Real-time reconstruction of downstream tracks

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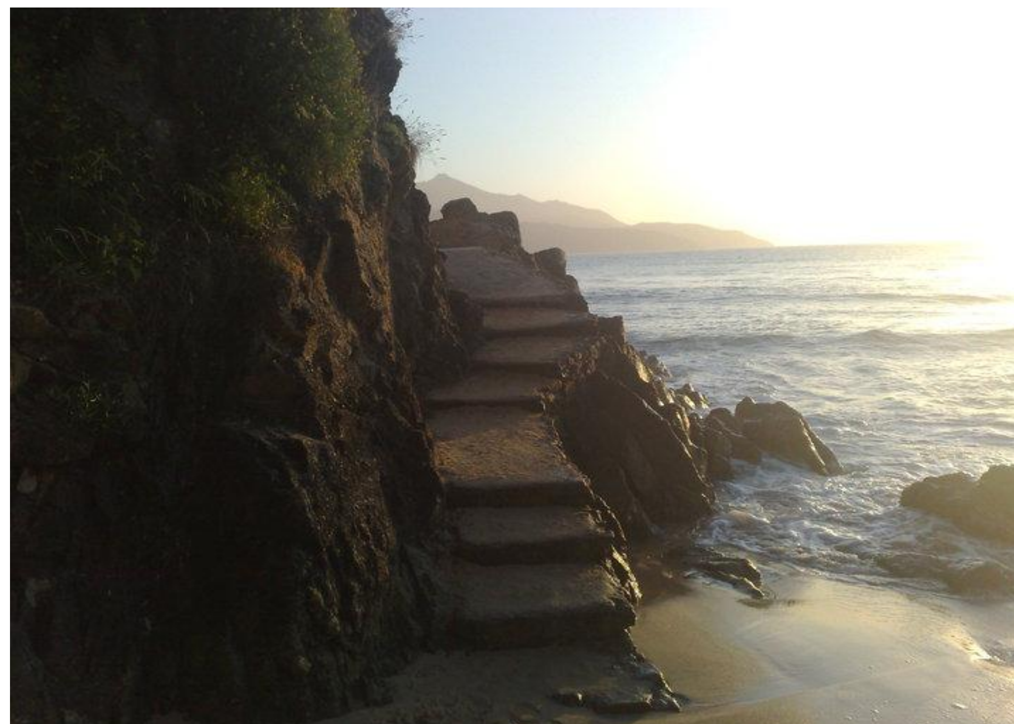
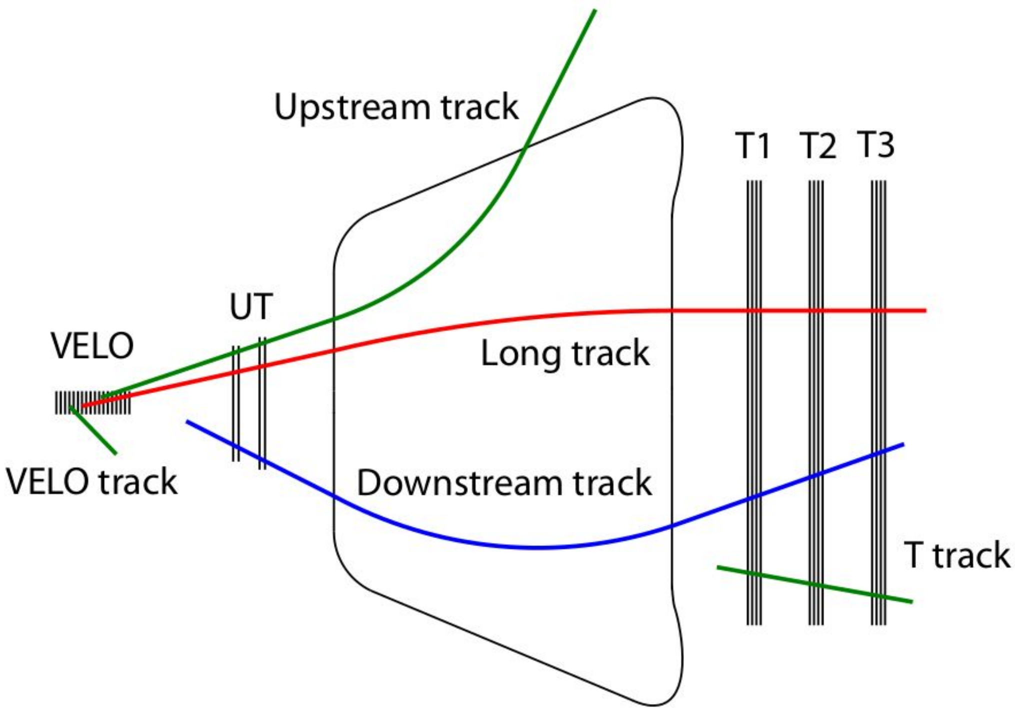
No Bonaparte was harmed during the preparation of these slides



Types of tracks to be reconstructed



Long lived particles in LHCb

	M (MeV)	τ (ps)
B_s	5300	1.5
K_S	500	90
K_L	500	50000
Λ	1100	260

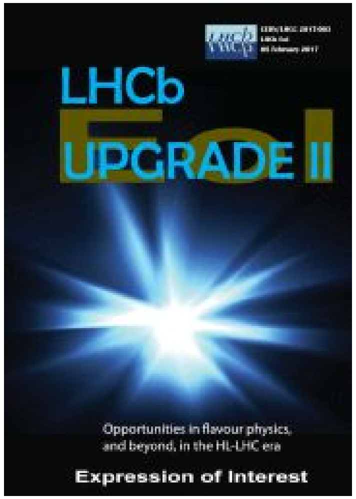
Long tracks: ~ 10^{14} K_S/fb^{-1} decay in LHCb acceptance

Downstream tracks: more statistics but worse p resolution

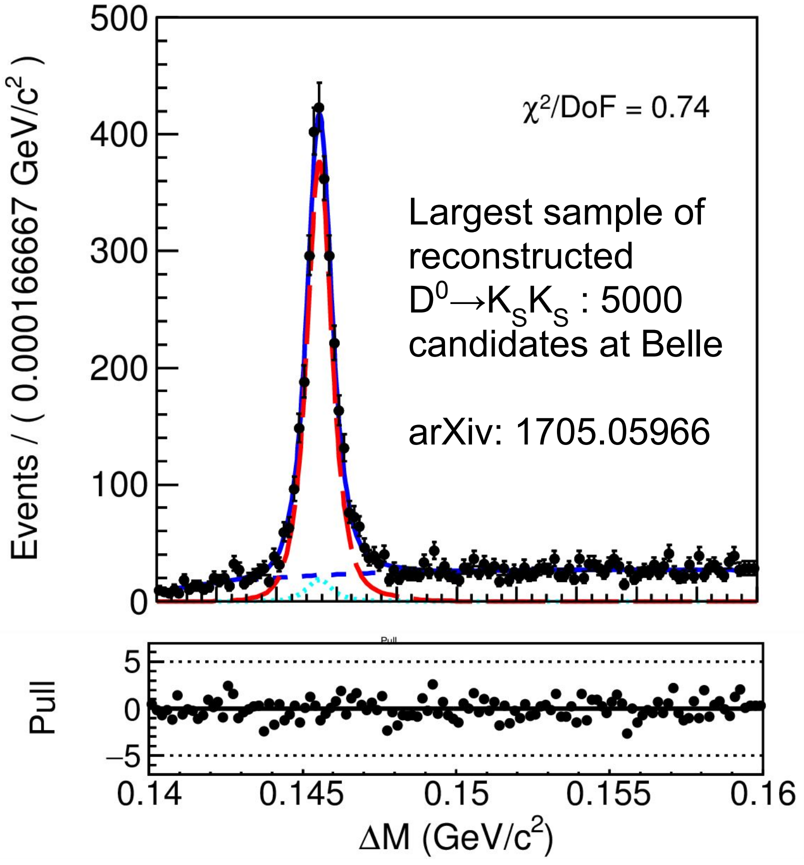
T tracks: very limited momentum resolution (if any)

The challenges ahead

- Order-of-magnitude growth in data volume: increased demand in offline storage and computing (+ thermal) power
- Most analysis will have to deal with the same challenges faced by ~~today's~~ upgrade's charm analyses
- Finding tracks downstream of the magnet at the earliest trigger level is not part of baseline trigger scheme (significant CPU time required)
- This would result in limited (if any) efficiency for decays with downstream tracks that cannot easily be triggered through other signatures

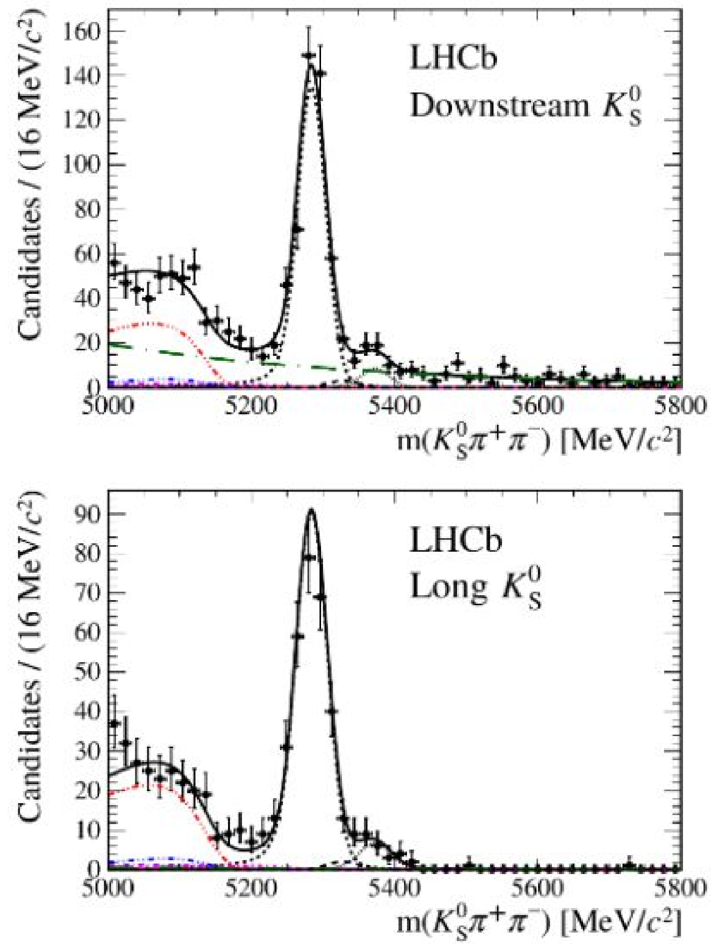


CERN-LHCC-2017-003



Motivation (1) - “core physics” channels

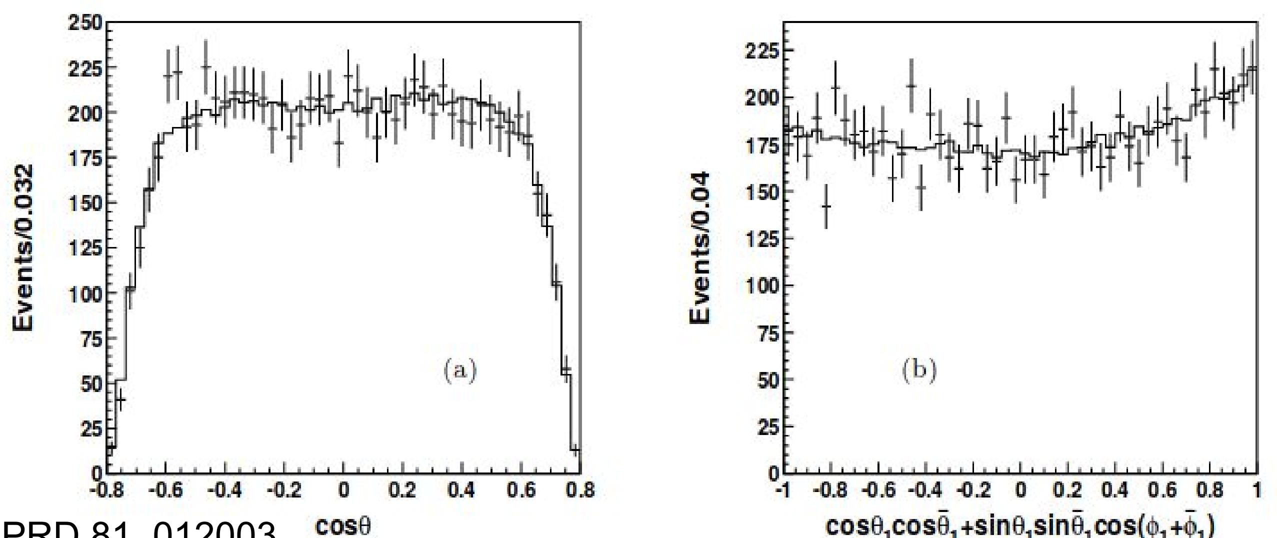
- **Neutral kaons (K_S and K_L) from charmless decays of B and B_s** to CP eigenstates, **and hadronic charm decays** → Increase yield and statistical precision, to face competition from Belle-II , BES-III
- **Lambdas in decays of charm and beauty baryons** → channels usually not studied at e^+e^- machines
- x2 improvement for channels with a K_S, expect greater gain for Lambda’s
- Control channels are important (for the experiment and for the theory)



JHEP10(2013)143

Motivation (2) - $K_{S,L}$ and Λ

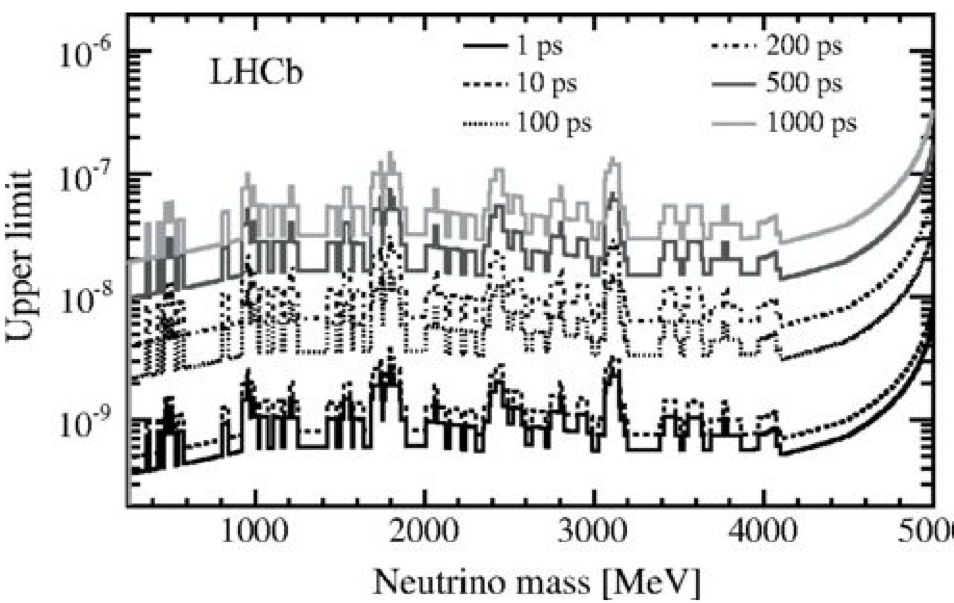
- Using downstream tracks it could be possible to increase **K_L reconstruction** efficiency and achieve a some K_S-K_L separation (by decay time)
- Access **very rare decays of K_S** (see presentation by Jessica yesterday)
- Precision study of the properties of **strange baryons**, e.g., using angular distributions (BES-II: PRD 81, 012003; BES-III in preparation)



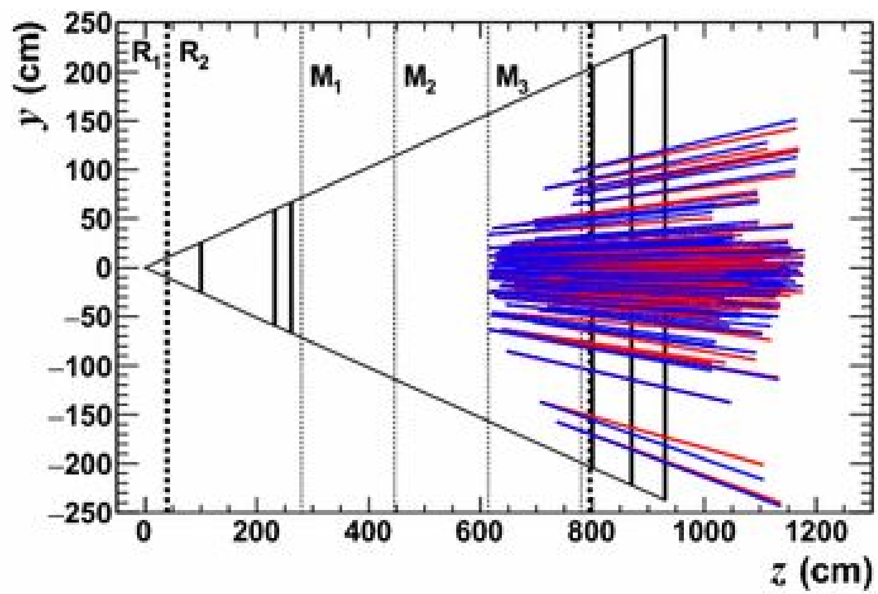
PRD 81, 012003

Motivation (3) - displaced vertices

- **Long lived particles** with various J^P: dark sector bosons, ALPs / higgs, majorana neutrinos ➜ increase the sensitivity at long lifetimes
- **Converted photons**?
- **Lambda baryons decaying inside the magnet** (for EDM / MDM measurements) ➜ allow the measurement, which relies entirely on the availability of T-tracks

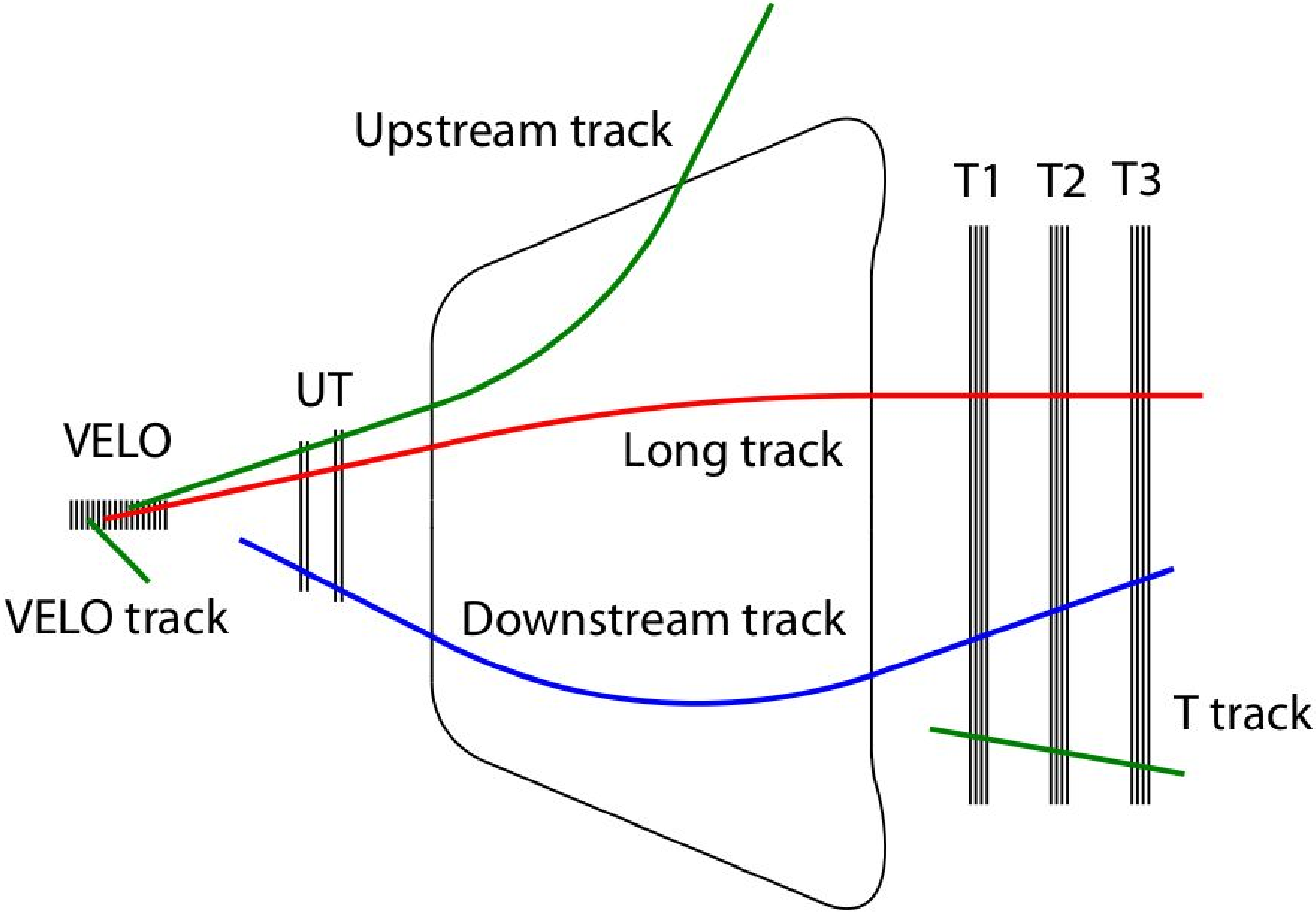


PRL 112, 131802



EPJC 77, 181

Without T- and downstream tracks, LHCb is only 50 cm long



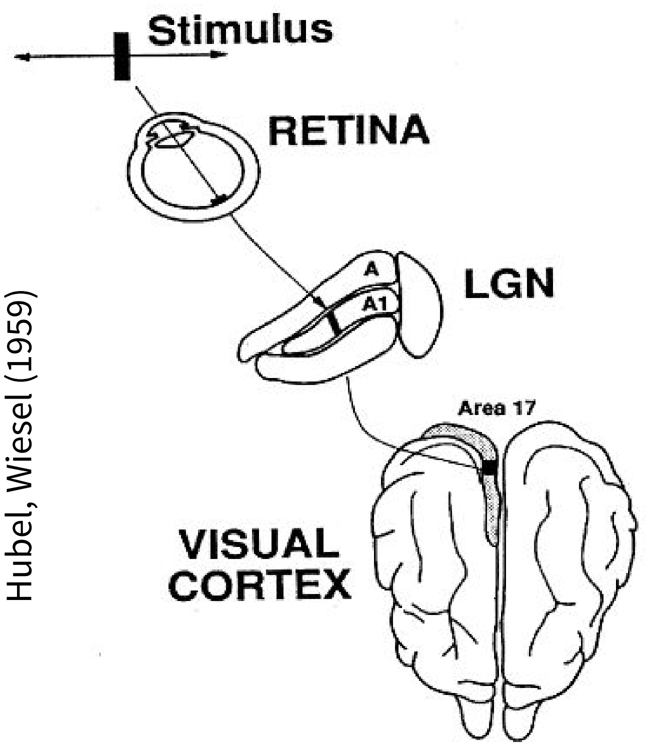
Proposed approach

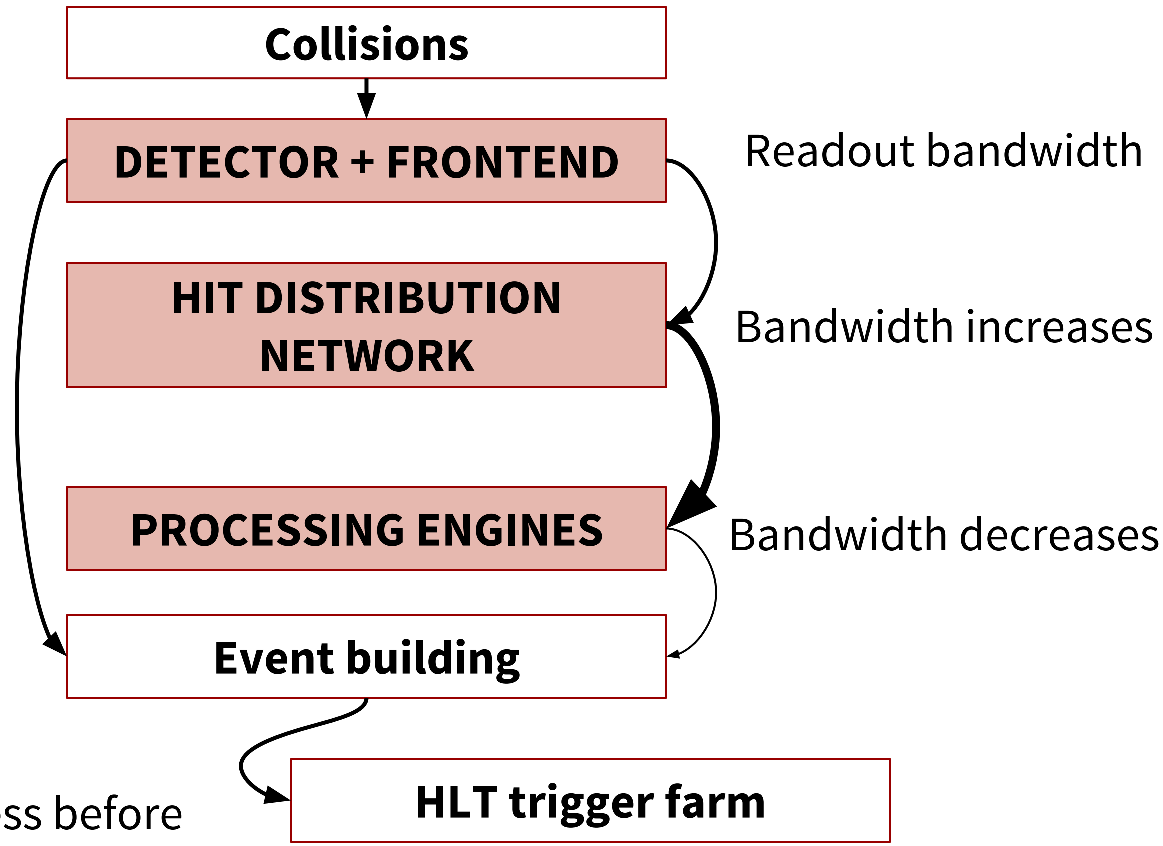
- We propose to build a **downstream tracking unit** that can be integrated in the DAQ architecture and **act as an "embedded track-detector"**
- This would make event reconstruction primitives immediately available to event-building and high-level-trigger farms (the trends of migrating event reconstruction to early stages is already there)
- **FPGA** is the appropriate technology: aim for high bandwidth and low and fixed latency comparable with that of other elements in detector DAQ (constraint set by the event building)

A biologically inspired architecture

- Rely on retina algorithm, whose architectural choices are targeted to the integration of tracking and DAQ (this is my definition of the algorithm)

Hubel, Wiesel (1959)

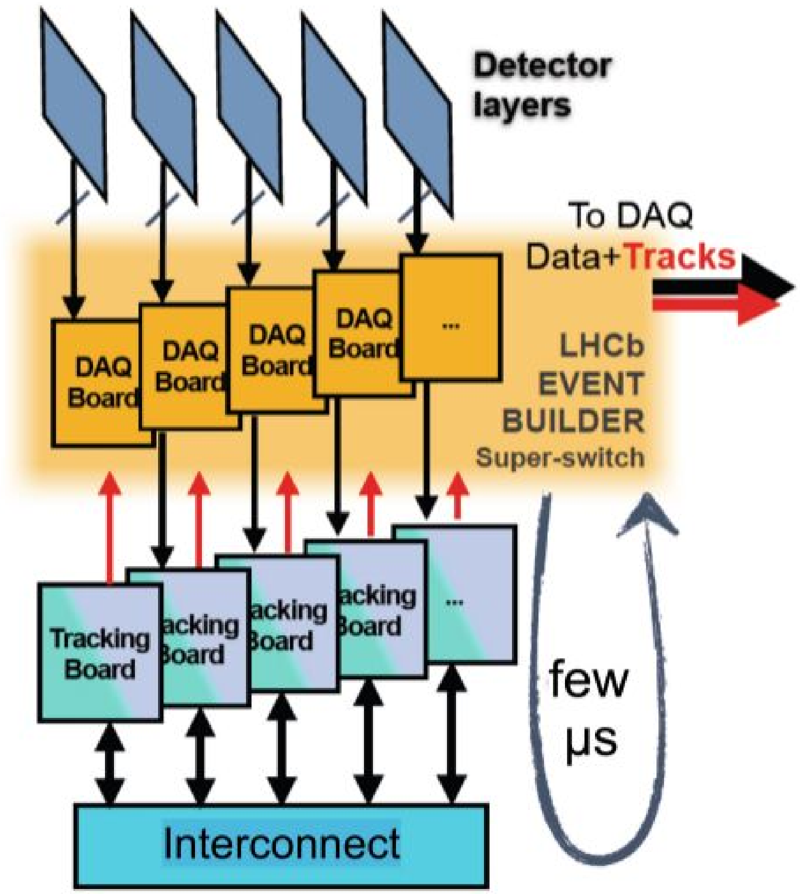




Conceived for parallelism: process before event building

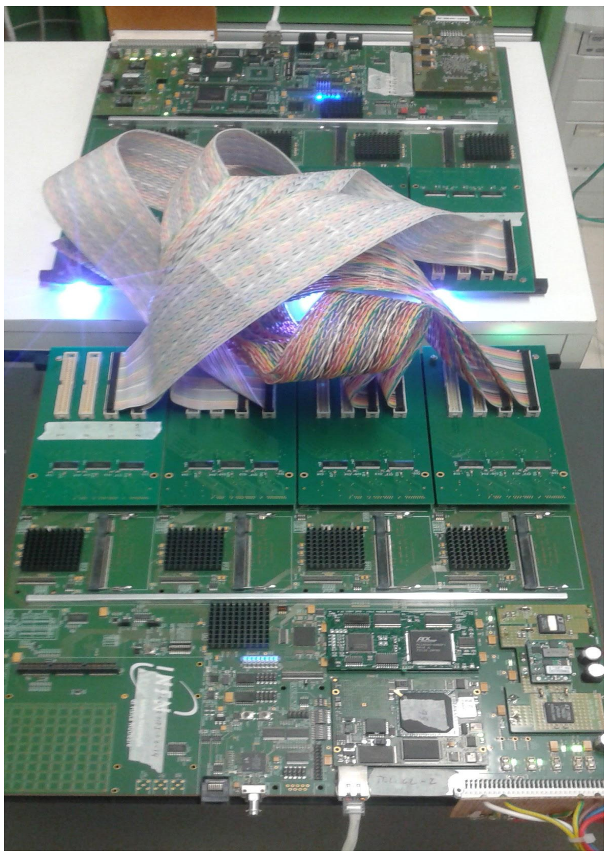
Distributed-embedded retina

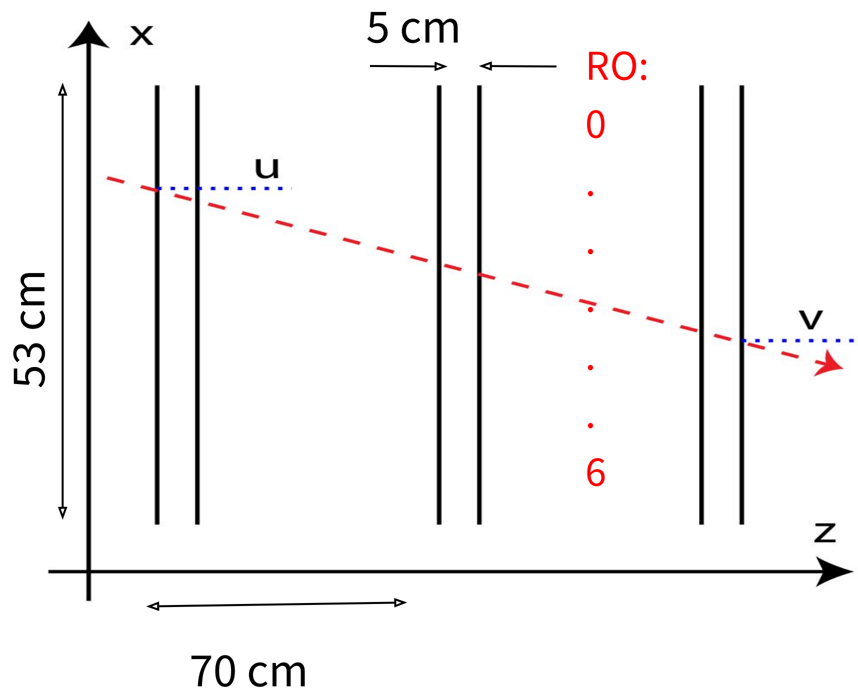
- A single tracking board performs both hit distribution and template matching
- Reads small detector portion, outputs small parameter space
- Easier to implement large global bandwidths
- May use standard commercial PCIe FPGA boards



Retina for tracking with silicon strips

- The algorithm can be applied to any tracking problem in which it is possible to define a distance between a hit (e.g., a pixel or a strip) and a template track
- Early prototype trained for 2D straight lines in 6-layer silicon strip detector
- O(2 MHz) track output per Stratix III FPGA (65 nm)





Latest prototype

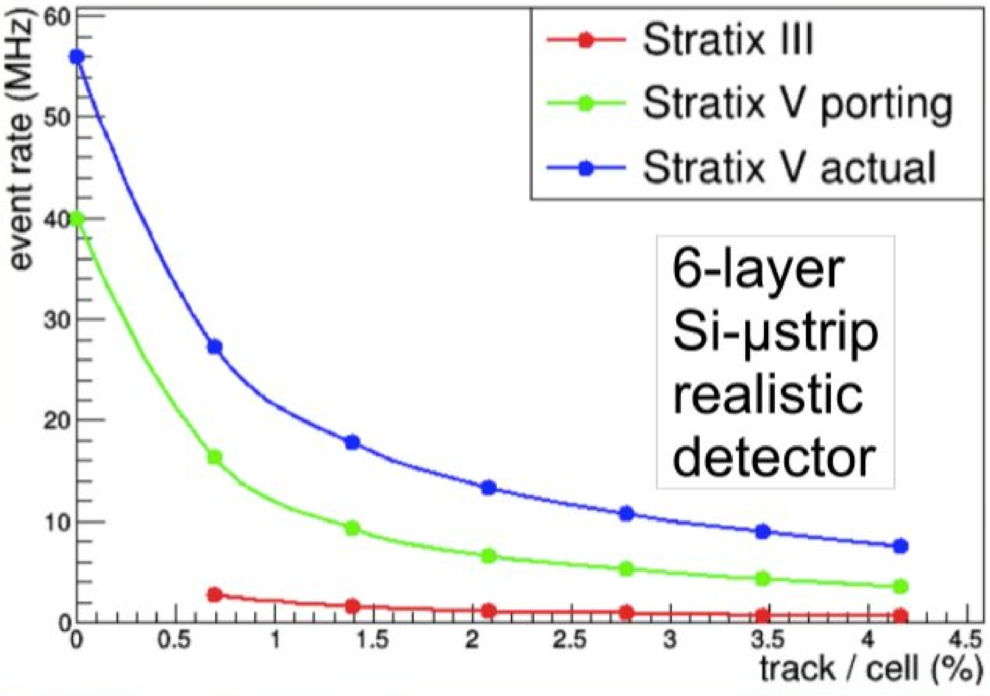
- INFN-CSN5 RETINA project

- 2 Stratix-V (28 nm)
  (1.2 Tb/s bandwidth, 700 MHz clock)
- On-board CPU, DDR memory,
  96 inter-FPGA LVDS connections
- 96 high-speed SerDes I/O (12 Gb/s)

- Can be used as building block for an entire tracker
- Results on this prototype readily extrapolate to real systems

Prototype measured performances

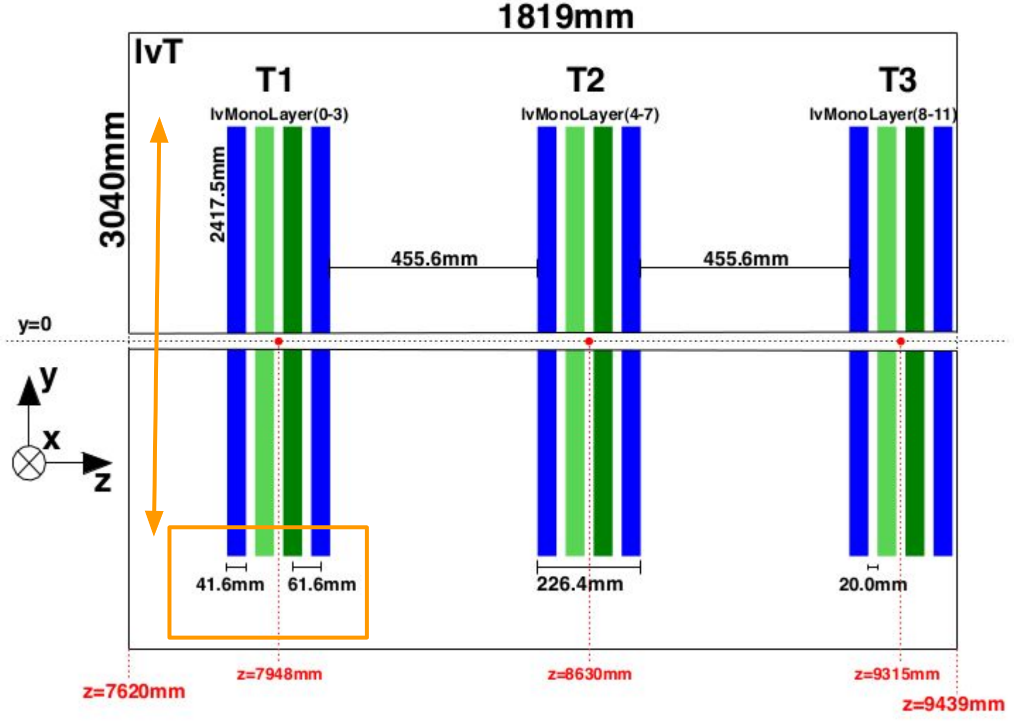
- Prototype achieved 20 MHz for occupancy compatible with **Phase 1b upgrade**
- Hardware cost <0.1 euro/kHz of tracks (prototype)
- Power cost: 0.2 mW/kHz of tracks
- Short latency <0.5 us facilitates embedding in the DAQ system
- **Promising technology for our task: powerful and reasonably cheap**



From generic R&D to LHCb

Reconstruction of T tracks with retina

- **LHCb Phase-1b (2×10^{33})**: intermediate step towards LHCb Phase-2 (2×10^{34})
- ~ 200 reconstructable tracks in the SciFi: 10 Gtracks/s (equivalent to all CMS tracks above 2 GeV at 5×10^{34})
- SciFi is split in 4 quadrants, with 50 tracks per quadrant
- Assume 150 DAQ nodes associated with SciFi and a tracking system consisting of one FPGA per node
- Fitting 550 cells per FPGA, we are left with 20k cells per quadrant



Retina output: accumulated weights

- Using only x-layers, a high number of ghosts is observed (and expected)
  - This is a consequence of the detector layout, and not of the algorithm
- Reduced imposing suitable thresholds on the accumulated weights
  - Weights depend on the number of hits associated with, and their distance to, each template

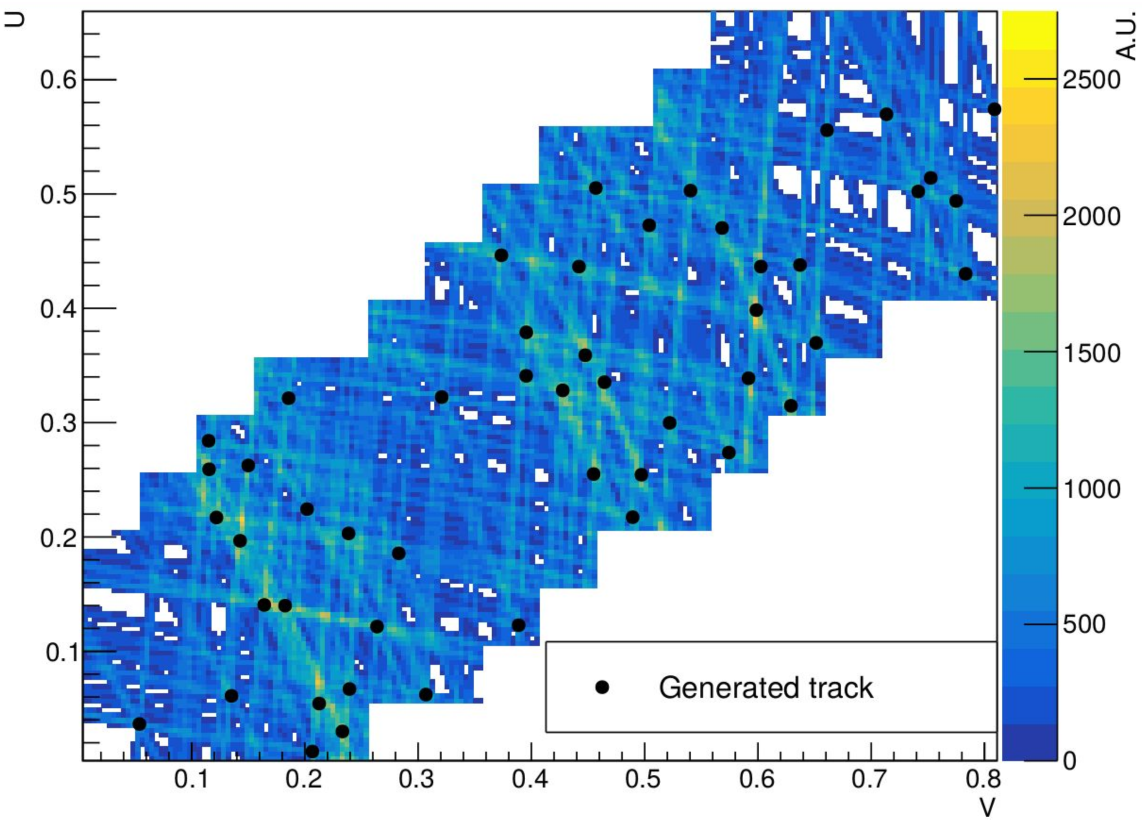


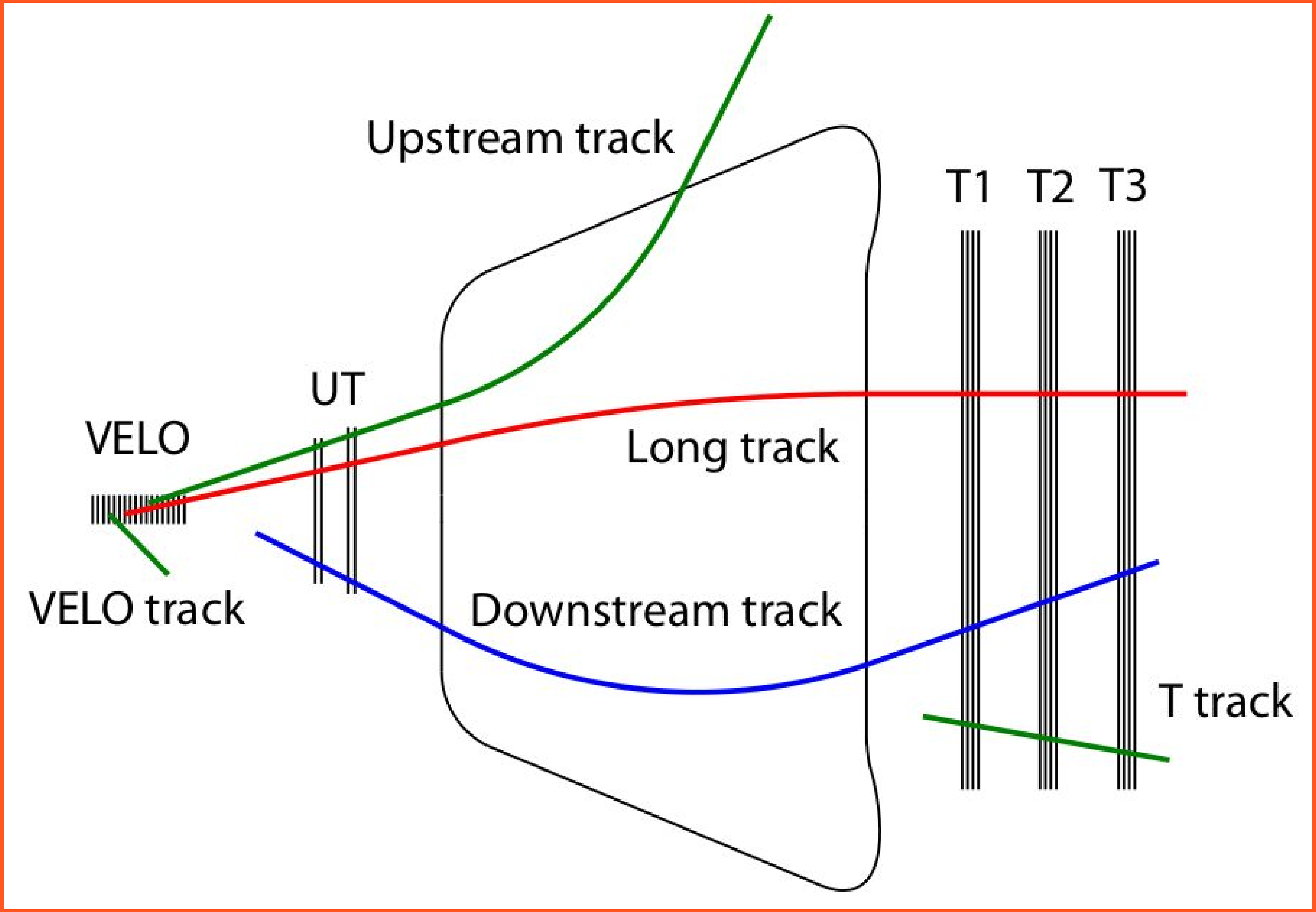
Figure: Weights accumulators in each cell for one event with **50 tracks**.

Comparison with offline

- In this comparison, the exercise with the retina neglects noise, multiple scattering, and (in the first configuration) the effect of the fringe magnetic field
- Next important step is to add stereo layers - then we'll add UT for downstream

	Straight 2D lines (retina)	Effect of magnet (retina)	2D Long p>5 GeV (offline)	3D Long p>5GeV (offline)	3D Long final track (offline)
Efficiency (%)	95	90	88	82	94
Ghosts (%)	48	52	49	4	7

* Offline performance extracted from plot provided by Renato Quagliani (Bristol)


Upstream track
T1
T2
T3
UT
VELO
Long track
VELO track
Downstream track
T track

Conclusions

- **Real-time reconstruction** capability by HEP experiments, especially in flavor physics, **will be key to success**, and detector choices are central in achieving fast tracking

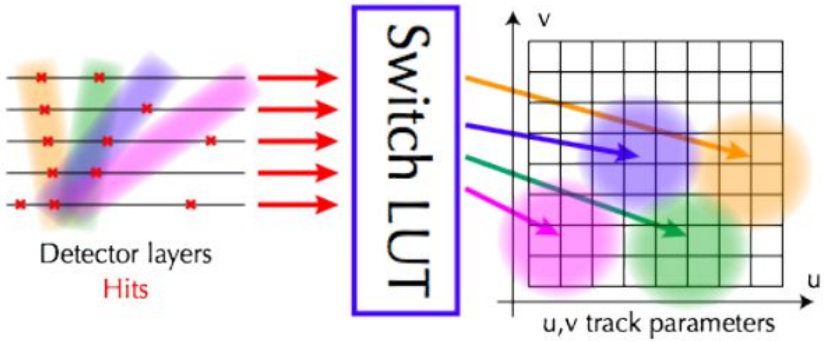
- Application to track reconstruction with T stations is well motivated by the ample **physics program involving long**(-ish) **lived particles**

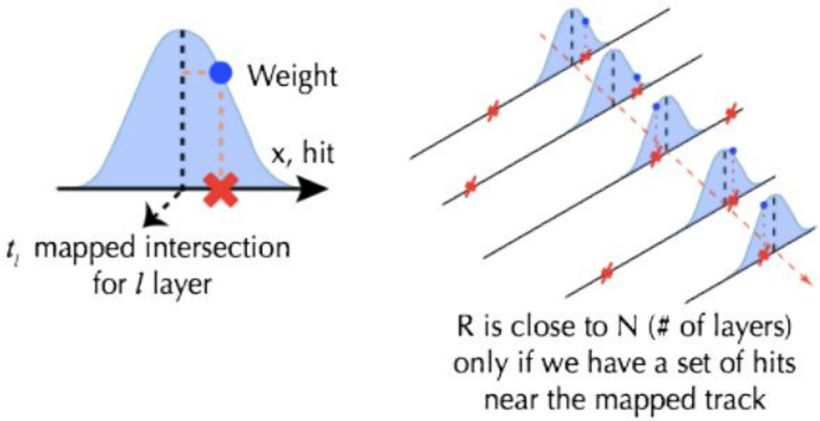
- Building on previous experience designing similar objects we propose a **special-purpose processor (FPGA based)** and moved the first steps towards designing a suitable device
    - G. Punzi et al., JINST 10 (2015) C03008
    - R. Cenci et al., NIM A 824, 260

Retina algorithm

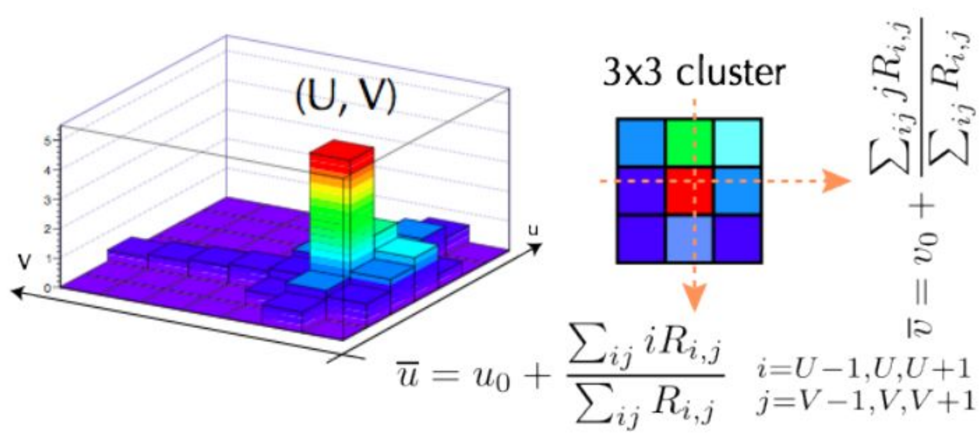
1) Template-space cells are routed only to the relevant detector elements.

2) An analog voting scheme is executed in parallel for each cell in processing engines.



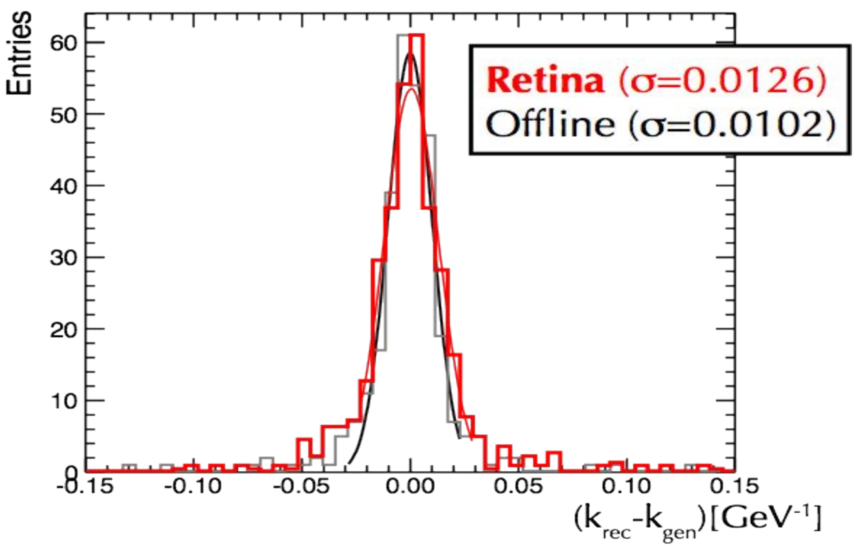


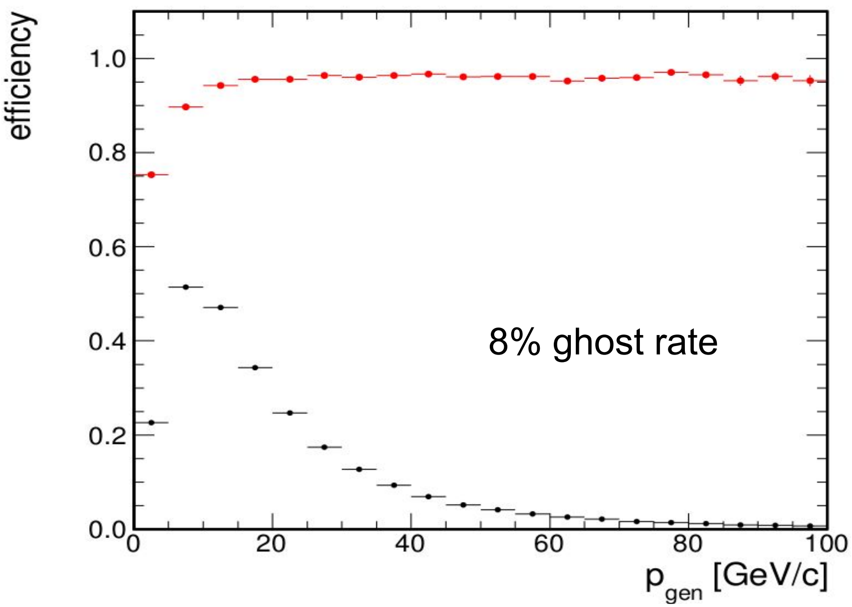
3) Tracks are identified as local maxima, using interpolation for increased precision.



Retina for tracking with pixel detector

- The algorithm can be applied, relatively easily, to any tracking problem in which it is possible to define a distance between a hit (e.g., a pixel or a strip) and a template track
- E.g., track finding in a pixel detector: with a system of 50000 cells (50 Stratix V FPGA), one can achieve O(100) MHz retina tracks / FPGA at a reasonable cost





Abba et al., JINST 10 (2015) 03, C03008

Data for $D \to PP$

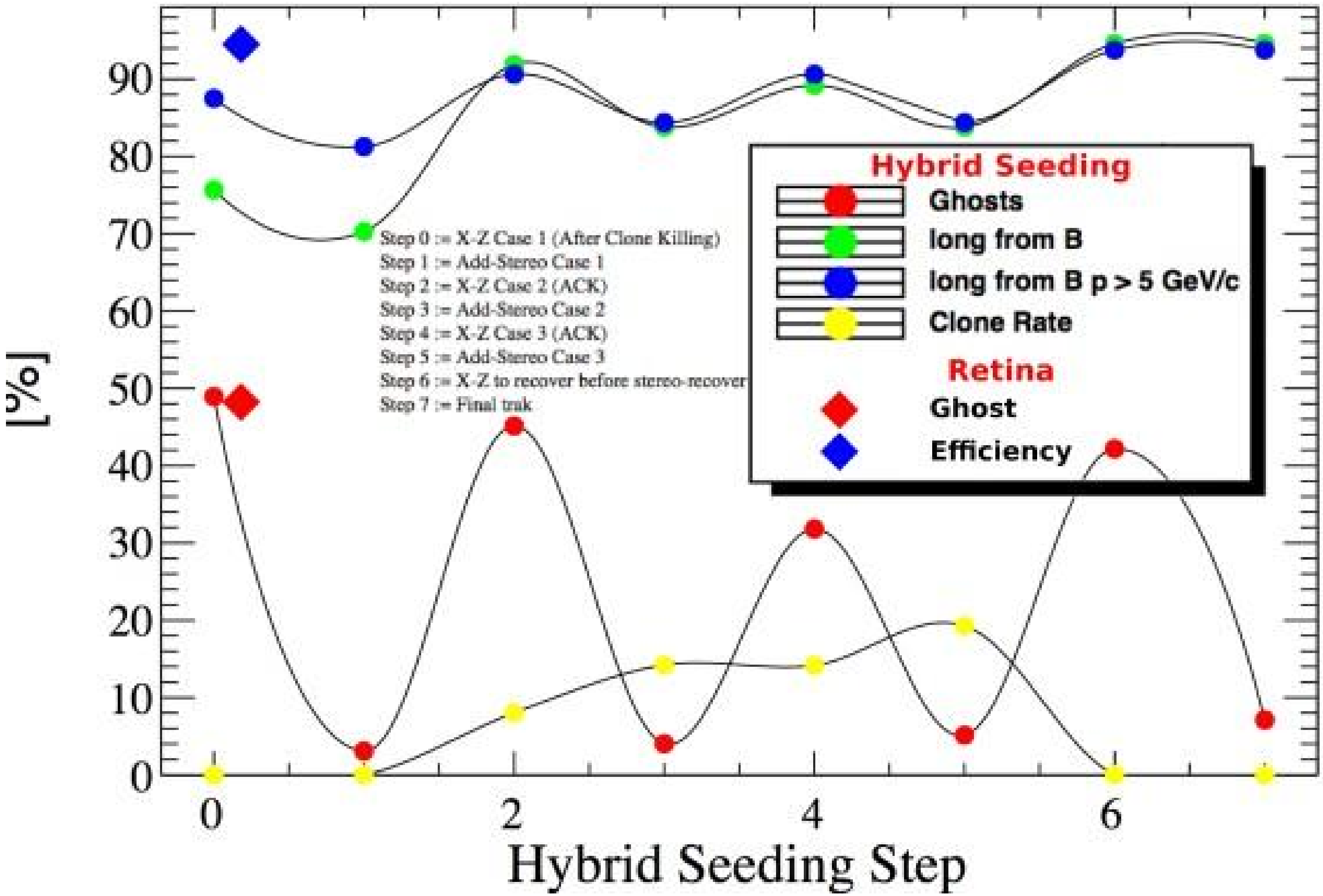
from LHCb, CDF, Belle, BABAR, CLEO and FOCUS

Red: Post Moriond 2013 Update

Observable	Measurement
SCS CP asymmetries	
$\Delta a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	-0.00329 ± 0.00121
$\Sigma a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	$+0.0014 \pm 0.0039$
$A_{CP}(D^0 \to K_S K_S)$	-0.23 ± 0.19
$A_{CP}(D^0 \to \pi^0\pi^0)$	$+0.001 \pm 0.048$
$A_{CP}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$
$A_{CP}(D^+ \to K_S K^+)$	-0.0011 ± 0.0025
$A_{CP}(D_s \to K_S \pi^+)$	$+0.012 \pm 0.007$
$A_{CP}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$
Indirect CP violation	
a_{CP}^{ind}	$(-0.010 \pm 0.162) \cdot 10^{-2}$
$\delta_L \equiv 2\mathrm{Re}(\varepsilon)/(1+\lvert\varepsilon\rvert^2)$	$(3.32 \pm 0.06) \cdot 10^{-3}$
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$18.25^\circ \pm 9.85^\circ$

Observable	Measurement
SCS branching ratios	
$\mathcal{B}(D^0 \to K^+K^-)$	$(3.96 \pm 0.08) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.401 \pm 0.027) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to K_S K_S)$	$(0.17 \pm 0.04) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(0.80 \pm 0.05) \cdot 10^{-3}$
$\mathcal{B}(D^+ \to \pi^0\pi^+)$	$(1.19 \pm 0.06) \cdot 10^{-3}$
$\mathcal{B}(D^+ \to K_S K^+)$	$(2.83 \pm 0.16) \cdot 10^{-3}$
$\mathcal{B}(D_s \to K_S \pi^+)$	$(1.21 \pm 0.08) \cdot 10^{-3}$
$\mathcal{B}(D_s \to K^+\pi^0)$	$(0.62 \pm 0.21) \cdot 10^{-3}$
CF branching ratios	
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.88 \pm 0.05) \cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_S \pi^0)$	$(1.19 \pm 0.04) \cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_L \pi^0)$	$(1.00 \pm 0.07) \cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_S \pi^+)$	$(1.47 \pm 0.07) \cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_L \pi^+)$	$(1.46 \pm 0.05) \cdot 10^{-2}$
$\mathcal{B}(D_s \to K_S K^+)$	$(1.45 \pm 0.05) \cdot 10^{-2}$
DCS branching ratios	
$\mathcal{B}(D^0 \to K^+\pi^-)$	$(1.47 \pm 0.07) \cdot 10^{-4}$
$\mathcal{B}(D^+ \to K^+\pi^0)$	$(1.83 \pm 0.26) \cdot 10^{-4}$

$\Rightarrow 8 \times a_{CP}^{\mathrm{dir}}$, $16 \times \mathcal{B}$, $1\times$ strong phase = **25 observables**



Hybrid Seeding
Ghosts
long from B
long from B p > 5 GeV/c
Clone Rate
Retina
Ghost
Efficiency
Step 0 := X-Z Case 1 (After Clone Killing)
Step 1 := Add-Stereo Case 1
Step 2 := X-Z Case 2 (ACK)
Step 3 := Add-Stereo Case 2
Step 4 := X-Z Case 3 (ACK)
Step 5 := Add-Stereo Case 3
Step 6 := X-Z to recover before stereo-recover
Step 7 := Final trak
[%]
Hybrid Seeding Step

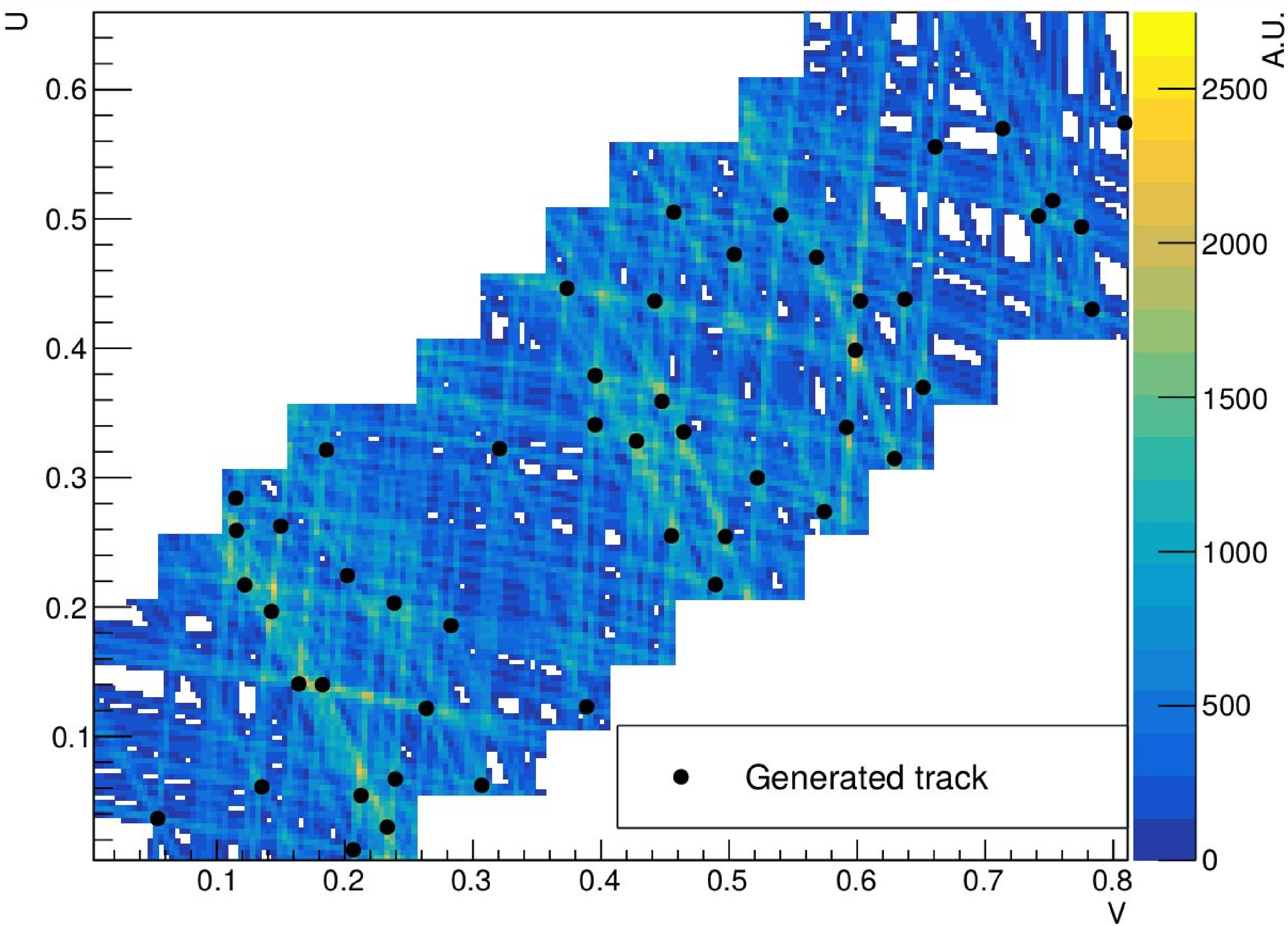


Figure: Weights accumulators in each cell for one event with **50 tracks**.