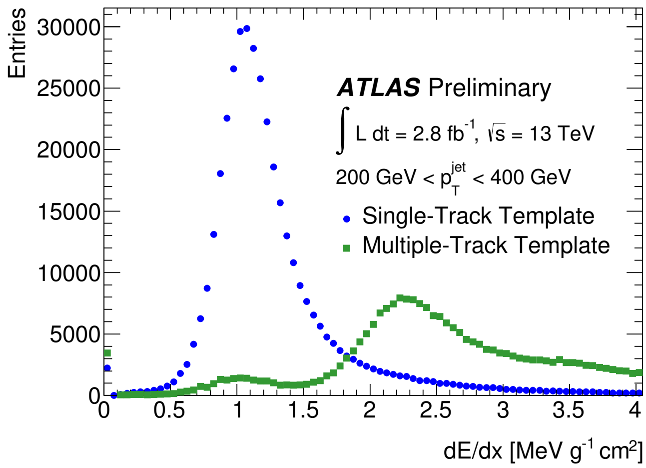

Figure 3: Single-track and multiple-track specific ionisation templates for 13 TeV proton-proton collision data in the ATLAS pixel detector (figure shown by Jason Mansour).

Pixel detectors close to the interaction region in the High Luminosity LHC (HL LHC) [12] should be designed to survive doses of about $10^{16}n_{eq}/cm^2$. 3D sensors have already shown to sustain this dose [13], but their large scale fabrication with good yield still requires some development. The decoupling between the thickness of a 3D sensor and its depletion depth allows low voltage (and therefore low power consumption) operation even after high doses. An alternative solution is the use of very thin planar sensors, such that a sufficiently high charge collection can be obtained after large doses still with a moderate voltage (and therefore a moderate power consumption). An interesting result on thin n-in-p planar sensors has been presented by Anna Macchiolo and is illustrated in Figure 4. Efficient operation of 100 μm thick sensors up to doses of $10^{16}n_{eq}/cm^2$ is possible with an estimated power consumption of about 50 mW/cm^2. Obviously also very thin planar sensors pose yield production (and handling) problems which need further studies.

2.2 Monolithic CMOS pixel detectors

In recent years some semiconductor foundries has opened the possibility to design CMOS circuits on high-resistivity silicon wafers to external users. This allows to implant read-out circuits and fast sensors on the same substrate. The sensor element is the deep n-well/p-substrate diode, as shown in the sketch of Figure 5. High voltage must be applied to deplete the part of the substrate around the n-well in such a way that charge collection mechanism is due to the drift (and not to diffusion) of the charge generated within the depleted region. Pixel electronics is implemented inside the deep n-well.

The availability of this design possibilities has triggered a robust and successful R&D program on monolithic CMOS pixel detectors. The outcome is that monolithic pixel have been adopted by HEP experiments [4, 5, 7] and start to play a role in x-ray applications as it has been shown in a dedicated session of the Pixel 2016 workshop by several authors. Monolithic pixel have many

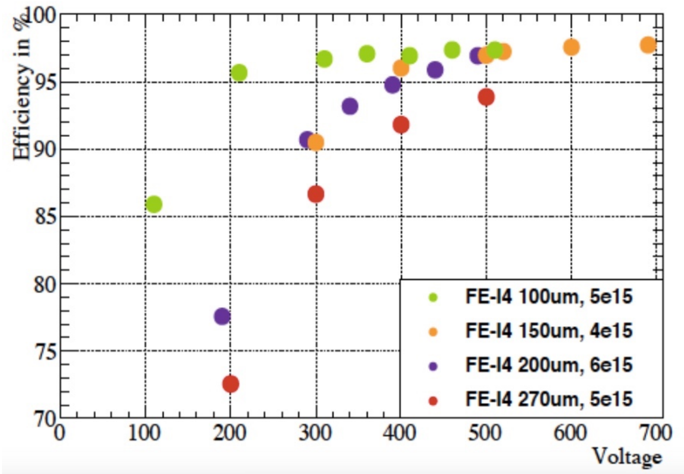

Figure 4: Efficiency of thin (from 100 μm to 270 μm) n-in-p planar sensors after high doses (from 4 10^{15}n$_{eq}$/cm^2 to 6 10^{15}n$_{eq}$/cm^2) applying a threshold of 1300 e$^-$.

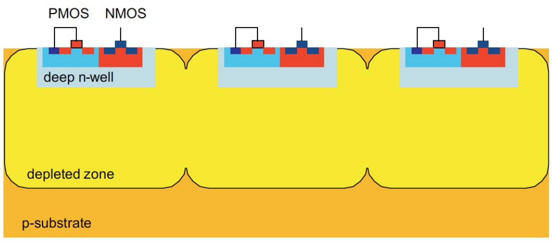

Figure 5: Sketch of a CMOS monolithic detector (three pixel cells shown), as presented by Ivan Peric.

advantages over hybrid pixel (cost, ease of manufacturing and thickness, to name a few) but also limitations (e.g. coupling of the digital activity to the sensor signals and shaping of the electric field such that the ionisation charge drifts rather than diffusing) which should be further addressed. Hybrid and monolithic pixels will both survive in the near future, sharing the applications in some way that will mostly depend on how far the R&D effort can overcome the above limitations. To extend the application to very high rate HL LHC environment [12], it is necessary to guarantee charge collection within 25 ns even after high radiation dose. CMOS sensors produced by TowerJazz after parameter optimisation indicate the possibility of meeting the HL LHC charge collection requirements up to a dose of 10^{14}n$_{eq}$/cm^2 with degradation of performance beginning at 10^{15}n$_{eq}$/cm^2 (see Figure 6).

While studies are continuing to improve on this parameter, the current results already open up the possibility of using monolithic pixel at a radius of $\approx$30 cm at HL LHC.

2.3 Fast timing

Precise timing information can be extracted from silicon detectors and, if these can be also segmented in pixels, we can have a detector able to locate in 4-dimensions (the three spatial coordinates and the time) the hit left by a charged particle track. Space resolution of O[10] μm are routinely obtained with pixel detectors, time resolution of O[30] ps can be obtained in silicon detec-

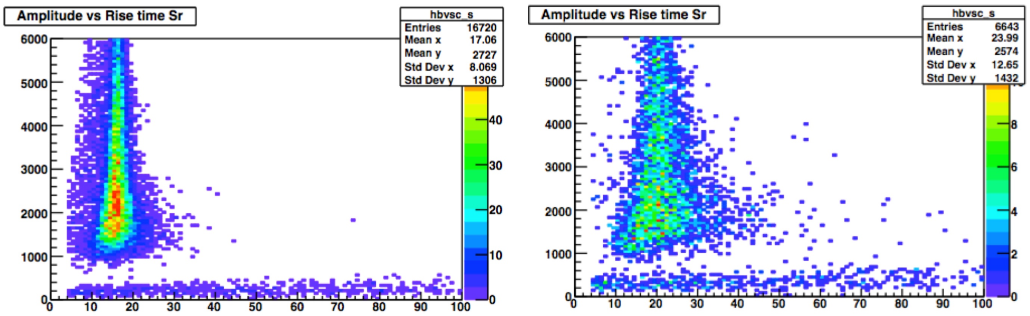

Figure 6: Test beam results of TowerJazz CMOS pixel detectors after irradiations to a dose of $10^{14}n_{eq}/cm^2$ (left) and $10^{15}n_{eq}/cm^2$ (right). The pulse height in electrons is shown versus the time (expressed in ns) of an external beam trigger (figure from Tomasz Hemperek).

tors using special doping profiles, as it will be shown in the following. If these two measurements capabilities are implemented on the same detector many new applications become possible. One example is the vertex reconstruction at HL LHC [12] where the number of proton-proton interactions per bunch crossing is expected to be ≈200, with an average distance between vertices of 500 μm and a timing spread of 150 ps rms. Assuming that the vertex separation resolution along the beam direction currently obtained by ATLAS and CMS (≈250 μm) is maintained in the harsh HL LHC environment, there will be ≈15% of vertices containing two interactions. A time information with 30 ps resolution would then resolve a sizeable fraction of the vertices which remain untangled after purely geometrical track reconstruction.

Fast timing information from each pixel detector would greatly simplify the pattern recognition at HL LHC as tracks from different vertices would have a different timing tag. This would significantly reduce the computing time for track reconstruction, but it is not a realistic solution because of the amount of power needed to operate a silicon pixel multi-layer detector in high-speed mode. A realistic, but still quite challenging, solution would be to add a layer of pixelated fast detectors to correlate geometry and timing. This is under consideration for the upgrade of ATLAS and CMS.

The detector under study is an evolution of the Avalanche Photodiode [14]. Its main feature is a much reduced amplification factor and the possibility to segment the collecting electrode. To make possible a precise timing measurement, a fast signal is necessary. This is achievable even with modest charge amplification if it happens in a very thin silicon layer. Adding a Boron doping layer at the n^{++}-p junction [15], as illustrated in Figure 7 where a standard silicon detector is compared to an Low Gain Avalanche Detector (LGAD), would serve this purpose.

Implanting $\approx 10^{16}$ Boron atoms per cm^3 over a thickness of ≈1 μm allows, after depletion, electric fields exceeding 300 kV/cm. Under this condition the electrons (and to a lesser extent the holes) in the silicon lattice acquire sufficient kinetic energy to generate additional e/h pairs which overall provide a charge multiplication of ≈10. As the p^+ layer is very thin the charge multiplication happens in a few picoseconds and gives the opportunity of a precise time information using a specially designed front-end electronics. This device has been realised and recently tested

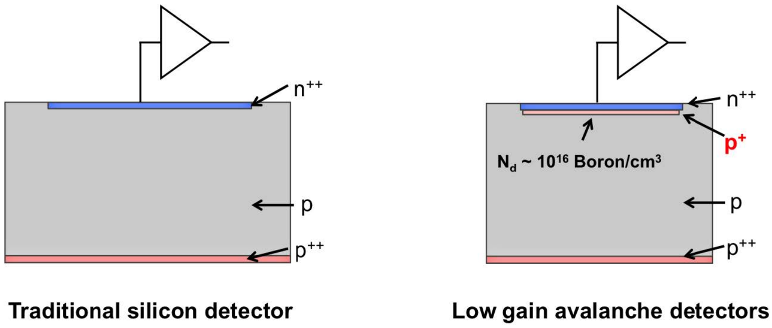

Figure 7: Schematic of a traditional silicon detector (left) and of a low-gain avalanche detector (right). The additional p^+ layer underneath the n^{++} electrode sustain, when depleted, a high electric field that generates charge multiplication (figure from Nicolo' Cartiglia).

on a 180 GeV pion beam [16] . It has been named Ultra Fast Silicon Detector (UFSD) and has shown a time resolution of 35 ps and the possibility of reaching a resolution of 20 ps through multiple timing measurements. The results are shown in Figure 8 for a 50 μm thick epitaxial silicon detector with large, by today standard, 1.4 mm^2 pixel implants.

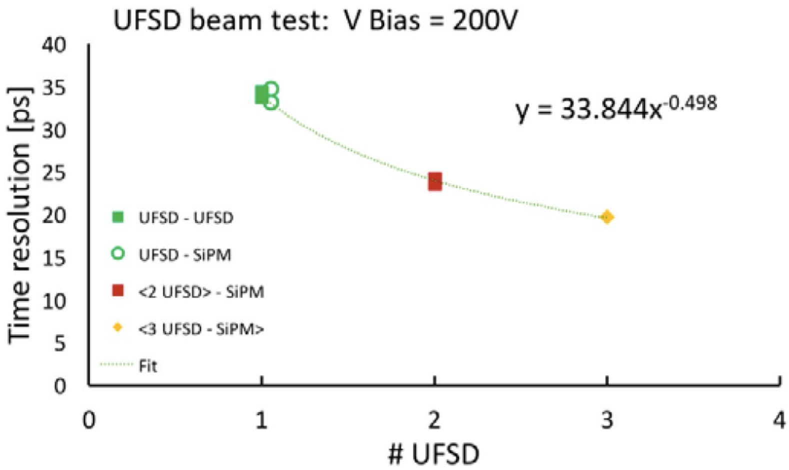

Figure 8: Timing resolution for: single Ultra Fast Silicon Detector (UFSD) averaged pairs of UFSD and average of 3 UFSD for bias voltages of 200V on a 50 μm thick detector with 1.4 mm^2 pixels. The detectors are placed on a 180 GeV pion beam and the resolution is measured with a constant fraction discriminator using as a reference a Silicon Photomultiplier (SiPM), and, in the case of the single UFSD, also using another UFSD as a reference (figure from Nicolo' Cartiglia).

3. Conclusions

The Pixel series of workshops is a lively occasion to discuss amongst experts about the development of the technologies and applications related to pixel detectors. Increasing overlap with the Vertex series of workshops, caused by the successful operation of pixel detectors in the HEP environment, calls for the optimisation of both scientific programs. A discussion between the two

Scientific Advisory Committees would be advisable to proceed in this direction and guarantee proper forums and long lifetime to both workshops.

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