Application of MRPC in Muography

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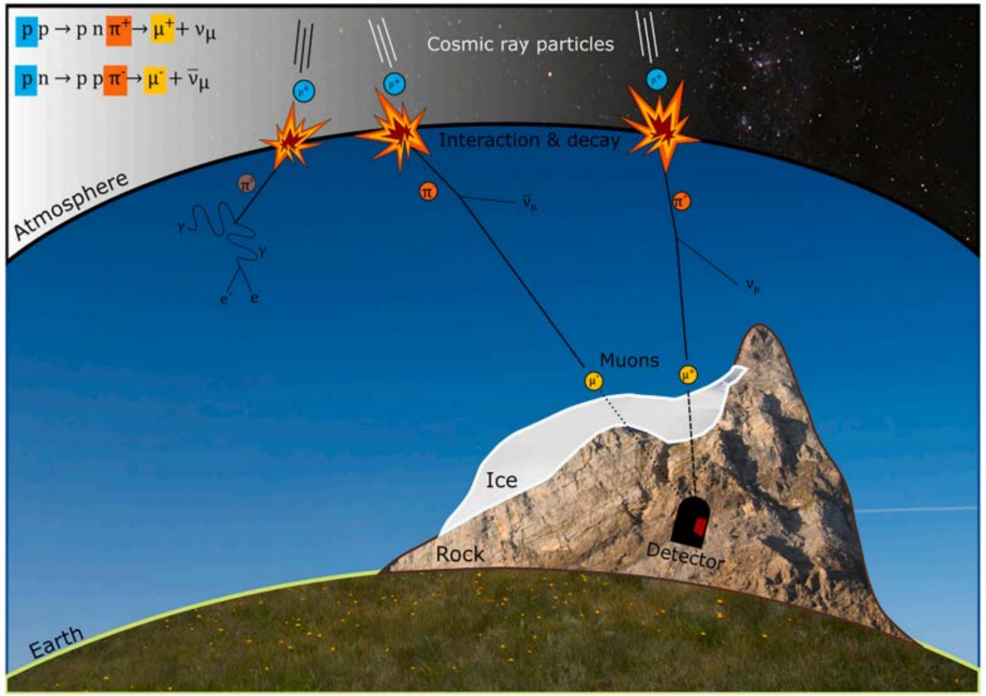
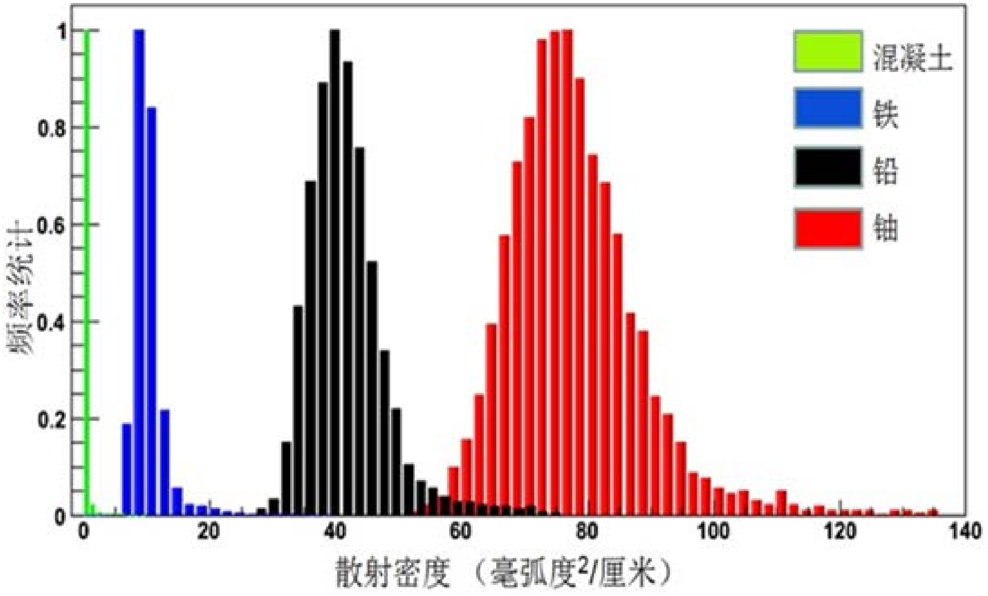
Research Background

- **Cosmic-Ray Muography(Muon Imaging Technology): Transmission vs. Scattering Tomography**

Cosmic-Ray Muons are secondary particles produced through the decay of atmospheric pions,.With a high mean energy (~4 GeV at sea level) and exceptional penetration depth (up to ~8 km water equivalent), these particles serve as ideal probes for imaging dense structures

  - Transmission Imaging： This technique reconstructs an object's geometric profile by statistically analyzing flux attenuation patterns.
  - Scattering Imaging： By measuring Coulomb scattering angles, this method enables material discrimination and Microstructure resolution





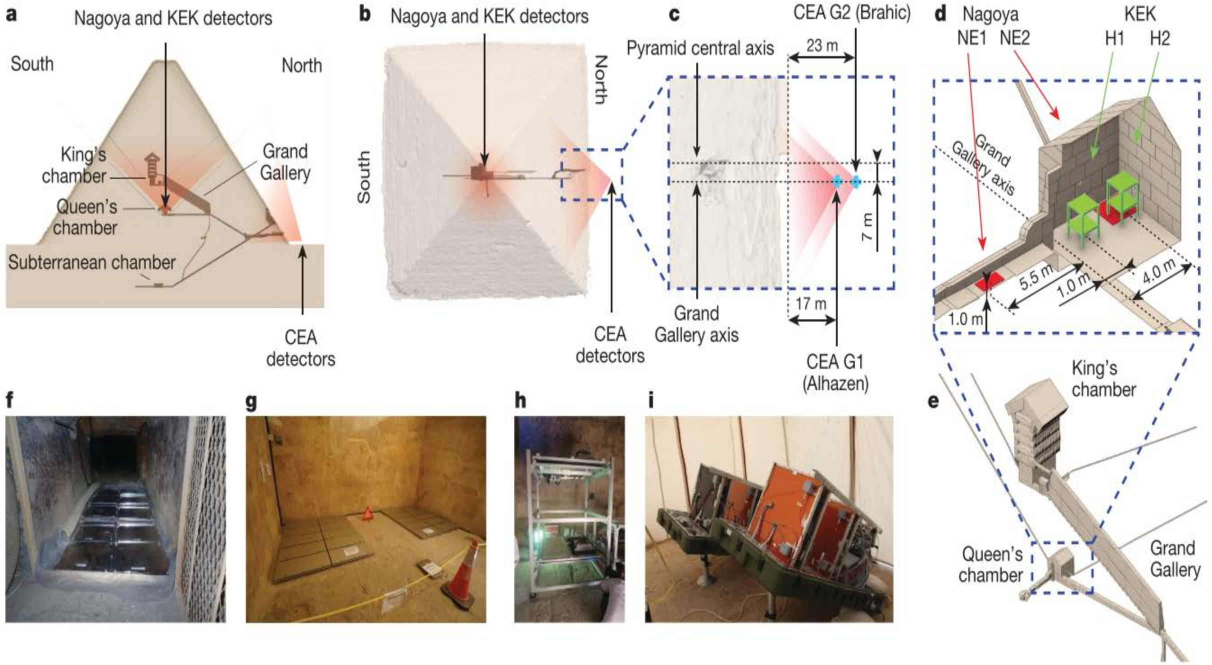
Research Background

- Muon Counting and Track Detection: Core Technologies for Muon Imaging Systems

  Current Mainstream Detectors: Gaseous Detectors, Scintillator-Based Detectors

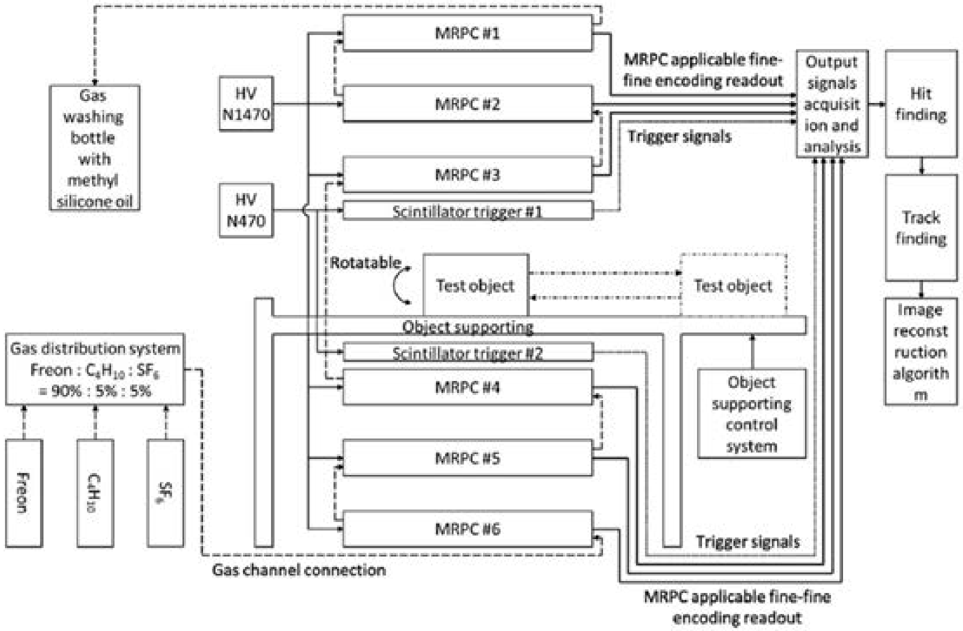
- Emerging Requirements for Next-Generation Systems:

  To **enable simultaneous transmission and scattering imaging**, modern Muography systems must fulfill the demands of **High Positional Resolution, Portability.**



Research Background

- Tsinghua University Muon Tomography (TUMUTY): An MRPC-Based Scattering Imaging System



Parameter:	
MRPC quantity	6
Gas consumption rate	800sccm
Position resolution	1mm
Sensitive area	1m×1m

(MRPCs) in Muon Tomography Systems:

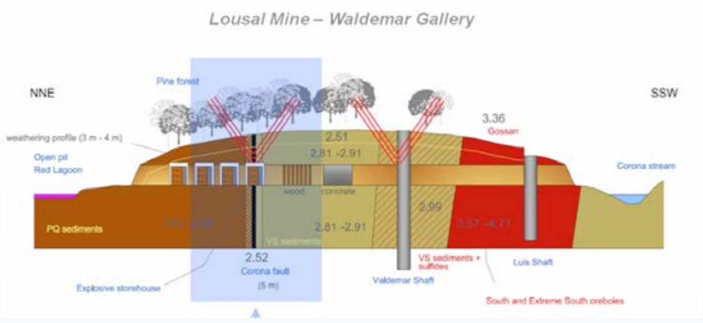
A Cost-Effective, High-Resolution Solution for Large-Area Detectors

Key Advantages of MRPC Technology for Muon Imaging:

International Research Status

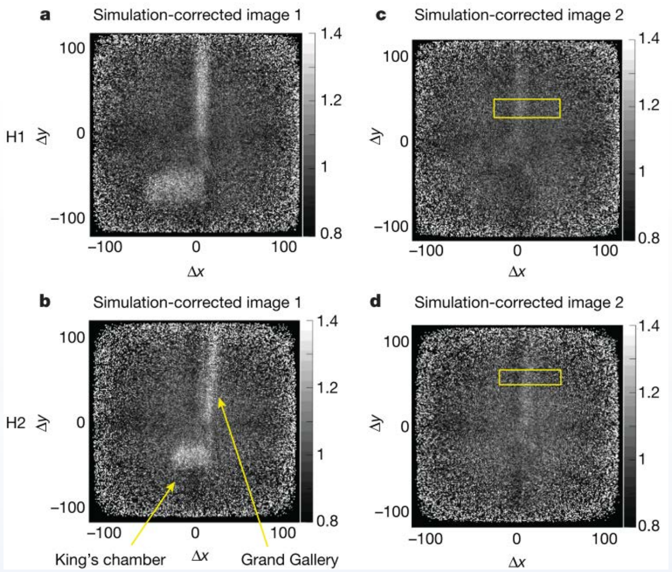
System status:

- **LANL (Los Alamos National Laboratory, USA)**
  Detector Type: Drift Tubes
- **AWE (Atomic Weapons Establishment, UK):**
  Muon imaging system based on wide-gap RPCs
- **AECL (Atomic Energy of Canada Limited):**
  Muon imaging system based on scintillators, equipped with calorimeters
- **INFN(Istituto Nazionale di Fisica Nucleare, Italy):**
  Muon imaging system based on drift chambers



Research status:

- (2017) A micromegas (Micro-Pattern Gas Detector)-based system was used to image the Great Pyramid of Khufu, revealing an approximately identified void space.
- (2022) RPC-based tunnel imaging was implemented.
- (2023) Scintillator-based imaging was employed for blast furnace inspection



Algorithm Upgrade:
The Necessity of Momentum Measurement

The momentum is a critical reference parameter in muon imaging, as evidenced by the mean scattering angle formula。

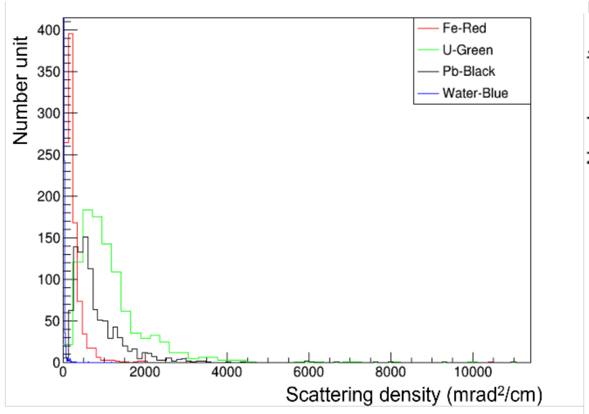
- Molière's theory provides a description of the multiple Coulomb scattering process: the projected components of the spatial scattering angle in both planes are independently and identically distributed (i.i.d.) and approximately follow a Gaussian distribution. The standard deviation of this distribution is related to the radiation length of the material and the momentum of the particle.

$$\sigma_\theta = \frac{13.6\mathrm{MeV}}{\beta c \boldsymbol{p}} \cdot z \cdot \sqrt{\frac{L}{L_{rad}}}\left[1 + 0.038\ln\left(\frac{L}{L_{rad}}\right)\right]$$

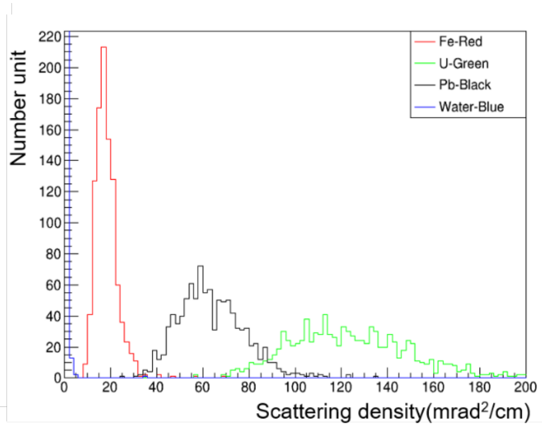
Simulation Case 1: Material Discrimination Under Short-Duration Muon Exposure (Rapid Identification)）

Simulation Results for 60s Discrimination of Uranium, Lead, and Iron

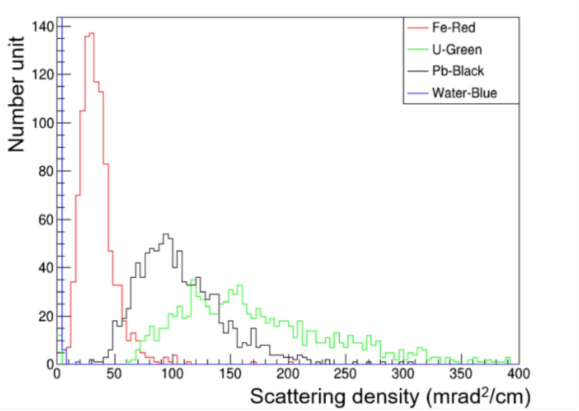
Without momentum:



Introduce precise momentum:



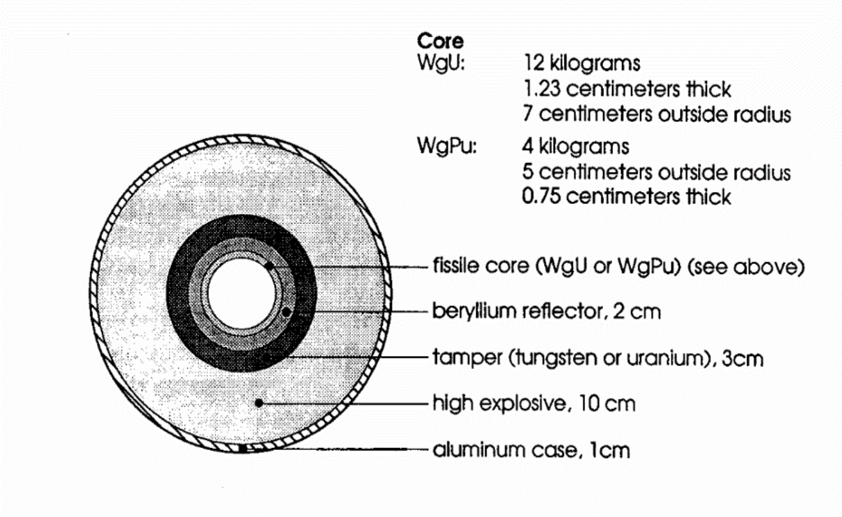
Considering momentum resolution:

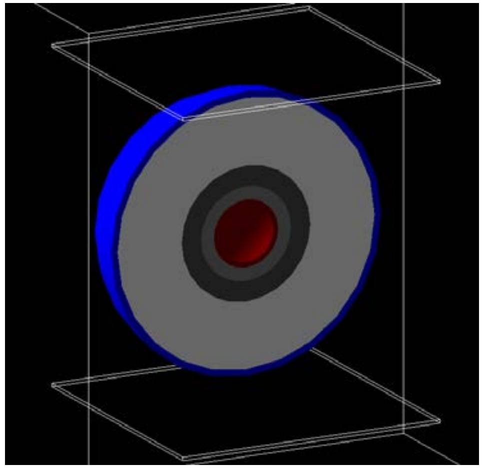


Algorithm Upgrade:
The Necessity of Momentum Measurement

Simulation Case 2: Fine-Grained Imaging with Monoenergetic Muons

Imaging Target: Standard Fetter Model





Algorithm Upgrade:
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Simulation Case 2: Fine-Grained Imaging with Monoenergetic Muons

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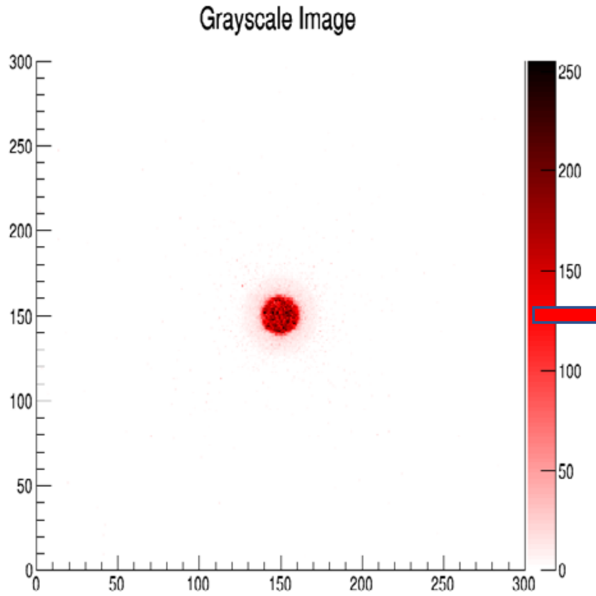
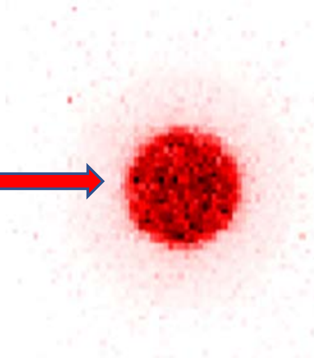




The left image shows the imaging results obtained from 76,000,000 naturally spectrum-sampled cosmic-ray muons incident on a 27 m^3 volume.

Upon magnification, it is evident that the outer layer consists of HMX, while the middle layer is a tamper encasing the fissile core.

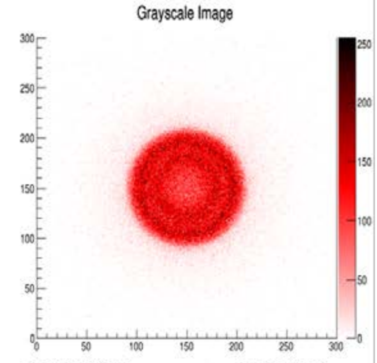
Based on sea-level muon flux and 46% geometric acceptance, the required imaging time was 11.58 hours.

Algorithm Upgrade:
The Necessity of Momentum Measurement

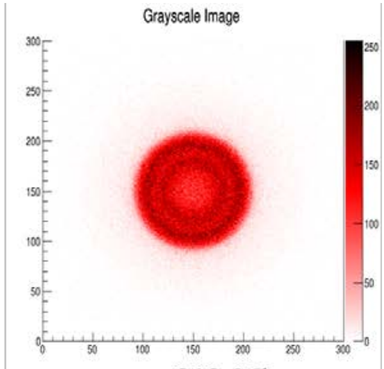
Simulation Case 2: Fine-Grained Imaging with Monoenergetic Muons

Imaging Target: Standard Fetter Model

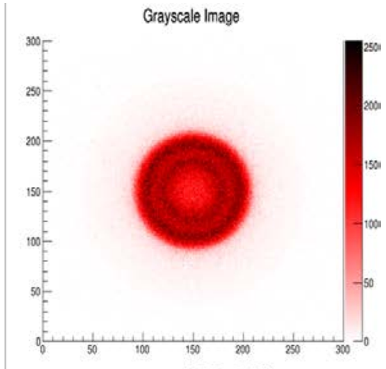
Set the kinetic energy to 0.5 GeV with near-vertical incidence.



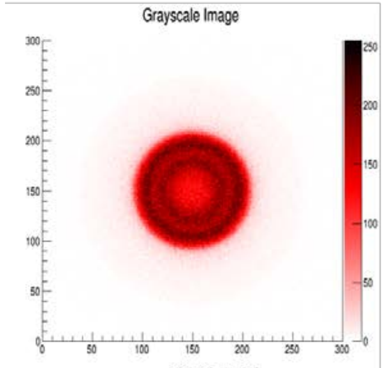
1794973muon ≈ 156.53h



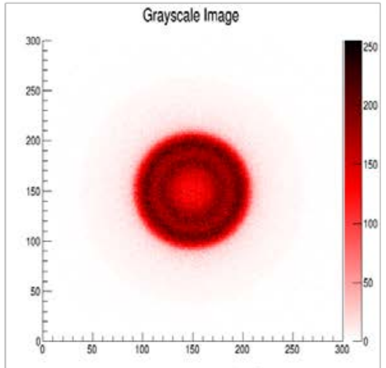
≈ 313.06h



≈ 469.59h



≈ 626.12h



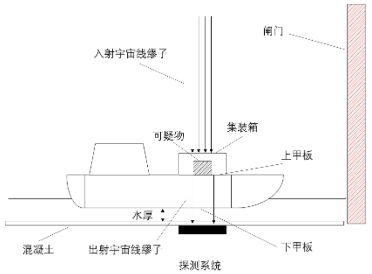
≈ 782.65h

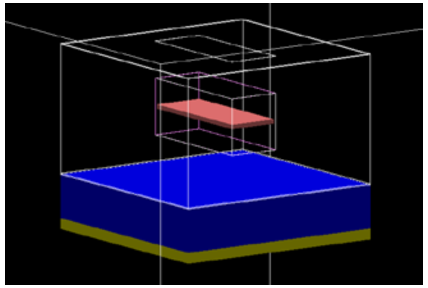
The imaging reveals the following layered structure (from outer to inner):

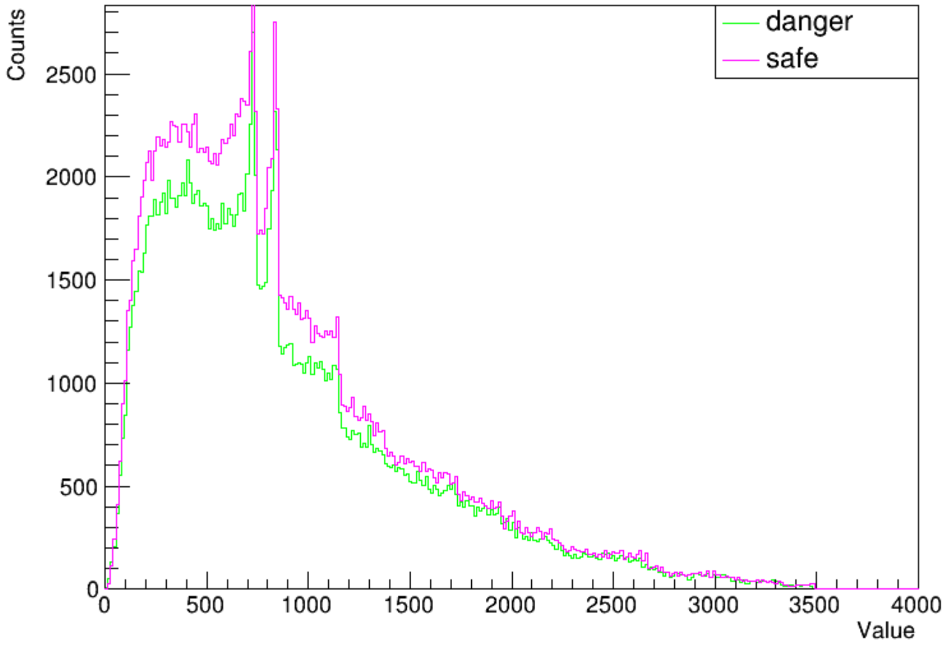
HMX (light red)
Tamper (U) (light)
Tamper (U) (dark)
Be (beryllium)
Fissile core (U)
Hollow core

Algorithm Upgrade:
The Necessity of Momentum Measurement

Simulation Case 3: Energy Spectrum Analysis in Cargo Transmission Imaging Scenario Inside a Ship Hull







The flux variation of low-energy muons shows significant differences.

System Implementation: Cosmic Ray Detection System with Momentum Measurement Capability

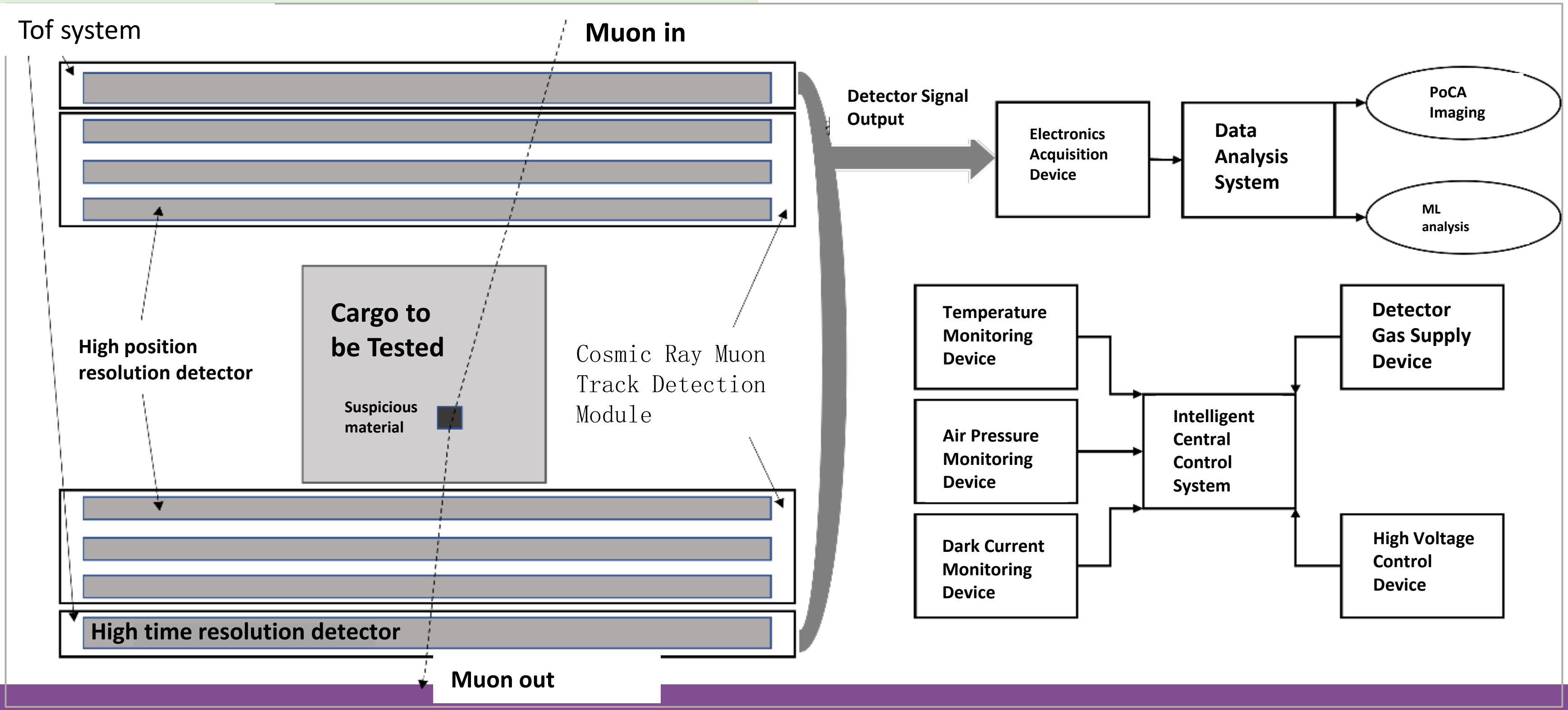
Deficiencies of Traditional Muon Imaging Systems and Requirements for Momentum Measurement

Position-Sensitive Detector:

Submillimeter spatial resolution (≤500 μm)
Large active area (e.g., ≥0.5 m²) with portability
Multi-scene compatibility (transmission/scattering modes)

Muon Momentum Detection via Time-of-Flight Method:

Time resolution at the 20-picosecond level
Feasibility for large-area fabrication



Overall Design of a Muon Imaging System

- Muon Imaging System Based on Position-Sensitive Sealed MRPCs

- System Requirements:

- 6 independent sealed MRPCs arranged in two layers (3+3):
- Upper layer (3 MRPCs): Measures pre-scattering muon trajectories
- Lower layer (3 MRPCs): Measures post-scattering muon trajectories
- 2 large-area scintillator detectors for external coincidence triggering
- Multiplexing technology required to reduce electronic channel count due to high signal channel numbers

Design Approach

Total Sensitive Area
- Total Sensitive Area: 45×45 cm²

Strip size
- Strip Design:
  Strip width: 1.44 mm
  Inter-strip gap: 1.1 mm

configuration
- Configuration:
  Two columns (3 detectors per column)
- Trigger System:
- Scintillator detectors positioned above/below MRPCs for external triggerin

structure
- MRPC Parameters:
- Single chamber: 5 gas gaps
- Gap width: 0.25 mm
- Type: Sealed MRPC
- Readout method: Microstrip single-ended

electronics

other
- Additional Systems:
- Mechanical structure
- Gas & high voltage supply

Design of sealed MRPC

- Design and Key Technical Considerations

 Large-Area High-Efficiency Sealed Structure

 3D-printed sealed frame

 combined with high-voltage electrode glass.

Bonding method: Epoxy resin adhesive.

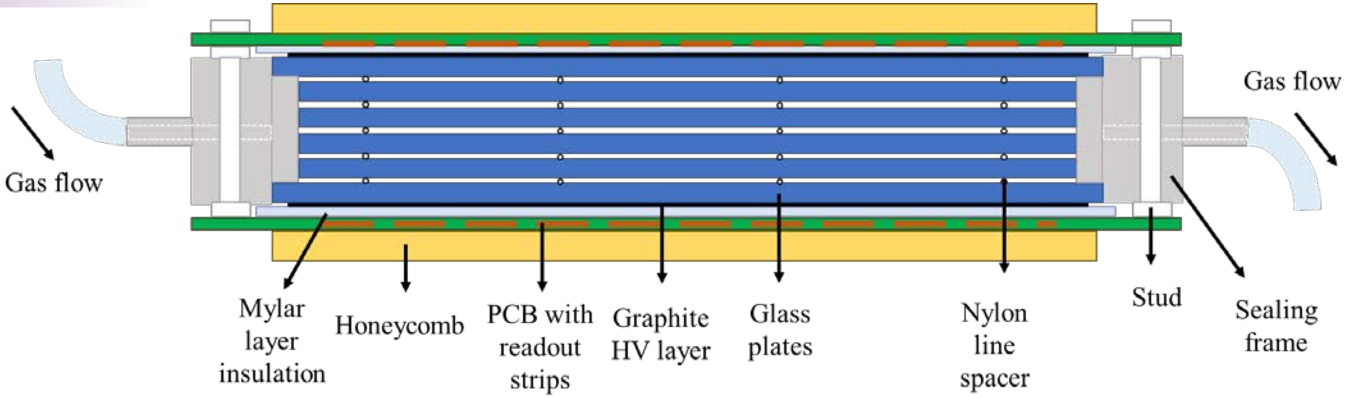
Precision machining: Ensures conformity

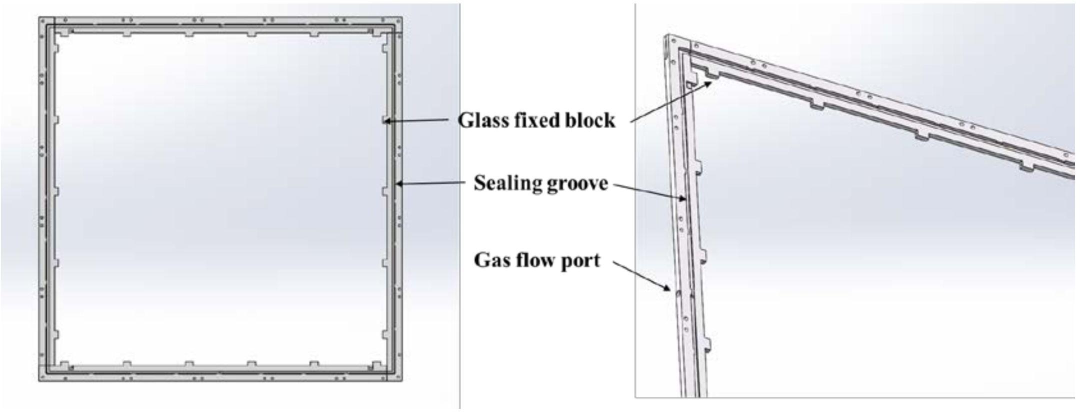
 with specified thickness and mechanical dimensions.

Support structure:

  Auxiliary parallel fishing wires for enhanced rigidity

  and reliable mechanical support





- 2. Key Technical Challenges

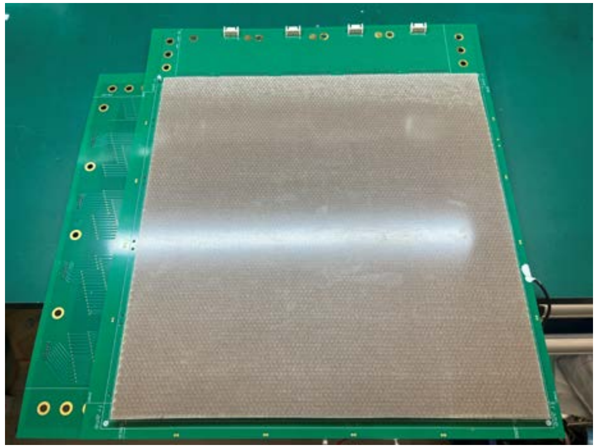
High mechanical precision: ±0.05 mm tolerance.

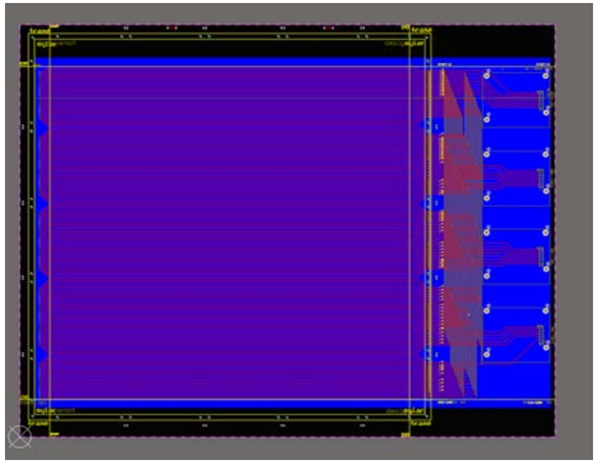
Low outgassing materials (critical for gas detector stability).

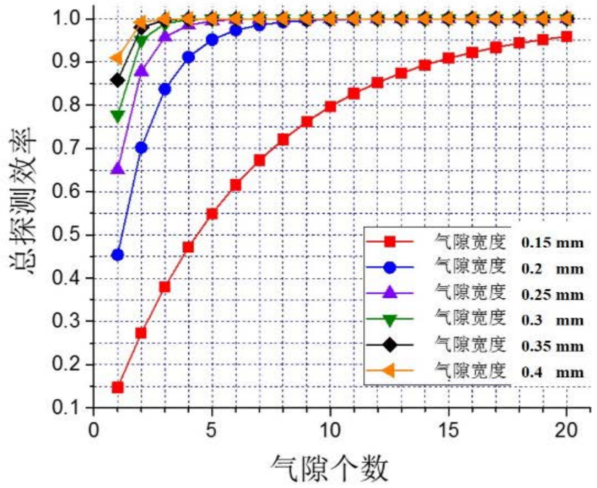
Electrical insulation stability: Must withstand ±12 kV without breakdown.

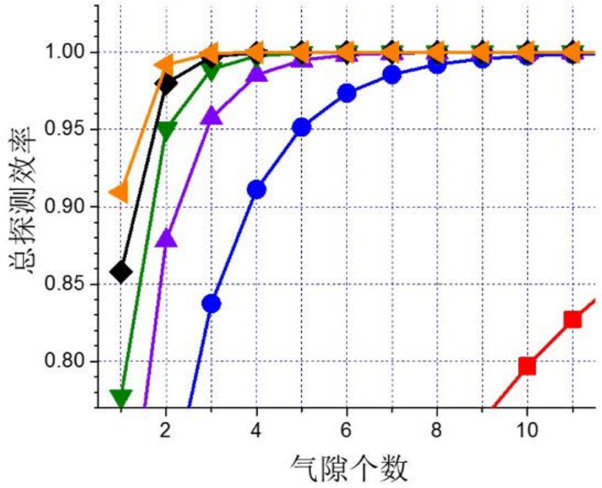
Fast-curing adhesive for efficient assembly while maintaining structural integrity.

Design of sealed MRPC









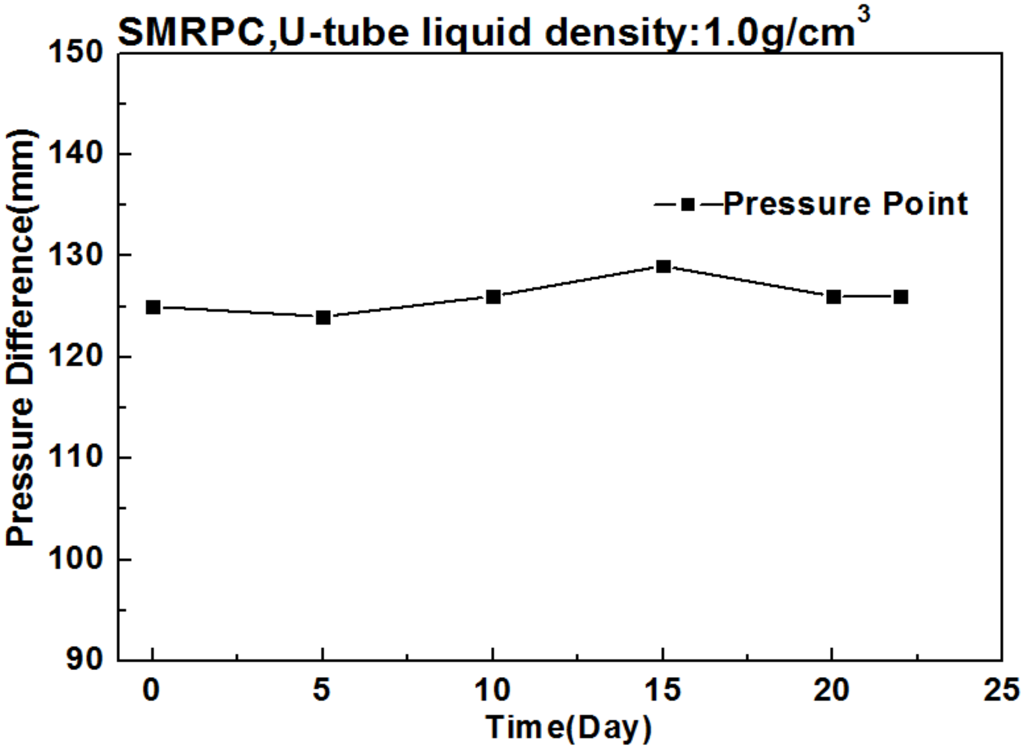
N of strips	160
N of gaps	5
Gap thickness(mm)	0.25
Glass thickness(mm)	0.7
High Voltage	±6700
Active area(mm^2)	500×500
Strip interval(mm)	1.44+1.1
Strip length(cm)	42

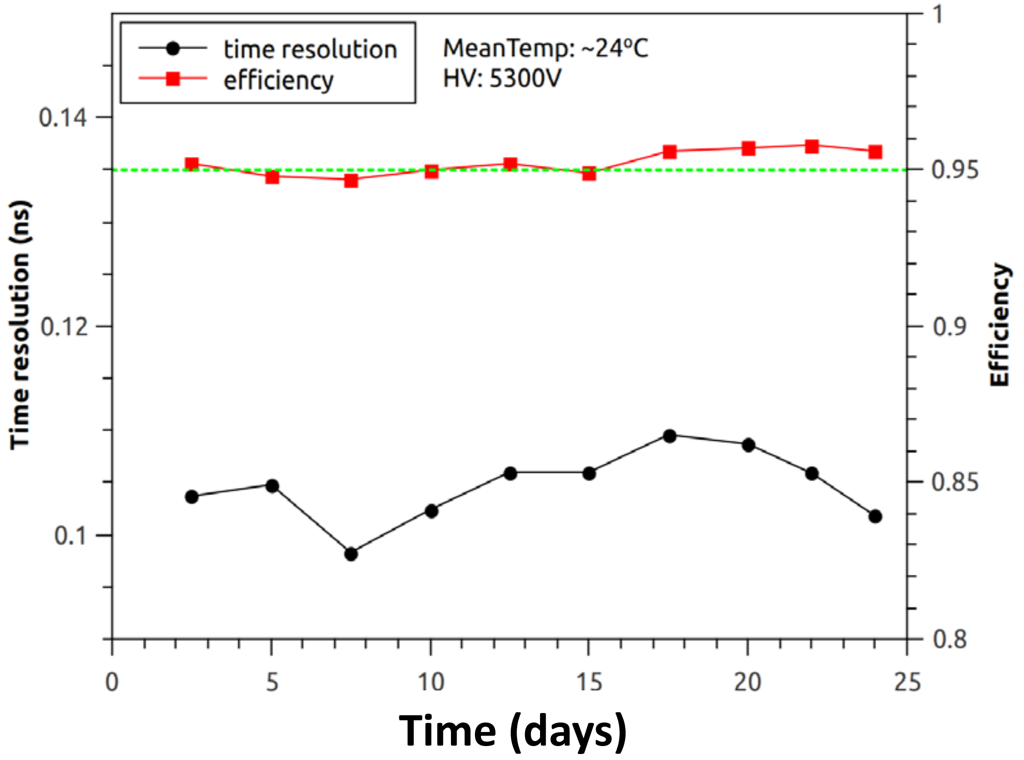
Performance research

- Prototype Design Focus: Gas Tightness and Performance Stability

22-day airtightness test: Internal pressure remained constant.

Long-term stability test: Performance maintained stability for 1 month under an extremely low gas flow rate of 1 mL/min.





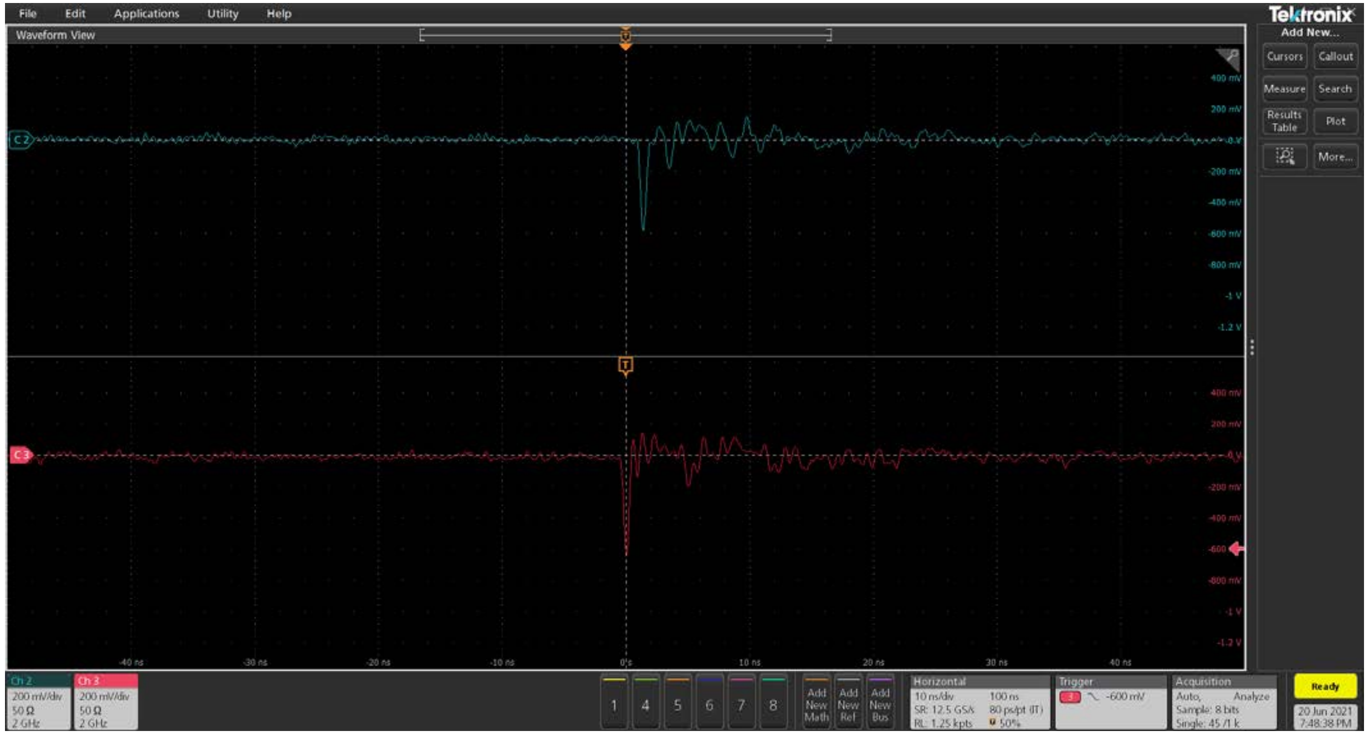
Performance research

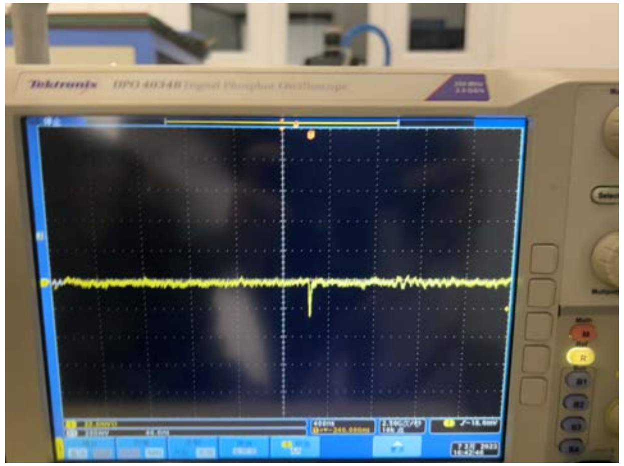
- Signal Characteristics of the Engineering Prototype Providing Guidance for Front-End Amplifier Design

The detector signals are directly extracted and analyzed using an oscilloscope to investigate the waveform features of cosmic-ray-triggered MRPCs.

- Single-Ended Signal Characteristics:

Amplitude: ~10 mV
Rise time: 100–500 ps
FWHM: 500 ps –1 ns
Fall time: ~500 ps
Output impedance: ~50 Ω

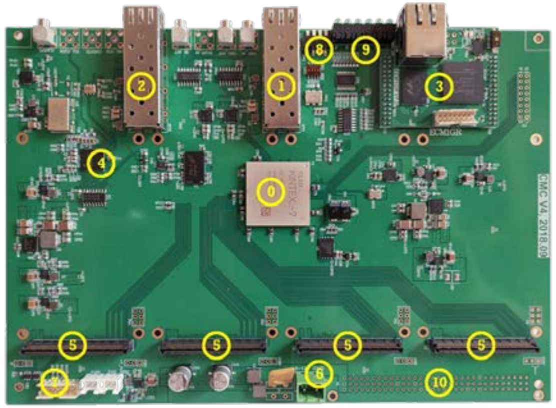


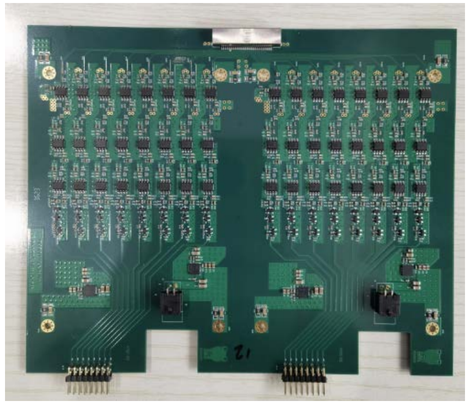


Construction and Testing of the Track Detection System

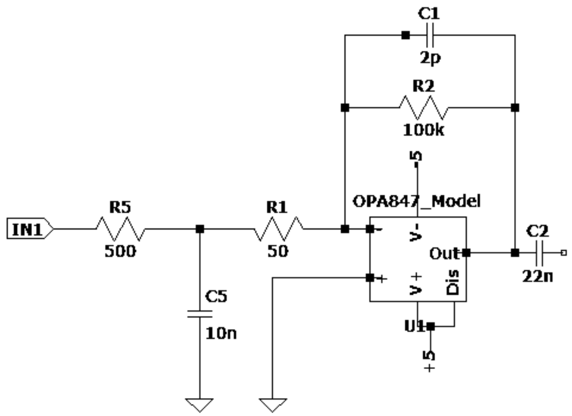
Electronics

- Retaining the front-end amplifier used in TUMUTY with modifications for compatibility with the new system.
- The data acquisition employs a GRS AD64A waveform sampling system based on an 8-channel ADC, totaling 384 sampling channels, with an adjustable sampling rate of up to 80 MS/s.





GRS AD64



RC active filter

FEE design

- The current-sensitive preamplifier lacks integrating capability, and the MRPC output pulse width (~10 ns) is poorly matched with the 80 MS/s sampling rate. Therefore, an RC active filter circuit was added at the output stage of the original circuit to stretch the pulse waveform

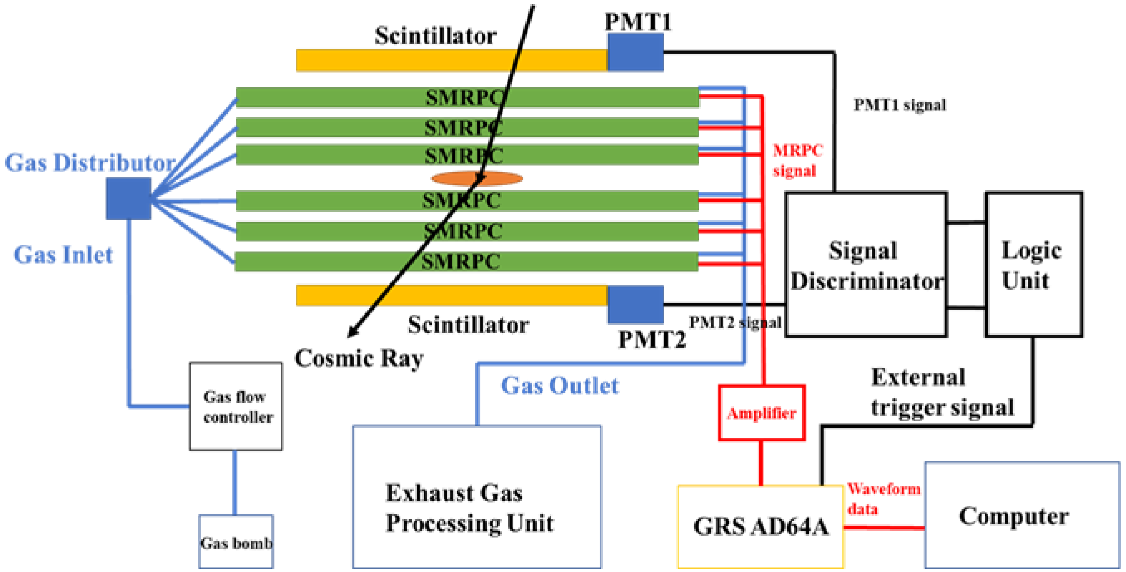
Program

- DAQ Host Program Modification:
  The host program has been rewritten to adjust built-in parameters, including division-based search time and data output format, ensuring compatibility with the system.

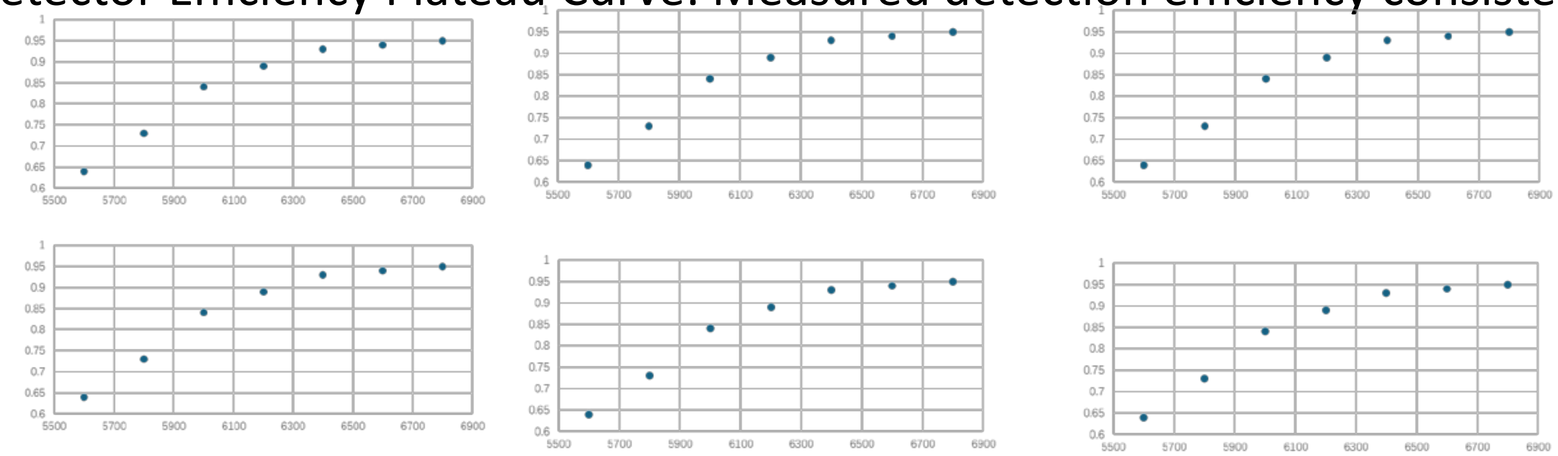
- DAQ Data Processing Program:
  Includes packet parsing and waveform visualization, supporting both decimal and binary operation modes.

- Post-Processing Program:
  Performs position demultiplexing, track reconstruction, and statistical performance analysis.

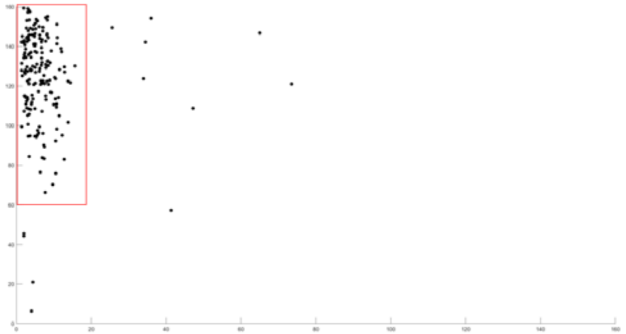
- Gas System Design: A parallel gas distribution scheme is employed, where the main gas line splits into multiple branches to ensure sufficient and uniform gas flow across all detectors.
- Trigger System: Plastic scintillator detectors are used for external triggering.
- Gas Monitoring & HV Distribution: Gas tightness is monitored via silicon oil bubblers. A voltage divider/filter box is utilized for high-voltage (HV) distribution.

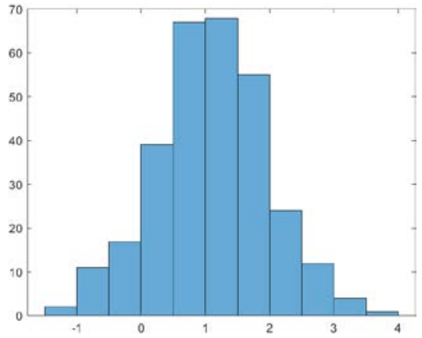


- System Performance Initial Testing Results:
- Detector Efficiency Plateau Curve: Measured detection efficiency consistently exceeds 95%.

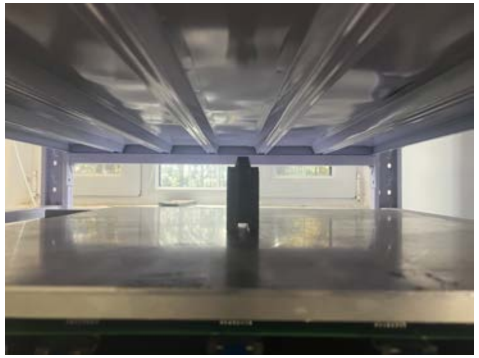


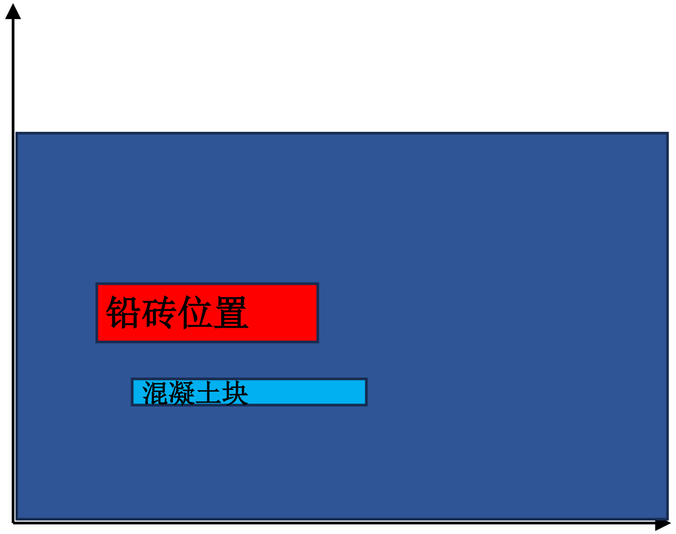
- Position Resolution (Cosmic Ray Test):Track reconstruction using three-detector coincidence fitting achieves a position resolution of ~0.8 mm.





Initial imaging of the lead brick was performed using the POCA algorithm.



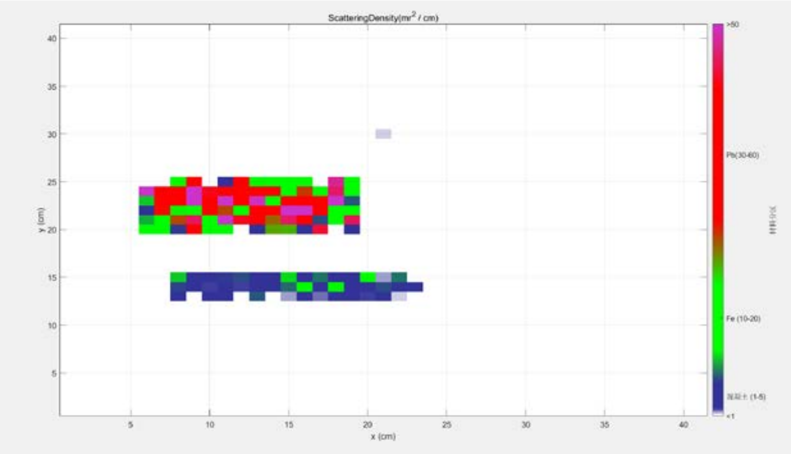


The sensitive area was divided into a 40×40 pixel array, with each pixel consisting of 4 readout strips (2.54 mm each), resulting in a pixel size of 10.16 × 10.16 mm².

Using the POCA (Point of Closest Approach) algorithm, the mean squared scattering angle (⟨θ²⟩) was calculated for each pixel region. The scattering intensity (λ) within each pixel was then determined using the following formula:

$$\sigma_{\theta}^{2} = \lambda_{L_{rad}} L$$

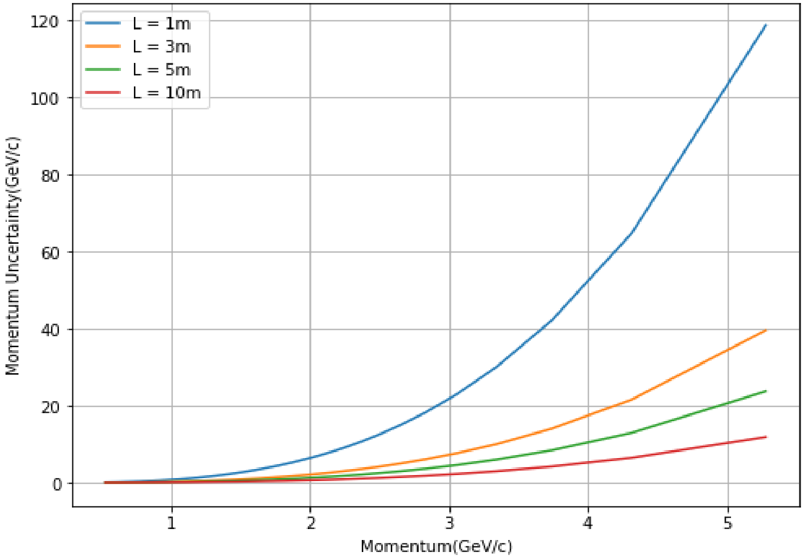
where L = 7 cm (thickness of the lead brick)



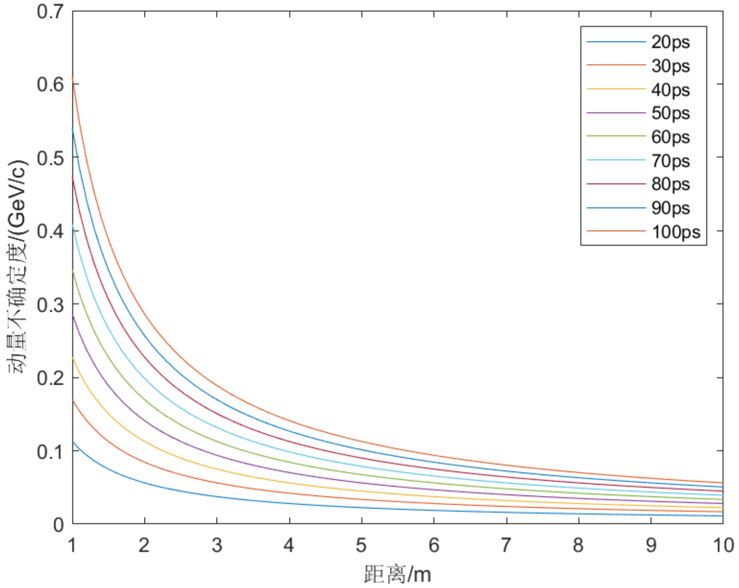
Development of a Momentum Measurement System: Design of a Large-Area, High-Time-Resolution MRPC

Measuring muon momentum using the time-of-flight (TOF) method imposes stringent requirements on the MRPC's time resolution.

The precision of TOF-based momentum measurement is primarily influenced by two key factors:
Detector spacing (TOF-Detector distance)
Detector time resolution

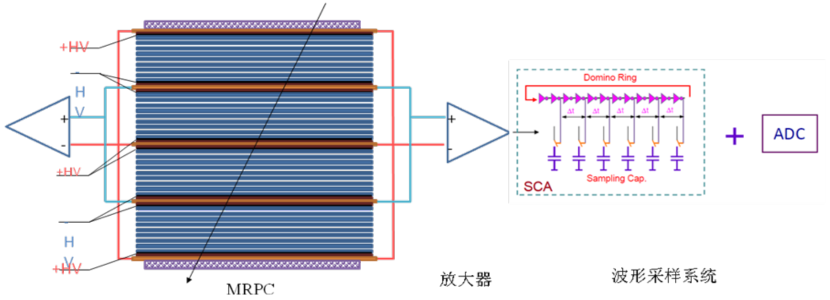


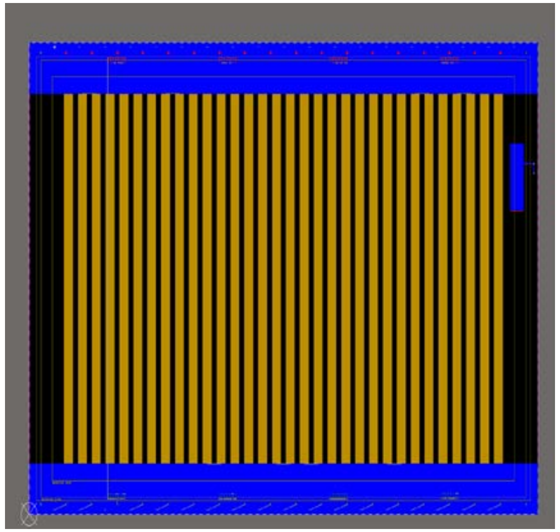
Momentum measurement uncertainty across different muon energy ranges, under varying detector spacings at a time resolution of 30 ps.



Under the condition of measuring muons with a momentum of 1 GeV/c, the momentum measurement uncertainty varies with different time resolutions.

Development of a Momentum Measurement System: Design of a Large-Area, High-Time-Resolution MRPC

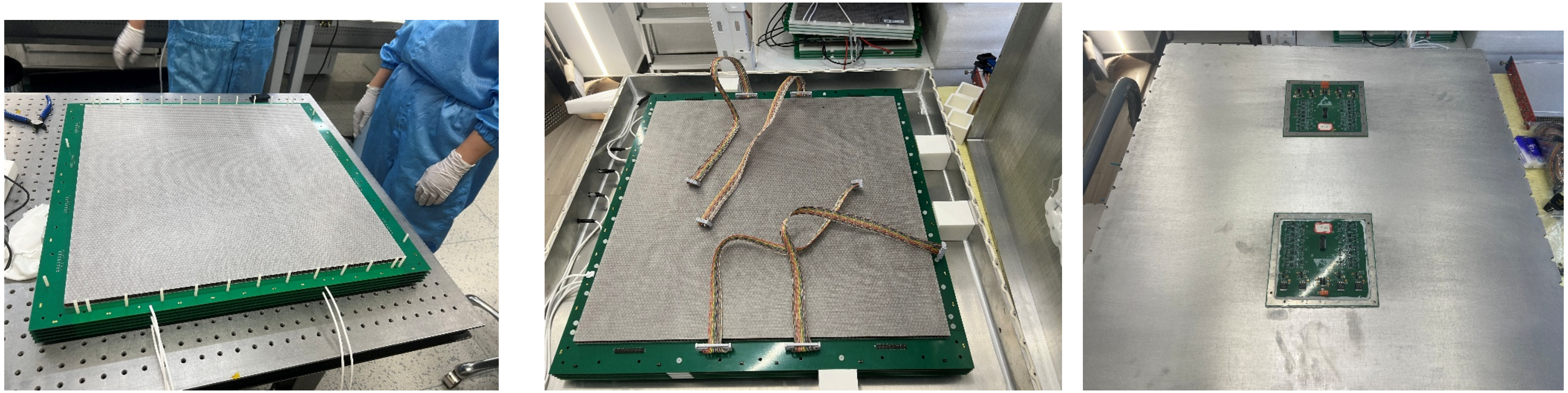




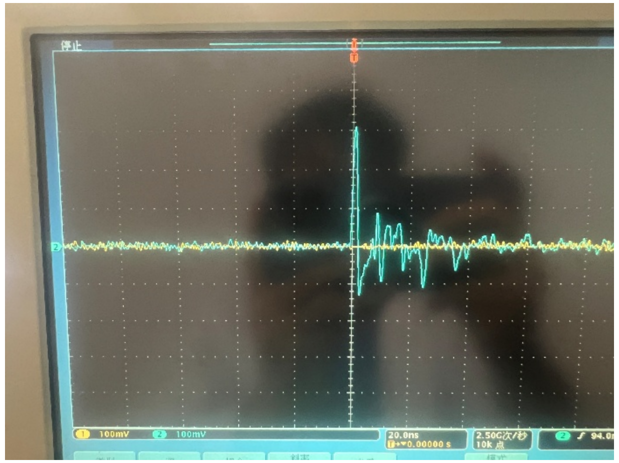
MRPC Detector Specifications:

Sensitive area: 50 × 50 mm²
Readout channels: 32
Readout strip pitch: 1.3 cm (+ 0.2 cm intergap)
Gas gap thickness: 0.128 mm
Operating field strength: 100 kV/cm
Achievable time resolution: ~30 ps

Development of a Momentum Measurement System: Design of a Large-Area, High-Time-Resolution MRPC



Large-Area High-Time-Resolution MRPC Prototype

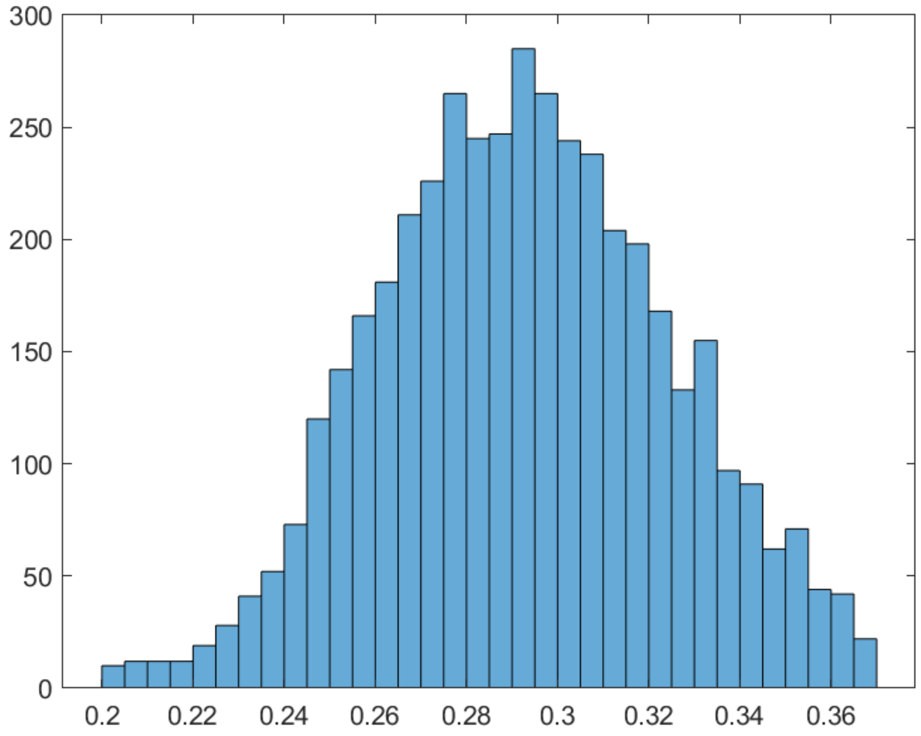


Raw Signals from Front-End Electronics in a Large-Area High-Time-Resolution MRPC Prototype

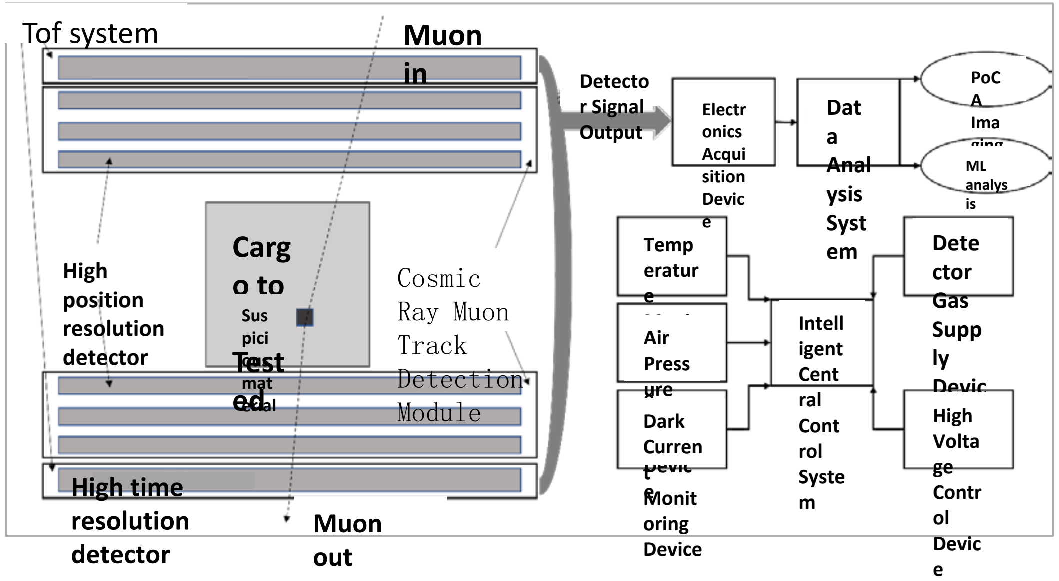
Time resolution test

Test system

Time resolution:31ps



Future Work Plan



Plan for System Installation and Testing in a 10m-High Experimental Hall

Thanks！