# Design and Test of the Off-Detector Electronics for the CMS Barrel Muon Trigger

**Luigi Guiducci**

M. Dallavalle, A. Montanari, G. Pellegrini

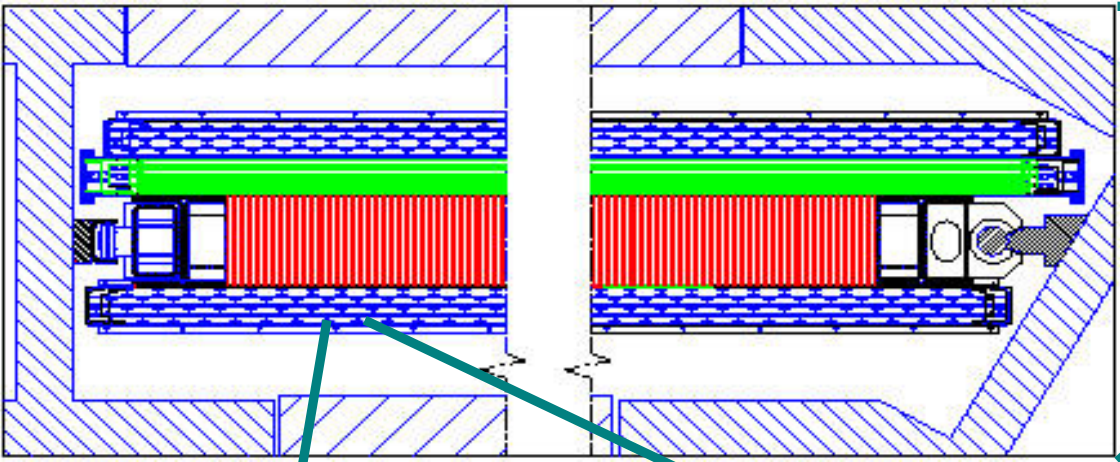
G. Torromeo, R. Travaglini

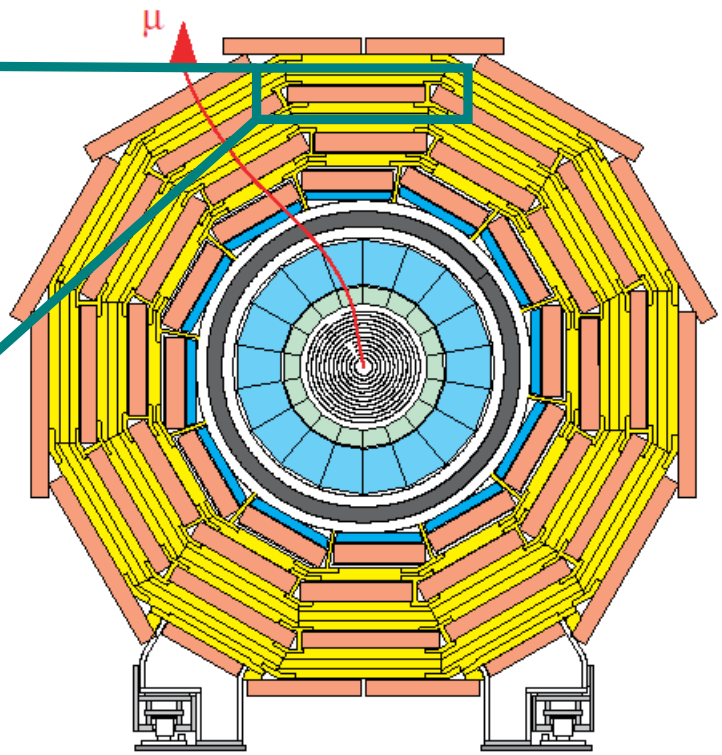
**Università di Bologna e INFN Sezione di Bologna**

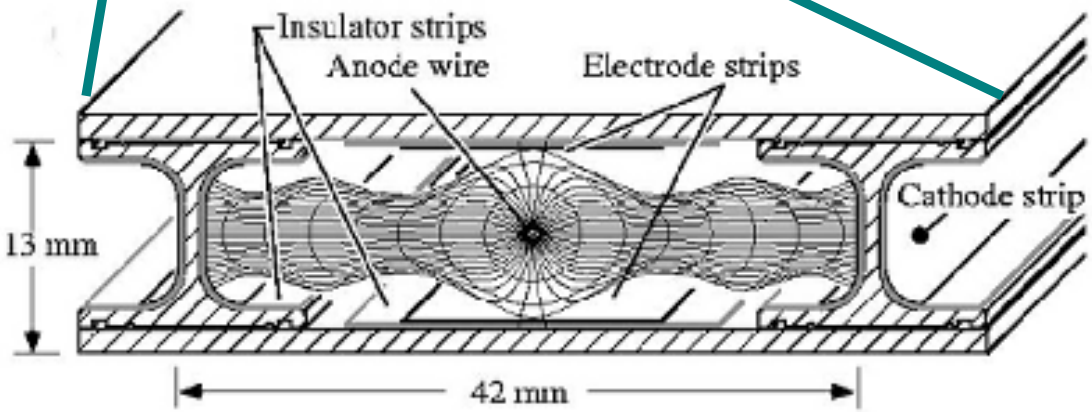
12th Workshop on Electronics for LHC and Future Experiments
25-29 September 2006, Valencia SPAIN

# CMS Drift Tubes muon detectors

250 DT chambers in 4 concentrical stations, in 30° sectors, in 5 wheels

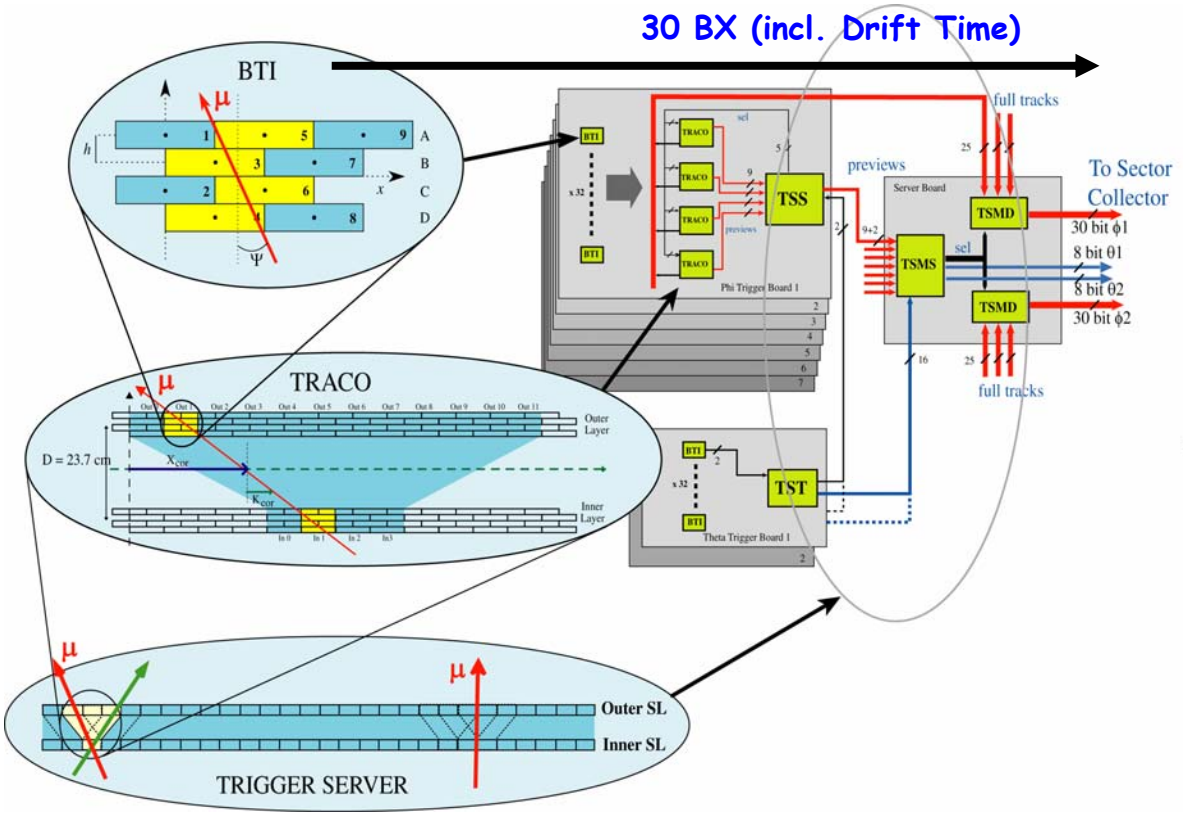




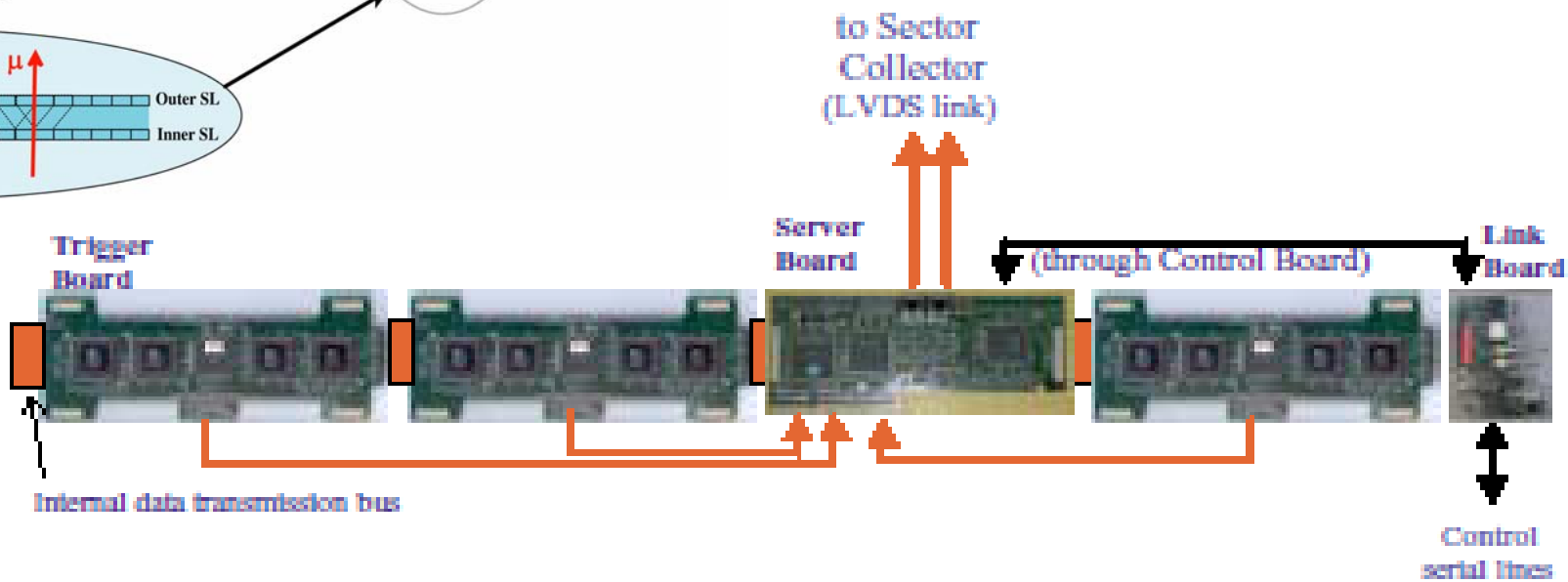




Each chamber is provided with **local trigger** logic that can build up to **two track segments** per chamber

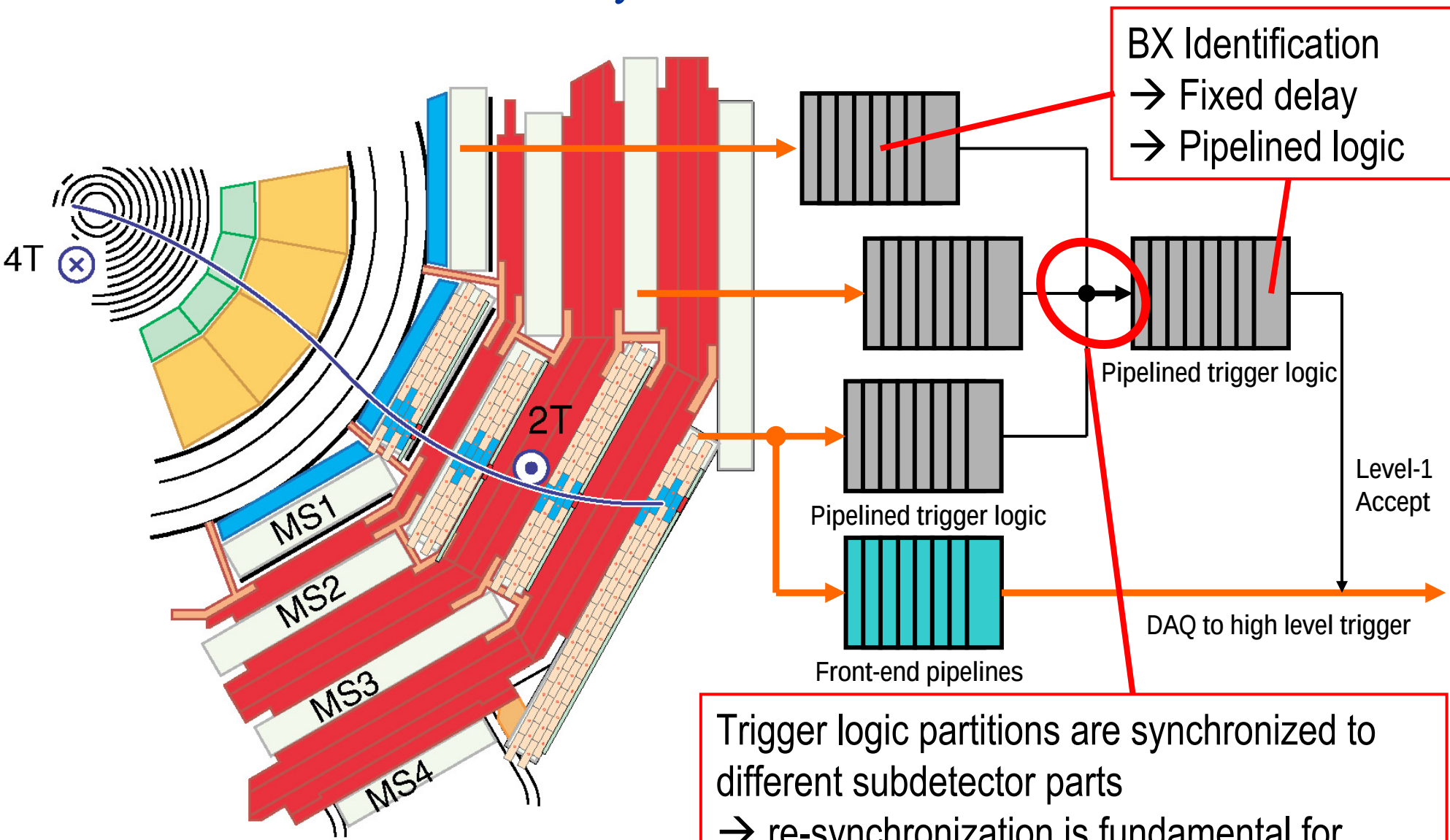
# DT Local trigger




- *Minicrate* mounted on DTC
- Outputs/BX:
  - 2 φ-view track segments (position, bending, reconstruction quality)
  - θ-view hits
- Links: 2 x FTP cables = 2 x 1.6 Gbit/s (up to 40 m)

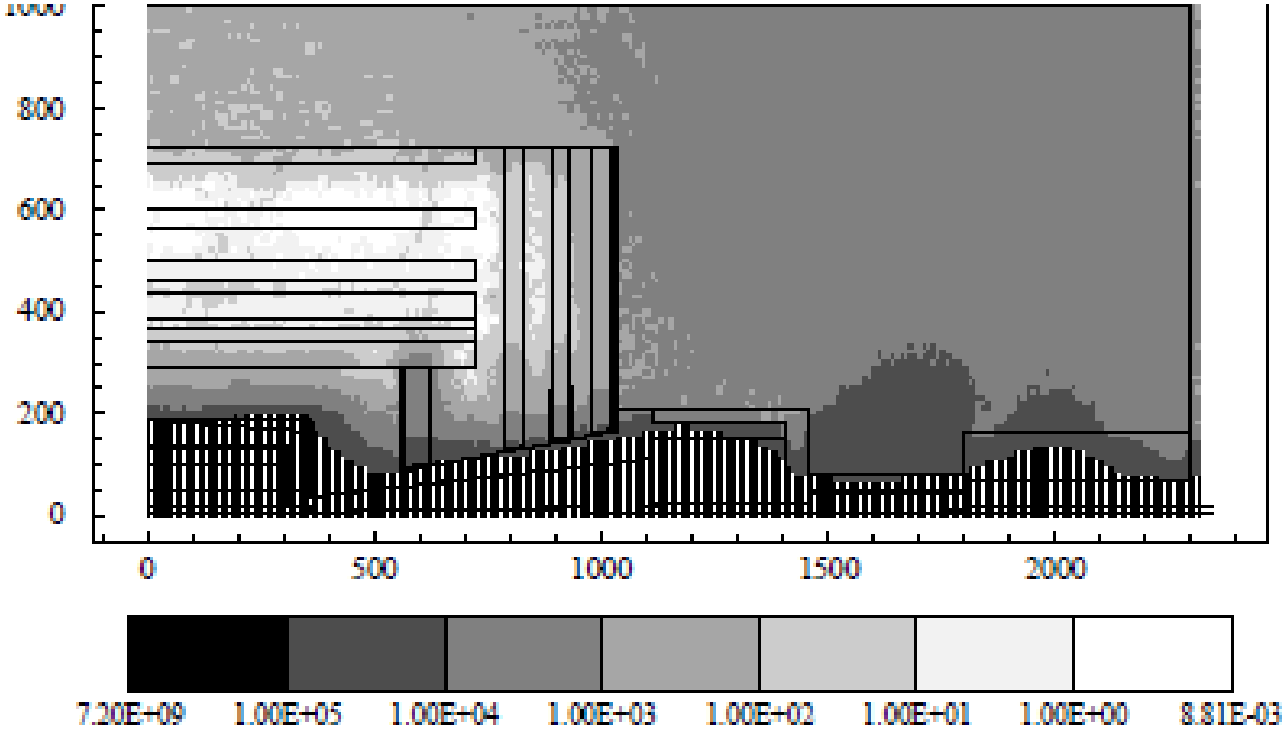


# Synchronization




Trigger logic partitions are synchronized to different subdetector parts
→ re-synchronization is fundamental for correct reconstruction of the full tracks!

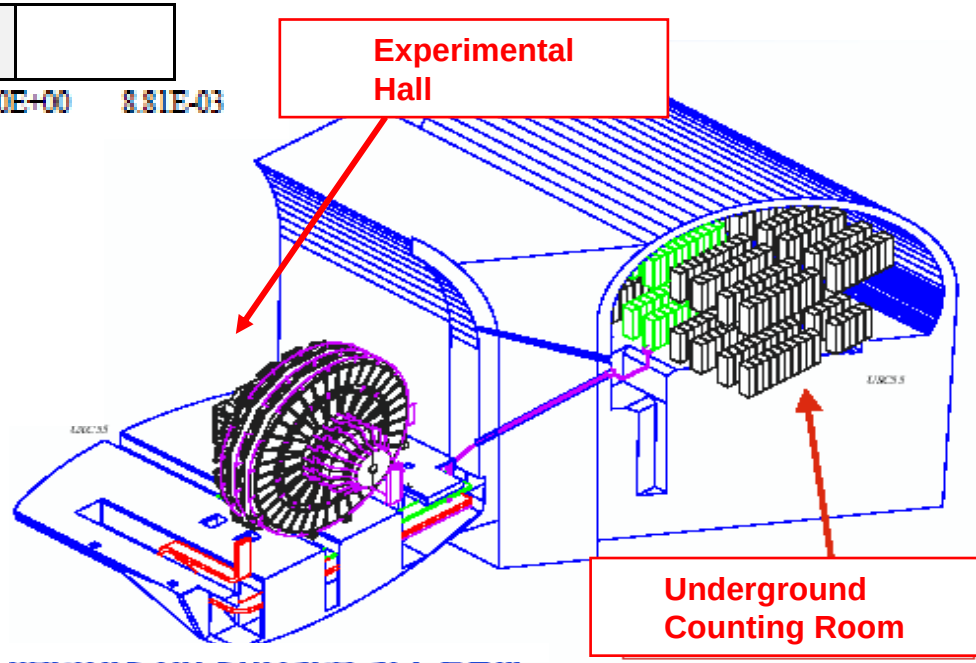
# Radiation tolerance




The radiation background must be considered for electronics mounted on detector or in the experimental cavern

Off – detector electronics, cavern:

- Neutron fluxes around CMS barrel are
  ~ 0.1—1 kHz/cm$^2$ for E > 100 keV
- Very low damage to electronics, but single event effects must be considered
- Memory cells can flip state until rewritten

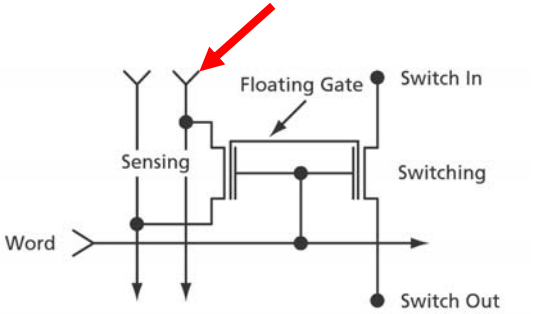


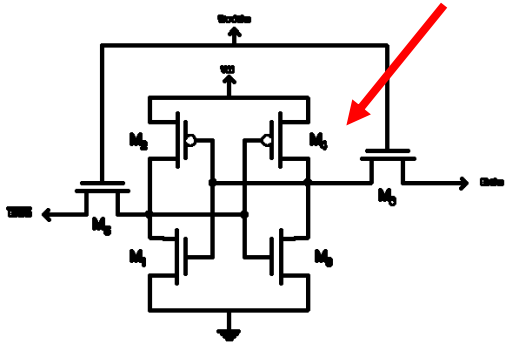
# Programmable devices technology

In the experimental cavern:


- Events due to neutron background may modify the FPGA configuration memory → change of device functionality
- ProAsicPlus FPGA from Actel
  - Configuration memory is FLASH-based
  - Embedded RAM (72 kbits) and configurable PLLs (2)

Flash cells are more robust than SRAM cells (~15 V for programming, smaller)





In the counting room:

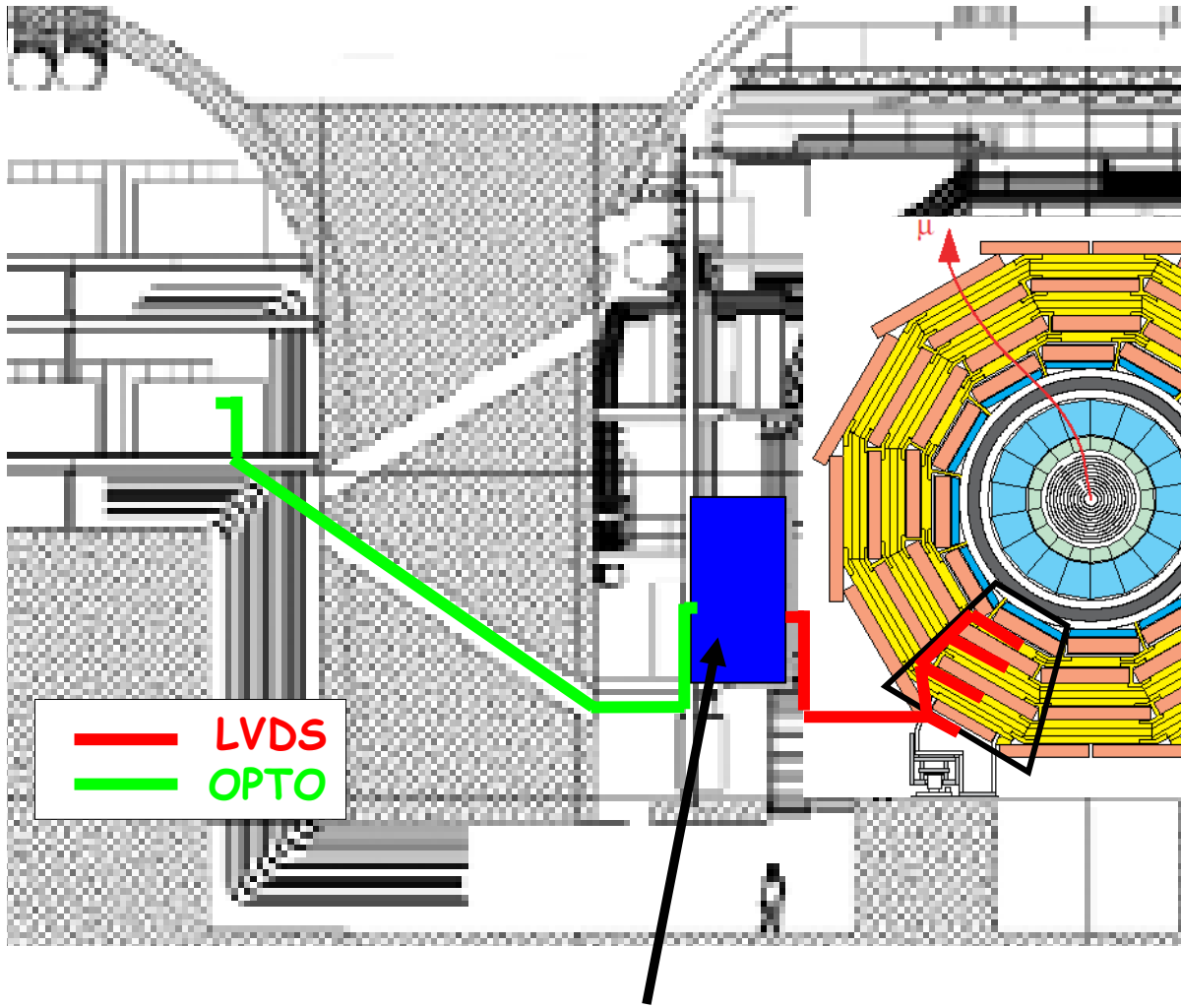
- No radiation issues
- Several SRAM-FPGA devices were chosen
- SRAM-FPGA market provides powerful optionals (embedded RAM, advanced I/O ...)

# Sector Collector system

- Located on detector towers, 60 SC boards (1/DT 30° sector)

Main tasks:

- Synchronization of sector links
- Monitoring of data
- Sector-level trigger generation and distribution
- Local trigger data sent on optical fibers to the regional trigger electronics in the counting room (DT Track Finder, DTTF)




*Sector Collector crates*

# Sector Collector – Implementation

Input links
Cat-5 FTP cables
from the minicrate

Opto-RX

Output links
Optical fibers

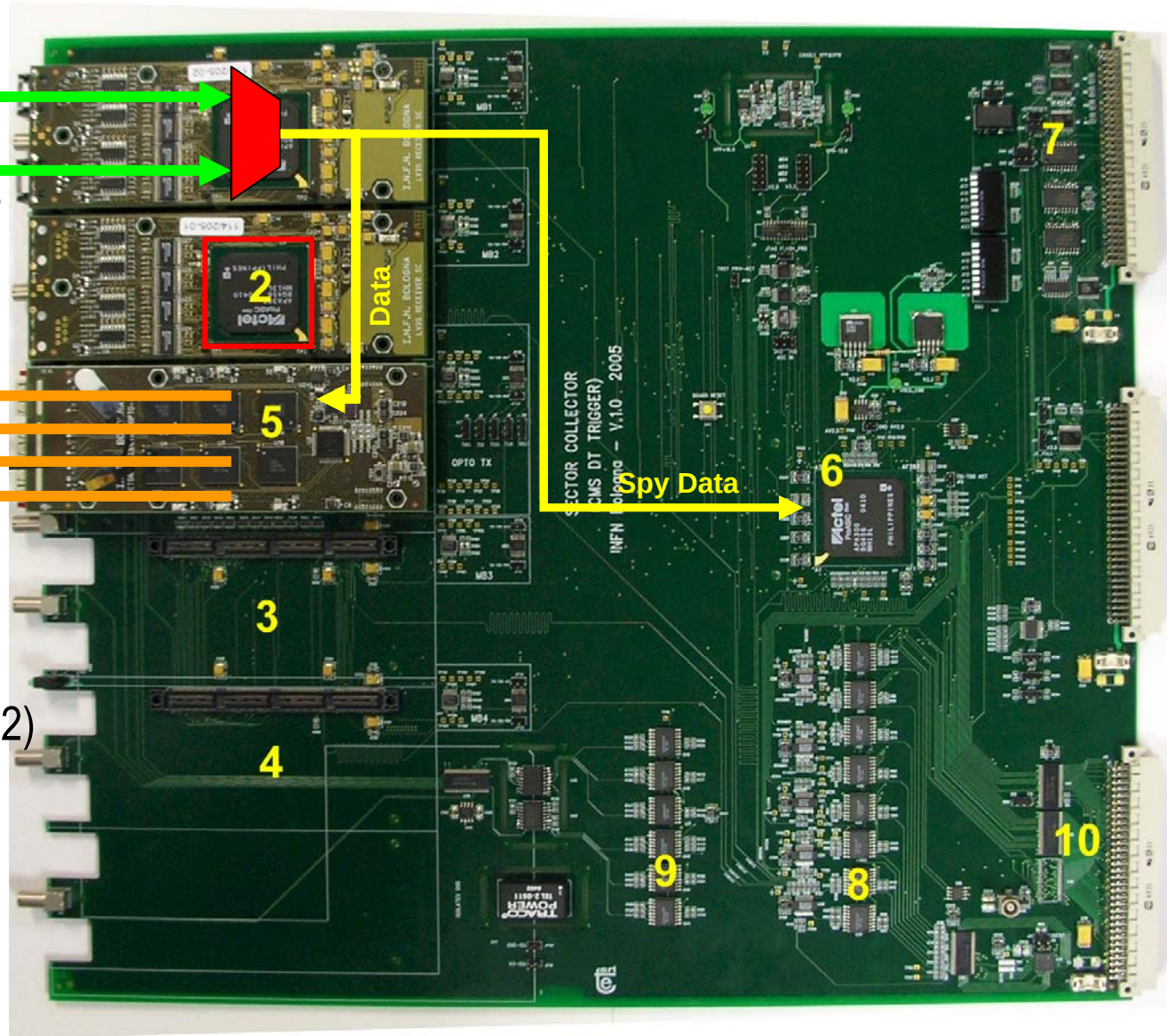
- 9U Motherboard (60)+ LVDS-RX (240)+ OPTO-TX(60) + OPTO-RX(72)

# Sector Collector – Implementation

Input links
Cat-5 FTP cables
from the minicrate

Opto-RX

Output links
Optical fibers



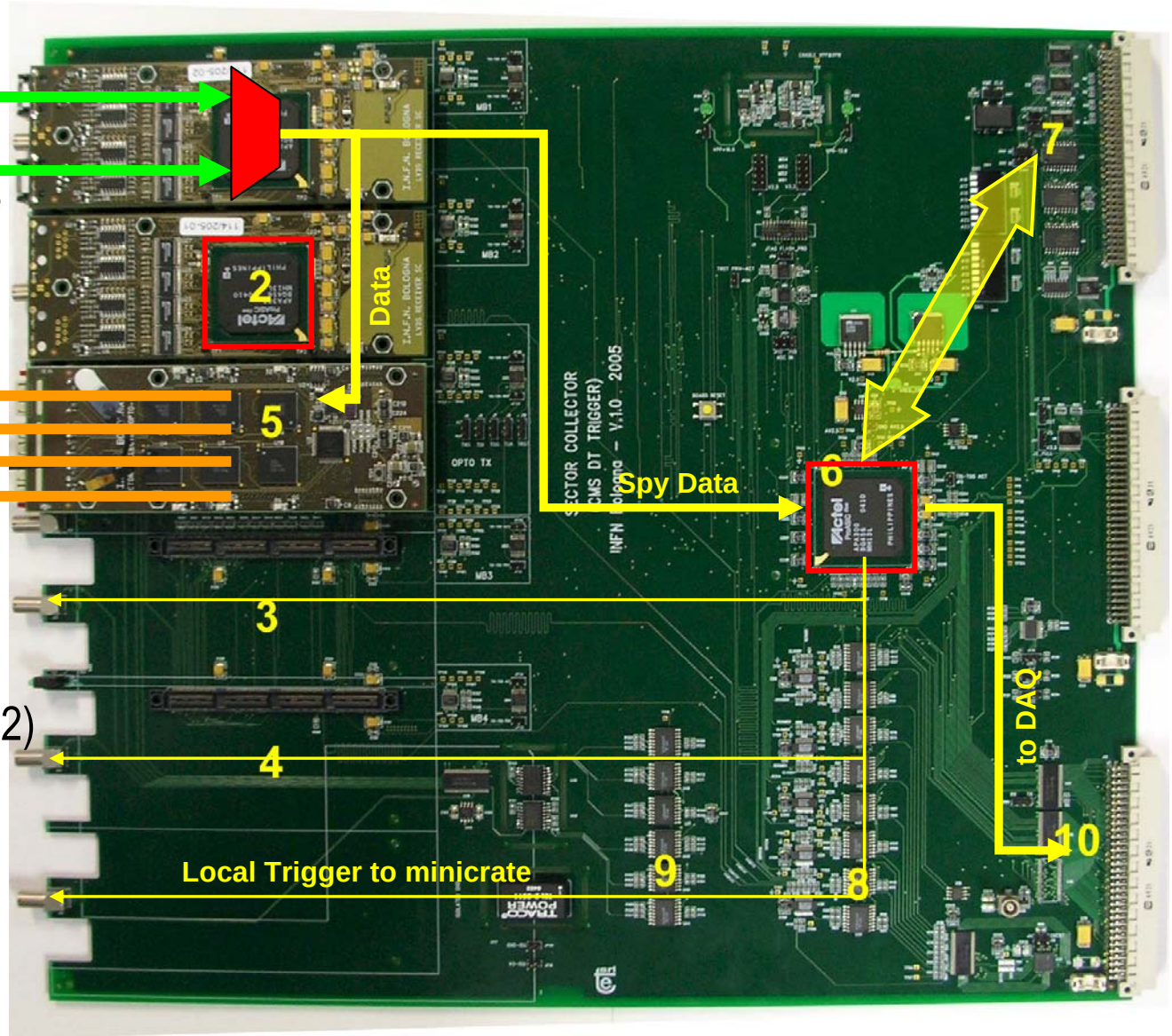

- 9U Motherboard (60)+ LVDS-RX (240)+ OPTO-TX(60) + OPTO-RX(72)
- LVDS-RX: segment sorting, piepeline, link quality monitoring

# Sector Collector – Implementation

Input links
Cat-5 FTP cables
from the minicrate

Opto-RX

Output links
Optical fibers



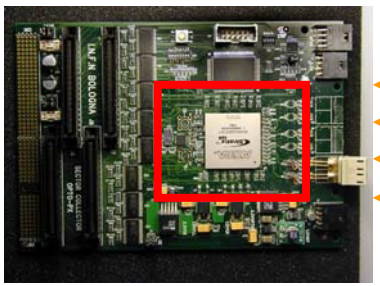

- 9U Motherboard (60)+ LVDS-RX (240)+ OPTO-TX(60) + OPTO-RX(72)

- Motherboard controller: VME interface, synchronization, spy data to DAQ, local trigger generation

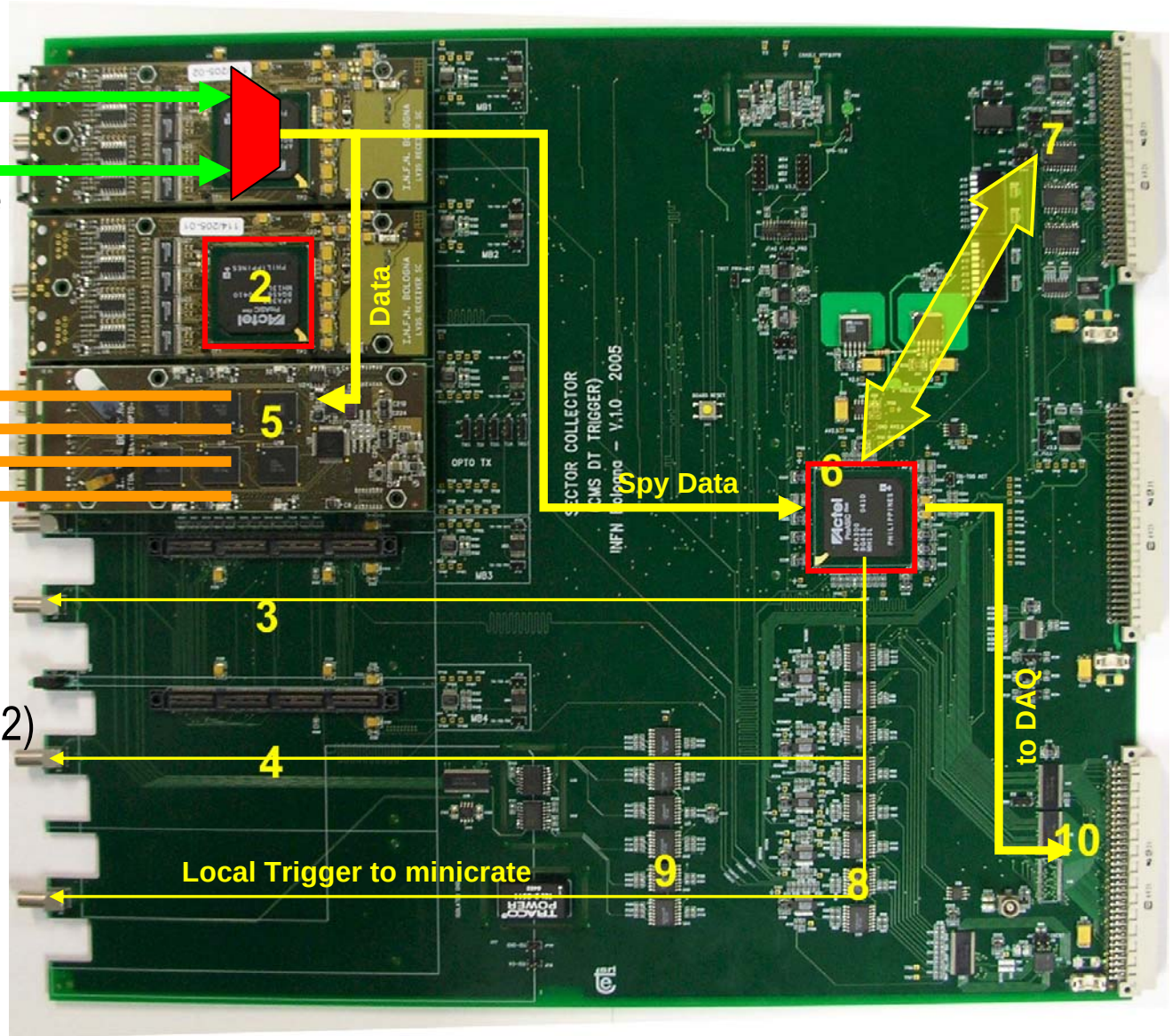
# Sector Collector – Implementation

Input links
Cat-5 FTP cables
from the minicrate

Opto-RX



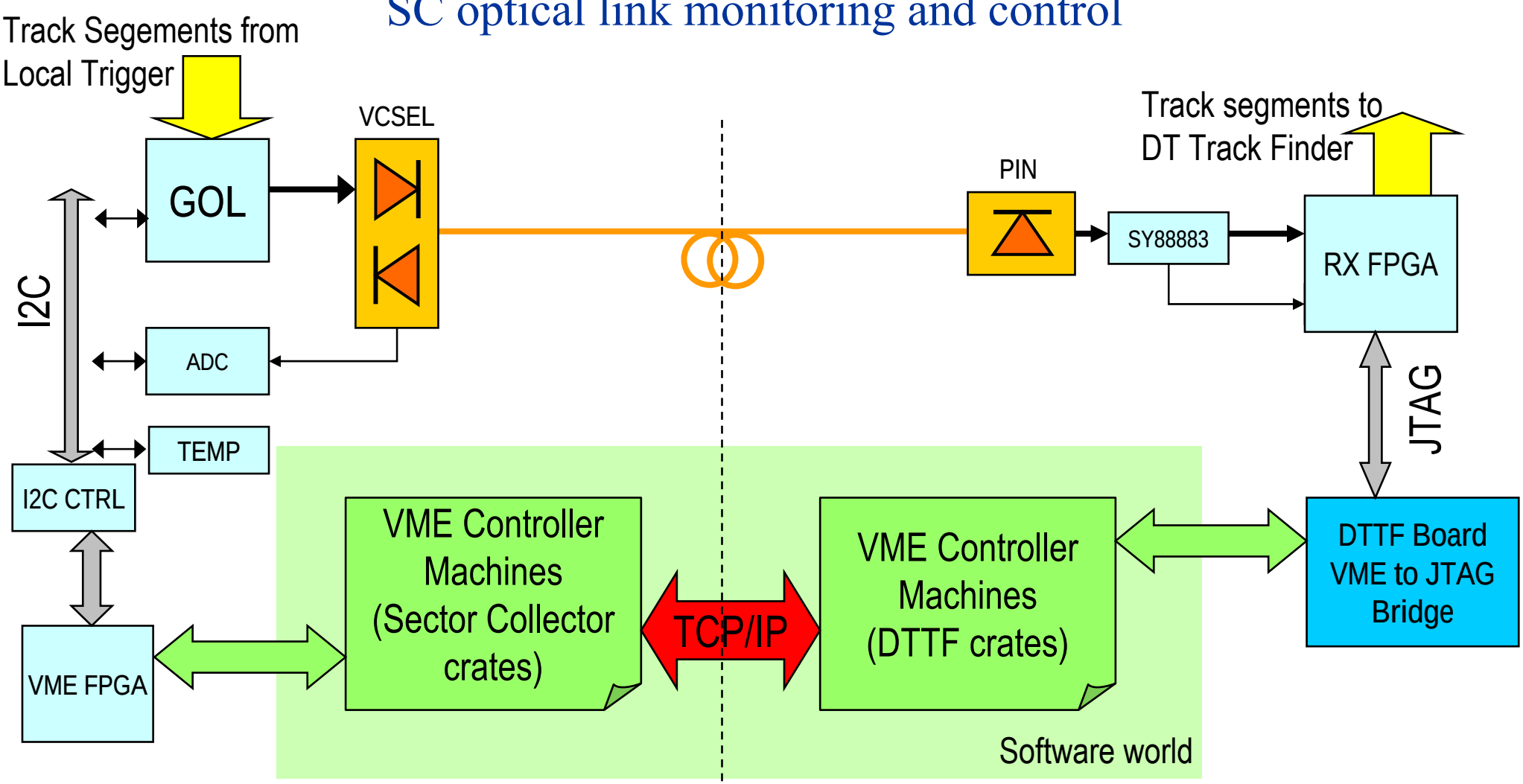
Output links
Optical fibers




- 9U Motherboard (60)+ LVDS-RX (240)+ OPTO-TX(60) + OPTO-RX(72)

- OPTO-RX: gigabit deserializers, deskewing, fan-out to DTTF

# SC optical link monitoring and control

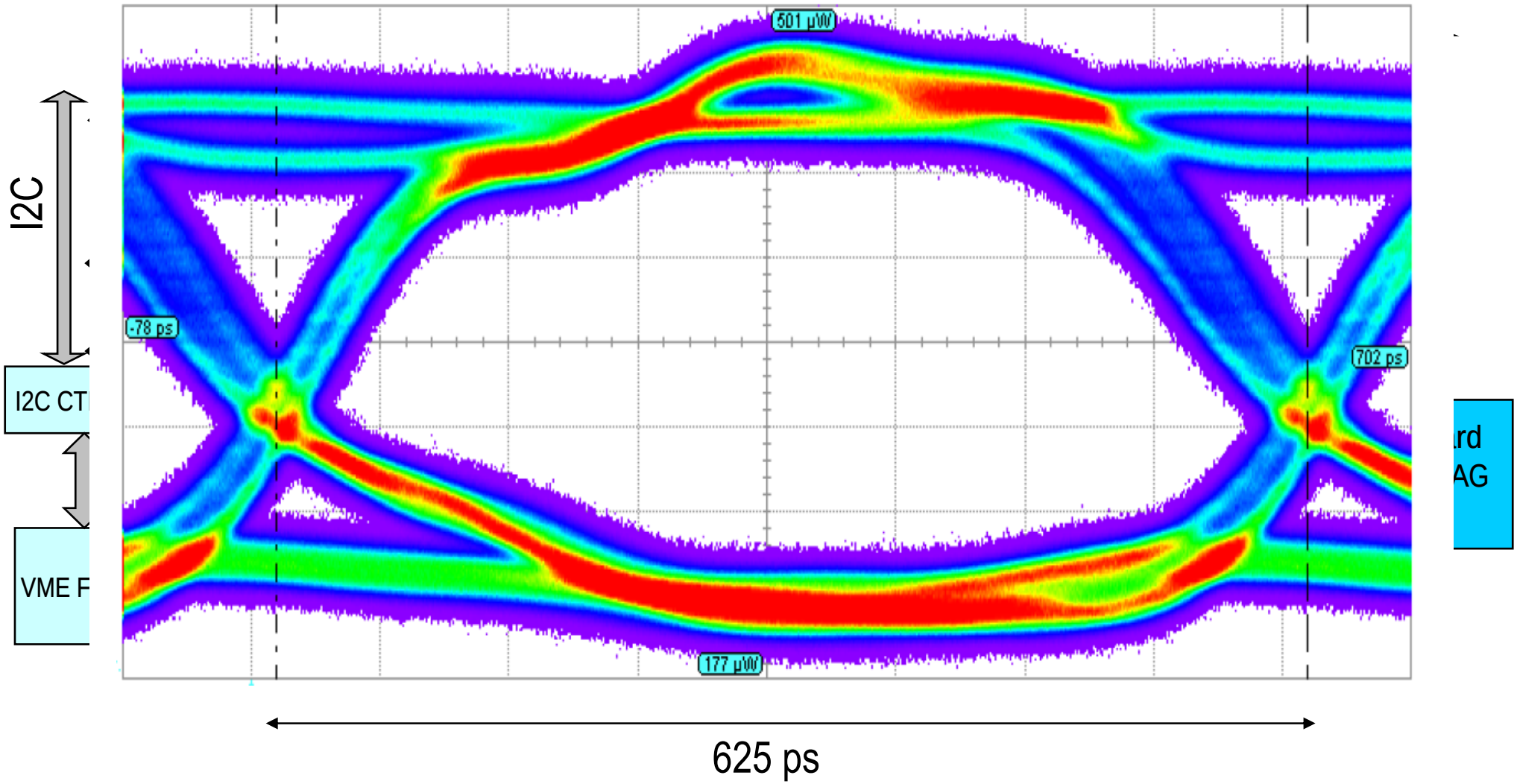



Set GOL bias current
Measure emitted light
Measure temperature

Check amplifier threshold condition
Check RX frequency lock
Check RX data parities

# SC optical link monitoring and control

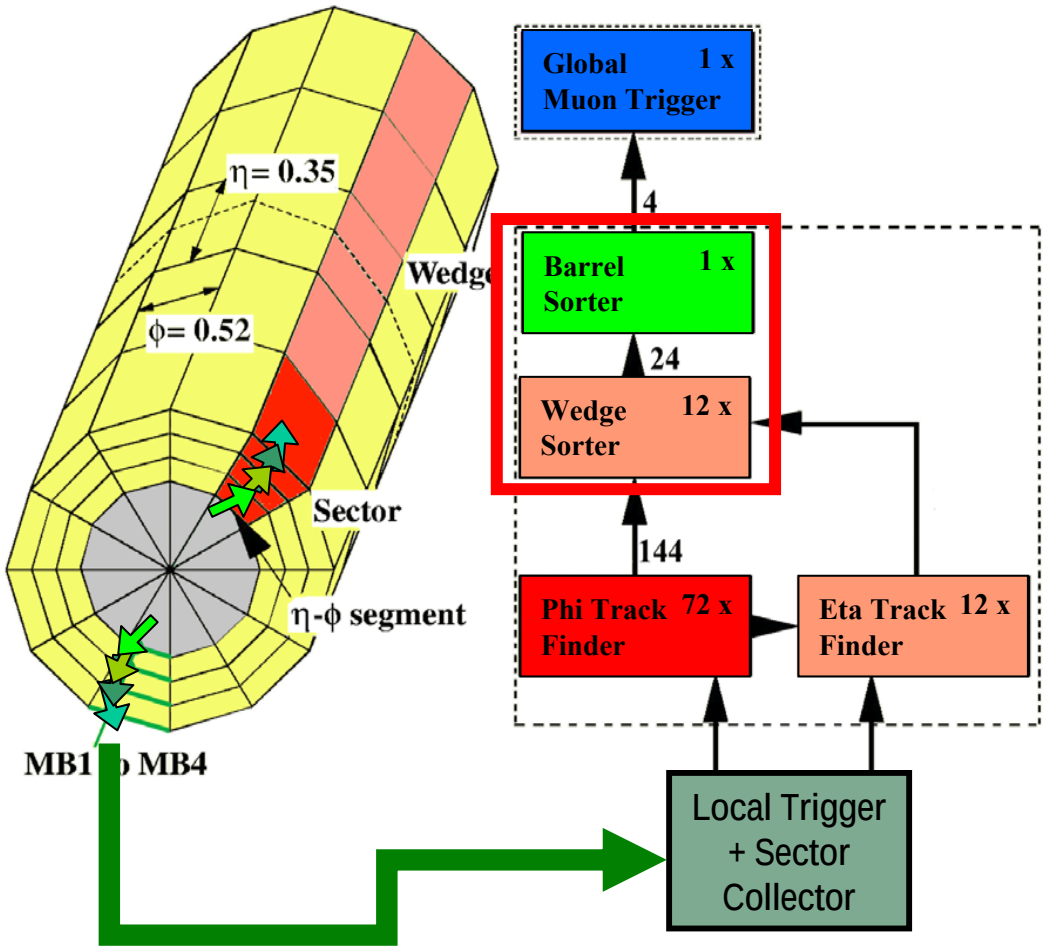
Track Segements from
Local T




Measure temperature

Check RX data parities

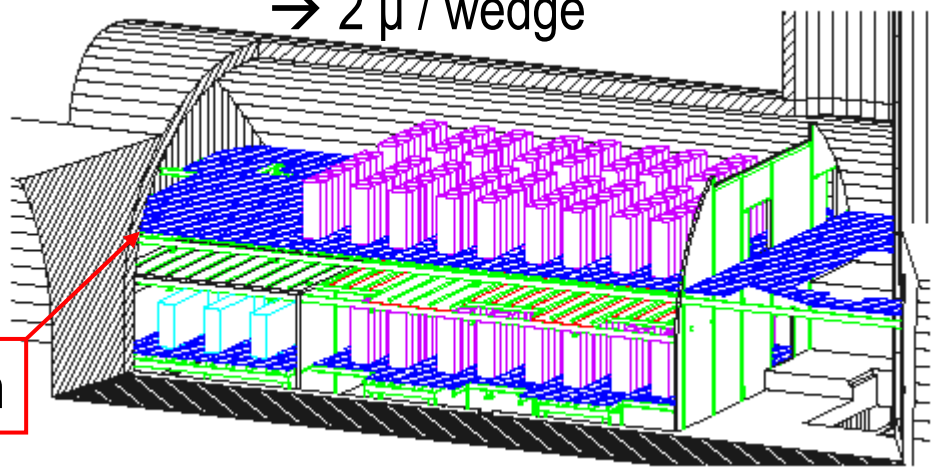
# Muon Sorter




The Track Finder builds full muon tracks using segments received from the SC

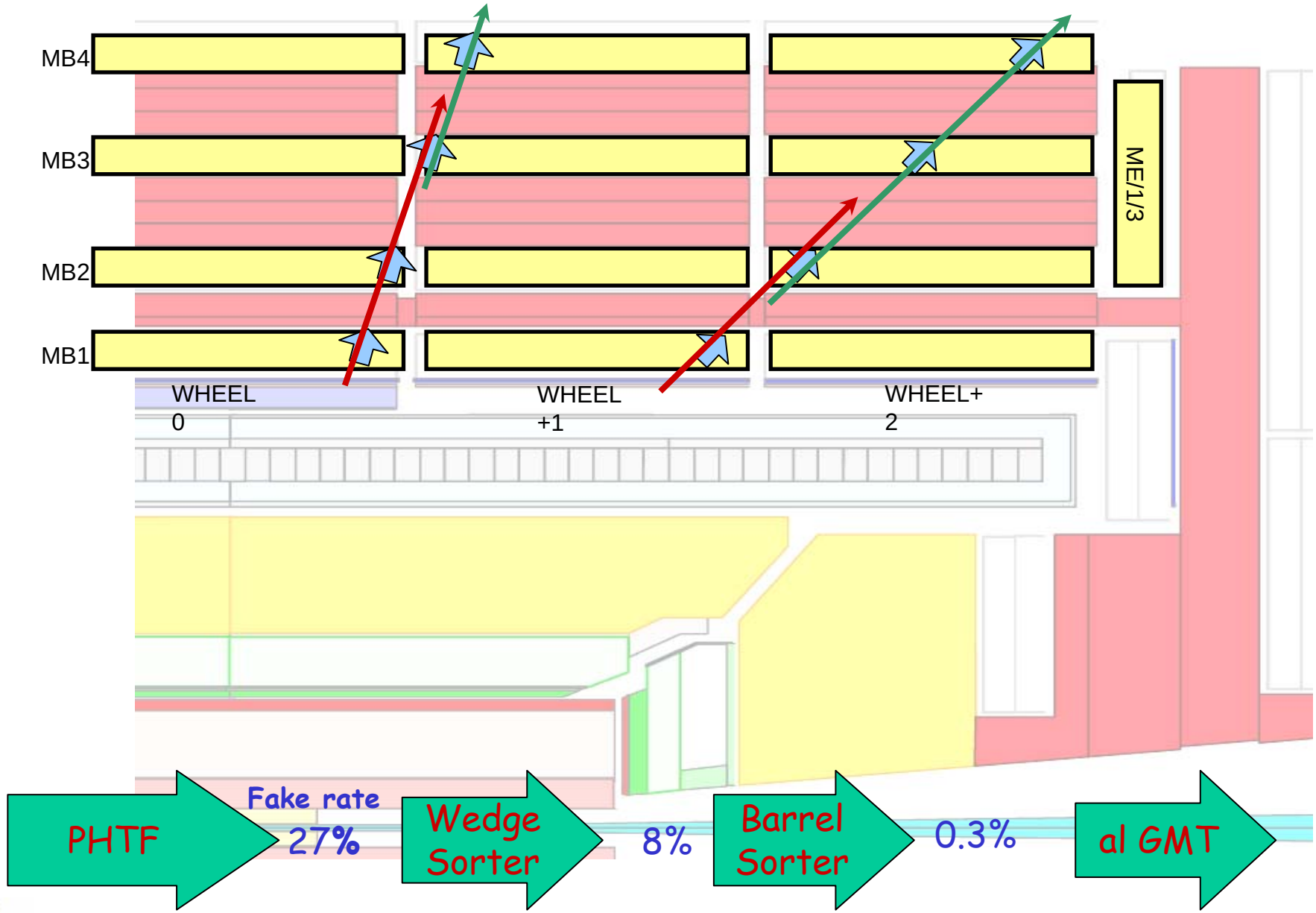
Muon Sorter main tasks:

- Select 4 muons from candidates built by the Track Finder system
- Partitioned in *wedges* before final sorting
- Keep dimuon efficiency high
  → 2 μ / wedge

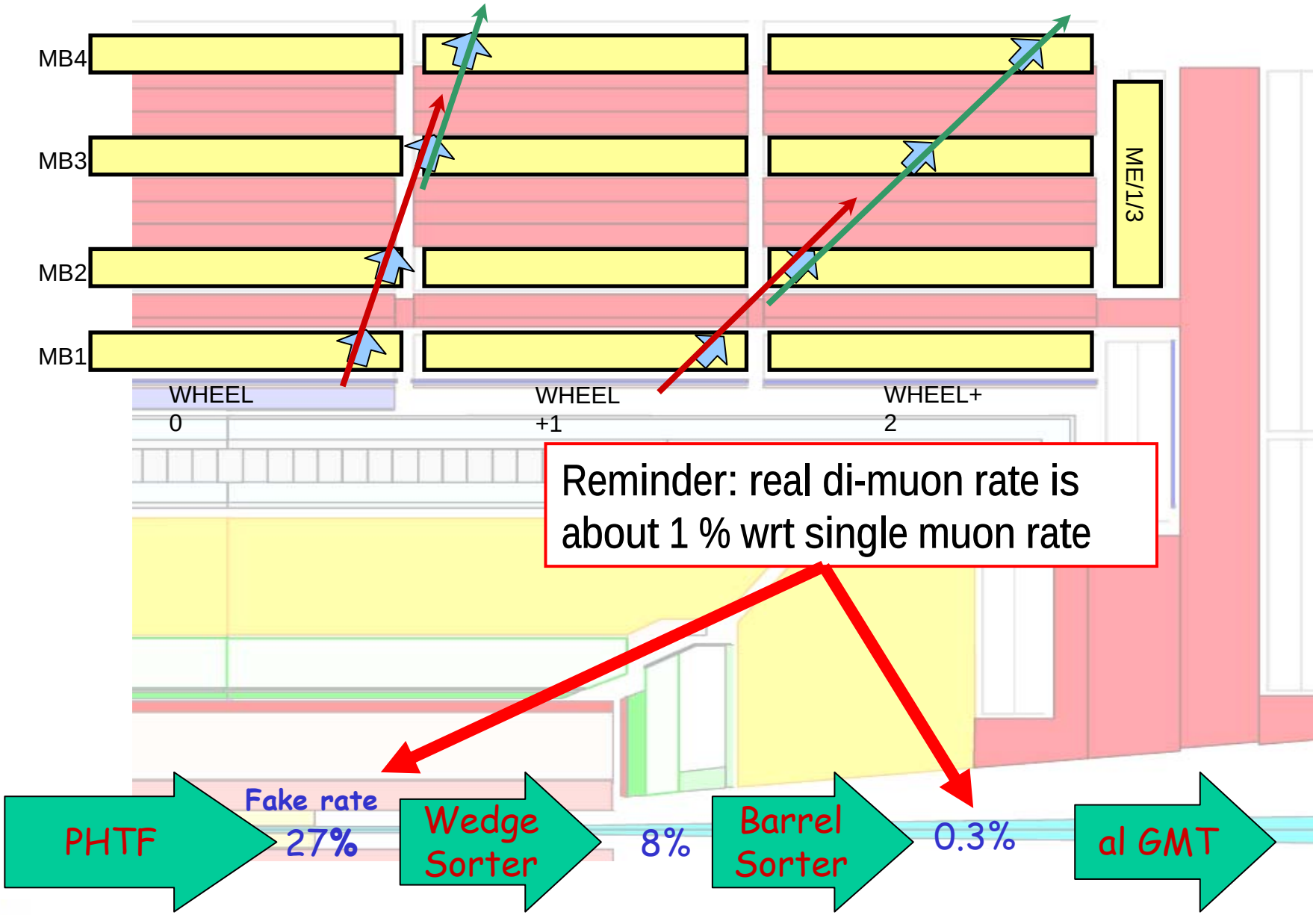


Underground counting room

# Muon Sorter – fake tracks suppression



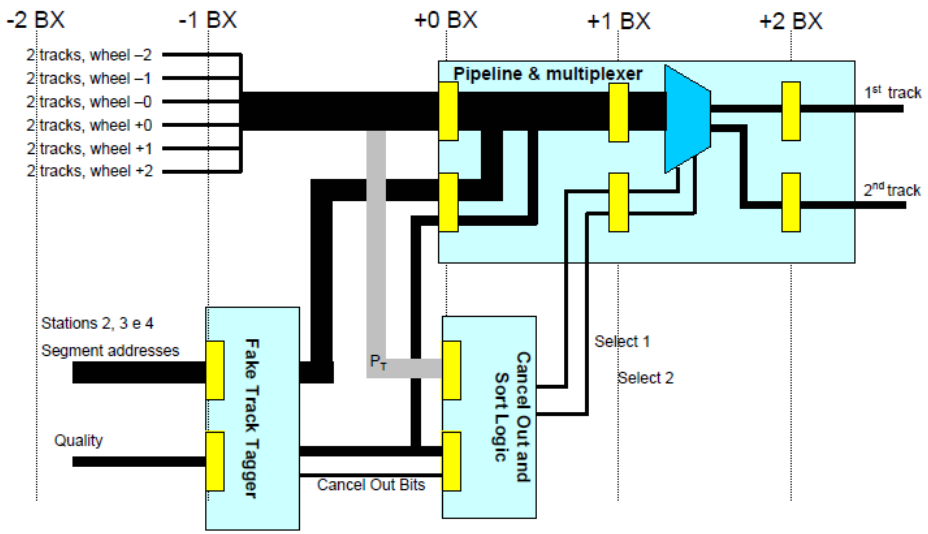
# Muon Sorter – fake tracks suppression

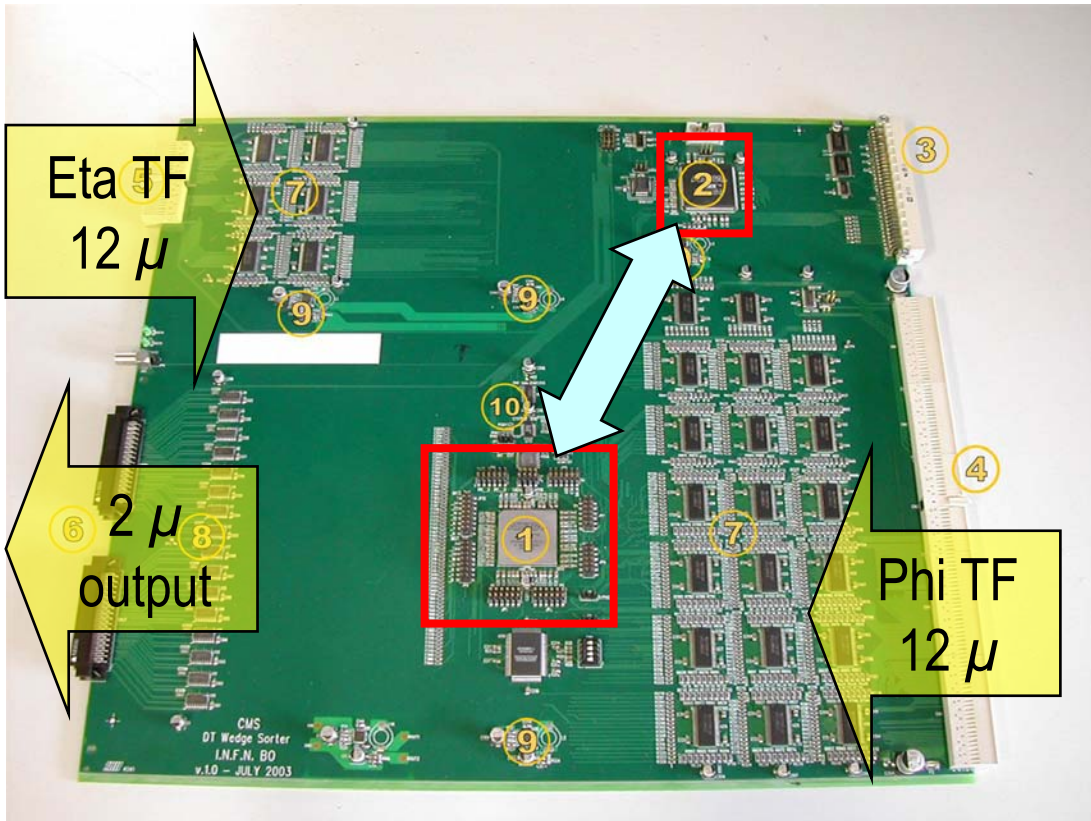


# Wedge Sorter board

- VME 9U board
- 12 input, 2 output muon tracks (~ 500 bits I/O) in GTL+/LVDS
- Computational core on a single SRAM-FPGA (= low latency, simpler design)
- VME interface on a separate FPGA with bridge to main processor

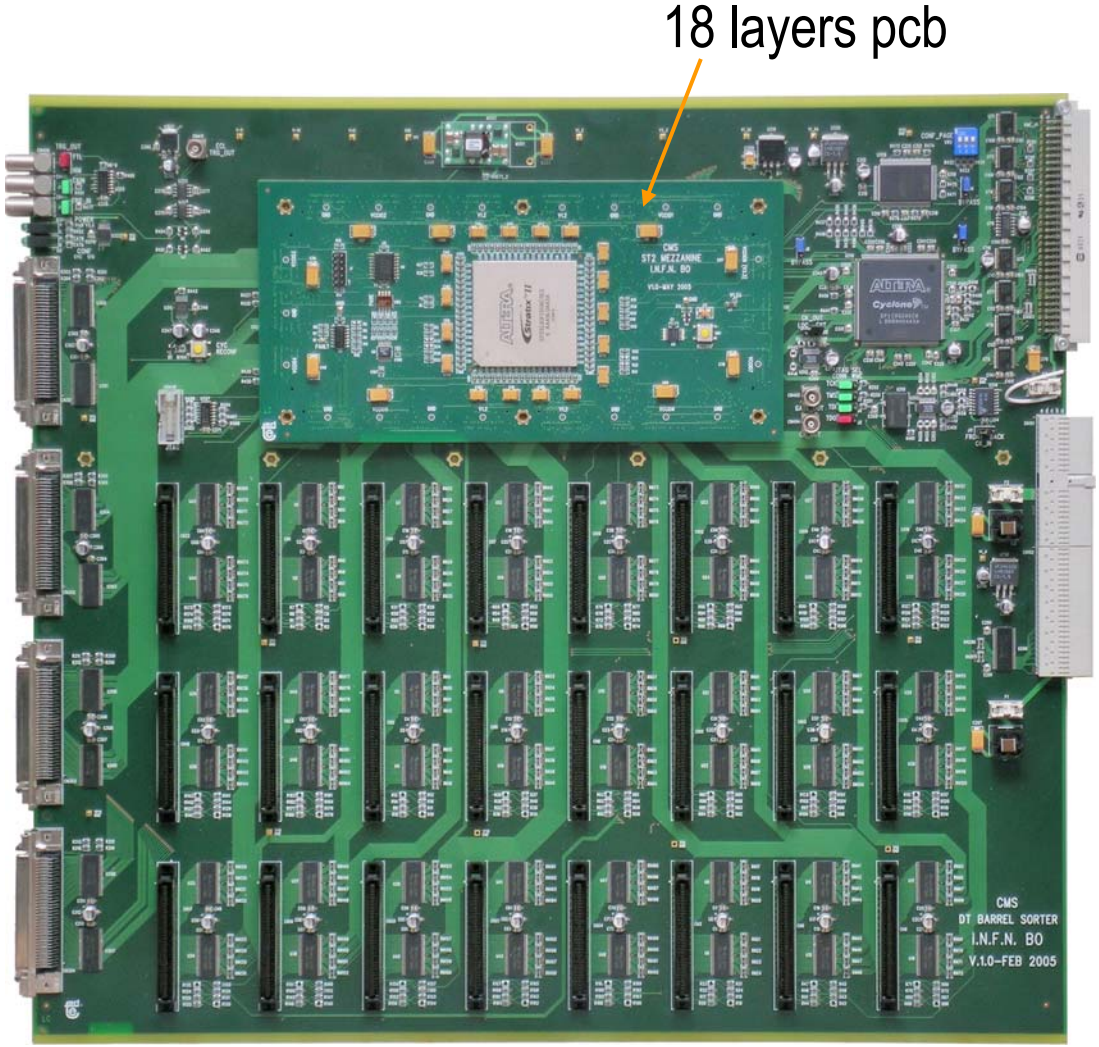
## WS main FPGA core



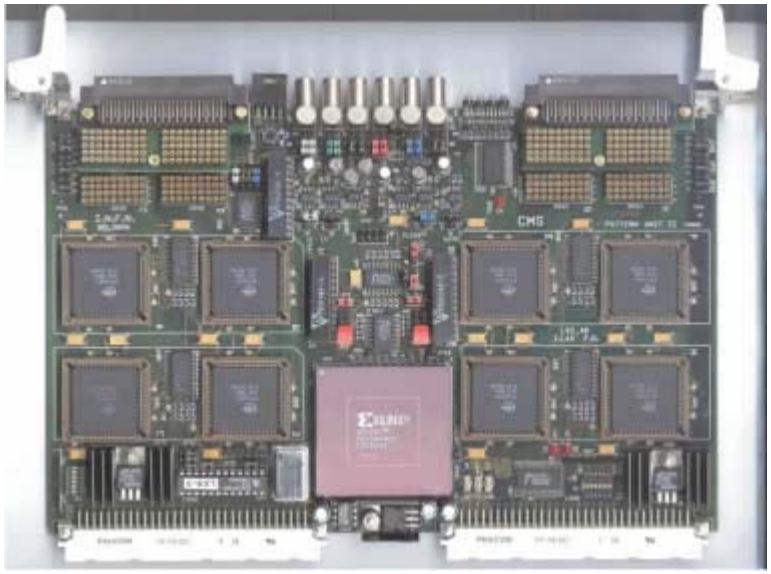
# Barrel Sorter board

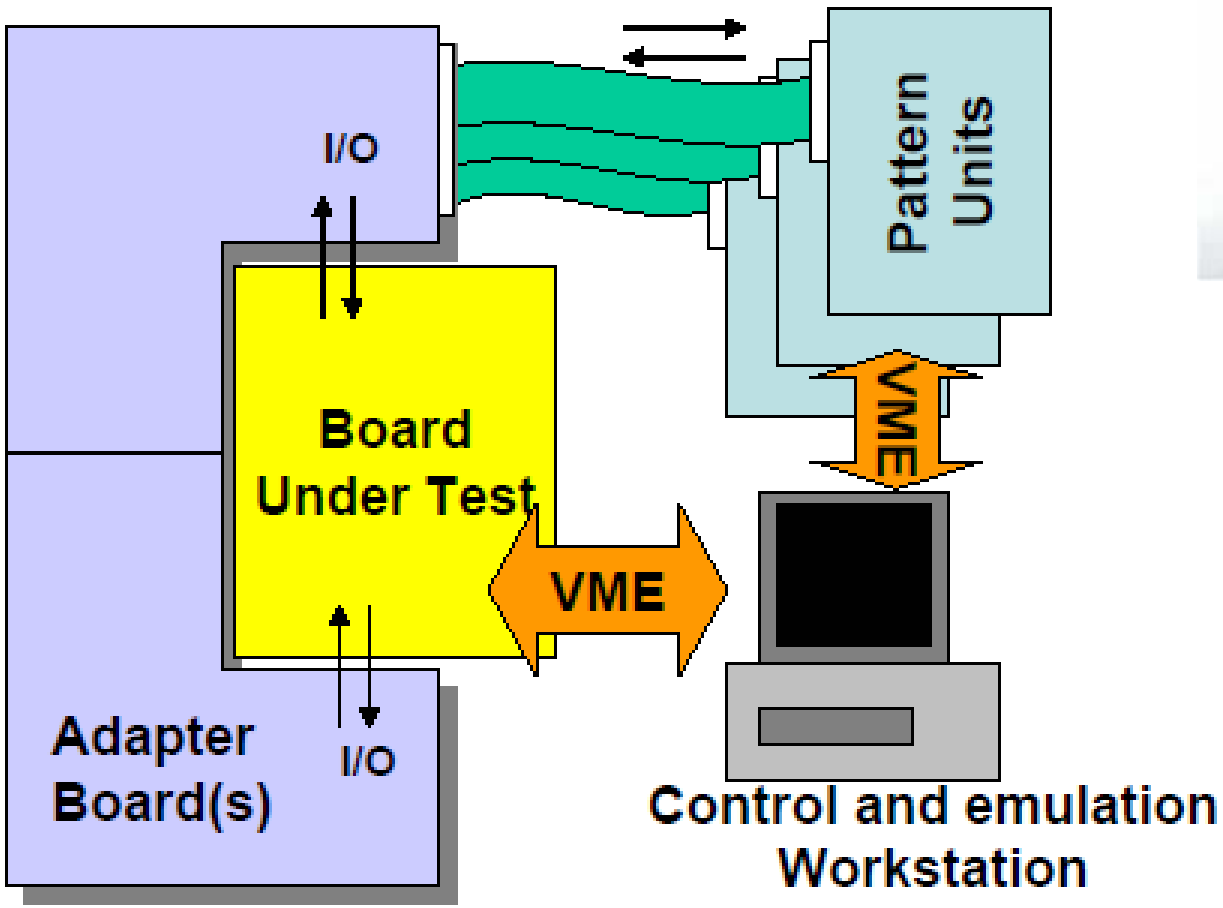
- VME 9U board
- 24 input, 4 output muon tracks (~ 1000 bits I/O) in parallel LVDS
- Computational core on a single FPGA (Altera StratixII 1508 pin) on mezzanine board
- VME interface FPGA with full speed bridge to main processor
- Full data spy system with direct VME access implemented on main FPGA
- Trigger output based on quality thresholds / pattern matching applied on track data



# Setup for dynamic tests

Pattern Unit is a VME testing device designed by CMS Bologna group:
- 128 I/O
- Up to 64k words
- Up to 100 MHz
- Multi board setup

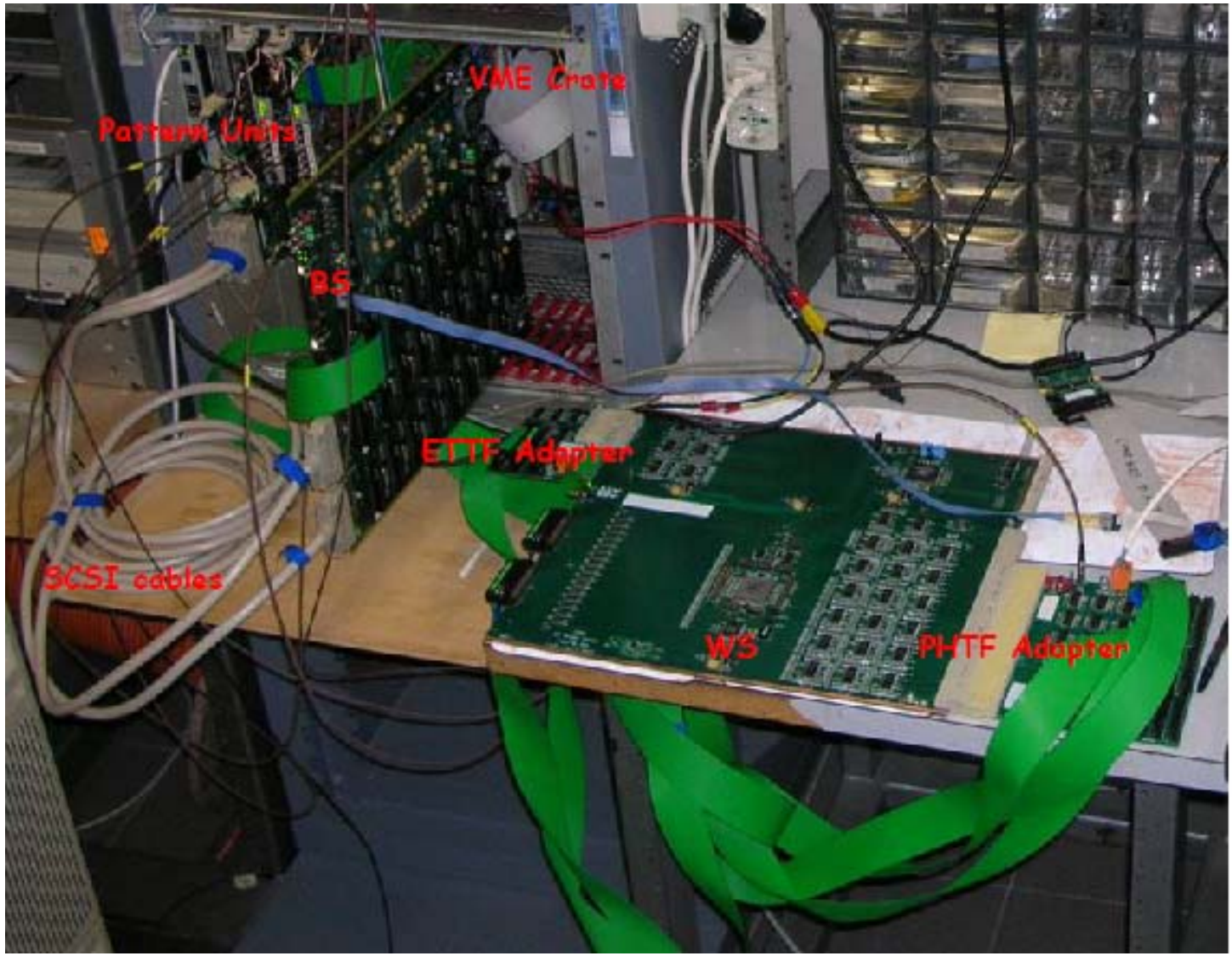


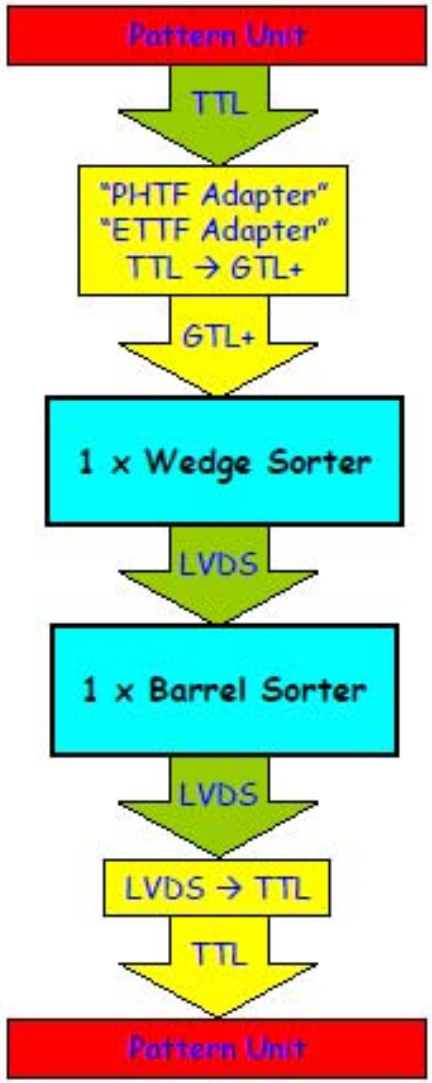



C++ software written to generate random data patterns, inject them into the board under test, and check the outputs

- Verification of custom algorithms
- Verification of all board components and connections

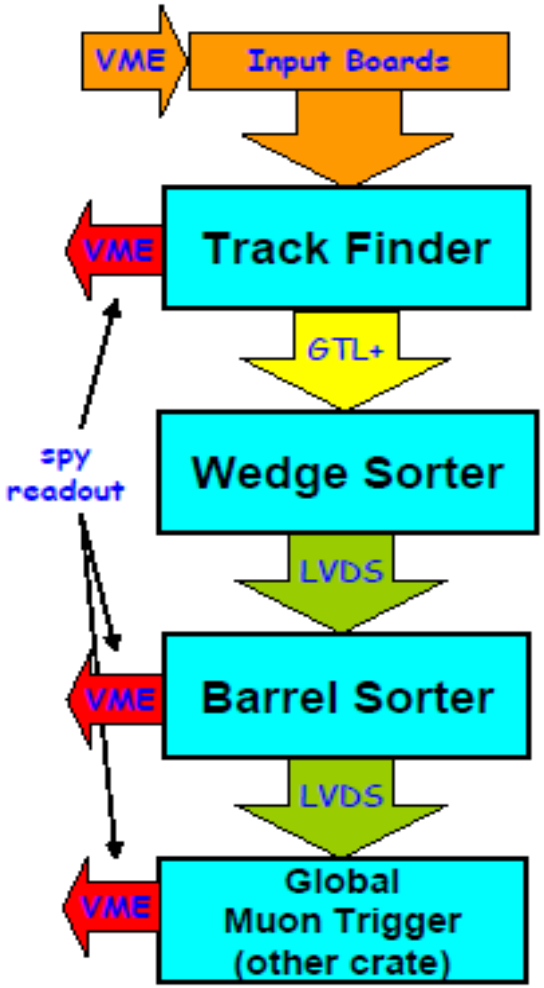
# Wedge—Barrel Sorter integration test setup

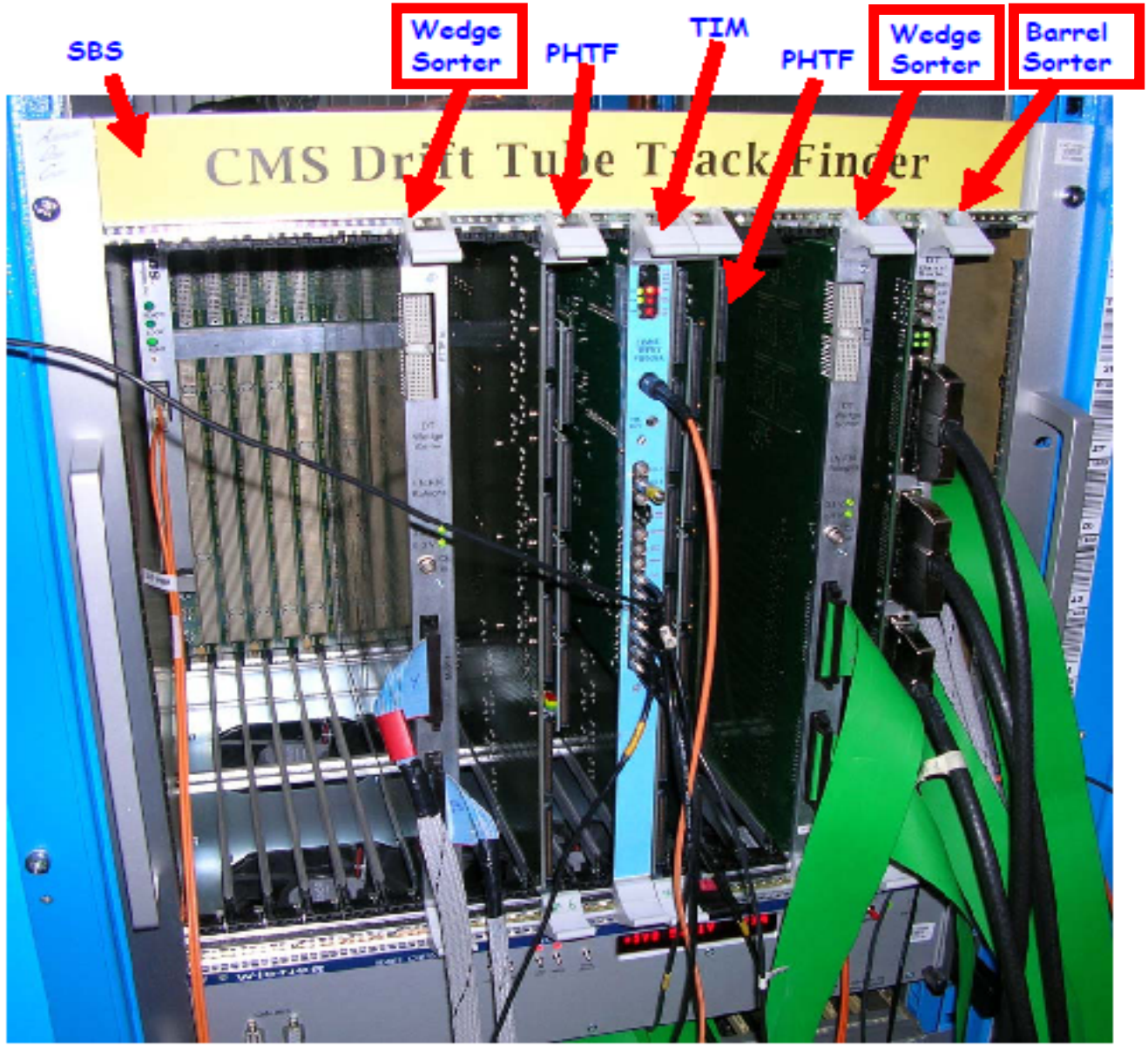


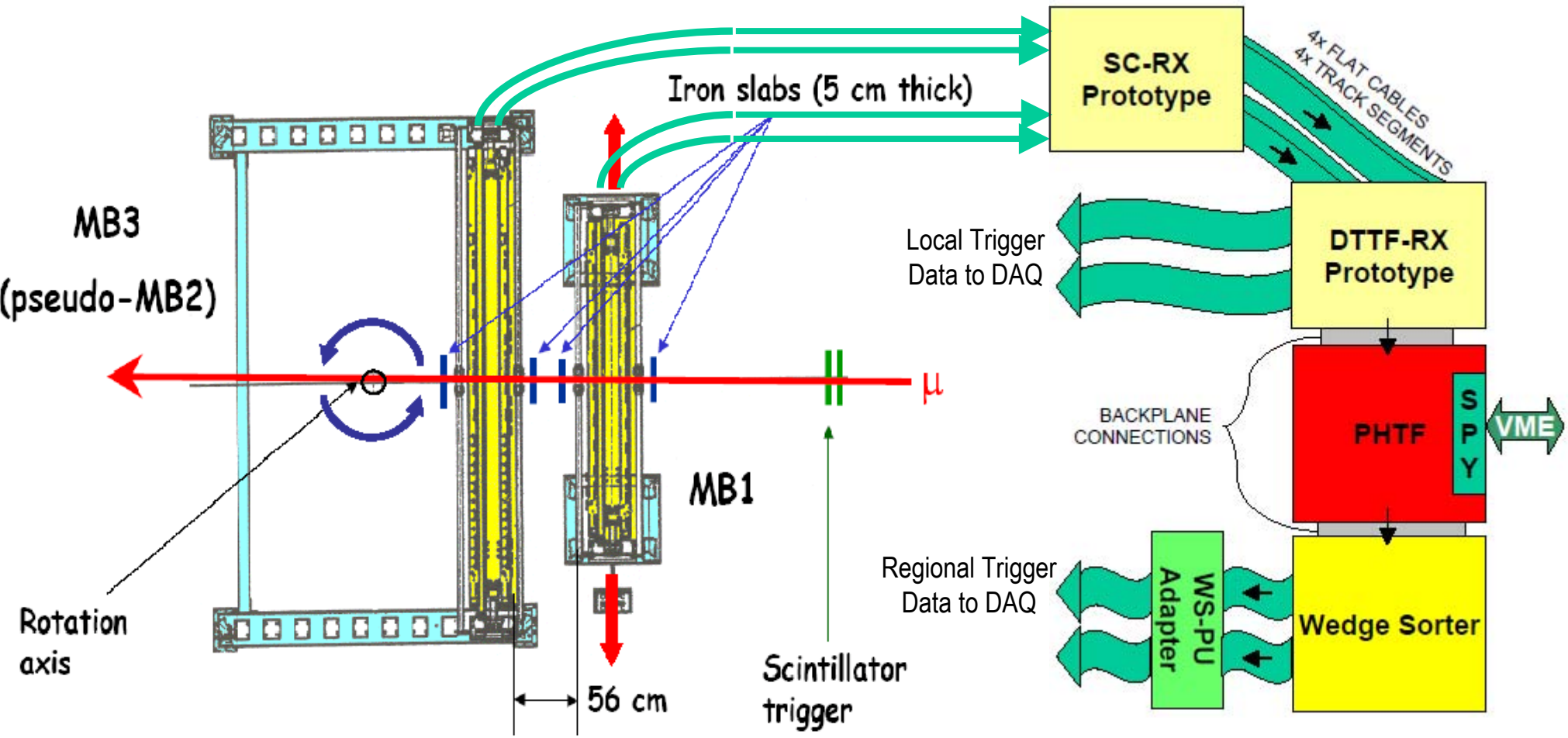

Several bugs (bad solderings, missing components) found and corrected

# Integration test in Track Finder crate



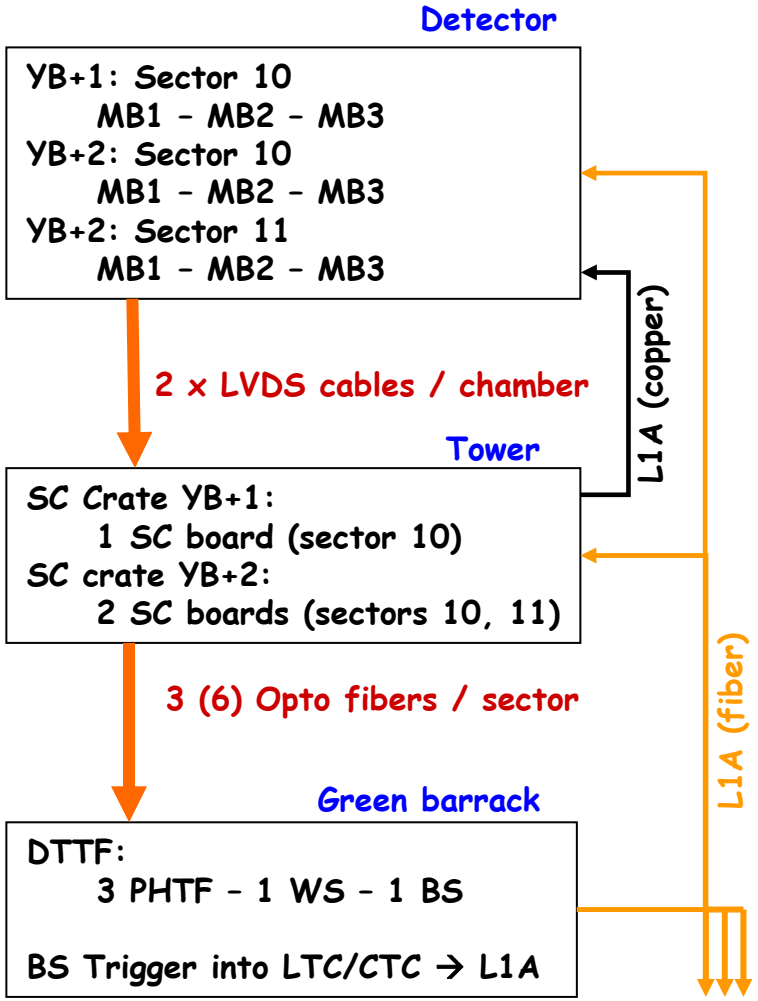
# Test Beam of the DT Muon Trigger

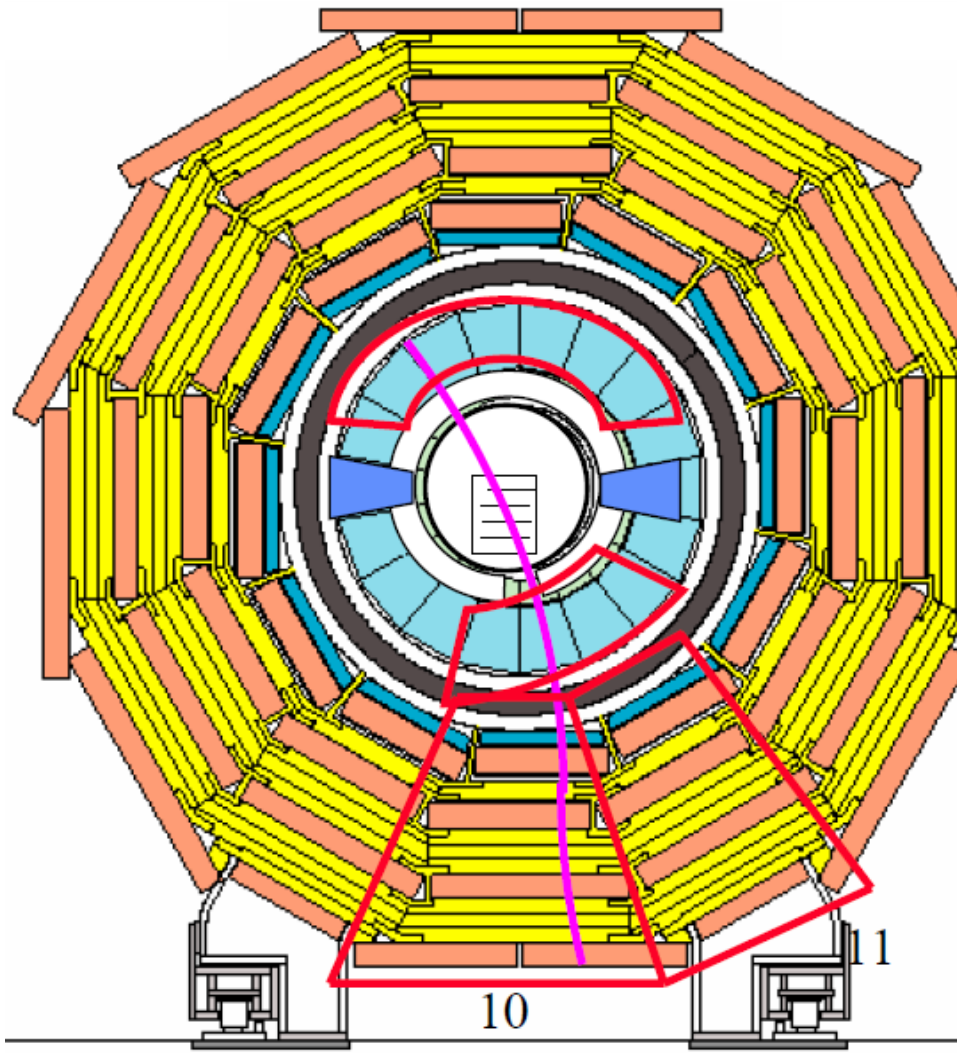



- Secondary muon beam with 25 ns bunched structure
- Chambers rotation and shift to emulate the bending in the magnetic field
- Off-detector electronics prototypes were effectively synchronized and readout

# CMS "Cosmic Challenge"

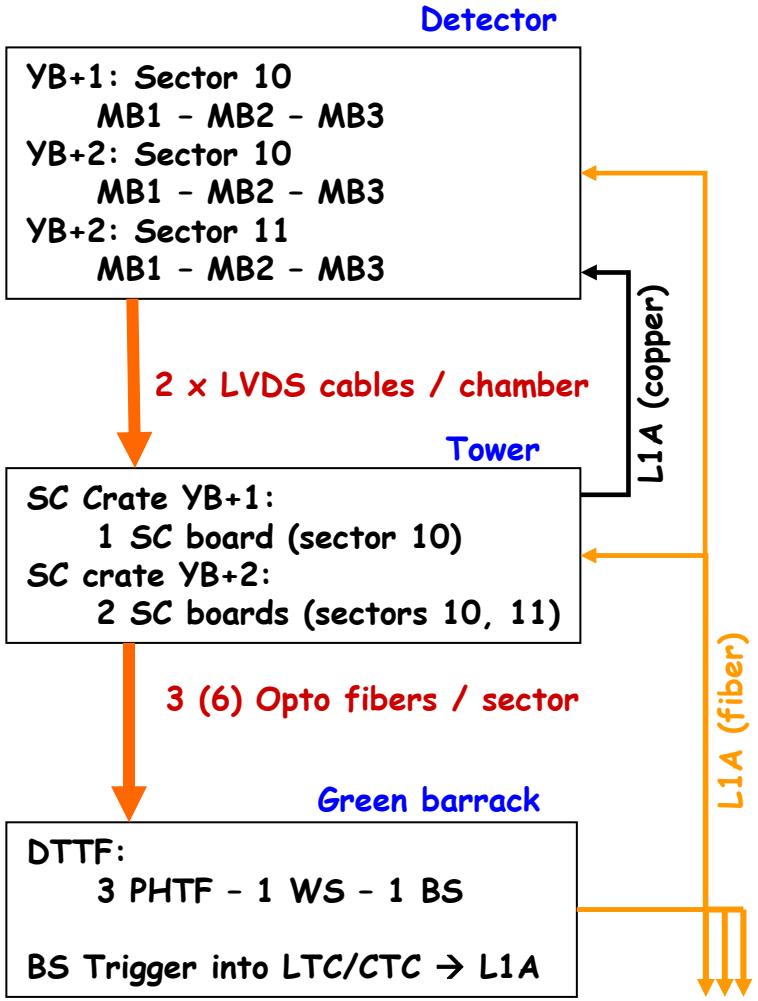
## DT Trigger Setup at Cosmic Challenge

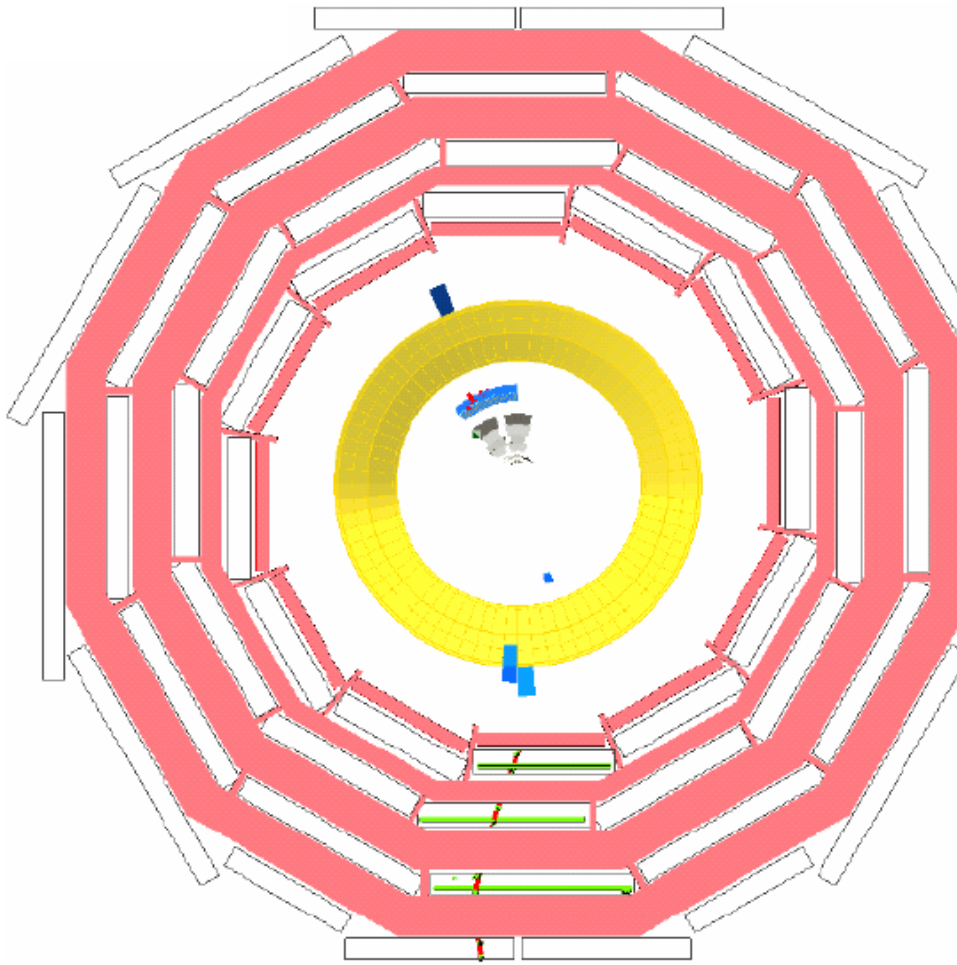


# CMS "Cosmic Challenge"

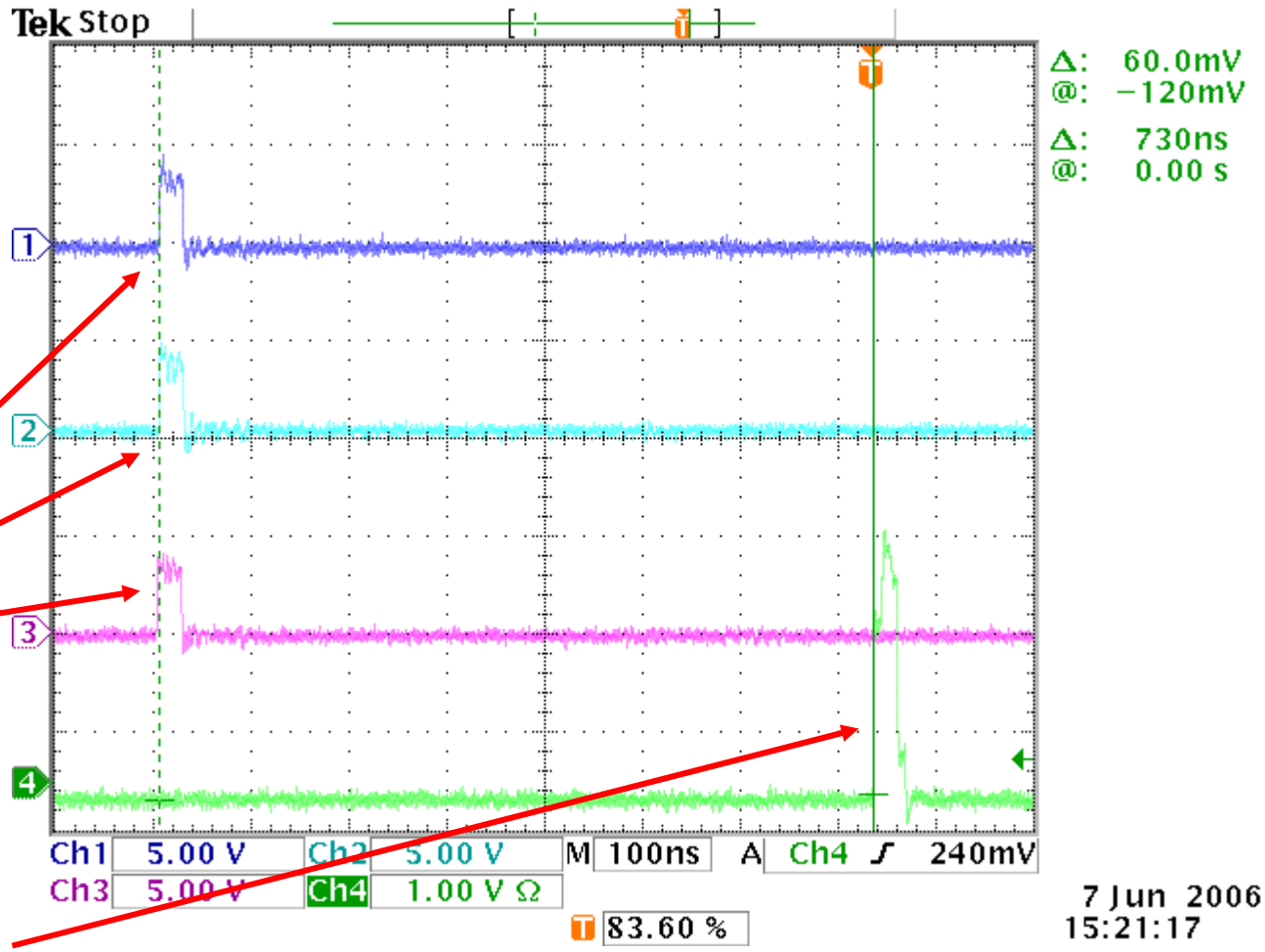
## DT Trigger Setup at Cosmic Challenge



# SC synchronization – 1: scope

At the very beginning, we could check the synchronization of the segments at DTTF inputs...
At a very low level!

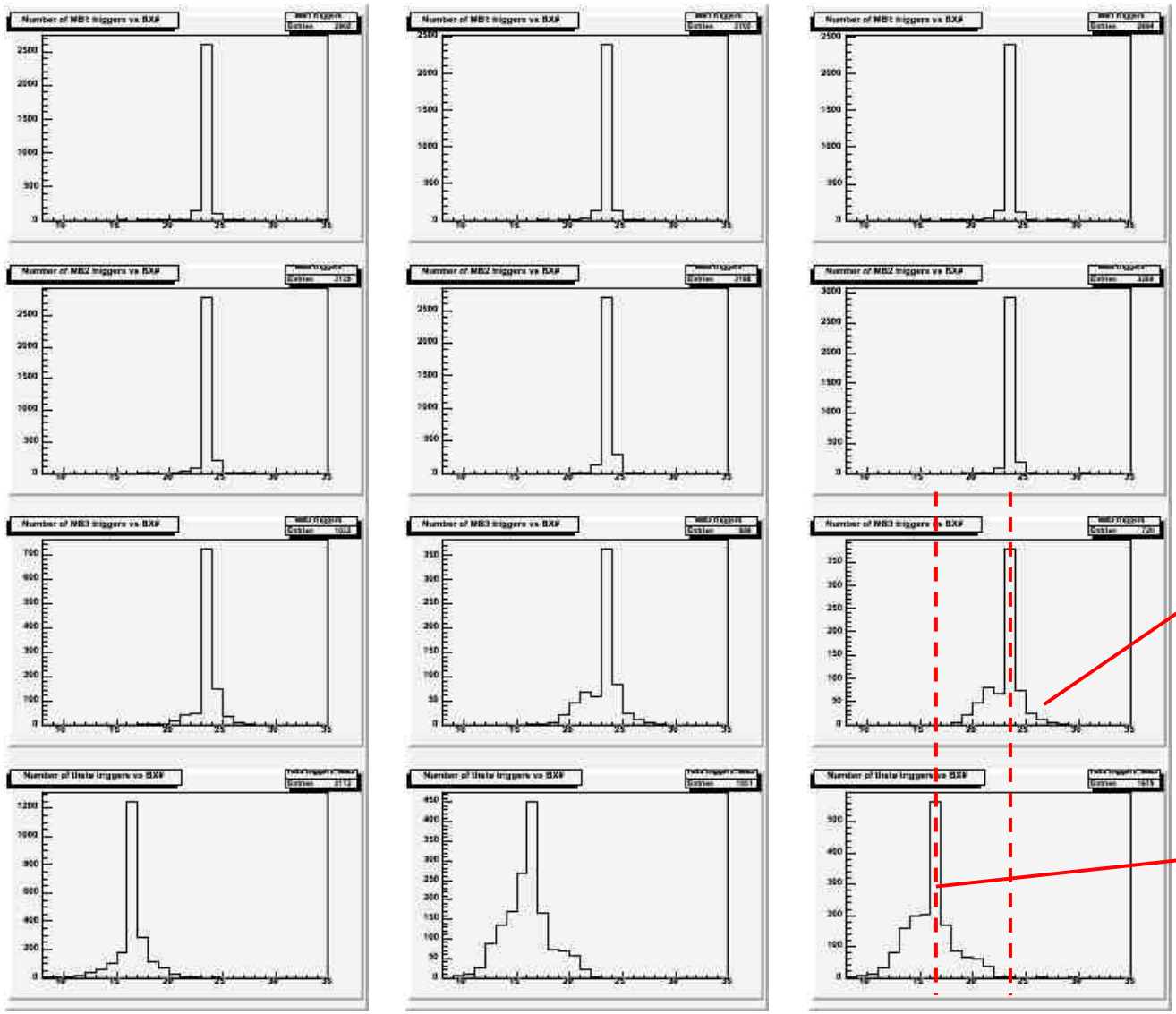



Non-null segments pulses (DTTF inputs)

BS trigger output
(DTTF built a track with quality > threshold)

(J. Ero)

# SC synchronization – 2: spy data plots




✓ Timing was found to be stable across several days of running

MB3 timing is downgraded by a "special" configuration

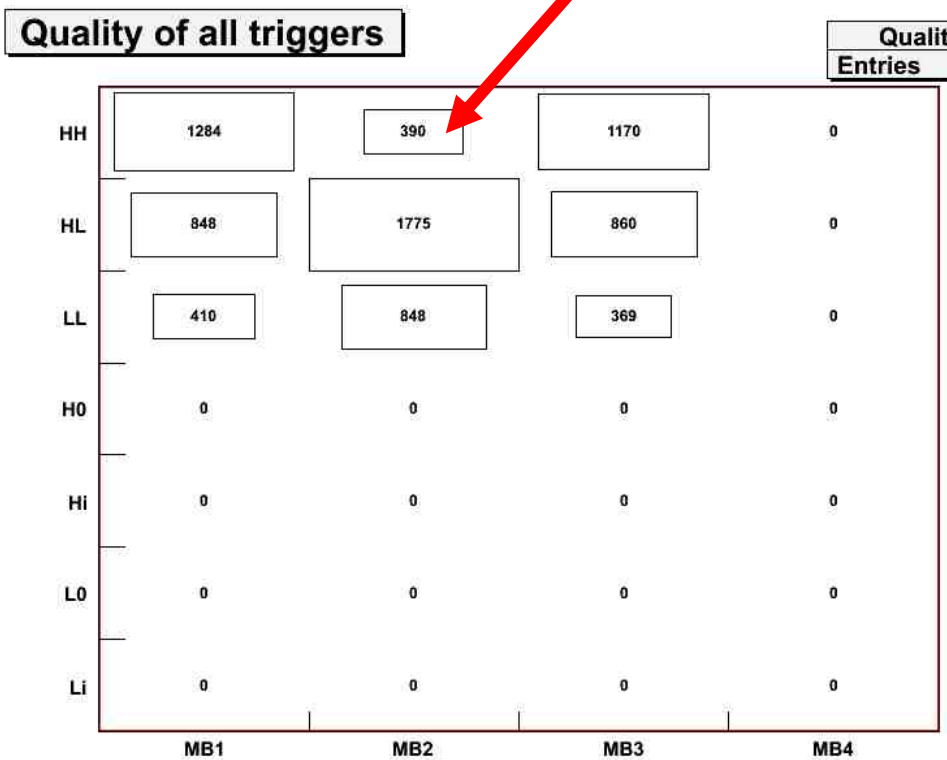
theta hits outputted 7 BXs before phi segments

Plots from SC SPY

# Monitoring with SC spy – trigger primitives quality

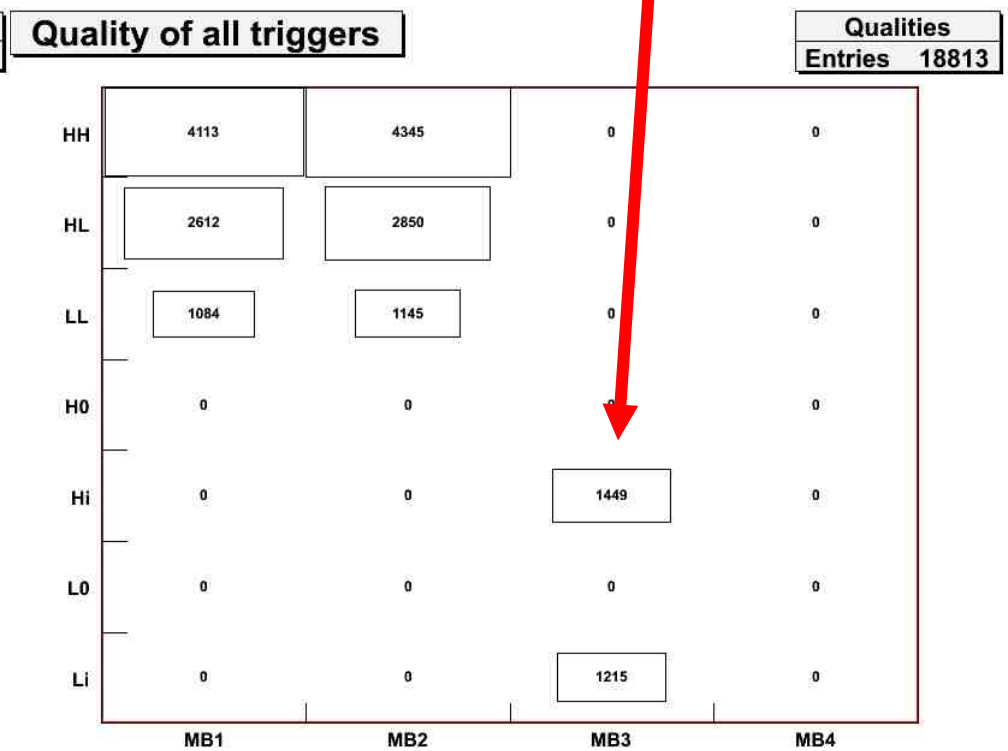
"Default" configuration:
Only correlated (HH+HL+LL) segments

Here: HH missing on MB2
(most of 1 layer had HV off)




"Pointing" configuration:

Only uncorrelated ($H_l$+$L_l$) phi segments
out of MB3 - it is ($H_l$+$L_l$) · $H_{theta}$




Plots from SC SPY

# Summary

- The DT Sector Collector and Muon Sorter systems have been implemented with several FPGAs technologies
- Tools for remote monitoring and configuration have been developed and validated
- Exahustive dynamic tests of all the hardware have been used to validate the designs and the produced boards
- Integration tests validated the whole system architecture
- In CMS “Cosmic Challenge” in August 2006 a full slice of the CMS detector was integrated and run on cosmic muons
- A complete slice of the DT Trigger system was integrated and operated reliably and proved good stability, millions of cosmics were triggered
- During the Cosmic Challenge the spying and monitoring tools were extensively used to check on-line and quasi-automatically the system performance

End....

backup slides following

# LHC: cross sections and rates

- Start in 2007
- *pp* collider reaching $\sqrt{s}$ = 14 TeV
- Design luminosity is $L = 10^{34}$ cm$^{-2}$s$^{-1}$
- The total cross-section at this energy is about

$\sigma \approx 70$ mb

corresponding to an interaction rate

~ 700 $10^6$ events/s

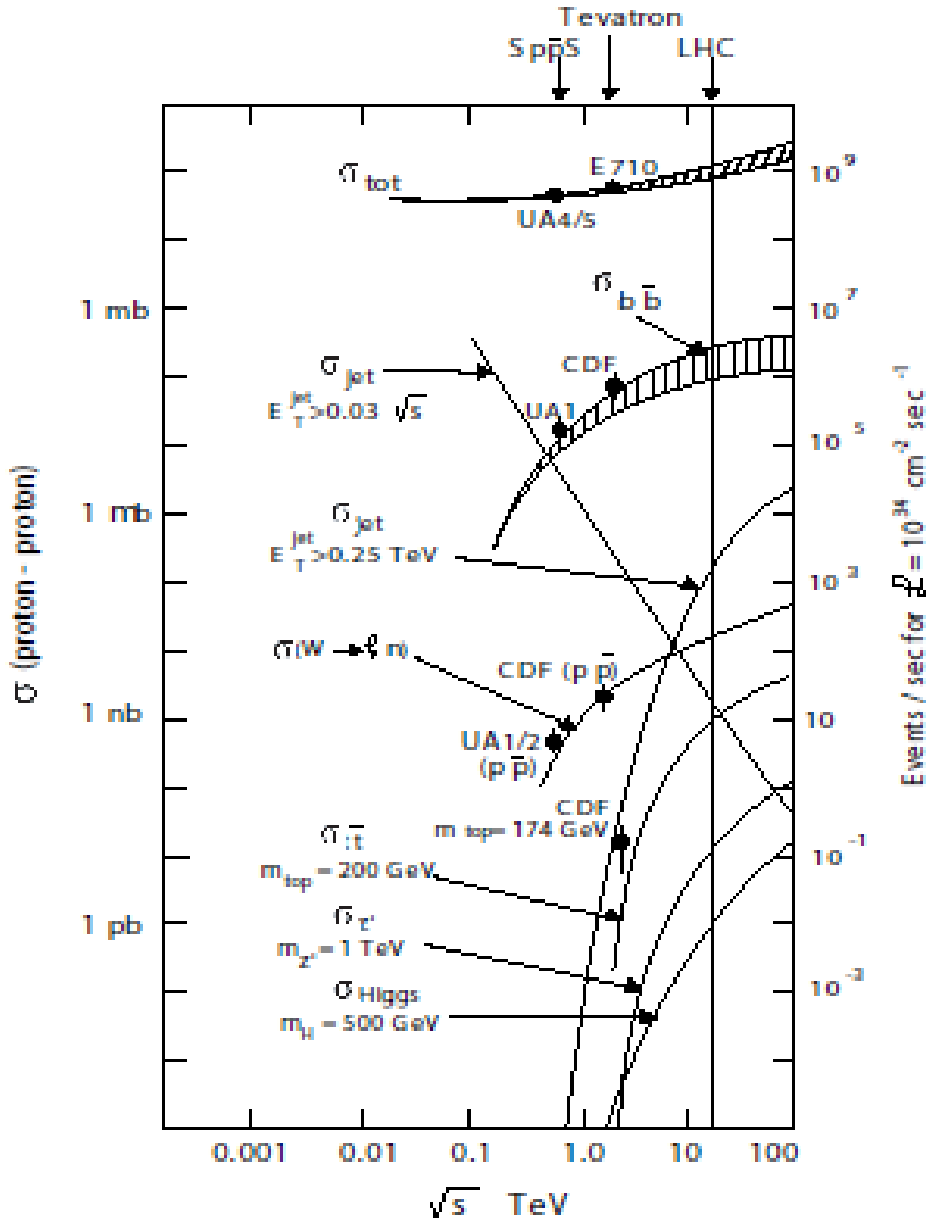
at a crossing frequency of

40 MHz

- Very good selectivity needed, i.e.

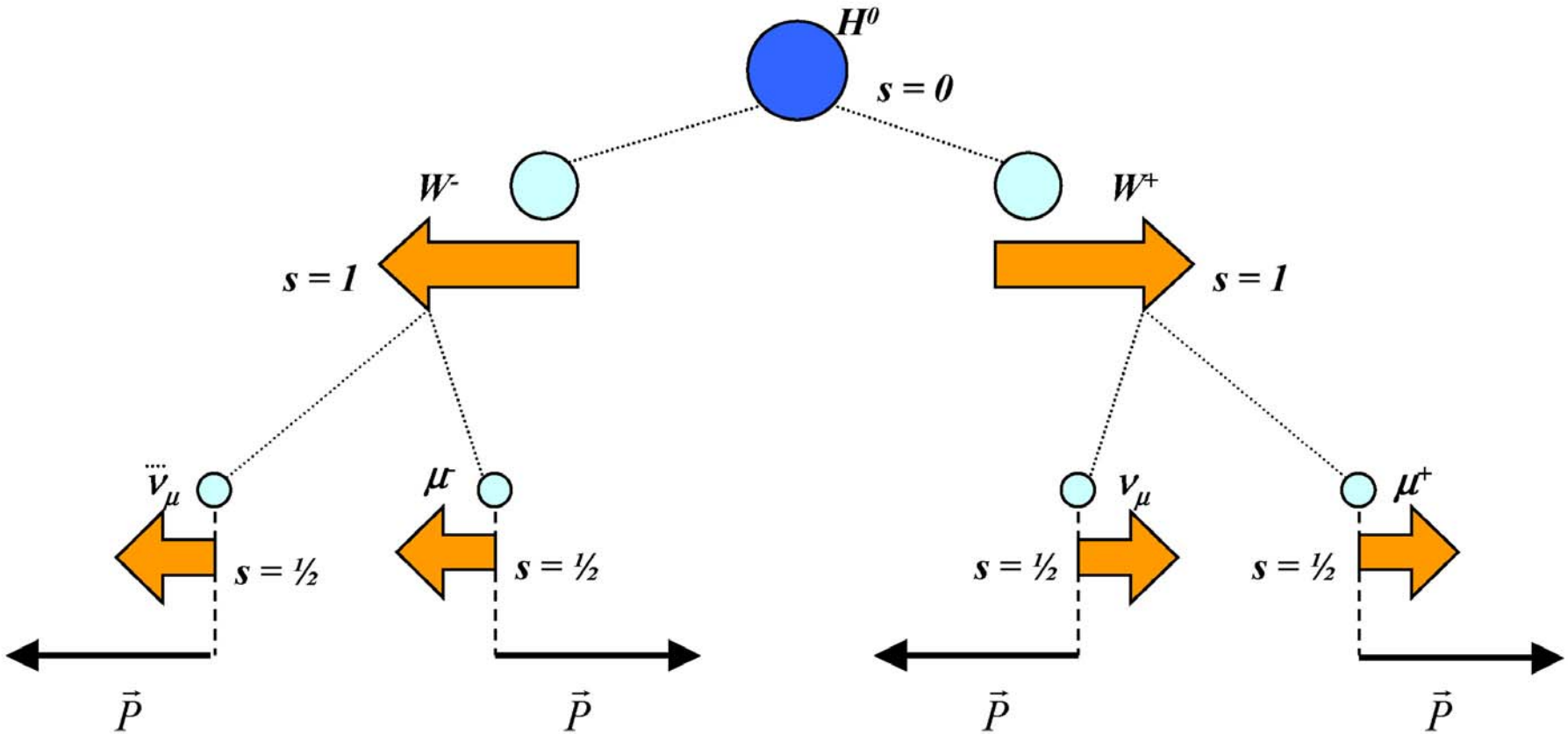
$\sigma_{HiggsSM}$ ~ 1 pb

→ need a selectivity ~ 1:$10^{11}$



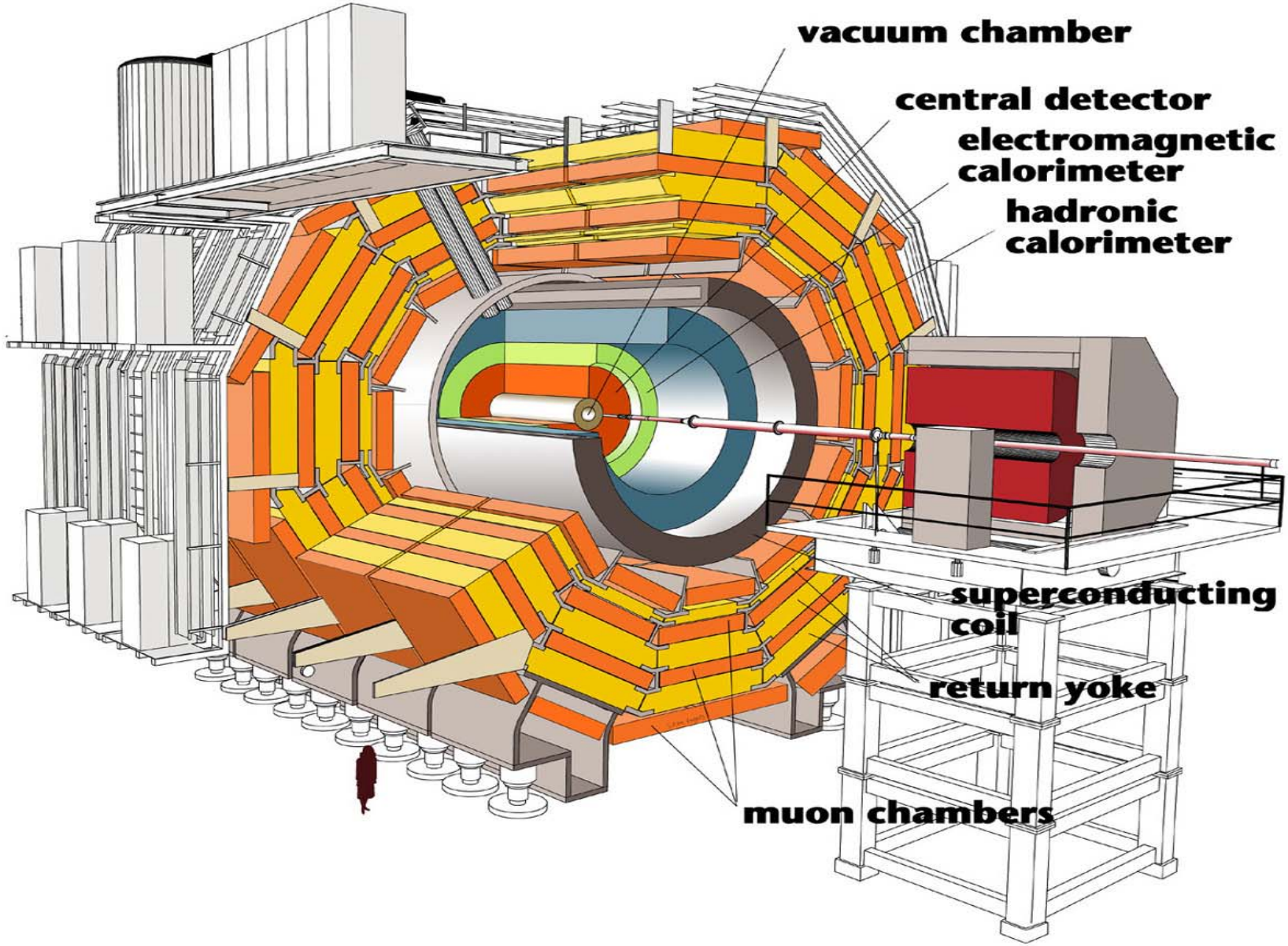
# Spin correlation

In the frame where *H* is at rest

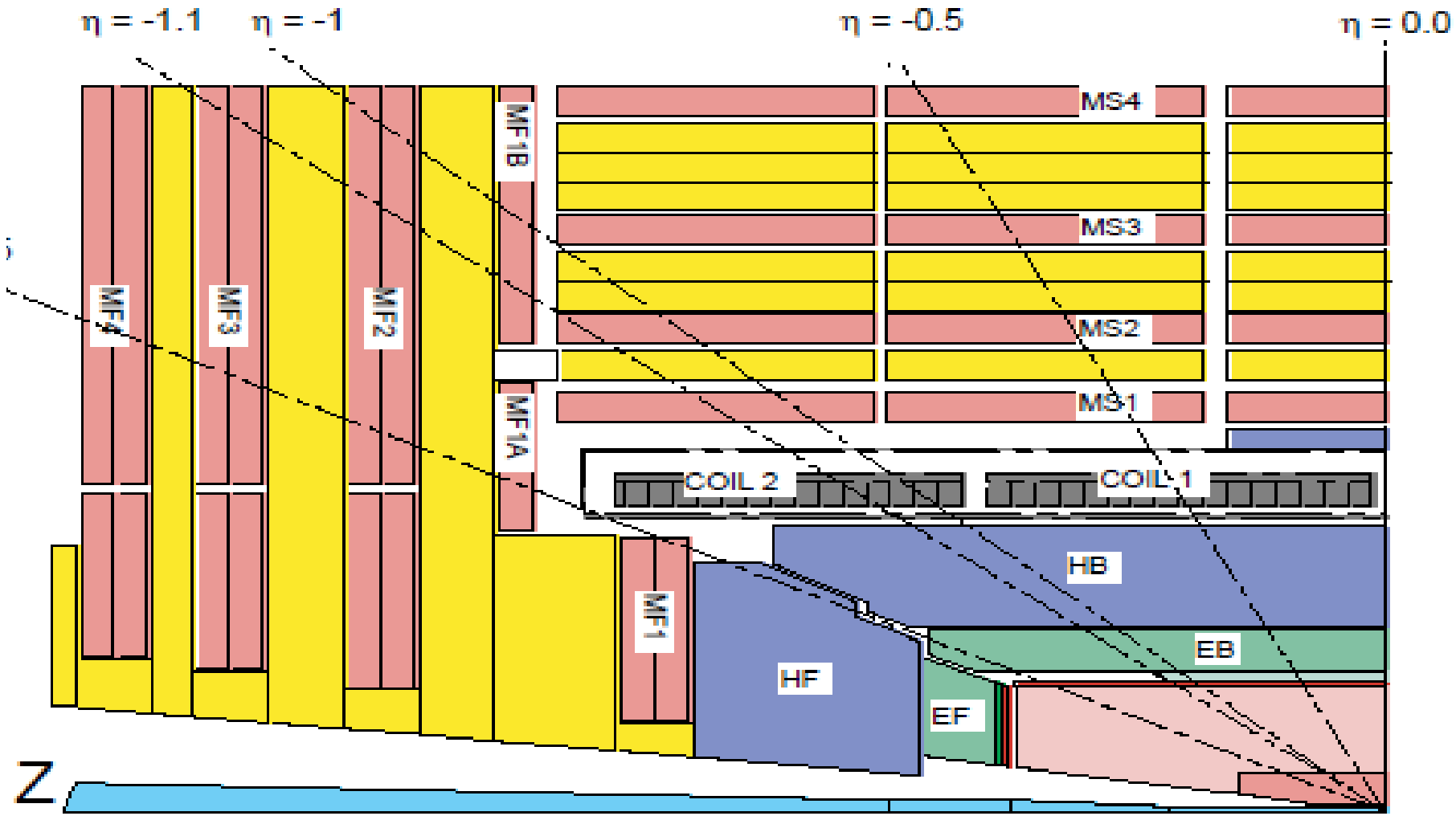



Definite elicity of neutrinos → same direction of μ momentum

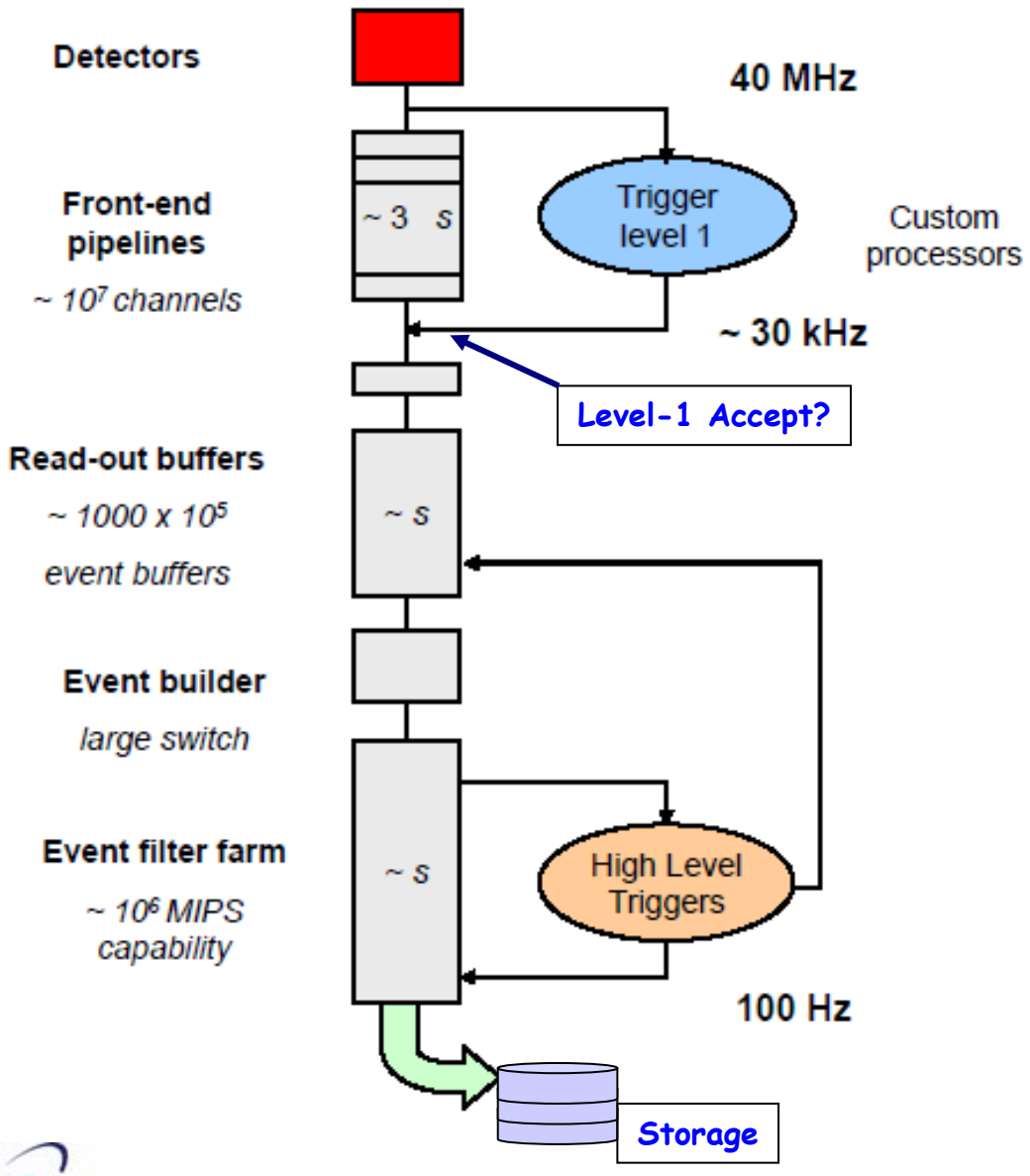
# CMS detector



# Muon Detectors transverse view



# Trigger system overview




- On-line reduction from interaction rate (~700 MHz) to storage rate (~ 100 Hz)

Trigger chain based on 2 levels

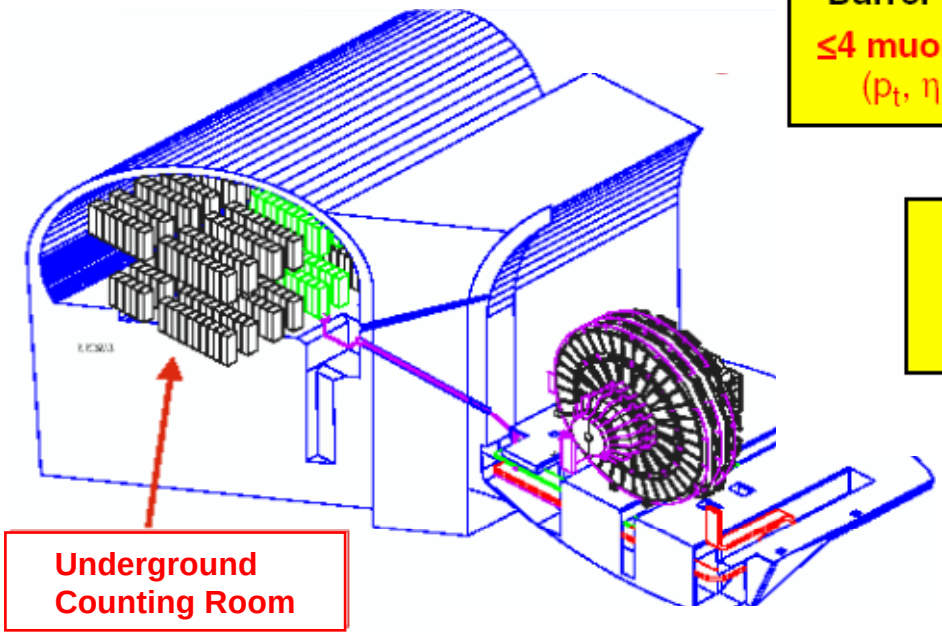
- Level-1
  - → custom processors
  - → muon and calorimeters
  - → pipelined (sync. 40 MHz)
  - → no dead-time
  - → 3.2 μs overall latency

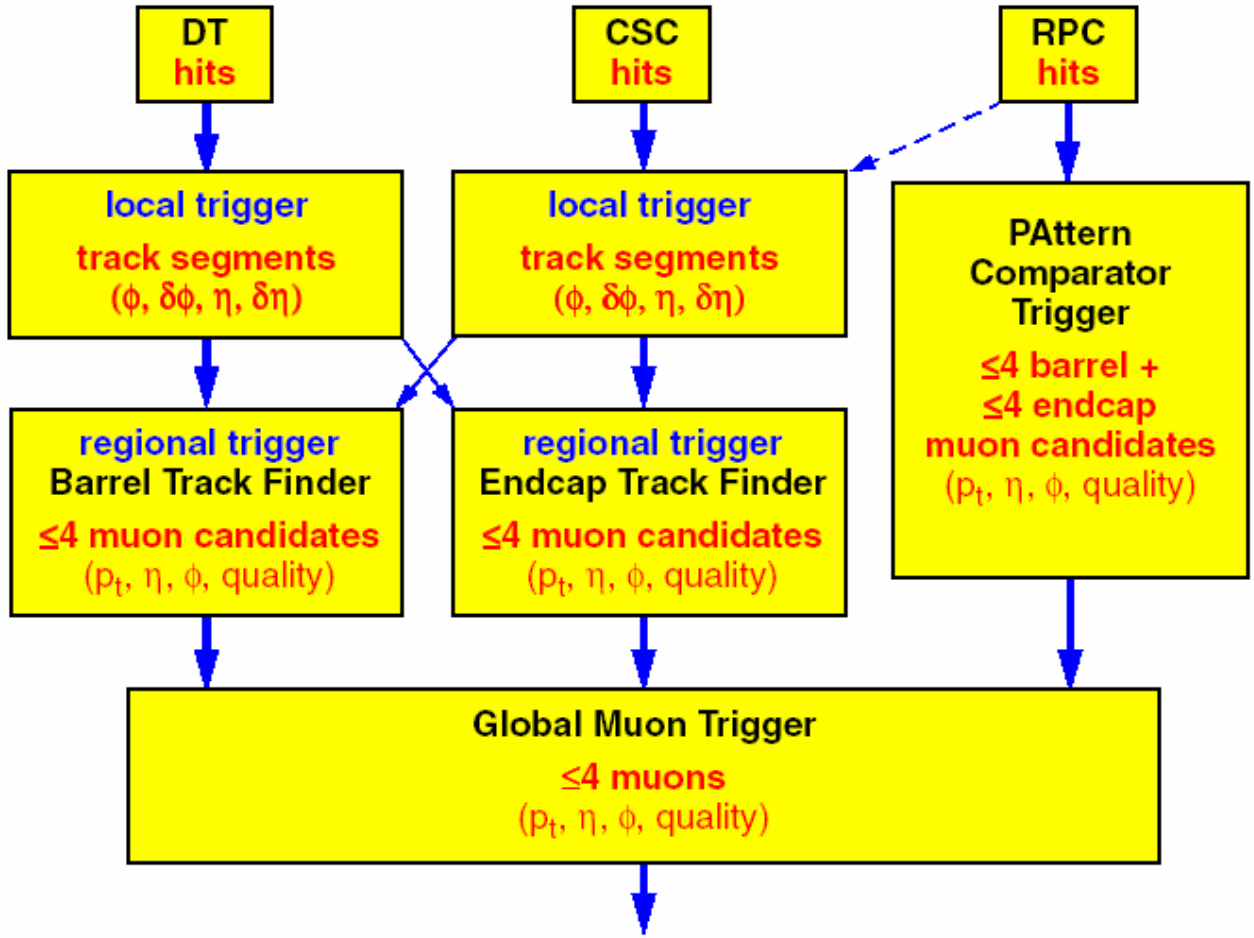
- High level
  - → Software on CPU farm
  - → ~ s latency

# Level-1 Muon Trigger overview

On-detector electronics →

Counting room electronics →



# Meantimer

$$T_1 = \frac{1}{v_{drift}}\left(d + \frac{5}{2}h\tan\psi\right)$$

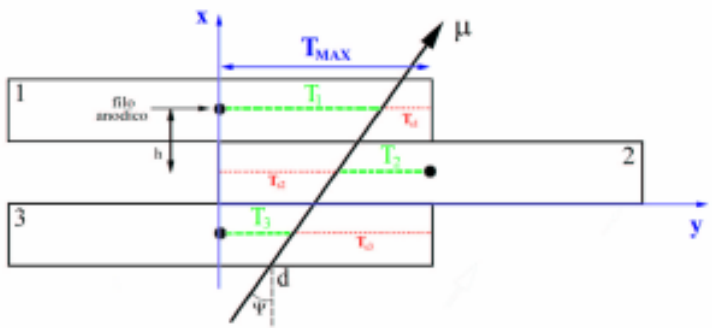
$$T_2 = T_{MAX} - \frac{1}{v_{drift}}\left(d - \frac{3}{2}h\tan\psi\right)$$

$$T_3 = \frac{1}{v_{drift}}\left(d + \frac{1}{2}h\tan\psi\right)$$

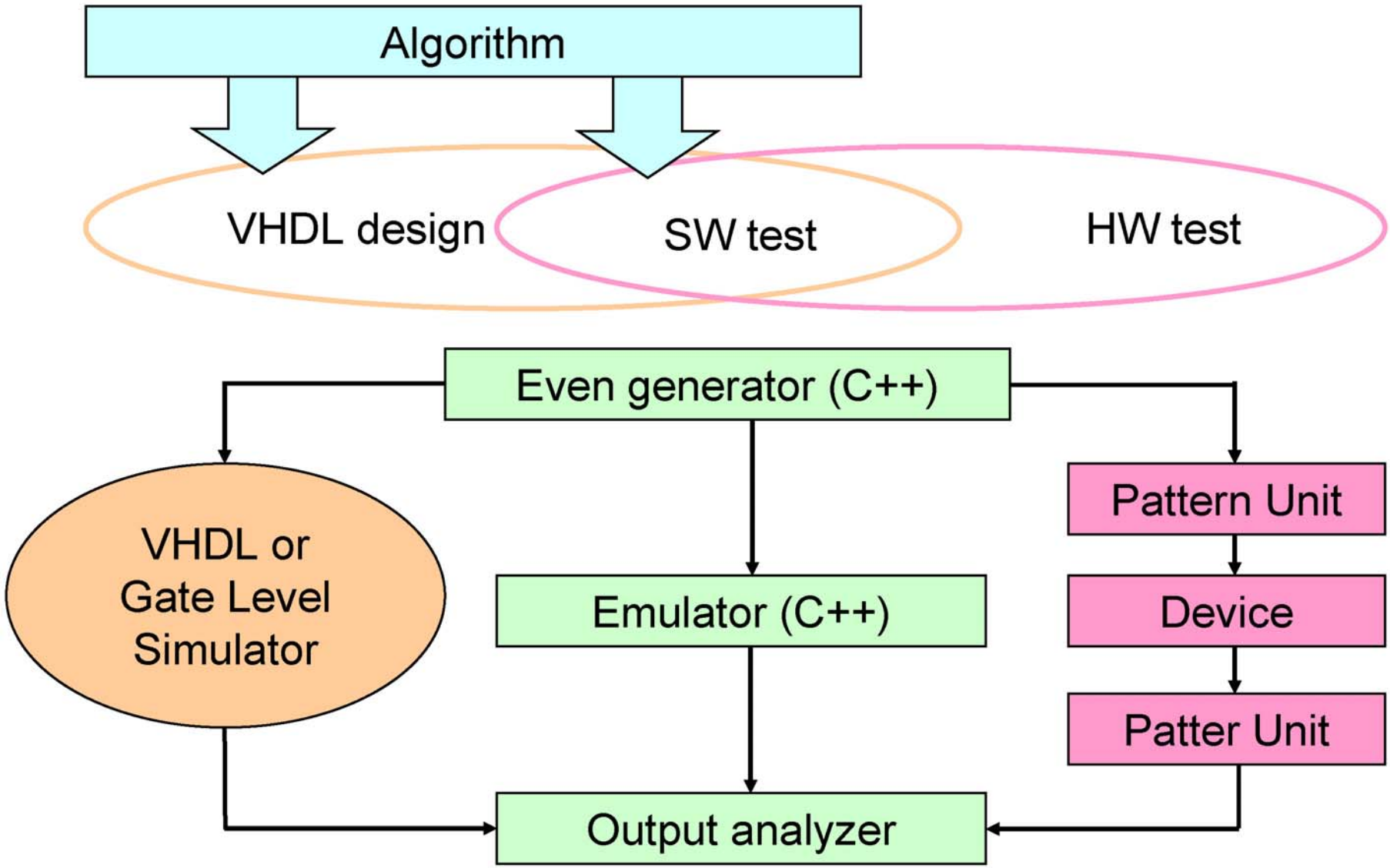
Thus,

$$\frac{T_1 + 2T_2 + T_3}{2} = T_{MAX}$$

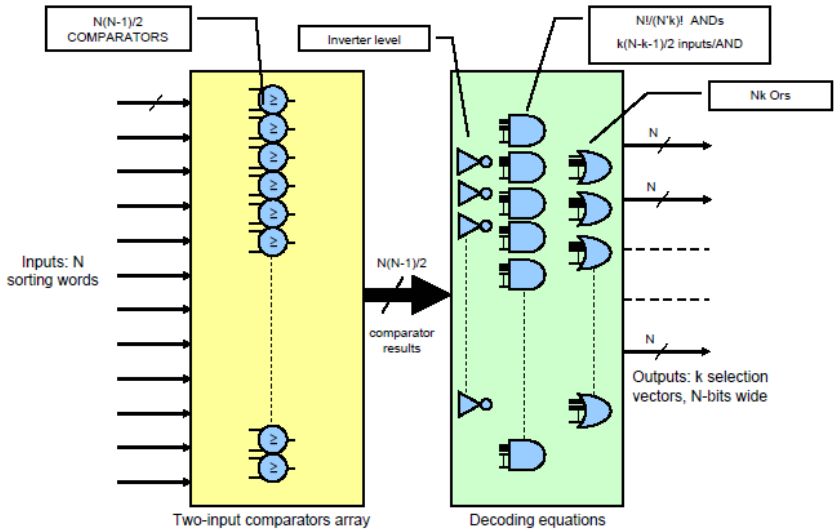
i.e. after a constant time $T_{MAX}$ from the bunch crossing in which a muon originated, three hits from the muon track satisfy that alignment relation (see BTI in section 2.3.1). That means the muon parent BX can be unambiguously identified. However this technique imposes severe constraints



# Design Method

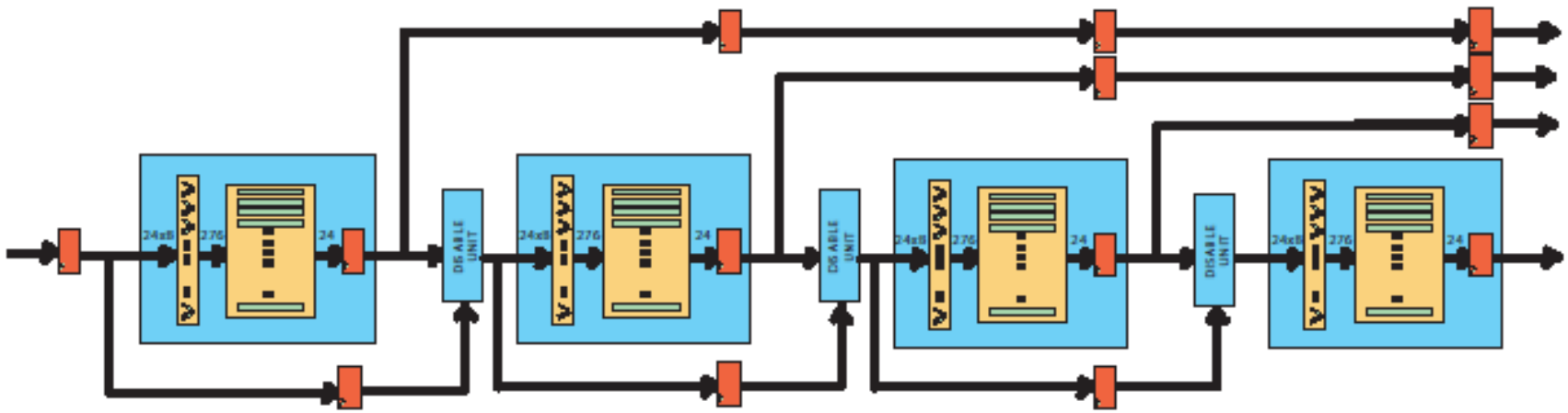


# Parallel Sorting Algorithms

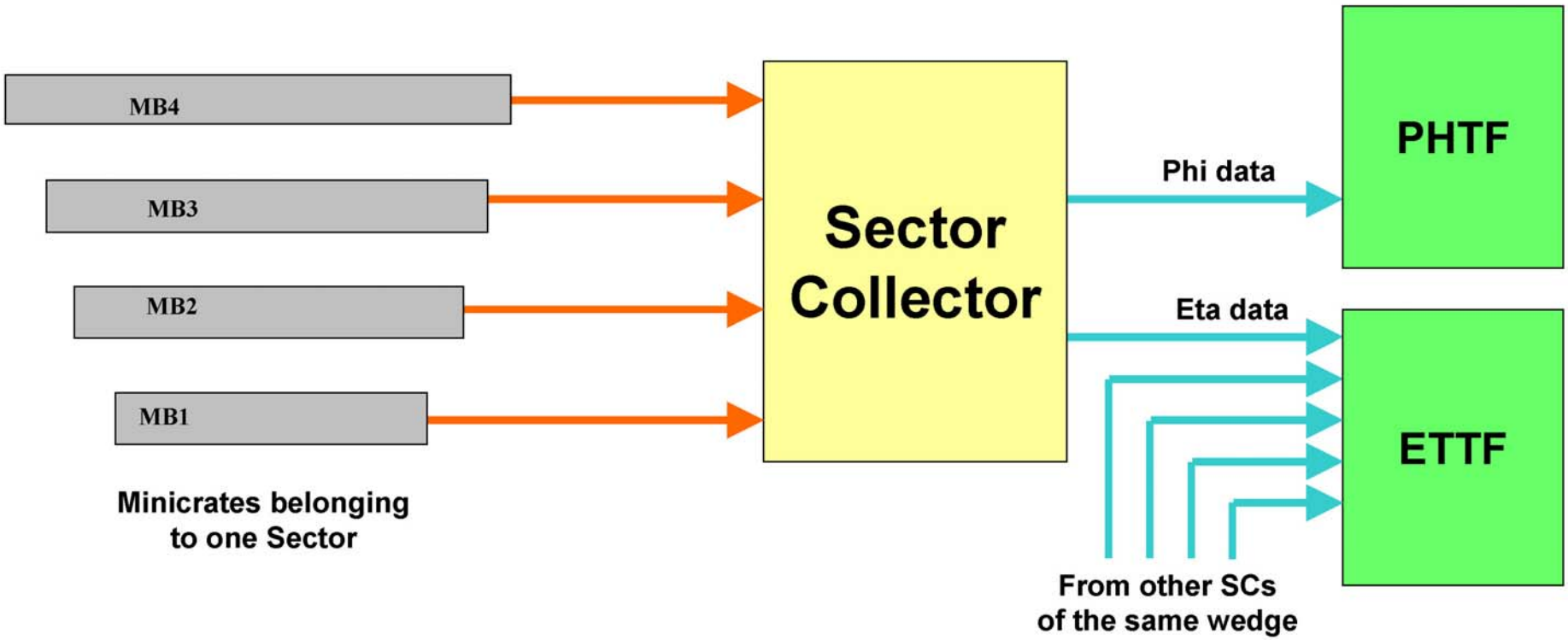



Fully parallel sorting: logic routing complexity increases with factorial dependence on the number of candidates to sort

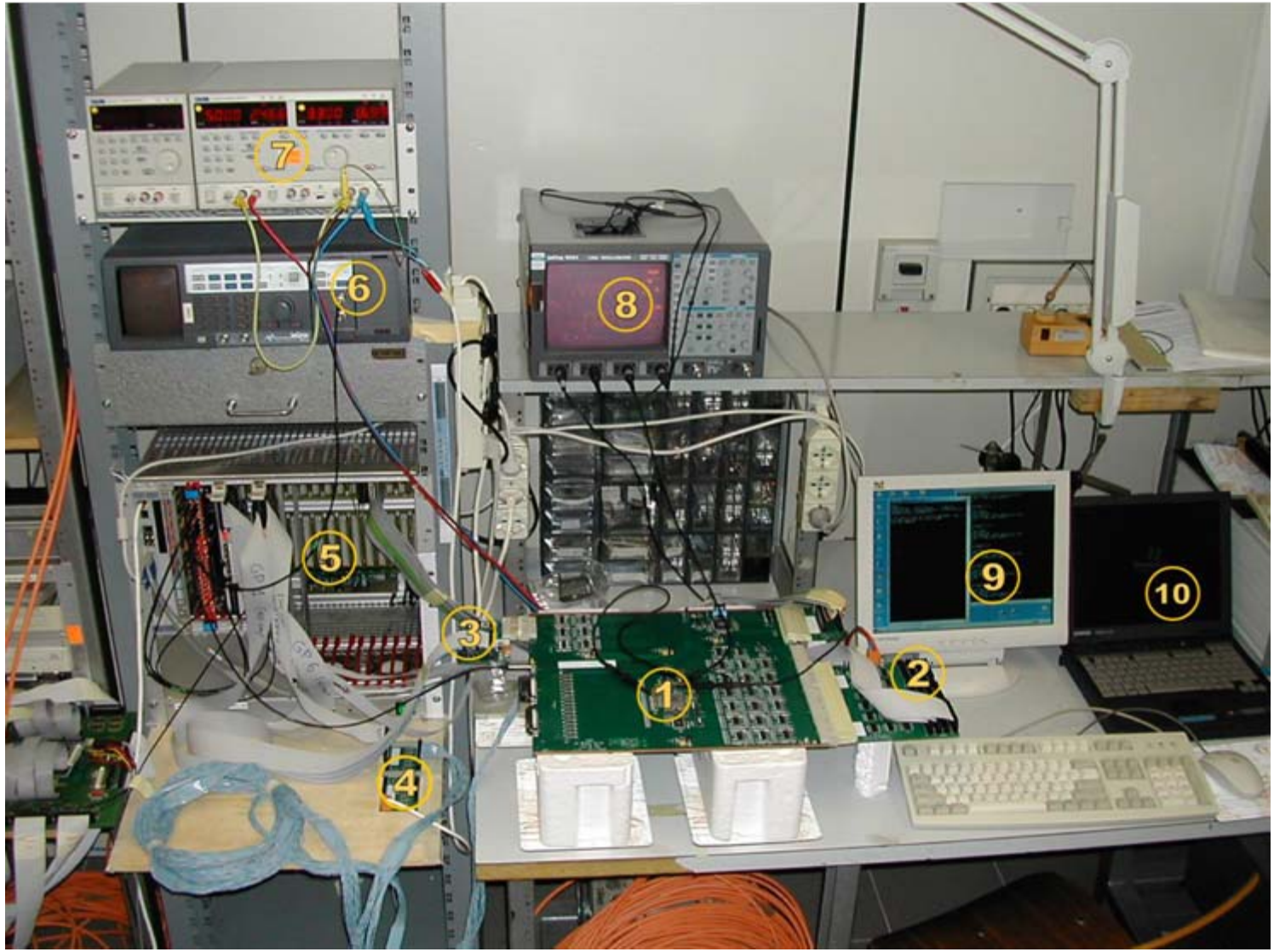
Hybrid sorting: sequential usage of a (simpler) parallel sorting block



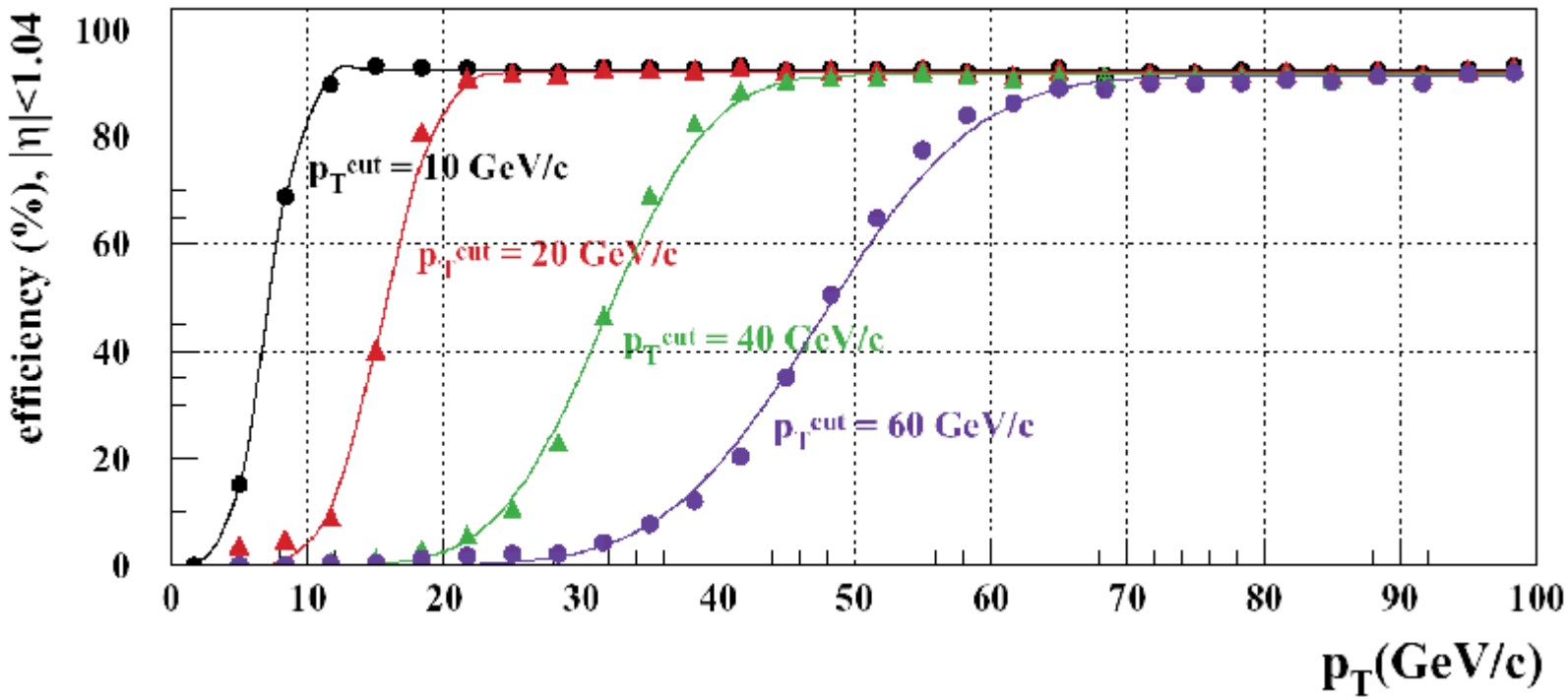
# Sector Collector Block Scheme



# Wedge Sorter stand alone test setup



# Turn-on curves for several Pt cuts



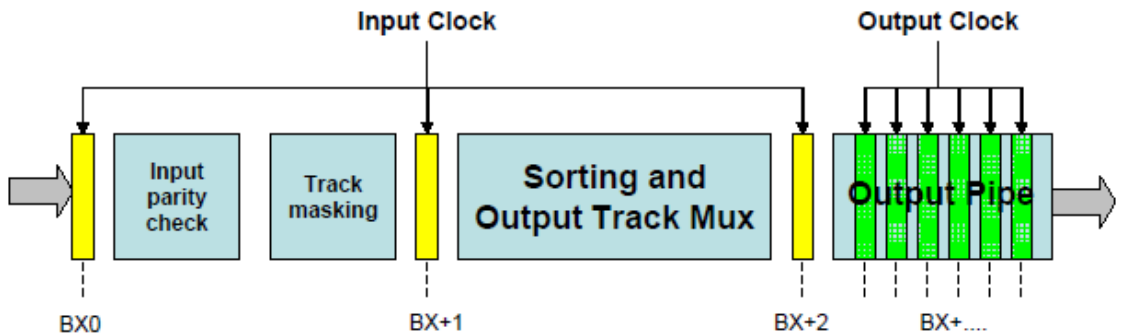
# Sector Collector – ProAsic firmware designs

Motherboard Controller

- VME interface
- Power control and monitoring of the RX- and TX- mezzanines
- Adjustment and monitoring of 8 different clock domains (4xRX, 1xTX, 1xDAQ, 2xinternal)
- Data quality is continuosly checked and reported to slow control
- Link state is monitored
- Spying of trigger data with several trigger sources
- 5 independent sector trigger outputs as logic of minicrate auto-triggers
- Optical transmission control (link resynchronization, status)

LVDS Receiver

- Input links status monitoring
- Data parity checks
- Sorting of track segments
- Output configurable pipeline for alignment with the other LVDS-RX of the sector



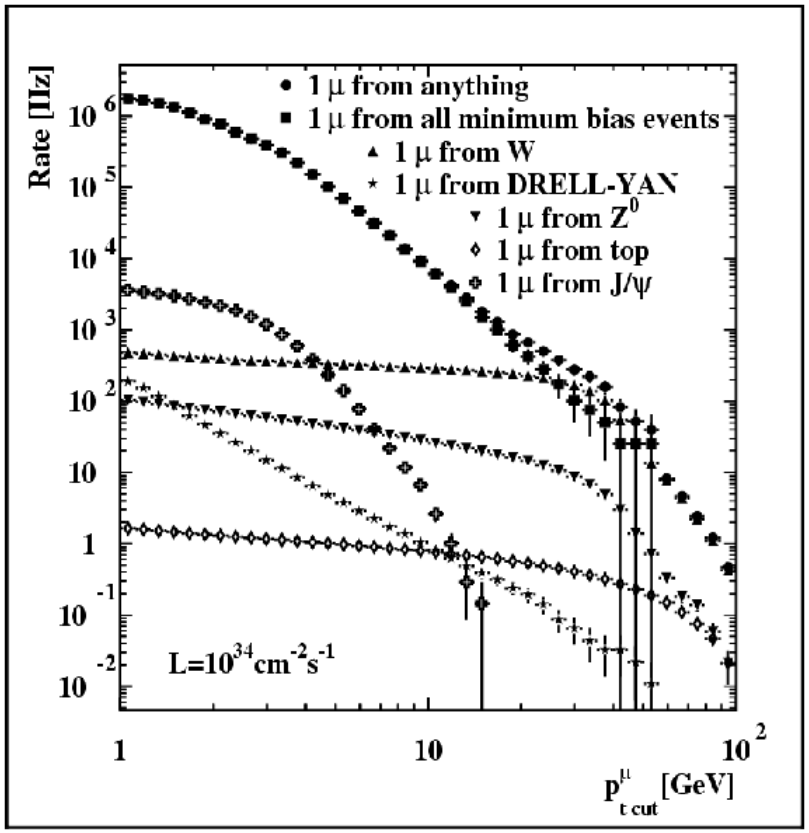
# Bit error rates from tests

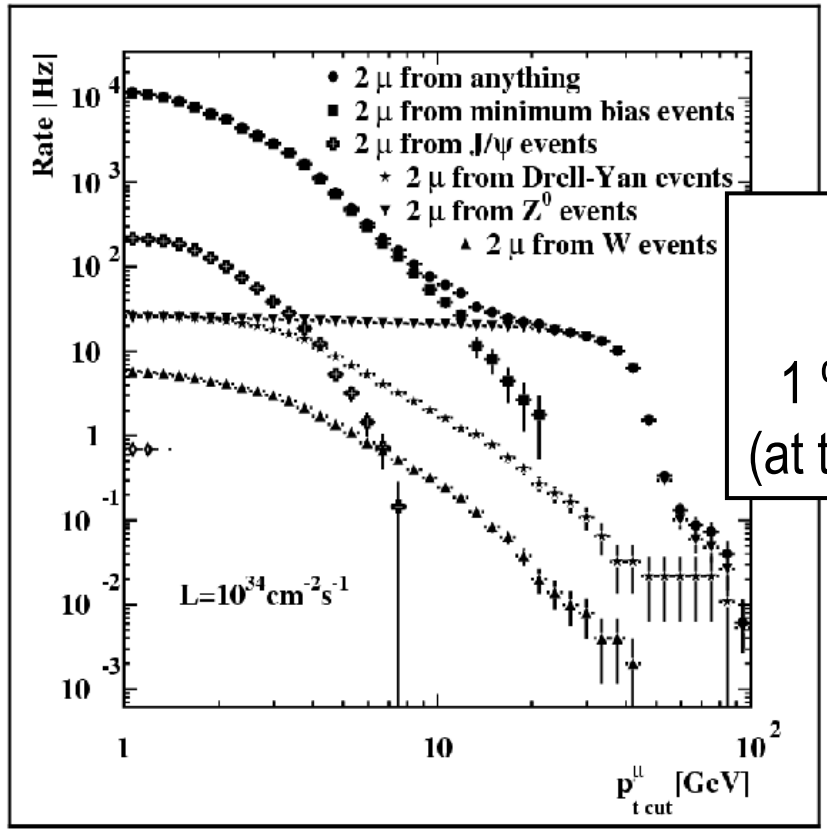
Binomial distribution, with large N (number of patterns) and no errors detected:

$$ER = - \ln(1-CL)/N$$

| | |
|---|---|
| Cable transmission tests | BER < $2\ 10^{-12}$ |
| Prototype boards tests | BER < $2\ 10^{-9}$ |
| Production boards tests | BER < $2\ 10^{-6}$ |

# Expected muon rates




di-μ rate
≈
1 % single-μ rate
(at the same $p_T$-cut)

Interest in dimuon trigger:

- Physics channels with dimuons in final state
- Several processes generate muons near in space

$H \rightarrow ZZ^{(*)} \rightarrow 4\,l$

$H \rightarrow WW \rightarrow l\,\nu\,l\,\nu$

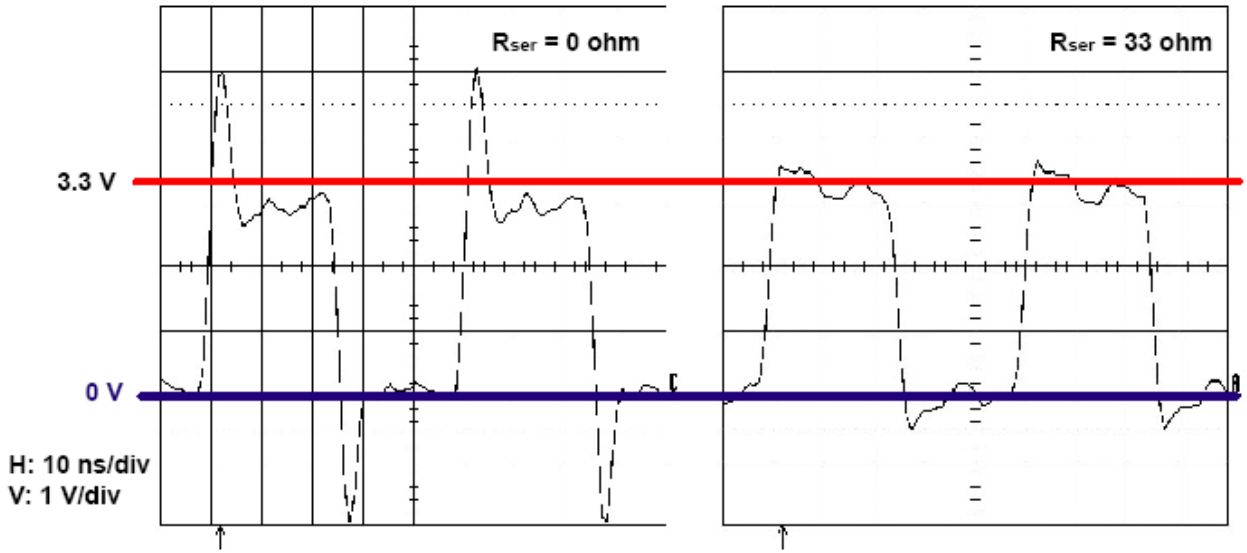
$H,\ A,\ h \rightarrow \mu\mu$

…

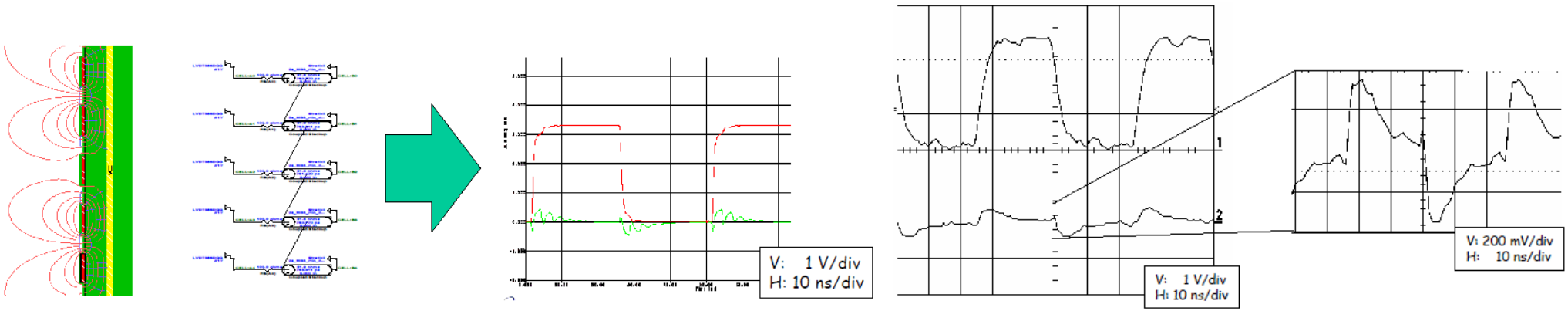
# Signal transmission issues

• On large boards, with long signal traces, signal transmission quality issues may generate sporadic bit errors

• Careful line termination removes signal reflections and improves transmission quality



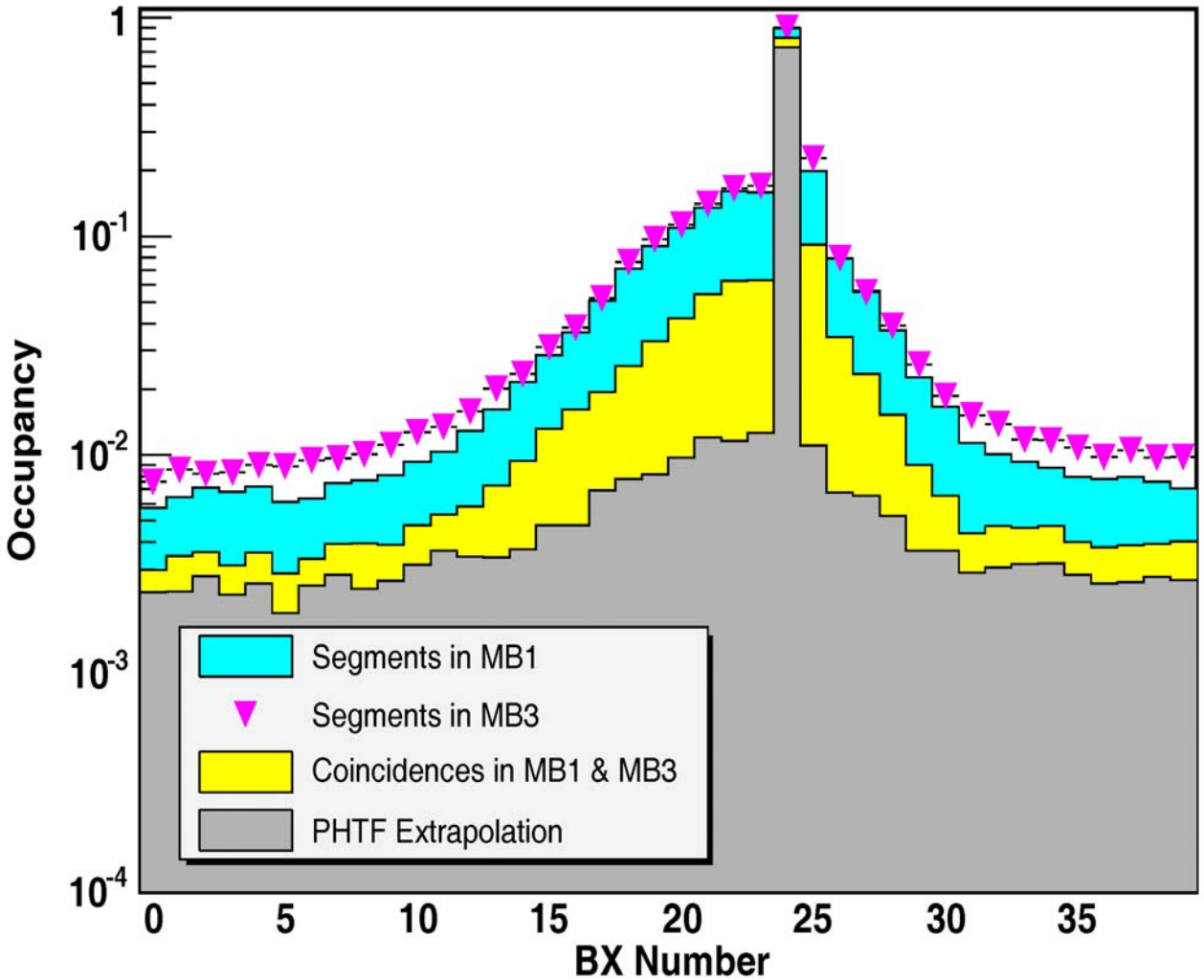

• Lines in long and dense busses can be subjected to cross-talk problems




Simulation at the design stage and real board measurement (Barrel Sorter)

# Test Beam – some result

Bunch crossing (BX) distribution of tracks found by DTTF




BX Identification:

- Out-of-time triggers suppressed at < 1%
- 99 % efficiency on high quality local trigger segments
- 94 % inclusive efficiency