

Fast track finding at HL-LHC

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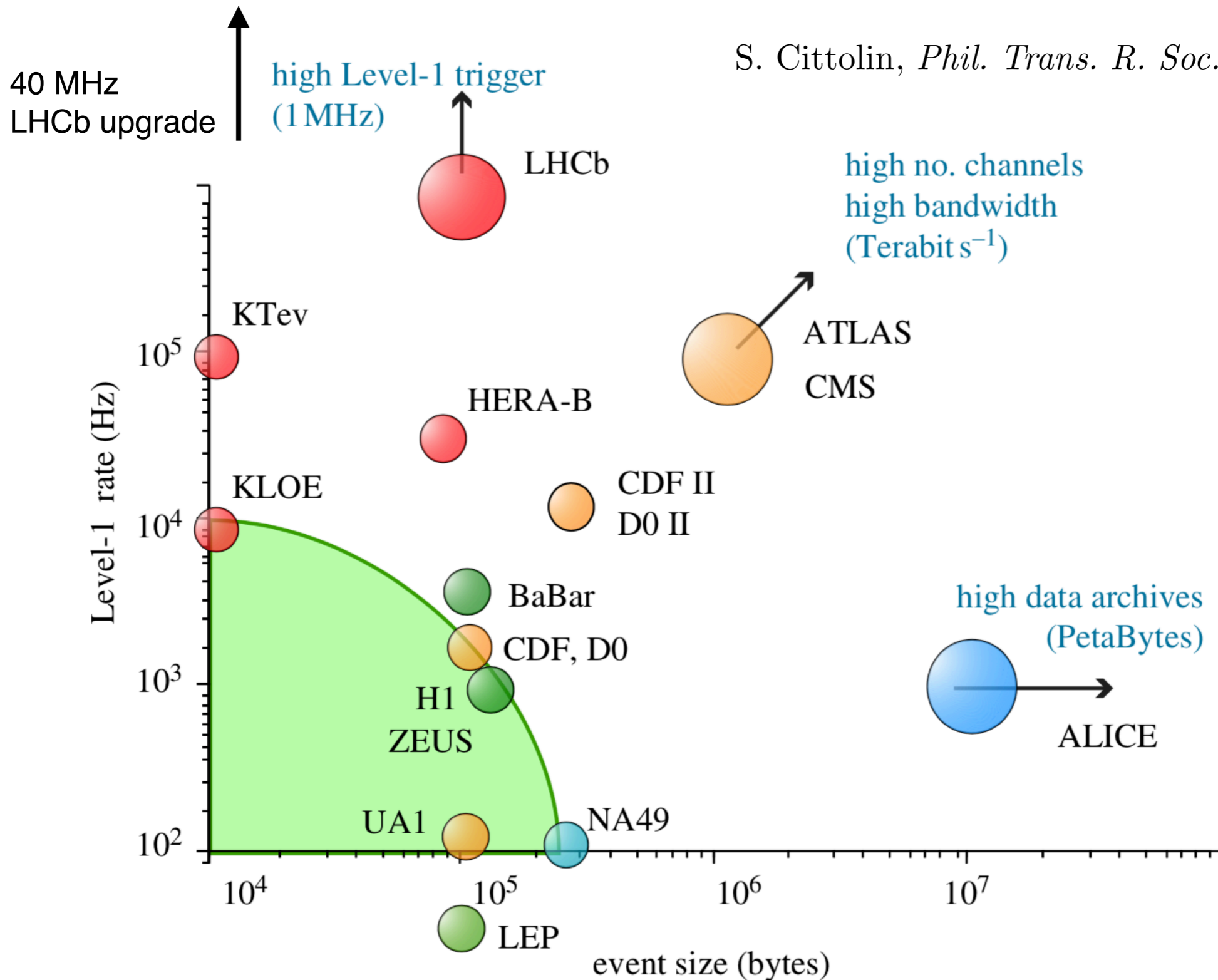
Milano, 23 Nov 2017

Outline

- ▶ Introduction
- ▶ Real-time tracking
- ▶ Artificial retina algorithm
- ▶ Detector prototype with embedded tracking capabilities
- ▶ 4D real-time tracking
- ▶ Summary

Summary of TDAQ in HEP

S. Cittolin, *Phil. Trans. R. Soc. A* (2012) **370**, 950–964



Trigger strategy at LHCb

- ▶ CPU-based trigger is already a big challenge for LHCb upgrade at $L=2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in 2020
- ▶ Trigger decision based on tracking information of the entire event

Tracking Algorithm	CPU time[ms]	
	No GEC	GEC = 1200
VELO tracking	2.3	2.0
VELO-UT tracking	1.4	1.3
Forward tracking	2.5	1.9
PV finding	0.40	0.38
Total @29 MHz		5.6
Total	6.6	5.4

- ▶ No obvious solution for CPU-based trigger at high luminosity $L=2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Upgrade HLT

VELO tracking

VELO-UT
 $p_T > 200 \text{ MeV}/c$

Forward reco
 $p_T > 500 \text{ MeV}/c$

PV finding

Trigger cuts to
reduce rate to 1 MHz

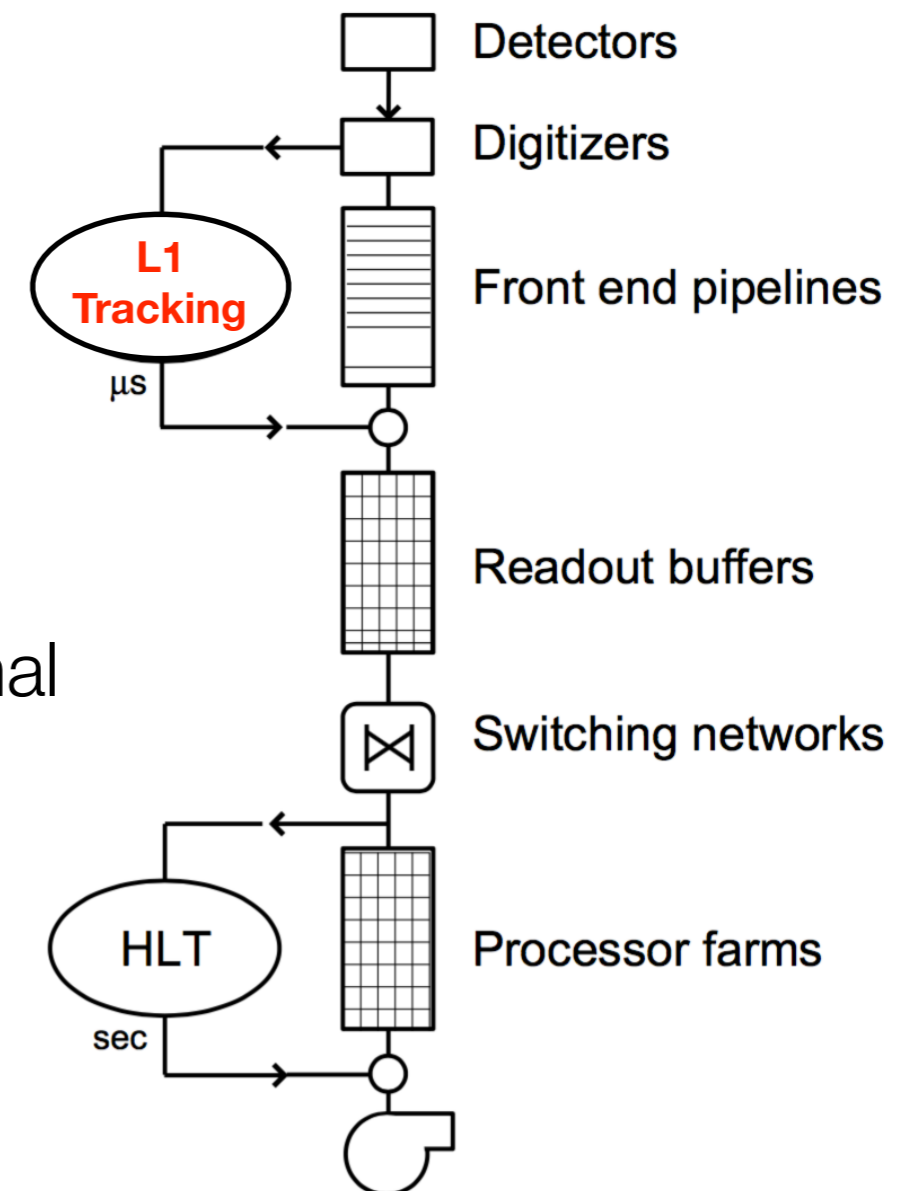
Muon ID

Simplified Kalman Fit

Online RICH PID

Real-time tracking for HL-LHC

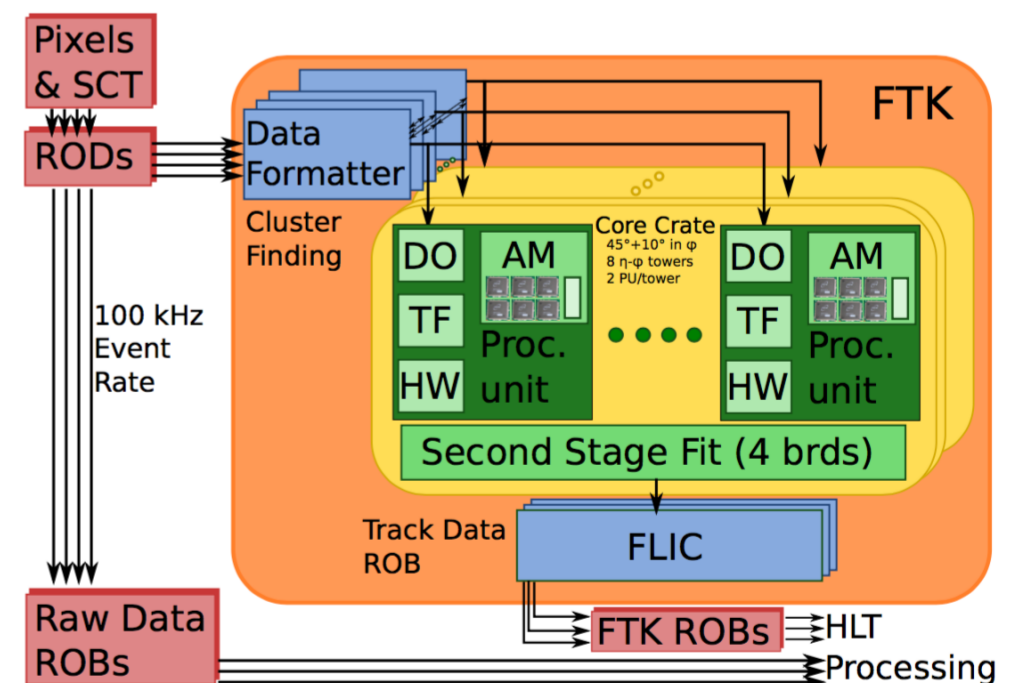
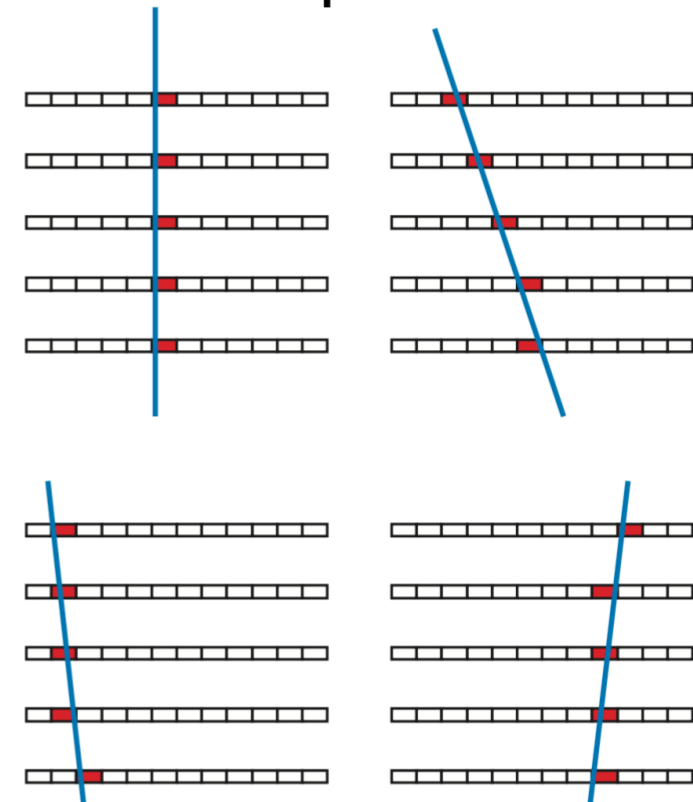
- ▶ Full exploitation of HL-LHC requires new detectors and trigger systems
- ▶ L1 trigger decisions based on tracking information are crucial:
 - reduce data rate to a sustainable level
 - maintain good efficiency and purity for signal events
- ▶ Real time tracking is extremely challenging at LHC: 40MHz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



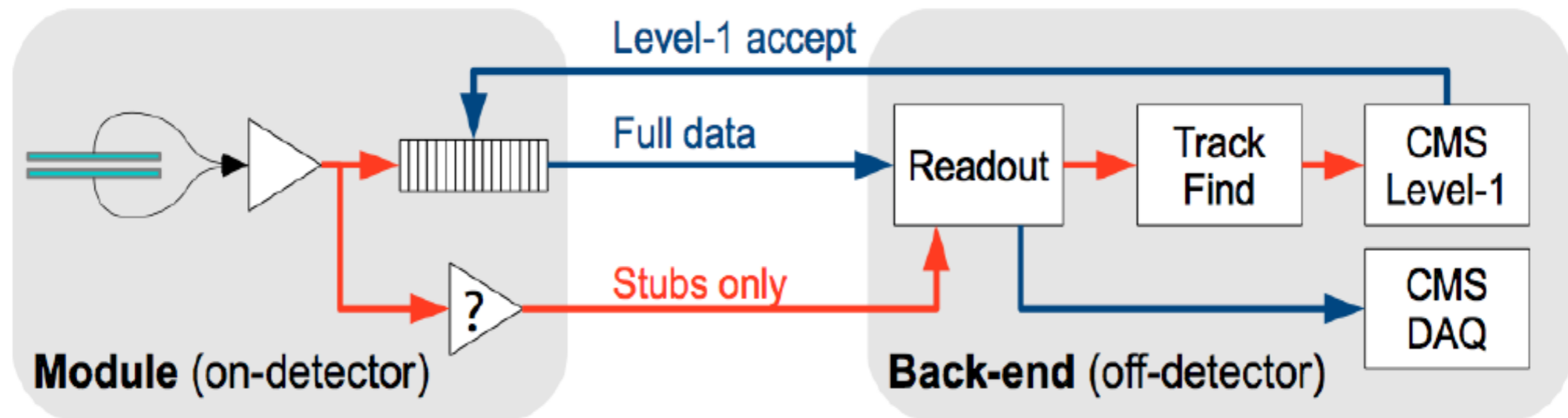
Existing fast track finders

- ▶ 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 $10\mu\text{s}$ and input rate 30 kHz
- ▶ FTK device in ATLAS use similar concept. Latency $\sim 50\mu\text{s}$ and input rate 100 kHz

Track patterns



CMS phase-II trigger scheme



L1 Latency 10 μ s
(20 μ s in option)
L1A rate ≤ 1 MHz
HLT rate ≤ 10 kHz

- ▶ Use stubs information at early stage of processing to reduce data rate and fast tracking for L1 trigger

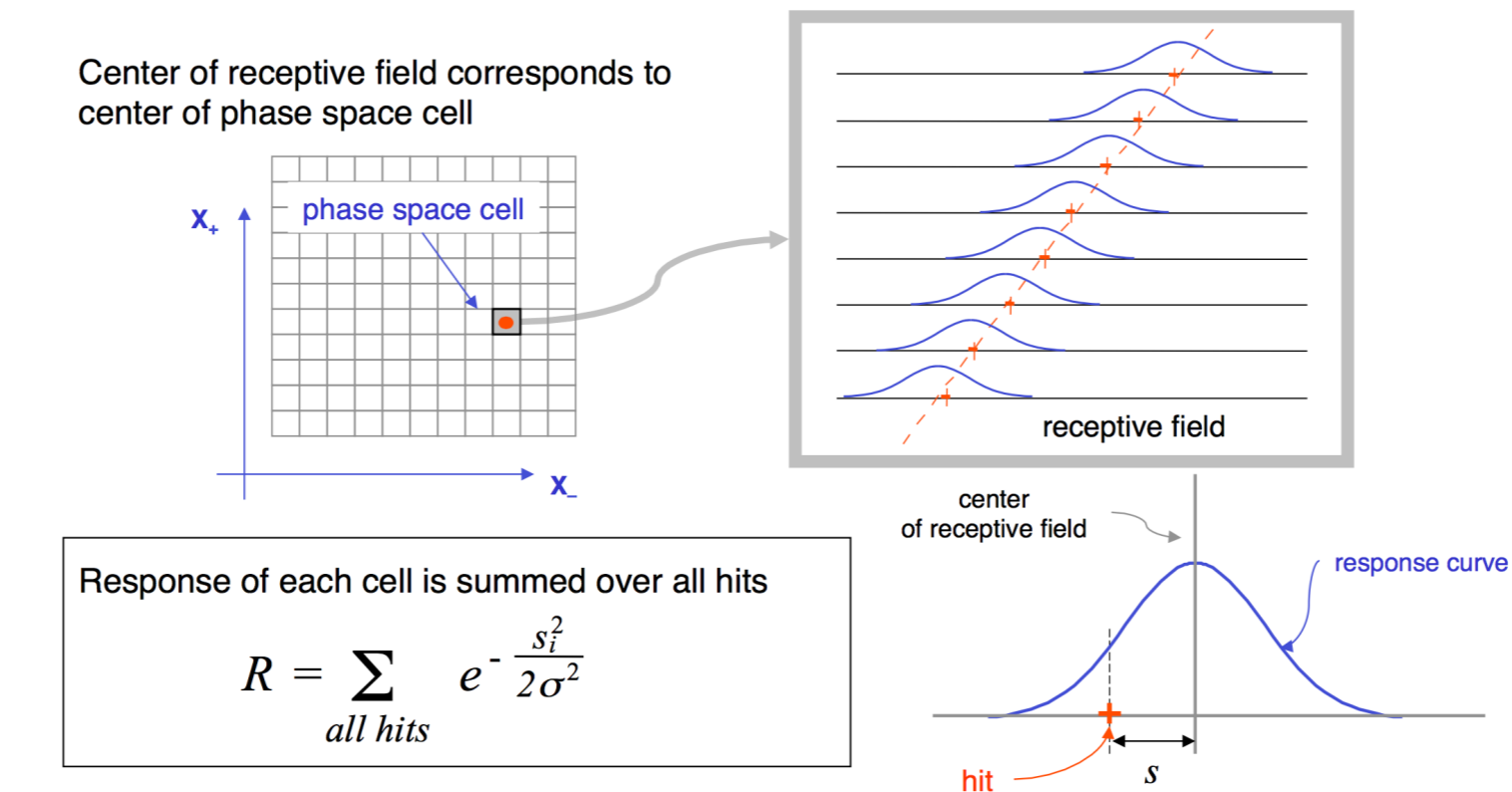
Retina INFN project

- ▶ 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 (see Marco Petruzzo's talk):
 - Real time tracking detector prototype for test beam
 - Fast track finding system compatible with large DAQ framework for test with simulated data at 40 MHz event rate

Artificial retina algorithm

- ▶ Basic algorithm for fast track finding

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



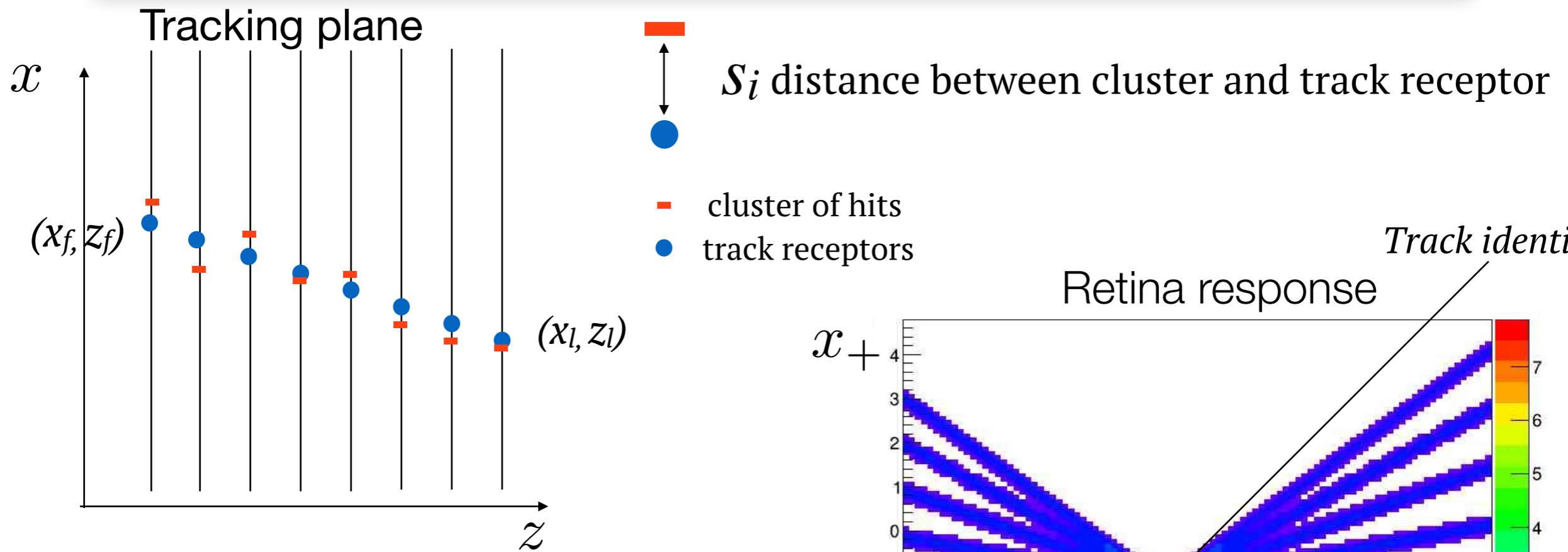
November 17, 1999

INSTR99 - An Artificial Retina for Fast Track Finding - L. Ristori - INFN Pisa

8

- ▶ 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



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

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

Excitation of the cellular units

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

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

► Track parameters obtained by interpolation of R values around maximum

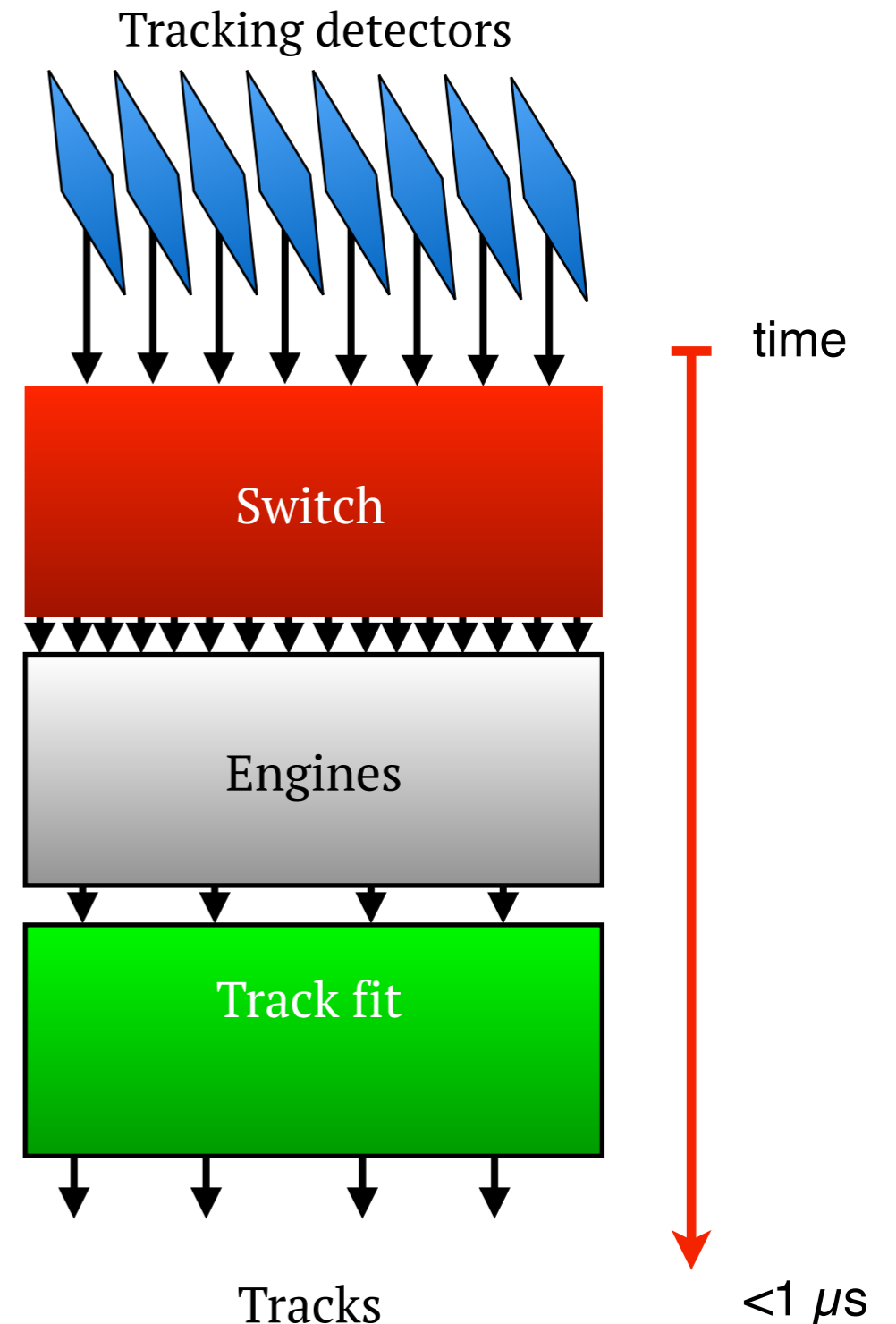
Artificial retina architecture

▶ 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

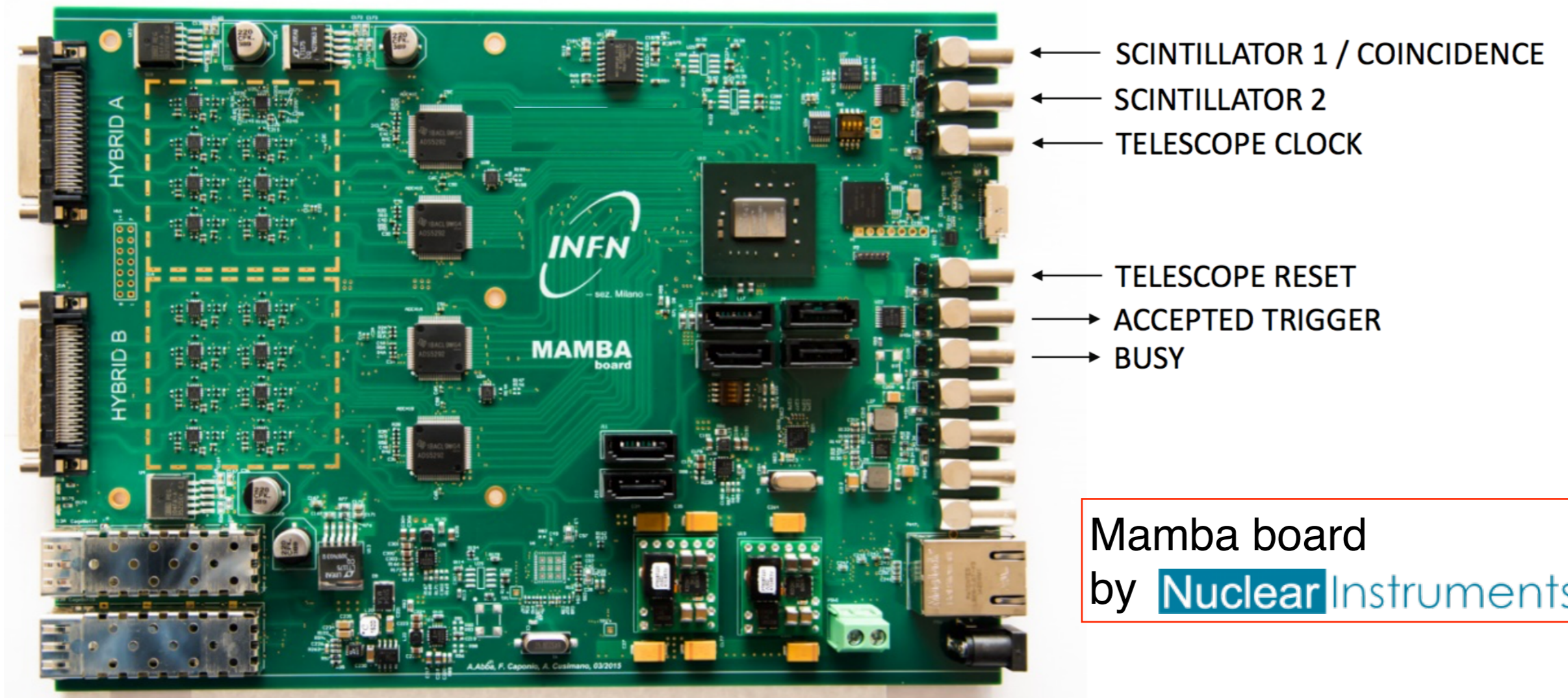
▶ Main differences with AM approach:

- ▶ 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



Mamba board

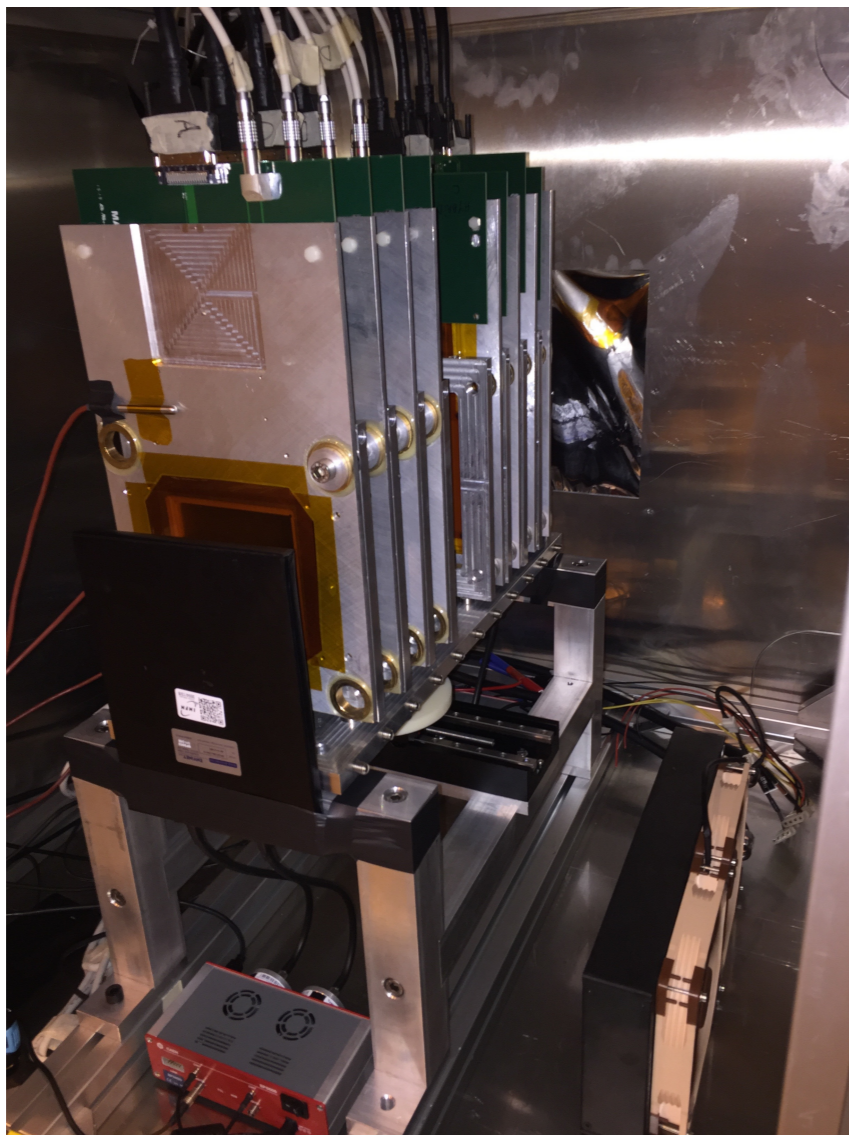
- ▶ Readout 8 detectors in 1x mode (300 kHz) or 2 detectors in 4x mode (1.1 MHz)



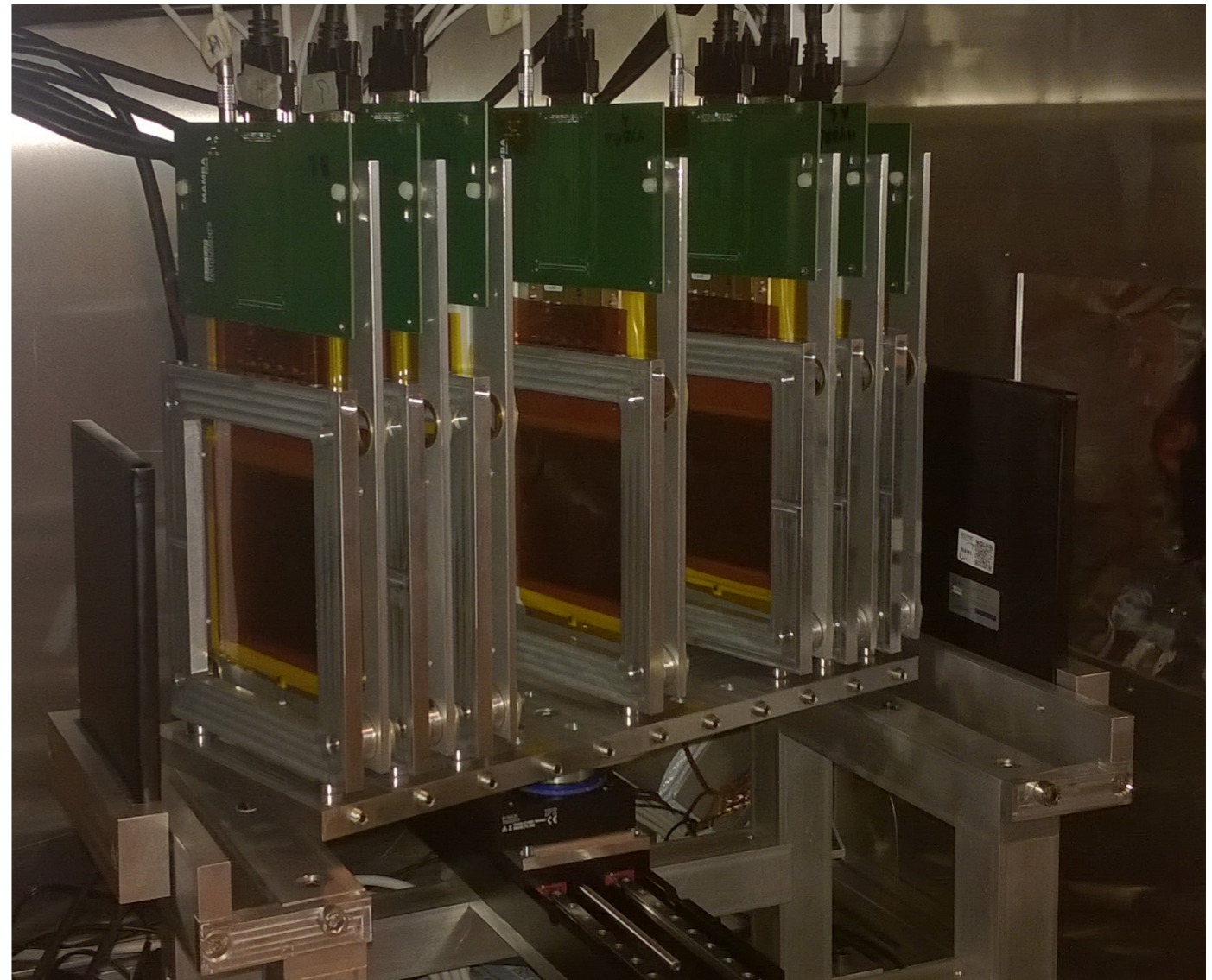
Telescope on beam at SPS

- ▶ Telescope tested on 180 GeV/c proton beam
- ▶ Rotation angle wrt beam axis: 0, 2, 4, 8, 16, 20 degree

Telescope aligned with beam axis

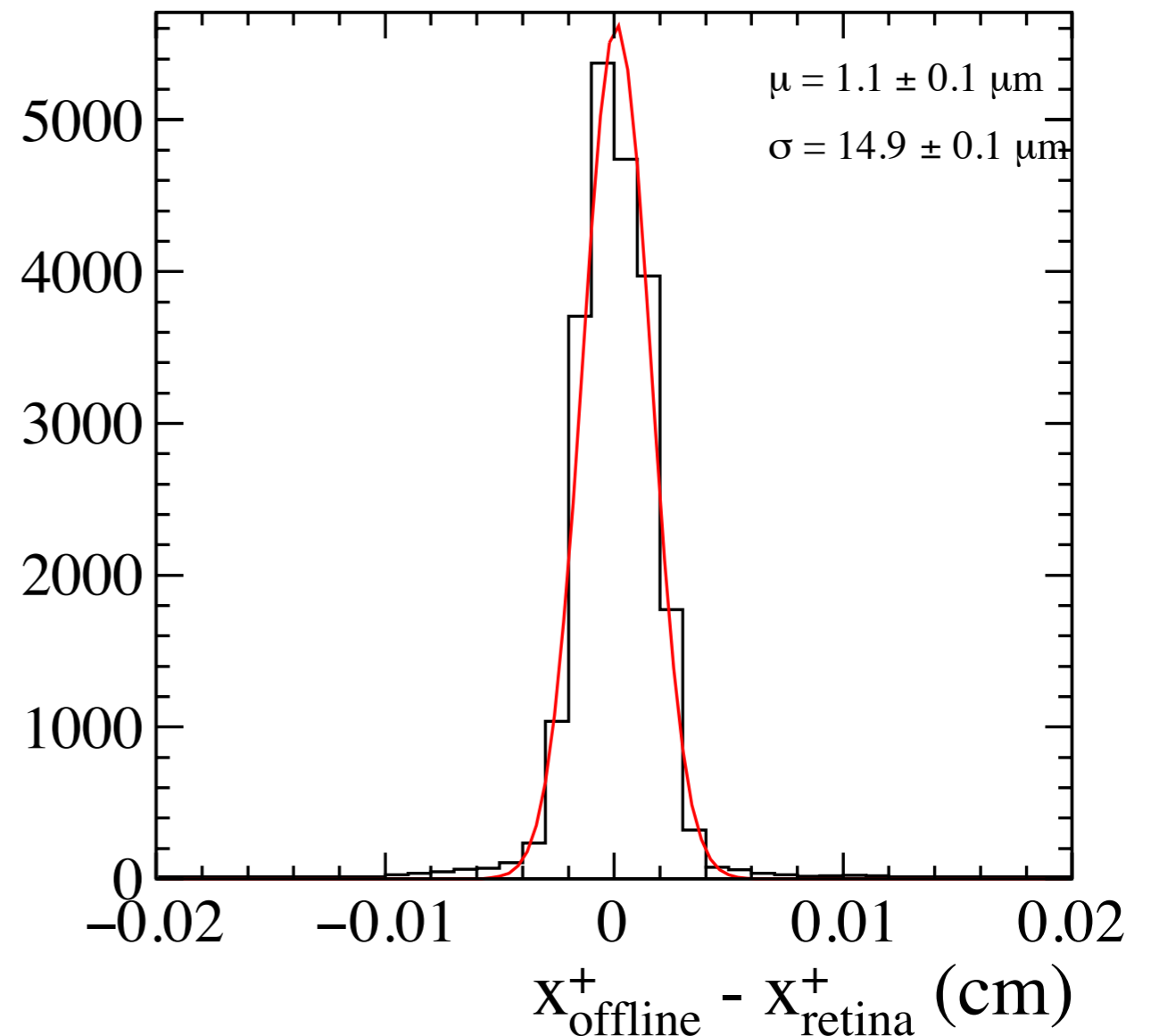
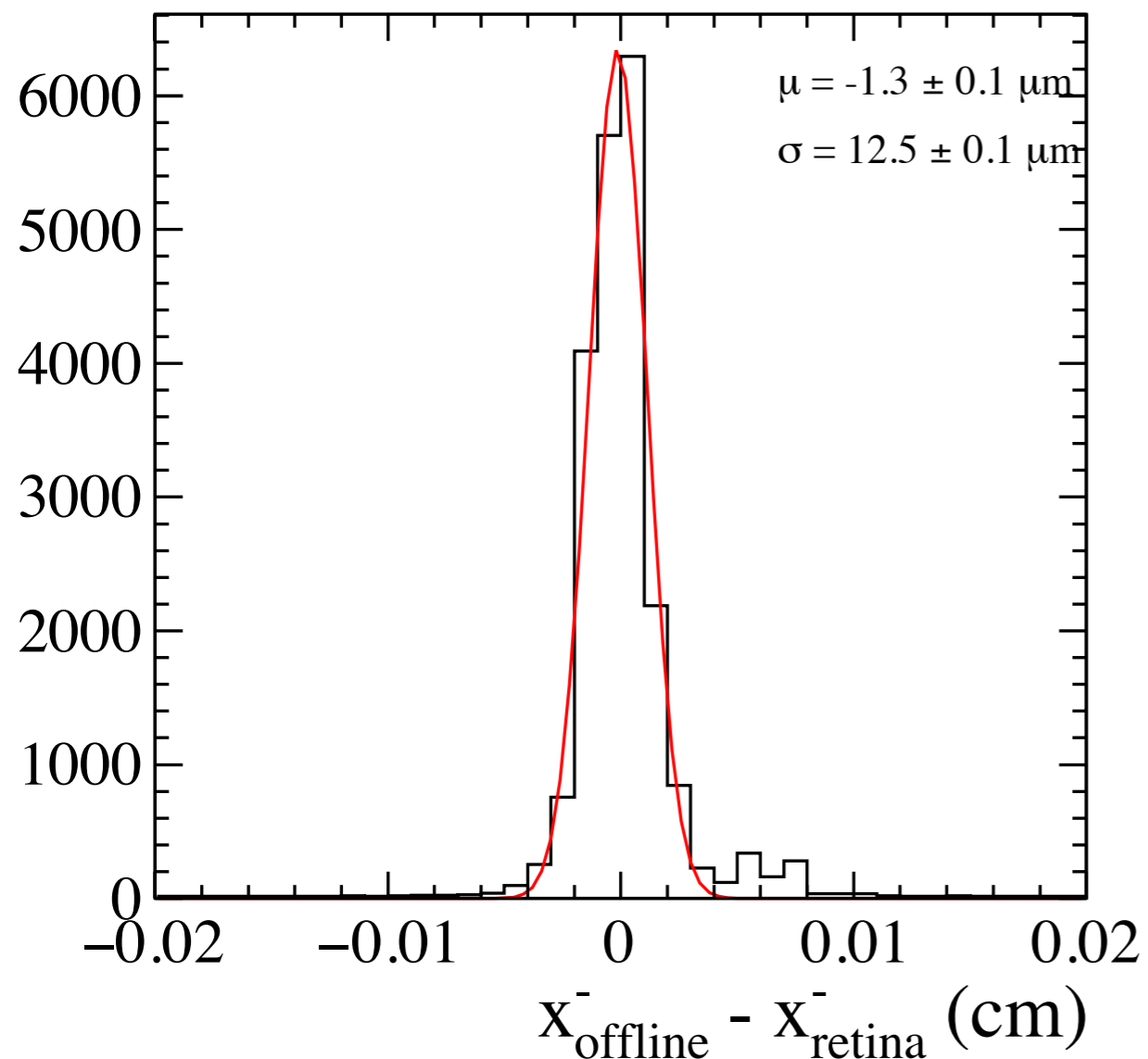


Telescope rotated wrt beam axis



Track residuals: offline - retina

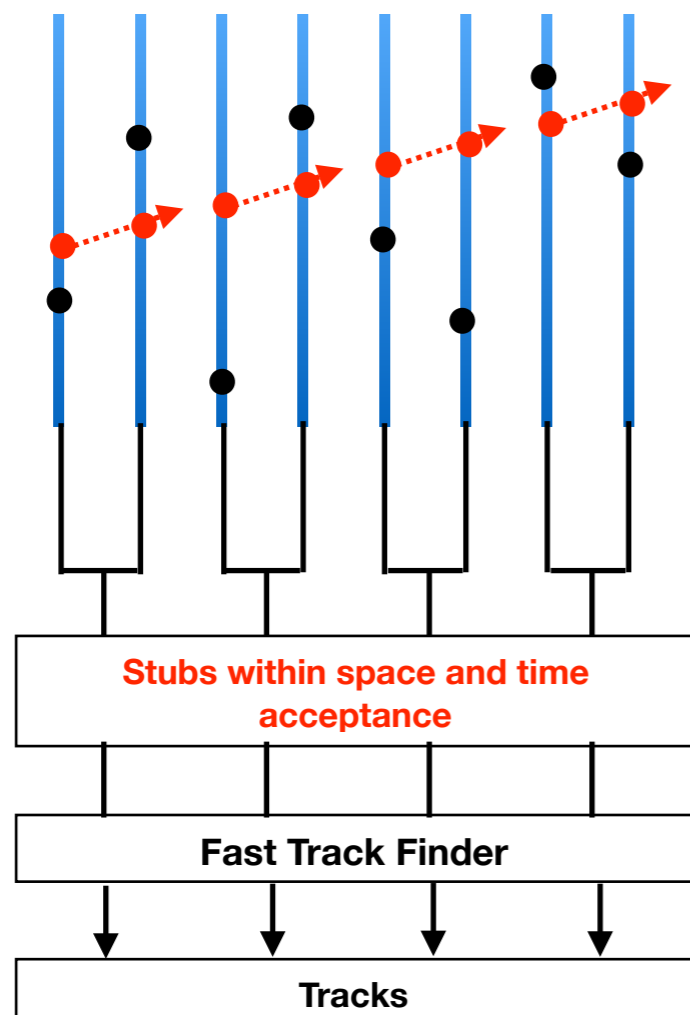
- ▶ It works! Offline-Retina track parameter residuals are peaked at zero



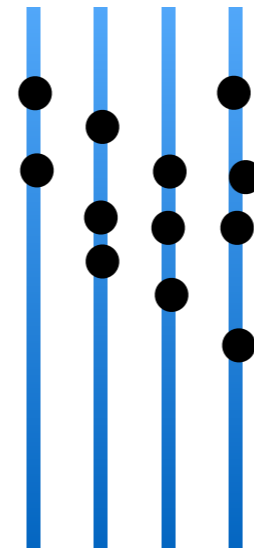
4D real-time tracking

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”

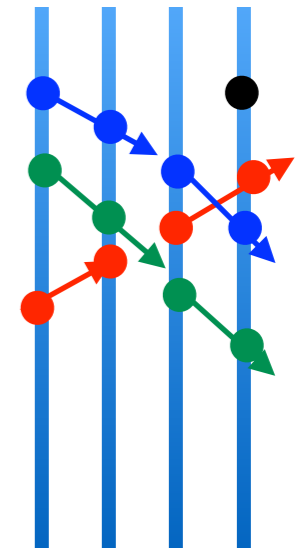


Hits no time information



hit

Stubs with time information



stub, time

$$\bullet \vec{x} \longrightarrow \bullet \begin{matrix} \nearrow \\ \searrow \end{matrix} (\vec{x}_1, \vec{x}_2, t_1, t_2)$$

- ▶ 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:

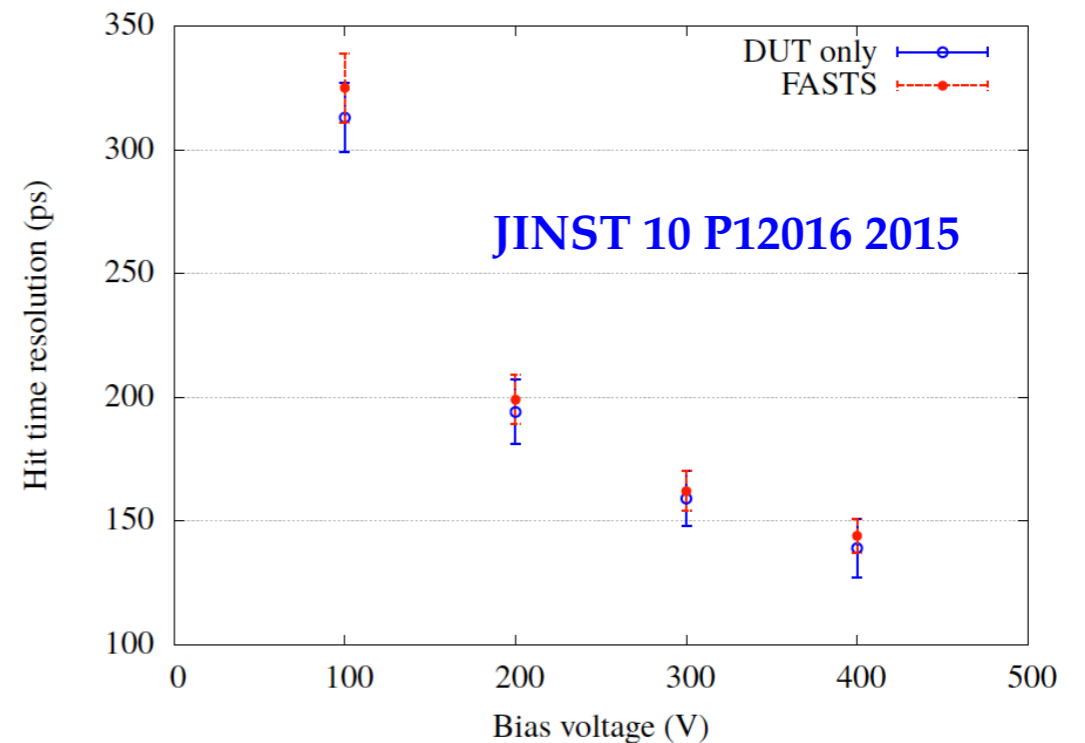
- **NA62 Gigatracker**, 150ps resolution in testbeam. Pixel size $300\mu\text{m} \times 300\mu\text{m}$, 200 μm thickness
- p-in-n sensor, FEE IBM 130nm technology, CO₂ active cooling

- **UFSD**, very promising results - 25ps time resolution (pad 1.4mm²)

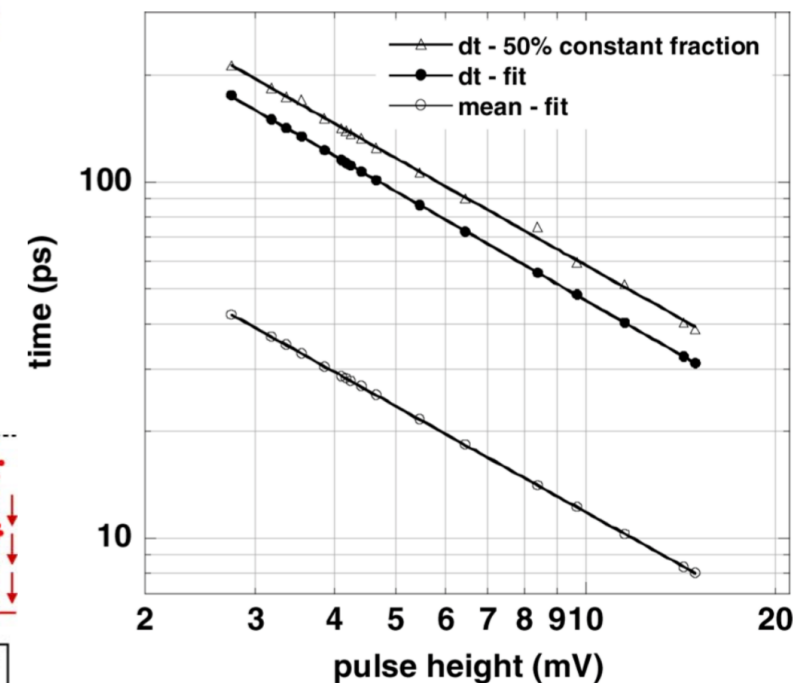
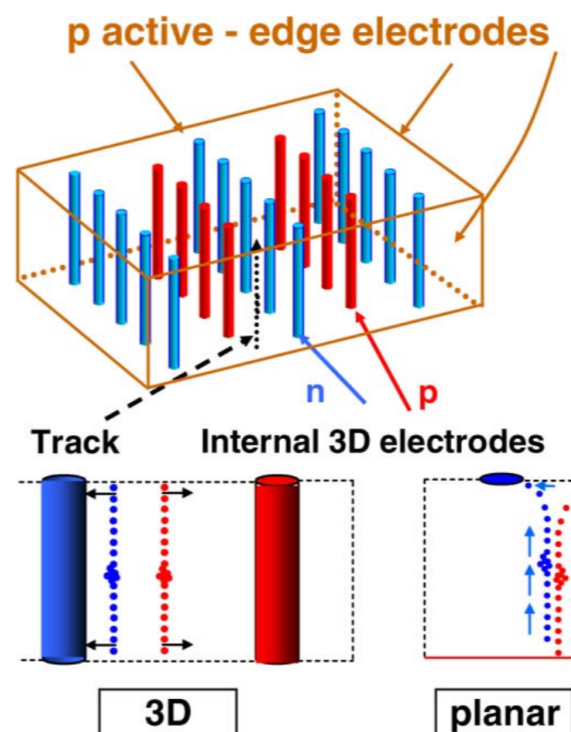
arXiv:1608.08681

► 3D silicon sensor technology:

- radiation hard, works at $10^{16}n_{\text{eq}}/\text{cm}^2$
- sub-ns time resolution is achievable
- R&D is needed to achieve the goal of **30ps time** and **40 μm hit resolution**



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

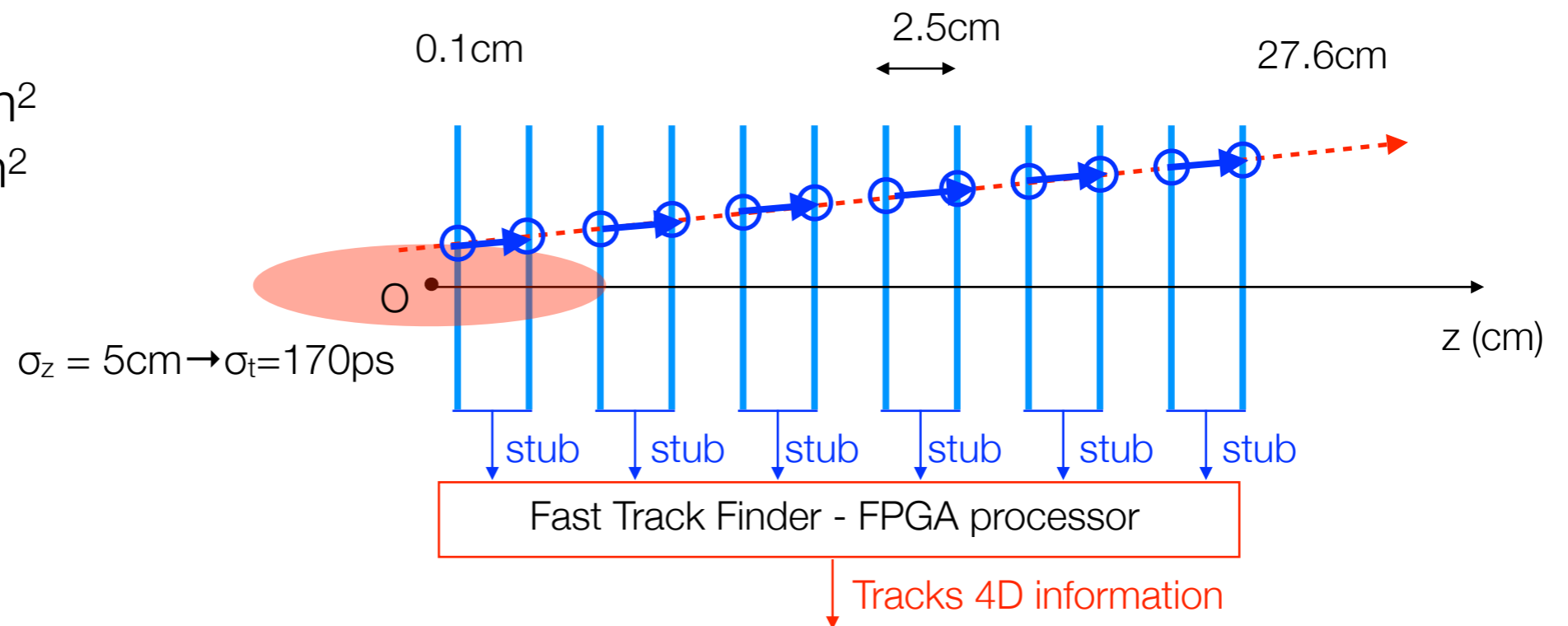


4D fast tracking simulations

NN, M. Petruzzo in preparation

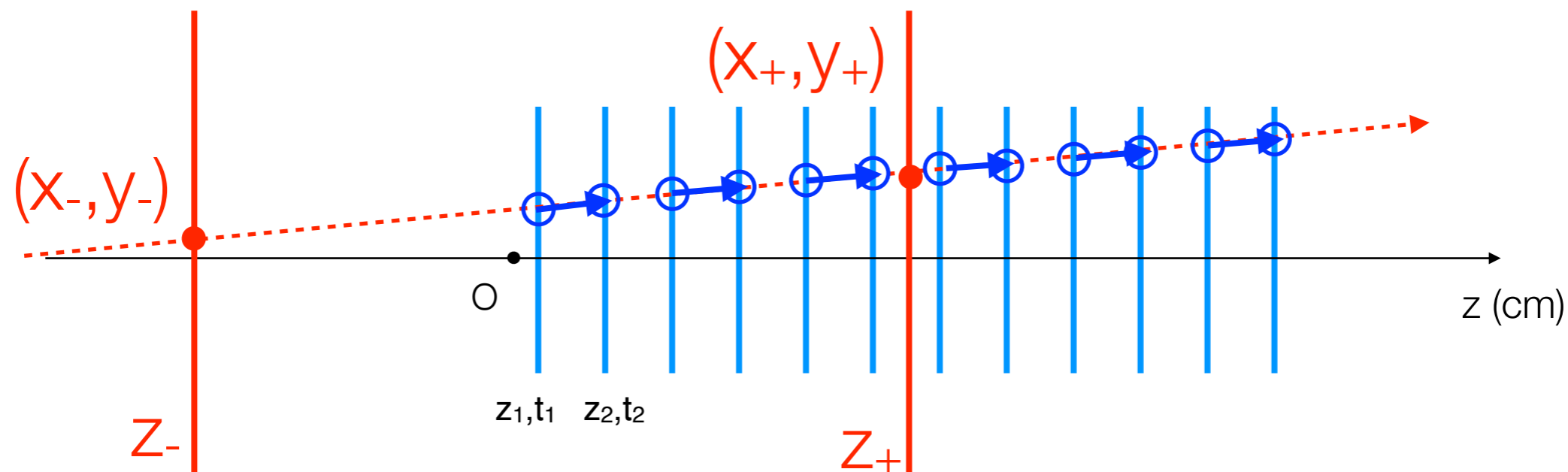
- ▶ Simple case: 12 layer telescope in forward region
- ▶ At $\text{lumi}=10^{34}\text{cm}^{-2}\text{s}^{-1}$: pileup ~ 40 and ~ 1200 tracks/event

Sensor area = $6\times 6\text{cm}^2$
pixel size = $55\times 55\mu\text{m}^2$
thickness = $200\ \mu\text{m}$
time res $\sigma_t=30\ \text{ps}$



- ▶ 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: $t_{\text{stub}} = (t_1 + t_2)/2$, 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

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

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

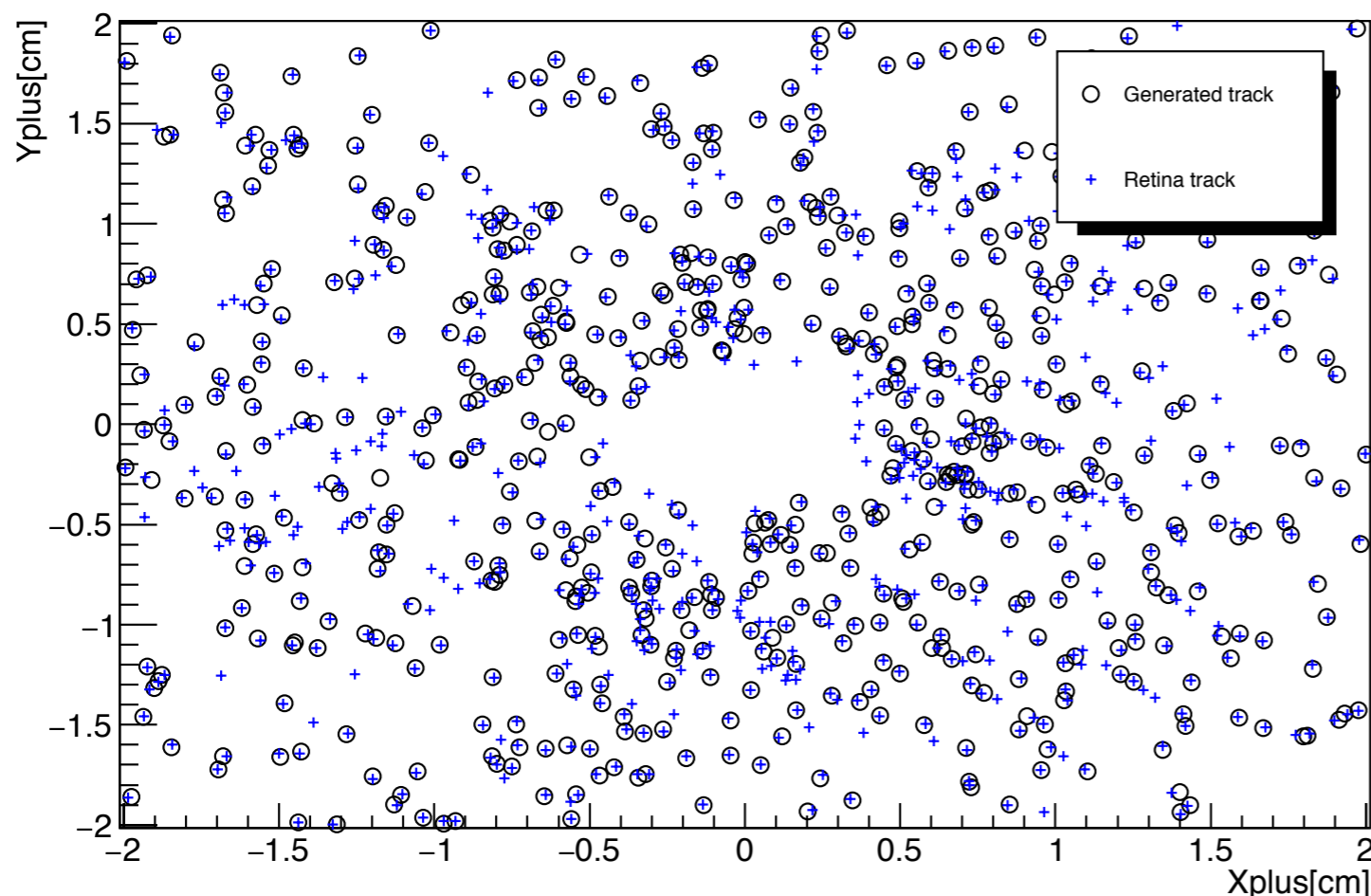
4D fast track finding algorithm

- ▶ Artificial retina algorithm adjusted to use stubs info:

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

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

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



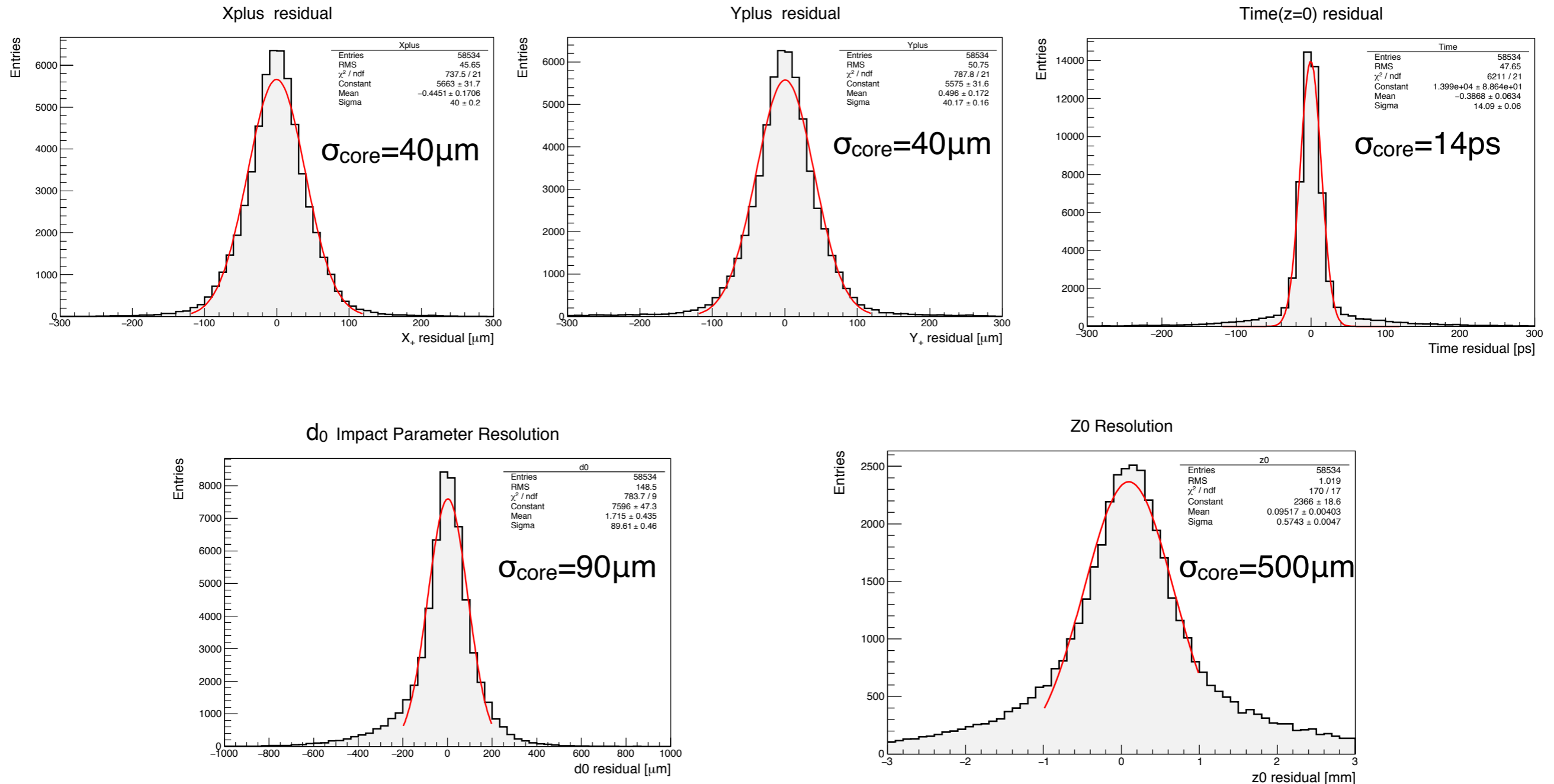
A local maximum of the artificial retina response W , identifies a track

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

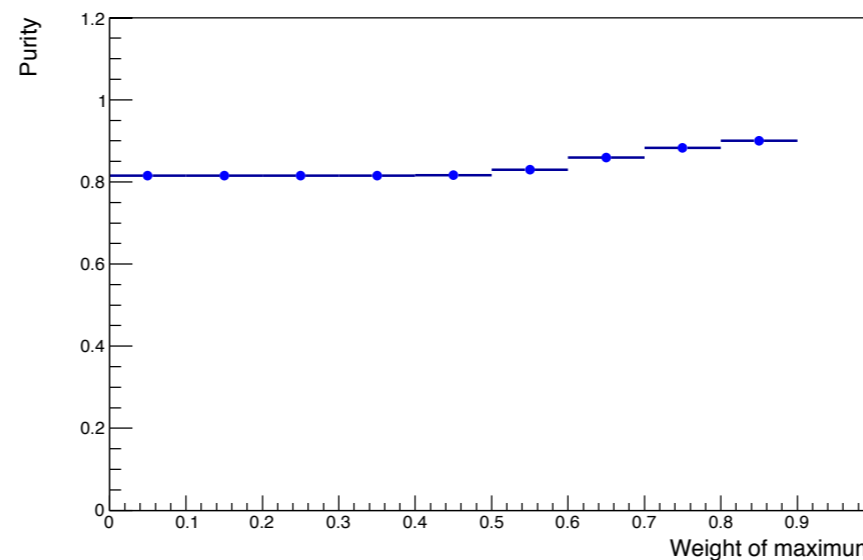
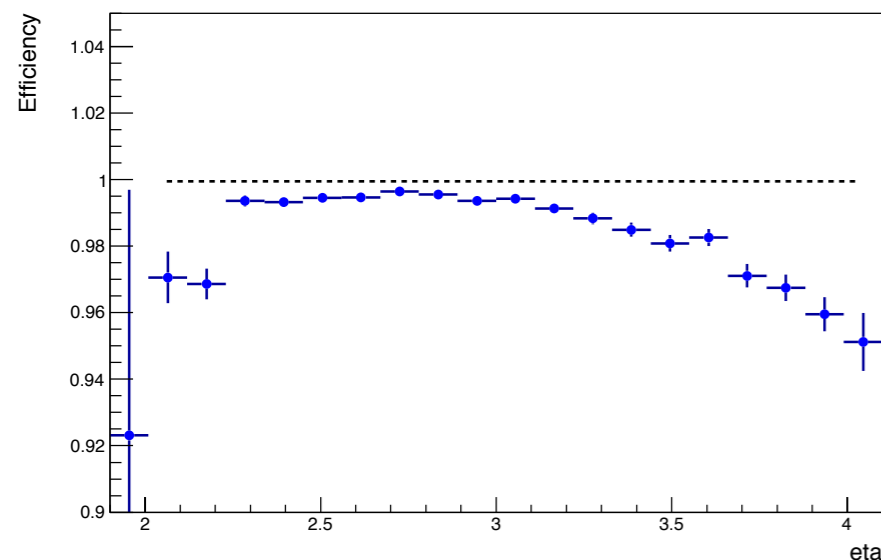
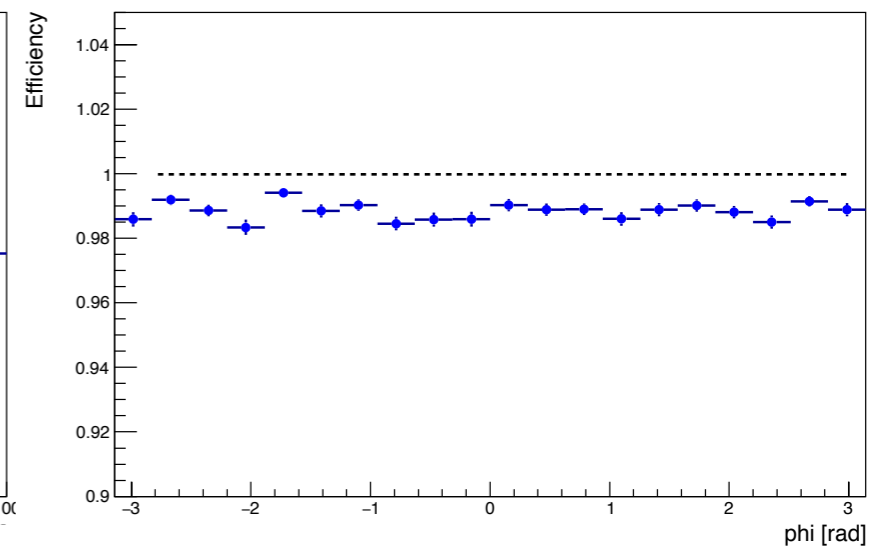
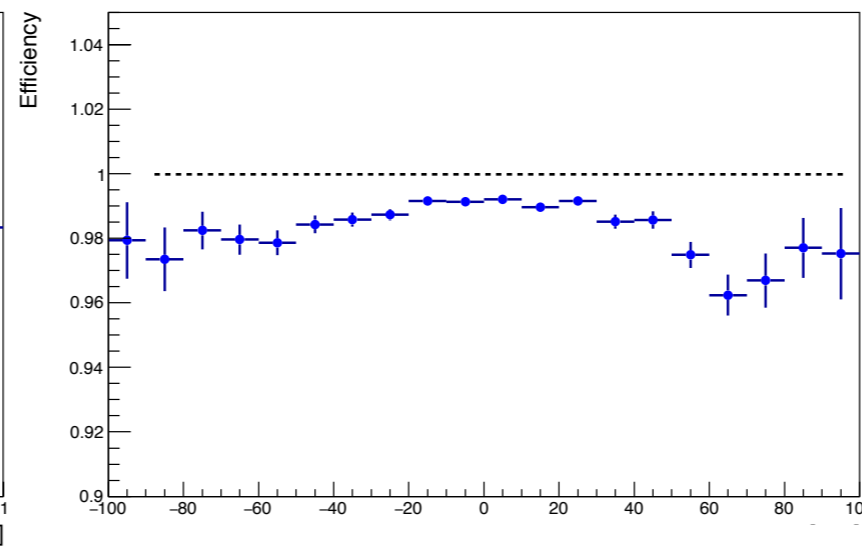
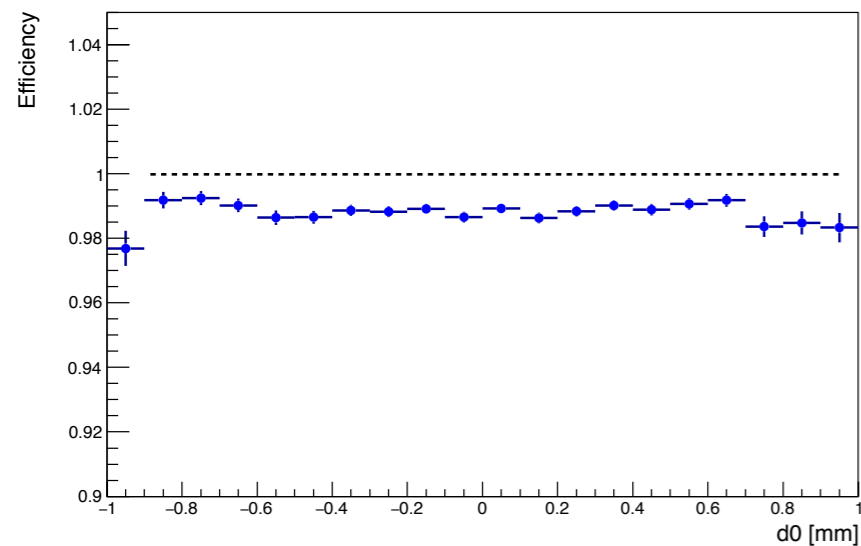
Resolution on track parameters

- ▶ Events with 40 pp interactions, 1200 tracks per event



Online track reconstruction efficiency

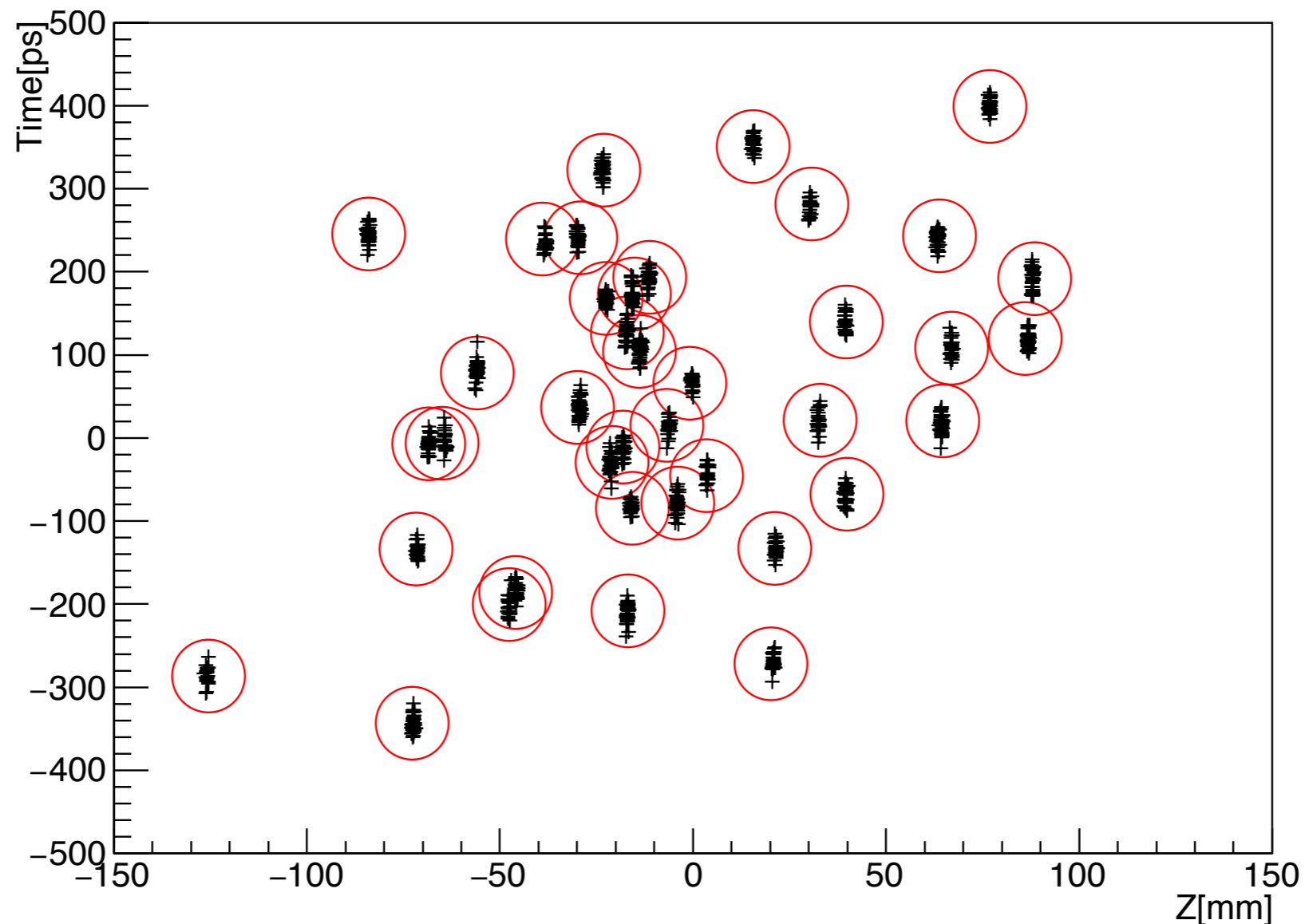
- ▶ Track efficiency vs track parameters: d_0 , z_0 , ϕ , η
 d_0 , z_0 (distance of closest approach to z axis), ϕ azimuthal angle, η =pseudo rapidity
- ▶ Track efficiency $\sim 99\%$ and track purity $>80\%$ with 1200 tracks per event \rightarrow track purity $\sim 60\%$ (without time information of 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) $\rightarrow <1\%$ using precise time information of the hit in offline reconstruction



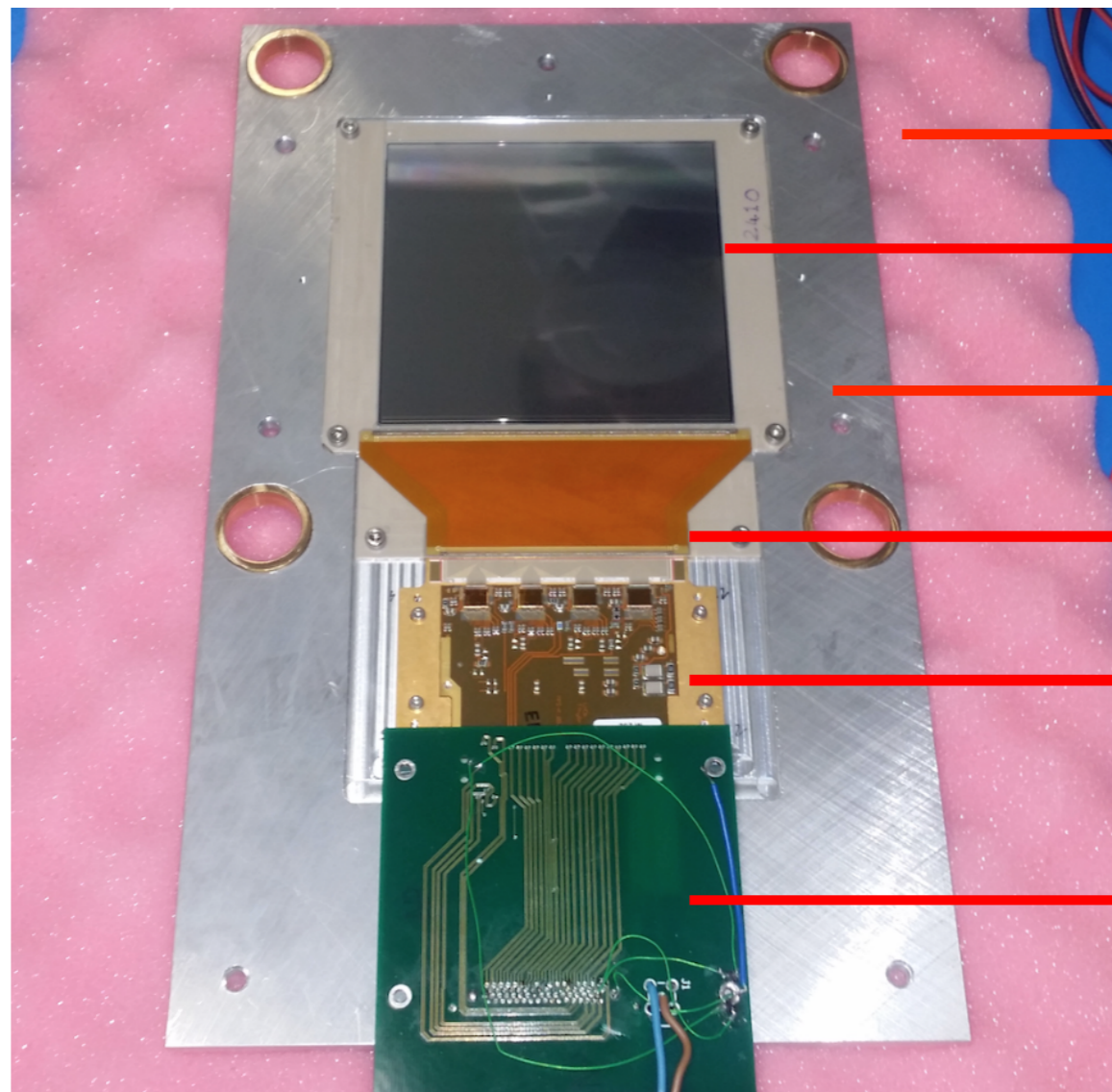
Summary

- ▶ **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
- ▶ **Let's start building it now!**

Backup slides

Telescope module

- ▶ Single-sided silicon sensors:
 - OB2 STM *p*-in-*n* sensor, 10 cmx10 cm active area
 - 512 strips, 183 μm pitch, 500 μm thickness



Aluminium support
Sensor with 512 strips

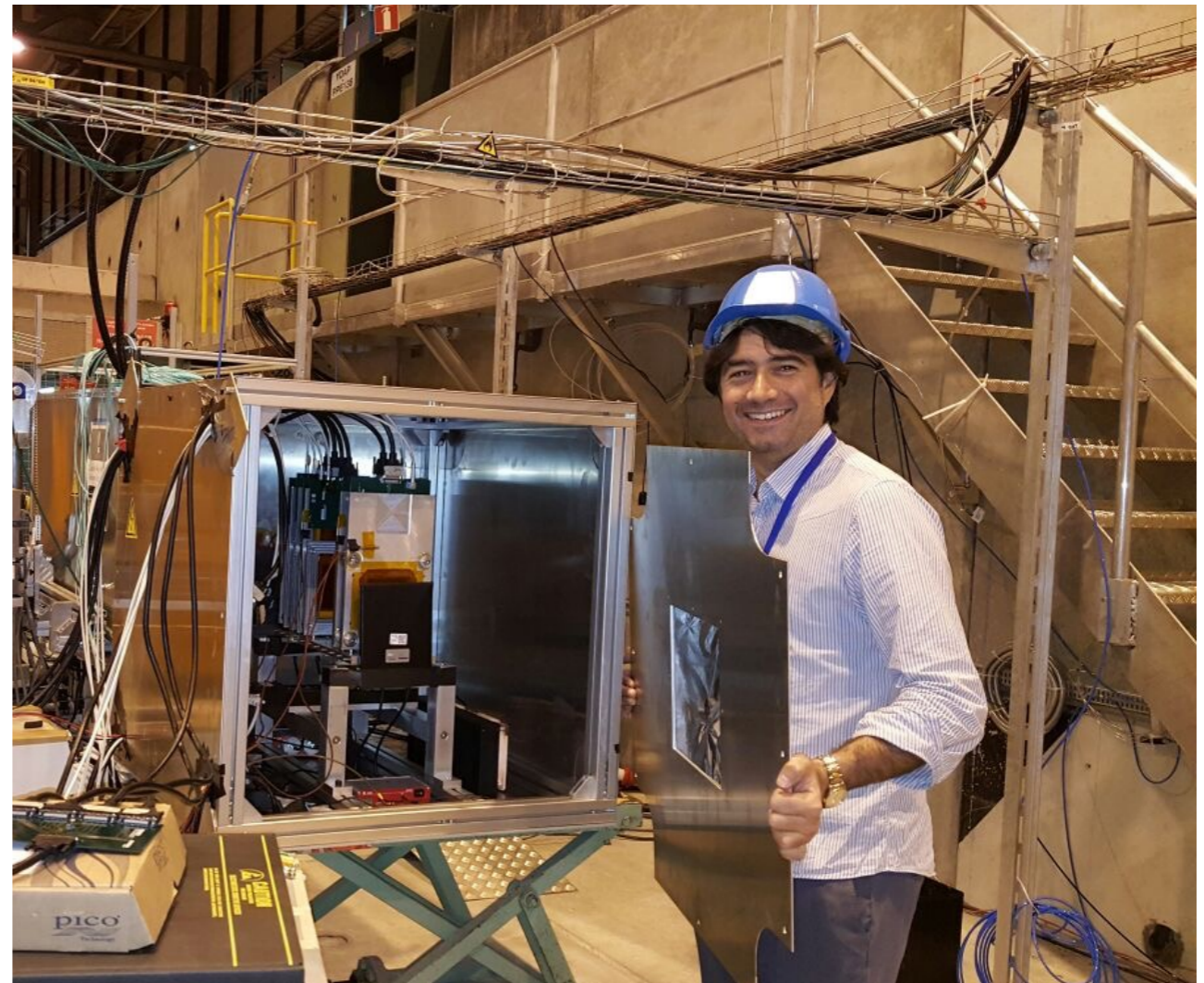
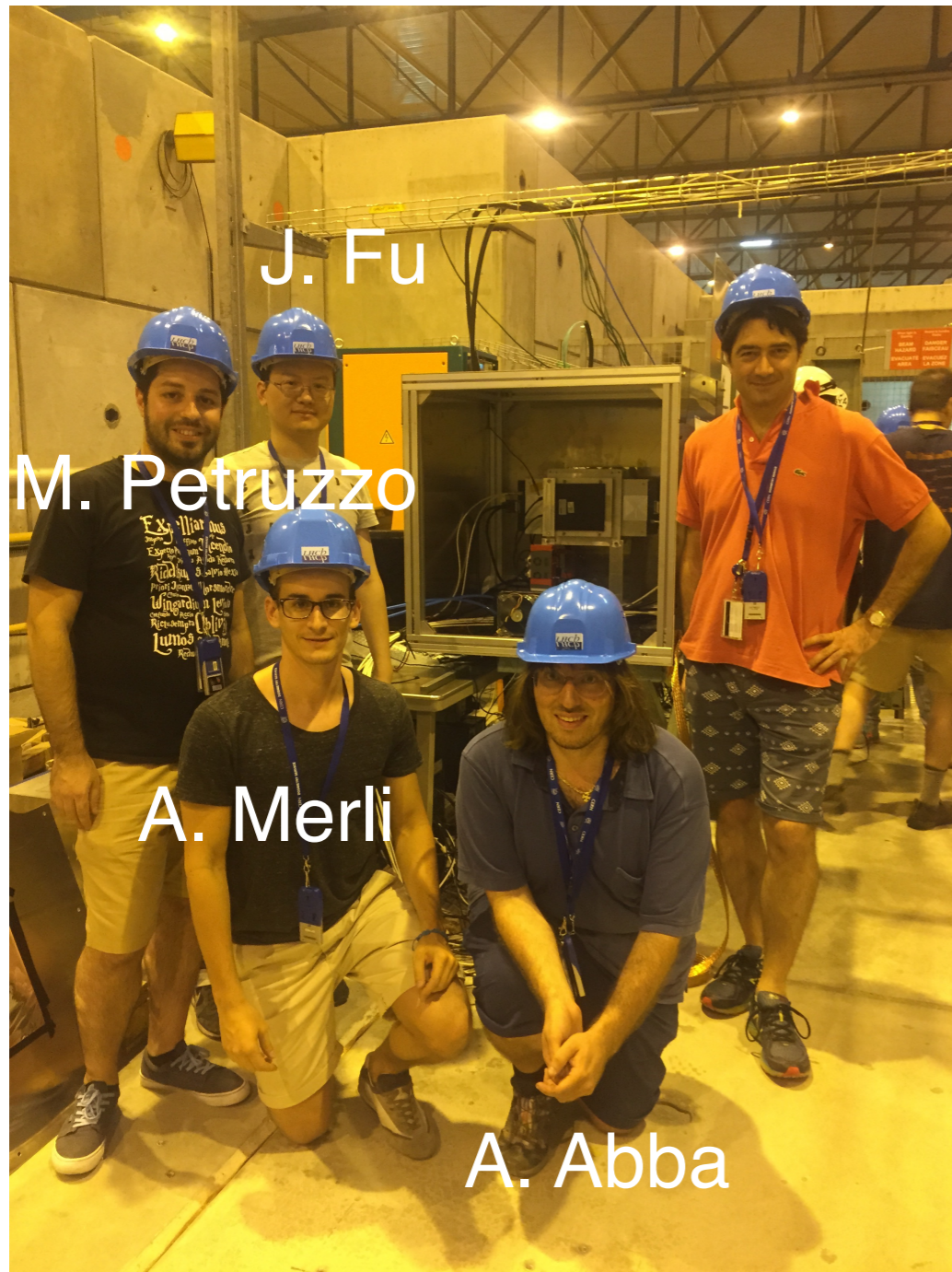
Peek support

Kapton pitch adapter from 112 to 183 μm

TT hybrid (4 Beetle chips)

DAQ board interface

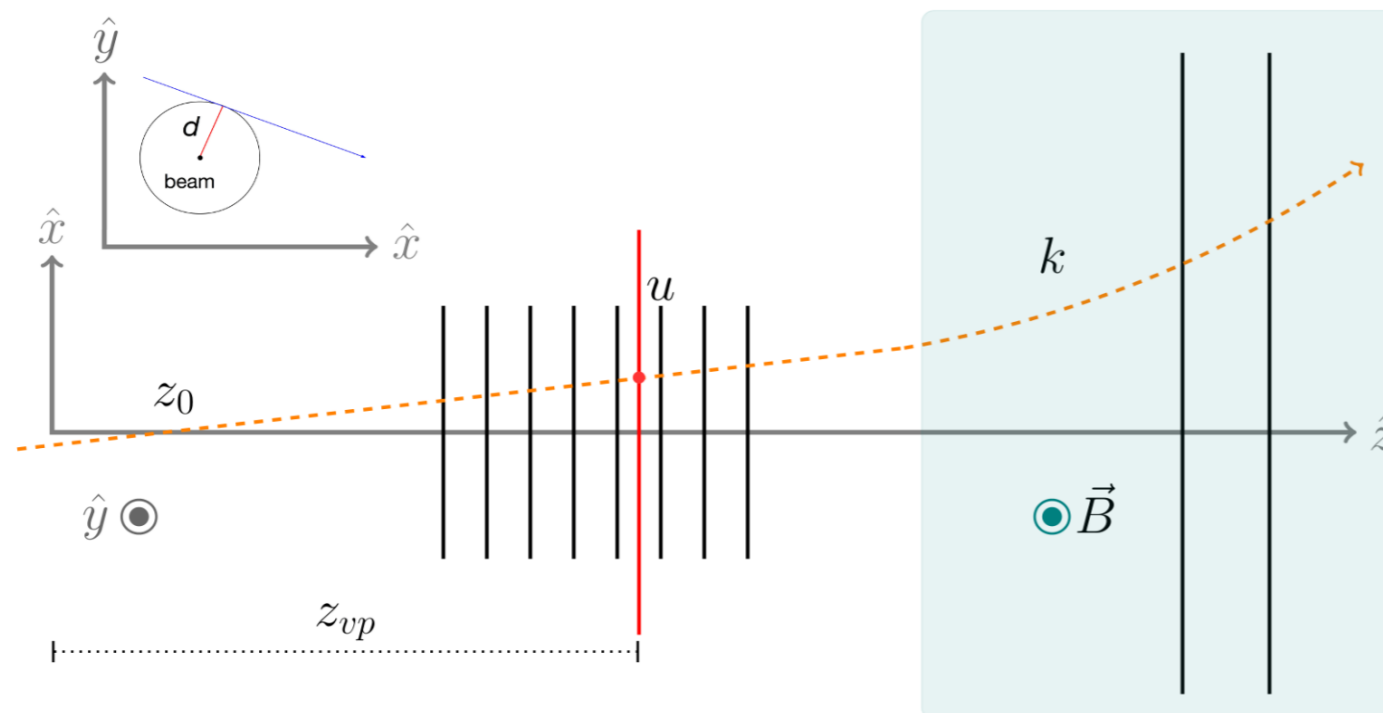
Testbeam crew



Feasibility study for LHC experiments

- ▶ The **Retina architecture is modular**, parallel processing units are scalable. Using adequate FPGA resources can **cope with high particle rates and large detectors**, e.g. **40 MHz event rate and 300 tracks/event of LHC**.
- ▶ Delivers **3D tracks with offline-like quality at 40 MHz with $<1\mu\text{s}$ latency**
- ▶ Case study for the LHCb upgrade simulated and documented here: LHCb-PUB-2014-026, JINST 9 C09001 (2014). Affordable resources and cost (50,000 cells \sim 50 FPGA)

Application in forward spectrometer experiment



- ▶ 50 mrad acceptance
 - $O(100)$ particles/event
- ▶ 8 pixel layers
- ▶ 2 silicon strip layers
- ▶ ~ 0.05 T magnetic field
- ▶ Pileup: ~ 8 pp events