ULtrafast Imaging and particle Tracking
Instrumentation and Methods
Argonne, 11-14 September 2018

# SENSORS, ELECTRONICS and ALGORITHMS for Tracking at the Next generation of Colliders

**Adriano Lai, INFN Sezione di Cagliari – Italy**

# Talk Outline

## 1. Introduction (as brief as possible)

The problem of tracking at very high luminosity colliders and posed requirements

## 2. Possible solutions

Examples taken from collider experiments (LHC Phase2)

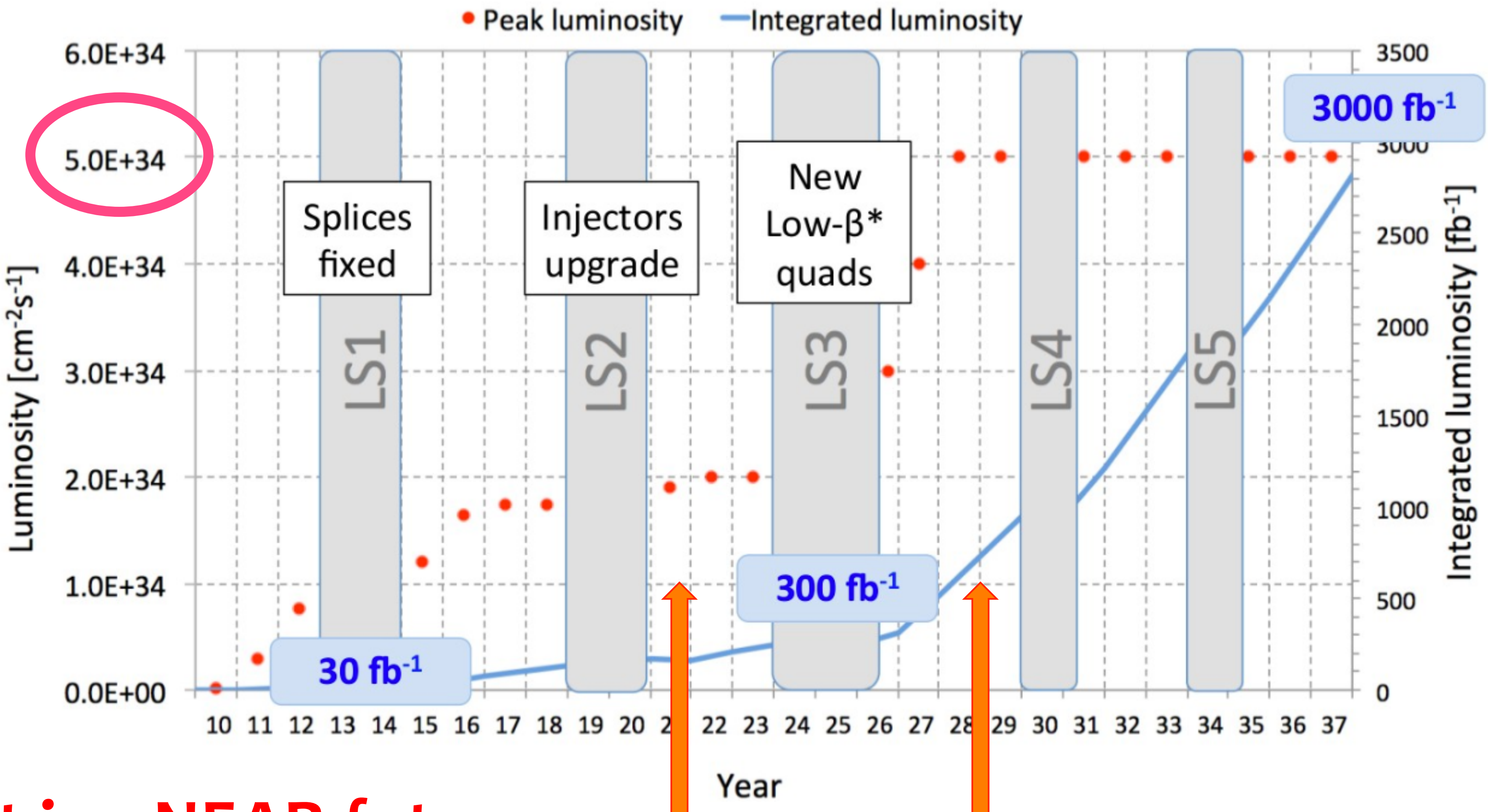
## 3. A different approach (our)

A: Sensors
B: Read-out electronics
C: Real-time algorithms

## 4. Conclusions

# The problem of tracking at HI-LUMI colliders and posed requirements

## LHC upgrade program

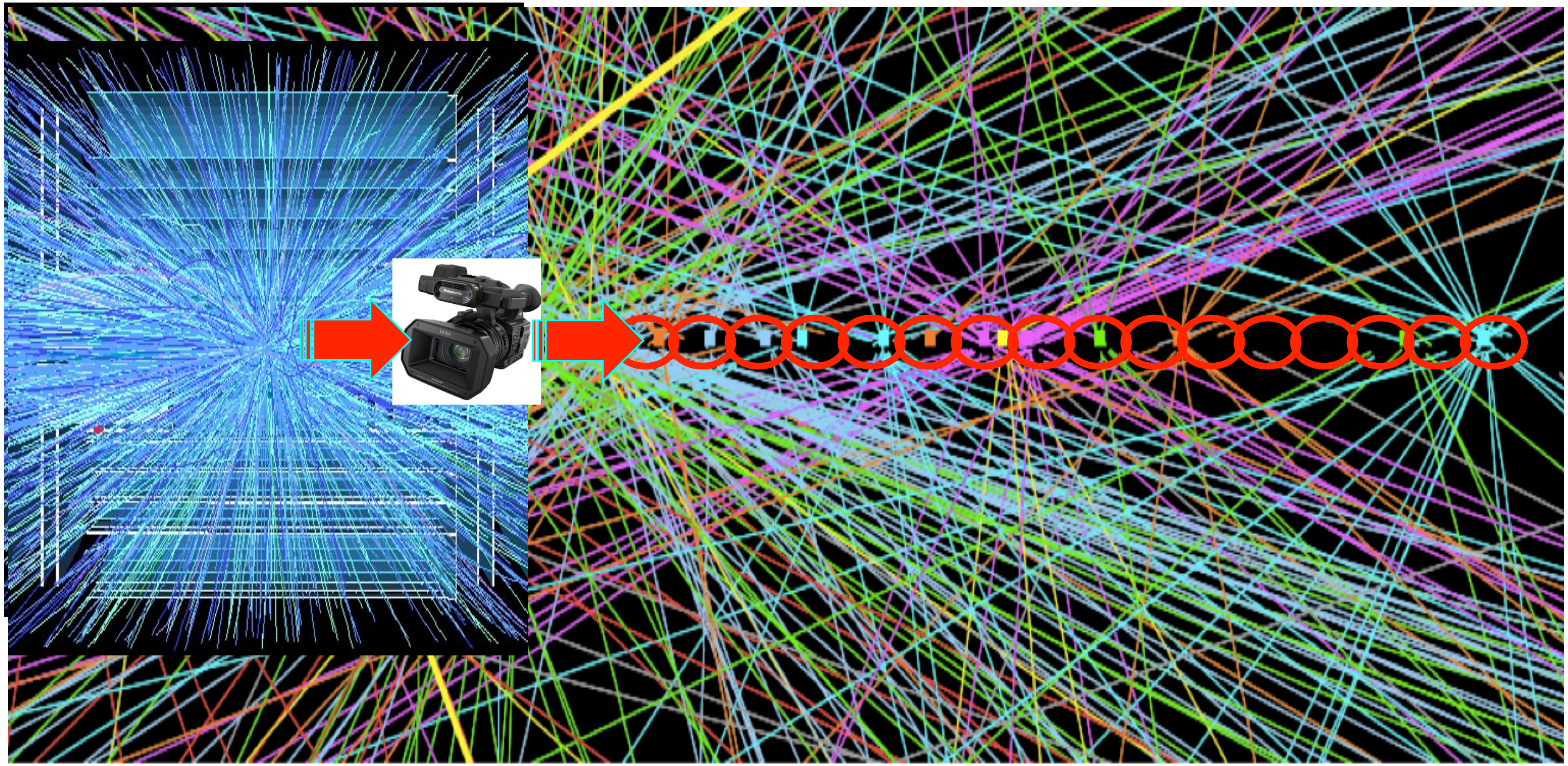


**It is a NEAR future**

Phase 1

Phase 2

# HI-LUMI, HI-PILEUP and the TIME coordinate concept



A (almost) Tfps "video camera" for ionizing radiation
(… plus something more)

# The TIME coordinate concept (cont’)

## Two approaches:

**Approach#1 (Physics POV):**
Consider 1) the minimum acceptable physics performance of the experiment; 2) the maximum affordable (time and money) budget and conceive a detector inside those specifications.

**Approach#2 (Technology POV):**
Given the State-of-the-art in detector technology and a time scale of about 10 years of R&D activity, what is the maximum performance we can reach?
Differently phrased: what are the maximum achievable performances for a high rate fps camera to be used in future collider experiments ?

# The TIME coordinate concept (cont')

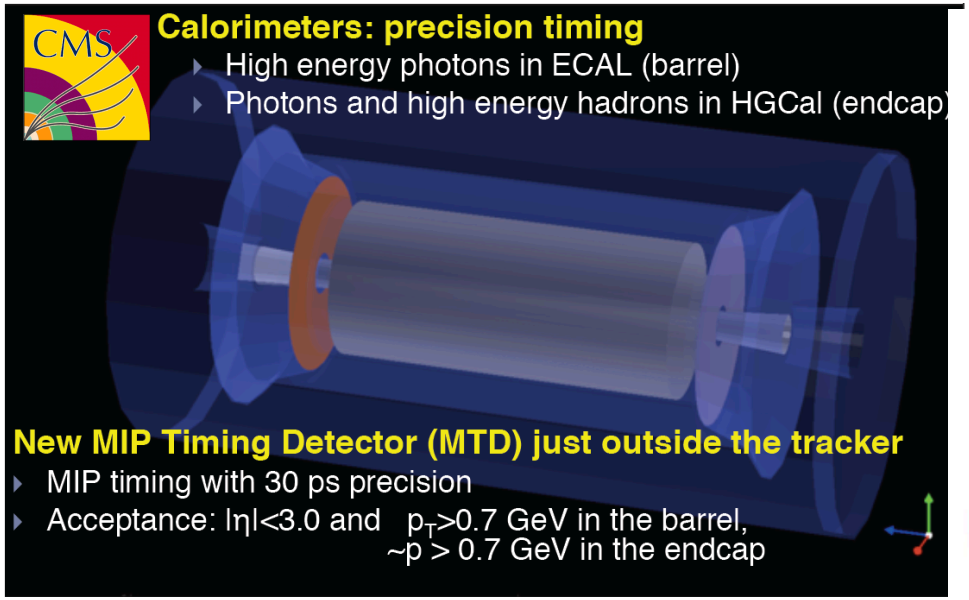
## Two approaches:

**Approach#1 (Physics POV):**
**ATLAS, CMS, (LHCb)**

**Approach#2 (Technology POV):**
**(LHCb), FCC**

# CMS and ATLAS Phase2:
# Timing Layers (Approach#1).

**Both experiments are aiming at an upgrade in Inner Tracking systems , but high pile-up (O(100)) merges vertices even after upgrades, causing important inefficiencies in Primary Vertex (PV) identification (around 15%)**

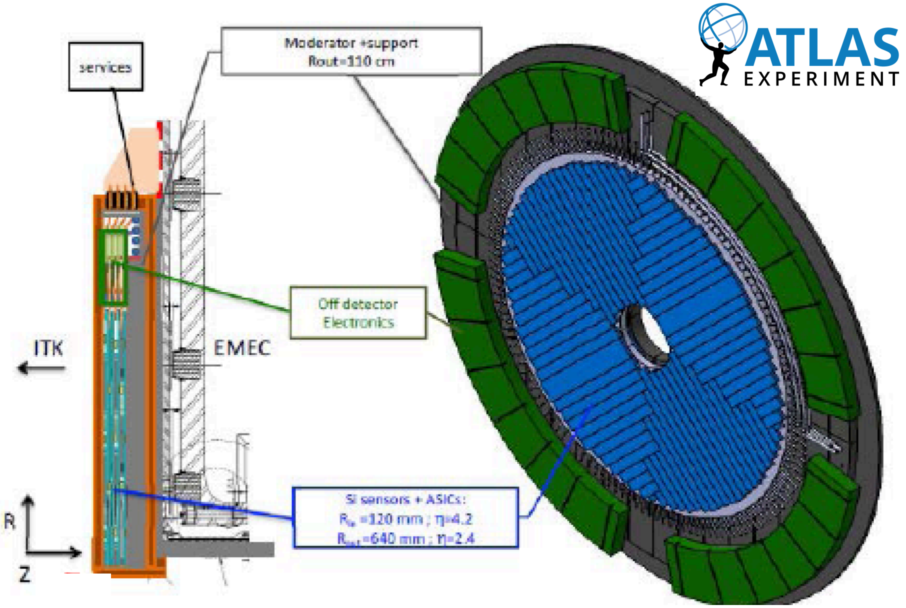


**Calorimeters: precision timing**

- High energy photons in ECAL (barrel)
- Photons and high energy hadrons in HGCal (endcap)

**New MIP Timing Detector (MTD) just outside the tracker**

- MIP timing with 30 ps precision
- Acceptance: $|\eta|<3.0$ and $p_T>0.7$ GeV in the barrel, ~$p > 0.7$ GeV in the endcap

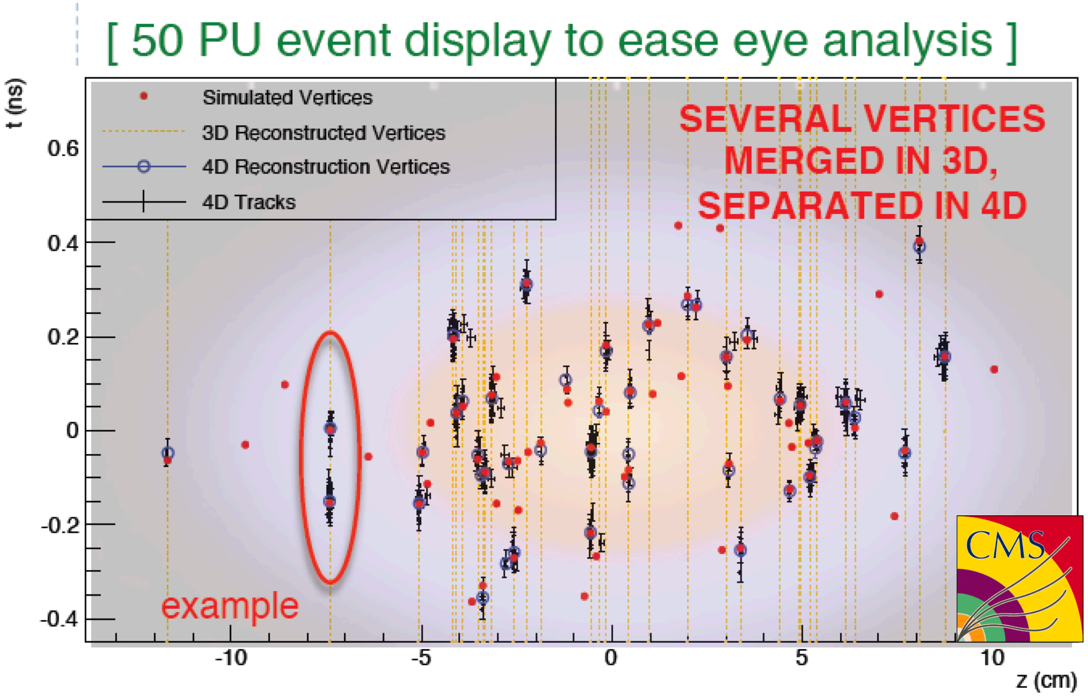


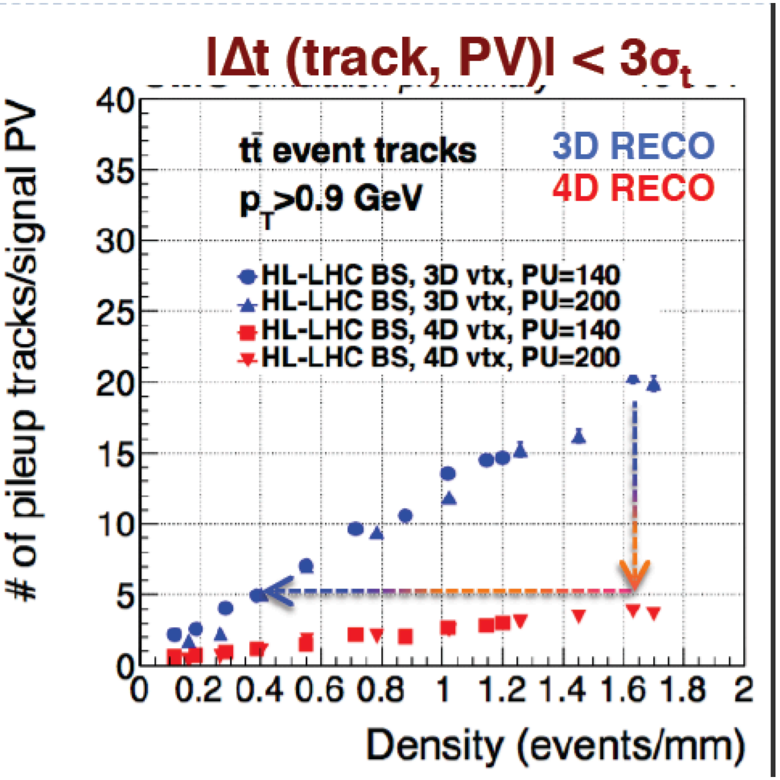
- **Coarser space resolution w.r.t. trackers (power and number of channels saving)**
- **Use measurement of track path length and momentum to determine time-at-vertex for the track**
- **Pick timing layer hits by means of tracking, integrating timing layer hits into 3D Kalman**
- **Filter**
- **Back propagate smoothly to tracker, using a higher-dimensions KF with timing information**

**→ Timing used at trigger and/or analysis level**

# CMS and ATLAS Phase2: Timing Layers (Approach#1).

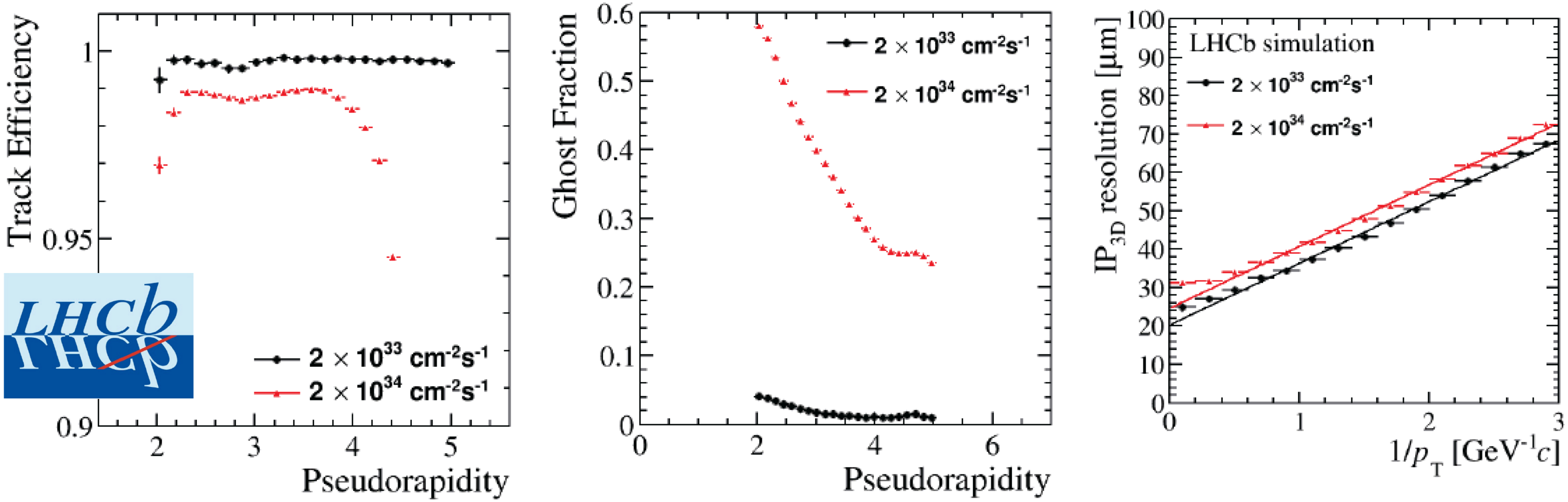
**Both experiments are aiming at an upgrade in Inner Tracking systems , but high pile-up (O(100)) merges vertices even after upgrades, causing important inefficiencies in Primary Vertex (PV) identification (around 15%)**





## Timing layers should take back inefficiencies to the level of Phase1 (1-2%)

# Approach#1.
# Timing Layers, are they sufficient?

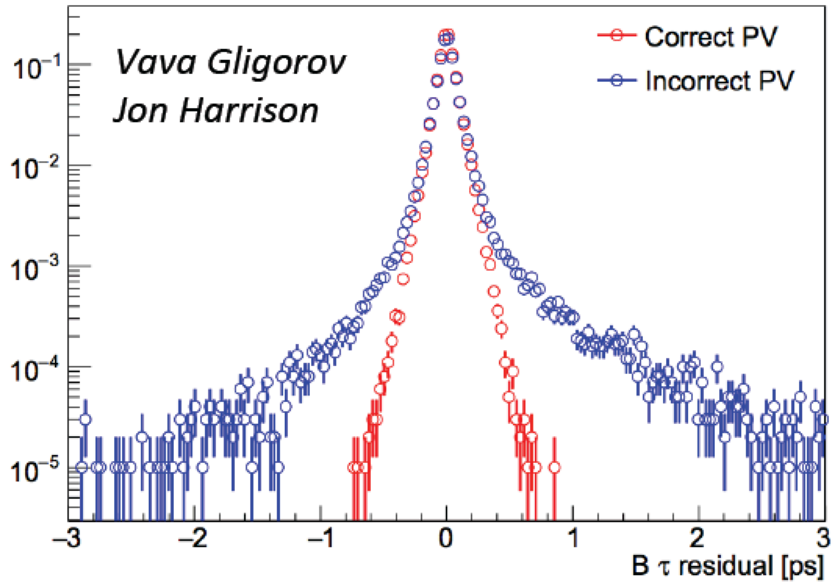


**The LHCb experiment has a slightly different time-scale for the upgrade. It will reach 2 x $10^{34}$ in luminosity after LS4 (year 2030)**

**Studies on physics perormance using a non-upgraded detector show a dramatic drop in performance, which can be (only partially) recuperated increasing (x4) the granularity of the vertex detector (or adding time information to pixels)**

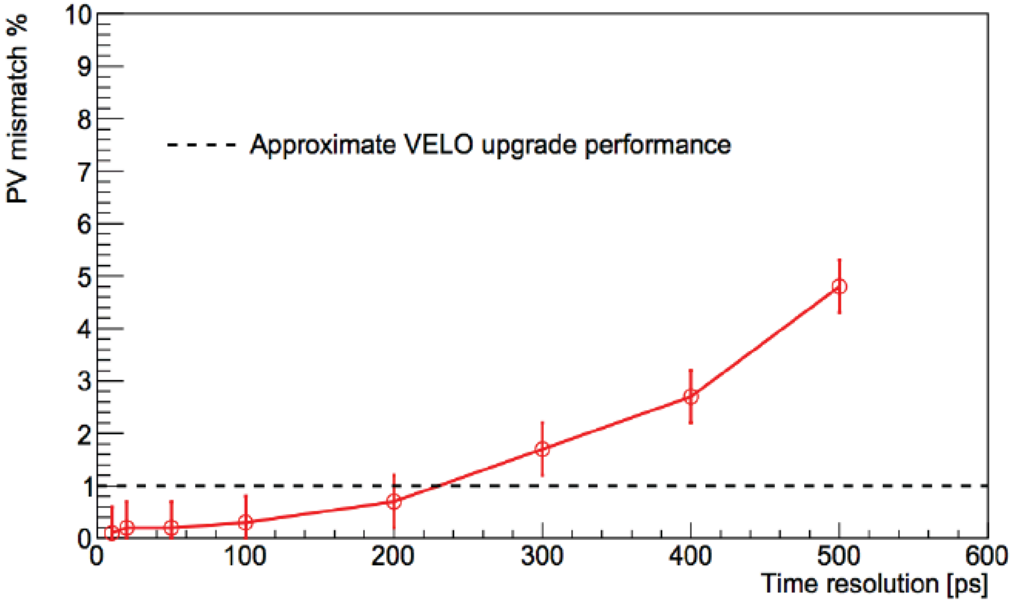
**Moreover, LHCb requirements in radiation hardness, are ≈ x10 those of ATLAS/CMS Phase2**

# Approach#1.
# Timing Layers, are they sufficient?



An important channel of activity in the LHCb physics program requires an accurate measurement of lifetime in B and C meson decays

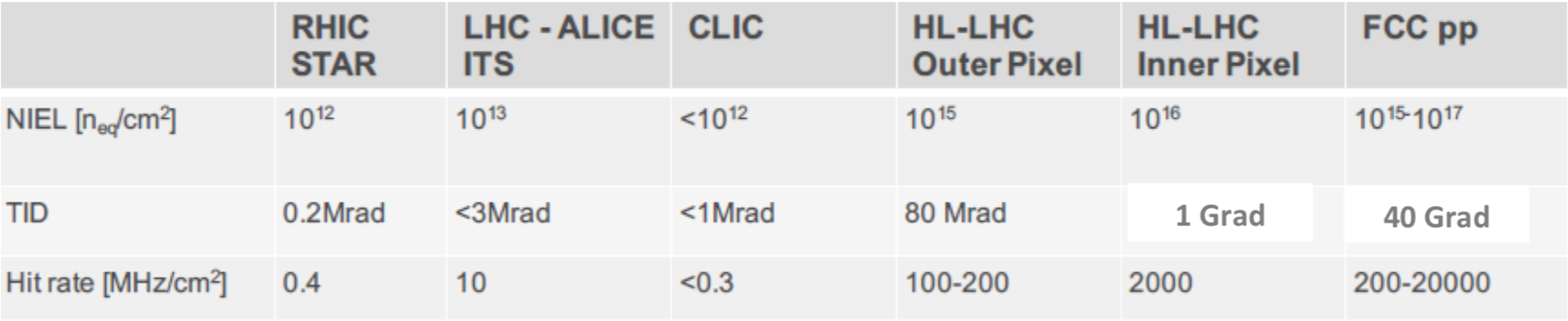
Incorrect PV identification dramatically spoils the lifetime measurement



To keep the PV reconstruction performance at the due level about 6 ps time resolution per track must be kept

Correspondingly, at least 200 ps per pixel are required: timing INSIDE the tracker

# What target specs?



| | RHIC STAR | LHC - ALICE ITS | CLIC | HL-LHC Outer Pixel | HL-LHC Inner Pixel | FCC pp |
|---|---|---|---|---|---|---|
| NIEL [$n_{eq}/cm^2$] | $10^{12}$ | $10^{13}$ | $<10^{12}$ | $10^{15}$ | $10^{16}$ | $10^{15}$-$10^{17}$ |
| TID | 0.2Mrad | <3Mrad | <1Mrad | 80 Mrad | 1 Grad | 40 Grad |
| Hit rate [$MHz/cm^2$] | 0.4 | 10 | <0.3 | 100-200 | 2000 | 200-20000 |

V. Bonvicini

## Approach #2

- **Space resolution: ≈ 50 μm**
- **Radiation hardness: $10^{16}$ to $10^{17}$ 1 MeV $n_{eq}$/ $cm^2$ (sensors) and > 1 Grad (electronics)**
- **Time resolution: 100 ps per pixel or better should be added**
- **Data rates of the order of n x Tb/s must be handled**

# Our Project

TIMESPOT (TIME and SPace real-time Operating Tracker) is an initiative for the development of a 4D tracker demonstrator.

It has been financed by INFN (Istituto Nazionale Fisica Nucleare – Italy) with about 1 M€ for 3 years of activity (2018, 19, 20). About 20 FTE are involved.

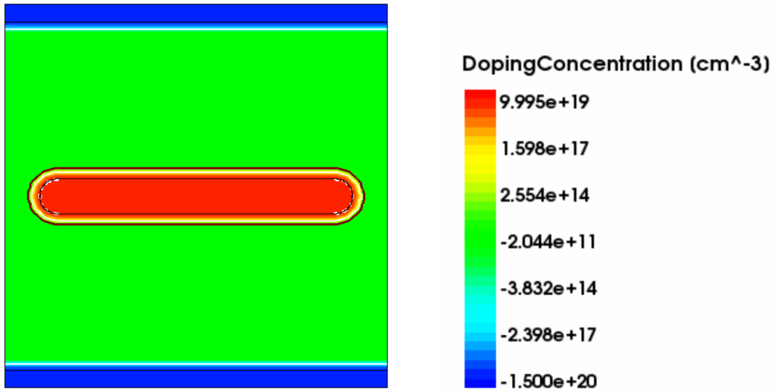
The aim of the project is to address the challenge of new-generation trackers from a system point of view, in order to exploit the potentiality of state-of-the-art technologies pushing them to the maximum achevable limit in the direction of a tracker with timing facilities.

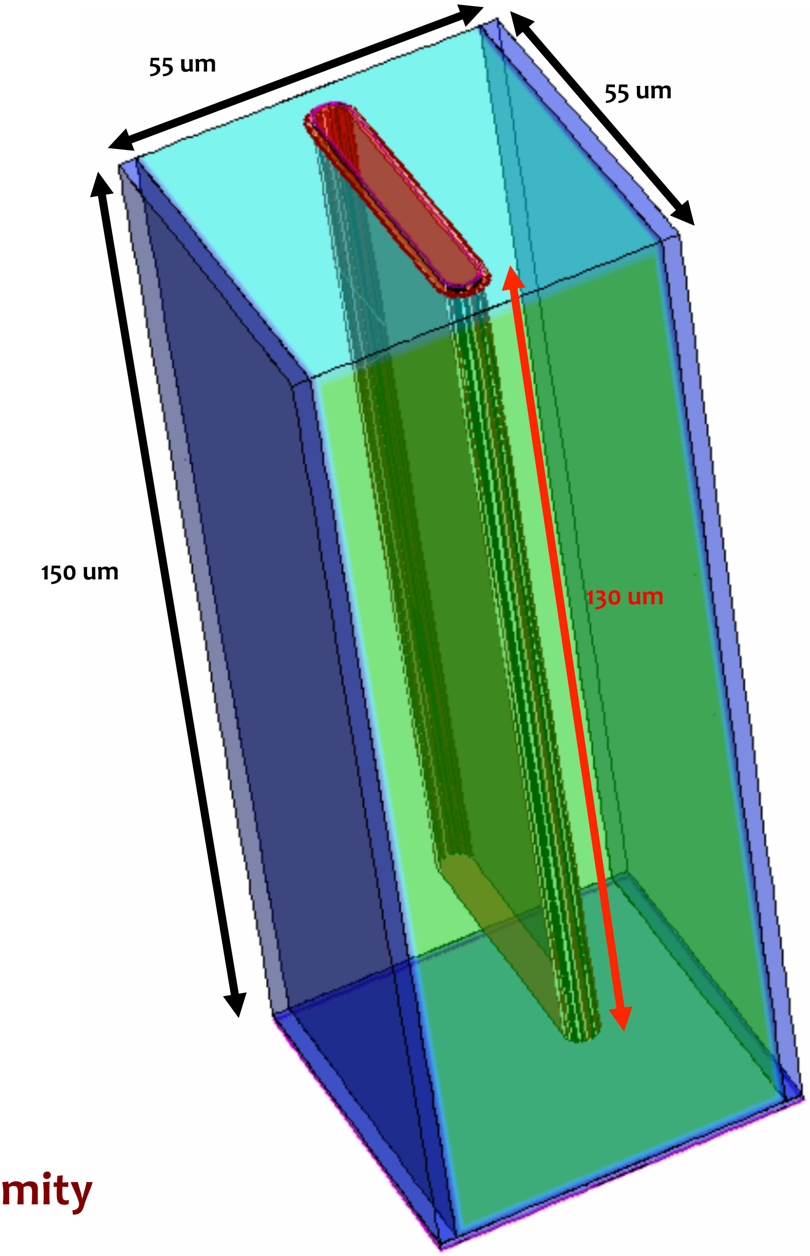
In this sense we have activities on six work packages:

1. 3D silicon sensors: development and characterization
2. 3D diamond sensors: development and characterization
3. Design and test of pixel front-end
4. Design and implementation of fast tracking algorithms
5. Design and implementation of high speed readout boards
6. System integration and tests.

# Sensors (1): 3D silicon

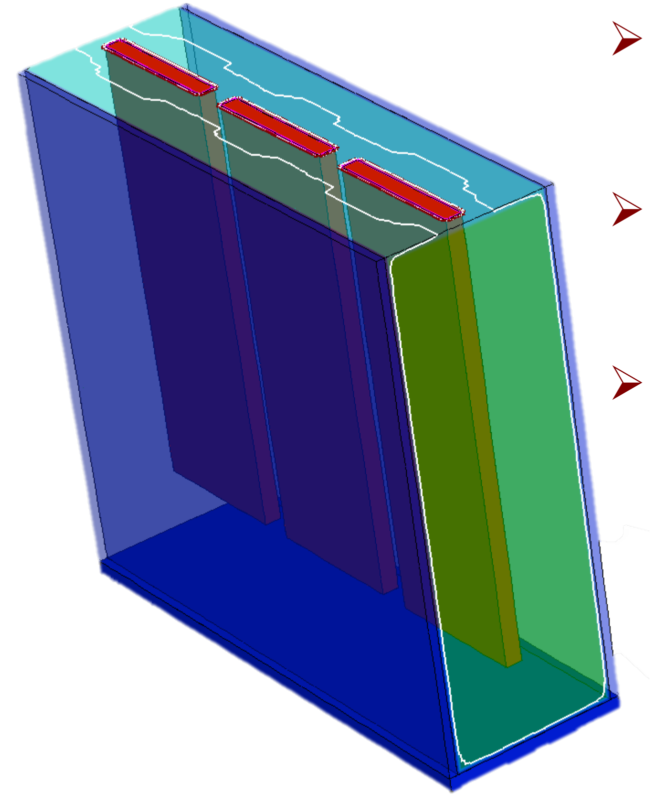
- The first batch is presently under fabrication @ FBK (Trento, Italy)
- Pixel pitch 55 μm, volume 55x55x150 μm$^3$
- Collecting electrode width 5 μm
- Details in a dedicated talk by GF Dalla Betta (this session)



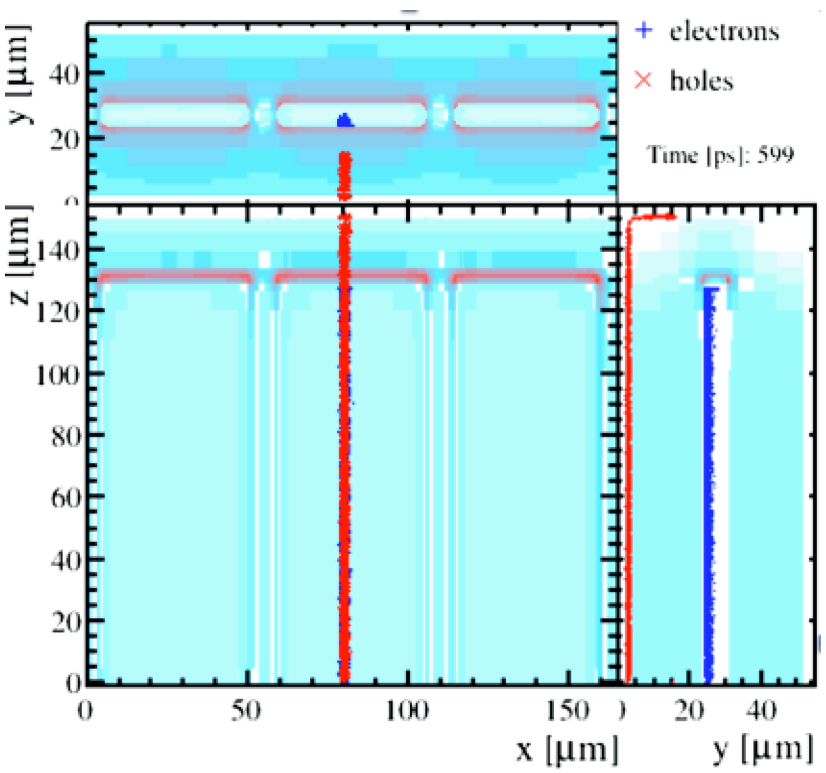


**Trench geometry for maximum E field uniformity**

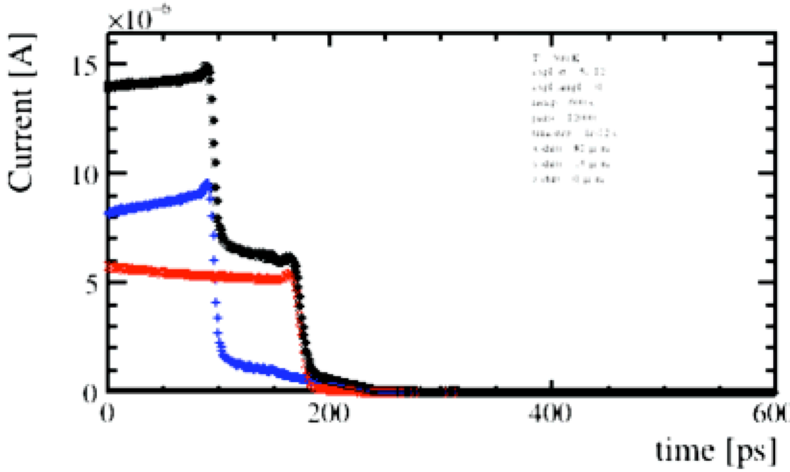
# Sensors (2): 3D silicon signals



- dE/dx detailed physics for MIP (Geant4)
- Detailed E field and mobility maps (TCAD)
- Induced signal evolution (custom code based on Ramo theorem)



- Average charge deposit ~ 2 fC
- Extremely fast signal
- Strong mitigation of Landau fluctuation by geometry
- Induced current signals rise instantly and end within ~200 ps



# Sensors (2): 3D diamond

- Column electrodes (realized) and trench electrodes (planned) geometries.

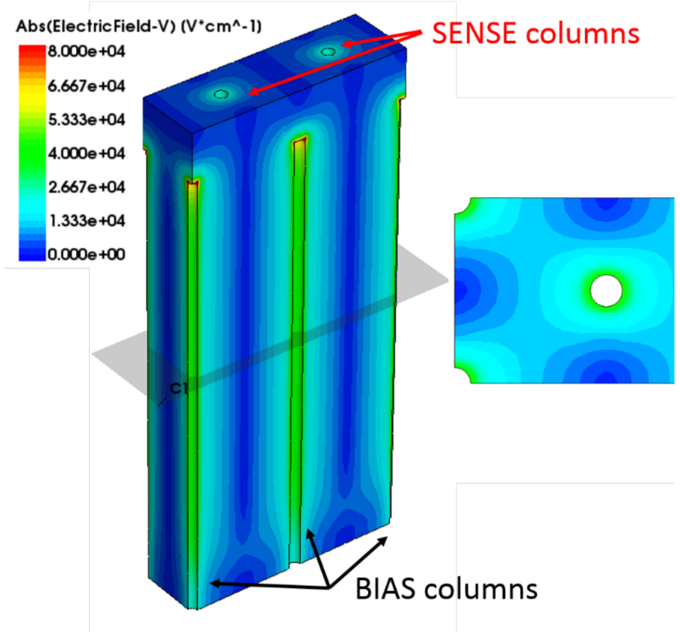
Technique: Selective diamond graphitization (burning by laser)

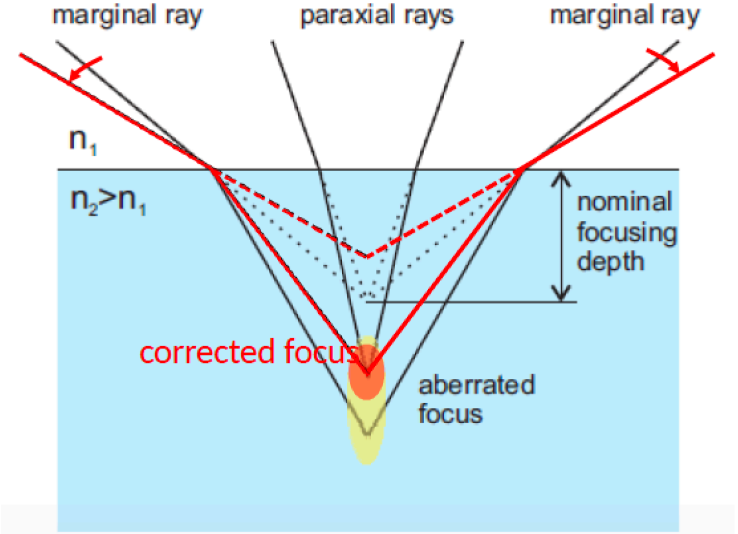
200 ps time resolution already reached (1)

Accurate sensor modelization (TCAD) and optimization of the geometry →

The key for better resolution is realizing low resistivity graphite electrodes

This can be done by corrections of spherical aberrations during graphitization process. A factor 100 has been obtained (2) →



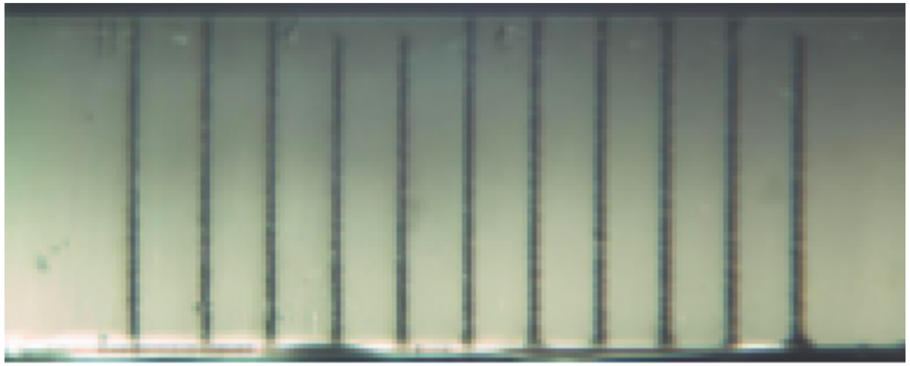


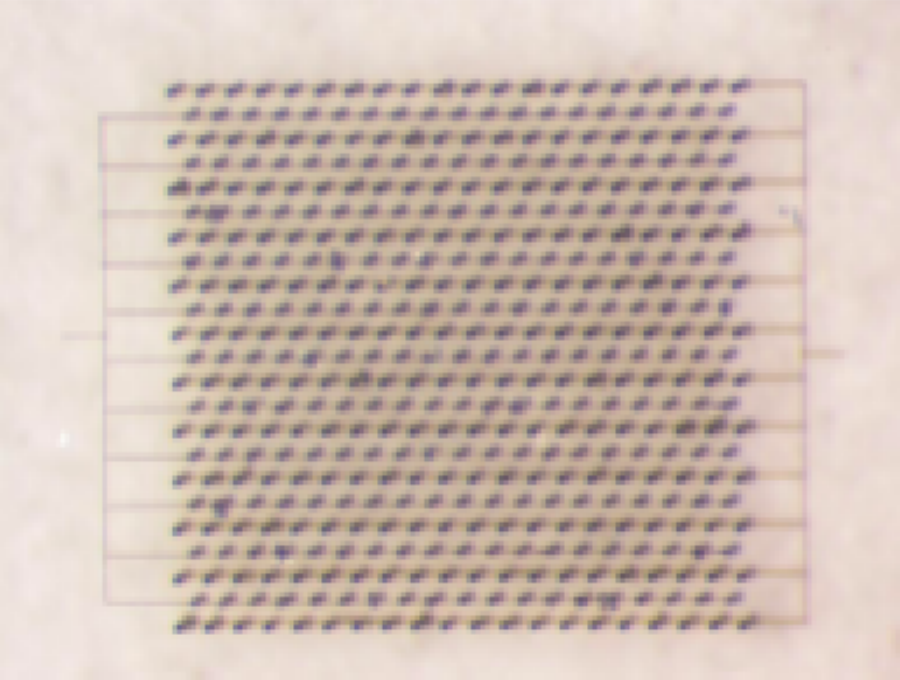
---

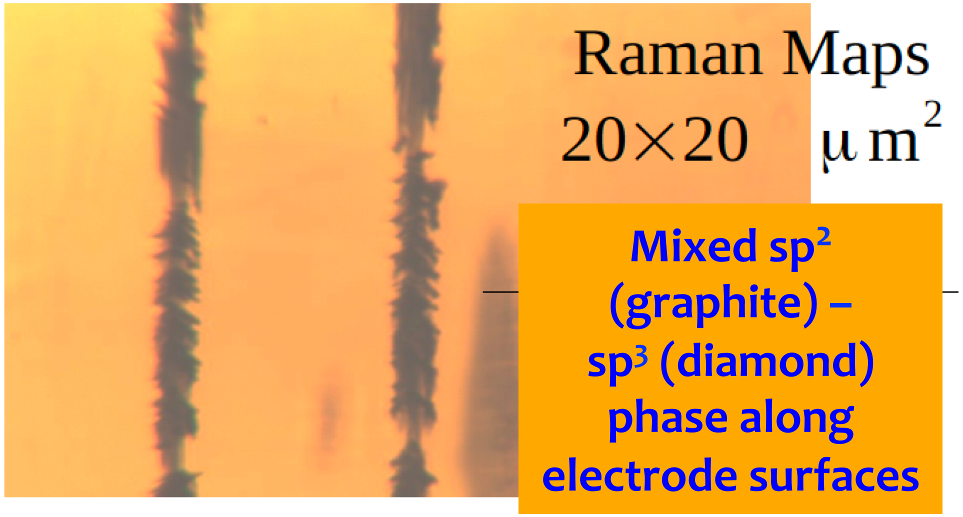
(1) N. Minafra, *Development of a timing detector for the TOTEM experiment at the LHC*, https://cds.cern.ch/record/2139815?ln=it

(2) Bangshan Sun, Patrick S. Salter, and Martin J. Booth, *High conductivity micro-wires in diamond following arbitrary paths*, Appl. Phys. Lett. 105, 231105 (2014);

# 3D diamond







**Mixed sp² (graphite) – sp³ (diamond) phase along electrode surfaces**

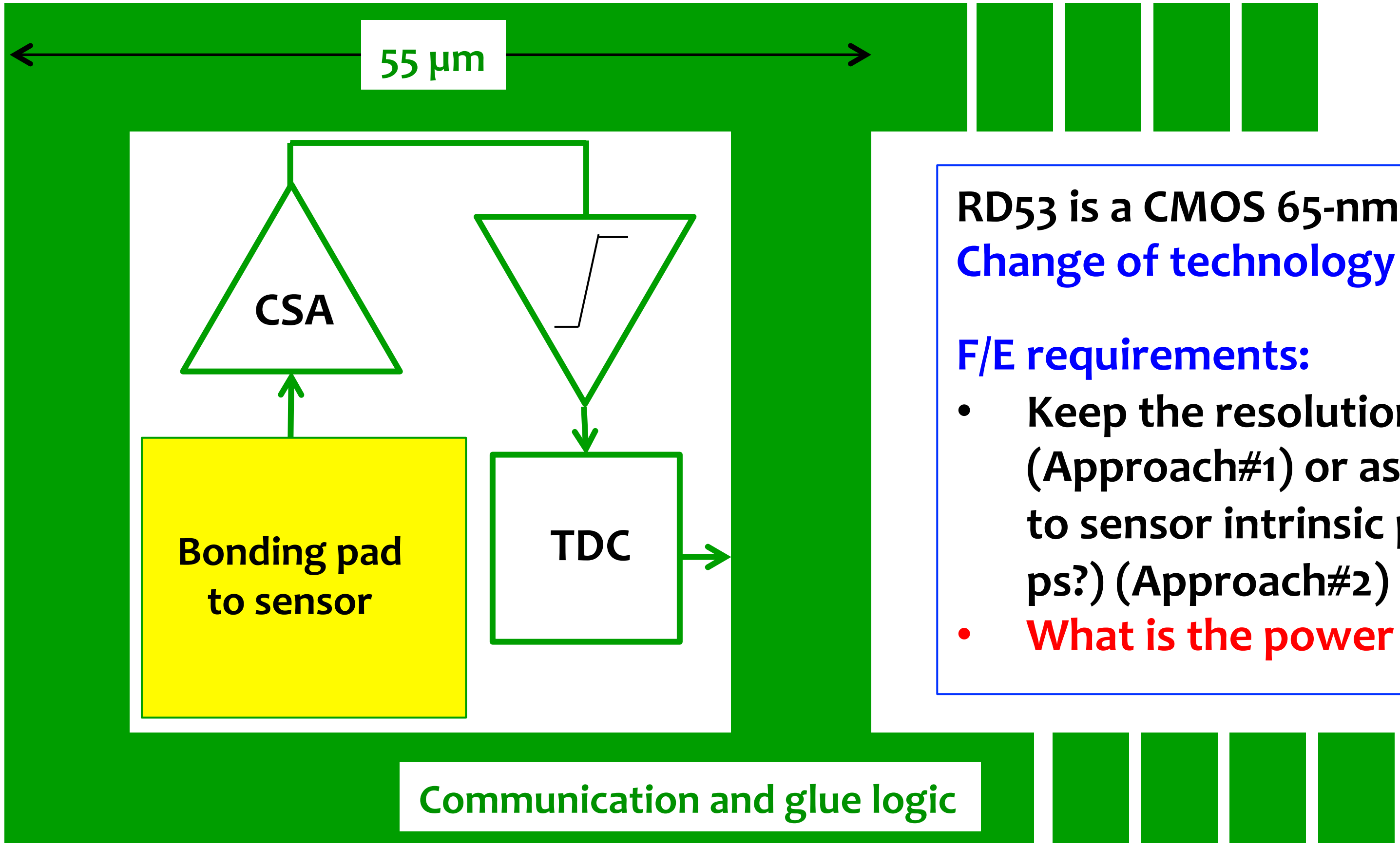
S. Lagomarsino et al., Diamond Relat. Mater., 43:23–28, 2014.

**Diamond sensor with single-side (sense and biasing) electrodes**

S. Sciortino, *Radiation hardness of three-dimensional sensors fabricated on different CVD diamond materials*, 28th International Conference on diamond and Carbon Materials, Goteborg, September 2016.

# Electronics (1)

- Our quasi-Tfps camera for 4D tracking requires a binary readout (with high resolution in time) and one TDC per pixel (or group of pixels)
- The first approach is to rescale a classic circuit (CMS RD53 style) to our purposes, adding a TDC per pixel

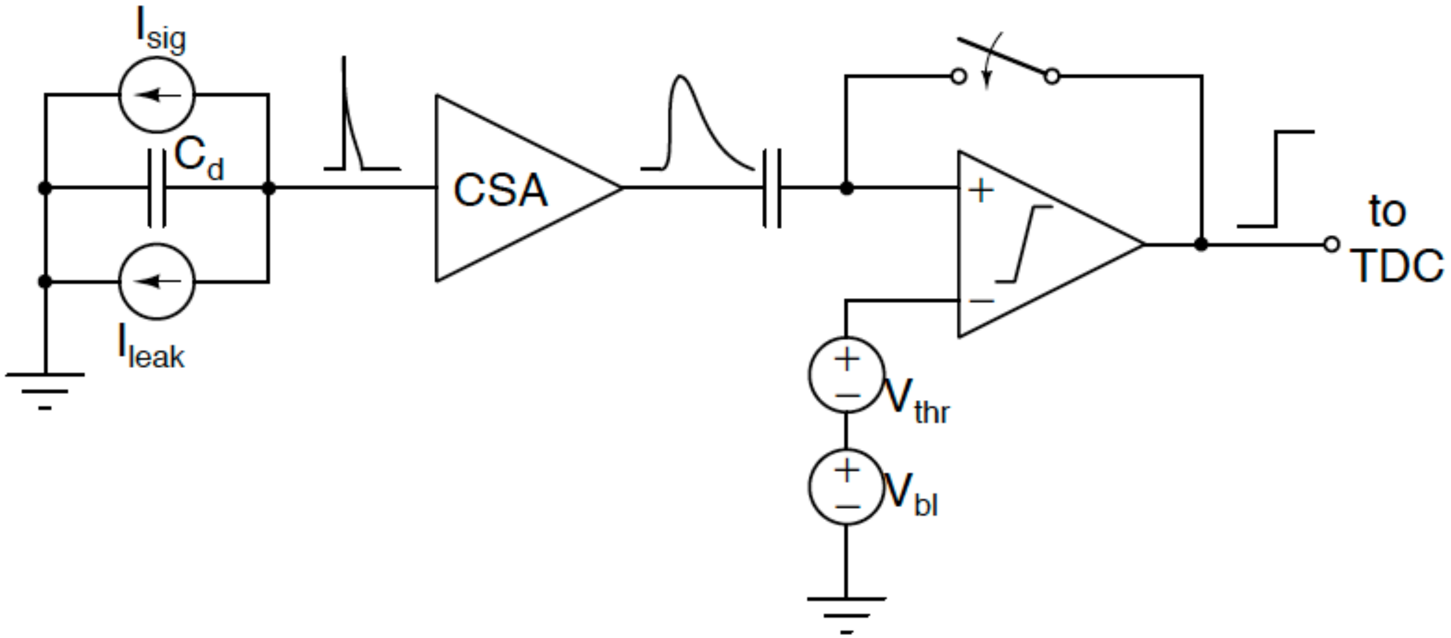


RD53 is a CMOS 65-nm: not enough !
Change of technology node?

F/E requirements:

- Keep the resolution below 100 ps rms (Approach#1) or as close as possible to sensor intrinsic performance (20 ps?) (Approach#2)
- What is the power budget per pixel?

# Electronics (2): CMOS 28-nm F/E scheme

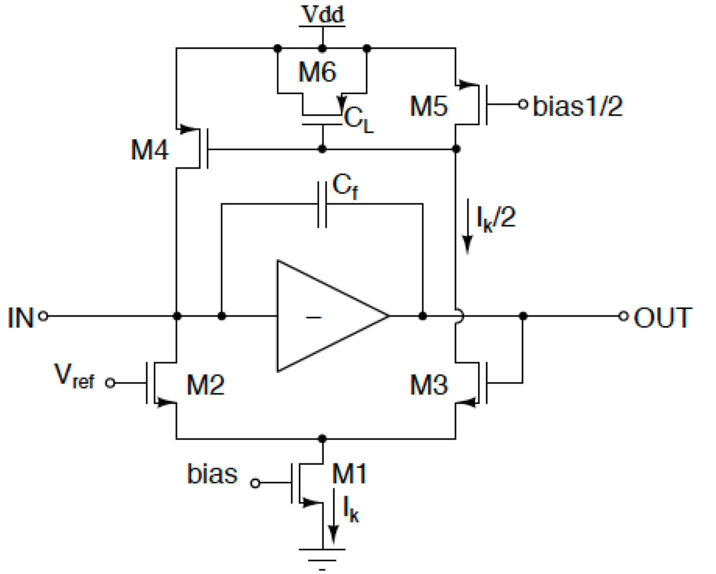


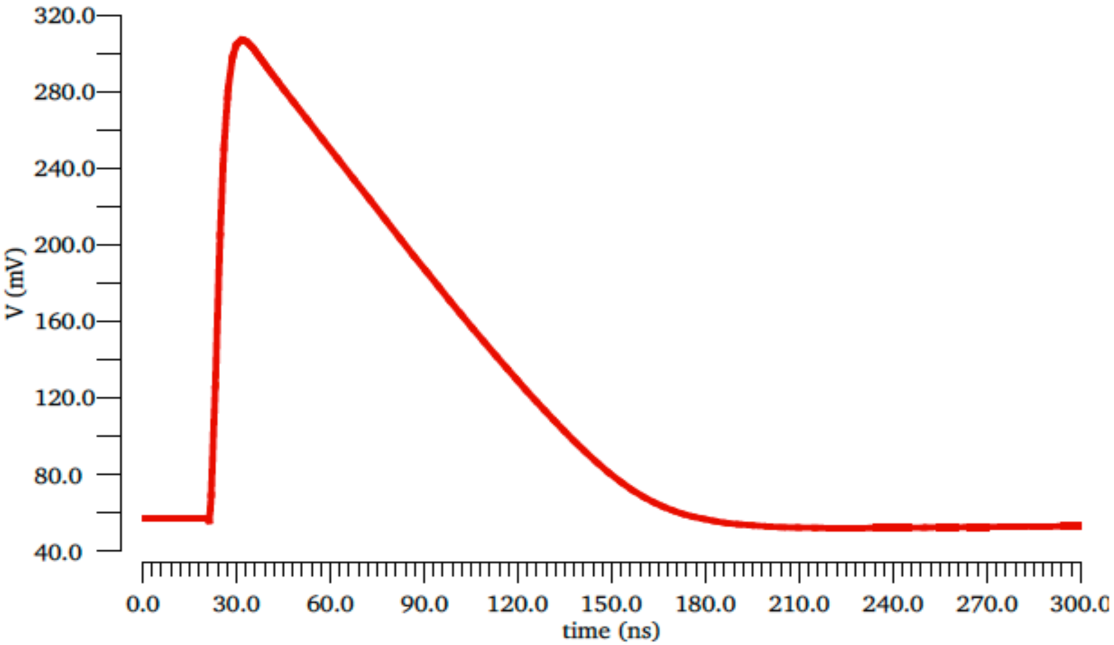
- Compact and low-power design (similar to RD53 65-nm CMOS)
- Sensor-modelled with parameters extracted from simulation
- CSA with DC current compensation and DC voltage setting
- Leading edge discriminator with offset compensation

# Electronics (3): CSA

## CSA

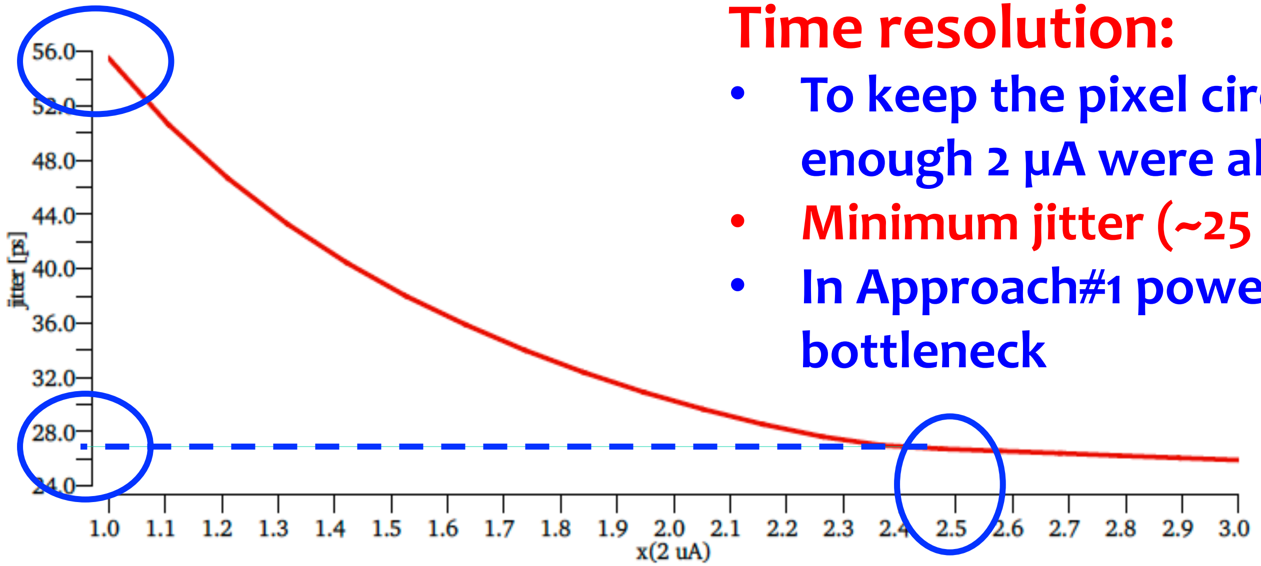
- **Output voltage proportional to input charge**
- **Constant peaking and falling times for better timing**
- **Low noise**
- **Krummenacher (active) filter: DC current compensation of input leakage current**





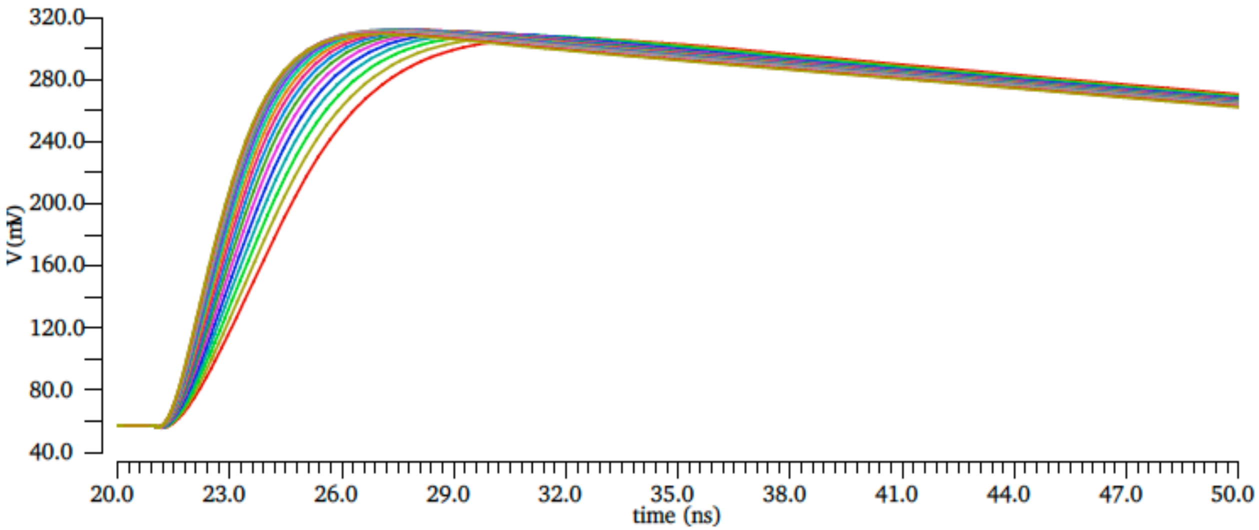
| | | |
|---|---|---|
| Gain | 199.2 | mV/fC |
| $T_{pk}$ | 11.86 | ns |
| $\sigma_N$ | 2.63 | mV |
| SNR | 95 | |
| ENC | 82 | e– |
| Jitter = $\sigma_N/Vr$ | 55 | ps |
| Consumption | 2 | µA |
| Area (LE D. incl.) | 30x15 | µm² |

# Electronics (3): minimum $\sigma_j$



## Time resolution:

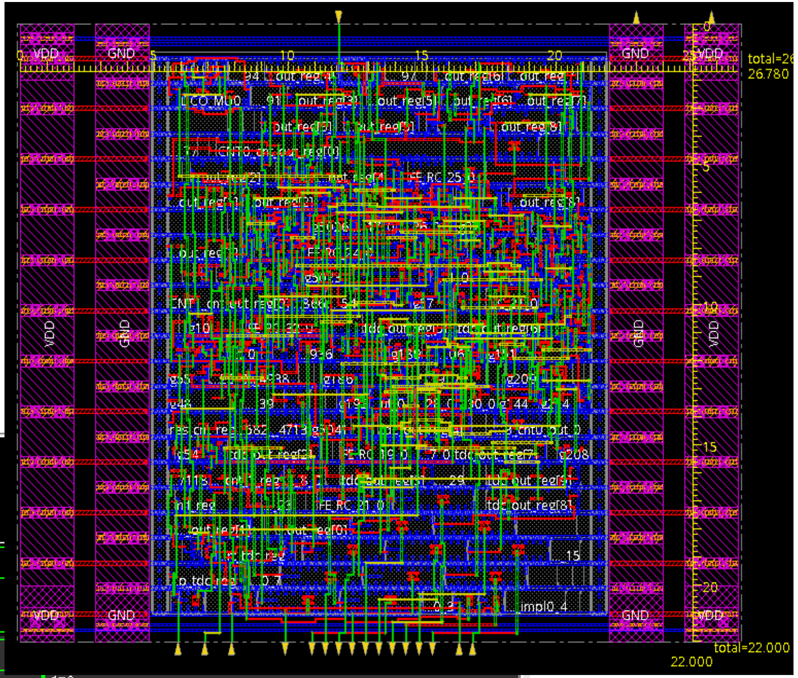
- To keep the pixel circuit power budget low enough 2 μA were allowed to Front-end
- Minimum jitter (~25 ps) is reached at 5 μA
- In Approach#1 power budget can be the bottleneck

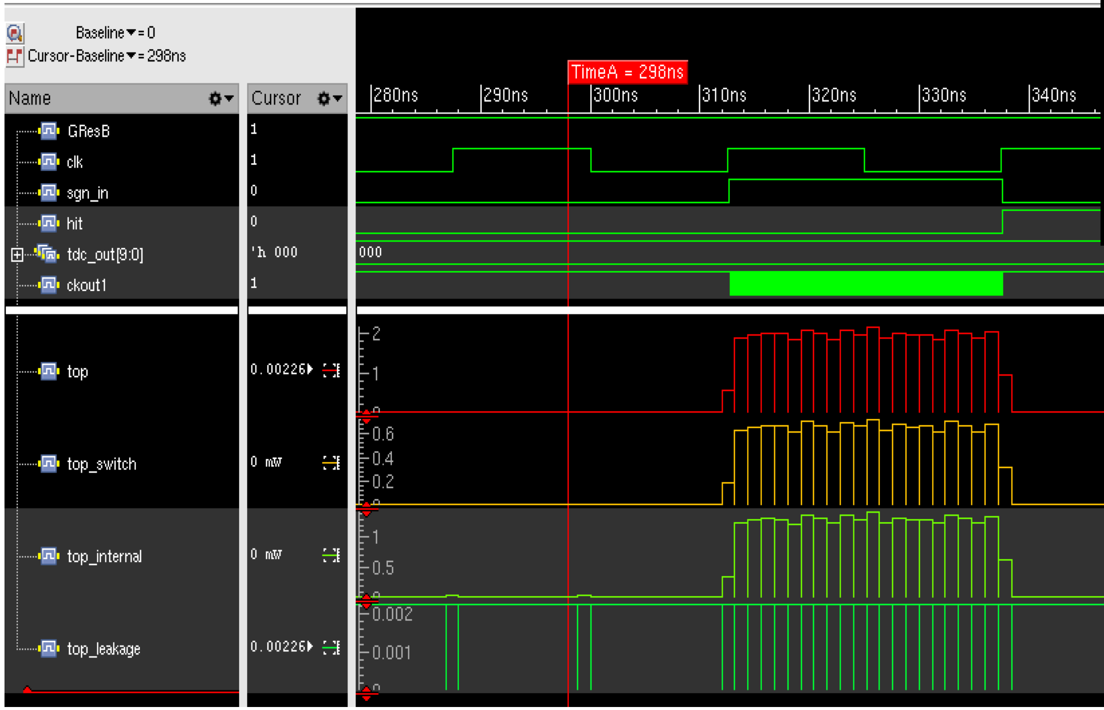


A different approach could be tried (next version): Current amplifier (too noisy?)

# Electronics (3): TDC

- The TDC is based on a “ALL digital fully-synthesizable design”(1)
- The DCO is standard-cell based
- DCO is enabled only on the occurrence of a hit for lower noise and consumption





| Master Clk | 40 | MHz |
|---|---|---|
| Resolution (LSB) | 50 | ps |
| Resolution(rms) | 15 | ps |
| NOB | 10 | bits |
| Area | 20x15 | µm$^2$ |

(1) **S. Cadeddu et al., *High Resolution Synthesizable Digitally Controlled Delay Lines*, IEEE TNS vol 62 No. 6, Dec 2015**

# Methods (1)

## Back-end: A Tfps to be used for tracking requires a fast, real time processing device to be really effective

G. Punzi

| Name | Tech. | Exp. | Year | Event rate | clock | cycles/event | latency |
|---|---|---|---|---|---|---|---|
| XFT | FPGA | CDF-L1 | 2000 | 2.5 MHz | 200 MHz | 80 | 4μs |
| SVT | AM | CDF-L2 | 2000 | 0.03 MHz | 40 MHz | ~1600 | <20μs |
| FTK | AM | ATLAS-L2 | 2014 | 0.1 MHz | ~200 MHz | ~2000 | O(10μs) |

Compare with the requirements of a L0@LHC:

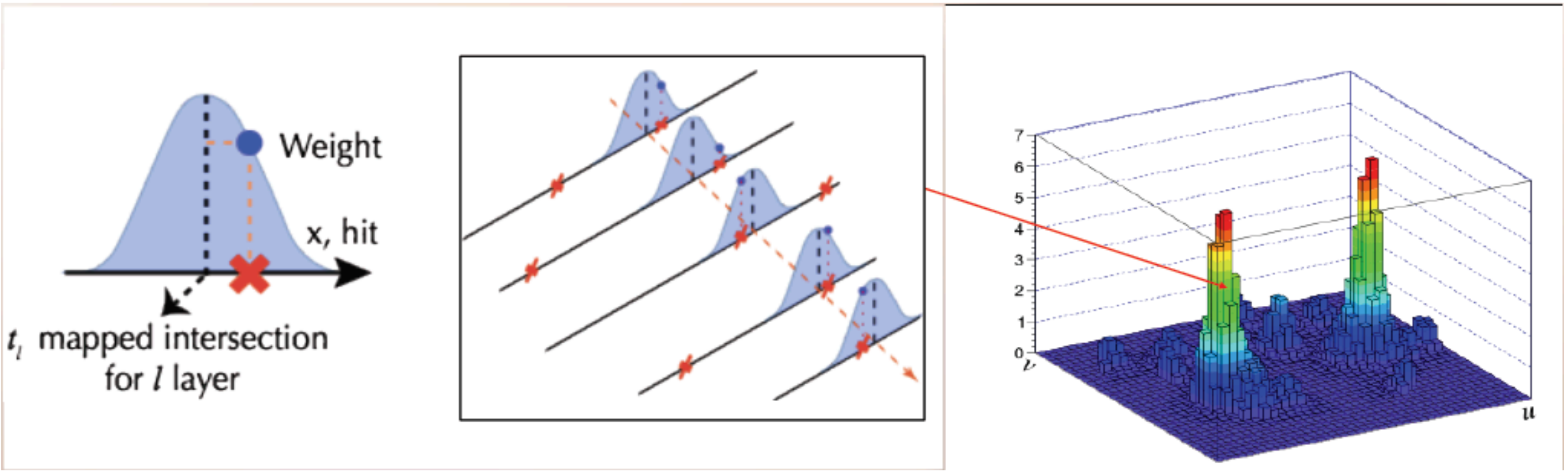
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *?* | *?* | *LHC-L0* | *~2018* | *40MHz* | *~1GHz* | *~25* | *few μs* |

In spite of technology developments, Tracking performance appears to be "stale" in effectiveness. Moore is too slow in this case!

Situation would not improve (will worsen) in the future, unless really new ideas are brougth into

# Methods (2)

**Our strategy is to follow the RETINA project approach (1), adding time information into the algorithm structure (2)**



G. Punzi

**RETINA concept:** The detector geometry defines a set of possible tracks. A possible track corresponds to a cellular unit. Any point "seen" by the detector can be associated a weight, according to its distance from the track hypothesis. The algorithm finds tracks as maxima in weight in the track space.

**TIMESPOT concept:** track points are substituted by stubs.

Each cellular unit can be processed in parallel. The algorithm can also be executed on commercial (powerful) FPGA.

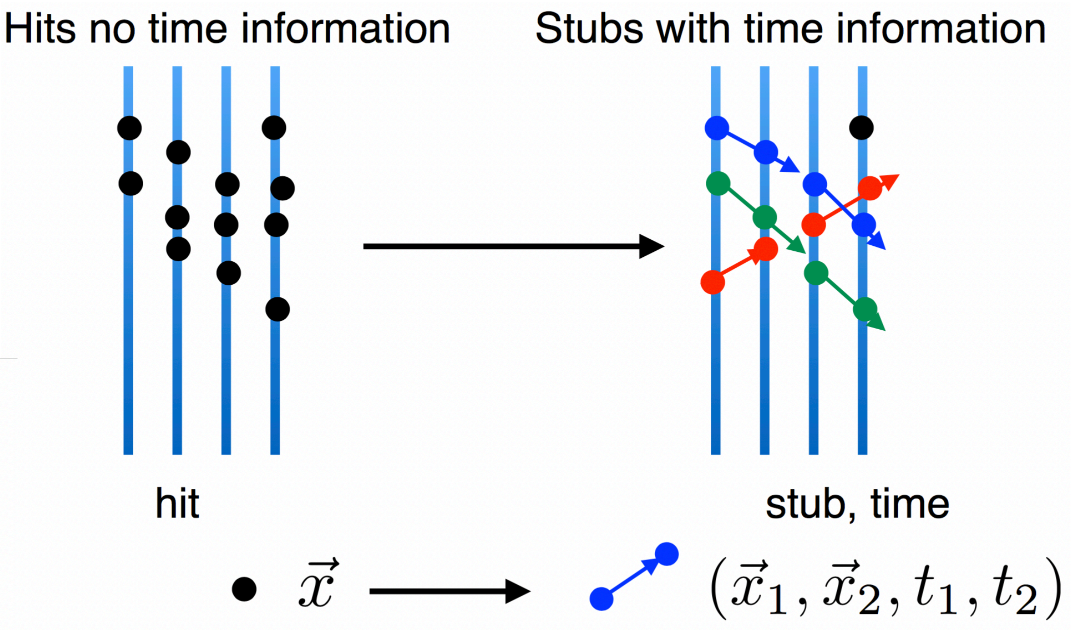
---

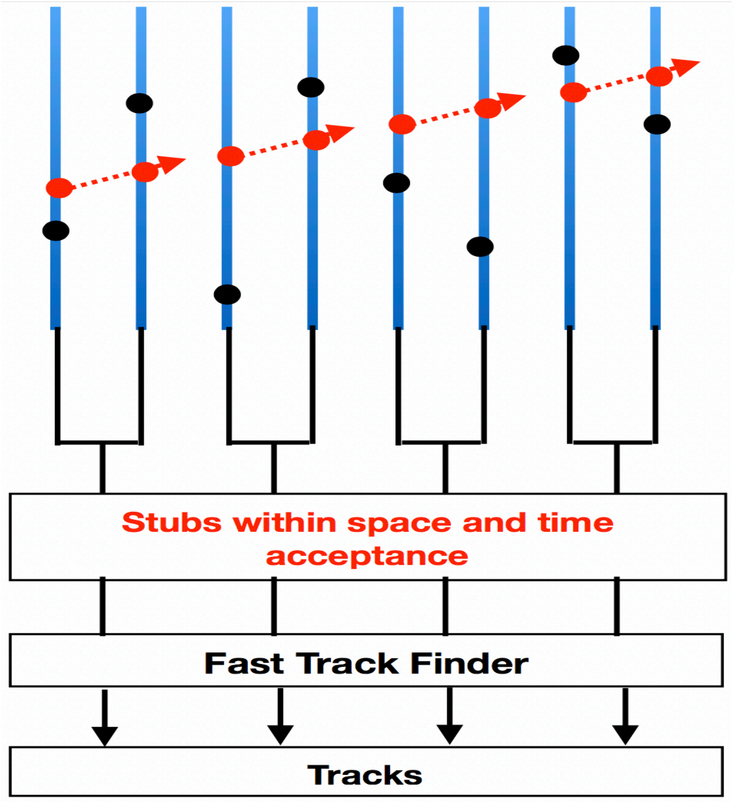
(1) A. Abba et al., Simulation and performance of an artificial retina for 40 MHz real time track reconstr., JINST 10 (2015) no 03, C03008

(2) Neri N. et al., *4D fast tracking for experiments at high luminosity LHC*, JINST 11 (2016) no. 11, C11040

# Stub concept

Track pattern recognition based on hits with no time information compared to track segments “stubs” with time information




Stubs within space and time acceptance

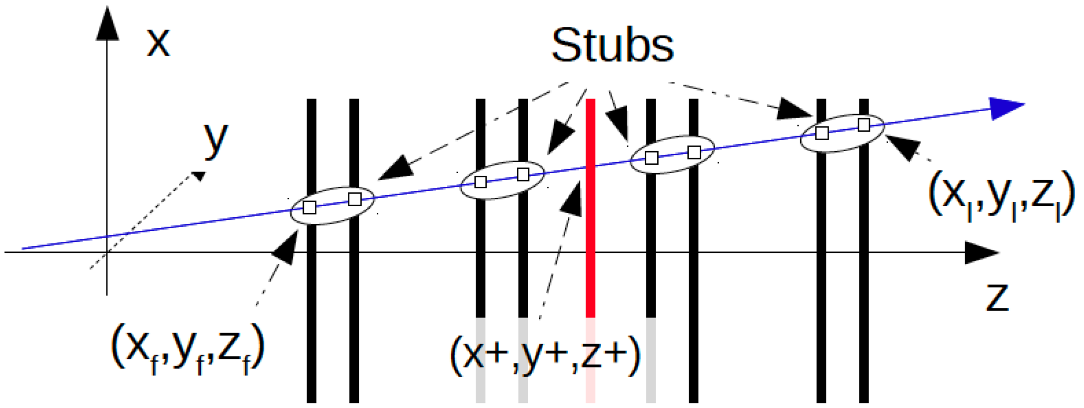
Fast Track Finder

Tracks

Conceptual design for a detector with embedded tracking capabilities based on stub information.

After stub construction, only “in time” points are considered by the algorithm

# Methods (3)



$$x_f, y_f, z_f), (x_l, y_l, z_l)$$

Intersactions with first and last plane

$$x_\pm = (x_f \pm x_l)/2$$
$$y_\pm = (y_f \pm y_l)/2$$
$$z_\pm = (z_f \pm z_l)/2$$

Intersactions with central plane. +/- used to define track slope

**5 parameters to define a track:**

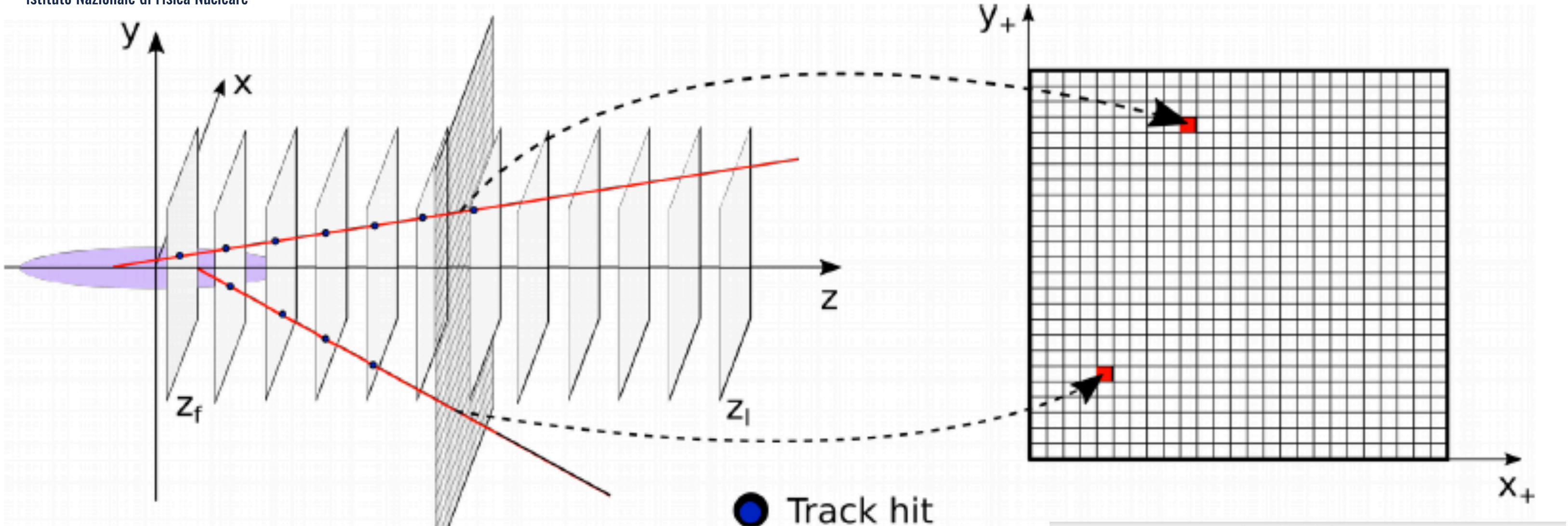
- **4 space parameters**
- **1 time parameter (time of the track at the origin)**

**The time of the other points is "centered" assuming v = c**

**High time resolution important for efficient (selective) stub definition**

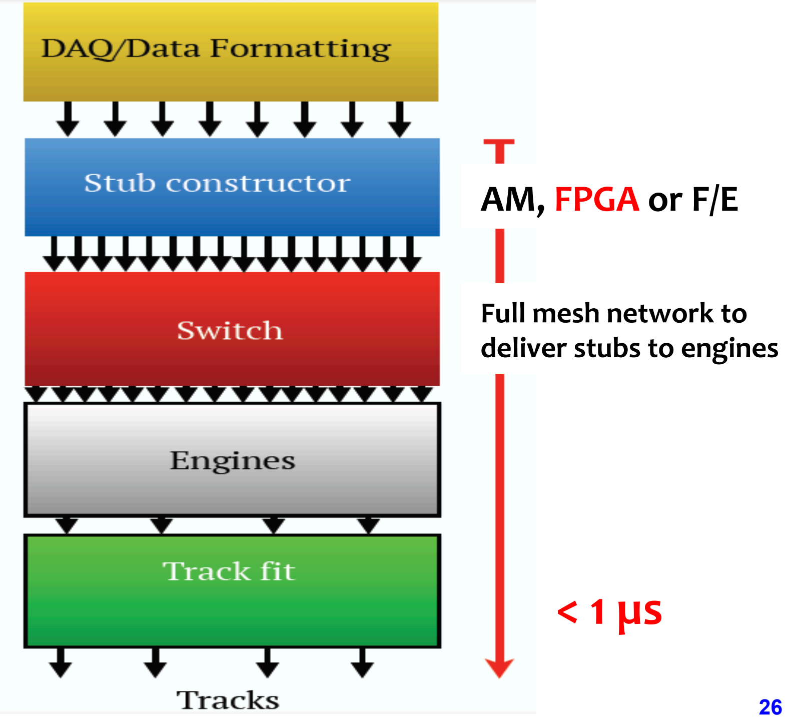
$$\begin{pmatrix} x_- \\ x_+ \\ y_- \\ y_+ \\ t \end{pmatrix}_{stub} = \begin{pmatrix} \frac{x_1 z_- - x_2 z_-}{z_1 - z_2} \\ \frac{x_1 (z_+ - z_2) - x_2 (z_+ - z_1)}{z_1 - z_2} \\ \frac{y_1 z_- - y_2 z_-}{z_1 - z_2} \\ \frac{y_1 (z_+ - z_2) - y_2 (z_+ - z_1)}{z_1 - z_2} \\ \frac{t_1 + t_2}{2} - \frac{z_1 + z_2}{2\ c\ \sqrt{1 + (x_-/z_-)^2 + (y_-/z_-)^2}} \end{pmatrix}$$

# Methods (4)



**Algorithm steps:**

1. Identify stubs i.e. couples of hit in adjacent planes compatible in space and time with tracks from the bunch interaction area;
2. Distribute the stubs in parallel to the Engines;
3. Engines identify tracks from clusters of stubs with similar parameters.

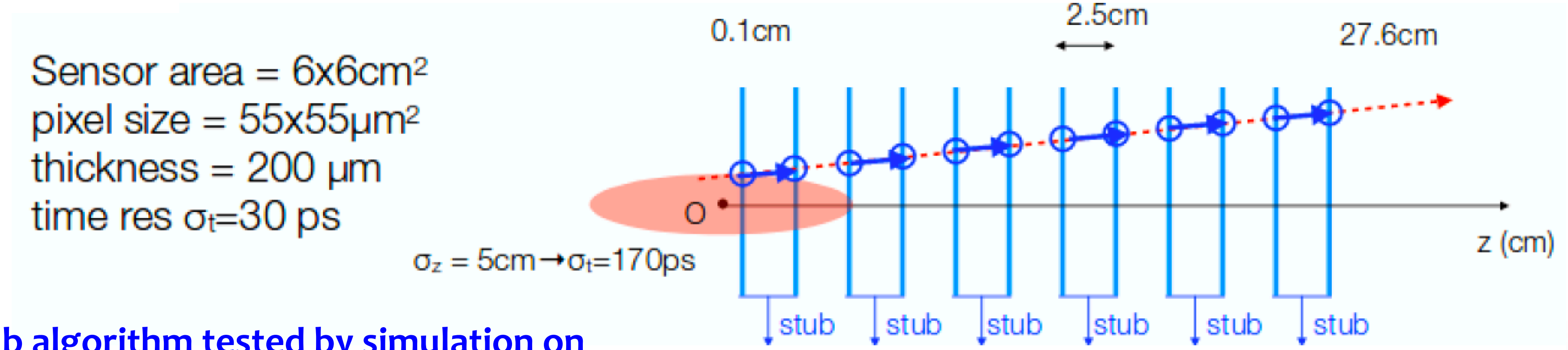


AM, FPGA or F/E

Full mesh network to deliver stubs to engines

< 1 μs

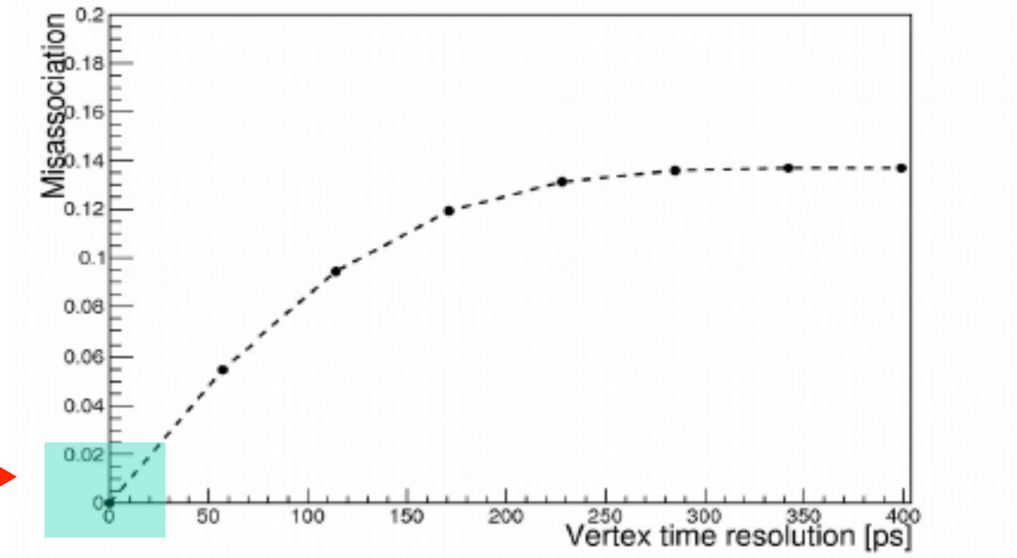
# Test on LHCb-like tracker



**Stub algorithm tested by simulation on a LHCb-like vertex detector:**

- **12 planes of silicon vertex detector**
- **Pilup = 40**
- **1200 tracks/event**
- **Interaction region of gaussian shape ($\sigma_z$ = 5 cm, $\sigma_t$ = 167 ps)**

**Mis-association vs vertex time resolution**



**The 4D fast tracking algorithm has also been in FPGA on a custom board (1):**

**Two Xilinx Virtex Ultrascale FPGAs**
**High-speed optical transceivers → up to 1 Tbps input data rate per FPGA**
**One Xilinx Zynq FPGA**

**(1) M. Petruzzo et al., A novel 4D finding system using precise space and time information of the hit , TWEPP 2018**

# Summary

**Timing** is a mandatory requirements for the next generation of tracking systems, starting from the next decade (high lumi LHC and future colliders)

**Besides timing**, other requirements have to be satisfied:

- Operation under extremely high radiation levels
- Processing of huge amount of information (pre-processing at the front-end level)
- Real time tracking

The **TIMESPOT project** has a system-level approach, starting from state-of-the art expertise in different fields. The aim is to trace a possible path towards the solution of this experimental challenge.

**First results** after less then 1 year of activity are already there…

# Aknowledements

**Many thanks to all the TIMESPOT team members**

**Special thanks to**

**Angelo Loi, Andrea Contu, Sandro Cadeddu (INFN Cagliari)**
**Lorenzo Piccolo (INFN Torino)**
**Marco Petruzzo, Nicola Neri (INFN Milano)**

***…And thank you for your kind attention!***