4D Real-Time Tracking for High Luminosity LHC Experiments

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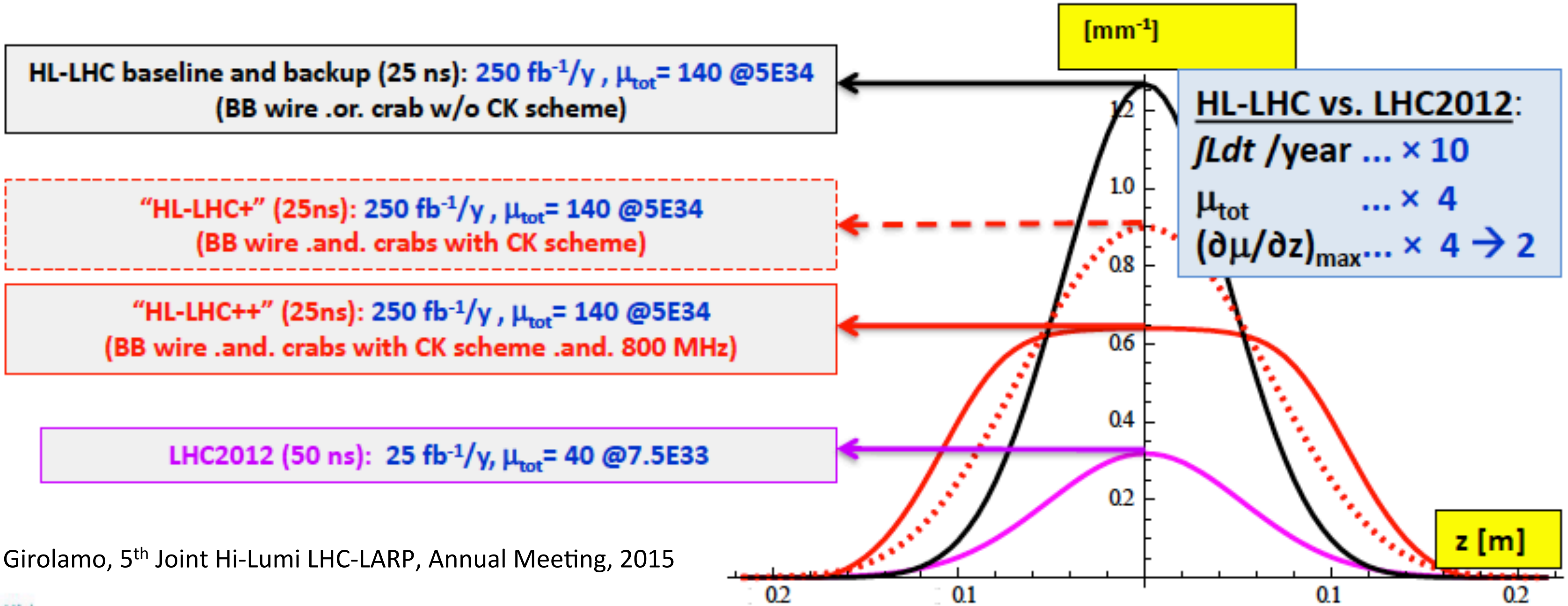
Introduction

- The High-Luminosity LHC (HL-LHC) phase will be characterized by an instantaneous luminosity of 5×10^{34} $cm^{-2}s^{-1}$ for the ATLAS and CMS experiments at CERN, and $1\div2\times10^{34}$ $cm^{-2}s^{-1}$ for LHCb
- HL-LHC will allow to collect an integrated luminosity up to 250 fb^{-1} per year
- The average number of visible interactions per bunch crossing will reach 140
- In such environment precise tracking will be extremely challenging, not only for the high fraction of expected ghost tracks, but also from the radiation-hardness point of view
- The full exploitation of the physics potential of the high luminosity LHC is a big challenge. Experiments will have to cope with very high data rates, huge amount of data to process and store, and severe radiation damage for the innermost detectors
- **New instrumentation and innovative tracking and data processing solutions are required**

The pile-up challenge



B. Di Girolamo, 5th Joint Hi-Lumi LHC-LARP, Annual Meeting, 2015

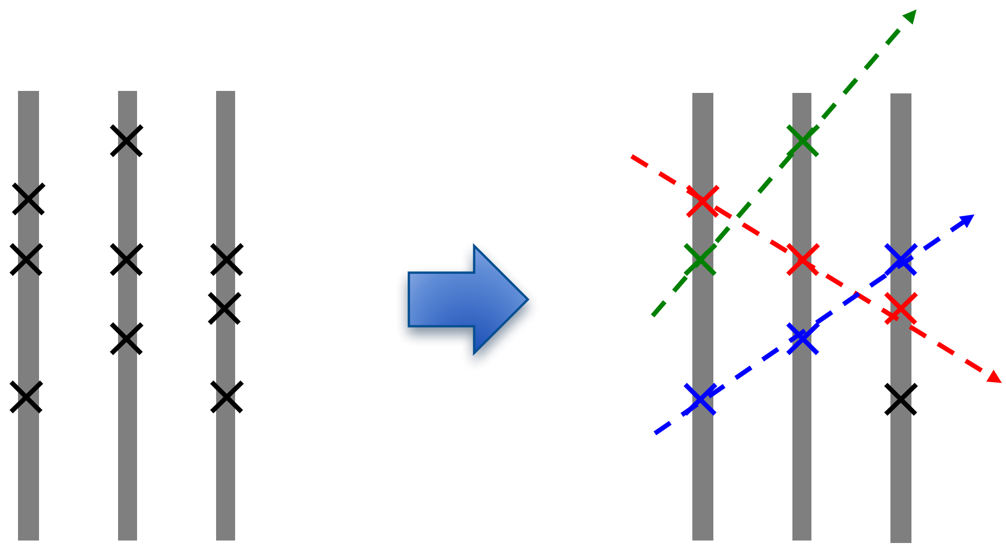
- With the foreseen pile-up density profile, a FWHM of about 300÷600ps is expected (depending on colliding scheme)
- A time-tagging resolution of O(10ps) will greatly help discriminating overlapping events with hit time-association

Time-stamped tracking

- Precise tracking is mandatory to identify unambiguously primary and secondary vertices

- Accurate track timing information can dramatically improve pattern recognition in the HL-LHC high pile-up conditions
  1. Simplification of pattern recognition (increased speed)
  2. Significant reduction in ghost tracks

- Effectively reducing occupancy in space and time

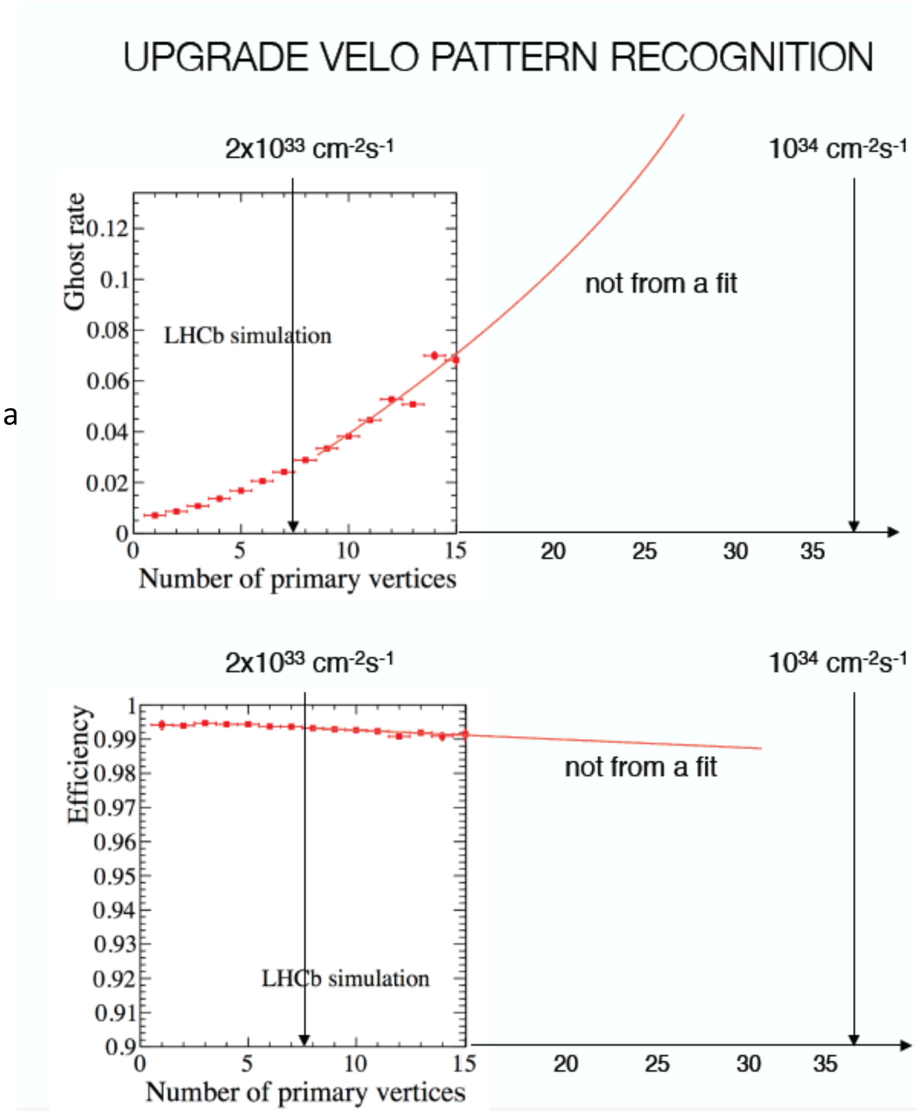


A Case Study: LHCb

- LHCb is investigating the possibility of running at a luminosity of $2x10^{34}$ $cm^{-2}s^{-1}$ (x10 w.r.t. current upgrade conditions)

- Tracking in the forward region, in particular in the vertex detector (VELO) volume, would be very challenging:
  - 10x track multiplicity, difficult pattern recognition with a huge increase of ghost track rate
  - 10x primary vertexes (PV), more difficult track association to PV
  - Accumulated dose approaching 10^{17} neq/cm^2 (in 10 years). For silicon sensors, present technology limited at 10^{16} neq/cm^2
  - For low p_T physics, the software trigger based on tracking information would demand large computing resources

- Huge amount of data to reconstruct and store is a main issue (already an issue at the current LHC)



The Proposal

- Develop and build an innovative 4D tracking detector
  - With excellent time (O(10 ps)) and position (O(10 μm)) hit resolutions
  - Able to operate in very harsh radiation environments (up to a total fluence exceeding 10^{16} 1 MeV neutrons equivalent per cm^2)
  - Capable of performing 4D real-time tracking allowing fast trigger decisions

- The precise measurement of the hit time is the key feature for an effective pattern recognition that can guarantee a high tracking efficiency and enhanced ghost track rejection

- Real-time track reconstruction with dedicated processors will allow an efficient operation in high-luminosity conditions

Detector Requirements

- In a timing detector the time resolution is given by

$$\sigma_t = \sigma_n / (dV/dt)_{@THR}$$

→ very low RMS noise σ_n and fast signals $(dV/dt)_{@THR}$ needed

- Many factors to be considered to achieve an accurate time response:
  - Fast charge collection in the detector
  - Large signals
  - Low detector capacitance
  - Matched amplifier bandwidth
  - Electric field uniformity in the detector
  - Energy release mechanism (total, straggling, direction)
  - Time-walk correction
  - Digitization (e.g. TDC bin size and linearity)
  - …

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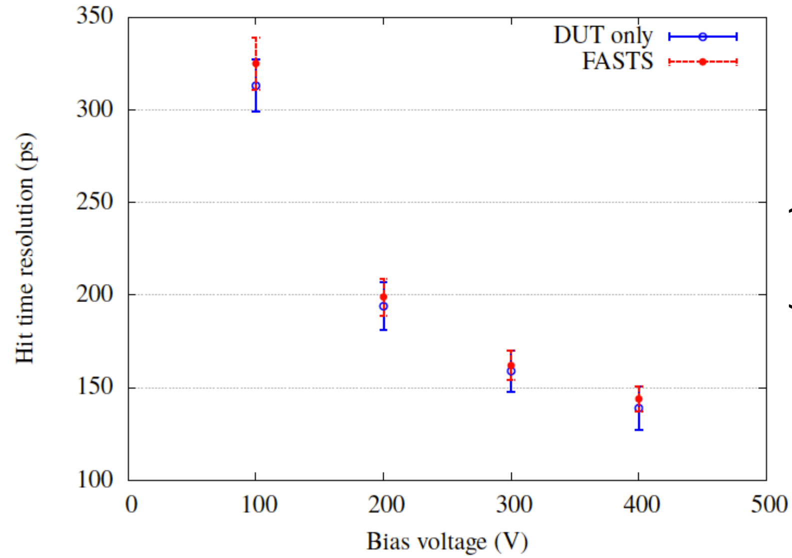
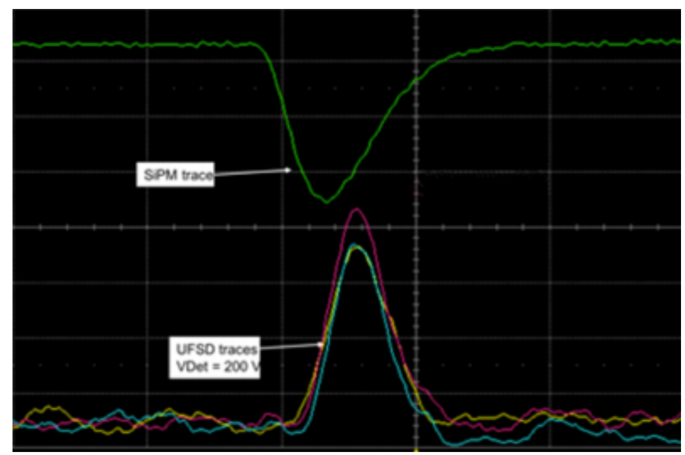
State of the Art

- Planar Silicon detectors: NA62 Gigatracker
  - 200um thick planar sensor (p-on-n and n-on-p), 300 um x 300um pixels
  - 98ps TDC bin, time-over-threshold discriminator (TDCpix ASIC)
  - Over-depleted operation (> 300V)
  - Time resolution better than 150ps



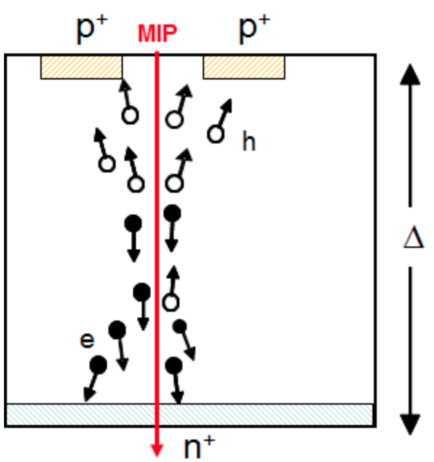
JINST 10 (2015) P12016

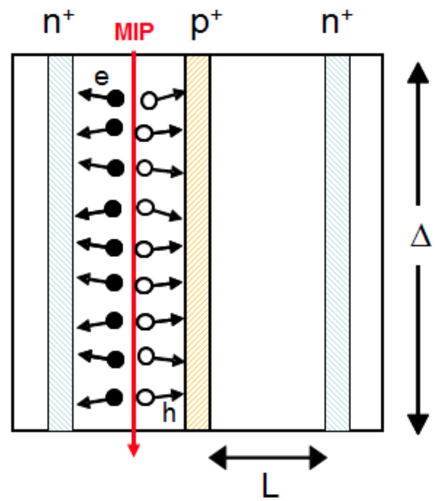
- Ultra-Fast Silicon Detectors
  - 50um thick n-on-p Low-Gain Avalanche Detectors (LGAD) with p+ multiplication layer
  - Recently measured an impressive time resolution of 25ps on 1.4mm^2 single-pad sensor operating at 200V

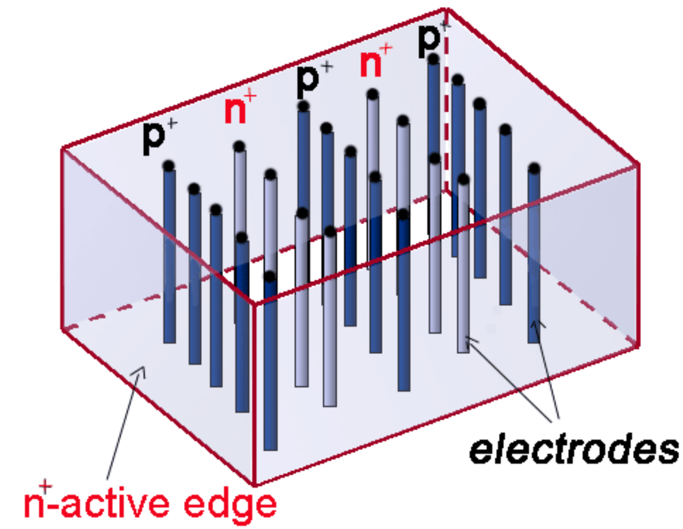


arXiv:1608.08681

3D Sensors





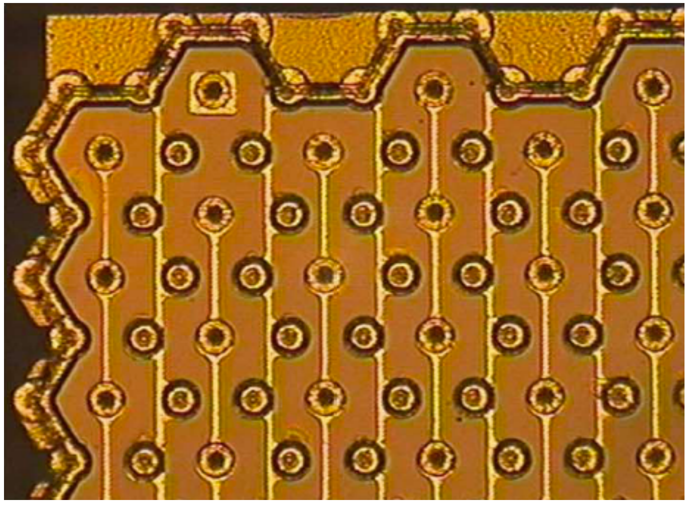


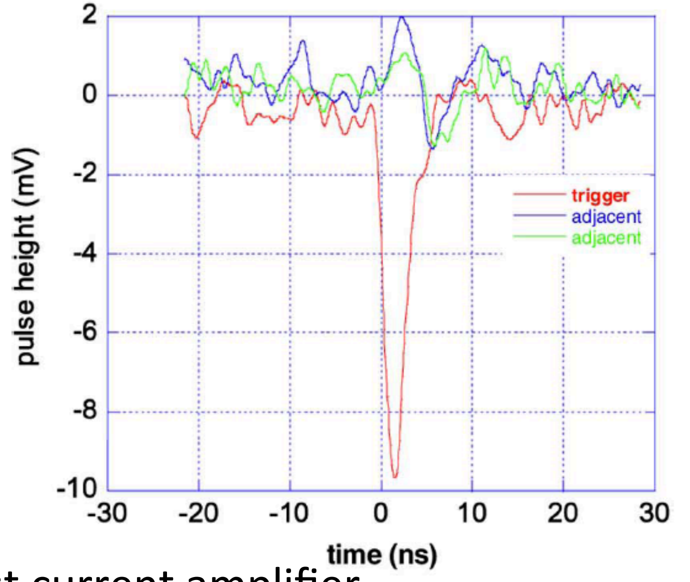
S. Parker et al., NIM A395 (1997) 328.

- Advantages
  - Low depletion voltage (lower power)
  - Short charge collection distance
    - Fast signals
    - Less trapping probability after irradiation
  - Lateral drift → cell "shielding" effect
    - Lower charge sharing
  - Active edges
- Disadvantages
  - Non-uniform spatial response
  - Higher capacitance w.r.t. planar sensors
  - Less well established (and more complicated) technology

Timing with 3D Pixels

S. Parker et al., Trans. Nucl. Sci. Vol. 58 No. 2 (2011)





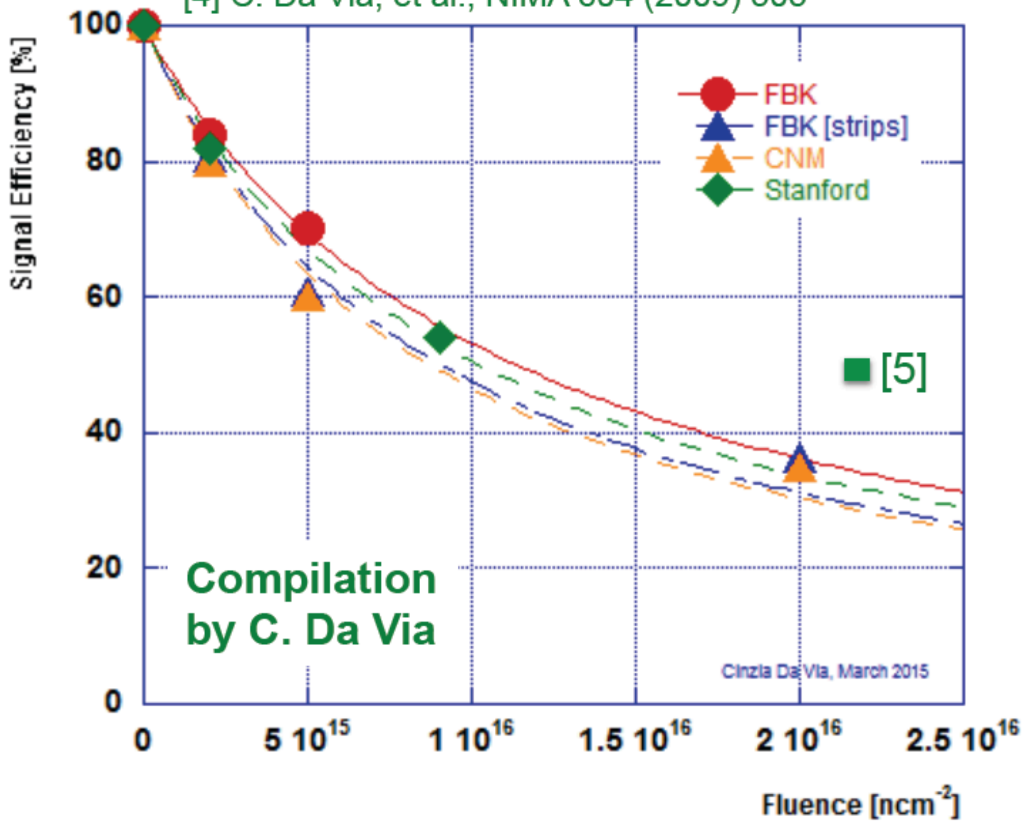
- Tested with 3D hexagonal cells with a fast current amplifier
  - Sensor exposed to ^{90}Sr source
  - Offline analysis of recorded waveforms
- Time resolution limited by FE noise, ranging from 30ps (large signals) to 180ps (small signals)

- New cell design – optimized for timing – are possible!
- Time resolutions of O(30ps) using CFD seem achievable

- 3D fast timing properties not yet exploited so far!

Radiation Damage

[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010
[2] G.-F. Dalla Betta, et al., NIMA 765 (2014) 155
[3] M. Koehler et al. NIMA 659 (2011) 272
[4] C. Da Via, et al., NIMA 604 (2009) 505
[5] I. Haughton et al., NIMA 806 (2016) 425

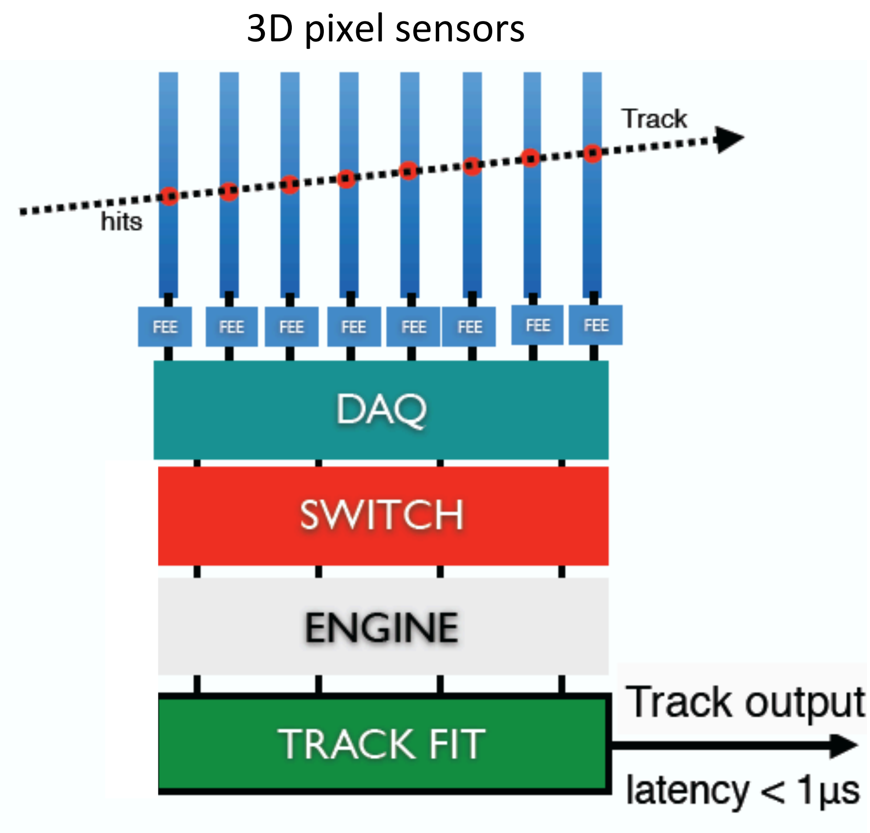


Impressive radiation resistance of 3D sensors

Real-Time Reconstruction

- Use fast track-finding devices based on custom processors to reconstruct tracks in real-time and relieve the workload of the online reconstruction and software trigger (save CPU time)

- Real-time track reconstruction can help selecting events with increased efficiency and reducing data size

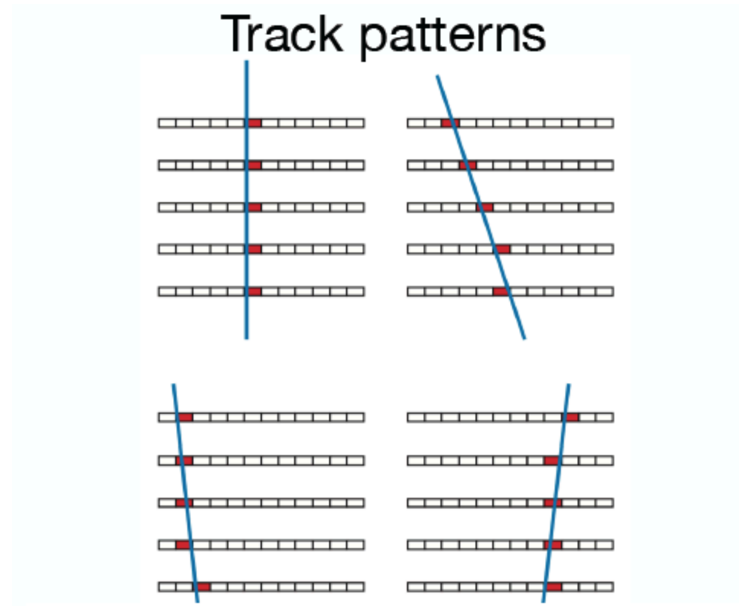


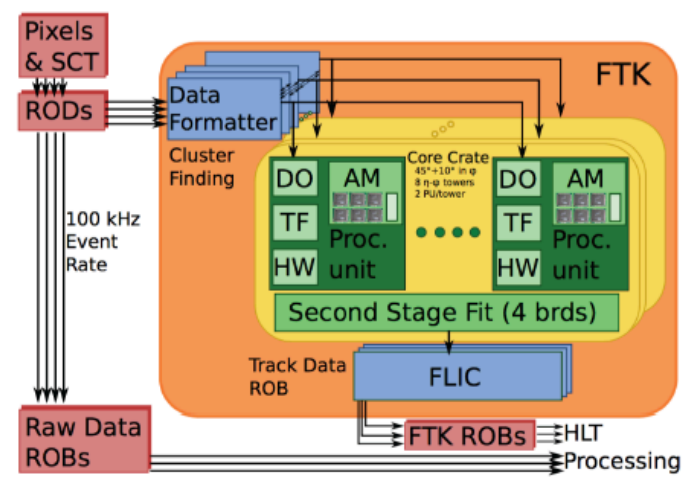
Existing Fast Track Finders

- Track pattern recognition without combinatorial:
  - Parallel matching of hits to pre-calculated track patterns, track parameters from linearized fit
  - Use custom ASICs: Associative Memory (AM), based on content addressable memory (CAM)

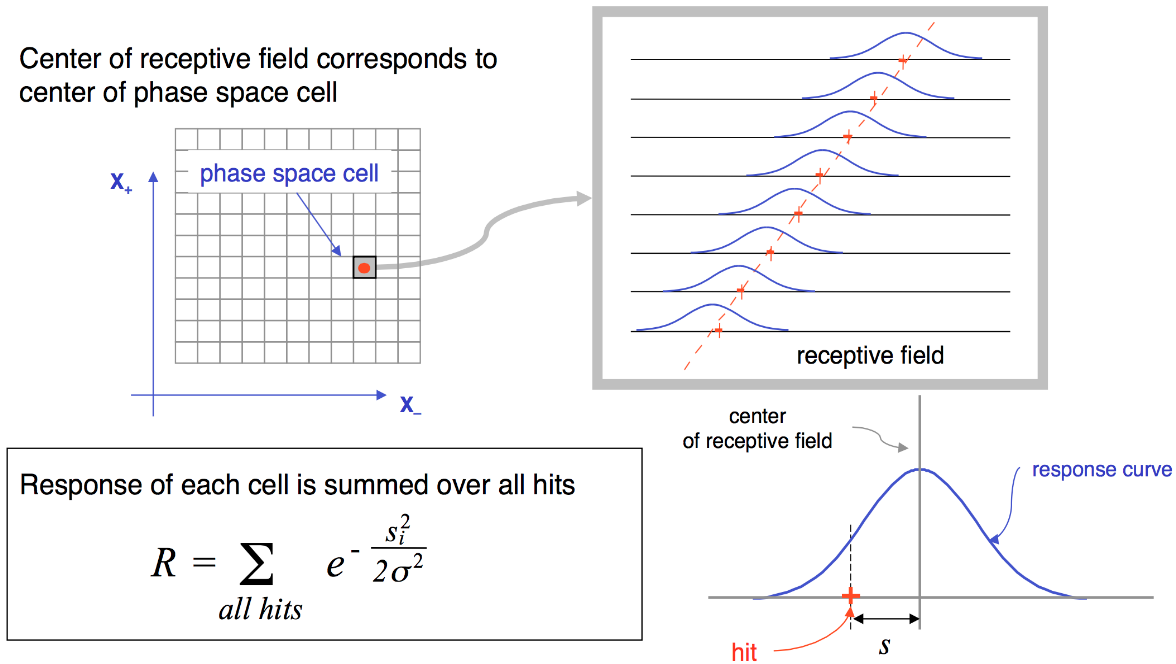
- First use in CDF experiment: SVT, latency 10μs and input rate 30 kHz

- FTK device in ATLAS use similar concept. Latency <100μs and input rate 100 kHz





A Possible Approach



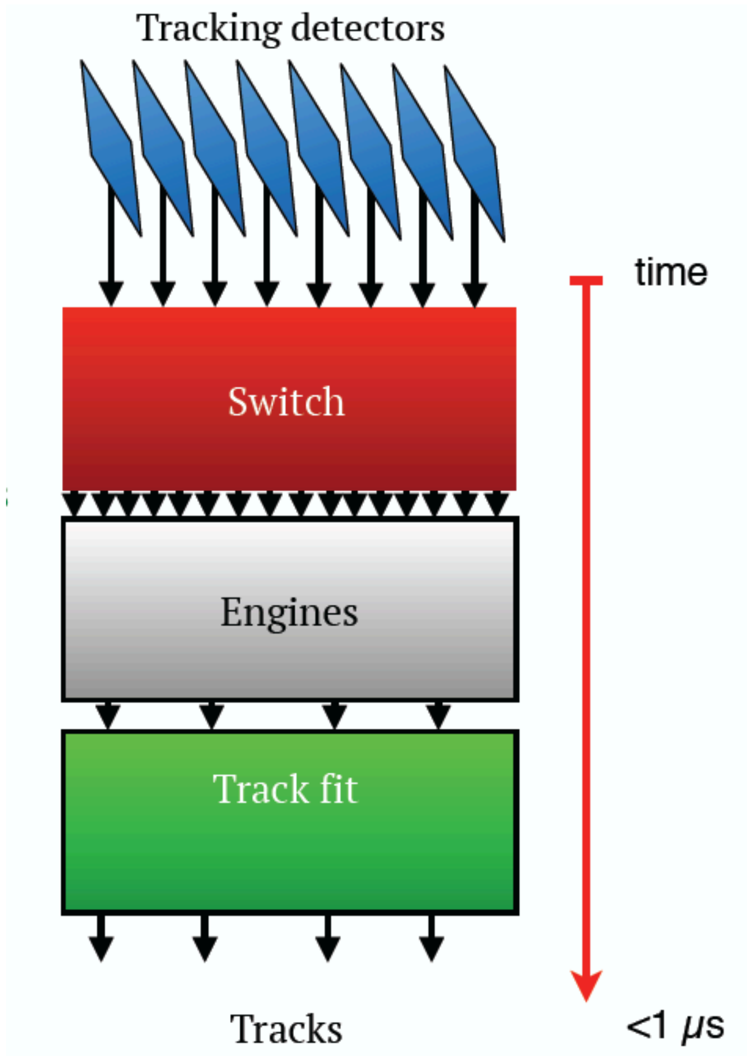
L. Ristori, NIM A453 (2000) 425.

- Inspired by mechanism of visual receptive fields
  - Massive parallelization and analog response of track receptors (*R*)
  - *P*attern recognition and track fit by interpolation of *R* values
- To be implemented in last generation FPGAs

The Architecture

- **Three main blocks**
  - Switch: delivers in parallel the hits from the detectors to only appropriate cellular units
  - Engine: block of cellular units for parallel calculation of the weights
  - Track fit: interpolation of adjacent cell weights for track parameter determination

- **Main differences w.r.t. AM approach**
  - Only relevant data reach the processing units (engines). Data processing already starts in the switch while data is transmitted
  - Retina algorithm provides analog response contrarily to AM "yes/no" pattern matching



Impact

- The impact of a 4D Real-Time Tracking Detector on the physics reach of future high-luminosity experiments is of paramount importance. The proposed concept could maximize the potential of experiments operating in the HL-LHC data taking conditions
- Flavor physics experiments operating at high luminosity will greatly benefit from this: high-efficiency triggering can only be done with a very configurable software trigger, and to afford the collection of huge data samples some tasks (pattern recognition, fitting, vertex finding) should be performed on the detector itself, which will provide more advanced "primitives" to the software trigger
- Such technologies are very likely to find interesting applications in many other fields, for example space research (where radiation-hard electronics is needed) and medical physics (faster real-time diagnostics could help in reducing the dose to the patient)

Summary

- Tracking at HL-LHC, and in particular in the forward regions – as in LHCb – will be a very challenging task

- 3D pixel detectors, optimized for an improved time response, appears to be a promising solution for an efficient tracking with a high ghost rejection capability, and are intrinsically capable of sustaining the huge radiation damage they will suffer

- Fast track-finders operating in real time appears to be crucial for effective triggering at level 1 and to reduce data rate to sustainable level