Time-Of-Flight based muography using LGAD sensors

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IMB
IFCA Instituto de Física de Cantabria
ITAINNOVA INSTITUTO TECNOLÓGICO DE ARAGÓN

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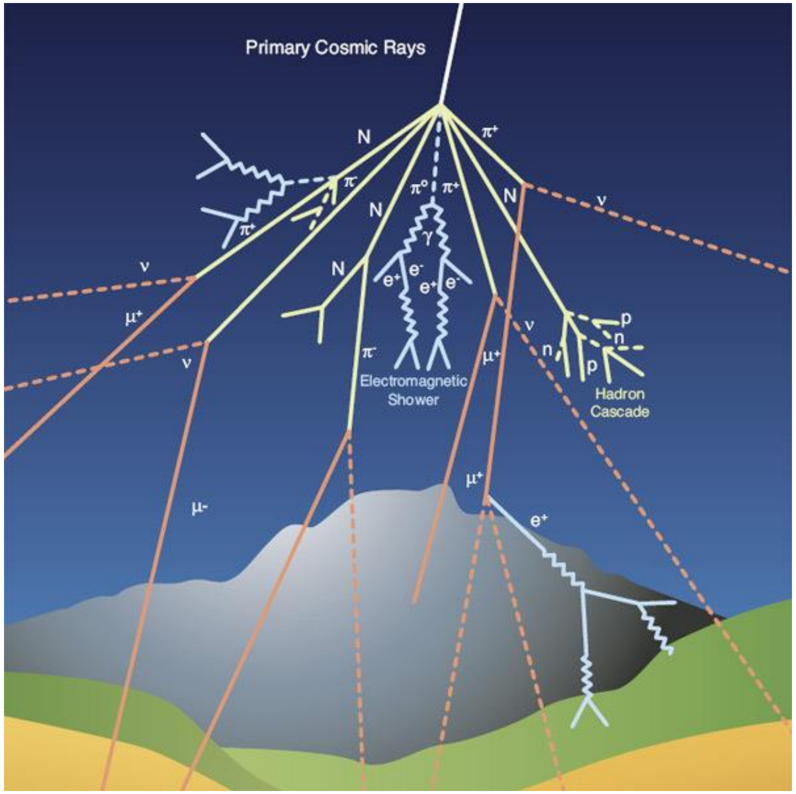
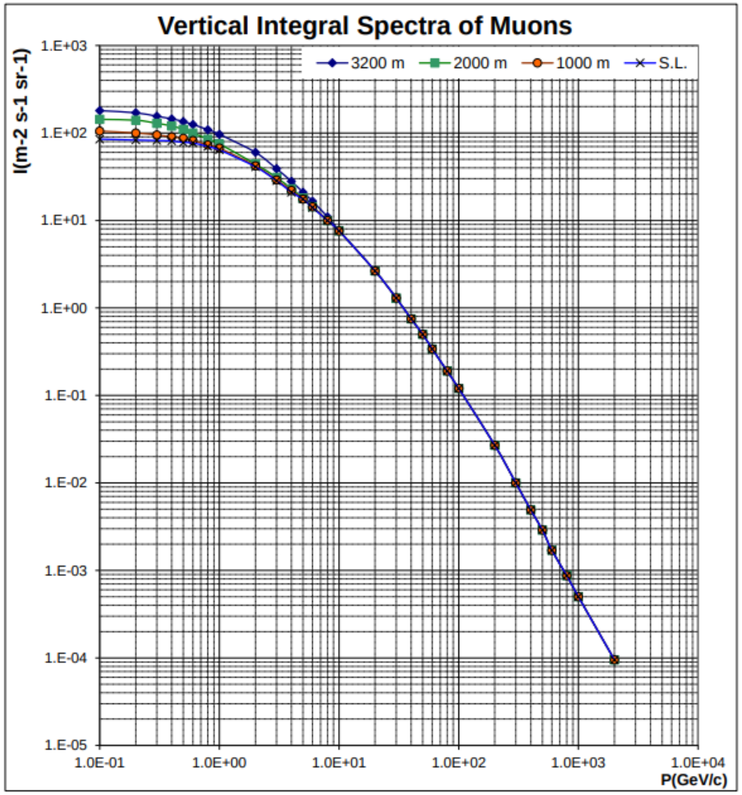
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

Cosmic Muons as Radiography source

- Cosmics rays hitting the outermost layers of the atmosphere produce muons (pion decays)
- Muon momentum spectrum peaks at low values (~1 GeV) falling quickly right after
  - Although cosmic rays and cosmic muons can be surprisingly energetic occasionally
- Angular distribution of muons follows approximately a cos2(θ) with the vertical
- Muon flux is approximately constant and equal to roughly 10000 muons per minute and m2



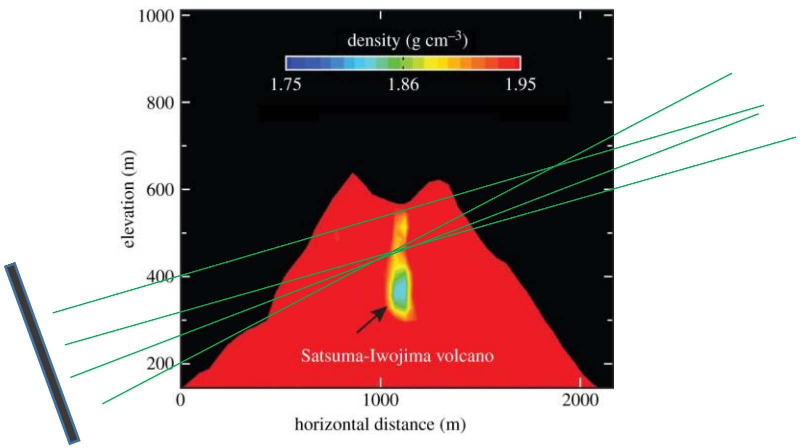


Muon Tomography

- Cosmics muons interact with matter mostly through energy loss and multiple scattering
- When crossing matter -> the denser the matter the more energy loss and angular deviation
- This opens the floor for using cosmic muons as a density testing tool

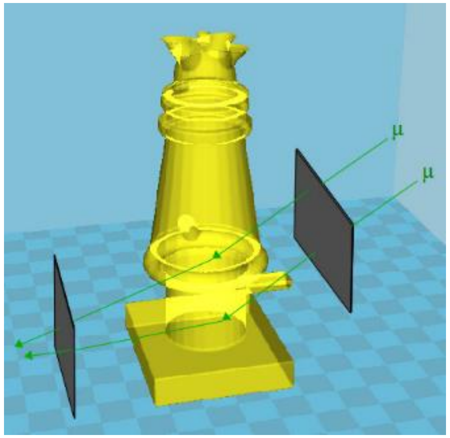
Absorption muon tomography

- Muon flux measured vs direction (attenuation)
- One single detector needed
- Need large object + long exposure times
- Typical applications:geology, volcanology, etc



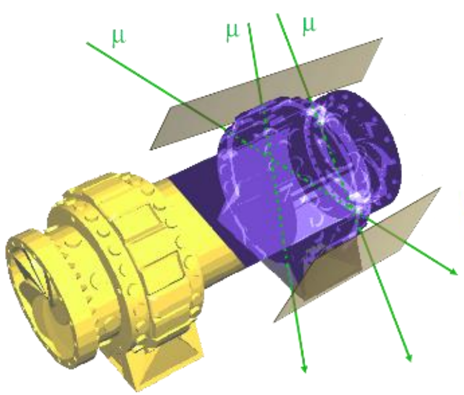
Scattering muon tomography

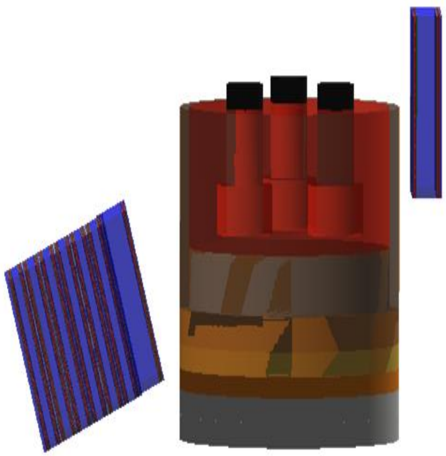
- Muon angular deviation (scattering)
- Two detectors needed
- Small-medium size objects + short exposure times
- Typical applications: border security, nuclear, etc

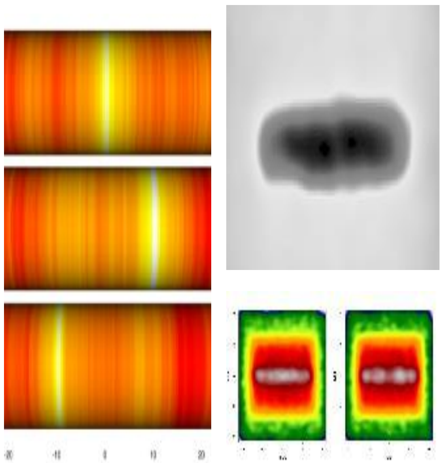


Muon Tomography in the industry

- Idea: use muon tomography as a Non-Destructive Testing (NDT) technique in the industry
  - Preventive maintenance of equipment (estimation of the degratation)
  - Quality control of the production process (measurement of liquid interfaces, tolerances, etc)
  - Risk assesement and evaluation (continuos monitoring of structural integrity)
- Muography has some unique properties than can be very useful for these applications
  - Large power of penetration (no problema to deal with several meters of steel)
  - No need to physically “touch” the object -> can be applied to equipment in production



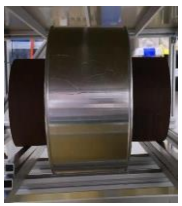


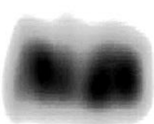


Muography in the industry: a few examples

Pipe corrosion

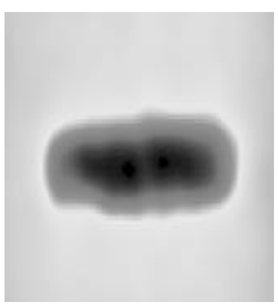
Measure of the wear: 1mm resolution
1 min exposure





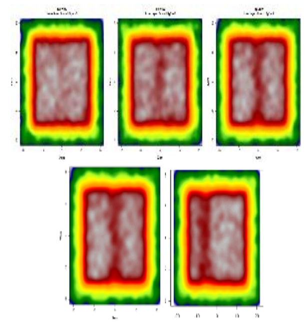
Cracks in **concrete**

Measure of the crack size:
2mm resolution
10 min exposure time



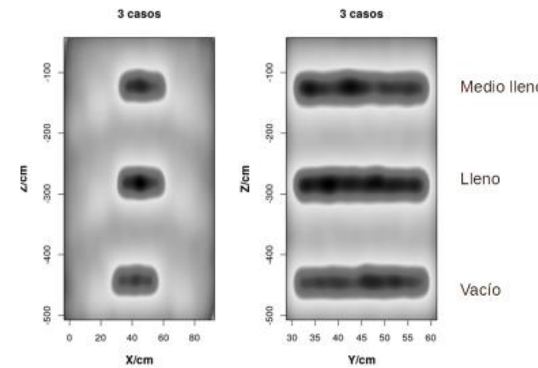
Tailings

$0.2 g \cdot cm^{-3}$ density loss detection



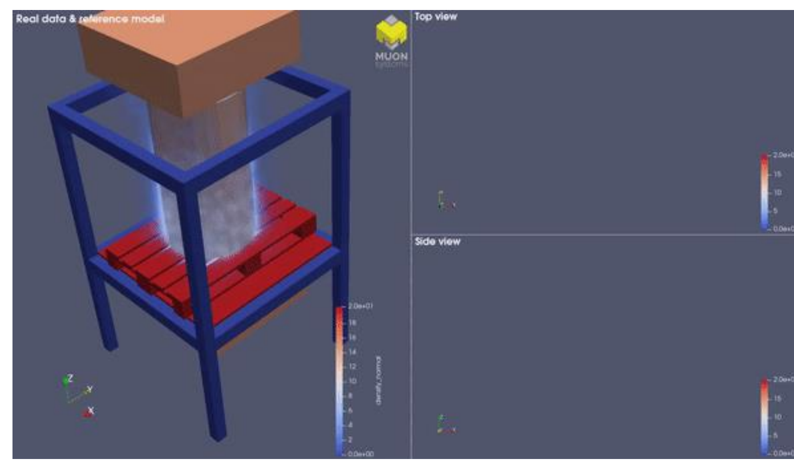
Prestressed concrete

grout level detection



Furnace hearth

Measure of the wall refractory:
1cm resolution
15 min exposure



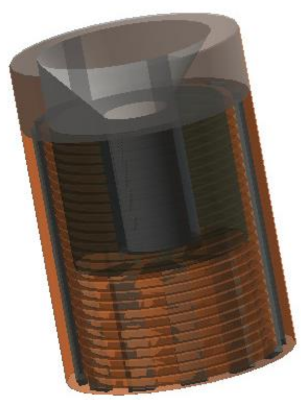
Real data 3D reconstruction of a silicon smelting furnace

The problem of the momentum

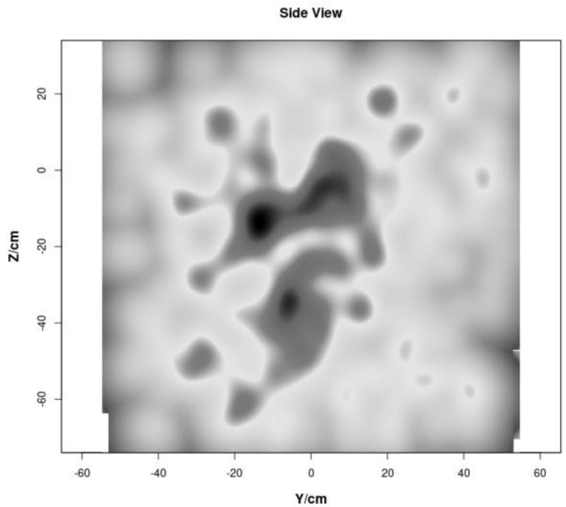
- Muon momentum operates with an intrinsic assumption in the reconstruction algorithms
  - Muon momentum is assumed to be known and equal to the most probable value
- The momentum plays an important role in Molière's scattering formula

$$\theta_0 = \frac{13.6}{\boxed{\beta c p}} z\sqrt{x/X_0}\left[1 + 0.038\ln(x/X_0)\right]$$

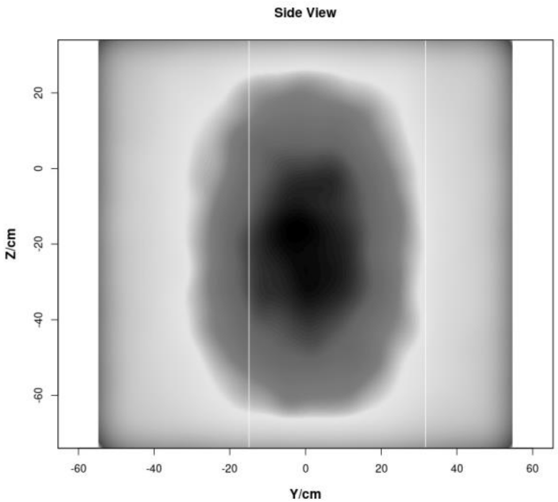
- There's entanglement between the momentum and the material radiation lenght
  - This produces a degradation of the resolution of the images
- On the other hand, measuring the muon momentum is not an easy task (in a cost-effective manner)



Voltaic Arc furnace



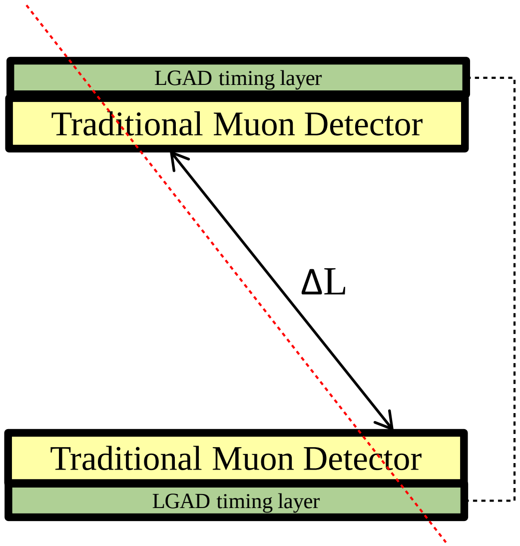
No momentum



10% momentum resolution

Time-Of-Flight momentum measurement

- Muon momentum can be estimated directly through the Time-Of-Flight of the muon
  - Need to estimate the muon time at the upstream and downstream detectors



$\Delta T = T2 - T1 \longrightarrow \beta = \frac{1}{c}\frac{\Delta L}{\Delta T} \longrightarrow p = m_{muon}\frac{\beta}{\sqrt{1-\beta^2}}$

Time resolution ~ 50ps and ΔL~ 1m → momentum resolution ~ 10-30% for low momentum muons

- Two layers of detectors with timing capabilities are needed in order to measure T2-T1
- **Low Gain Avalanche Diodes (LGADs) are a perfect match for this task**

LGADs as timing detectors in CMS

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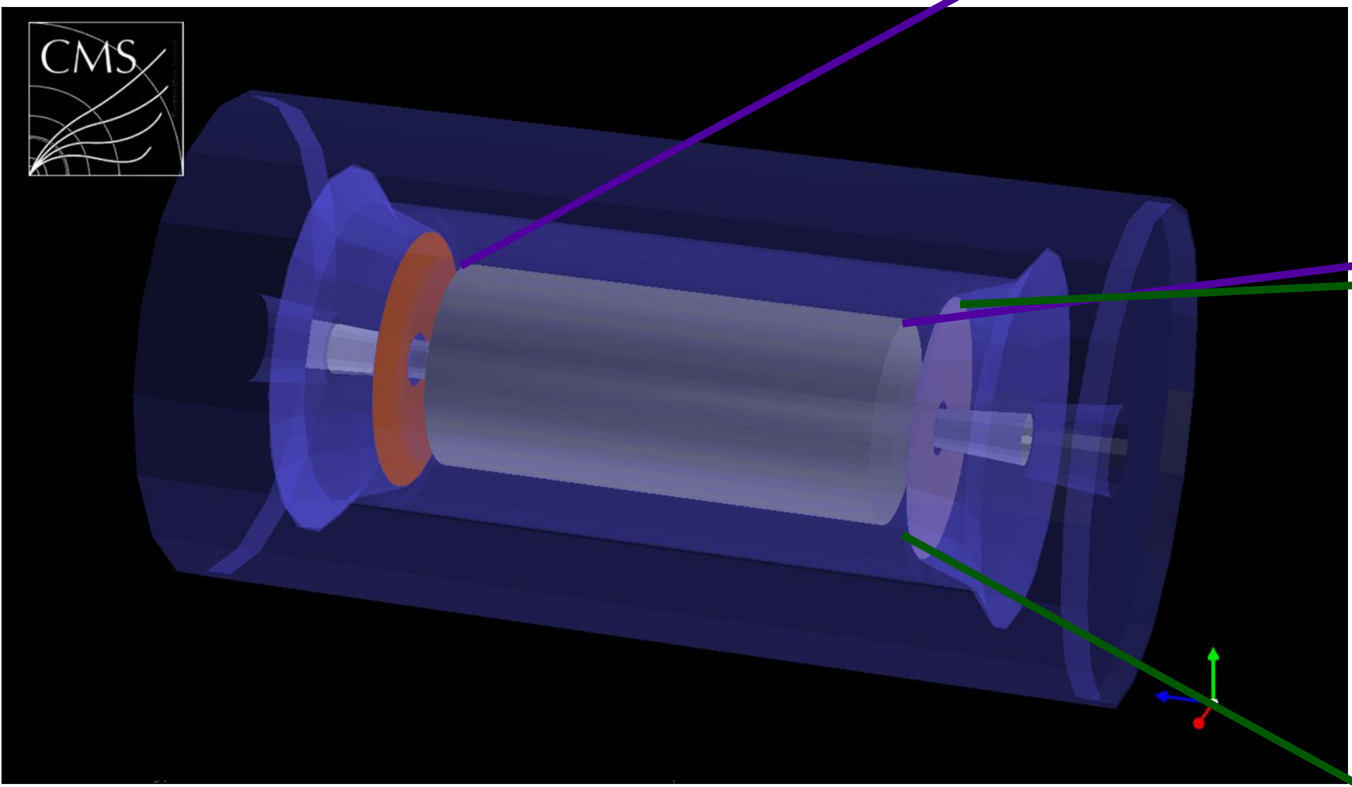
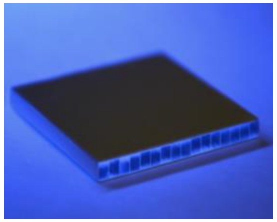
- The MIPs Timing Detector (MTD) is part of the Phase-2 upgrade Project in CMS
  - Provide time measurement of charged particles with 30-40 ps resolution
  - Endcap Timing Layer (ETL) using LGAD technology
  - Large involvement from CNM, IFCA and ITAINNOVA



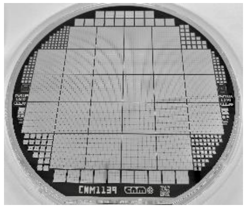
BTL: LYSO bars + SiPM read-out

- TK/ECAL interface ~ 45 mm thick
- |η|<1.45 and p_T > 0.7 GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL:Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- 1.6 < |η| < 3.0
- Active area ~ 14 m^2; 8.5M channels
- Fluence at 3 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2



The 4D-TOMULGAD project

- Target: build a muography demonstrator with Time-Of-Flight momentum measurement capabilities

PDC2021-121718: 2 years project

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Optimization and fabrication of LGAD sensors

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Integration, validation and 4D muon image reconstruction

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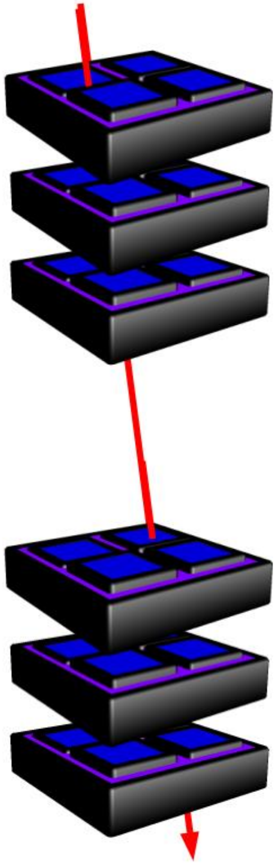
Distributed Clock network and power distribution system



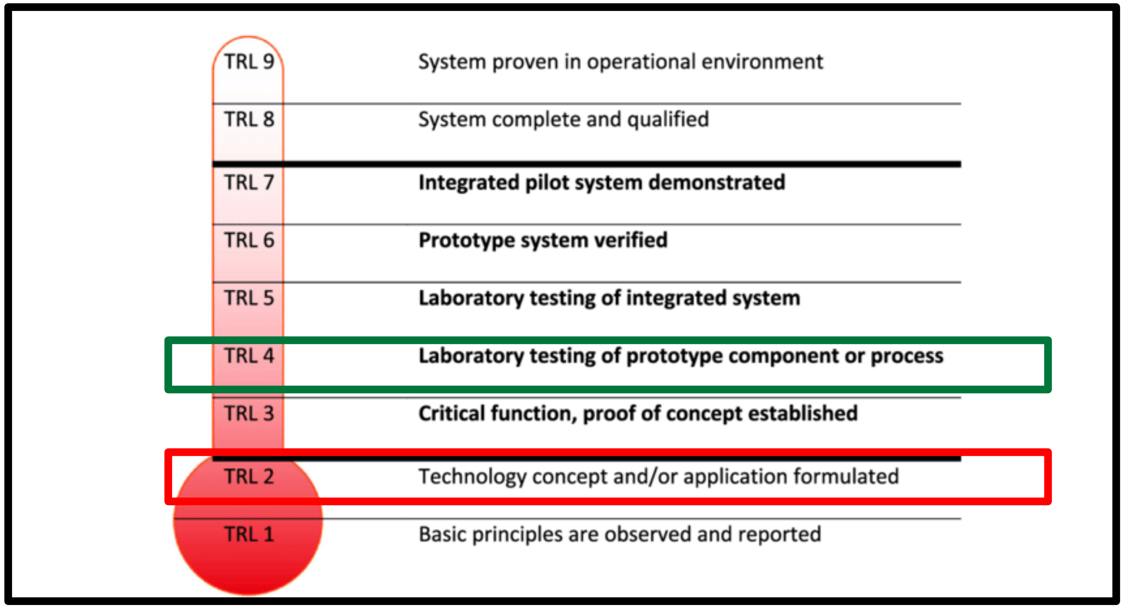
Stakeholders

MUON systems

sidenor

Ferroglobe

TOMULGAD goals and status



GOAL:

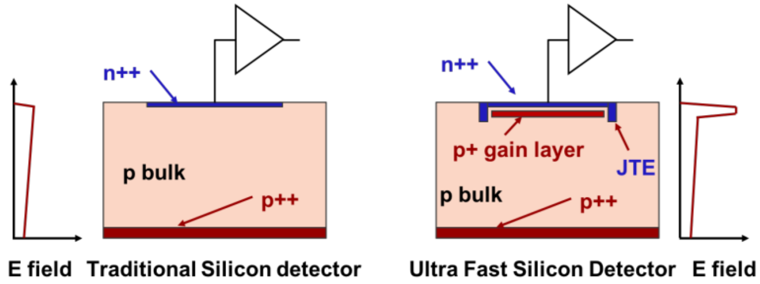
Small-area technological demonstrator and experimental assessment of the feasibility of a large scale muon tomograph

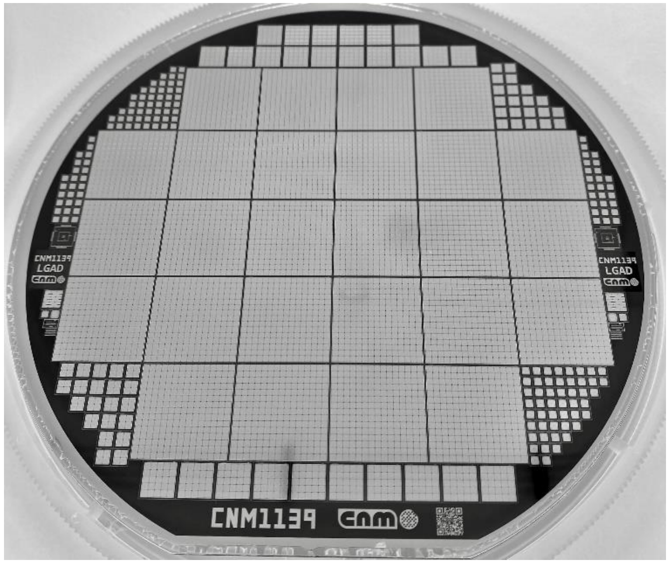
STATUS:

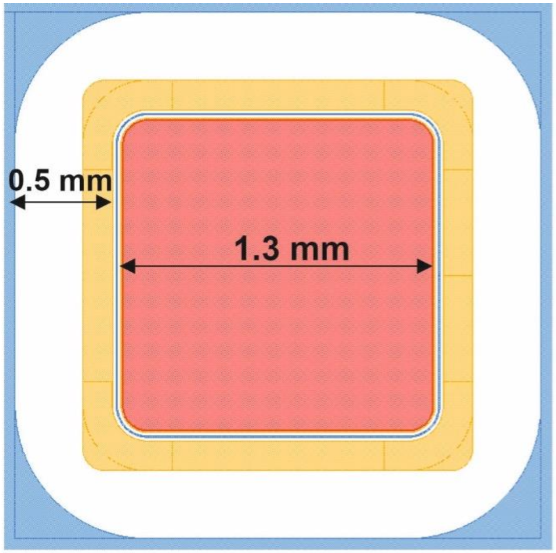
- Manufacturing and characterization LGAD sensors for the technological demonstrator
- Integration of a small-area technological demonstrator with full capabilities
  - Sensors and readout electronics (large delays, first testbeams taking place now)
  - Reconstruction and simulation software
  - Powering and clock distribution system
  - DAQ and final integration (need readout electronics)
- Development of a high-resolution Deep Learning reconstruction algorithm using timing information

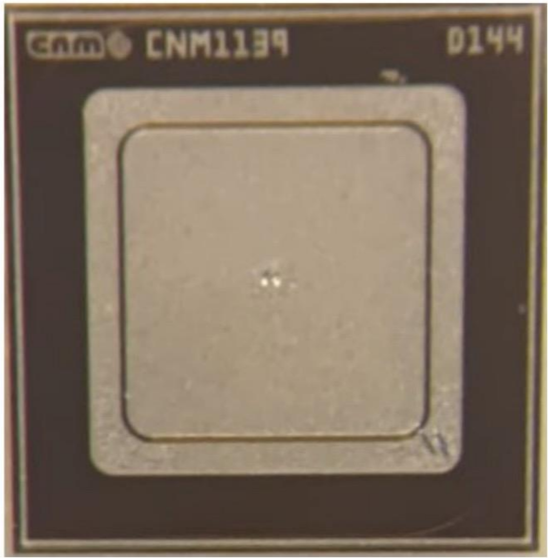
Low-Gain Avalanche Diodes at CNM

- Traditional silicon detectors with extra multiplication layer and gain in the range ~ 10 – 20
- Relatively large sensors 21.2 x 21.2 mm^2
- Thickness of 300 µm (50 µm depletion region)
- Pads of 1.3 x 1.3 mm^2 in 16x16 matrix fashion
- Excellent timing capabilities of ~ 50 ps
    - Time resolution mainly dependent on jitter and time-walk
- Readout using dedicated ASIC (ETROC2): versión 2 curently being tested in test beams









LGAD characterization

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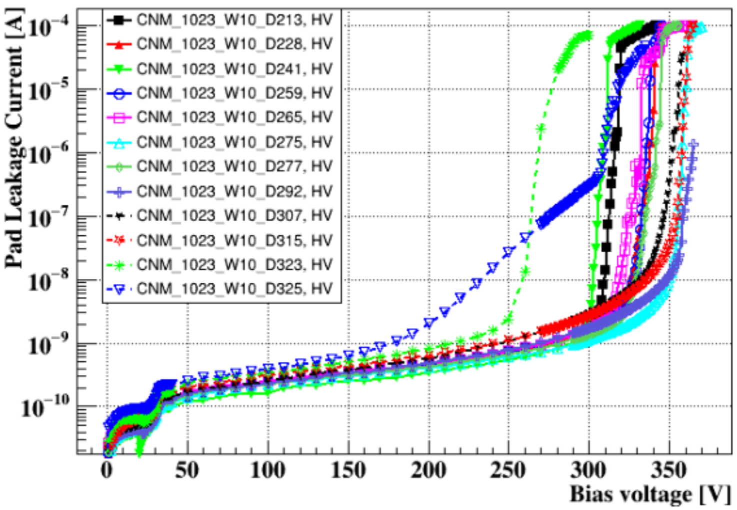
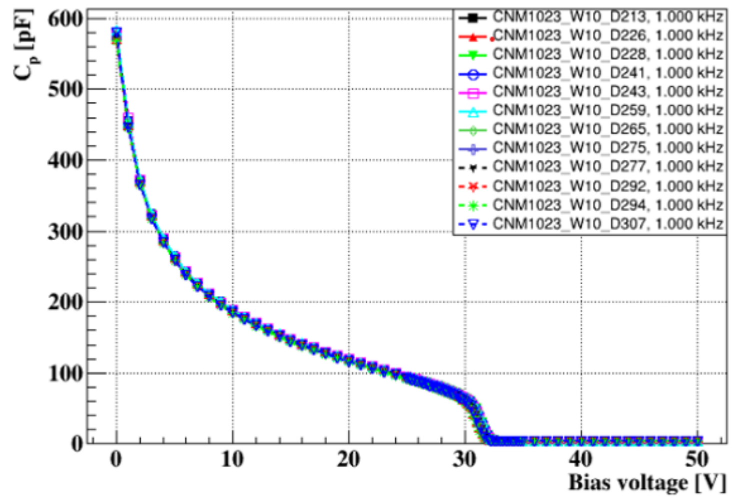
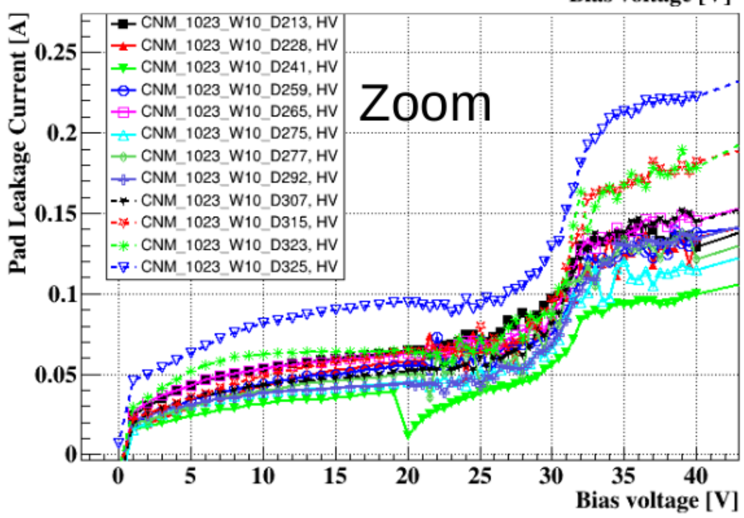
- LGAD sensors extensively tested and characterized through different sensor production campaigns

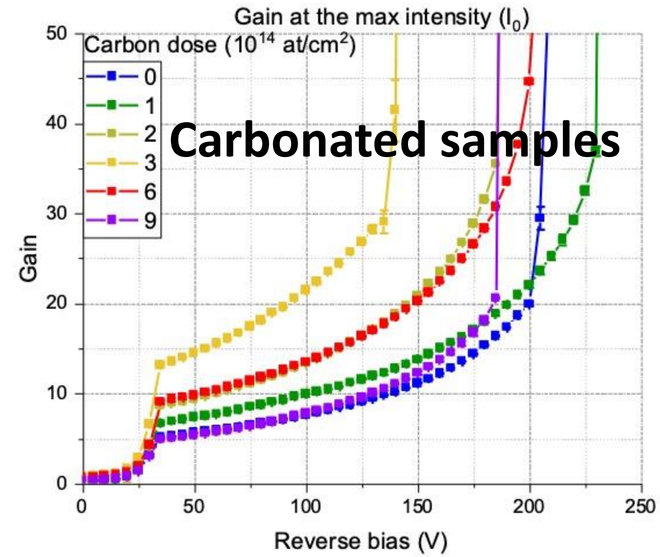
Standard, CNM, RT



Standard, CNM, RT







Simulation software and reconstruction

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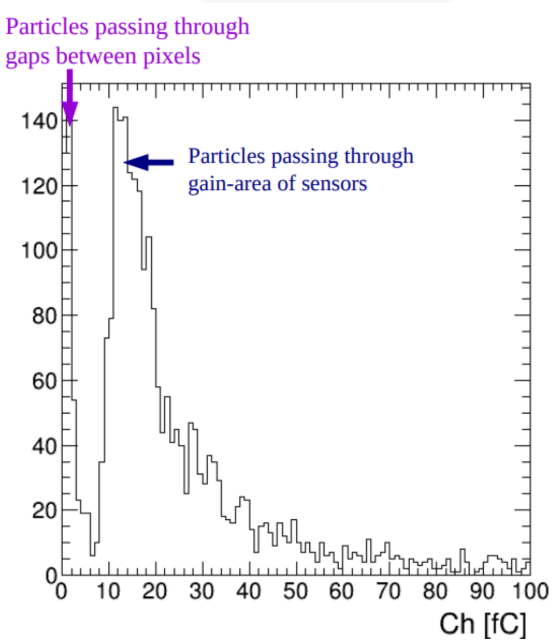
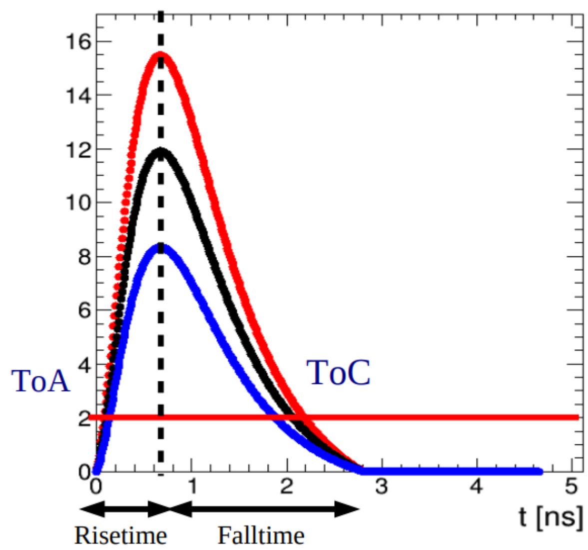
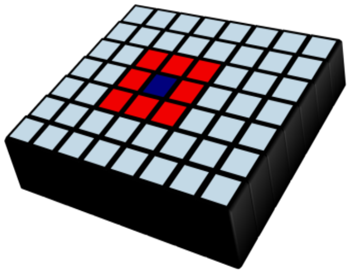
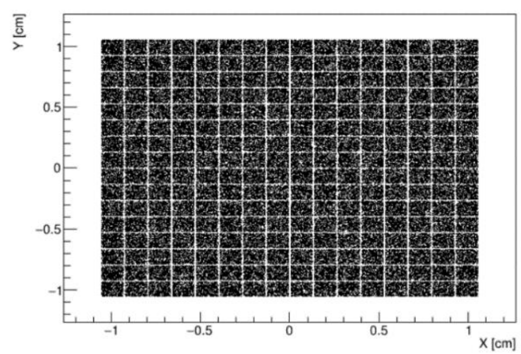
- A full GEANT4 model of the telescope has been made with 4 LGAD sensors per layer
  - Final geometry still under optimization waiting for final performance numbers
- Full simulation setup deployed including detailed digitization model with timing resolution
  - Multipad 16x16 structure of LGADs implemented logically in the digitization
  - Deposited energy from GEANT4 is converted into charge and multiplied by the gain
  - Signal shape scaled by the charge to estimate the Time-Of-Arrival and Time-Over-Threshold
  - Possibility to randomly simulate spurious hits and cross-talk among sensors



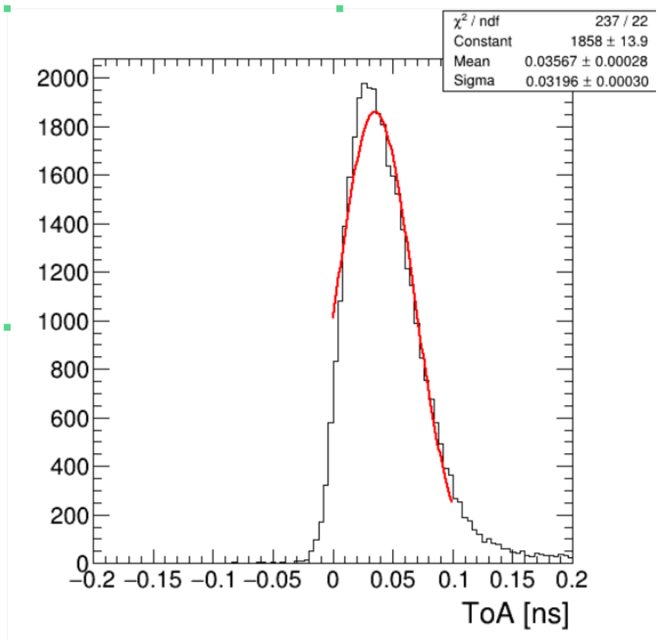


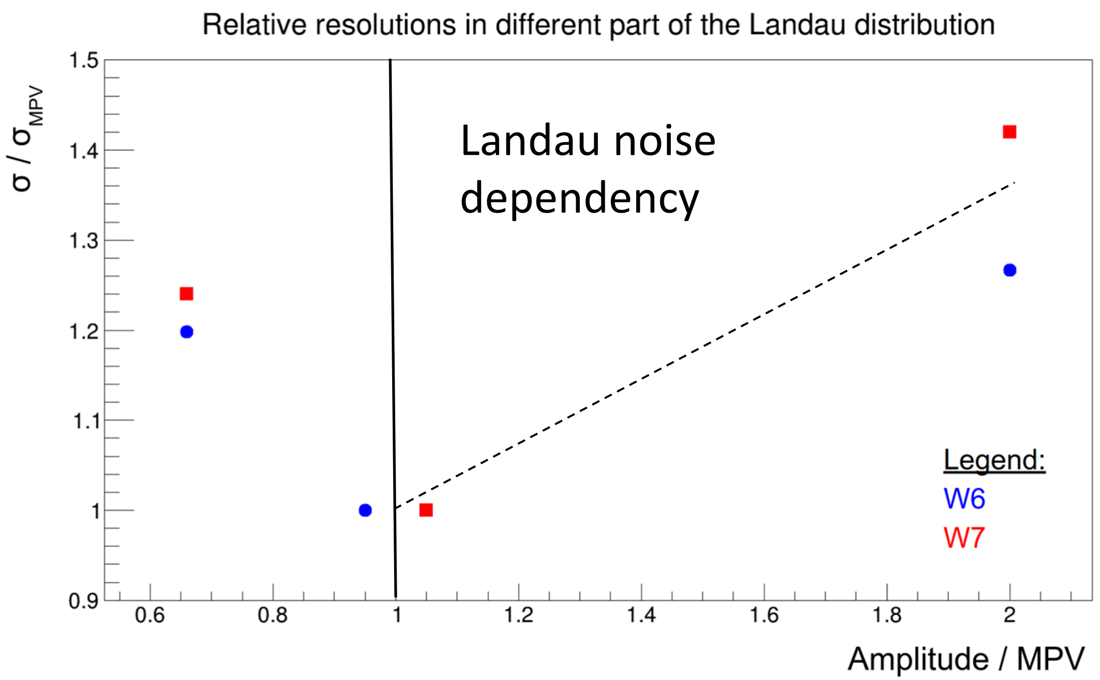




Timing resolution model in digitization

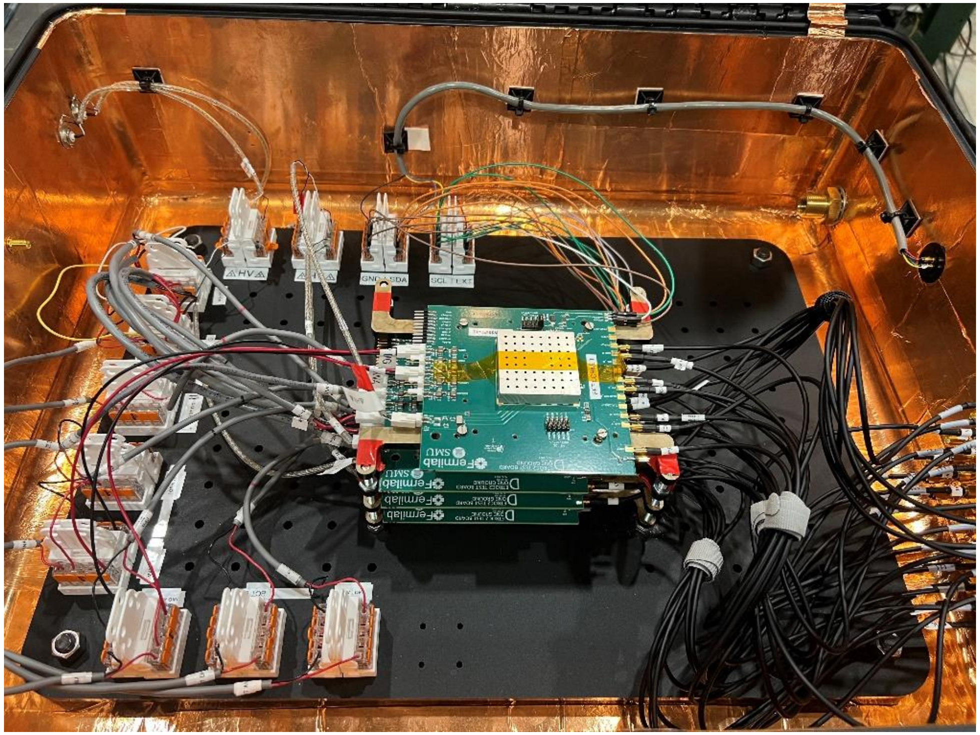
- Time resolution components are modeled in different ways
  - Landau fluctuations on the deposited energy are accounted for automatically
  - The jitter is gain-dependent and simulated as a gaussian smearing
  - The TDC and the distorsion are simulated as gaussian smearing with constant sigma
  - Landau noise simulated as a gaussian smearing with sigma dependent on muon energy
- Time-walk corrections implemented right after digitization process

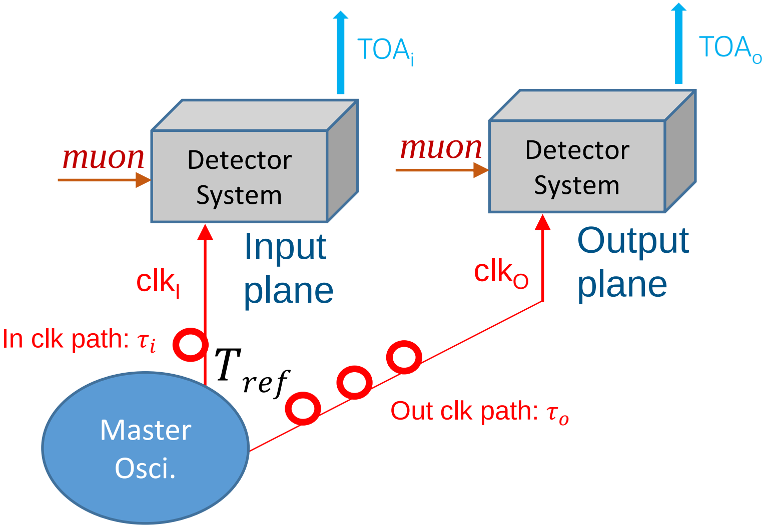




Clock distribution and sync for 4D detectors

- Need to measure time of arrival of distant 4D detector planes with respect to a clock
- Depending on the application or the setup there might be different clock paths
- Move from dedicated clocking technologies requiring calibration to self-calibrated technologies
- The White Rabbit Project originated for High Accuracy Profile under the IEEE 1588 standard
  - Ethernet-based technology for deterministic distribution of timing data





TOF computation in 4D detectors

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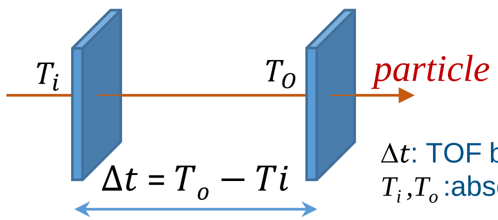
We want to compute:

Δt: *Time of Flight* (TOF)

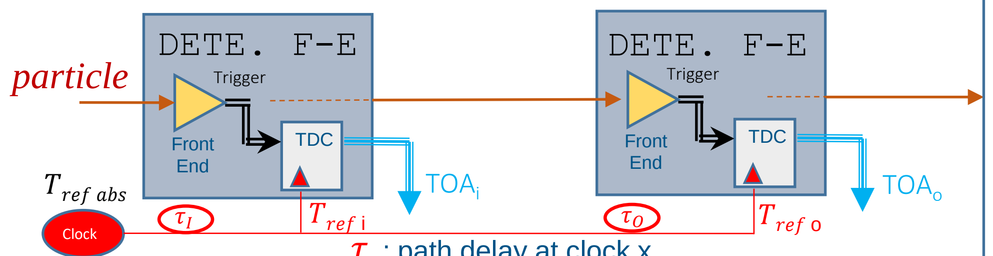


Δt: TOF between detector planes

T_i, T_o :absolute times

We measure:

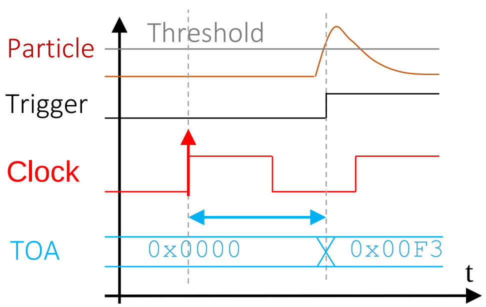
2x Time Of Arrival (TOA) w.r.t ref. clock



τ_x: path delay at clock x

$T_{ref\ x}$: local ref. clock at node x

We use a local reference clock $T_{ref\ x}$

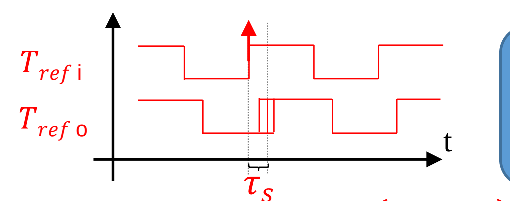


$$T_x = T_{ref\ x} + TOA_x$$

T_{ref} needs to be a common synchronized reference among all nodes

We need clean Clock distribution ensuring accuracy, precision and coping skew

Phase of the Ref clock at Detectors

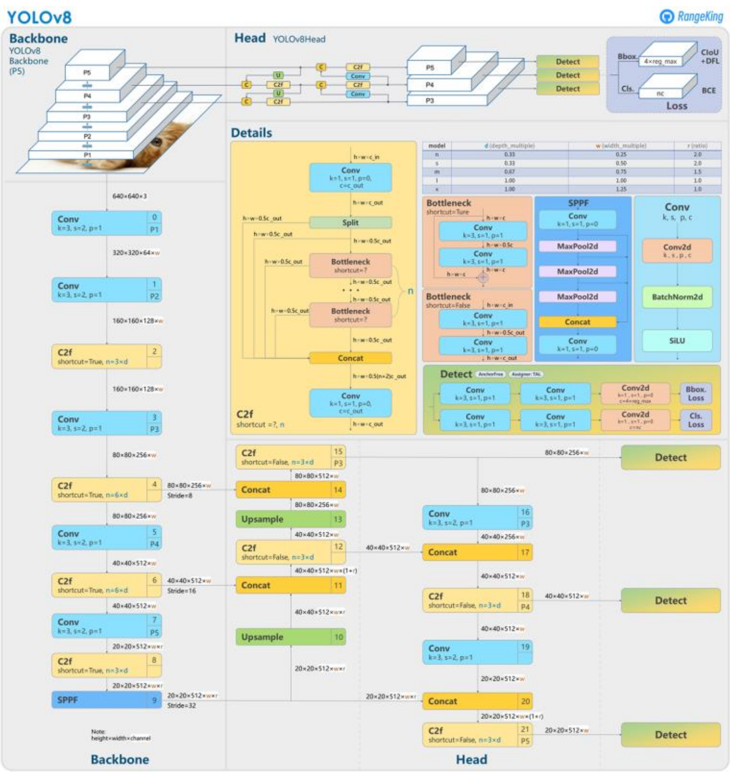


Clock Skew $\tau_s = (\tau_0 - \tau_i)$

IEEE 1588 standard – High Accuracy profile???

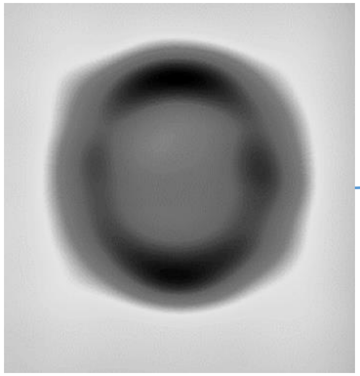
Muon imaging with 4D capabilities

- Classic muography algorithms adapted to consider timing in reconstruction
  - Point-Of-Closest Approach (POCA) algorithm with time modulation
  - Time Maximum-Likelihood Expectation Maximization (MLME) with modern minimization
- Development of automatic Detection + Segmentation based on artificial vision algorithms
  - Training of YOLO v8 with MLME muographic images with timing

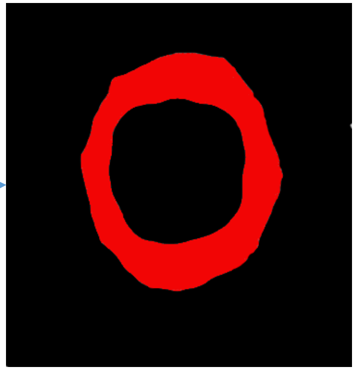


Example: transversal view of furnace

POCA with Timing



Furnace Wall mask



Semantic segmentation

Conclusions

- Muon tomography can be applied as an NDT technique of structural integrity in the industry
- The 4D-TOMUGAD Project is addressing the problema of the momentum measurement
  - Surely a game changer for many applications in the context of muon tomography
- The project aims at building a demonstrator (TRL4) but considering also scalability
- The project is now catching up with the readiness of the sensor readout electronics
- A successful outcome could motivate to build a large scale detector