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Summary of Vertex 2015

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The international workshop on vertex detectors reviews recent progress in the field of semiconductor tracking and vertexing detectors for high energy physics. The impressive performance of the silicon systems of the Large Hadron Collider experiments and their consolidation work during the LHC shutdown were presented. A wide array of future detector systems and of emerging technologies were surveyed. Tracking, alignment and triggering algorithms were discussed. Applications of similar technolofies outside high energy physics were also considered.

24th International Workshop on Vertex Detectors - VERTEX2015
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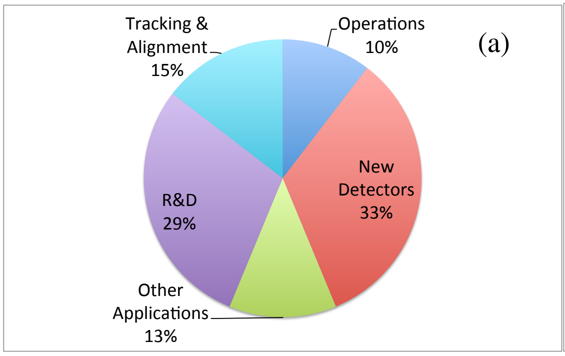

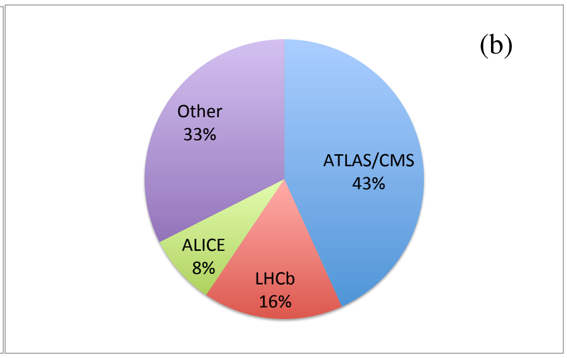

Figure 1: (a) Distribution of topics covered by presentations at Vertex 2015 (b) Distribution of presentations across high energy physics experiments for those talks that primarily focused on one experiment.

1. Introduction

The 24th International Workshop on Vertex Detectors (Vertex 2015) was held from the 1st – 5th June 2015 in the spectacular location of Santa Fe, New Mexico. The workshop featured fifty presentations spread over five days and covering all aspects of semiconductor tracking and vertexing detectors for high energy physics.

The areas covered in the conference included the operational experience with detector systems, the design of new detector systems, R&D on new technologies, triggering, tracking and alignment algorithms, and applications of similar technologies outside high energy physics. The distribution of talks between areas is illustrated in Figure 1, along with the major experiments that were represented. Notable amongst the talk distribution was a significant rise in the number of presentations on CMOS sensors. The talks also included a significant number of presentations on software algorithms. This was a welcome development as this area has sometimes been less well represented in previous conferences. As one would expect, the bulk of experiment focussed talks were from the four large LHC experiments, but with a third of talks coming from other experiments there was also good representation from smaller experiments.

2. LHC Detectors in Operation

Run 1 physics data taking of the LHC occurred from 2010 to 2013. At the time of the conference the LHC had recently restarted after a two year shutdown. Significant consolidation work had been undertaken on the accelerator and on the detectors. Run 2 of the LHC is expected to continue till the end of 2018 and provide proton-proton collisions at a centre-of-mass energy of 13 TeV; the collisions in Run 1 occurred at 7 and 8 TeV. Indeed, the first collisions between 13 TeV stable beams occurred during the conference on Wednesday 3rd June, with first event display images being shown by several speakers. The collision frequency will be increased moving from the 50 ns bunch-spacing of Run 1 to 25 ns in Run 2 and significantly higher instantaneous luminosities are anticipated at ATLAS and CMS than in Run 1.

All four major LHC experiments reported on the status and performance of their existing silicon detector systems and consolidation work performed during the shutdown. As in previous

Vertex conferences valuable lessons were learnt from experiments openly sharing information on problems they have encountered as well as their successes.

The CMS inner tracker [1] is the largest silicon tracker ever built with 75 million channels and 200 m^2 of silicon. The CMS pixel endcap disk had 8% of its channels non-operational by the end of Run 1 and the pixel system was removed and repaired on the surface. Detector repairs were performed to the endcap disk including fixing misaligned flex cables, unplugged analogue electrical-to-optical converters, and replacing problematic modules. After repair this FPix system regained an impressive 99.9% of operational channels. Problems occurred during barrel pixel repairs leading to shorts, which were thought to be caused by condensation in the cooling box. The detector was repaired from damage caused by this issue in only three months using spare and repaired modules.

Consolidation work was also performed on the ATLAS silicon tracker. In the pixel system after repairs 98% of modules were functional. The major change for the ATLAS system was the insertion of a new inner pixel detector system - the Insertable B-Layer (IBL) in May 2014, see Figure 2. This fourth layer of pixels is located at a radius of 3.3 cm from the beam and is comprised of 12M pixels of $50 \times 250\ \mu$m^2. The system uses both planar and 3D pixels (see below). Mid-way through production an issue with corrosion of bond wires was found. As with CMS, the issues appear to have arisen from exposure to condensation. All staves were reworked appropriately. The system has 99.7% operational pixels. Misalignment effects in the detector are discussed in section 5. The system has been fully commissioned and is operational for Run 2.

The ALICE silicon system [2] is comprised of pixel detectors and strips detectors but also includes drift detectors. New more powerful FPGA based readout boards were constructed and deployed for the silicon drift detectors. Upgrades to the strip detector readout system were performed to improve the single event upset (SEU) tolerance.

LHCb has a silicon strip Vertex Locator (VELO), located only 8 mm from the LHC beam during physics data taking, and silicon strip tracking systems (ST) [3, 4]. The VELO has carefully monitored its radiation damage and showed currents in line with expectation. Charge collection measurements, including high statistics measurements of the behaviour of n-on-n and p-on-n sensors, suggest a longevity somewhat better than anticipated from the conventional Hamburg model. However the VELO sensors incorporate a second metal-layer to route signals and after irradiation some charge-loss to this layer has been reported though without affecting the tracking efficiency of the detector. ATLAS have also monitored the leakage currents in the different layers of their pixel detector using a dedicated current measurement board. Good agreement with the expectation is obtained and the inner layer of the system is expected to withstand the radiation damage arising from 450 fb^{-1} of data [5].

A recurring theme in the presentations on operational experience was issues with cooling systems, with consolidation work being reported by all four experiments. The CMS tracker cooling system was modified to improve the sealing and insulation and upgrade the cooling plant. This will allow the system to operate at $-10/-15°$C during Run 2 to reduce the leakage current and limit the reverse annealing from radiation damage. The major operational issue for the ALICE pixel system in Run 1 had been with the cooling system, leading to 63% of modules being operational in 2011. The issue arose from clogging of filters. These were drilled to correct the issue, a highly challenging task as the nearest accessible point was 4.5 m away and the inner pipe of only 4 mm

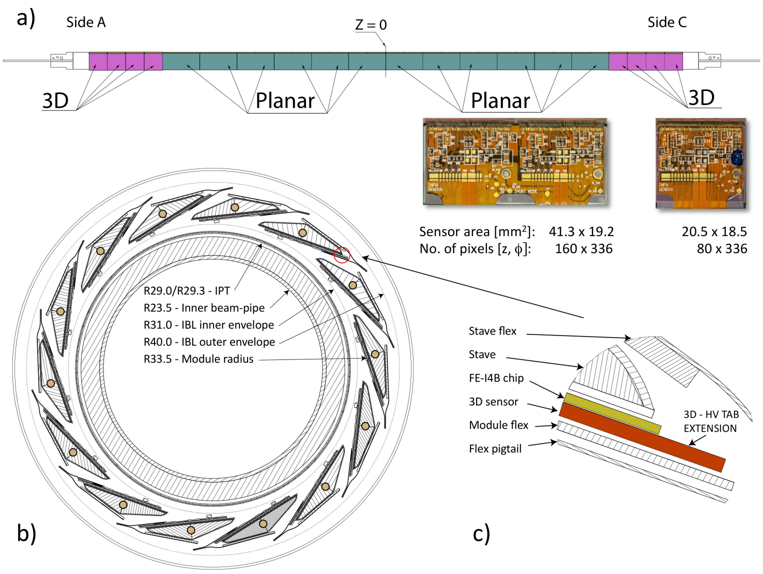

Figure 2: The ATLAS Insertable B-Layer, added for LHC Run2 operations, includes both planar and 3D pixels (a). The layout of the staves (b) and a zoom of one stave (c) are illustrated. Reproduced from [6].

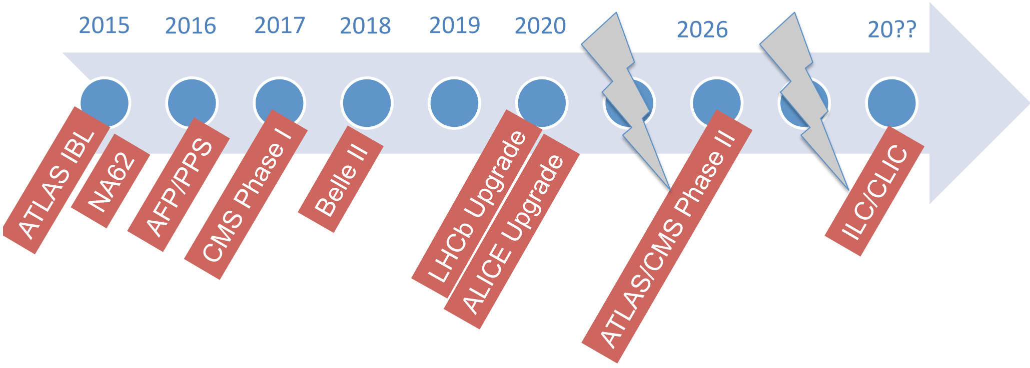

Figure 3: The expected operational dates of new detector systems discussed at the conference.

diameter. A new cooling plant has been introduced for the LHCb ST during the LHC shutdown. The LHCb VELO system reported highly successful operational experience with its bi-phase CO_2 based cooling system. A similar approach has been adopted for the ATLAS IBL.

3. New Detectors and New Technologies

A significant number of detector systems that are in preparation were reported at the conference. A timeline for the potential deployment dates of these detectors is provided as Figure 3.

A wide and inventive variety of future strip and pixel detector module geometries were presented at the conference. The so-called "Origami" modules of Belle-II were particularly remarkable, illustrated in Figure 4. These double sided silicon strip sensors have their readout chip (the APV developed for CMS) mounted on the sensor on the n^+ doped side. Signals from the p^+ doped side are routed to the front with a bent flex circuit. CMS [7] reported modules combining strips and macro-pixels for application in their future track trigger (discussed further below). The LHCb

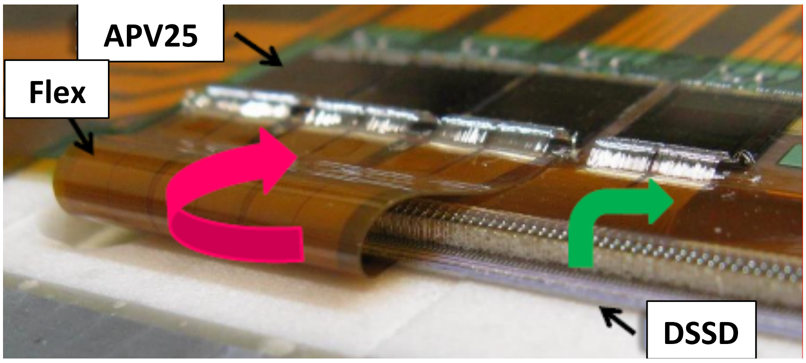

Figure 4: The Belle "Origami" modules, showing the double sided silicon detectors (DSSD), readout chip (APV) and bent flex circuit. Reproduced from [14].

VELO upgrade [8] showed "L" shaped modules that close around the beam, with the active pixels located only 5 mm from the beam.

A number of presentations discussed developments for the future detector systems of ATLAS and CMS. The next to be installed will be the CMS Phase I pixel upgrade scheduled for deployment in 2016/2017 and for which pilot run modules have already been deployed [9, 10]. The high luminosity phase of LHC operations will commence from LHC Run 4, after a significant (up to three years duration) shutdown and increase the design luminosity by a factor of five to $5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ or beyond. The increase in particle density and radiation damage motivates major changes to the detector systems. The ATLAS [11] and CMS [12] pixel systems for Phase II upgrades, for deployment in the mid-2020s, require radiation tolerance in the 10^{16} 1 MeV neutron equivalents $/\mathrm{cm}^2(\mathrm{n_{eq}})$ range and will further increase their size from the current systems. The ATLAS pixel system is expected to comprise 6,000-13,000 modules. The proposed strip detector [13, 7] systems have even larger numbers of modules. The ATLAS silicon system will expand (due to removal of the TRT) to the dimensions of the CMS system, with 190 m^2 of silicon and 20,000 modules. CMS have selected to use 200 μm thick sensors on p-type material based on wafers produced with the magnetic Czochralski process.

Looking further ahead reports were given on developments for the detector systems of potential future linear colliders, both ILC and CLIC. A Japanese site has been proposed for the ILC and it was reported that a statement on whether this project is likely to proceed to construction is expected by the time of Vertex2016. The bunch structures of the two machines differ significantly, leading to differing timing requirements, but the drive to produce low material sensors and services is in common. The long timescale of the projects is such that the development of highly advanced technologies should be pursued, such as true 3D integration of sensors and electronics, as actively illustrated for the ILC at the conference.

The rise of CO_2 cooling systems already noted above was also apparent in the reports on new detectors. Indeed we learnt in the presentation on AMS [15] that they have already ascended into space! ATLAS and CMS strip and pixel upgrades as well as LHCb (VELO and ST) expect to utilise this technology for their upgrades. The new development on the cooling side concerned the use of micro-channel cooling. The NA62 Gigatracker is taking first data this year and utilises

$70 \times 200\ \mu$m channels etched into a silicon substrate to make micro-channels through which a cooling fluid (C_6F_{10}) flows. This cooling design significantly decreases the material in the active acceptance of the detector. The LHCb VELO upgrade will also utilise micro-channel cooling and combine this with utilising bi-phase CO_2.

The conference was also notable for the deployment in detector systems of a number of technologies that had been reported as R&D items in previous conferences. As commented above, the ATLAS IBL makes the first use of 3D detectors [16], based on the semi-3D design that simplified the construction where columns do not pass through the full silicon wafer. Further deployment of 3D sensors will occur in very forward detector systems in both ATLASFP and CMS PPS. Further work is ongoing on improving the etched columns aspect ratios. Diamond sensor beam monitors [17] have been deployed in ATLAS for Run 2 utilising IBL style pixel modules. Work is also progressing on developing 3D diamond sensors, using lasers to produce conductive graphite columns in diamond. The pixel detector of Belle II will be based on DEPFETs [18]. The material is minimised by using a handling wafer which is etched away in the centre to 50 μm providing mechanical support only where it is required around the edge of the sensors. An impressive interaction length of $0.2\%X_0$ per layer is reported.

The conference reported an explosion of development work on CMOS sensors [19, 20, 21, 22]. The operational performance of the STAR Tracker utilising MIMOSA family sensors was reported [20]. The development of 50 μm thin MAPS with a sub-5 μm resolution and $0.3\%X_0$ per inner Barrel layer was presented for the ALICE upgrade [19]. Speakers reported research for potential application in ATLAS (strips and pixel) and future linear colliders on high resistivity and high voltage (typically 120 V) CMOS sensors. The ATLAS sensors aim for relatively high radiation tolerance (10^{15} n_{eq}/cm^2) and 25 ns readout. The driving motivation is the utilisation of technology advances to produce low cost sensors, say 5-10 €$/cm^2$. The ATLAS developments focus on utilising CMOS for the sensors with a separate ASIC but the possibility exists to include circuitry in the sensor. The option of gluing the pixel readout chip to the sensor to capacitively couple them, rather than bump-bonding, is also being investigated.

Another new theme emerging from the conference was the incorporation of timing information into pixel sensors to complement the spatial information. The recently deployed NA62 Gigatracker reports a time resolution of 200 ps [23]. R&D work is being actively pursued [24, 25] on detectors with gain and large electron drift velocity, with the hope of achieving 40 ps resolutions.

New radiation hard pixel ASICS for LHC upgrades were discussed. A common development in the CERN RD53 collaboration for the ATLAS and CMS HL-LHC pixel detectors was presented. The ASIC is being developed in 65 nm feature size technology with $50 \times 50\ \mu$m pixels. The chip is required to drive 5 Gbps electrical signals over a distance of 6m. The chip aims for approximately 1MHz trigger rate. On a shorter timescale, the VELOPix chip of the LHCb upgrade is developed in a 130 nm technology. It is based on the TimePix family of chips and will provide $55 \times 55\ \mu$m pixels. It also will provide 5 Gbps per output serialiser, with four serialisers per chip. It will operate at 40 MHz, *i.e.* LHCb beam crossing frequency, trigger-less output mode.

Important tools for designing and understanding the response of new detectors after radiation damage were reported. Work was presented showing highly performant simulations based on TCAD simulations through the modelling of effective donor and acceptor levels up to fluence levels of 1.5×10^{15} n_{eq} [26]. Apparatus to allow Transient Current Technique (TCT) measurements has been developed and used to perform an impressive array of measurements. The system is available for purchase [27].

4. Other Applications

The session of talks on semiconductor detectors in use outside particle physics reported a wide-variety of applications. It was remarked that while funding agencies often ask us to emphasise the impact of developments on industrial and commercial applications it is clear that techniques developed in high energy physics are also making a significant impact in other scientific disciplines.

Photon science applications were discussed over an energy range of six orders of magnitude, 50 eV to 50 GeV, for a scientific field larger than that of high energy physics. Many of the developments are being driven by the Free Electron Laser facilities, notably LCLS at SLAC that came online in 2009 and the European FEL that is planned to start in 2017.

Another major facility currently in construction is the European Spallation Source, a neutron source scheduled to start in 2019. The development of this facility coupled with a shortage of ^{3}He is leading to significant activity on silicon based neutron detectors. The etching techniques, also used in 3D detectors and micro-channel cooling, are exploited to produce cavities which are then filled with a converter material. Etched silicon micro-probes are also being used to push forward our understanding of the response of the eye to visual stimuli.

The successful operation of silicon detectors in space was reviewed in presentations from AMS [15] and Fermi-LAT. New opportunities for these particle physics detectors in space were highlighted, such as the strong science case for the construction of a 100 keV-1 GeV gamma ray sensitive instrument and high energy cosmic ray detector for the Chinese Space Station. Detector applications in an antihydrogen experiment, AEgiS, were also discussed [28].

5. Tracking and Alignment

A central issue for the LHC experiments and their upgrades is providing an effective triggering strategy in the high multiplicity environment of the LHC as the detectors move to operating at higher instantaneous luminosities. ATLAS, CMS and LHCb are all pursuing different approaches to this key challenge. ATLAS [29] is planning the installation of a dedicated processor, the Fast Tracker, which will reconstruct the trajectories of charged particles with transverse momentum above 1 GeV using the ATLAS inner tracker information and relying on pre-stored patterns of hits. The track parameters are expected to be available in 100 μs allowing the high level trigger to use these tracks. Large scale integration will occur in 2016. CMS are planning a system [30] for their detector upgrade in LS3 that will identify tracks with transverse momentum above 2 GeV at the first level of triggering. The technique relies on the construction of "$\mathrm{p_T}$ modules"; these modules have two layers of silicon detector modules separated by a few mm. The modules consist either of two layers of strip modules, or one strip module and one using elongated pixels (1.5 mm $\times$ 100 μm). A schematic illustration depicting how high and low transverse momentum tracks are distinguished is shown in Fig. 5. Options for the track finding approach are under study but will be implemented using FPGAs. LHCb is removing its first level hardware based trigger for its upgrade [8]. All detectors will be read out at the LHC bunch-crossing frequency, providing complete flexibility in

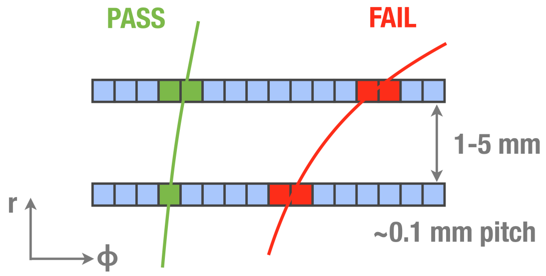

Figure 5: The CMS approach to track triggering. The trajectories of high and low-p_T tracks in a magnetic field are illustrated. Reproduced from [30].

the trigger CPU-farm. Hence vertexing and tracking information from the VELO and tracking systems will be available at the first level of triggering, allowing tracks from heavy flavour events to be distinguished from their impact parameters and momenta.

An array of improvements to the tracking algorithms at experiments were reported at the conference. While each of these improvements may give a comparatively small change their cumulative effect can be large. For example significant improvements in B-tagging performance at ATLAS were reported through the use of clusters that can be shared between tracks [31], and a factor four improvement in tracking algorithm speed in high pile-up conditions at CMS.

The alignment of the ATLAS IBL has received particular attention [32]. Distortions in the IBL have been observed due to a mismatch between the coefficient of thermal expansion of the bare stave and the polyamide flex bus line, with a magnitude of the stave bowing of 10 μm per $^{\circ}C$. The expected temperature variation during collision data taking is 0.2$^{\circ}C$ and consequently after alignment no significant degradation in performance is anticipated.

LHCb have introduced a novel real-time alignment and calibration strategy for LHC Run 2 [33]. Alignment and calibration constants are calculated in the trigger farm within a few minutes. For example, the VELO modules in each half are retracted by 3 cm and reinserted for every LHC physics run once stable beams are obtained. The detector can be aligned using tracks to an accuracy of 2 μm, a factor two improvement over that achieved using mechanical measurements as shown in Fig. 6. The new constants can then be made available to be used online in the trigger and for further reconstruction. This minimises the difference between online and offline performance, and facilitates the ability to perform physics analyses directly on the output of the trigger. Consequently only the information on the tracks of interest needs to be stored offline instead of all the signals recorded by the detector. In 2016 this approach is being tested but the raw data also retained. This approach would reduce the event size for those events by more than one order of magnitude.

6. Summary of Summary

The workshop surveyed a wide range of topics in semiconductor tracking and vertex detectors, with many new developments presented by the participants (see Figure 7). The large scale silicon systems of the LHC experiments are still improving their detector performances through hardware

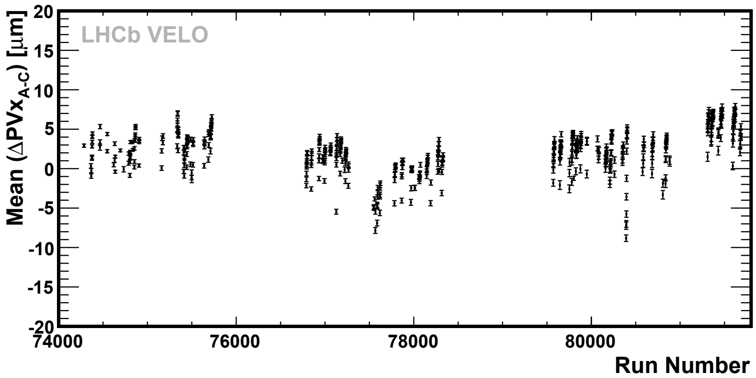

Figure 6: Misalignment between the two VELO halves obtained in LHC Run 1, relying on mechanical measurements of the position. Track based alignment can achieve an improvement by a factor of two, and the constants made available online for use in the trigger in LHC Run 1 within minutes of the run starting. Reproduced from [33].

Figure 7: The happy participants at a tremendously productive meeting held in a spectacular location.

interventions and algorithm development. A large number of new detectors are planned in our field, and there were several examples of fruitful inter-experiment collaboration. The range of technologies deployed in large scale detector systems has significantly expanded, including sensors using 3D detectors, diamond detectors, and soon DEPFETs and the development of micro-channel cooling. The addition of timing information to spatial information from vertex detectors and the wide array of development on HV/HR-CMOS sensors are both important trends to follow for the future.

7. Acknowledgements

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References

[1] C Lange. CMS inner detector: the Run 1 to Run 2 transition and first experience of Run 2. *PoS*, VERTEX2015:002, 2015.

[2] D Colella. ALICE ITS: the Run 1 to Run 2 transition and recent operational experience. *PoS*, VERTEX2015:003, 2015.

[3] K Rinnert. LHCb silicon detectors: the Run 1 to Run 2 transition and first experience of Run 2. *PoS*, VERTEX2015:004, 2015.

[4] J Wang. LHCb upstream tracker upgrade. *PoS*, VERTEX2015:012, 2015.

[5] S Seidel. Radiation damage monitoring of the ATLAS pixel detector. *PoS*, VERTEX2015:035, 2015.

[6] G Darbo. Experience on 3D Silicon Sensors for ATLAS IBL. *JINST*, 10(05):C05001, 2015.

[7] M Dragicevic. Upgrade of the CMS tracker for the high luminosity LHC. *PoS*, VERTEX2015:011, 2015.

[8] S Richards. The LHCb VELO Upgrade. *PoS*, VERTEX2015:008, 2015.

[9] L Caminada. The Phase 1 upgrade of the CMS pixel detector. *PoS*, VERTEX2015:017, 2015.

[10] B Akgun. Pilot system for the phase 1 pixel upgrade of CMS. *PoS*, VERTEX2015:018, 2015.

[11] R Bates. ATLAS pixel upgrade for the HL-LHC . *PoS*, VERTEX2015:006, 2015.

[12] R Stringer. Upgrades of the CMS pixel detector for the HL-LHC . *PoS*, VERTEX2015:007, 2015.

[13] Z Liang. ATLAS strip detector upgrade for HL-LHC. *PoS*, VERTEX2015:010, 2015.

[14] C Schwanda. The Belle II Silicon Vertex Detector Upgrade. Presentation at 24th International Workshop on Vertex Detectors (Vertex 2015) Santa Fe, NM, USA, June 1-5, 2015, 2015.

[15] M Pohl. AMS tracking in-orbit performance. *PoS*, VERTEX2015:022, 2015.

[16] J Lange. Recent progress on 3D silicon detectors. *PoS*, VERTEX2015:026, 2015.

[17] G Kasieczka. RD42: Radiation hard diamond sensors. *PoS*, VERTEX2015:033, 2015.

[18] M Boronat Arevalo et al. Belle II pixel detector. *PoS*, VERTEX2015:014, 2015.

[19] M Kofarago. Upgrade of the inner tracking system of ALICE. *PoS*, VERTEX2015:009, 2015.

[20] G Van Buren et al. Developments in tracking with STAR's heavy flavor tracker. *PoS*, VERTEX2015:013, 2015.

[21] N Sinev et al. Chronopixel project status. *PoS*, VERTEX2015:038, 2015.

[22] M Deveaux. Monolithic active pixel sensors. *PoS*, VERTEX2015:045, 2015.

[23] M Perrin-Terrin. The NA62 GigaTracker. *PoS*, VERTEX2015:016, 2015.

[24] A Seiden. Ultra-fast silicon detectors. *PoS*, VERTEX2015:025, 2015.

[25] M Baselga Bacardit. Radiation hard semiconductor devices for very high luminosity colliders. *PoS*, VERTEX2015:032, 2015.

[26] T Peltola. Simulation of Radiation-induced defects. *PoS*, VERTEX2015:031, 2015.

[27] Particulars advanced measurement systems. TCT Apparatus. Presentation by V. Cindro at 24th International Workshop on Vertex Detectors (Vertex 2015) Santa Fe, NM, USA, June 1-5, 2015.

[28] A Gligorova. Antimatter annihilation detection with AEgIS. *PoS*, VERTEX2015:024, 2015.

[29] G Volpi et al. The ATLAS fast tracker processor design. *PoS*, VERTEX2015:040, 2015.

[30] M De Mattia. CMS developments for track-triggers. *PoS*, VERTEX2015:039, 2015.

[31] G Facini. Novel Methods and Expected Run 2 Performance for ATLAS Track Reconstruction in Dense Environments. *PoS*, VERTEX2015:041, 2015.

[32] P Butti. Alignment of the ATLAS inner detector for the LHC Run II. *PoS*, VERTEX2015:047, 2015.

[33] G Dujany. Novel real-time alignment and calibration of the LHCb detector in Run II. *PoS*, VERTEX2015:046, 2015.