Scintillation Detector for Muon Imaging System

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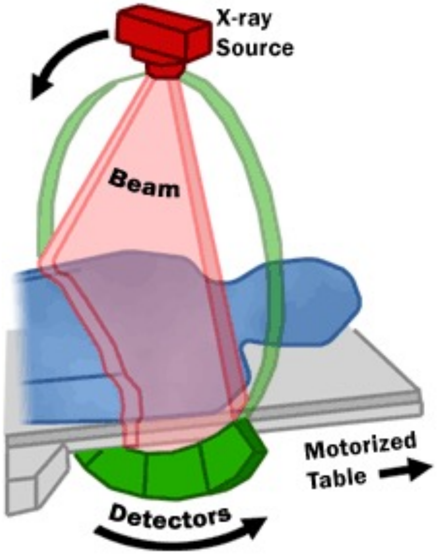
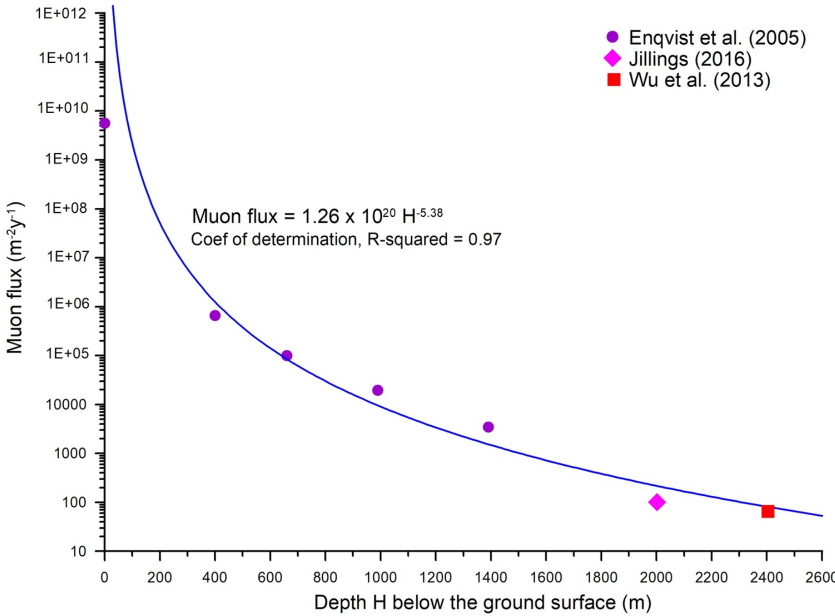
From X-ray to muon imaging





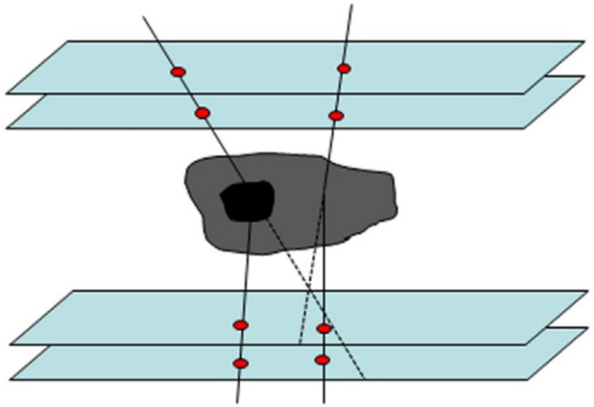
Muons flux below the ground surface

https://doi.org/10.1007/s00603-020-02199-9

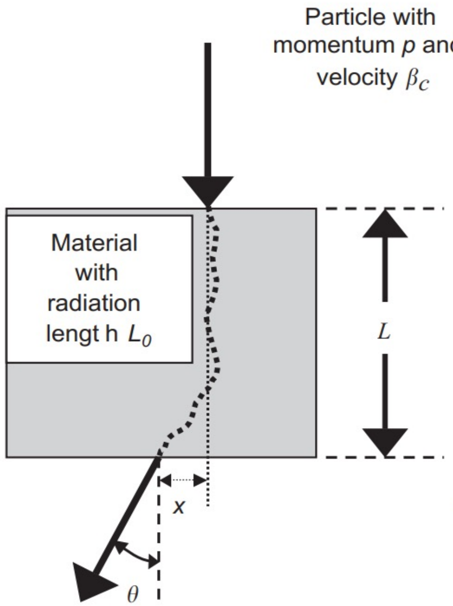
- Medical X-ray imaging:
  - Use X-ray photons as probe
  - Reconstruct X-ray absorption map in different tissues
- Muon imaging:
  - Use cosmic ray muons as probe, penetrating far deeper
    - High penetration
    - No extra radiation
  - Reconstruct muon absorption or **scattering**

Muon scattering tomography (MST)

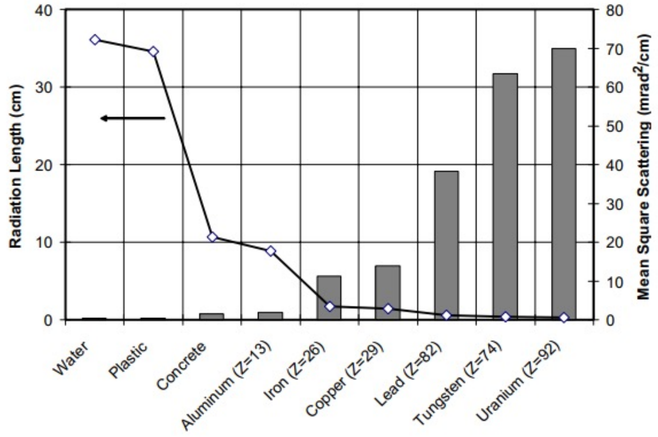
- Multiple Coulomb Scattering (MCS):
  - $\sigma_\theta \approx \frac{13.6\text{MeV}}{p}\sqrt{\frac{L}{L_0}}, \sigma_\theta^2 \propto \frac{1}{L_0} \propto Z$
- $p = 3\text{ GeV}, L = 1\text{ cm}$:
  - $\sigma_\theta \approx 0.7$ mrad for water, 8 mrad for Uranium
  - Distinguish high Z material
- Reconstruction algorithm:
  - Measure $\Delta\theta_x, \Delta\theta_y$, estimate $\hat{p}$, get point of closet approach (PoCA)
  - Assign signal S to PoCA voxel, 0 to other candidate voxels
  - Get 3D tomography image



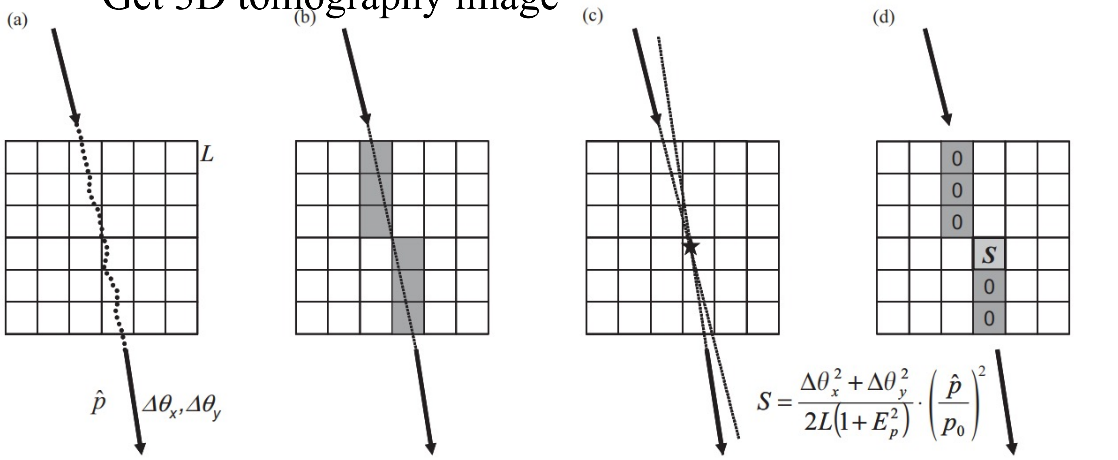
Detector for scattering imaging



MCS of muon passing



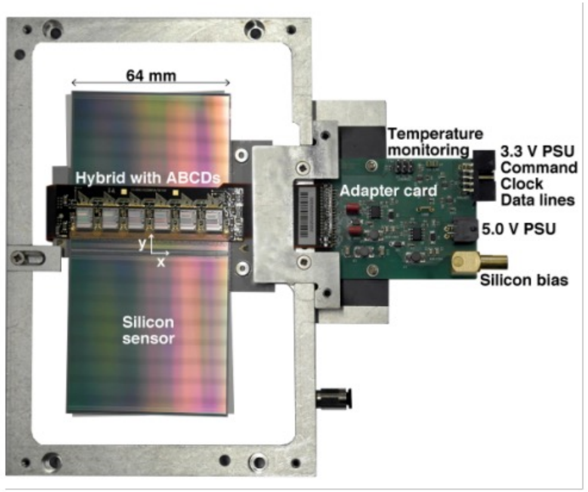
Radiation Length and mean square scattering per unit depth of 3 GeV muon



Scattered point can be deducted by measuring ingoing and outgoing tracks

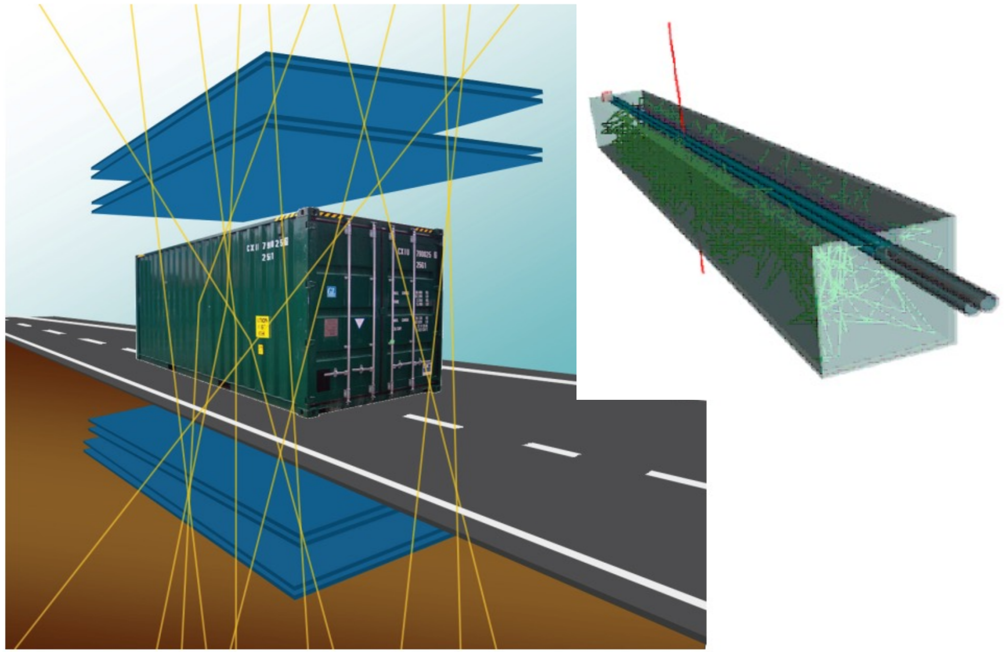
https://doi.org/10.1016/j.nima.2003.11.035

Detector used in muon tomography



ATLAS silicon muon tracker
pitch = 80μm

Micromegas developed by USTC



Muon Portal Project by INFN

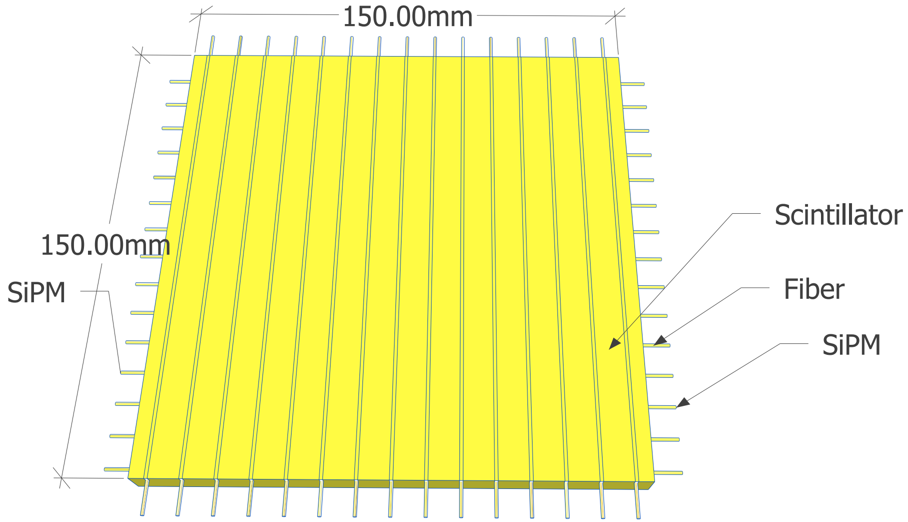
- Measuring ingoing & outgoing tracks
  - At least 4 layers 2-D position detector
  - Large detection area

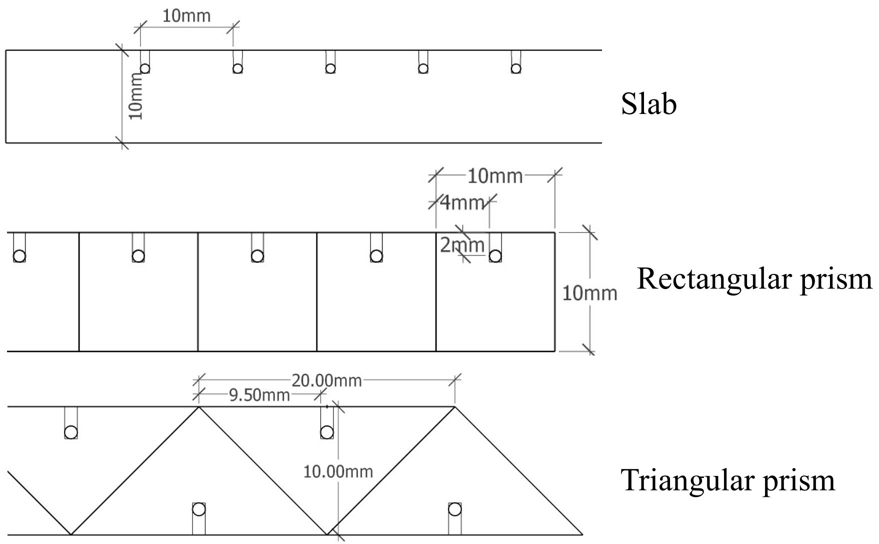
- Silicon tracker
  - Best performance: < 80 μm
  - Extremely high cost

- Gas detectors
  - Higher spatial resolution: ~ 100 μm
  - Need gas & HV supply system

- Scintillation detectors
  - Pitch ~ 10 mm, spatial resolution ~ 3 mm
  - Robust, lower cost, high efficiency, stable

PSD for muon tomography @ USTC



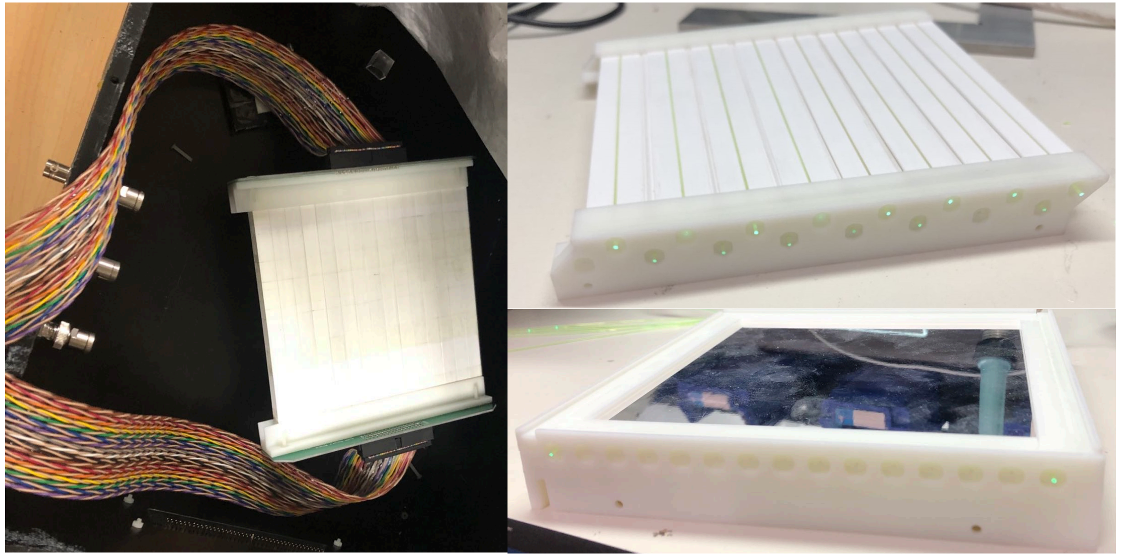


- Detector design:
  - Plastic scintillator
  - WLS fibers
  - Read out by SiPM
- Pitch: $p = 10$ mm
- Integrated slab
- Isolated prisms: rectangle, triangle

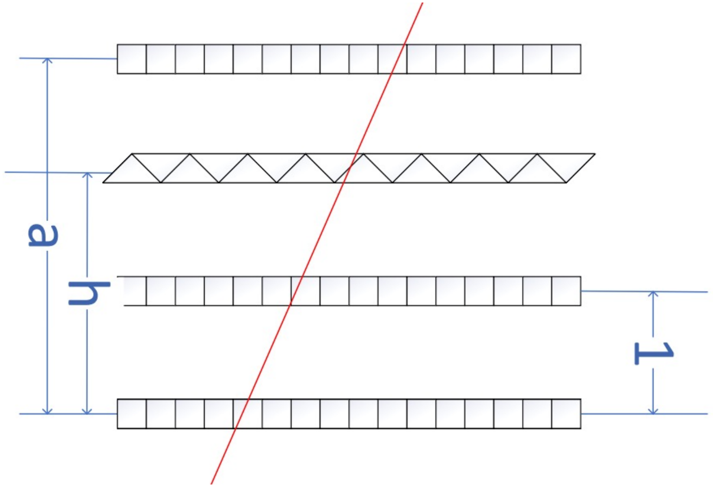
GEANT4 Simulation results for 3 prototype detectors

Detector structure	Simulated spatial resolution (mm)
Slab	5.3
Rectangle	2.9
Triangle	1.6

Performance of prototype detector



Detector assembling



Spatial resolution measurement

- Prototype detector:
  - Sensitive area: 15 cm×15 cm
  - Pitch: $p = 10$ mm
  - Thickness: 10 mm

Electronic board

- Electronic board:
  - CAEN® DT5702
  - Bias supply, signal shaping & discrimination, time & charge measurement

Comparison of simulation and measurement

Detector structure	Simulated spatial resolution (mm)	Measured spatial resolution (mm)
Slab	5.3	6.4
Rectangle	2.9	3.3
Triangle	1.6	1.7

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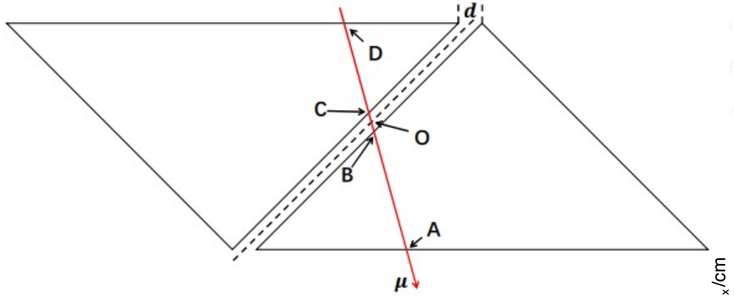
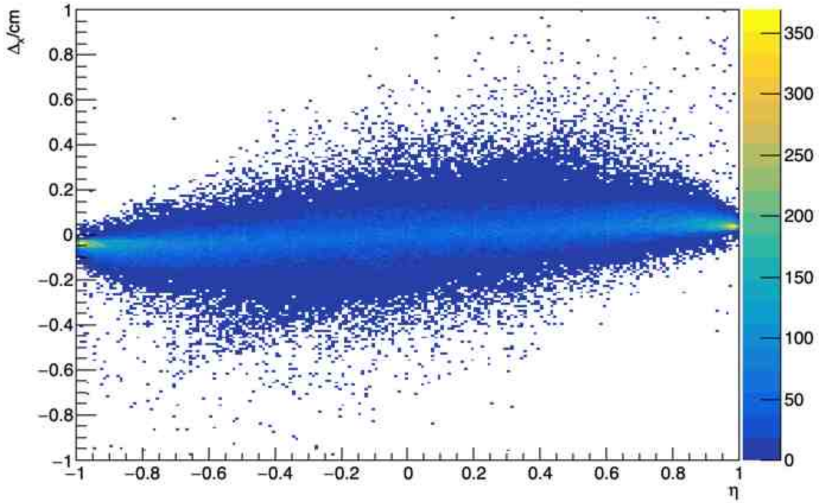
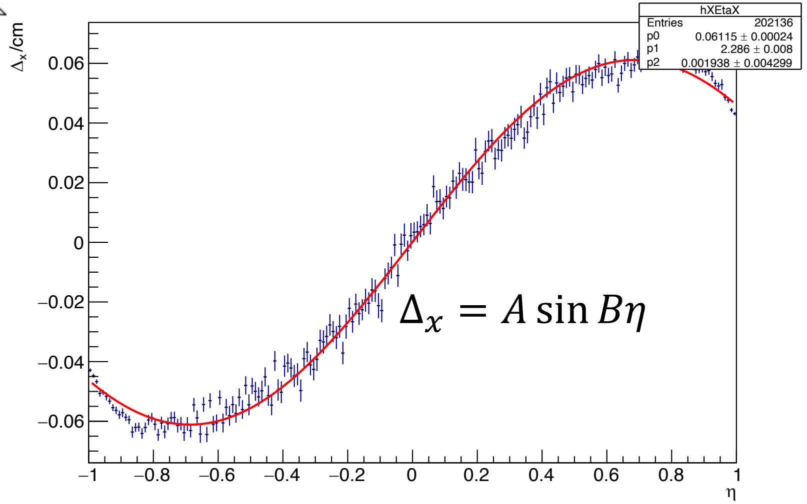
Precise correction for triangular prism



Air gap between 2 strips



Position residue Δ_x varies with charge distribution η



Residue can be fit with sine function

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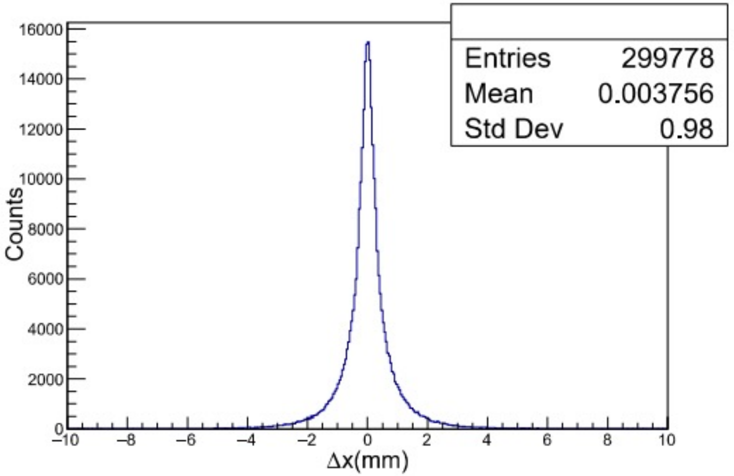
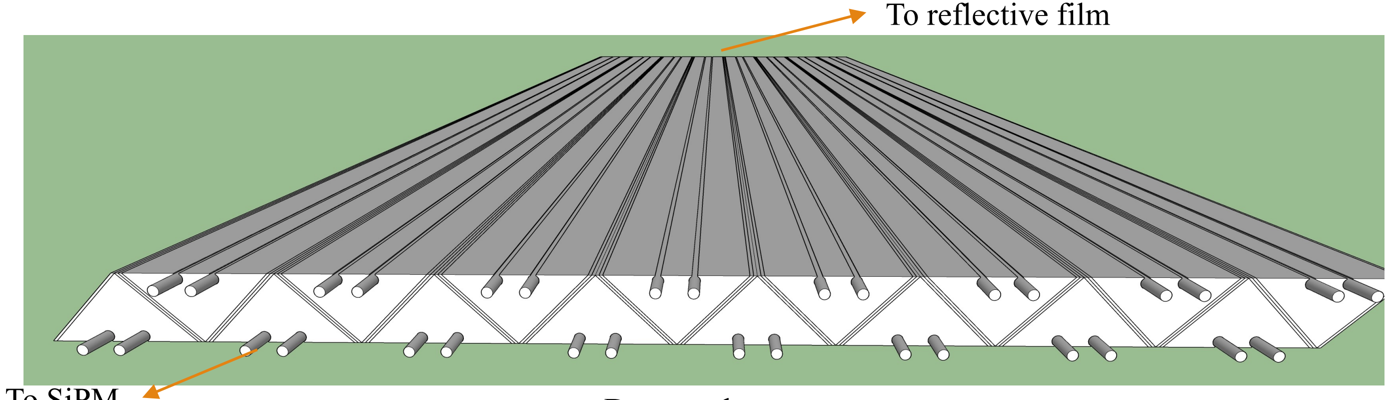


Spatial resolution after correction

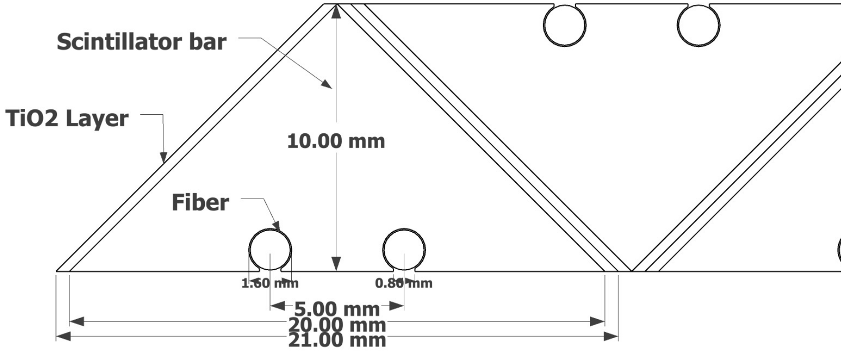
- Dead gap in detector:
  - Wrapping material
  - Energy distribution changes

- Correction:
  - $\Delta_x \equiv x_{real} - x_{calc}$
  - Measured: $\eta = \frac{Q_2 - Q_1}{Q_2 + Q_1}$
  - Subtract function $\Delta_x(\eta)$, got $\sigma_x = 1$ mm

Detector upgrade



Detector layout

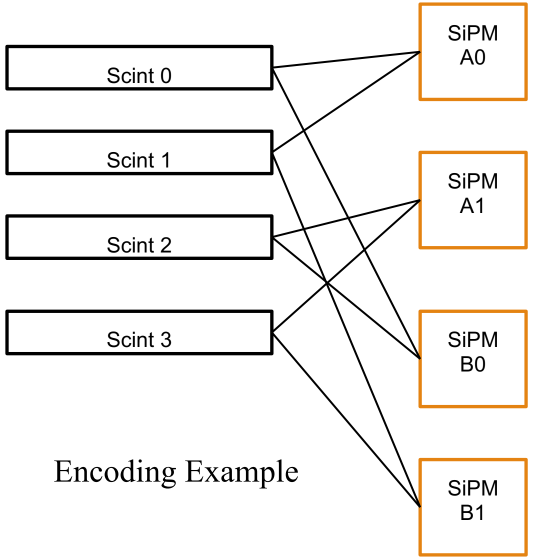


Cross section of a single strip

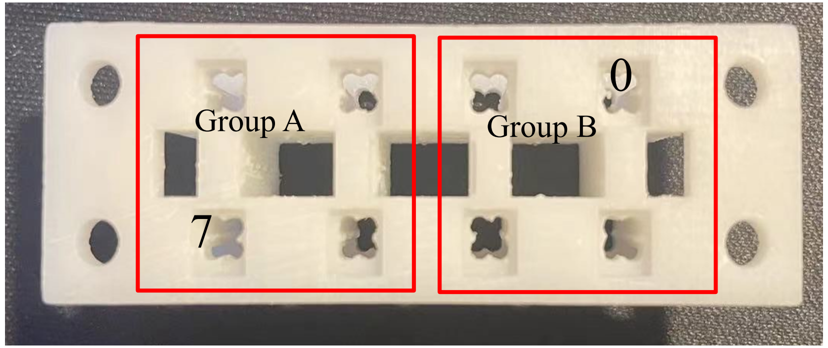
- Larger detection area:
  - Sensitive area: 50 cm×50 cm
  - Higher acceptance
  - Hard to shape & groove
- Better Spatial resolution
  - Adopt triangle cross section
- Better layout
  - Double fibers in one strip
  - Convenient for SiPM coincidence

- Improvement on photon collection:
  - Wider fiber ($d = 1.5$ mm)
  - High reflective coating:
    - Tyvek paper or TiO_2
  - Reflective 3M™ Enhanced Specular Reflector film (far end)

Fiber encoding



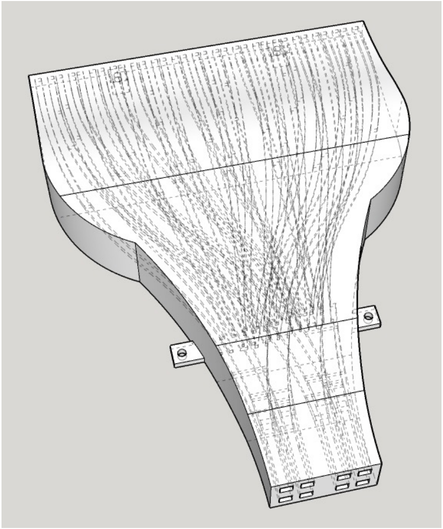
Encoding Example



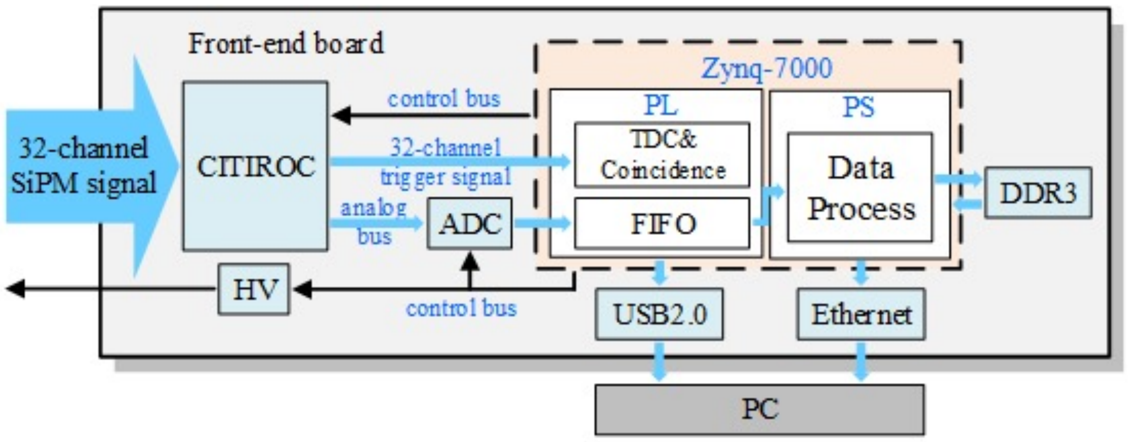
SiPM & Fibers are connected through air coupling

- Encode readout
  - Group 32 fibers from neighboring 16 strips
  - Add signals from different strips
    - 2 fibers in 1 strip, labeled as A, B
    - 4 fibers from A or B fed into 1 SiPM
    - Coincidence of A & B is required
  - Compression ratio: 1/4

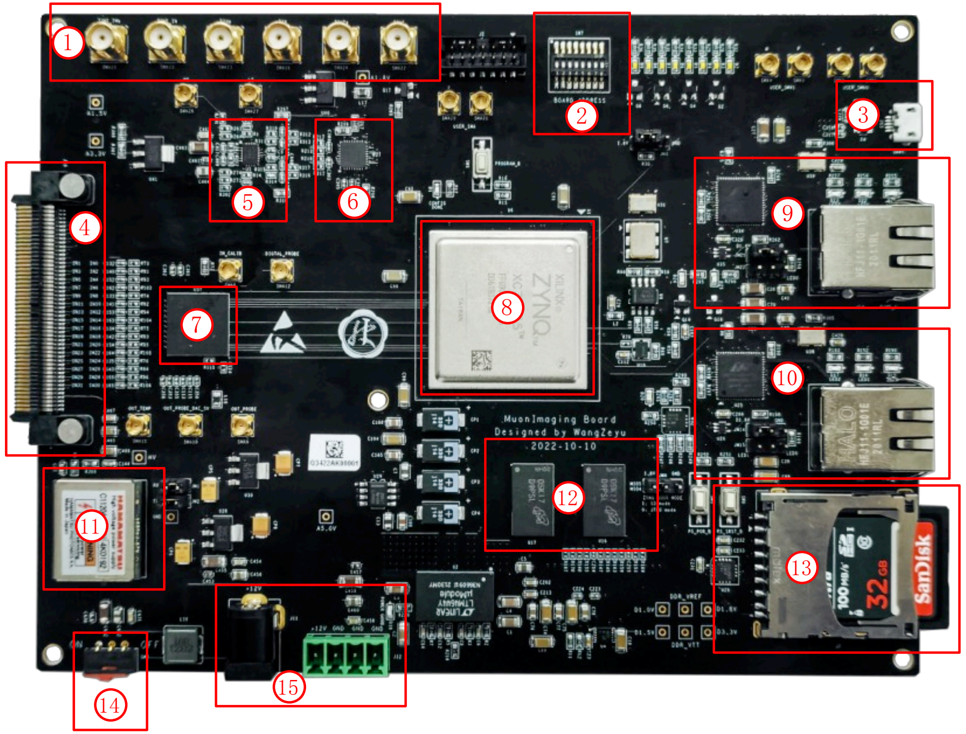
- 3D printed components:
  - Air coupling between SiPM & fibers
  - Fiber encoding component
    - Fibers inserted from one side
    - Avoid tangling of fibers



Readout system

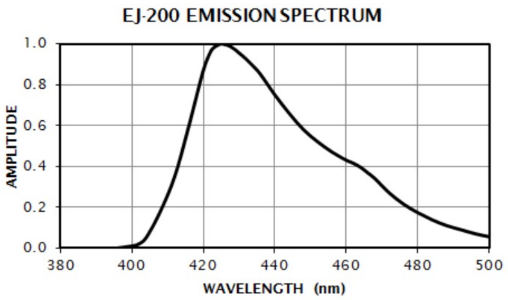


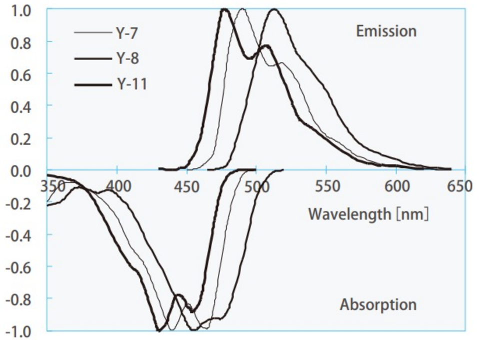
FEE board scheme

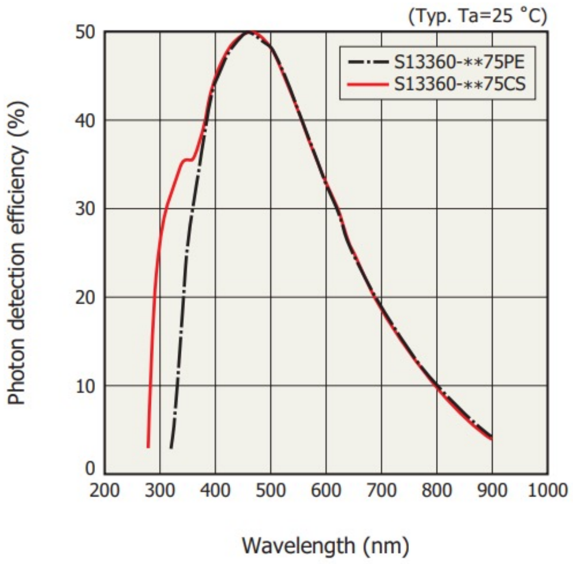


- Electronic board:
  - Weeroc ® CITIROC 1A: signal shaping, discrimination
  - XILINX ® ZYNQ:
    - PL: FPGA part, TDC & Logic
    - PS: control part, CPU
  - ADC: charge measurement
  - Provide bias, signal processing, charge & time measurement for 32 channels

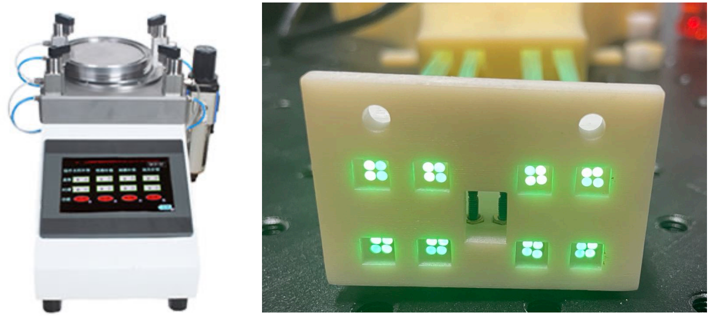
Material and processing



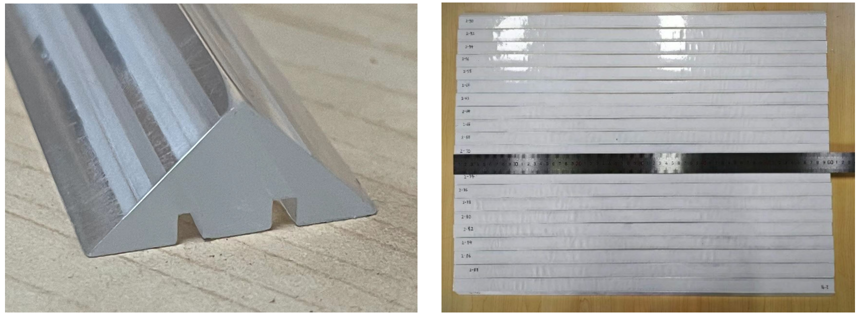




SiPM PDE



Fiber polishing

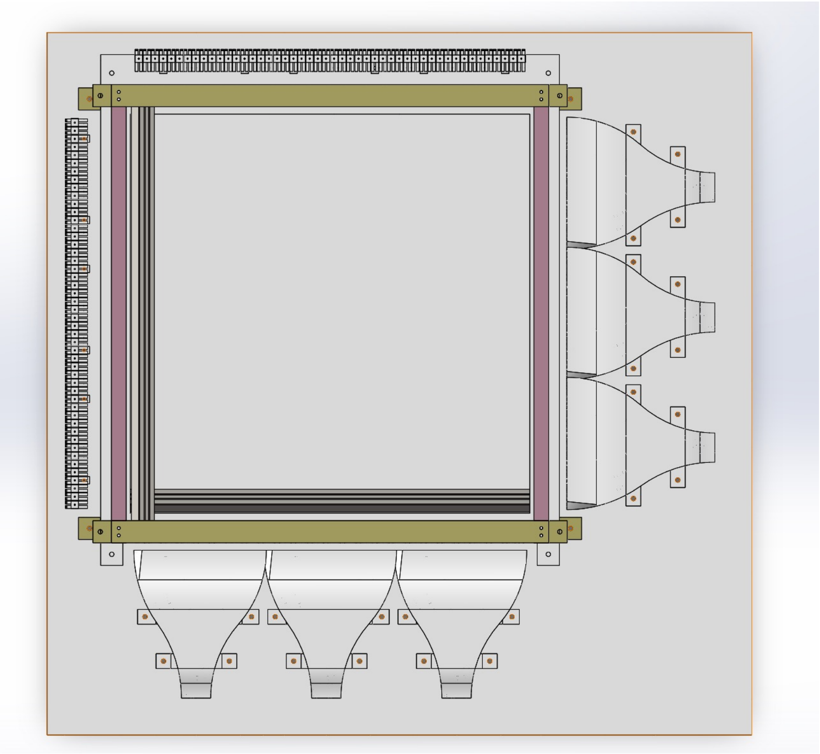


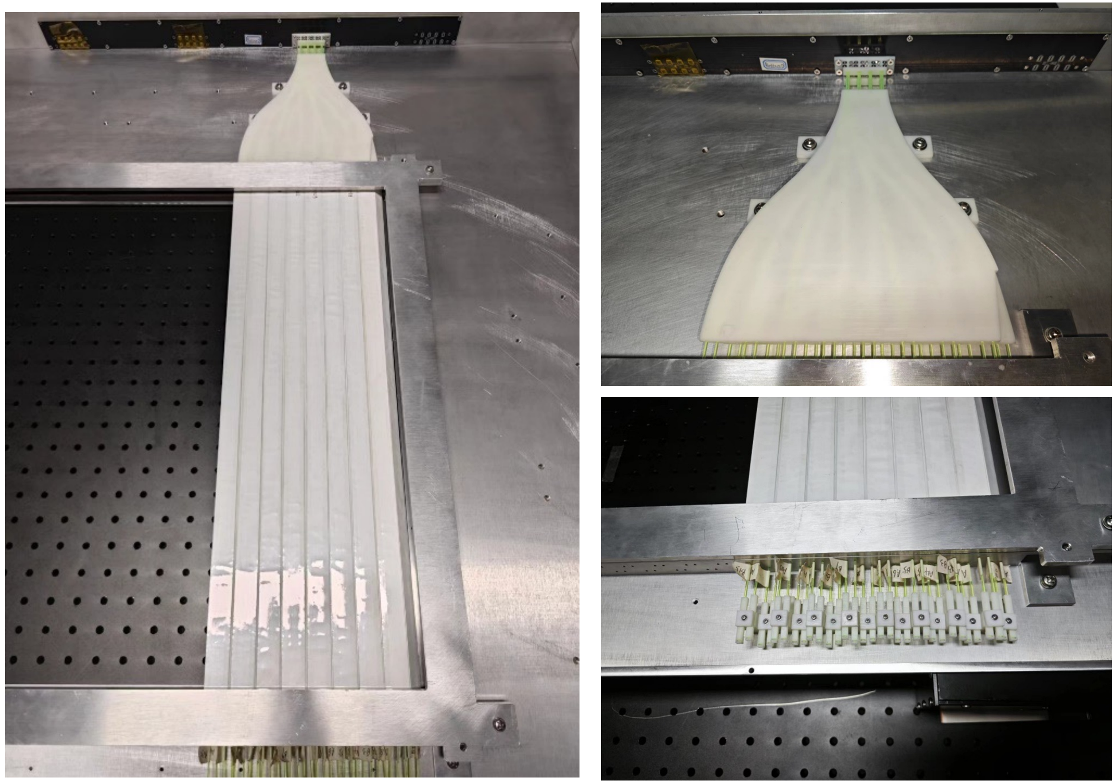
Scintillator machining and wrapping

- Scintillator: Eljen® EJ-200
- Wavelength shift fiber: Kuraray ® Y-11
- SiPM: Hamamatsu ® S13360-3075PE

- Fiber polish:
- Scintillator:
  - Machining: 2 polished grooves inside triangular prism
  - Wrapping: Tyvek paper with shrink film
- Test all material before assembling for QA

Detector layout & assembling

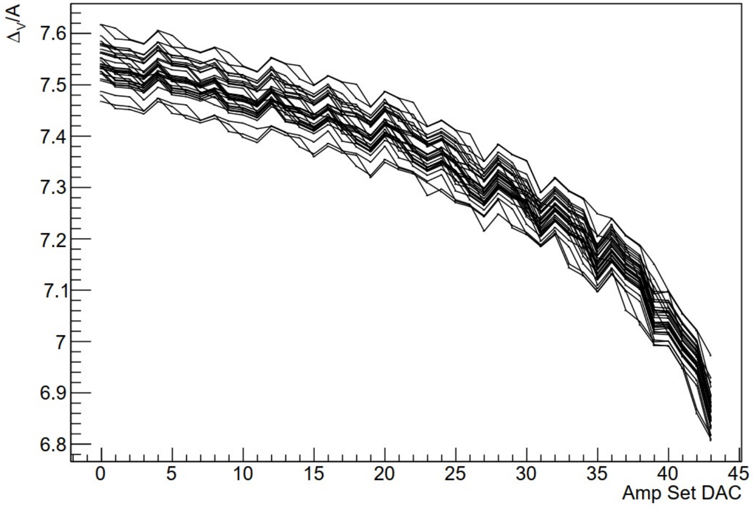




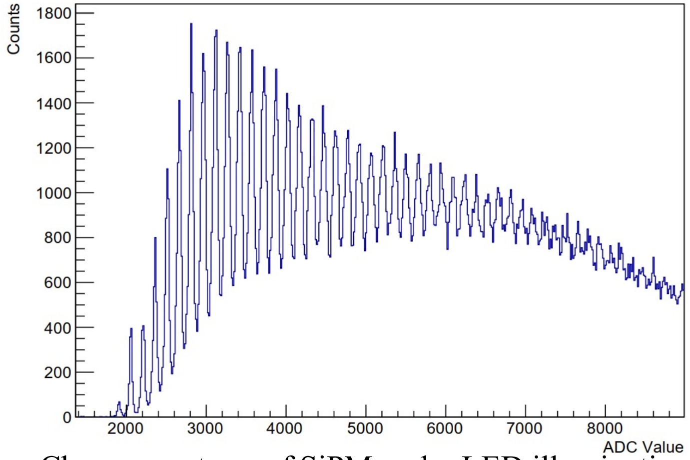
Layout of Module in Detector (left), encoder (right top), reflector (right down)

- A 2-D position detector:
  - Put inside 80 cm×80 cm light tighten box
  - 2 layers consist of 6 modules, 96 strips, 192 fibers, and 2 electronic boards
- A module:
  - 16 scintillation strips & 32 fibers in the same encoding group
  - 8 SiPMs & related electronic channels
  - Coincidence inside

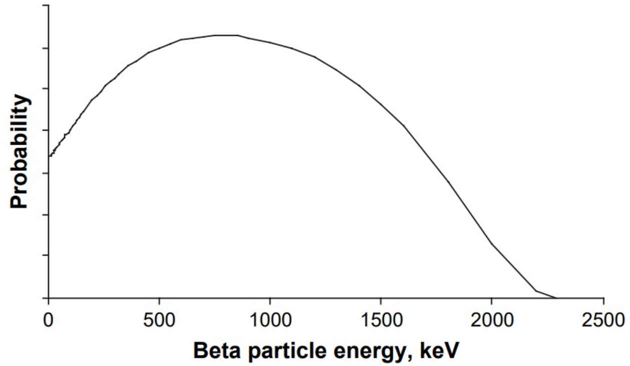
Performance of detector component



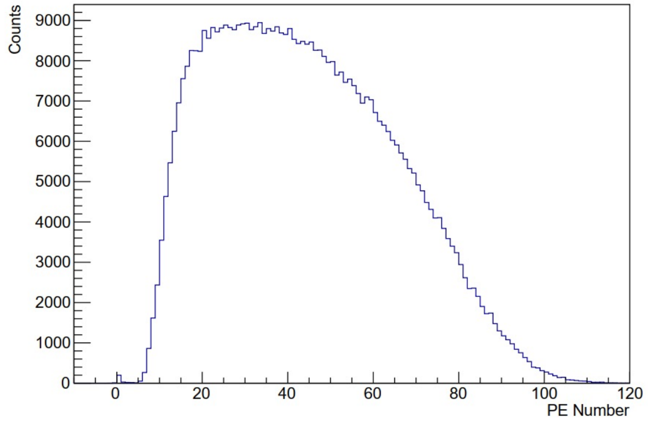
Gain measurement of amplifier, 32 channels



Charge spectrum of SiPM under LED illumination, used to determine PE resolution of SiPM



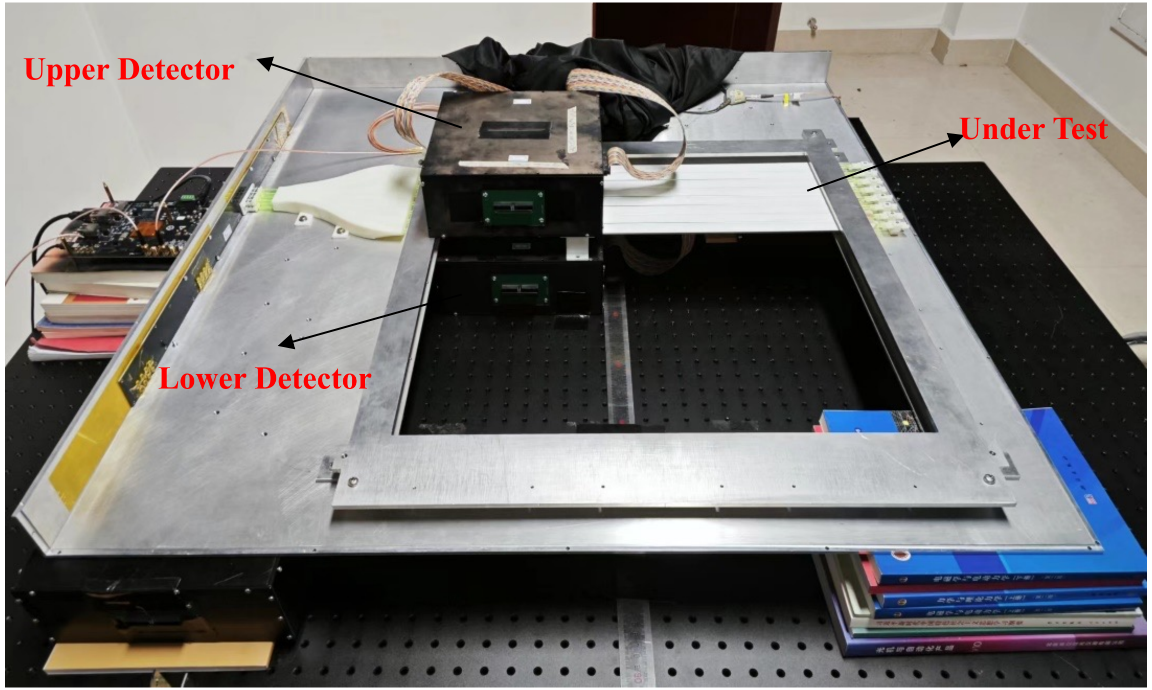
Spectrum of Sr90/Y90 radioactive source

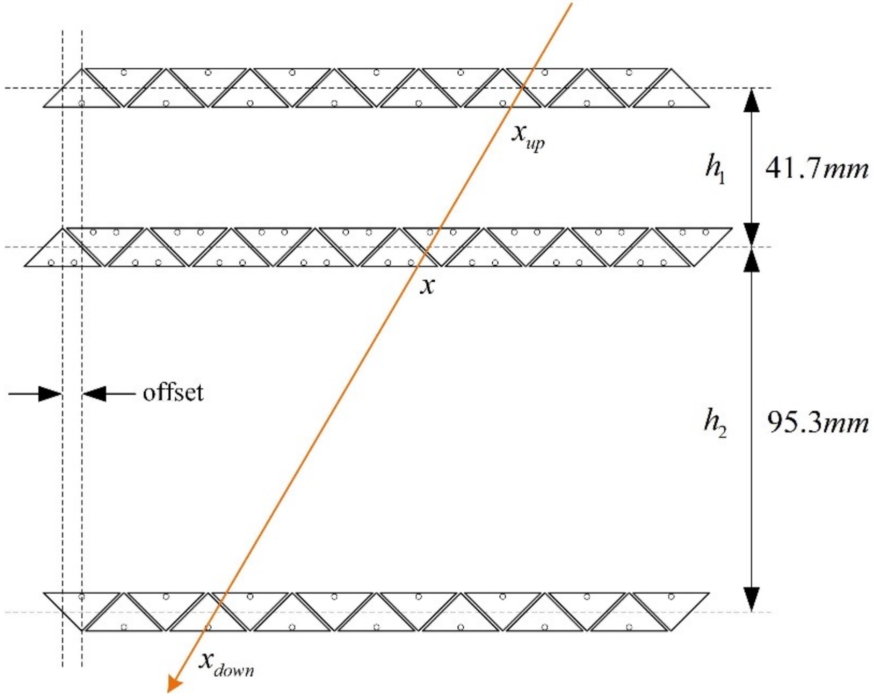


Scintillator spectrum under Sr90, used to estimate photon collection

- Measure all characteristics of electronic board and restore in database
  - Preamplifier gain
  - Bias voltage
  - …
- SPE resolution of SiPM:
  - SPE resolution: $\frac{\sigma_{SPE}}{Gain} = 7.0\%$
- Light collection in 1 fiber:
  - ~ 50 photons/MeV

Detector module test



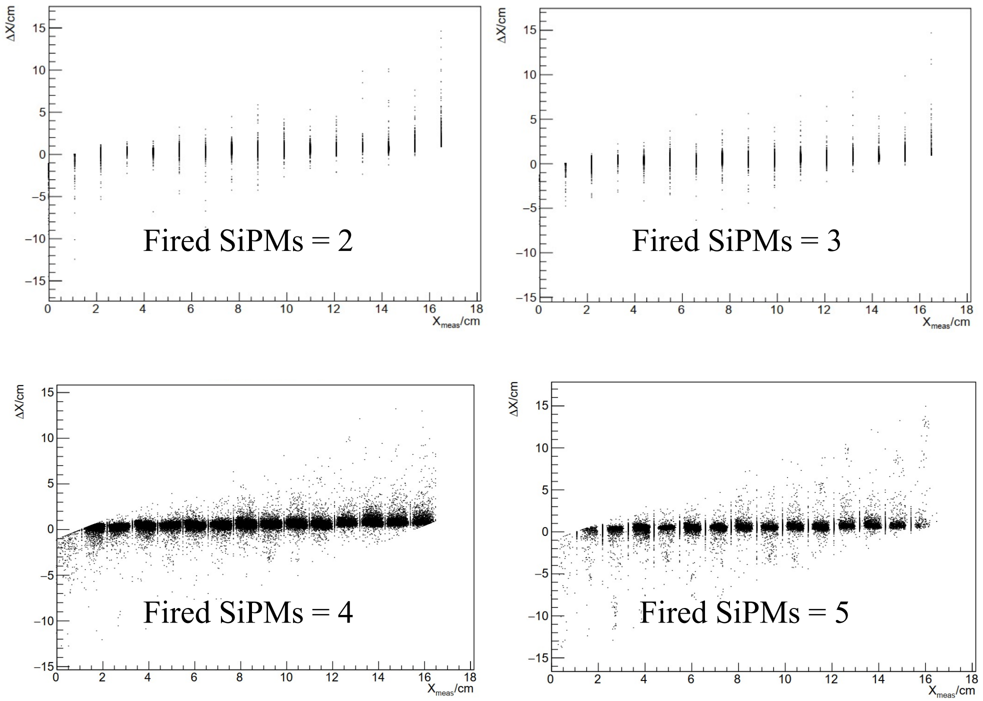


Layout of test system & trigger logic of the system

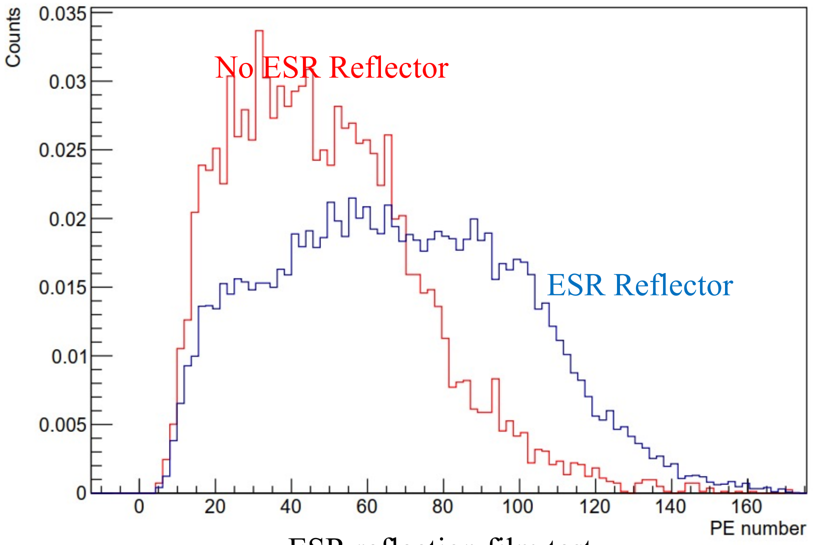
- A module has been tested under cosmic ray
  - 16 strips, with 16 cm×55 cm sensitive area
  - Pitch 11 mm
- 2 prototype detectors:
  - Trigger & track measurement

- Purposes:
  - Verify encoding design
  - Verify ESR reflection film
  - Measure rough spatial resolution

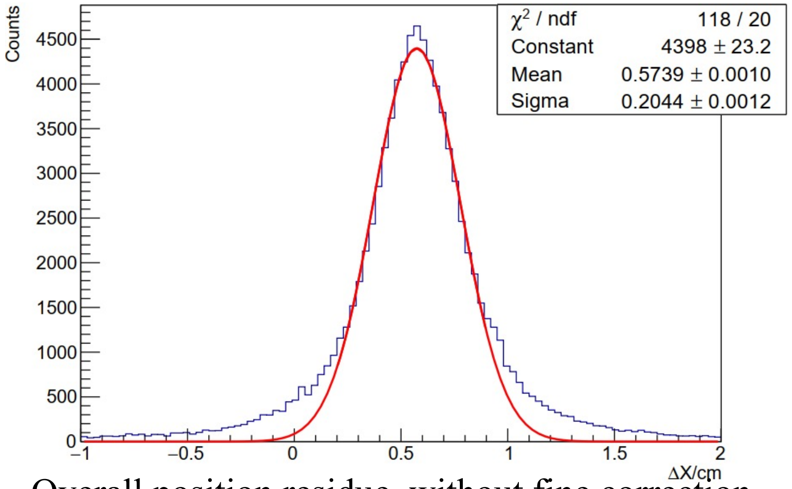
Test results



Position residue with different fired SiPM counts



ESR reflection film test



Overall position residue, without fine correction

- Decode & calculate position separately successfully
- Photon collection efficiency increase 40% with ESR film
- Measure overall spatial resolution:
  - pitch $p = 11\text{mm}$
  - $\sigma_x = 2.0$ mm (0.18 pitch)

Summary

- Plastic scintillation detector for muon tomography system has been studied
- Detectors with triangular cross section show the best performance in 3 prototype detectors (1.7 mm, 0.17 pitch) with 15 cm×15 cm area
- Upgraded detector with 50 cm×50 cm detection area:
  - Overcome difficulties in machining
  - Adopt encoding readout design, reduce electronic cost to 1/4
  - Electronic boards give SPE resolution better than 7%
  - Measured rough resolution is 2.0 mm (0.18 pitch), expect to achieve 0.1 pitch with additional correction for dead gap between strips

Outlook

- Expand detection area:
  - Challenge:
    - Length (60 cm) is limited by machining
  - Solutions:
    - Splice multiple scintillation strips
    - Replace plastic scintillator with liquid organic scintillator

Thanks!