4D fast tracking for experiments at HL-LHC

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Outline

- HL-LHC main challenges
- Fast timing pixel detectors
- Fast track finding device
- Simulation studies for a harsh case scenario
- Conclusions

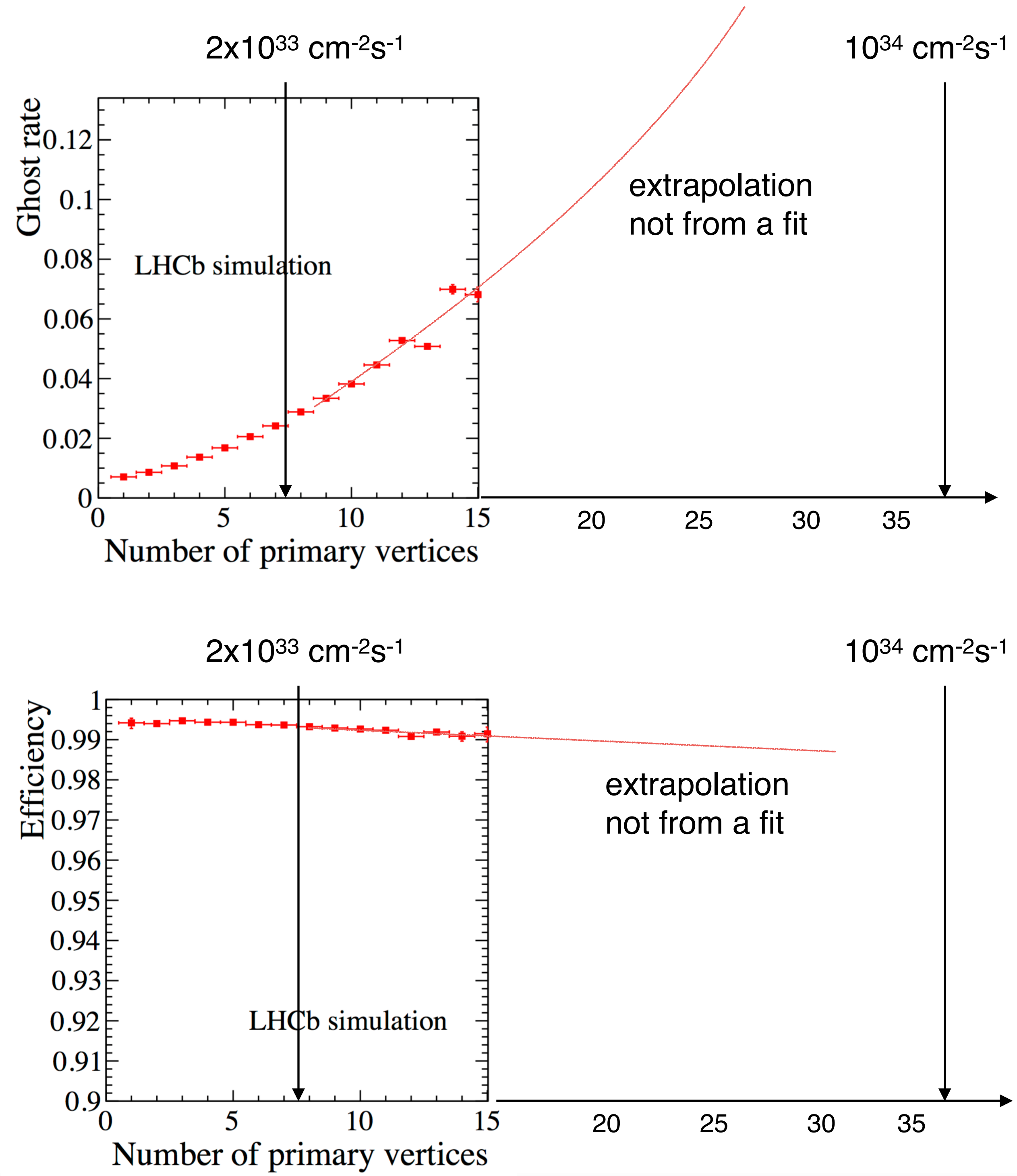
HL-LHC main challenges

- Full exploitation of the HL-LHC physics potential is a big challenge:
  - x10 nominal LHC luminosity
  - difficult event reconstruction, high pileup 140 pp interactions at $L=5x10^{34}$ $cm^{-2}s^{-1}$
  - radiation damage for innermost detectors
  - 40 MHz bunch crossing, very high data rates, huge amount of data to reconstruct and store
  - tracking at high lumi is very challenging in FW region for low p_T flavour physics experiments

LHCb VELO pixel detector as case study

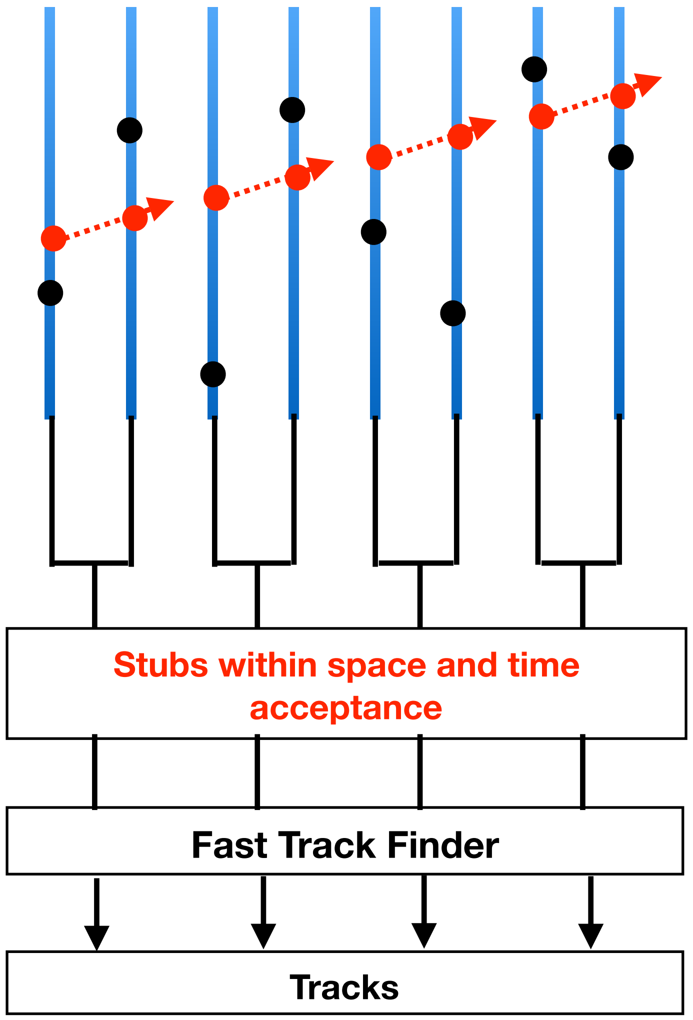
- A high-luminosity phase of LHCb aims at 10x lumi wrt upgrade conditions
- Tracking in FW region very challenging
  - radiation hardness, accumulated dose ~$10^{17} n_{eq}/cm^2$ (in 10 years)
  - silicon sensors, present technology can operate at $10^{16} n_{eq}/cm^2$
  - 10x track multiplicity, difficult pattern recognition - higher ghost track rate
  - 10x primary vertexes (PV), more difficult track association to PV
  - low pT physics, L1 software trigger based on tracking info would demand large computing resources

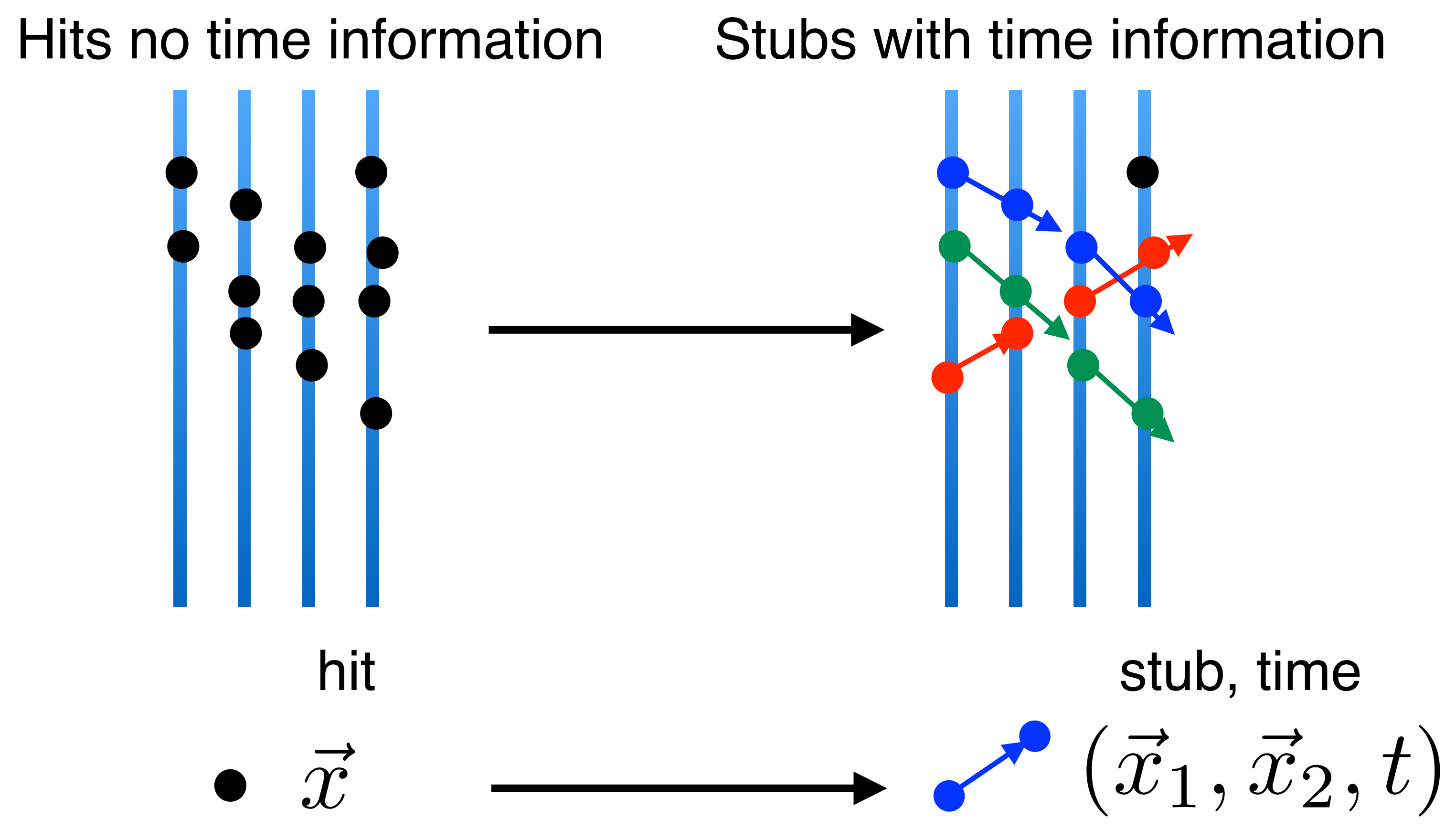
UPGRADE VELO TDR: LHCB-TDR-013



4D fast tracking pixel detector proposal

- Rad-hard pixel detector with precise space and time information for 4D tracking
- Detectors with embedded tracking capabilities providing track segments “stubs”



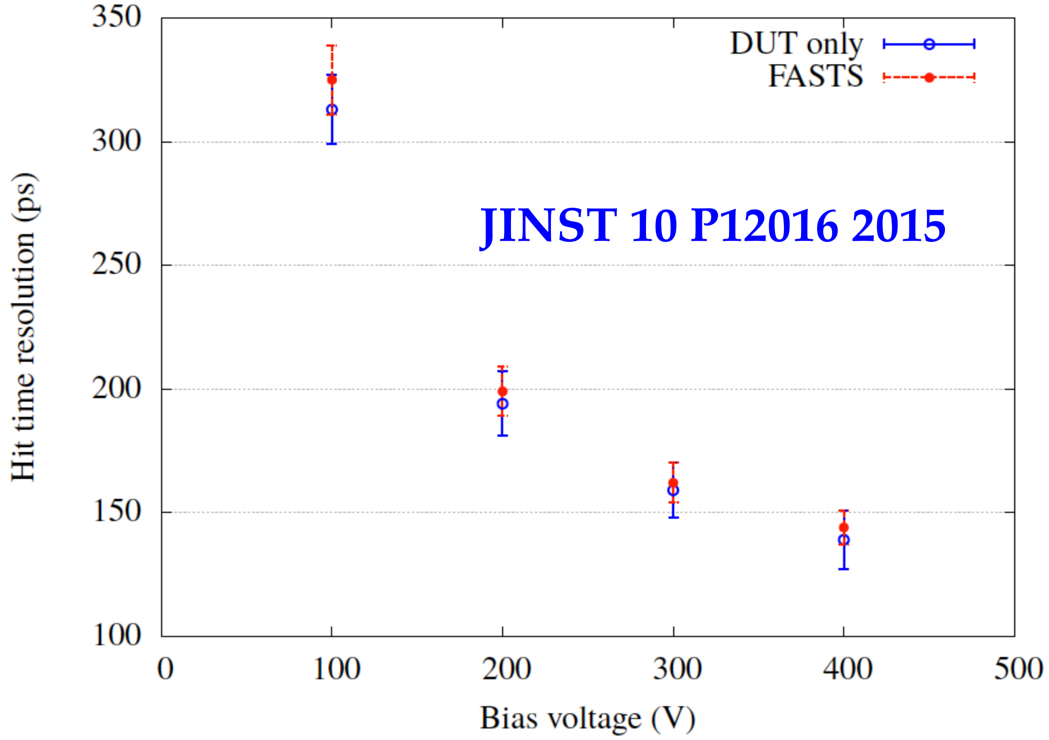


- Devices with embedded tracking capabilities in real time. Relieve workload of online trigger (save CPU time)
- Real-time track reconstruction can help selecting events and reducing data size (save bandwidth and disk space)

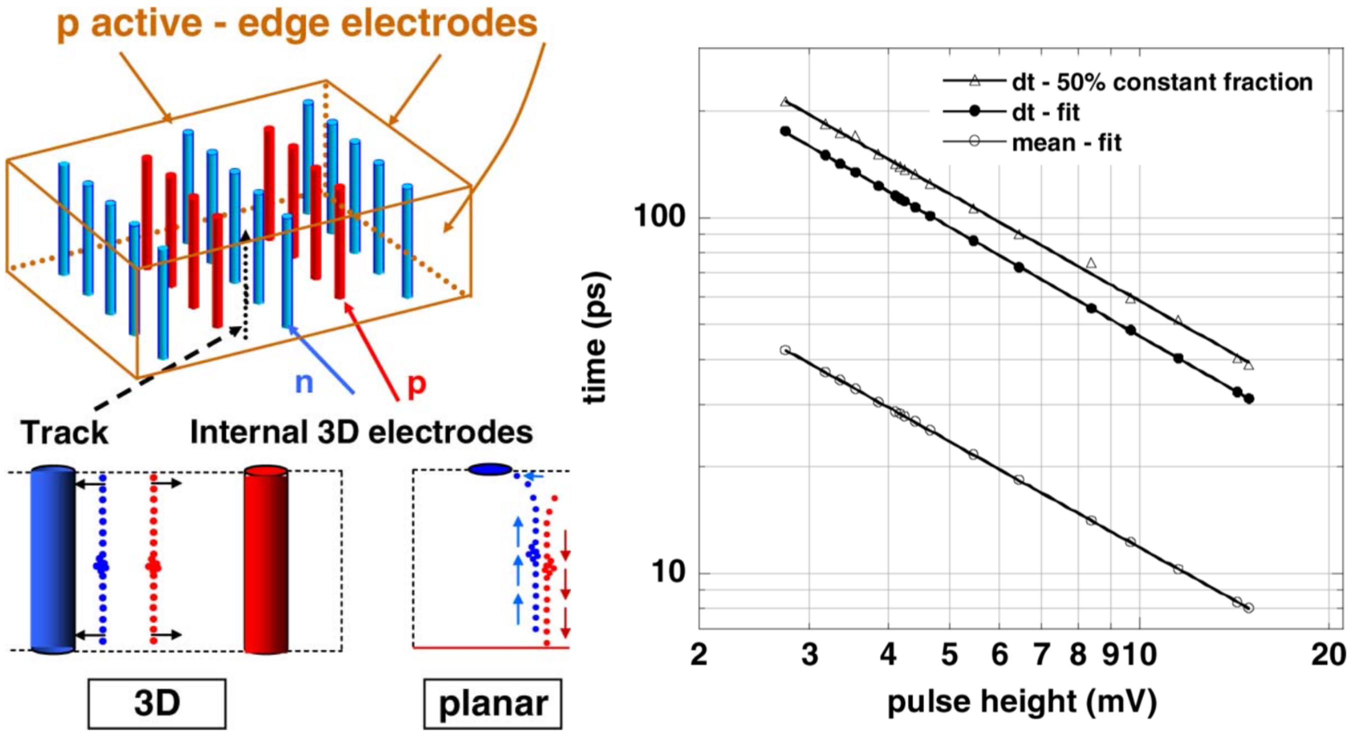
Fast timing rad-hard pixel sensors

- Status of art:
  - NA62 Gigatracker, 150ps resolution in testbeam. Pixel size 300μmx300μm, 200μm thickness
    - p-in-n sensor, FEE IBM 130nm technology, CO_2 active cooling
  - UFSD, very promising results - 25ps time resolution (pad $1.4mm^2$)

    arXiv:1608.08681
- 3D silicon sensor technology:
  - radiation hard, works at $10^{16} n_{eq}/cm^2$
  - sub-ns time resolution is achievable
  - R&D is needed to achieve the goal of 30ps time and 40μm hit resolution



IEEE Trans. Nucl. Sci. 58 (2011) 404-417



Fast track finding device

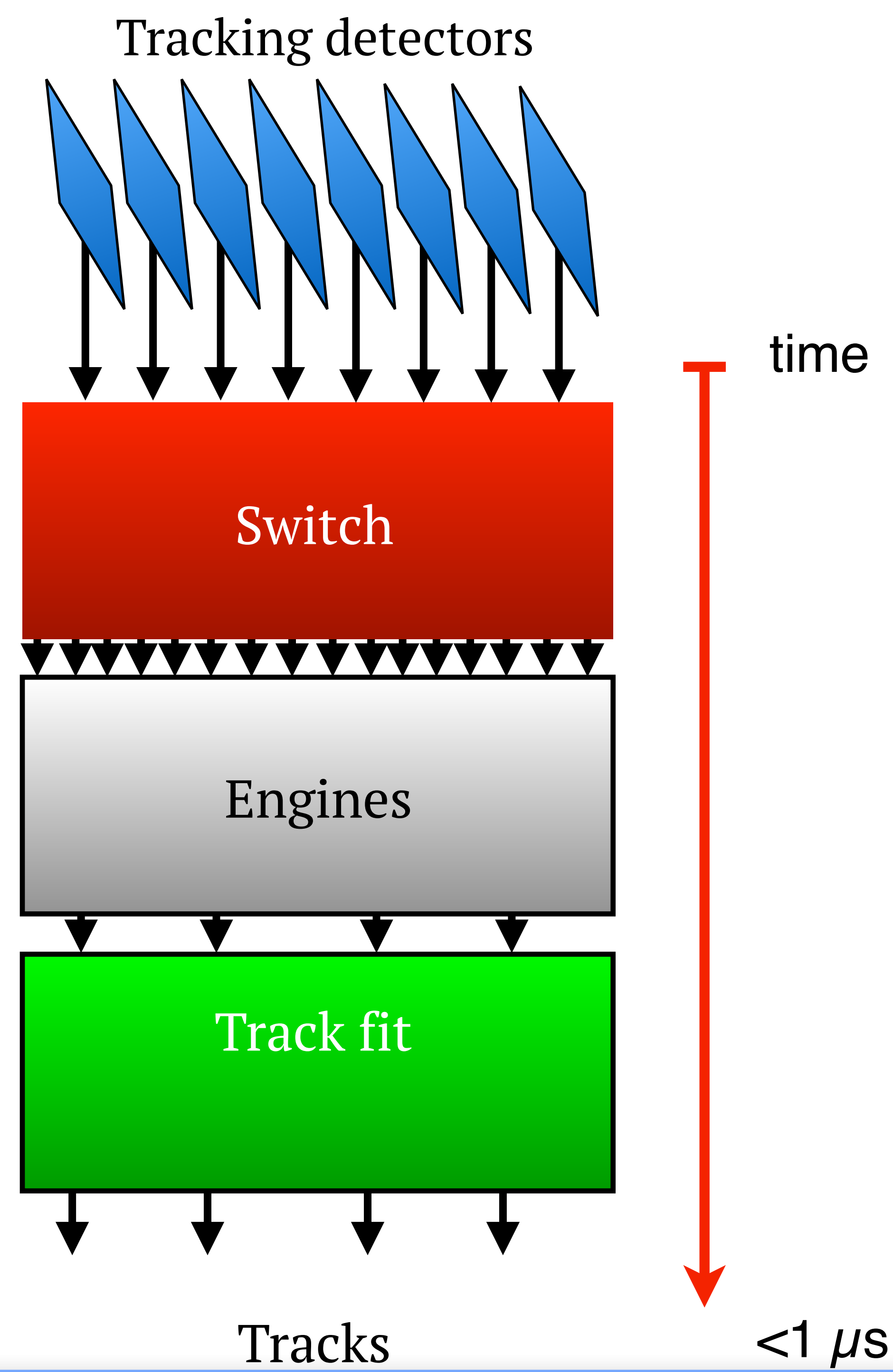
- **System based on artificial retina**

L. Ristori, NIM A453 (2000) 425-429 A. Abba et al., CERN-LHCb-PUB-026

First test beam results

NN et al, http://dx.doi.org/10.1016/j.nima.2016.05.129

- **Three main blocks implemented in FPGA:**
- Switch: delivers in parallel the hits (stubs) 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 with AM approach:**
  - only relevant data reach the processing units (engines). Data processing starts already in the switch while data is transmitted
  - retina algorithm provides analog response contrarily to AM “yes/no” pattern matching

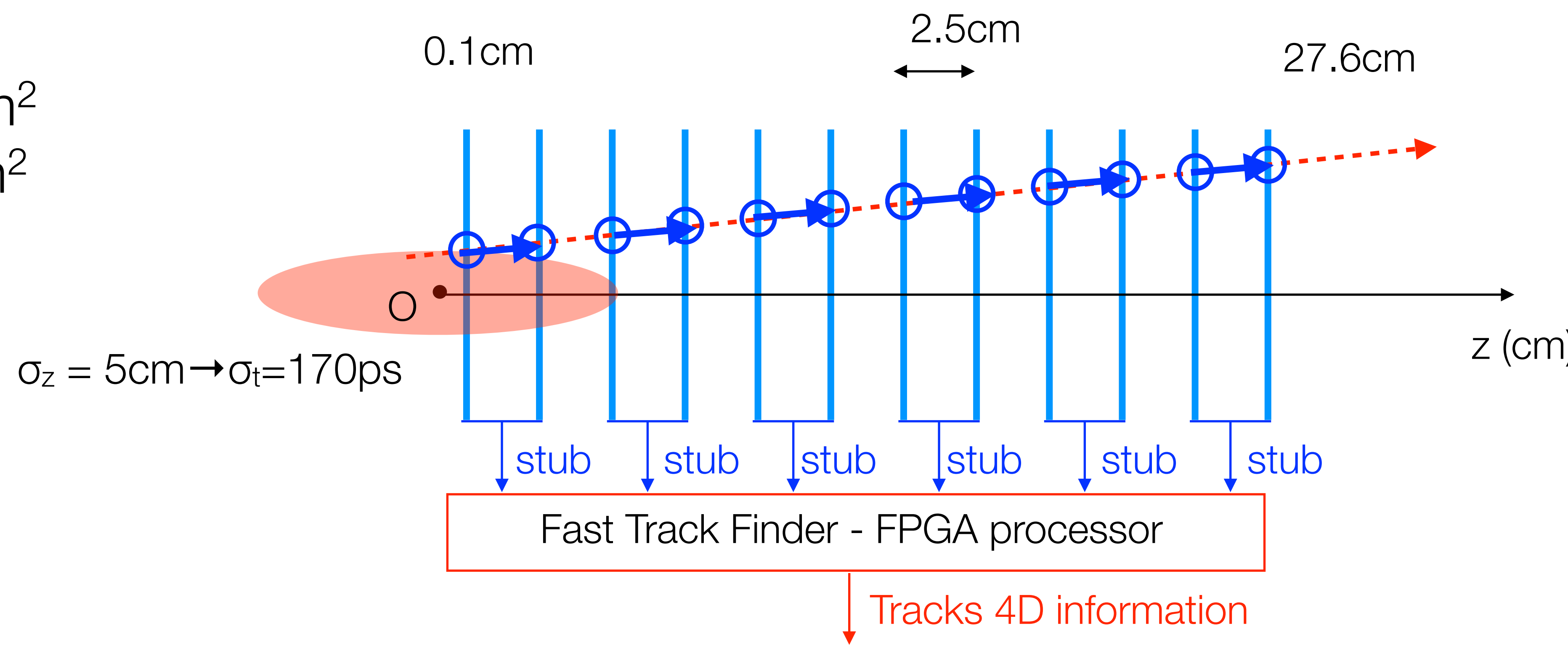


4D fast tracking simulations

NN, M. Petruzzo in preparation

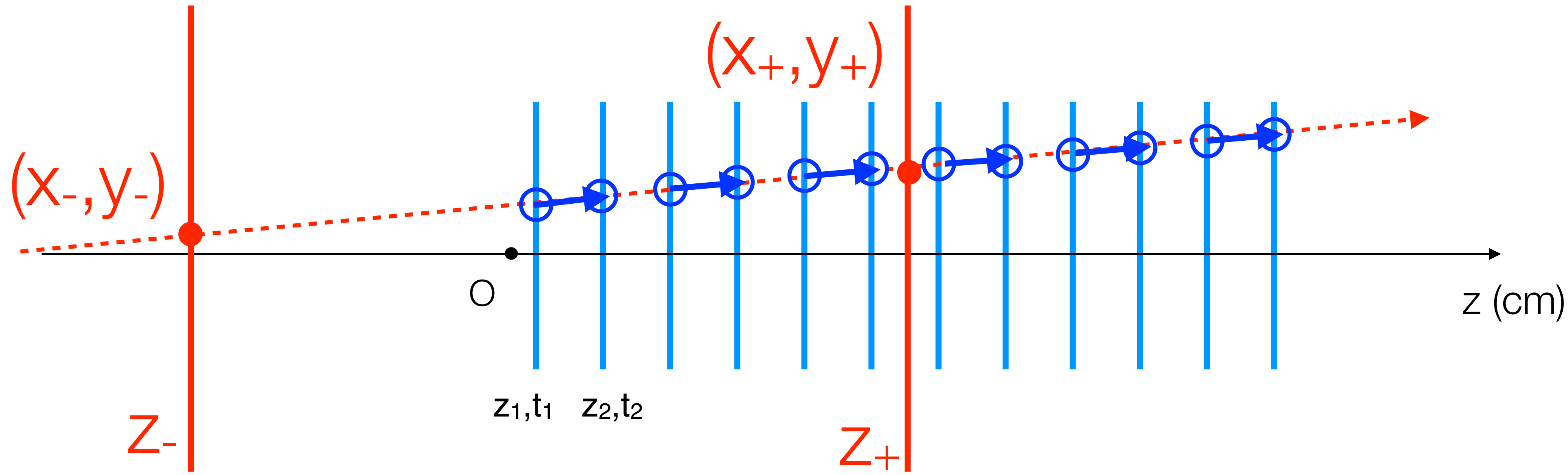
- Simple case: 12 layer telescope in forward region
- At lumi=$10^{34}cm^{-2}s^{-1}$: pileup~40 and ~1200 tracks/event

Sensor area = $6x6cm^2$
pixel size = $55x55\mu m^2$
thickness = 200 μm
time res σ_t=30 ps



- Reconstruct stubs at early stage, e.g. in FPGA: apply acceptance cuts (time, direction), reduce data flow and simplify track reconstruction
- Provide stubs in input to Fast Track Finder FPGA processor for real-time 4D track reconstruction using space and time information

Stub based fast tracking approach



- Stubs are projected to reference planes (in red) and a (x_-,y_-), (x_+,y_+) pair identifies a 3D track. No further processing required, see CERN-LHCb-PUB-026
- Time of the stub: $t_{stub}=(t_1+t_2)/2$, velocity $v = \frac{t_2 - t_1}{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2}}$
- Select stubs within space and time acceptance

$$\left|\frac{dx}{dz}\right|, \left|\frac{dy}{dz}\right| < 0.3 \quad \mathrm{IP}_{xy} < 1\mathrm{mm} \quad |z| < 10\mathrm{cm} \quad |v/c - 1| \leq 4\sqrt{2}\sigma_t c/\Delta z$$

- Measure 3D track parameters and time of the track at the origin, t_0

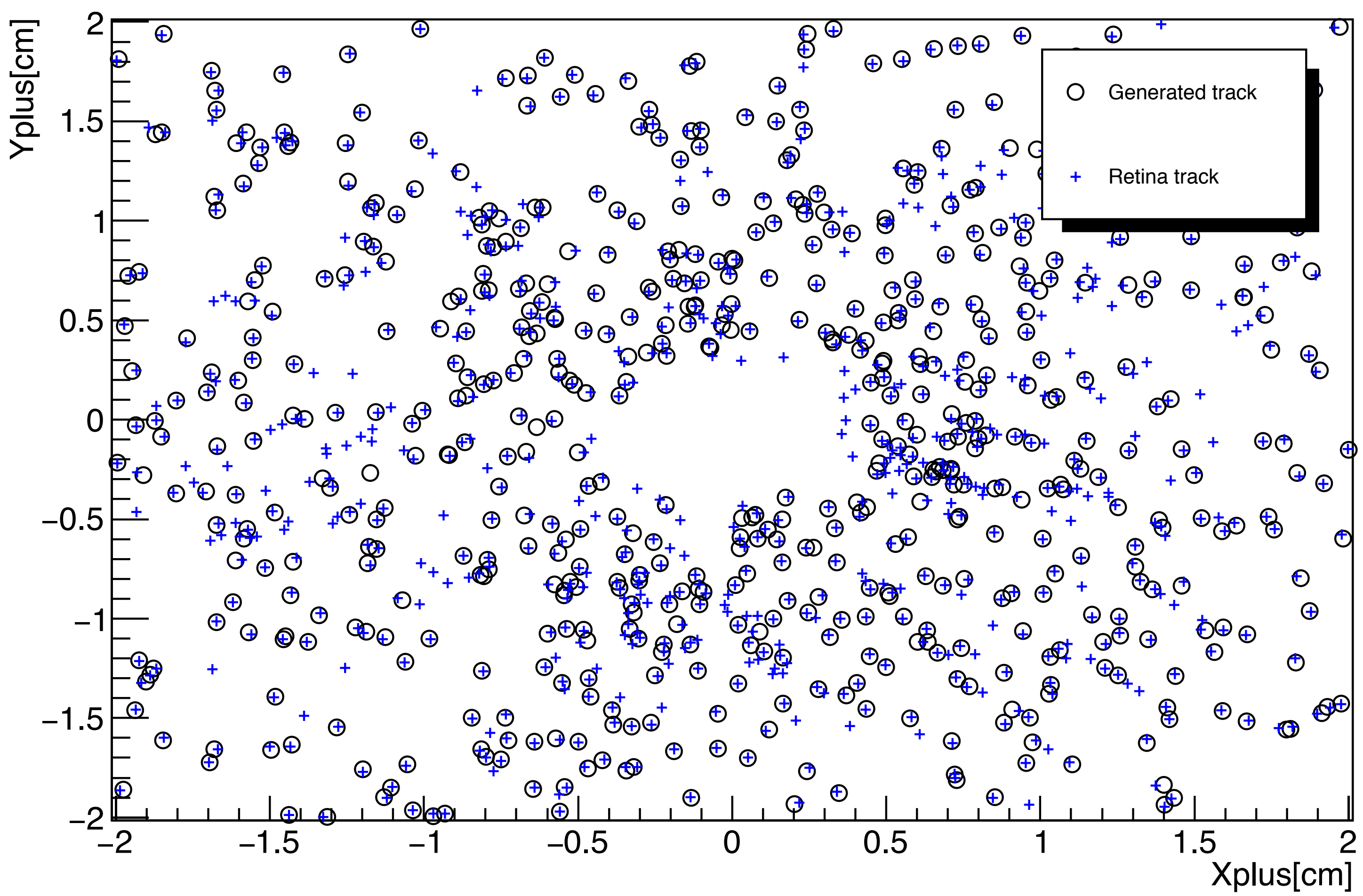
4D fast track finding algorithm

- Artificial retina algorithm adjusted to use stubs info:

$$W = \sum_{all\ stubs}^{N} \exp\left(-\frac{s_i^2}{2\sigma^2}\right) \qquad W_N = W/N$$

$$s_i = |(x_+, y_+)_{\mathrm{stub},i} - (x_+, y_+)_{\mathrm{engine}}|$$

Distance of the stub projection from the track receptor in the reference plane (x_+,y_+)



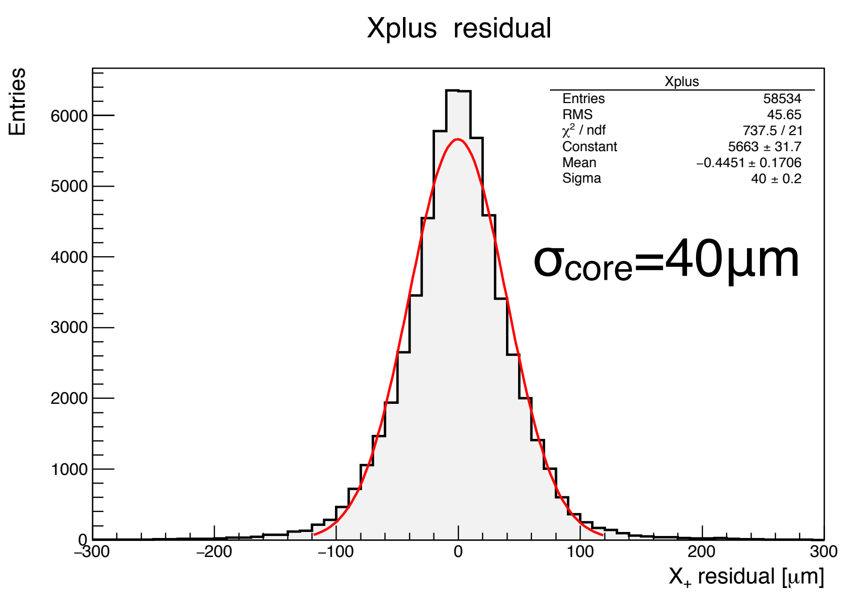
A local maximum of the artificial retina response W, identifies a track

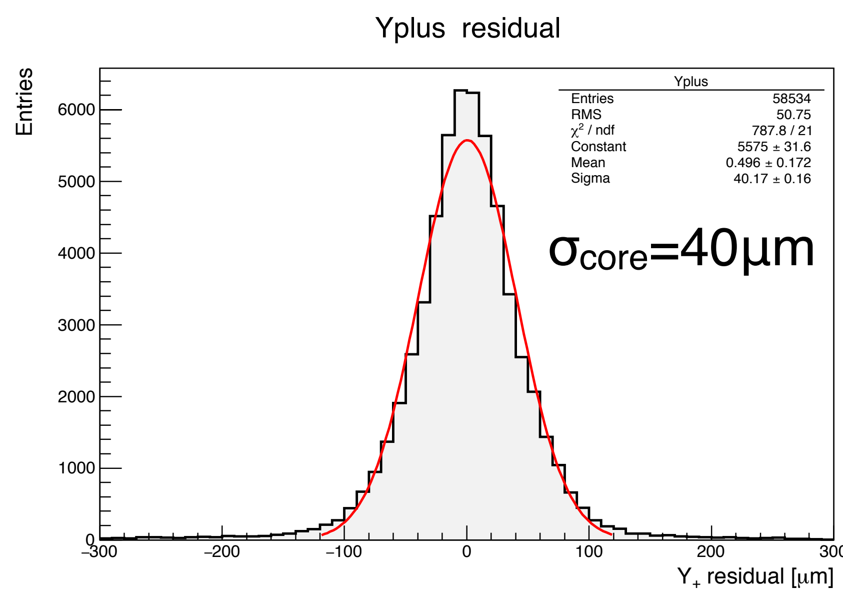
x_+,y_+ track parameters are calculated by interpolation of W values around maximum response

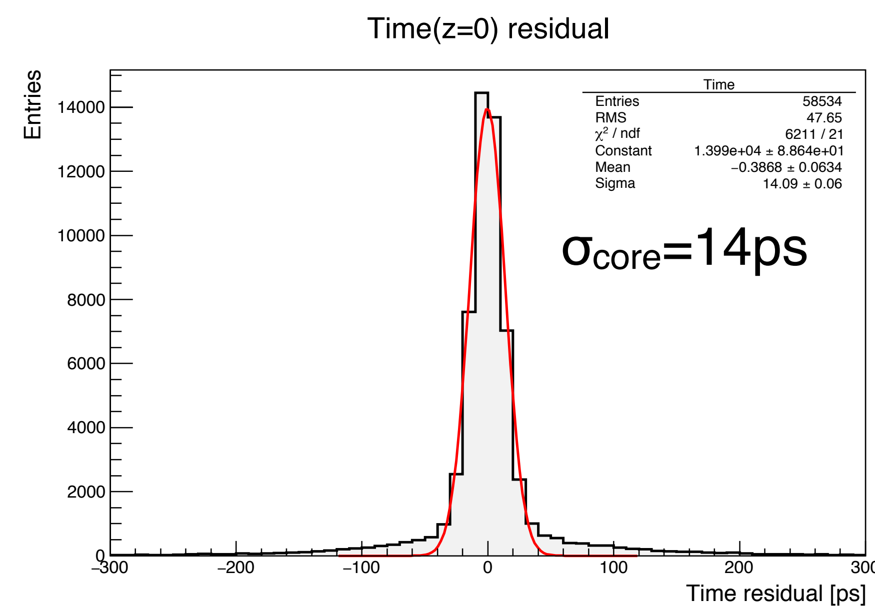
x_-,y_- track parameters and time of the track at the origin t_0 are determined by the engine with maximum W value

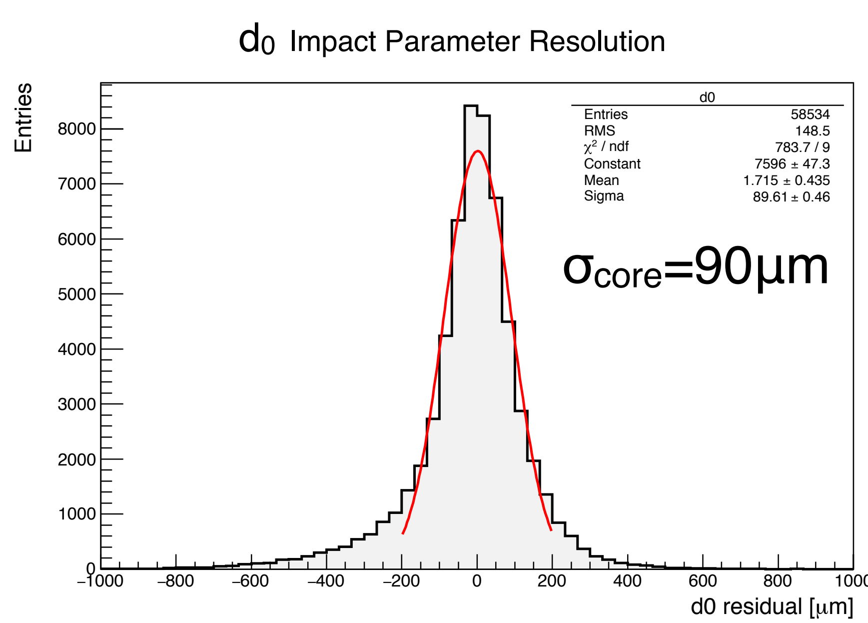
Resolution on track parameters

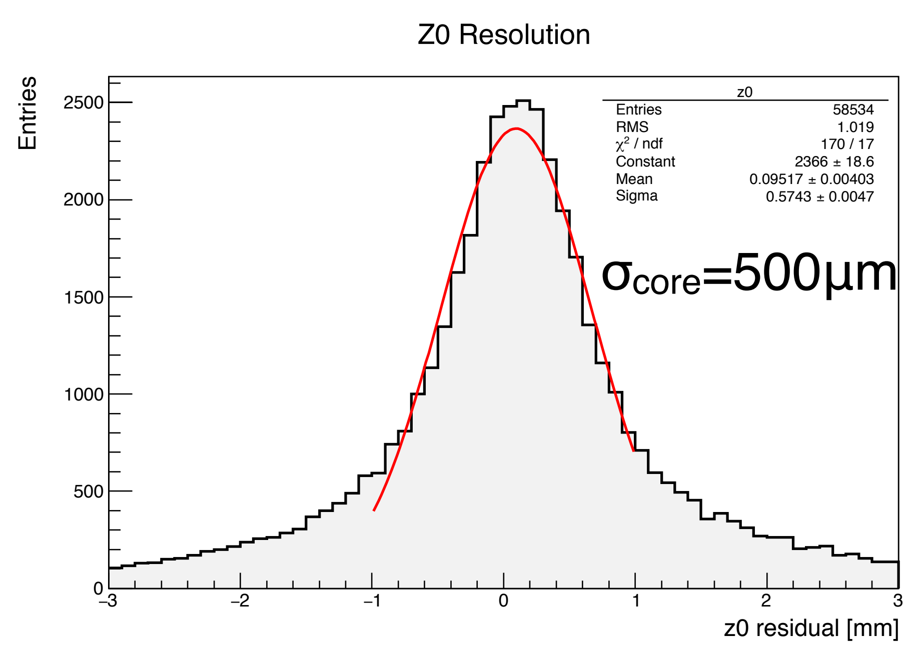
- Events with 40 pp interactions, 1200 tracks per event









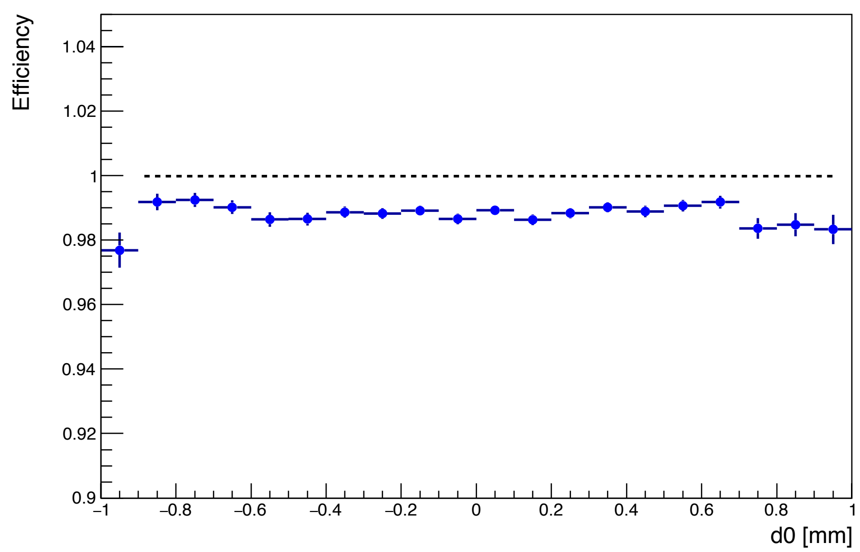


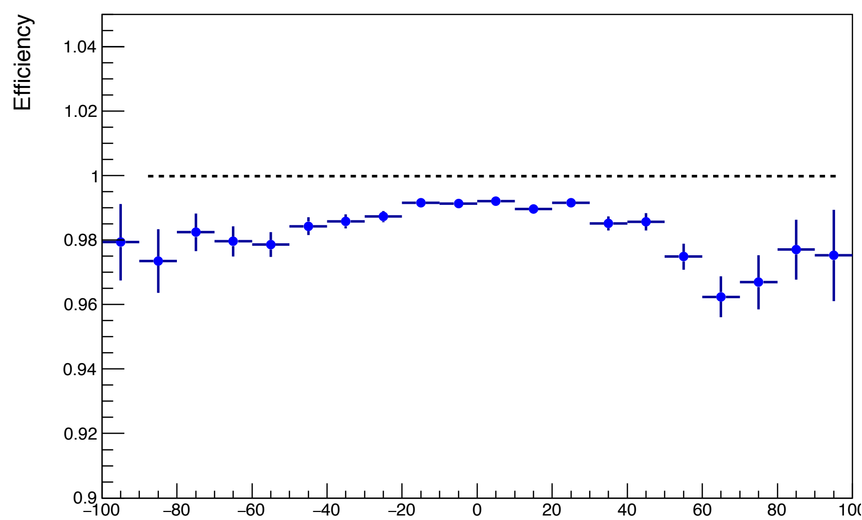
Online track reconstruction efficiency

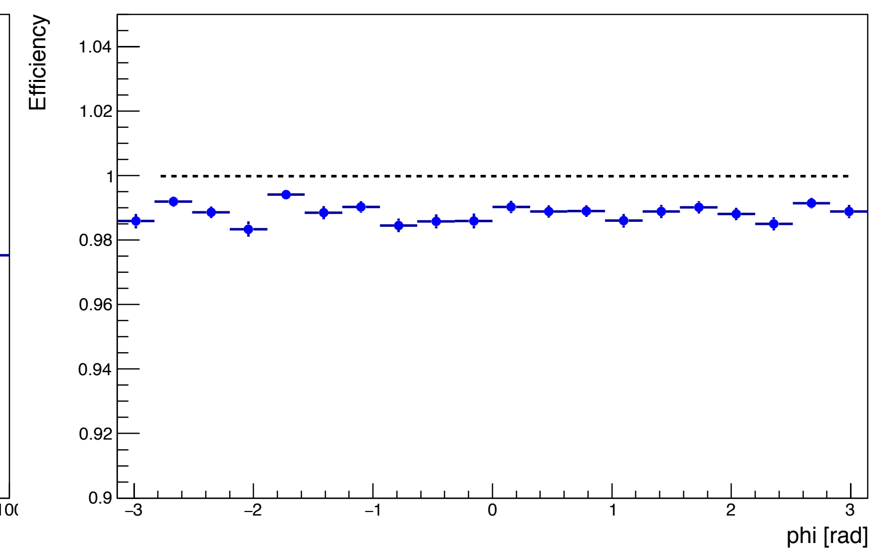
- Track efficiency vs track parameters: d_0, z_0, ϕ, η

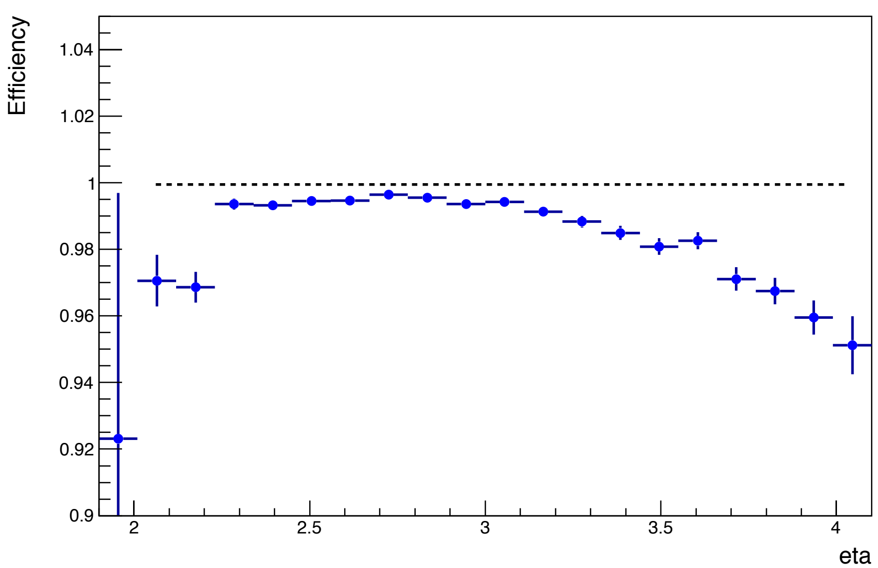
  d_0, z_0 (distance of closest approach to z axis), ϕ azimuthal angle, η=pseudo rapidity

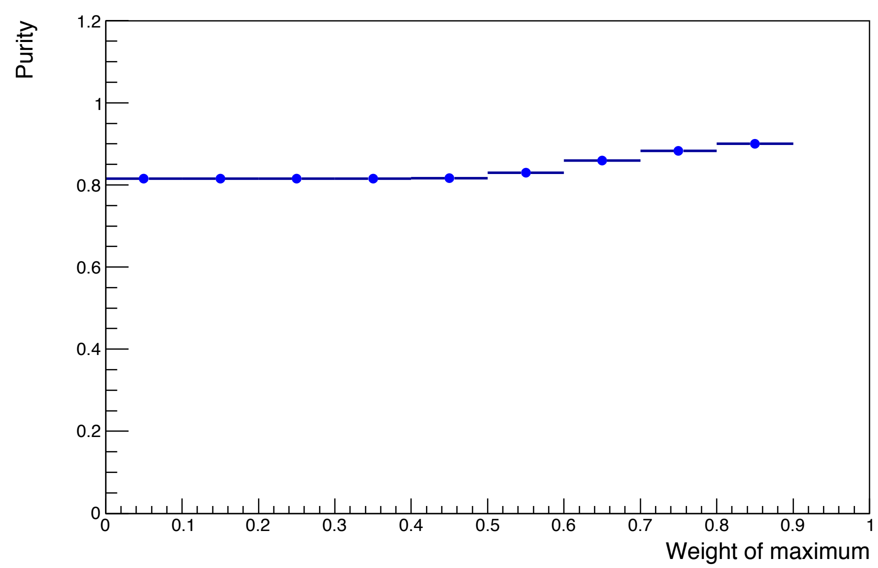
- Track efficiency ~99% and track purity >80% with 1200 tracks per event → track purity ~60% (without time information of the hit)









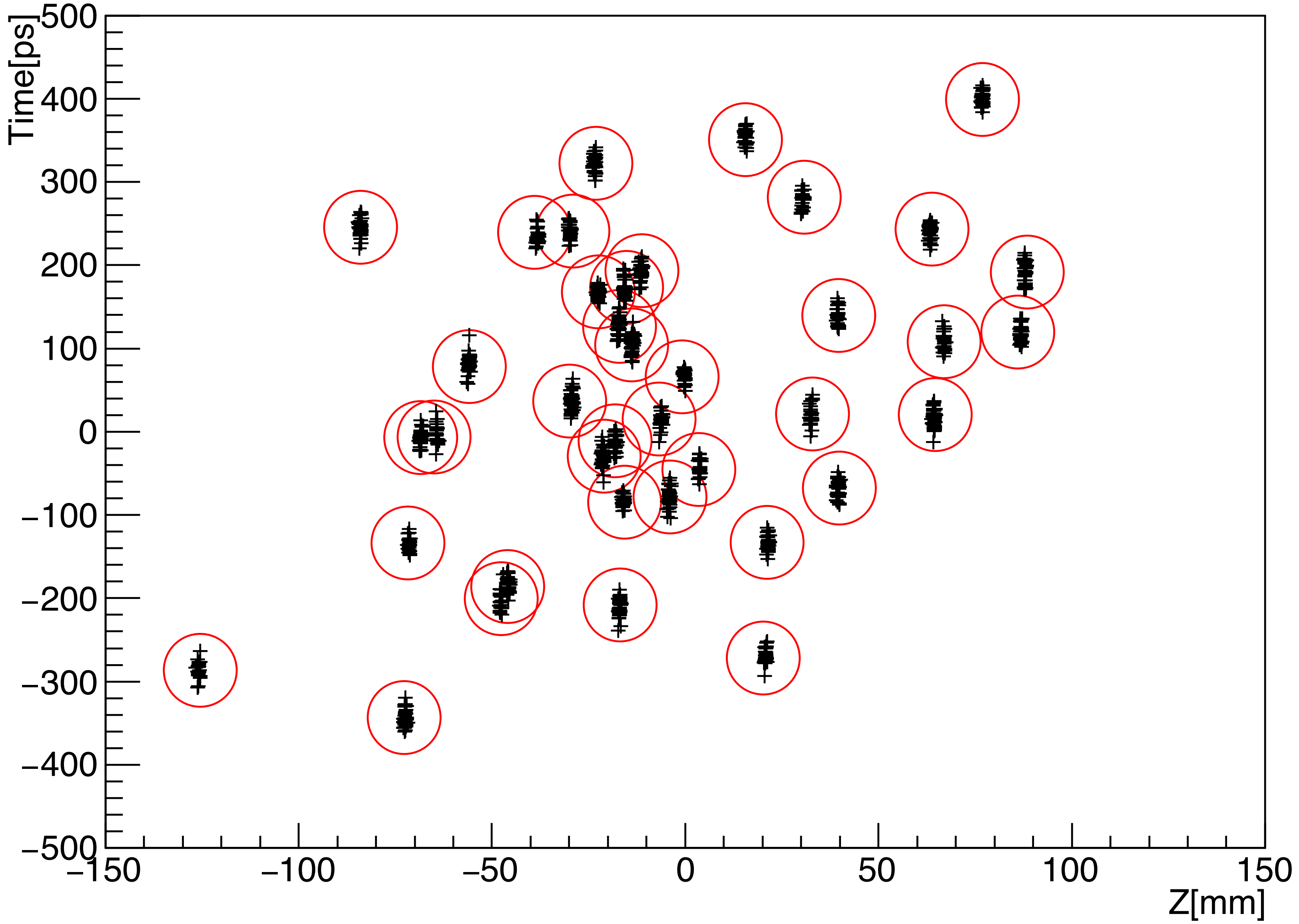


- With 2400 tracks/event, online track efficiency 98,7% and purity 60%

- System is not optimised, room for improve track purity

Track association to primary vertex

- Separate tracks in space and time: improved association of tracks to primary vertex
- Track mis-association >10% (no time information) → <1% using precise time information of the hit in offline reconstruction



Conclusions

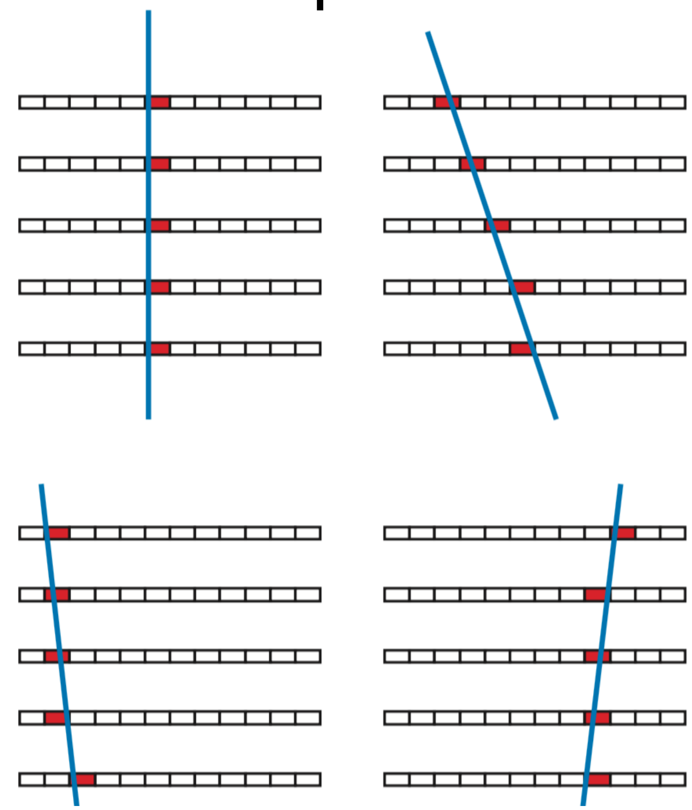
- Tracking at HL-LHC is very challenging and requires new instrumentation and advanced solutions
- Radiation hard pixel sensors with precise space and time information are crucial for charged particle tracking at high luminosity
- Fast track finders are also crucial to reduce data rate to sustainable level and maintain good efficiency and purity for signal events
- A conceptual design for a 4D fast tracking device based on rad-hard fast timing pixel detectors and artificial retina architecture has been proposed here:
  - preliminary results of simulated tracking performance in the harsh FW region environment are encouraging
  - good reconstruction efficiency, purity and association of tracks to primary vertexes using space and time information
  - R&D is ongoing/planned at INFN on sensors, front-end electronics and real-time tracking. Eventually organise a system design

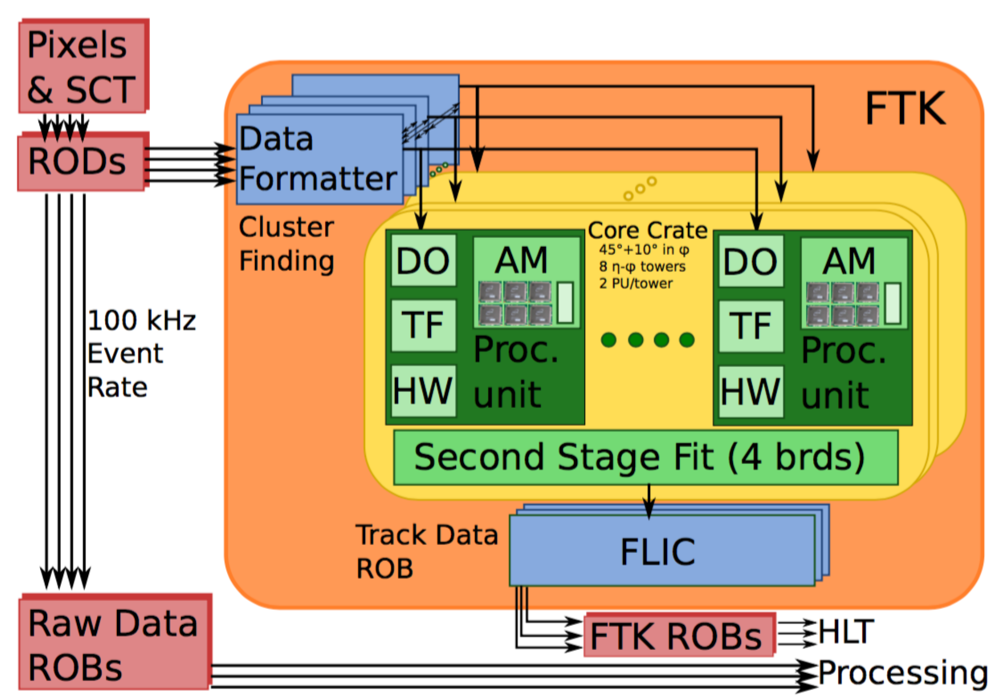
Backup

Fast track finders

- Track pattern recognition without combinatorics
  - parallel matching of hits to pre-calculated track patterns, track parameters from linearised 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 ~50μs and input rate 100 kHz
- Real time tracking is extremely challenging at LHC: 40MHz throughput, large flow of data Tbit/s, short latency ≲1μs

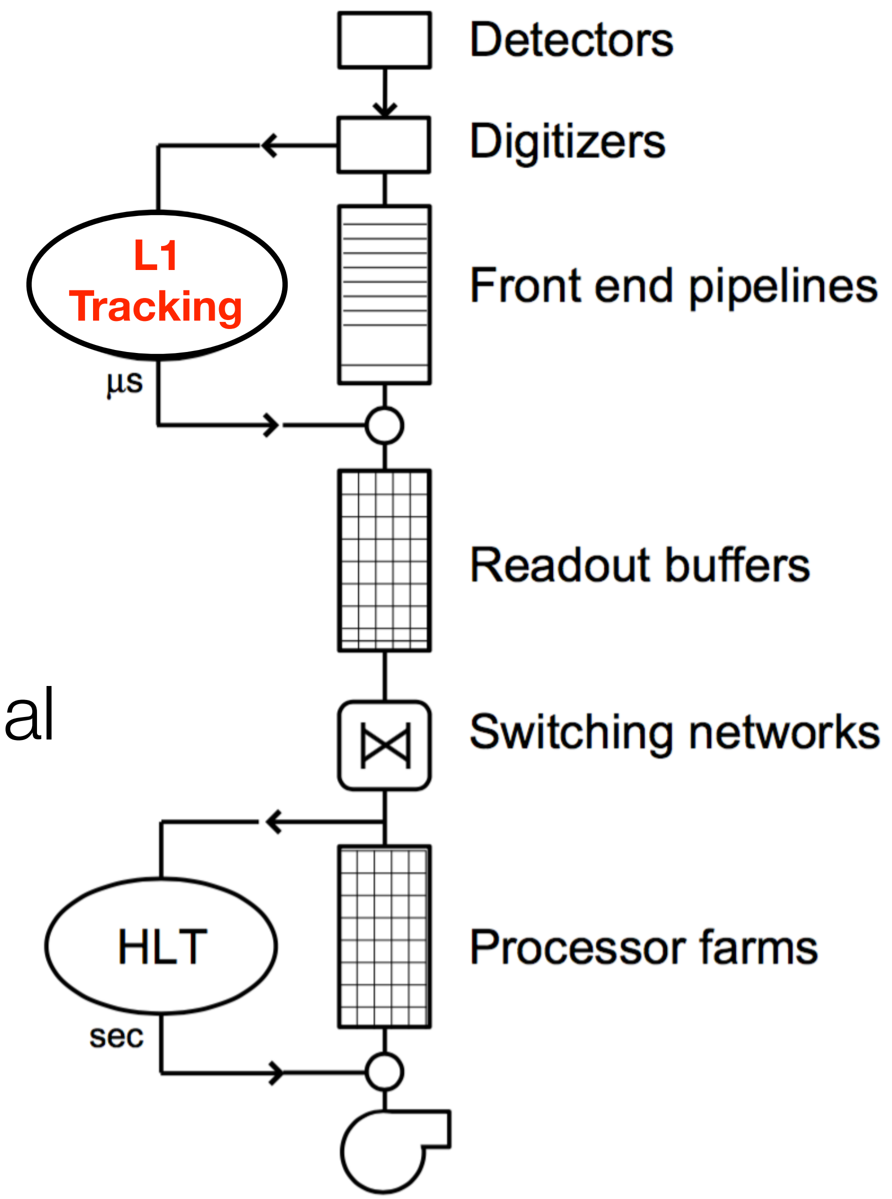
Track patterns





Real time tracking for HL-LHC

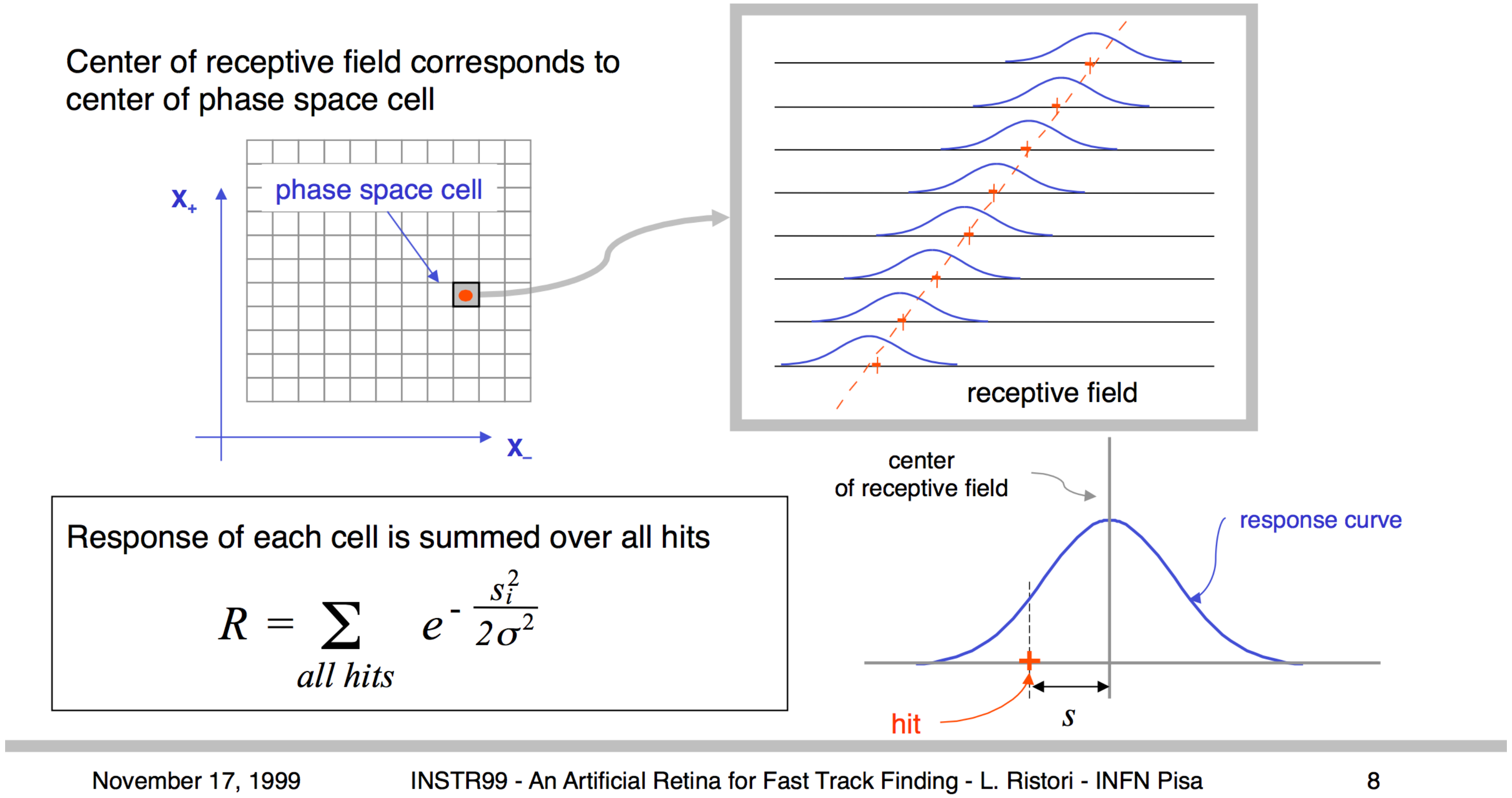
- Full exploitation of high luminosity LHC (HL-LHC) requires new detectors and trigger systems
- L1 trigger decisions based on tracking information are crucial:
  - reduce data rate to a sustainable level
  - maintain good efficiency and purity for signal events
- Real time tracking is extremely challenging at LHC: 40MHz throughput, large flow of data Tbit/s, short latency ≲1μs
- Necessary to find innovative solutions



Artificial retina algorithm

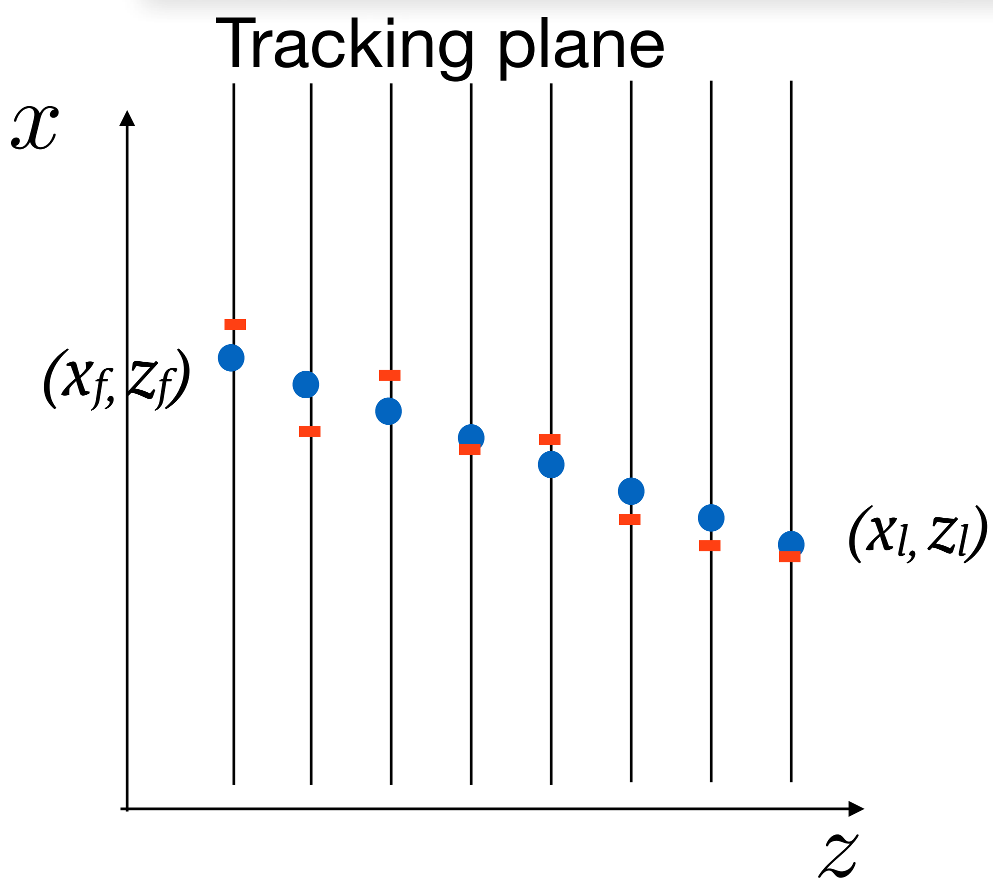
- Basic algorithm for fast track finding

L. Ristori, "An artificial retina for real-time track finding" [NIM A453 (2000) 425-429]



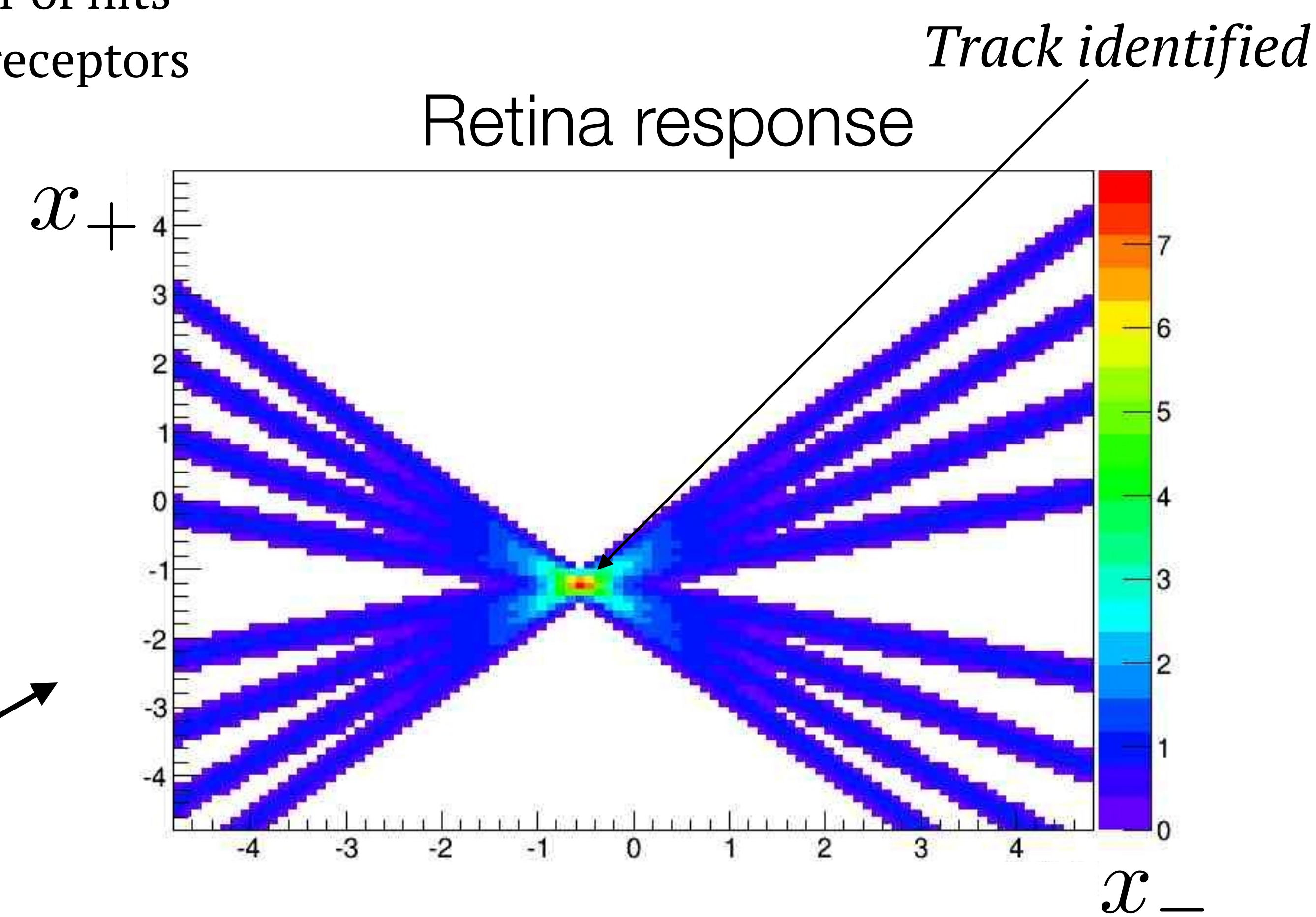
- Inspired by mechanism of visual receptive fields
  - massive parallelisation and analog response of track receptors (*R*)
  - pattern recognition and track fit by interpolation of *R* values

Track identified by retina algorithm



S_i distance between cluster and track receptor

- cluster of hits
- track receptors



2D track: $x(z) = x_+ + x_- \dfrac{z - z_+}{z_-}$

Track parameters $x_\pm = \dfrac{x_l \pm x_f}{2}$

Excitation of the cellular units

$$R = \sum_i \exp\left(-\frac{s_i^2}{2\sigma^2}\right) \quad \text{if} \quad s_i < 2\sigma$$

$$R = 0 \quad \text{if} \quad s_i > 2\sigma$$

- Track parameters obtained by interpolation of R values around maximum

Retina INFN project

- INFN-Retina R&D project started in 2015. Milano and Pisa groups involved
- Develop hardware prototype of a real time tracking device for intensive tracking applications (1-100 Giga tracks/sec), *e.g.* HL-LHC experiments
- Main deliverables:

- Real time tracking detector prototype for test beam

Completed: NN et al, http://dx.doi.org/10.1016/j.nima.2016.05.129

- Fast track finding system compatible with large DAQ framework for test with simulated data at 40 MHz event rate (next step)