Development of large area, high spatial resolution Micromegas detectors for muon tomography imaging

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PKμ Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP 2024)

Outline

- Introduction
- Thermal bonding Micromegas
  - § Method and performance
- For Muography
  - § Large detector and challenges
  - § Muography study
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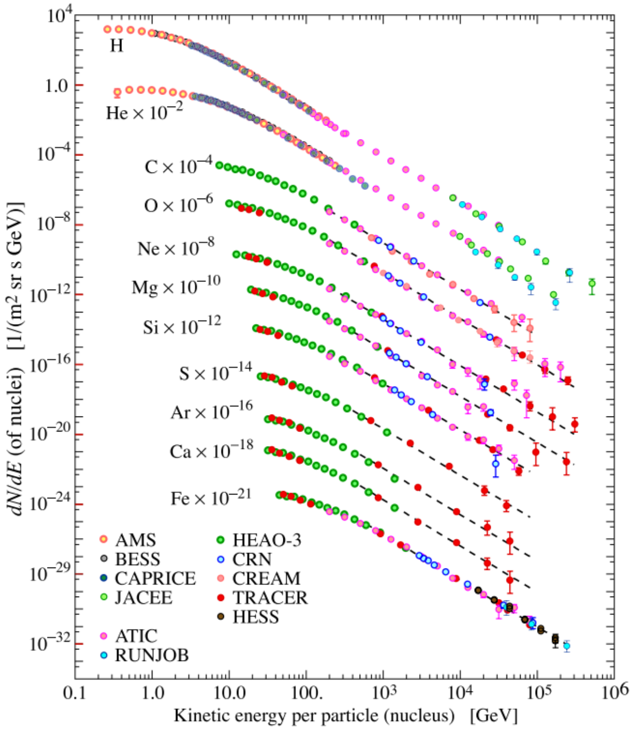
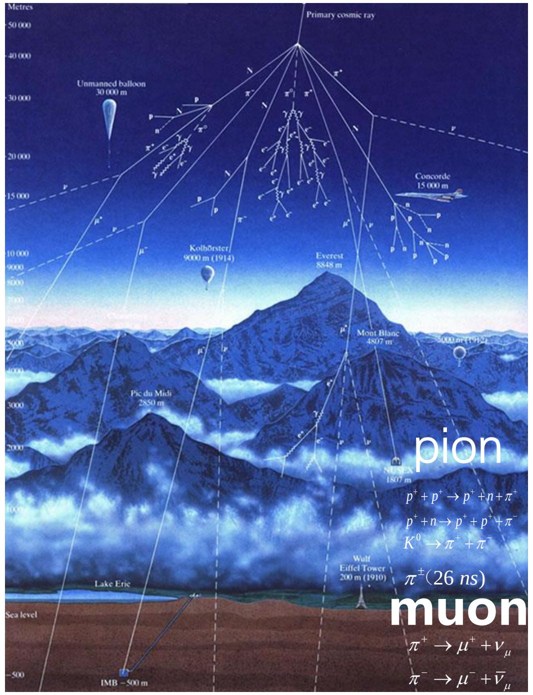
Cosmic-rays: particle species

Cosmic muons are produced by hadronic shower that induced by primary cosmic-ray accelerated at astrophysical sources

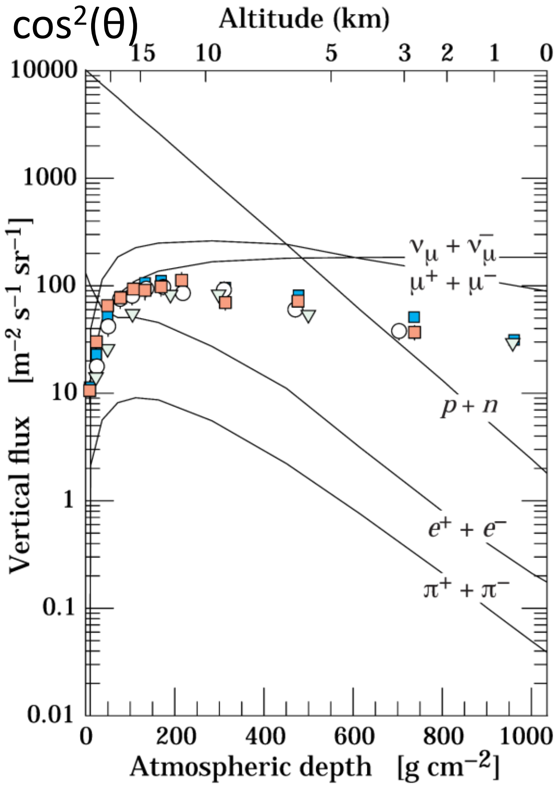
- 10,000 cosmic rays/min/m^2 hit the Earth's surface (~600 pass through our bodies every minute)
- Muons at sea level have an average momentum of 3-4 GeV/c
- The flux is maximum at the zenith direction, approximately proportional to $\cos^2(\theta)$



DOI:10.1093/ptep/ptac097



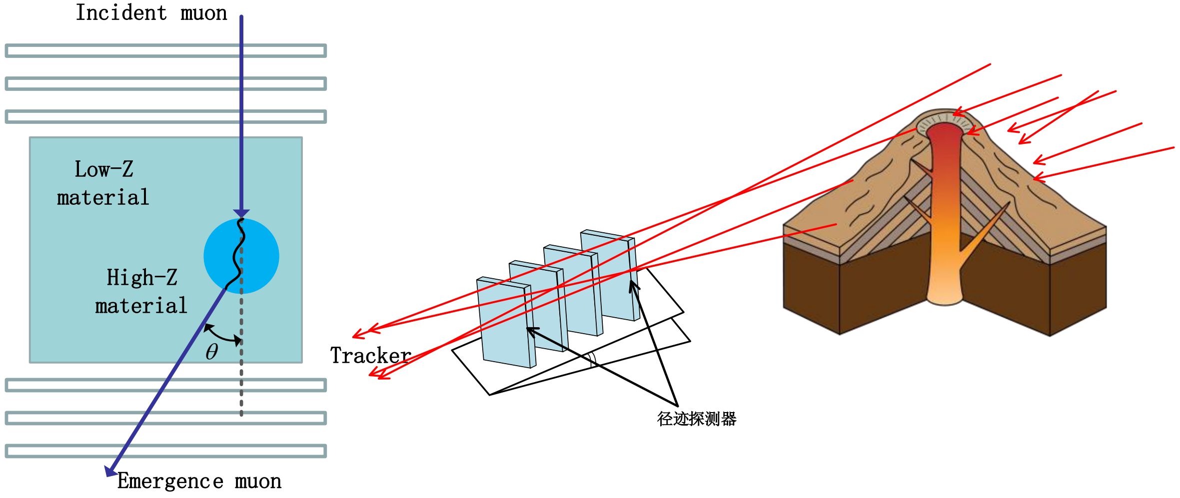
http://fafnir.phyast.pitt.edu/particles/conuni5.html

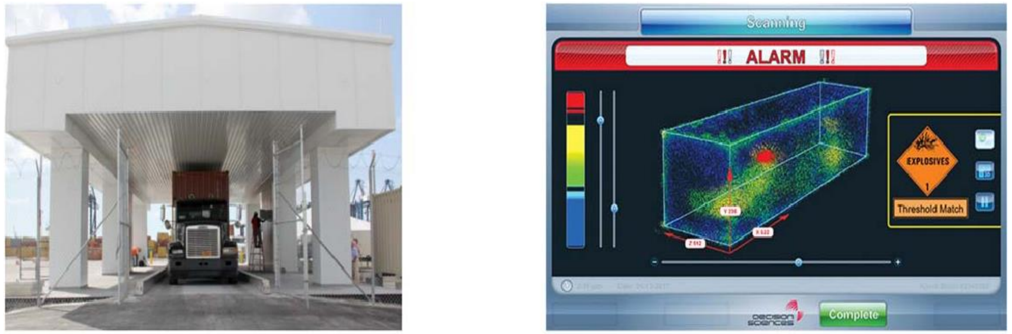


DOI:10.1088/1674-1137/40/10/100001

Muon Tomography and radiography

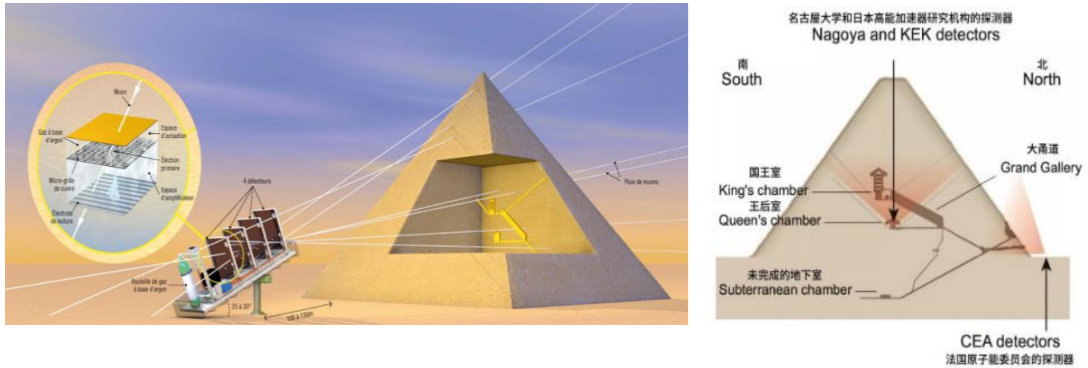
$\theta \propto Z$





(a) (b)

A Multi-Mode Passive Detection System by LANL & the DSC, for detecting trucks and large shipping containers at borders, customs, and ports.



Discovery of a hidden chamber in the Khufu Pyramid (Nature 2017) by Japanese and French teams

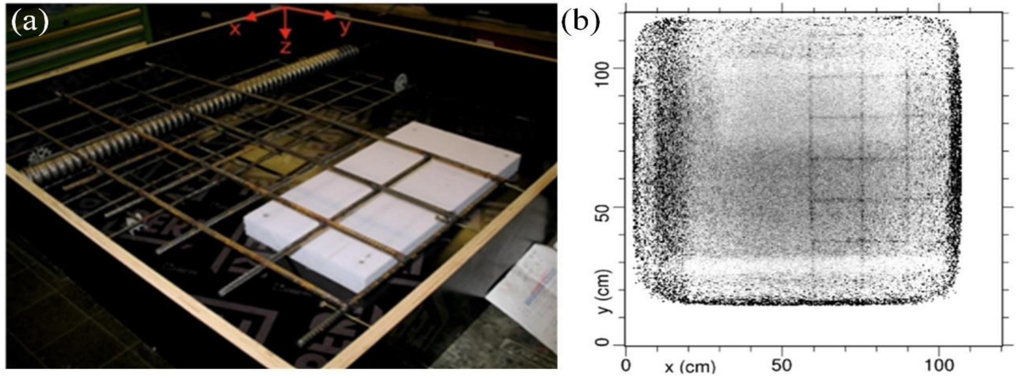


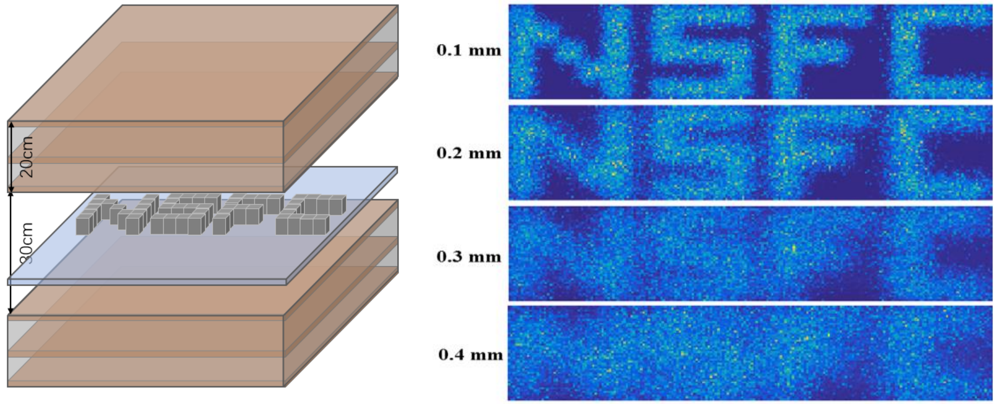
Image of the reinforced concrete (cost 43days)

DOI:10.1088/1674-1137/40/10/100001

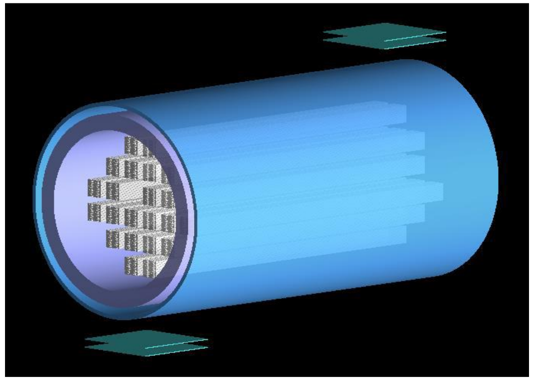
Requirements for muon detectors

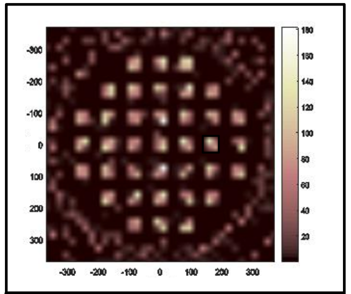
Monte Carlo simulation by Xiaodong Wang, Weibo He:

The imaging performance changes with the detector spatial resolutions

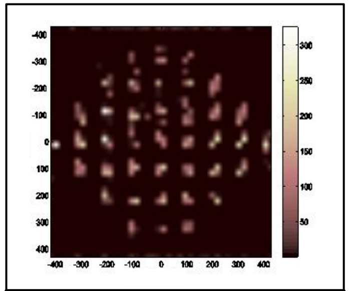


Resolution **better than 200 microns** are expected to achieve a imaging with proper clarity

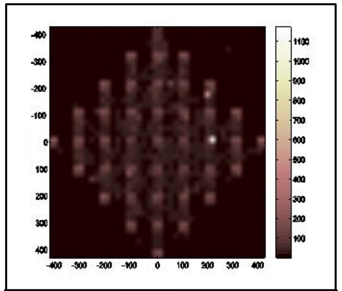




σ= 0 mm



σ= 0.2mm



σ= 0.3mm

Requirements for muon tomography

The requirements for the detector and the available options :

- Large area, as well as low cost
- Better than 200μm resolution
- High detection efficiency
- Stable performance

Detector	Large area	resolution	cost
MPGD	Single piece	100 μm	low
Scintillator	Array	1-10 mm	moderate
Silicon	Small	<100 μm	High

Large-area, high resolution MPGD is an competitive option

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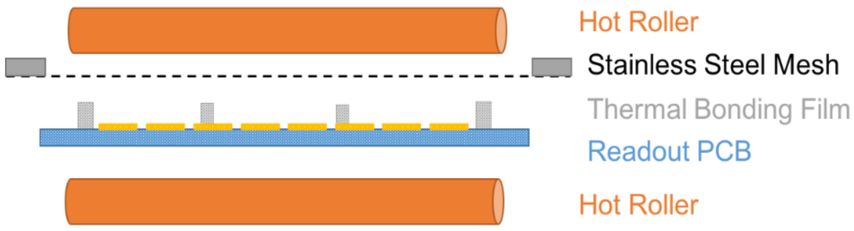
1
- Thermal bonding method

2
- Detector performance

The thermal bonding method

Over the past decade, we have developed a novel thermal bonding method for manufacturing Micromegas detectors at USTC.






- No etching, no pollution
- Easy to handle at lab
- Easy to make new structures
- Φ0.5mm- Φ1mm spacers, ~1cm pitch
  - ➔easy to clean, especially for large area
  - ➔less than 1% spacer area

A thermal bonding method for manufacturing Micromegas detectors, NIM-A, 989 (2021) 164958.
A novel resistive anode using a germanium fiem for Micromegas detectors, NIM-A, 1031 (2022) 166595.

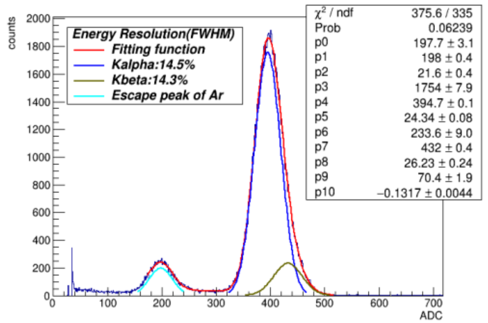
Performance for small size detector(150mm)

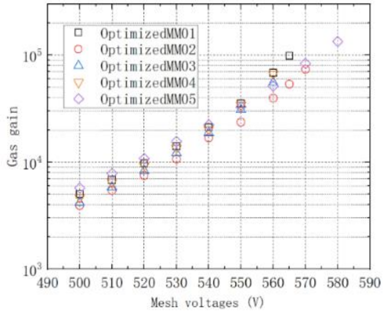
5.9 keV X-ray test

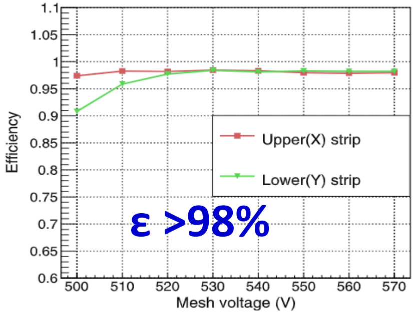
- Gas gain ： ~10^5 (Ar+7%CO_2)
- Energy resolution ： better than15% (FWHM)
- High counting rate: >MHz/cm^2

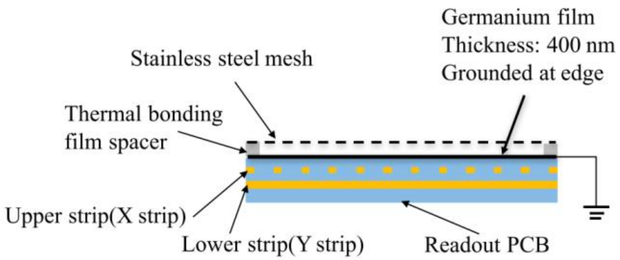
Electron beams （5GeV） at DESY

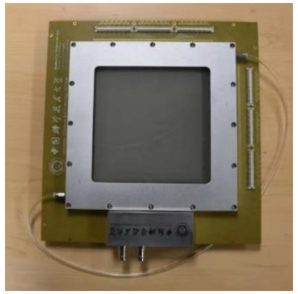
- X-Y 2D readout
- Efficiency ： >98%
- Resolution ： 65μm

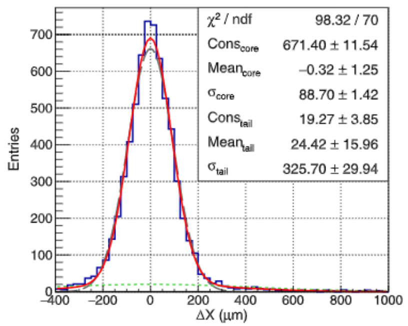


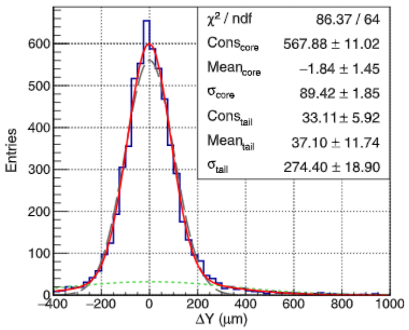






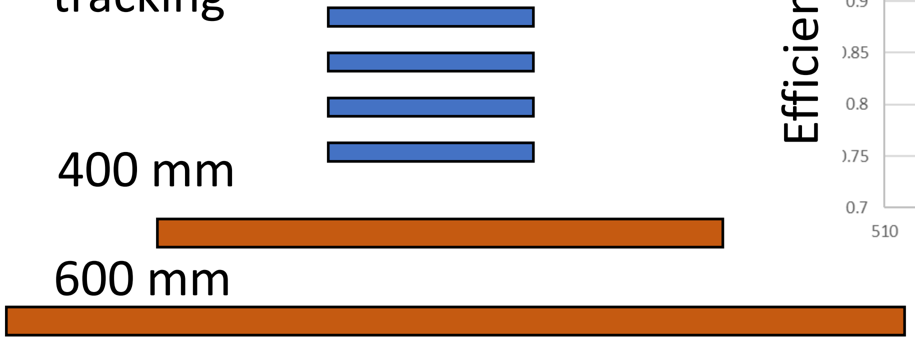


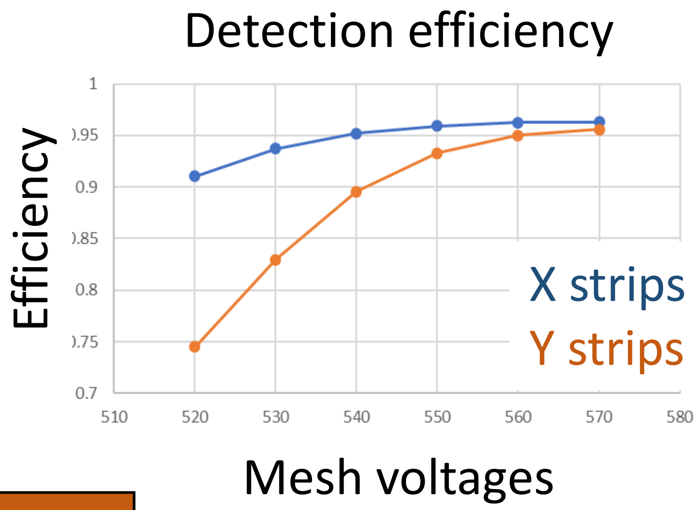


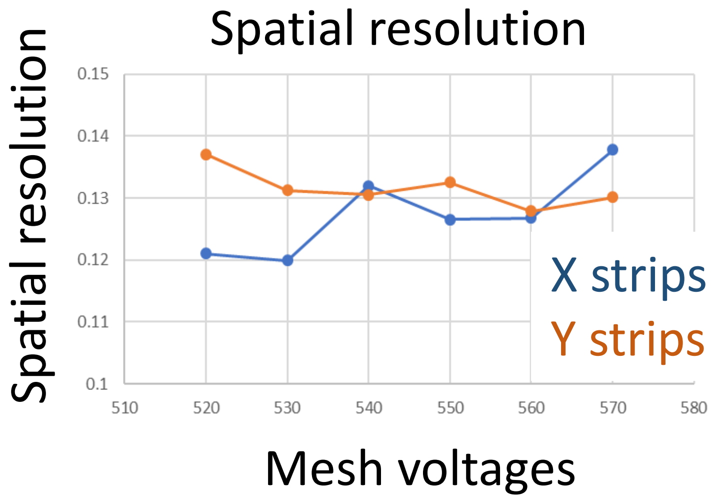


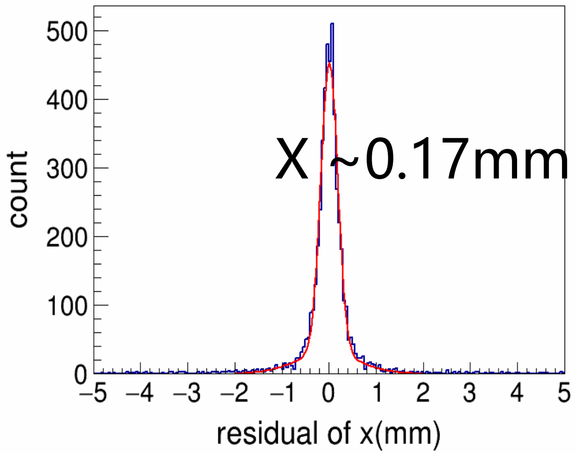
Performance for larger detectors (400/600mm)

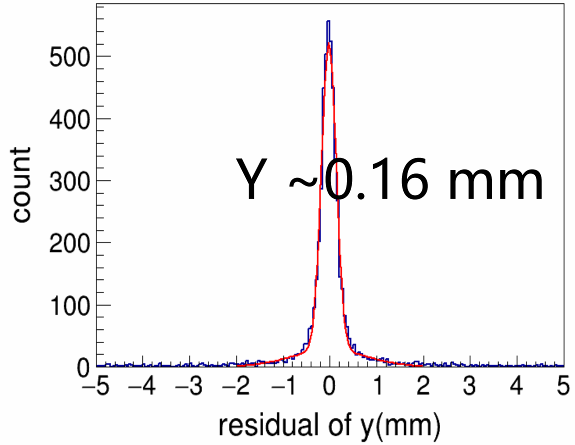
150 mm for reference tracking





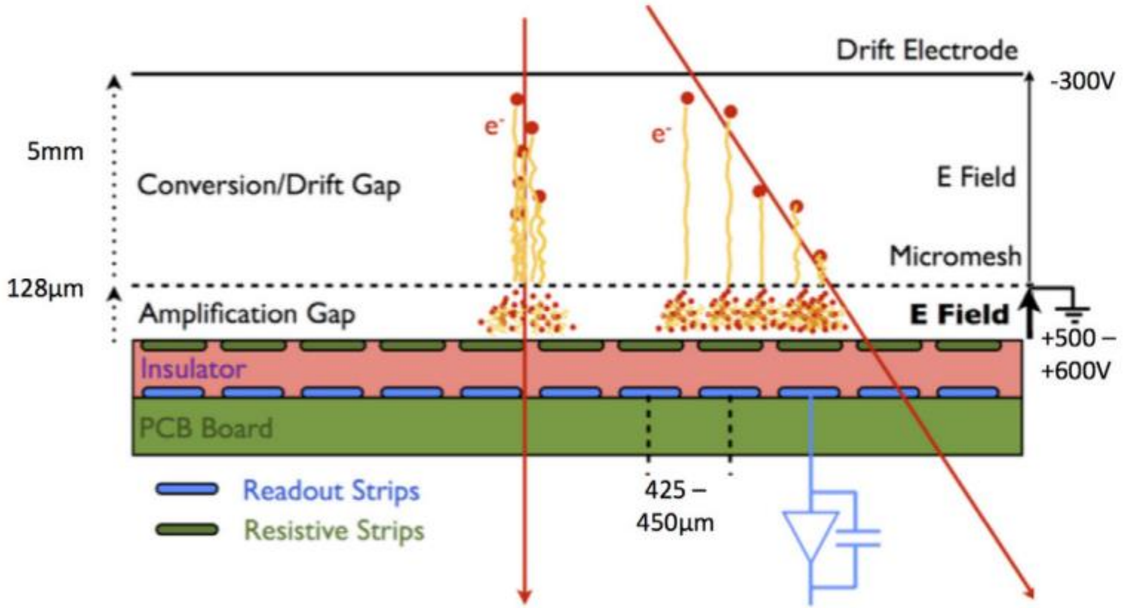


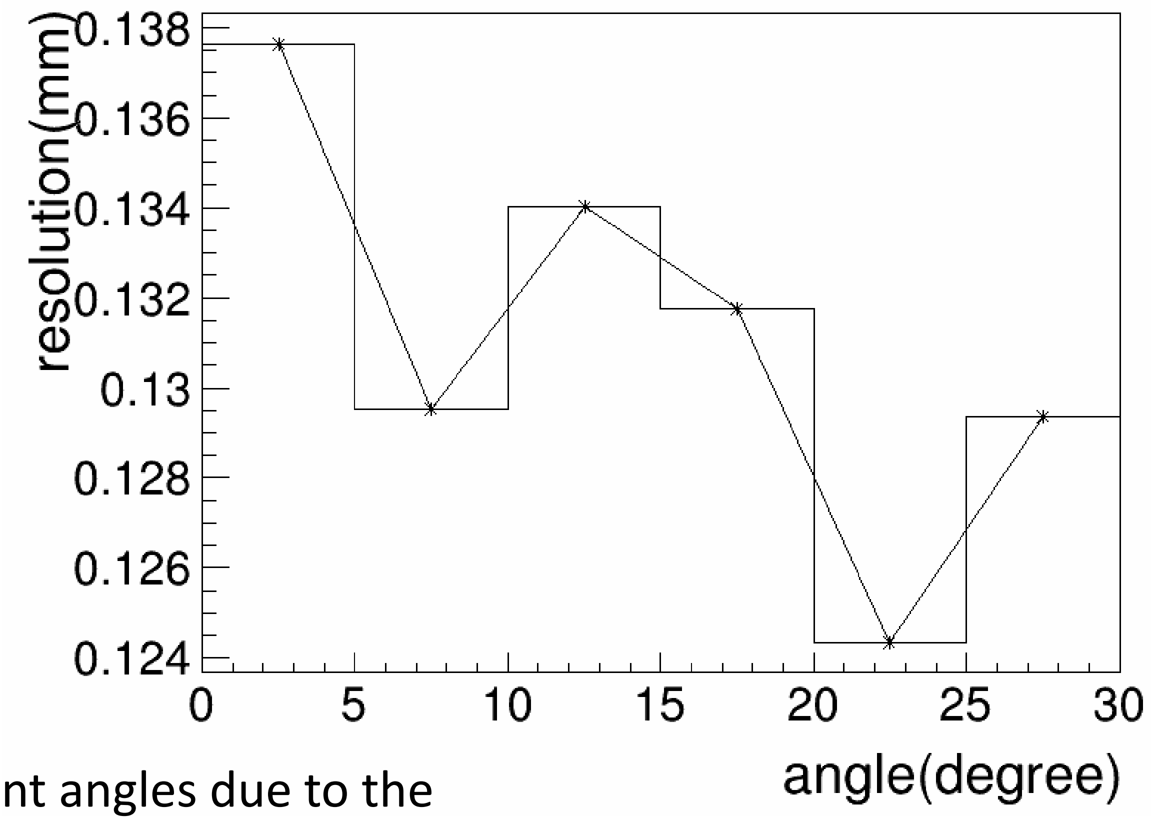




400 mm detector:
>95% efficiency, ~130 μm resolution
600 mm detector:
Better than 200 μm resolution

Micro-TPC correction (400mm)





The spatial resolution becomes worse for large incident angles due to the uncertainty of the primary ionization ;

It is practical to improve by micro-TPC mode when we have the arriving time information for each charge clusters

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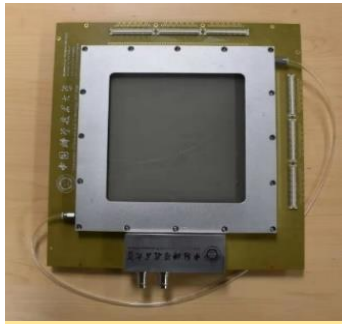
1
- Challenges for mass production

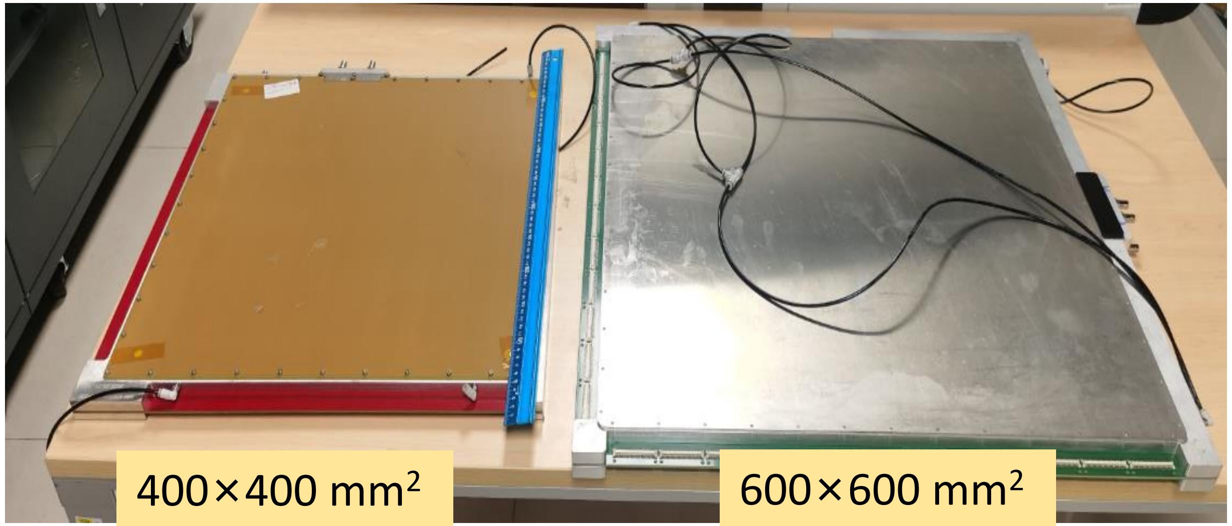
2
- And electronics

3
- Muography studies

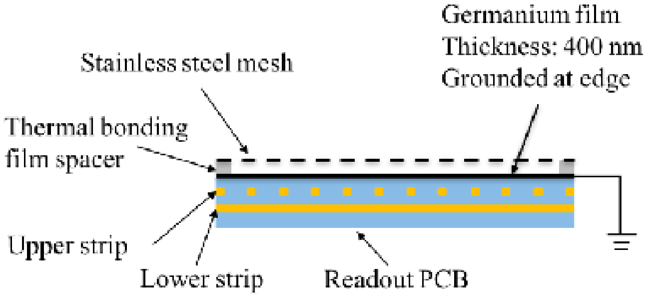
Challenges for manufacturing and electronics



150×150 mm²

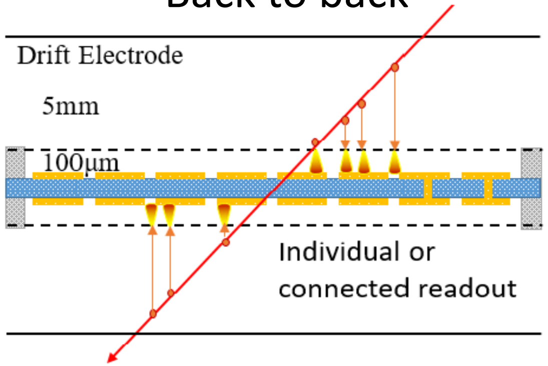


Single side



400µm strip pitch

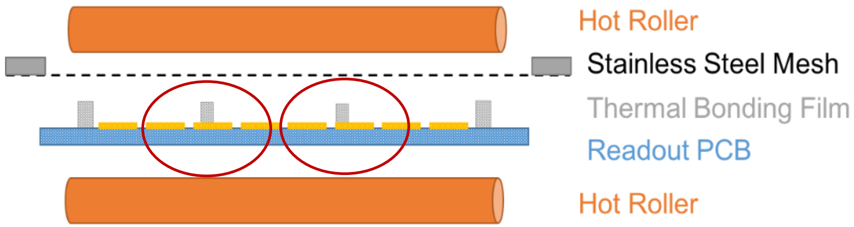
Back to back



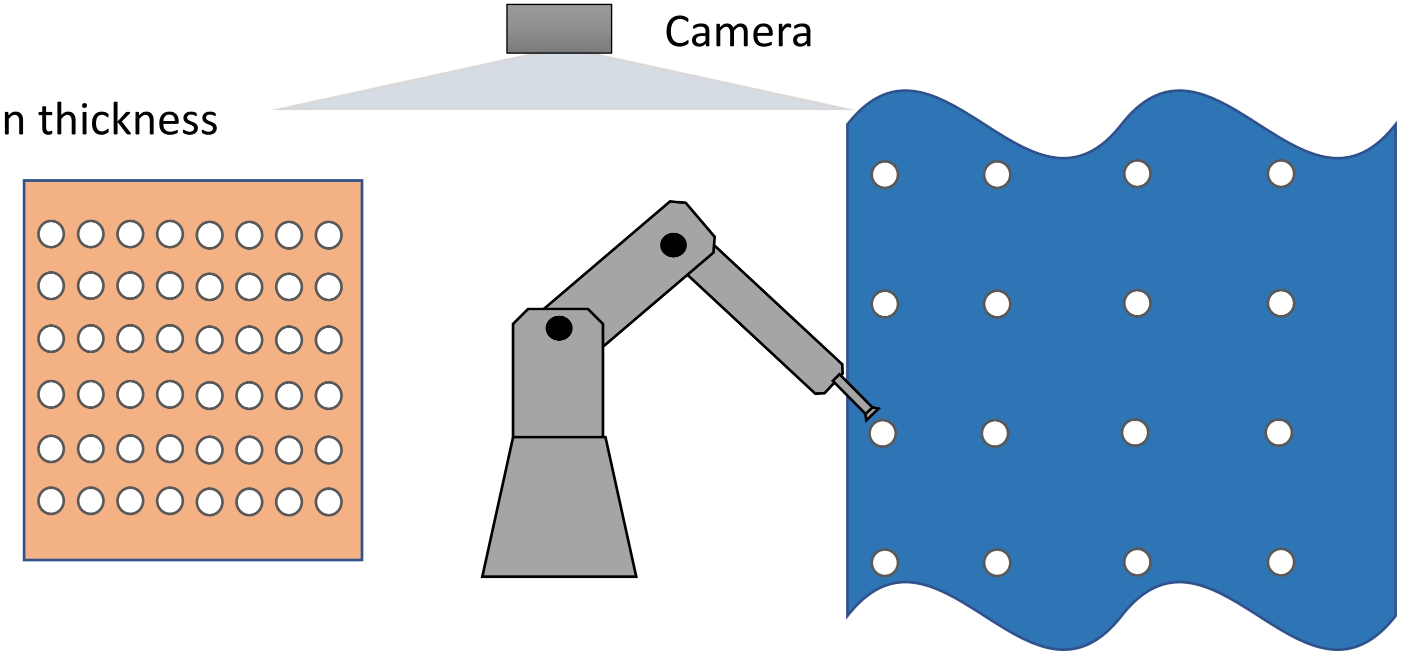
Size	Readout structure	Number of channels	Time consuming
150×150	Single side	768	< 1 day
400×400	Single side	**2000**	3-4 days
600×600	**Back to back**	**3000**	**~15 days**

- Limited by the state of the art for the PCB production.
- Huge signal channels need to be readout.
- The most time-consuming process is to preset the spacers of the avalanche gap （>60%）

Automatic spacer setting with robot arms



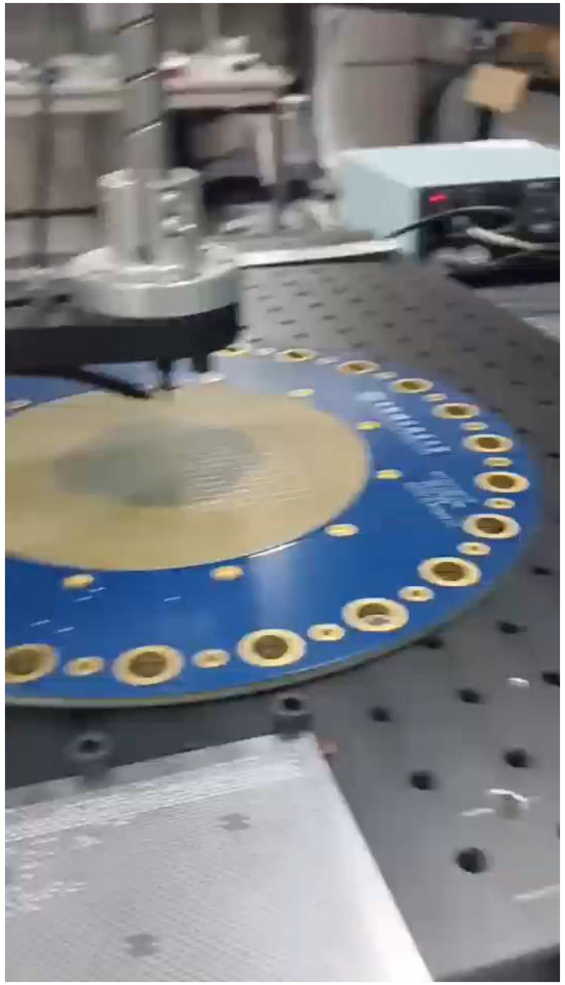
Spacers are 1 mm in diameter and 100µm in thickness



Spacers Pre-setting Readout PCB

- There are 7200 spacers needed to be preset on the PCB.
- Manual arrangement have to be replaced by robots.

Automatic spacer setting with robot arms



This video shows the progress of the automatic setting

It is promising to build a larger one, 1m × 1m

- We have finished the detector design
- First prototype can be carried out this year

Electronics

Challenges

- Large number of readout channels
  - ➔Eg: A single 60cm × 60cm detector has 3000 readout channels.
- Low noise measurement of MIPs signals
- Should be stable in the outdoor conditions

Solutions

- Channel encoding method to minimum the readout channels
- Develop low noise front-end electronics with ASICs
- Modular design to ensure the extensibility of the system

The channel encoding method

It is practical to encode the readout channel for very low rate of the cosmic muons

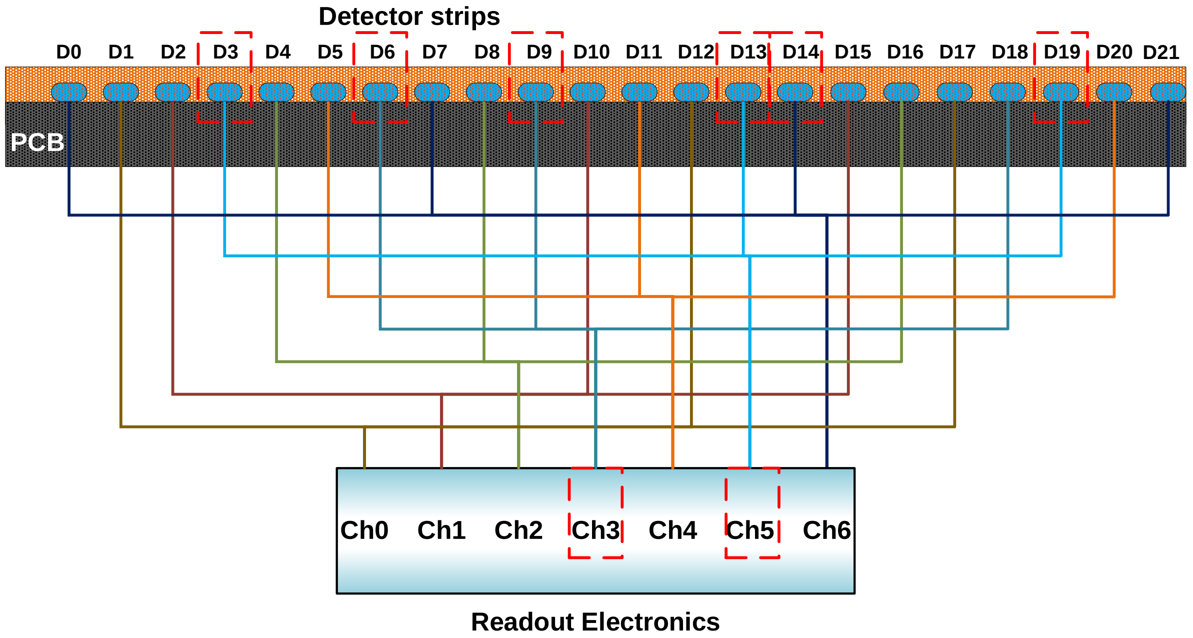
- The required number of readout channels can be reduced by an order of magnitude

Eg：

1. At readout side:ch3 and ch5 are fired
2. The possible hit strips are

   3， 6， 9， 13， 14， 19

3. As the hit strips should be contiguous, the real hits are 13 and 14



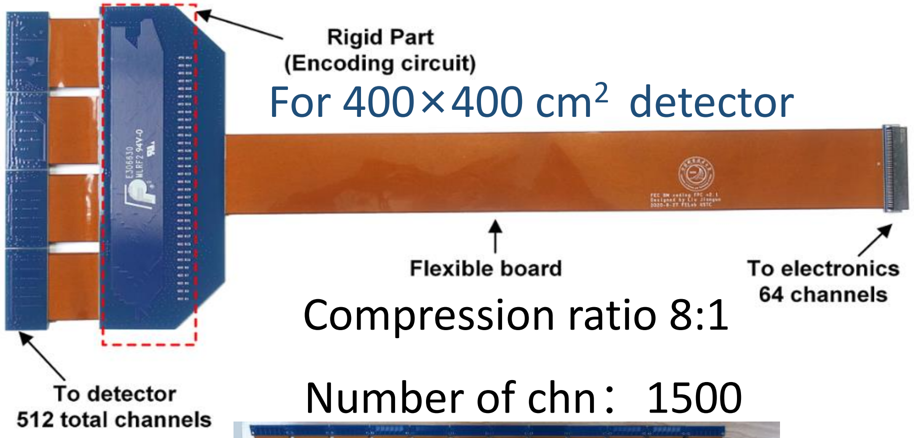
The channel encoding multiplexing method

- We have established a mathematical model using graph theory, specifically Eulerian graph theory, to describe the scheme of electronic channel multiplexing

Two different schemes were attempted

- Interleaved Coding Readout Scheme
- Hamilton Circuit Coding Readout Scheme

Number of chn：512



For 400×400 cm^2 detector

Compression ratio 8:1

Number of chn：386

Compression ratio 6:1

For 150×150 cm^2 detector

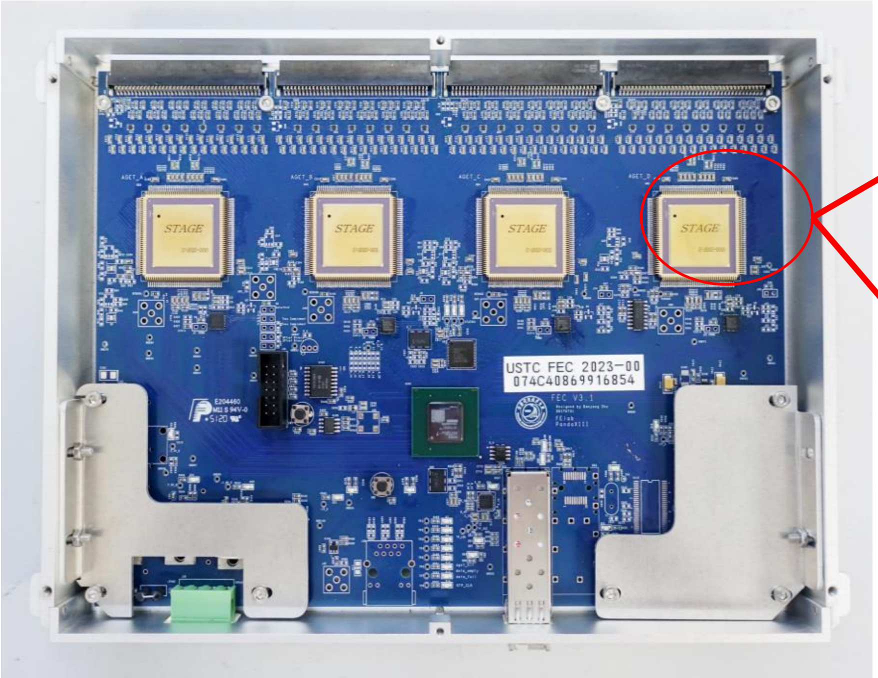
Number of chn： 1500

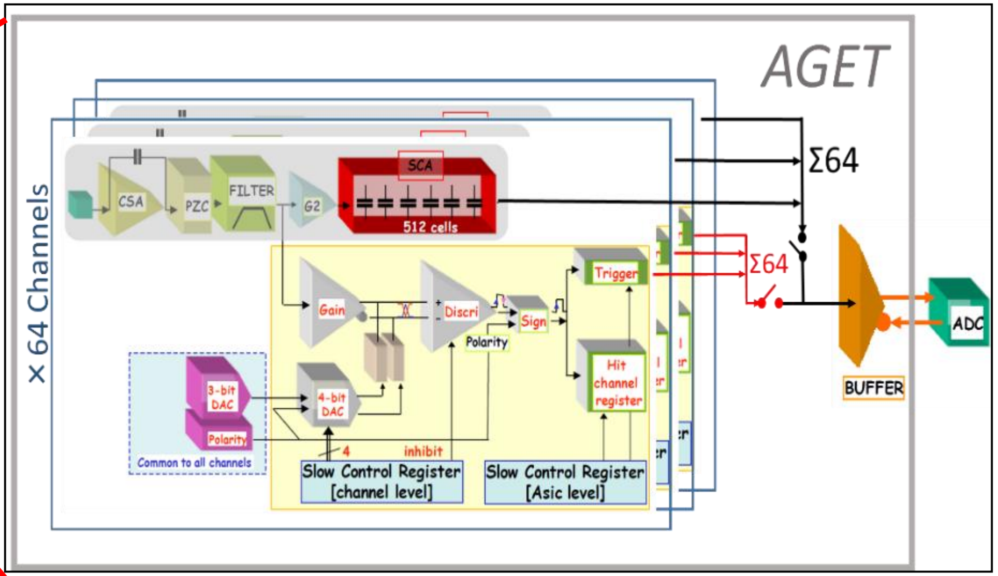
Compression ratio 12:1

For 600×600 cm^2 detector

Front-end Electronics Card

- Each board integrate 4 chips for readout 256 channels
- Sample rate from 1MHz to 100MHz
- Very low noise for single channel: better than 0.2fC
- Data transmission with optical fiber



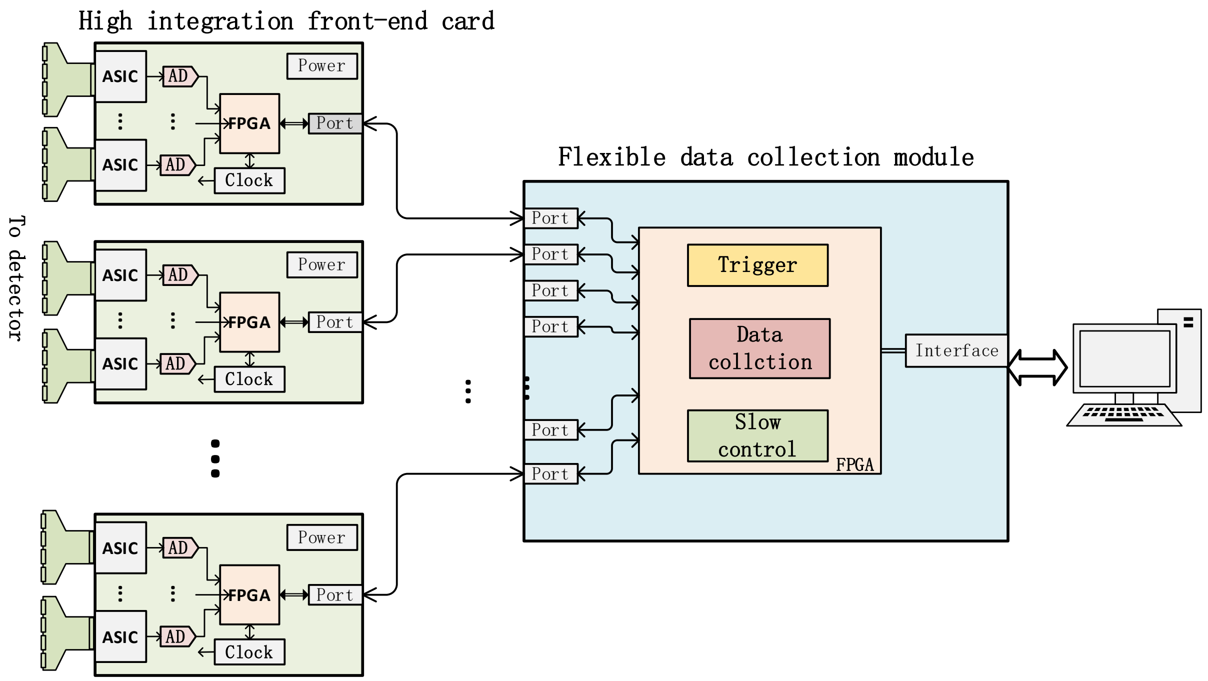


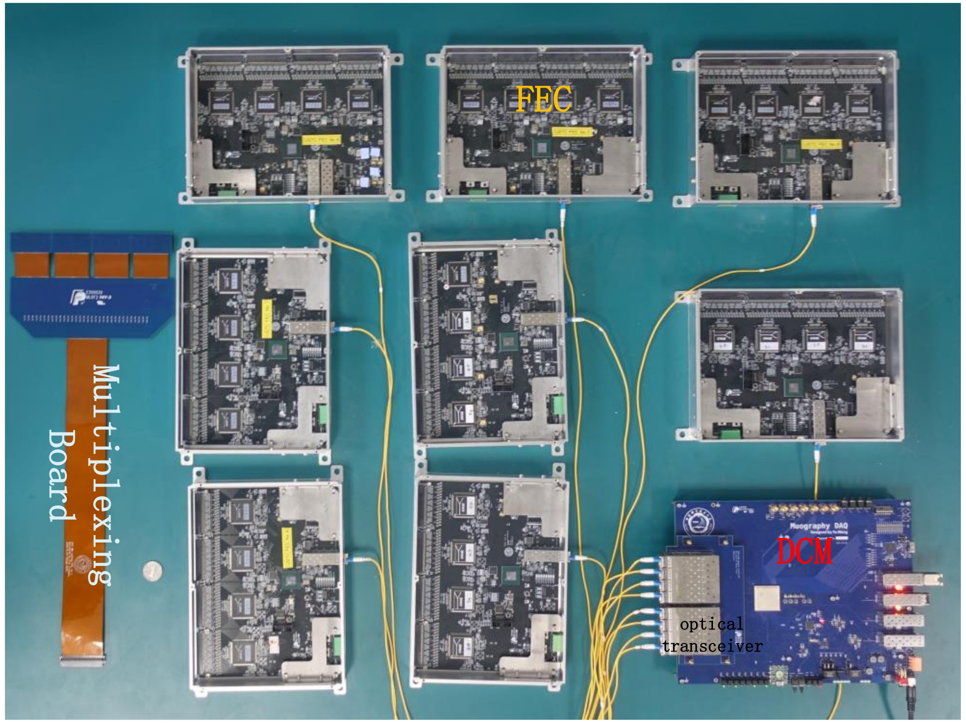
This chip is provided by IRFU/CEA Saclay

Extensible module design

A versatile readout system

- High integration front-end card (FEC)
- Flexible data collection module (DCM)





Schematic design

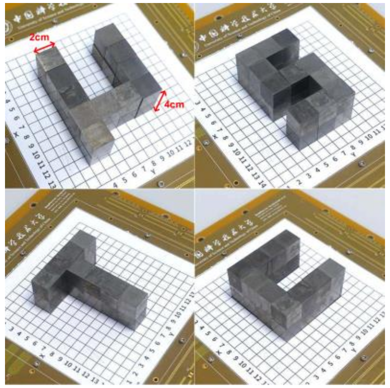
μSTC : μ(muon) Scattering tomography & Transmission radiography imaging faCility

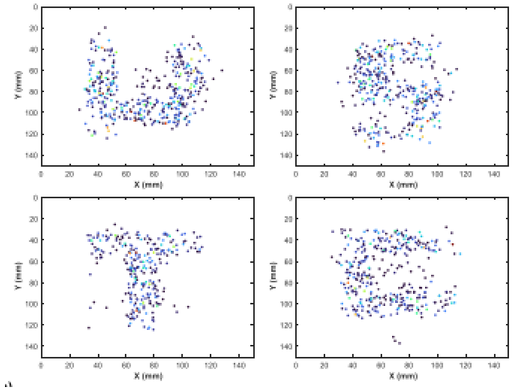
μSTC-T for tomography and μSTC-R for radiography

Design goals:

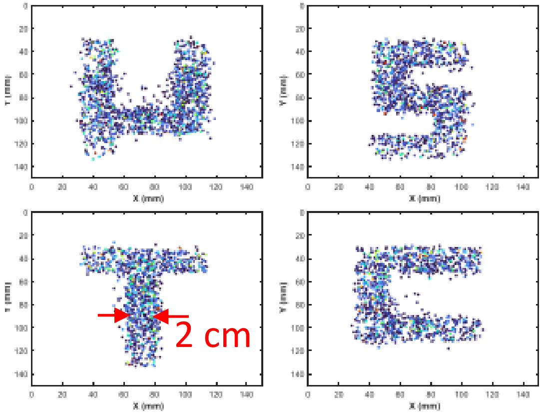
- Up to 60 ×60 cm^2 active area;
- < 200 μm spatial resolution for single detector layer;
- Rotatable horizontally and vertically.

Tomography with small prototype

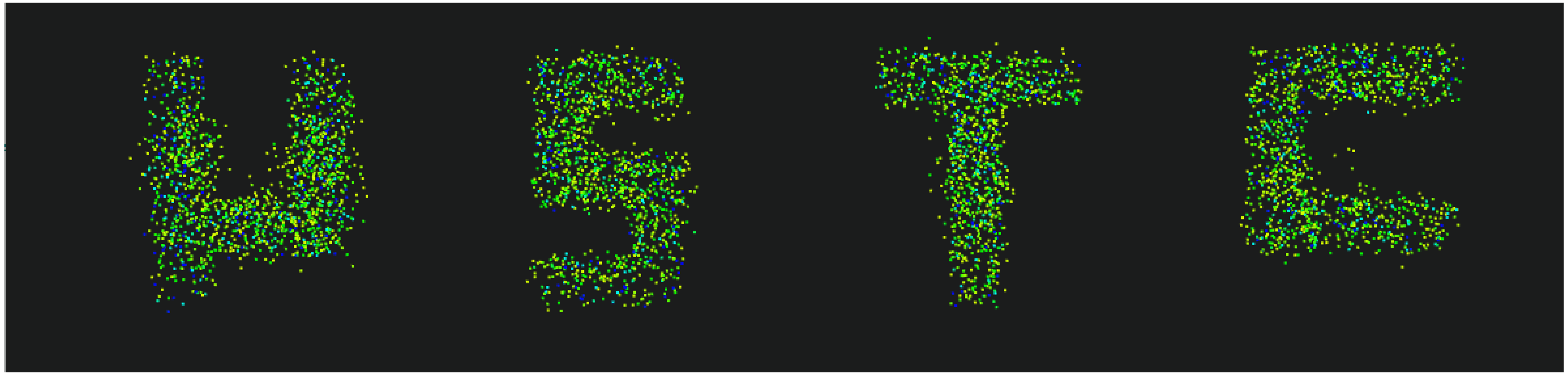




4-hour exposure

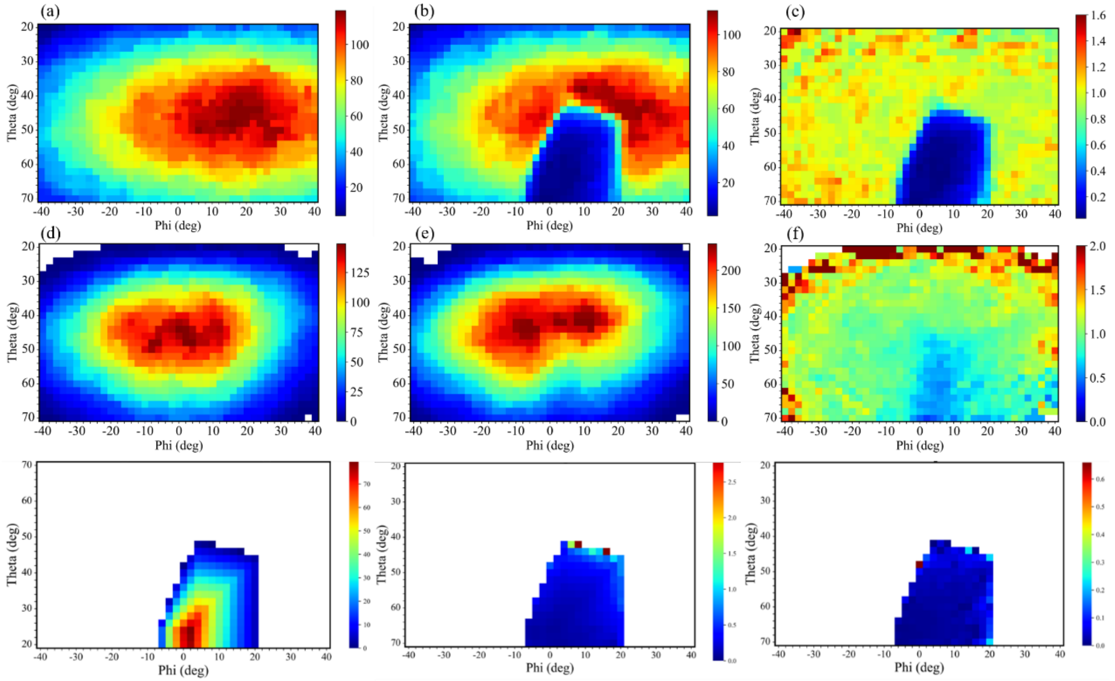


24-hour exposure



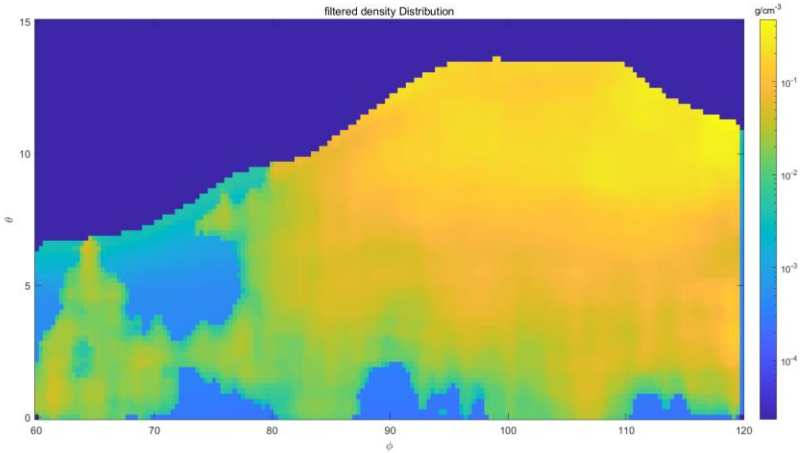
Radiography with small prototype

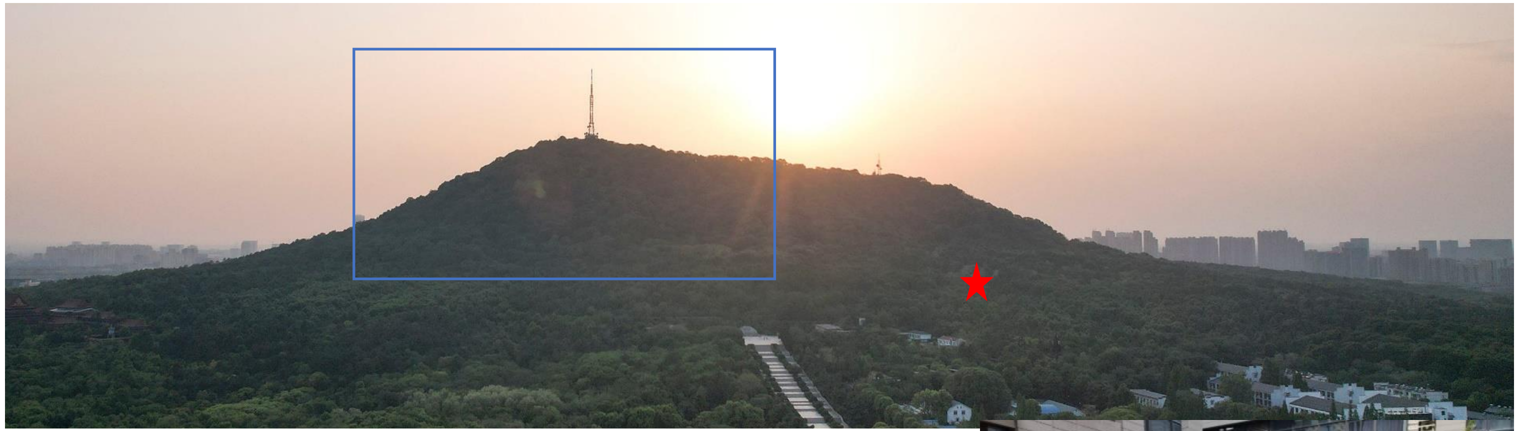
- ■4 layers of 15cm×15cm detectors
- ■Validation test with a building



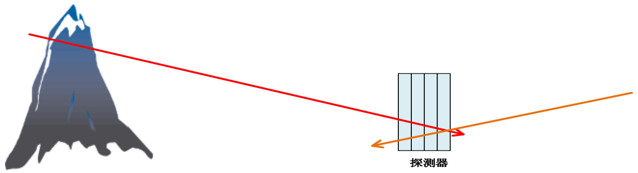
Radiography of Mt. Dashu

- An ancient volcano formed 65 million years ago
- Adjacent to the urban area of Hefei city
- Altitude of the mountain and facility location is 280m and 60 m respectively





- **4 layers of 40 cm×40 cm detectors**
- The facility was set at horizontal angle
- Recording muons from both mountain side and the other side (for reference)
- Test for duration of ~100 days



Muography study for blast furnace (in progress)

For material composition study inside a blast furnace, which is very crucial for safe and efficient iron production.
More facilities will be arranged for a 3D imaging.

Test on-site and event display

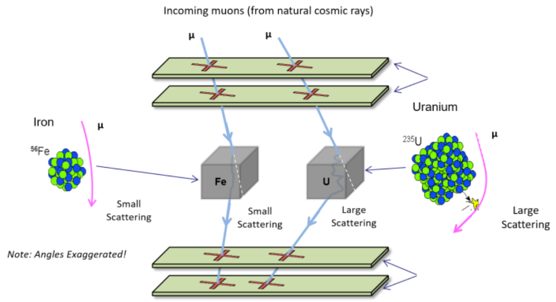
Summary

- Micromegas with large area (600 × 600 mm^2) and high resolution (better than 200 μm) have been achieved at USTC, dedicated electronics and encoding method were also developed.
- Performances of the μSTC prototypes were verified by testing with the building, ancient volcano etc.
- Inspection for blast furnace imaging is important, and muography now is the only possible method for it, than we will focus on.

Thank you

Requirements for muon detector

- Discriminating High-Z Materials



$$\sigma_\theta = \frac{13.6\text{MeV}}{\beta c p} z \sqrt{\frac{X}{X_0}}[1 + 0.038\ln(\frac{X}{X_0})]$$

Materials (3 cm)	Z	Multiple scattering X_0		RMS of scattering angle (mrad)		
		g/cm^2	cm	0.5GeV/c	3GeV/c	20GeV/c
Air	7.3	36.7	28000	0.29	0.05	0.01
water	7.5	36.1	36.1	8.01	1.31	0.20
concrete	11.1	24.6	10.7	14.7	2.40	0.36
Aluminum	13	24.0	8.9	16.1	2.63	0.39
Iron	26	13.8	1.75	36.4	5.94	0.89
Lead	82	6.40	0.56	64.3	10.5	1.57
Uranium	92	6.10	0.32	85.0	13.9	2.08

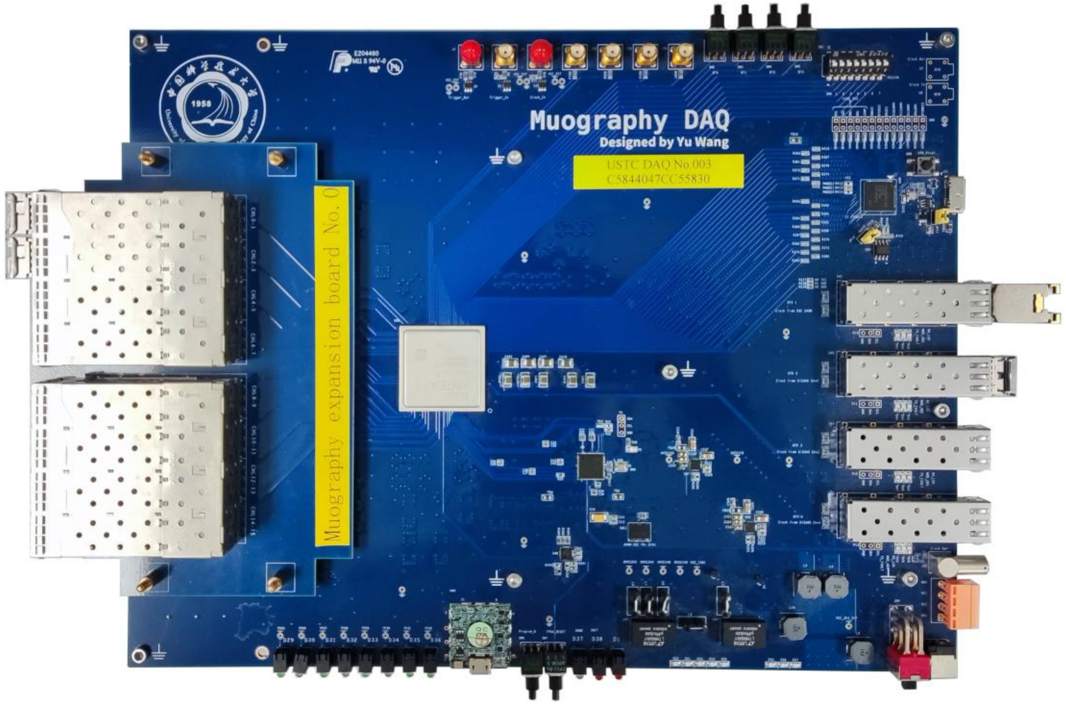
~mrad angle resolution

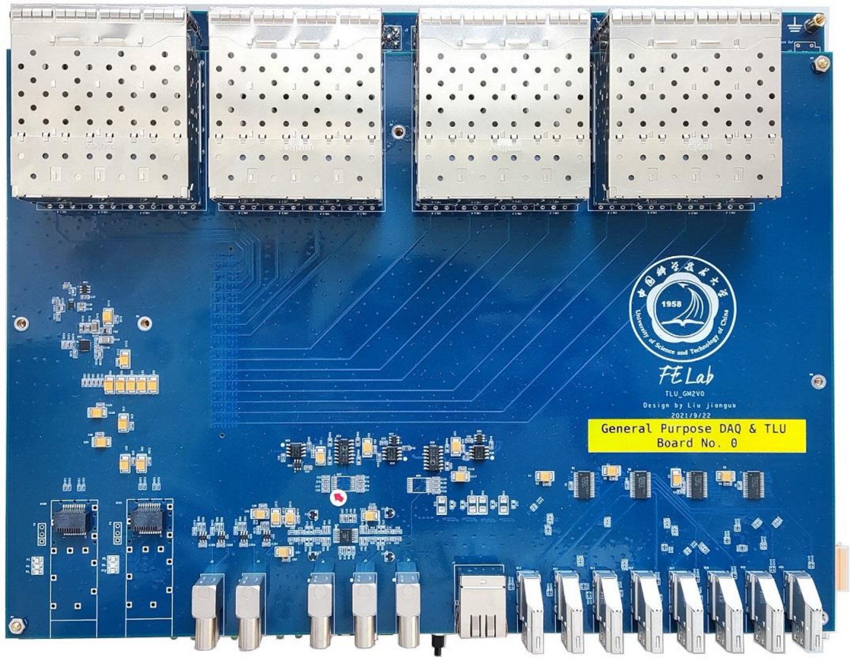
➔ 1mm resolution with 100cm detector distance

➔ 0.1mm resolution with 10cm distance

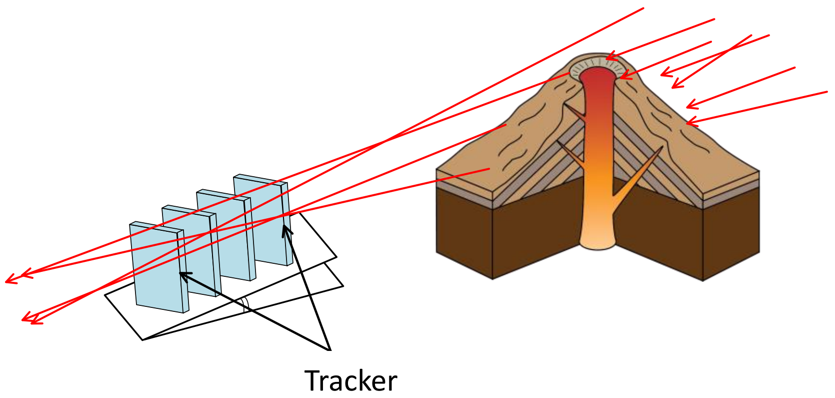
Data Collection Module

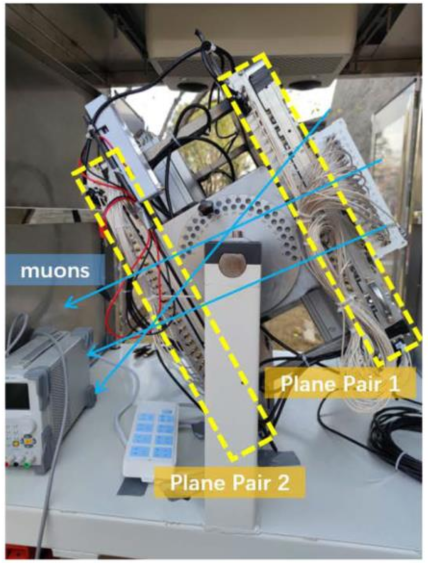
- Adapt to various scales and types of front ends
- Optical fibers connection, enabling long-distance communication
- Multiple data transmission interfaces, suitable for different imaging scenarios
- Trigger reception, generation, and distribution

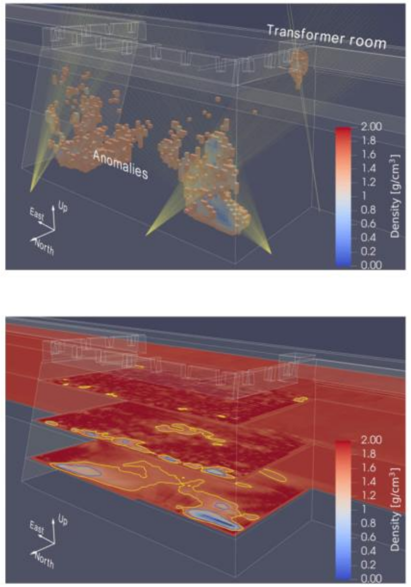




Muon Radiography







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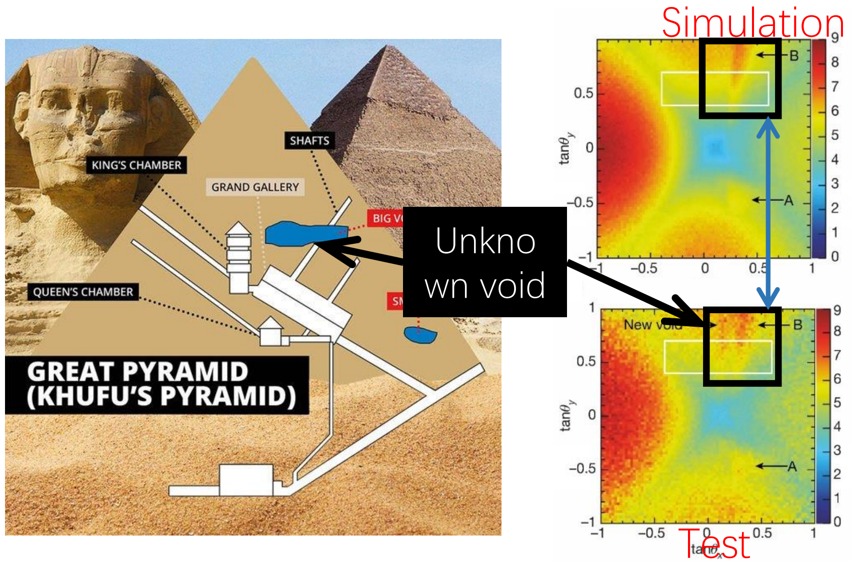
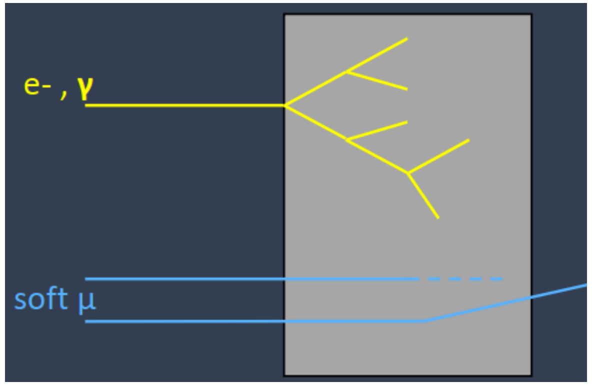
geological investigation/ archaeological site detection





(M. D'Errico et., al, 2023)