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A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

Junghyun Bae, Ph.D.

School of Nuclear Engineering, Purdue University

***Eugene P. Wigner Distinguished Staff Fellow*, Oak Ridge National Laboratory**

USA

27 July 2022

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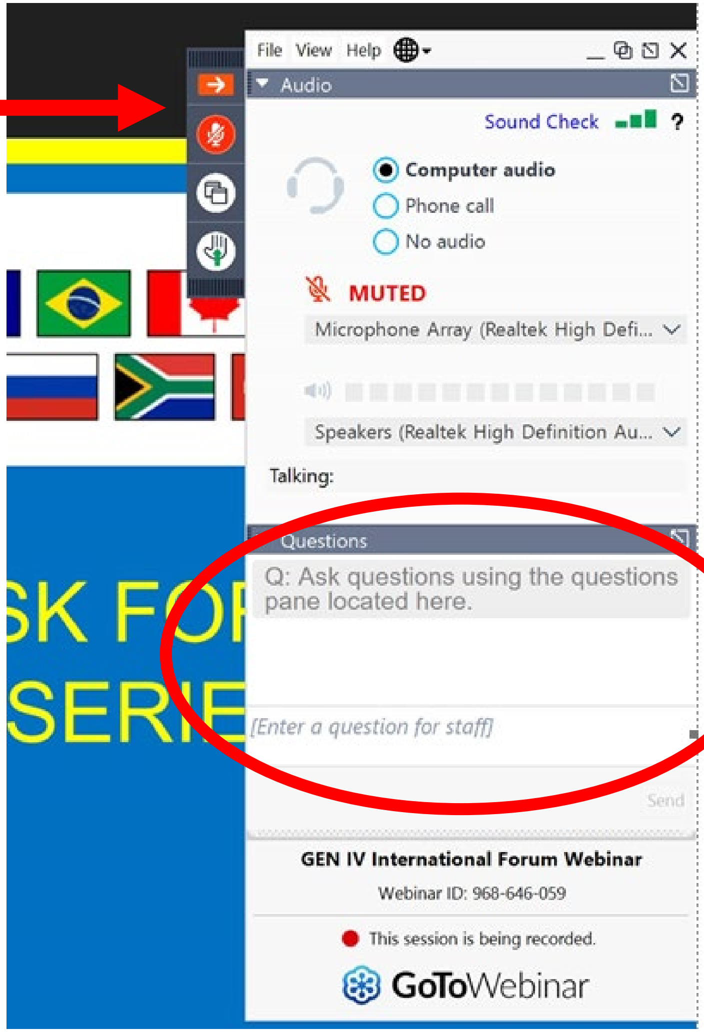

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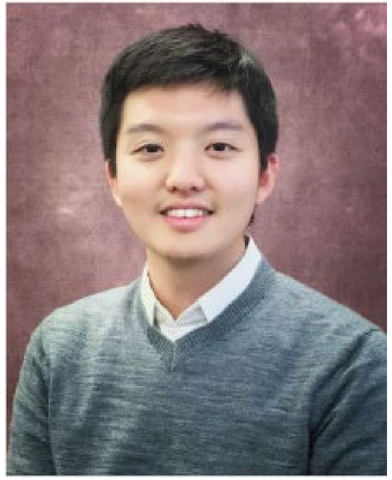
Meet the Presenter



Dr. Junghyun Bae recently completed his Ph.D. at the School of Nuclear Engineering at Purdue University. He will join the Used Fuel and Nuclear Material Disposition group of the Nuclear Energy and Fuel Cycle Division at the Oak Ridge National Laboratory as a *Eugene P. Wigner Distinguished Staff Fellow*.

His research focuses on the development of a high-resolution fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications, i.e., muon tomography, nuclear security, Spent Nuclear Fuel (SNF) casks imaging. He earned his M.S degree in nuclear engineering from the University of California, Berkeley and his B.S. degree in Nuclear and Quantum Engineering from the Korea Advanced Institute of Science and Technology (KAIST).

Dr. Bae won the ‘Pitch Your PhD’ competition during the 2021 ANS Winter Meeting and Technology Expo in Washington, D.C. He has also been nominated and awarded the Roy G. Post Foundation scholarship, ANS, and KSEA graduate scholarships for his contribution to the safe management of nuclear materials.

Email: Bae43@purdue.edu

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

GEN IV International Forum
Expertise | Collaboration | Excellence

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

GEN IV International Forum
Expertise | Collaboration | Excellence

I. Introduction

1. Motivation

- Muon tomography has been emerged as one of promising non-invasive monitoring and imaging techniques for dense and large objects.
- Cosmic ray muons have benefits over traditional induced radiation probes for non-destructive imaging due to their high-energy (109~12 eV vs 103~6 eV)
- For example,
  - Spent nuclear fuel cask imaging
  - Nuclear reactor (e.g., monitoring damaged reactor core in Fukushima nuclear site)
  - Nuclear materials inspection in a cargo container
  - Archeology (e.g., finding a hidden chamber in the Great Pyramid of Giza)
  - Geotomography (e.g., investigating magma chamber underneath volcano to predict upcoming eruption)

I. INTRODUCTION

2. Problem Statement

- Benefits of measuring muon momentum in muon applications (monitoring and imaging) has been explored.
- Therefore, often a mean cosmic ray muon momentum value (3–4 GeV/c) represents the entire spectrum.
- Because none of existing muon spectrometers can be deployed in the field.

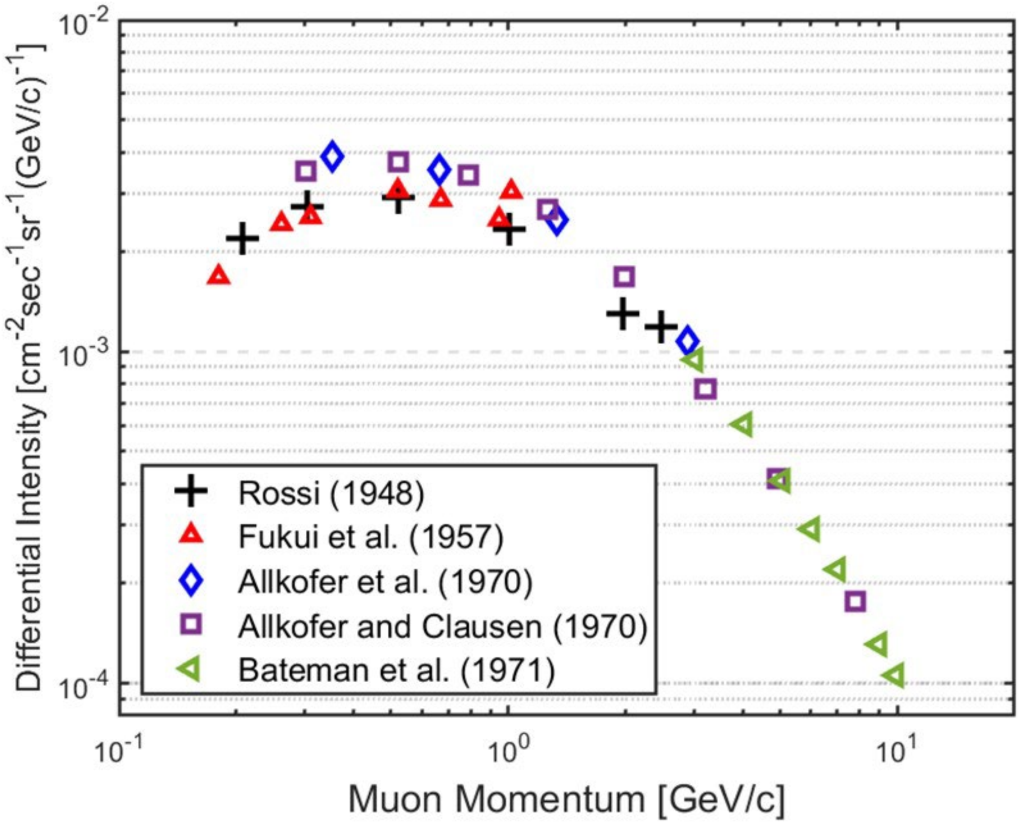


Fig. 1.1 Vertical differential cosmic momentum spectrum at sea level with zenith angle 0°

Grieder, P. K. F. (2001). Cosmic Rays at Earth. In Elsevier Science. Elsevier Science.

I. INTRODUCTION

2. Problem Statement

Importance of measuring muon momentum

$$\sigma_\theta = \frac{13.6\ MeV}{\beta c p}\sqrt{\frac{X}{X_0}}\left[1 + 0.088\log_{10}\left(\frac{X}{X_0}\right)\right]$$

- σ_θ: standard deviation of scattering angle distribution
- βcp: product of cosmic muon velocity and momentum
- X/X_0: Ratio of scattering length to radiation length

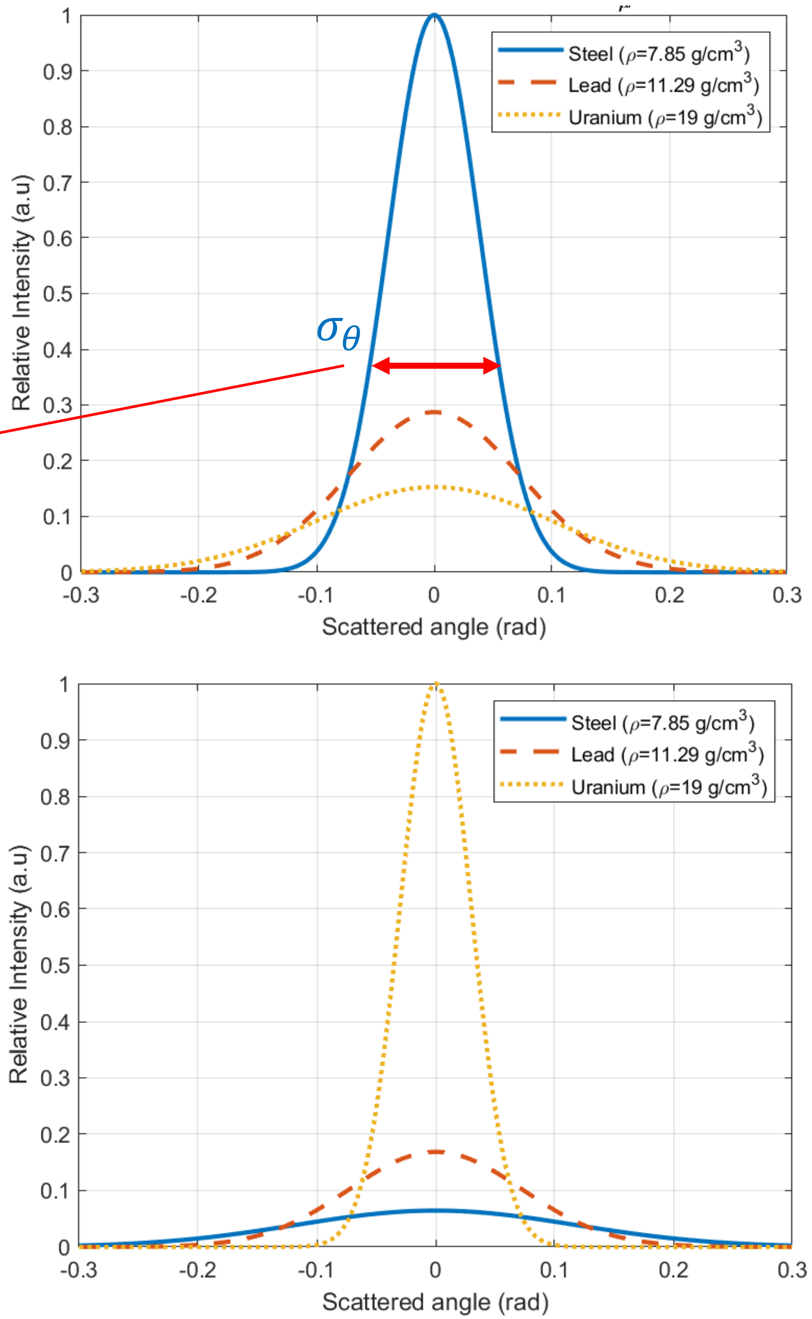


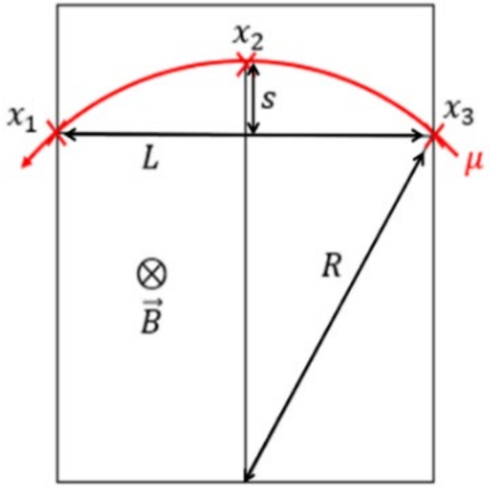
Fig. 1.2 Reconstructed Gaussian distributions for steel, lead, and uranium when muon momentum is 3 GeV/c (top) and 1, 3, and 10 GeV/c (bottom).

I. INTRODUCTION

2. Problem Statement

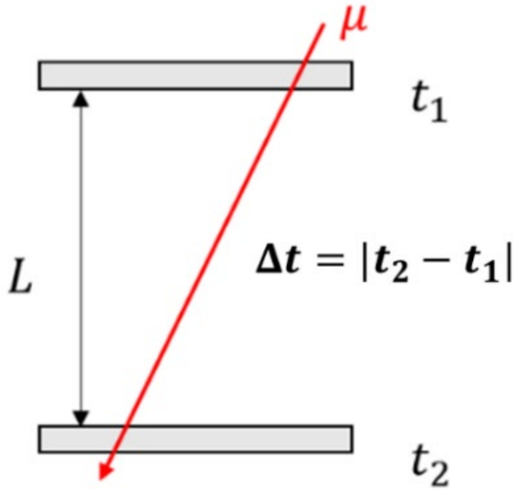
Three existing techniques to measure muon momentum

Magnets



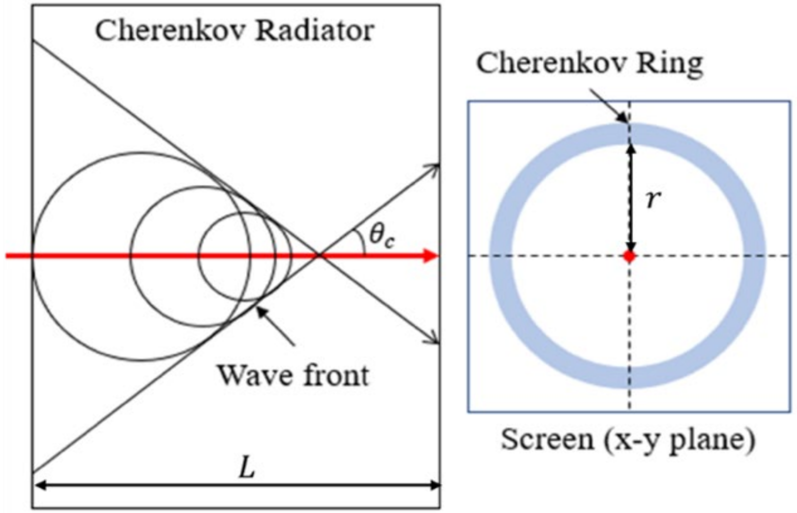
- High resolution
- Large and bulky magnets are required
- Impact the muon trajectory

Time of Flight



- Low resolution
- Long distance is required

Cherenkov Ring Imager



- High resolution
- Liquid radiator is required
- Array of optical sensors are required

I. INTRODUCTION

3. Research Objective

1. Development of fieldable muon spectrometer

   * Requirements in design
   - Easily coupled with existing muon tomography system
   - Compact, portable, and light-weight
   - Compatible momentum measurement resolution
   - High accuracy
   - Preserve incoming and outgoing muon trajectories
2. Development of momentum-integrated imaging algorithm without increasing computational costs
3. Improvement in imaging resolution and reducing monitoring times in various muon applications

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

GEN IV International Forum
Expertise | Collaboration | Excellence

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

1. Operational Principle

- Cherenkov Effect

$$\beta_\mu n > 1$$ Criterion for Cherenkov radiation

$$p_{th}c = \frac{m_\mu c^2}{\sqrt{n^2 - 1}}$$ Cherenkov threshold momentum, $\boldsymbol{p_{th}}$

- Lorentz-Lorenz Equation

$$n \approx \sqrt{1 + \frac{3A_m p}{RT}}$$ Refractive index (***n***) of gas as a function of ***p*** and *T*

$$p_{th}c = m_\mu c^2 \sqrt{\frac{R}{3A_m}\frac{T}{p}}$$ Threshold momentum, $\boldsymbol{p_{th}}$, gas as a function of ***p*** and *T*

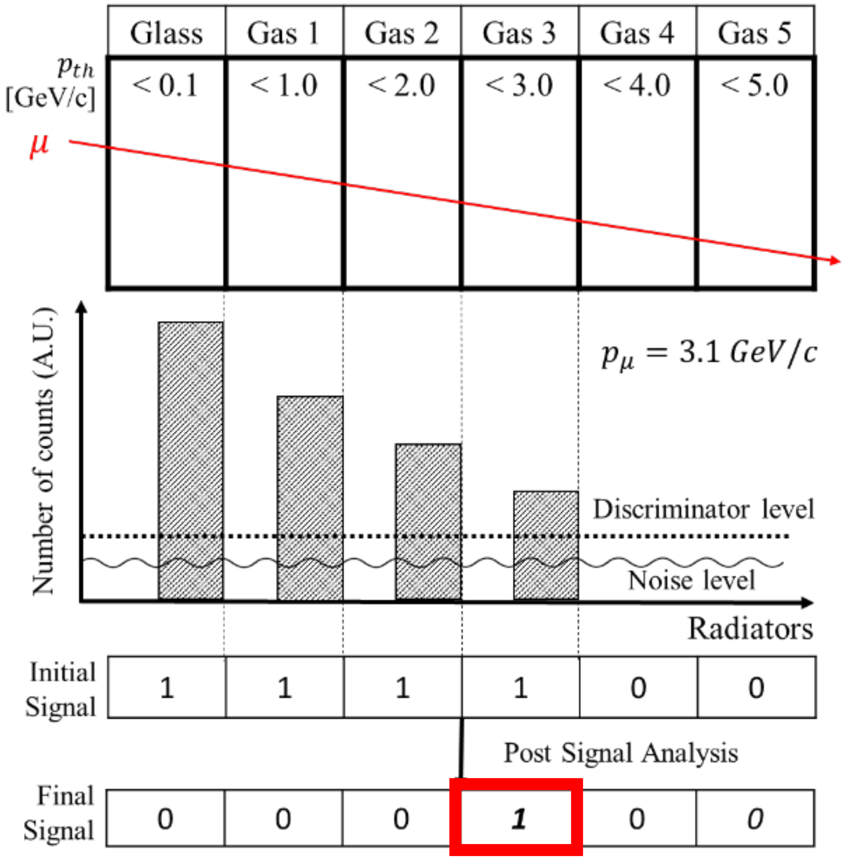


Fig. 2.1 Operational principle of Cherenkov muon spectrometer

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

1. Operational Principle

Prototype Design

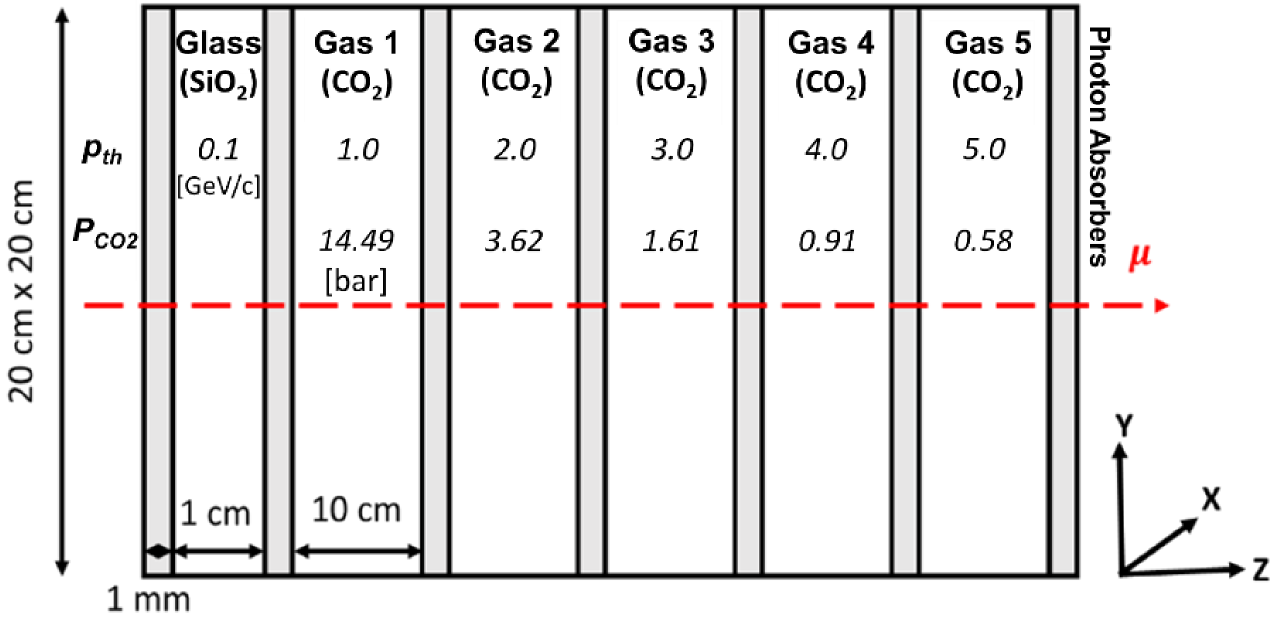


Fig. 2.2 Overview of Cherenkov muon spectrometer using one SiO_2 and five pressurized CO_2 radiators.

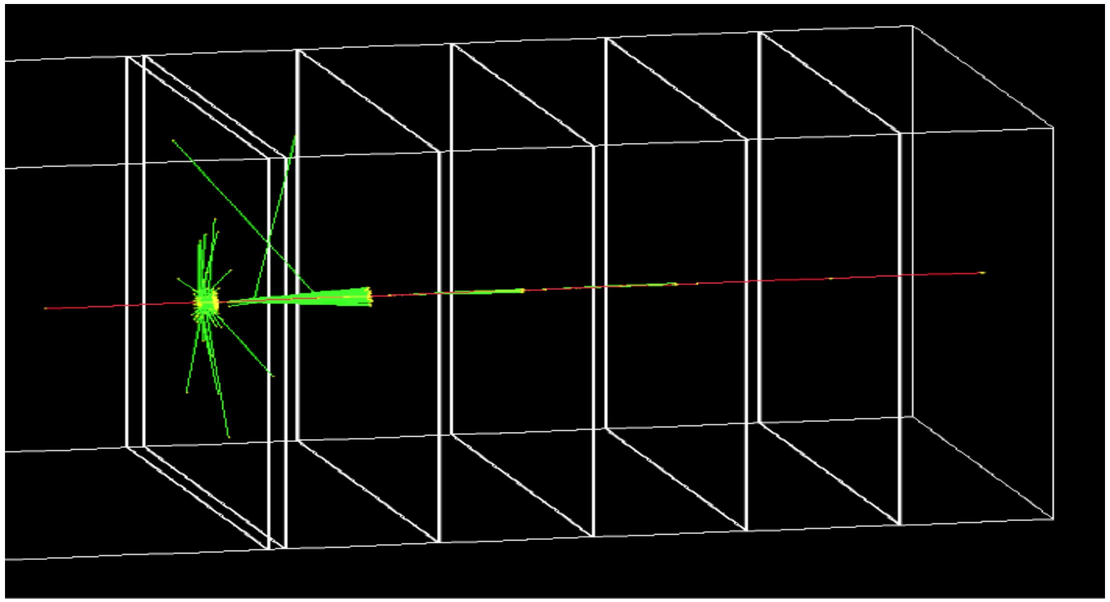


Fig. 2.3 Visualized Gean4 simulation when p_{μ}= 3.1 GeV/c

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

2. Optical Photon Emission

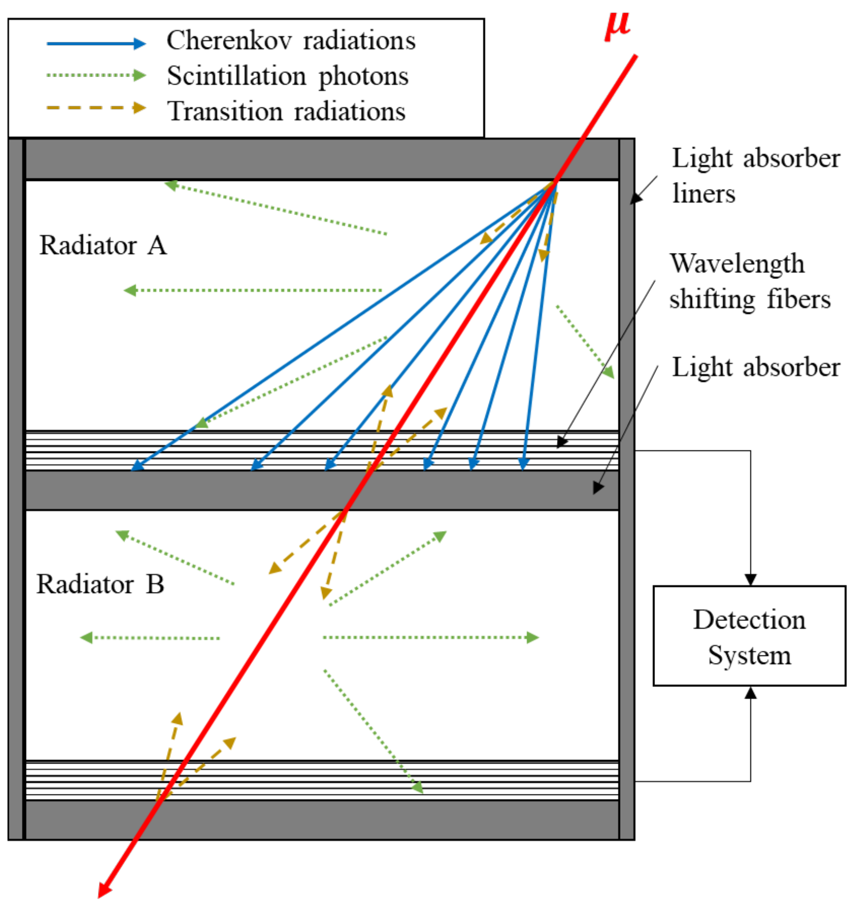


Fig. 2.4 Three optical photon emission mechanisms

1. Cherenkov radiation

$$\frac{dN_{ch}}{dx} = 2\pi\alpha \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) \frac{d\lambda}{\lambda^2}$$

- dN_{ch}/dx: Light intensity of Cherenkov radiation in a unit length
- α: Fine structure constant
- n: Refractive index
- $\lambda_{1,2}$: Lower and upper limit of Cherenkov light wavelength

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

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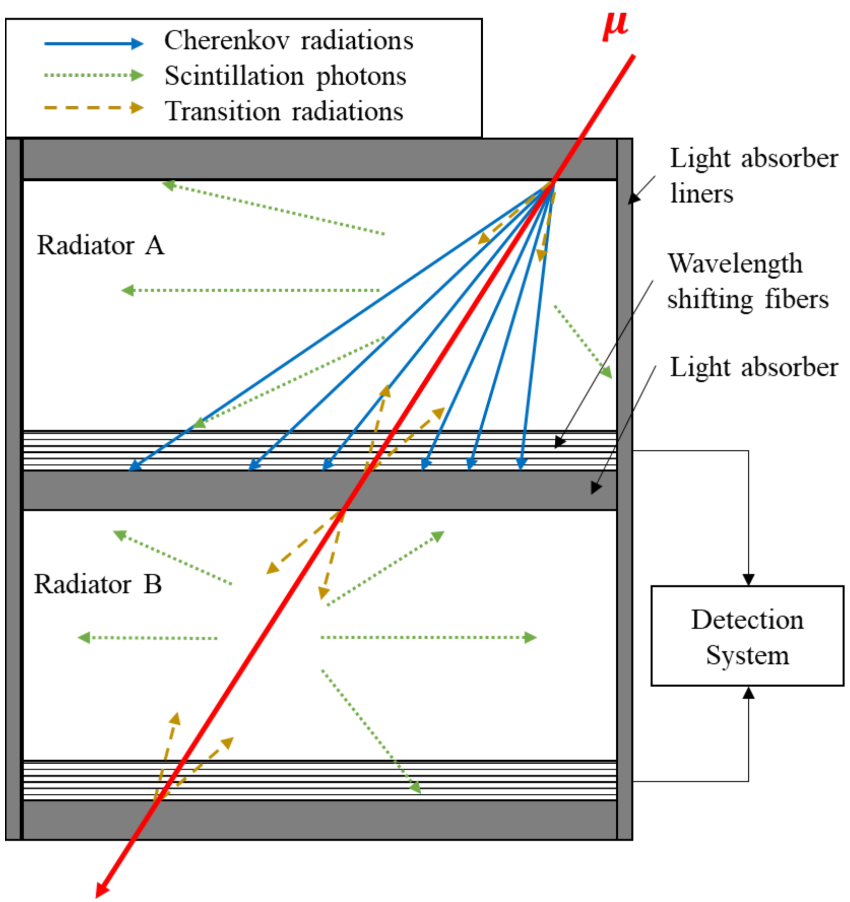

Fig. 2.4 Three optical photon emission mechanisms

2. Scintillation

$$\frac{dN_{sc}}{dx} = S\frac{dE/dx}{1 + k_B(dE/dx)}$$

- dN_{sc}/dx: Light intensity of scintillation in a unit length
- dE/dx: Energy loss of muon in a unit length
- k_B: Birks' constant
- S: Scintillation efficiency

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

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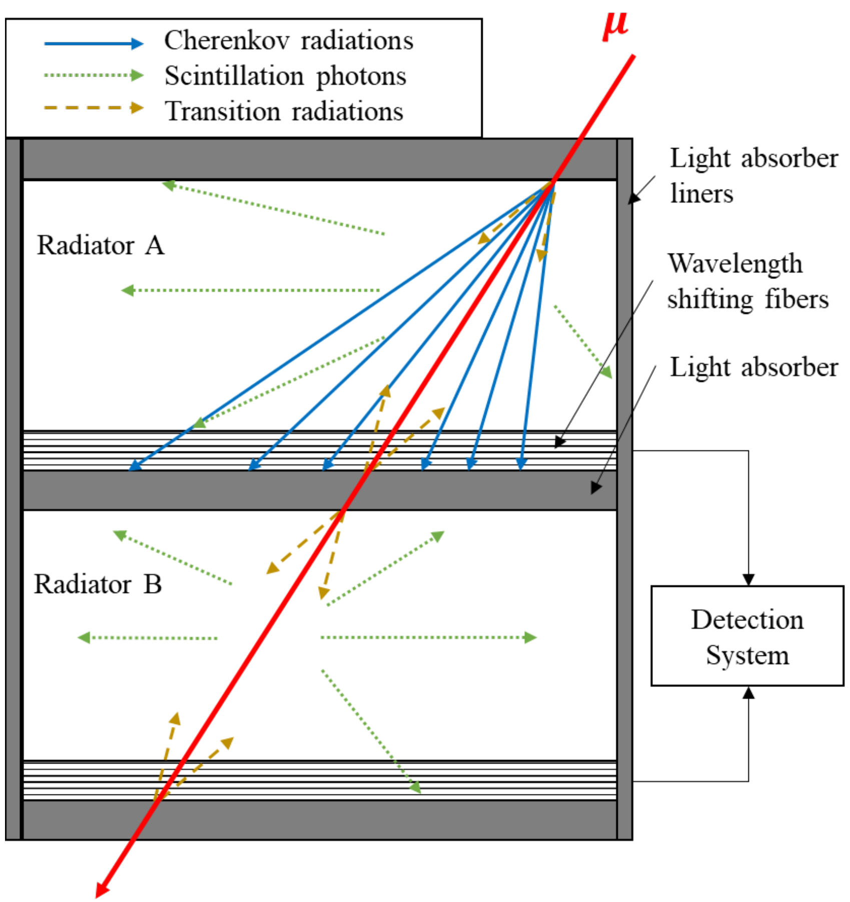

Fig. 2.4 Three optical photon emission mechanisms

3. Transition radiation

$$N_{tr}\Big|_{\text{per boundary}} = \frac{\alpha}{\pi}\left[(\ln\gamma - 1)^2 + \frac{\pi^2}{12}\right]$$

- N_{tr}: Light intensity of transition radiation.
- α: Fine structure constant
- γ: Lorentz factor $(= 1/\sqrt{1-\beta^2})$
- β $(\equiv v/c)$: Particle velocity in terms of c (speed of light)

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

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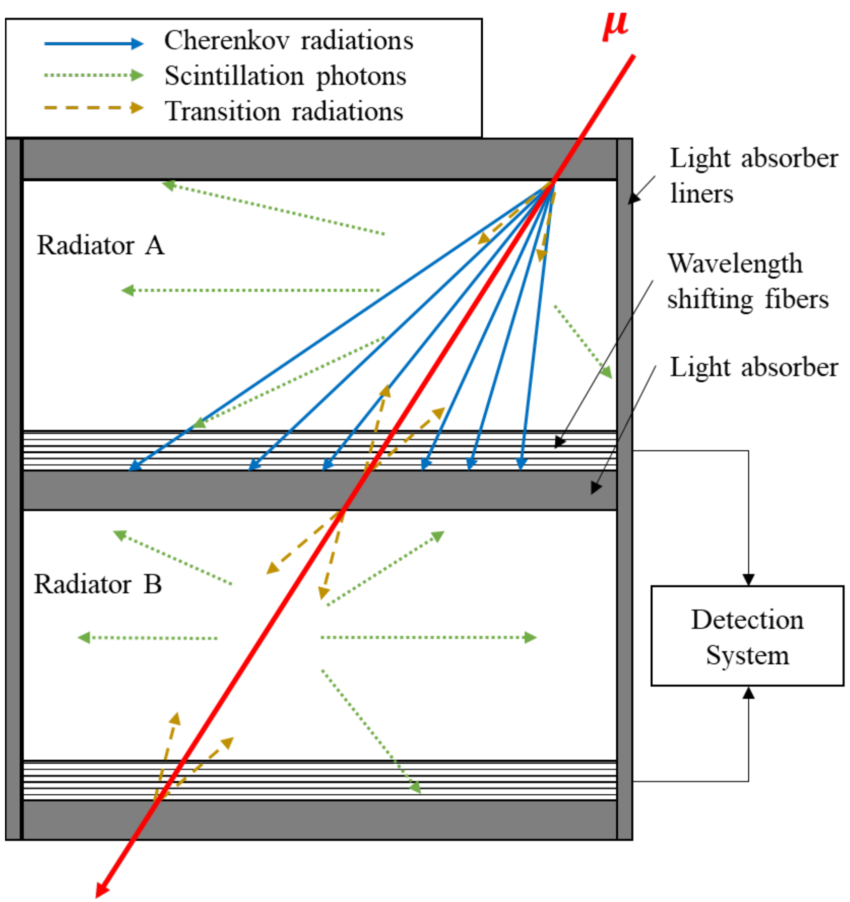

Fig. 2.4 Three optical photon emission mechanisms

4. Cherenkov radiation by secondary electrons, (1) μ decay (2) mu2e conversion

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu N_{Al} \rightarrow e N_{Al}$$

$$p_{th,e} = \frac{m_e}{m_\mu} p_{th,\mu} \sim \frac{1}{207} p_{th,\mu}$$

- m_e: Rest mass of electron (~0.511 MeV/c)
- m_μ: Rest mass of muon (~105.66 MeV/c)
- $p_{th,\mu}$: Cherenkov threshold momentum for muons
- $p_{th,e}$: Cherenkov threshold momentum for electrons

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

2. Optical Photon Emission

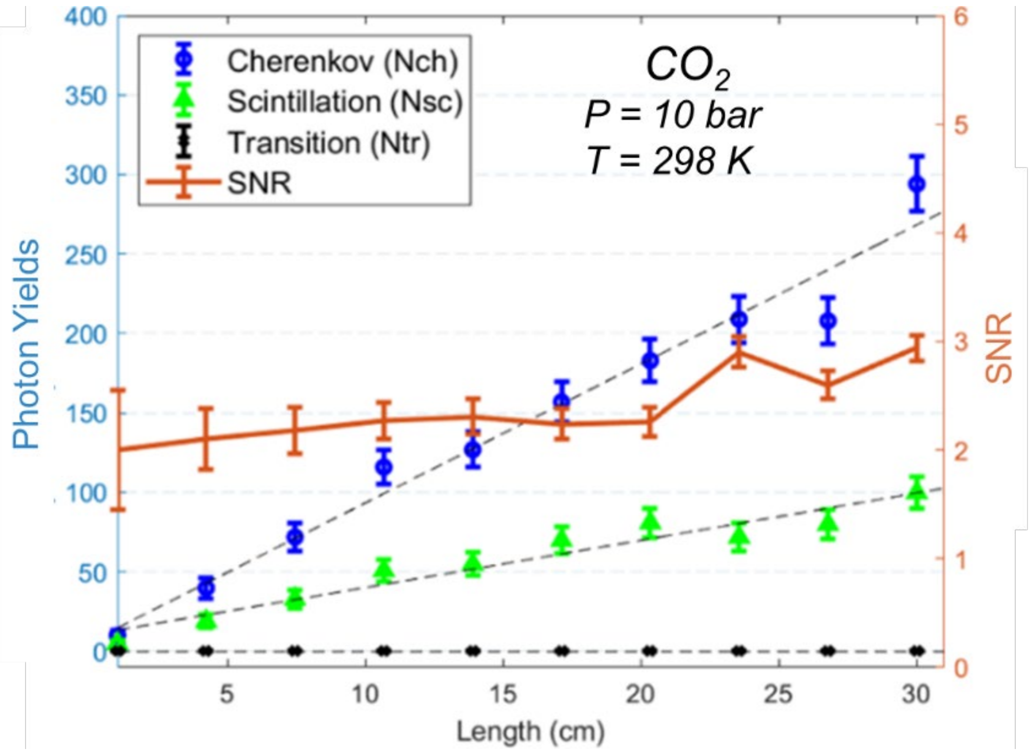

Fig. 2.5 Expected light yield by three optical photon emission mechanisms

1. **Cherenkov radiation**

$$\frac{dN_{ch}}{dx} = 2\pi\alpha \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) \frac{d\lambda}{\lambda^2}$$

2. **Scintillation**

$$\frac{dN_{sc}}{dx} = S \frac{dE/dx}{1 + k_B(dE/dx)}$$

3. Transition radiation

$$N_{tr}\Big|_{\text{per boundary}} = \frac{\alpha}{\pi}\left[(\ln\gamma - 1)^2 + \frac{\pi^2}{12}\right]$$

4. Cherenkov radiation due to secondary e-
   (1) μ decay
   (2) mu2e conversion

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu N_{Al} \rightarrow e N_{Al}$$

J. Bae, S. Chatzidakis, *A Development of Compact Muon Spectrometer Using Multiple Pressurized Gas Cherenkov Radiators*, *Results in Physics* ***39*** (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

3. Results

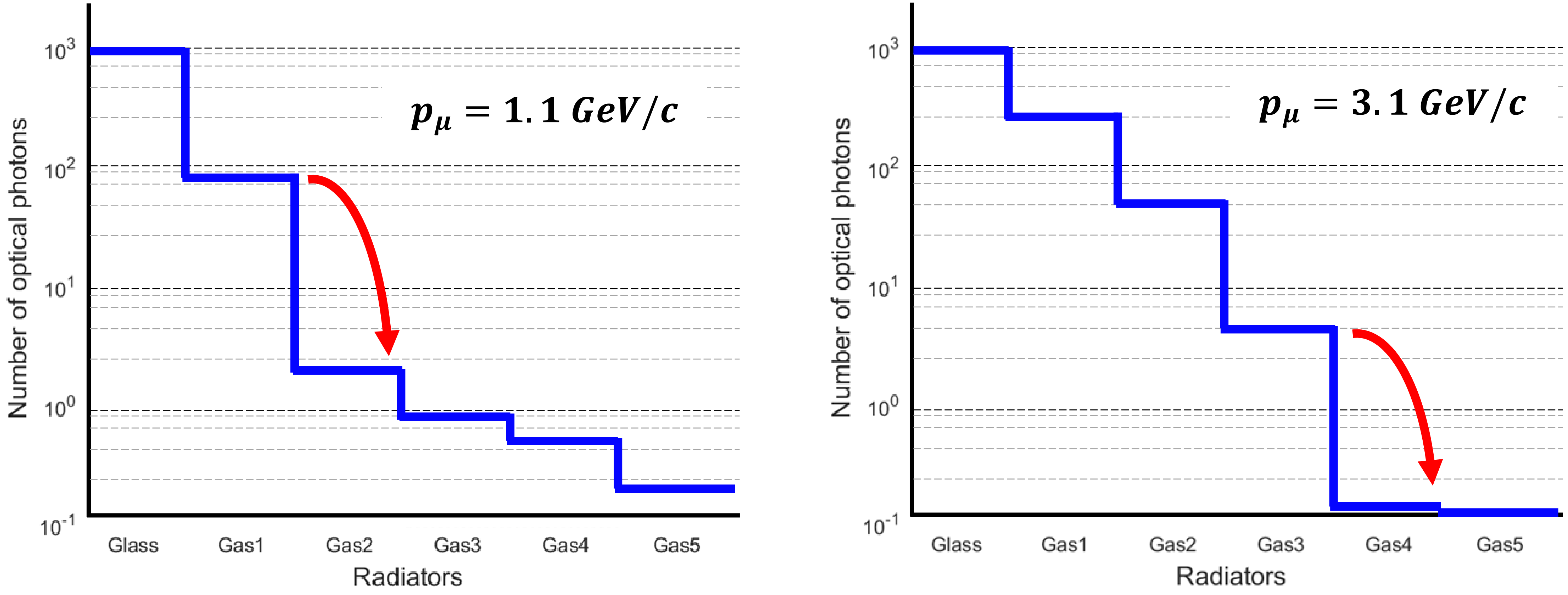

Fig. 2.6 Expected number of photon by Cherenkov radiation in each radiator when $p_\mu = 1.1$ (left) and 3.1 GeV/c (right).

J. Bae, S. Chatzidakis, *A Development of Compact Muon Spectrometer Using Multiple Pressurized Gas Cherenkov Radiators*, *Results in Physics* ***39*** (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

3. Results

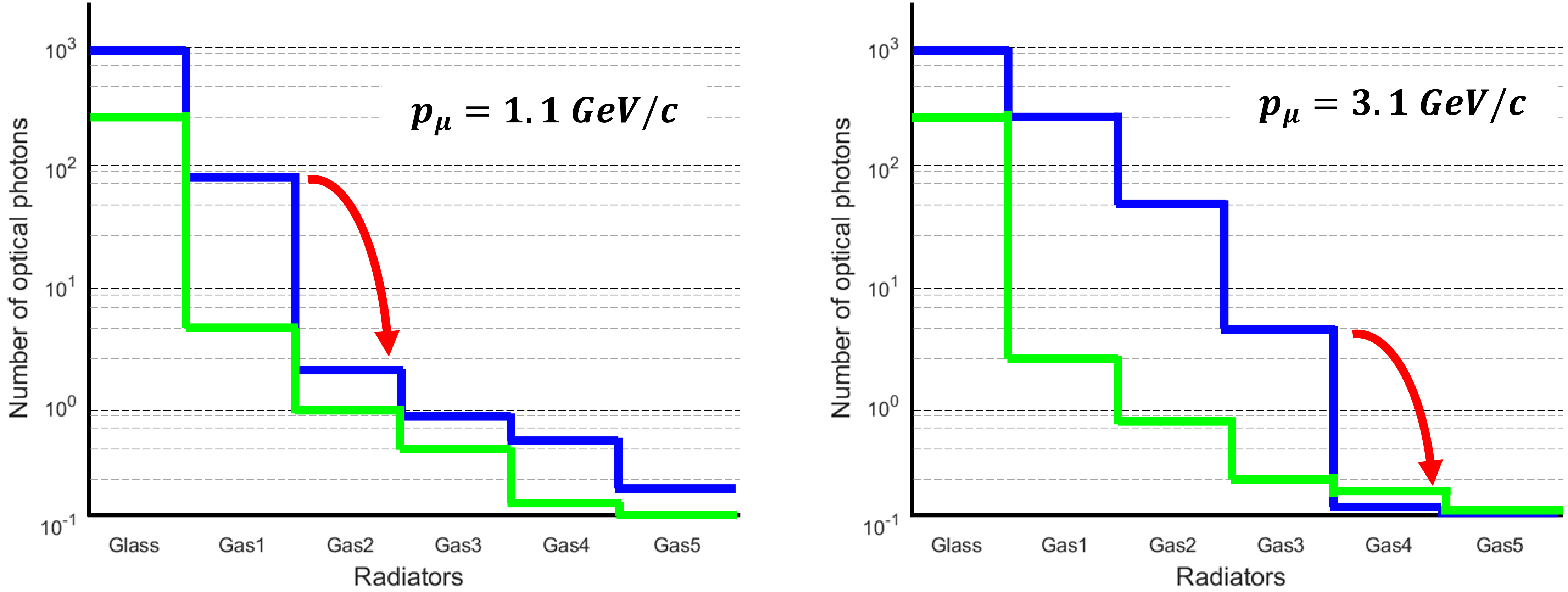

Fig. 2.7 Expected number of photon by Cherenkov radiation and scintillation in each radiator when $p_\mu = 1.1$ (left) and 3.1 GeV/c (right).

J. Bae, S. Chatzidakis, *A Development of Compact Muon Spectrometer Using Multiple Pressurized Gas Cherenkov Radiators*, *Results in Physics* ***39*** (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

3. Results

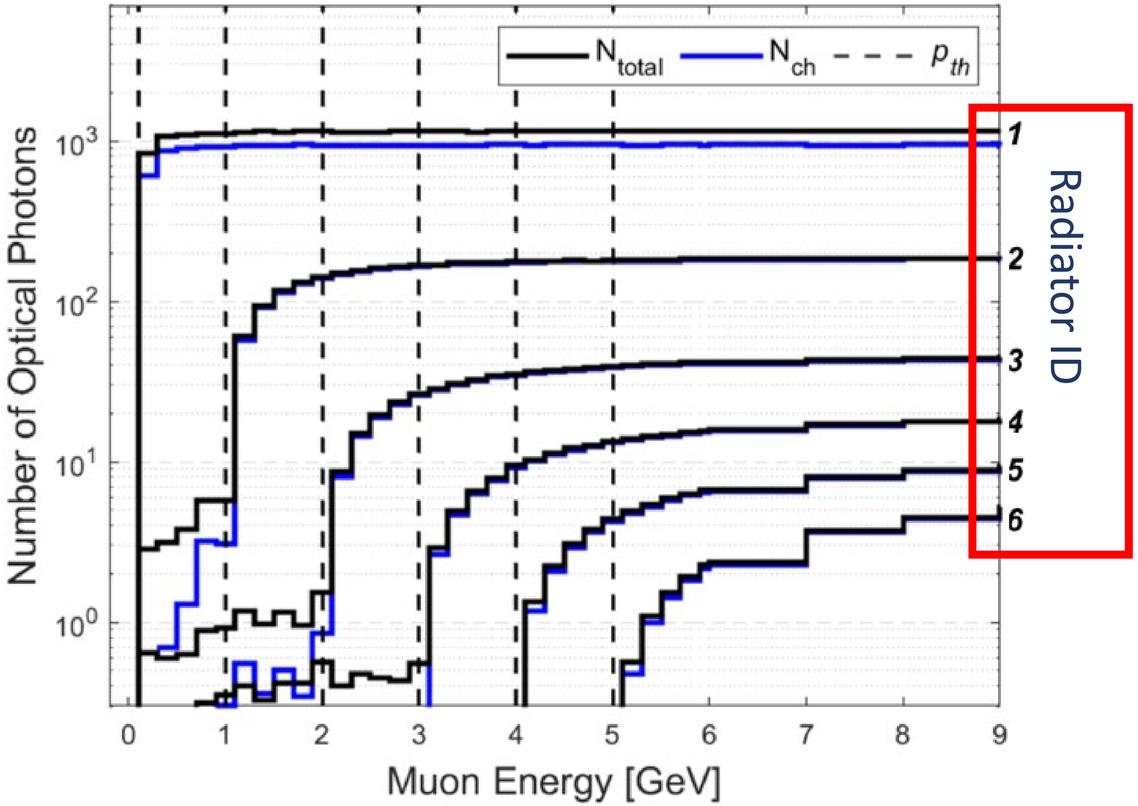

Fig. 2.8 Total Number of photons (Cherenkov radiation + Scintillation) as a function of $E\mu$ in each radiator

- Total number of optical photons provides clear signal (rapid increase) of muon momentum.
- The results demonstrate the feasibility of our Cherenkov muon spectrometer.

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

3. Results

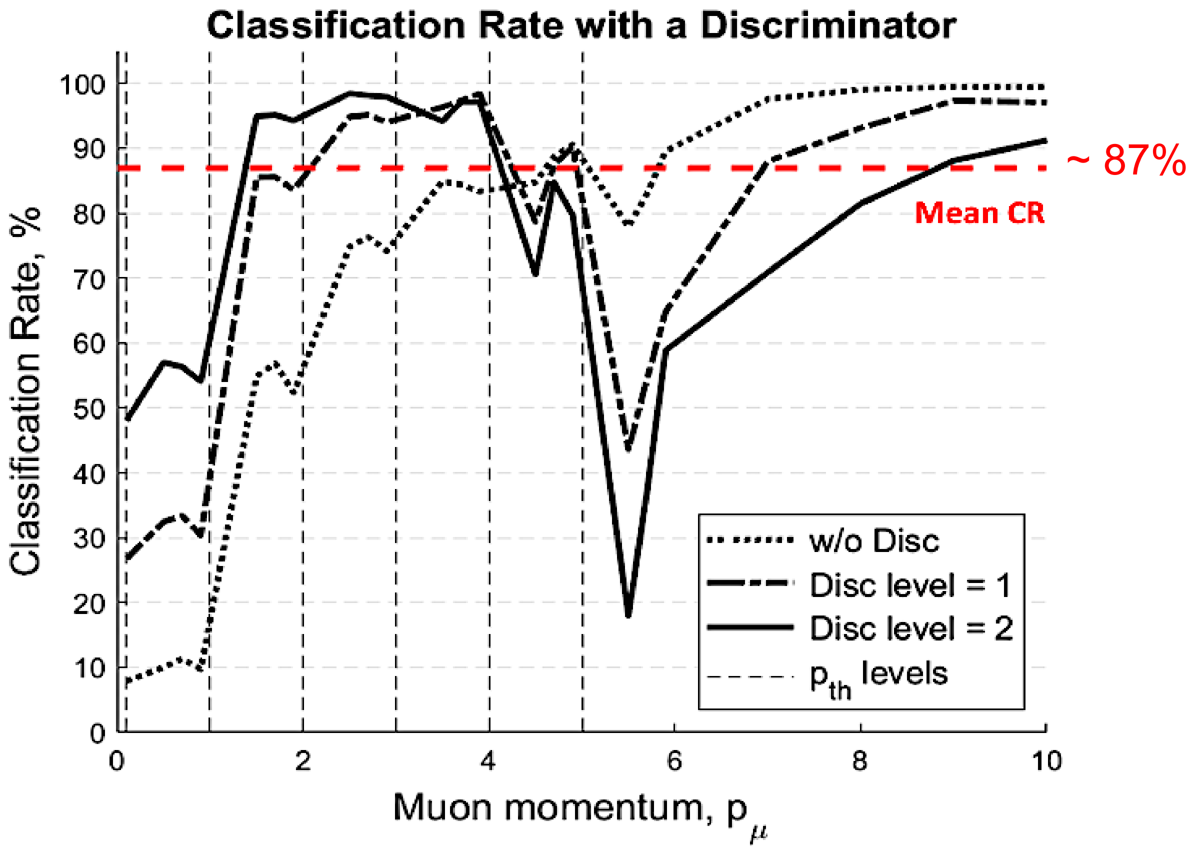

Fig. 2.9 Classification as a function of muon momentum with various discriminator levels

$$\text{CR} = \frac{\text{True Positive Classification}}{\text{Positive Classification}}$$

- Discriminator uniformly deducts photon signals to eliminate noise.
- By using a combination of various levels of discriminators, the mean CR is ~87%

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

3. Results

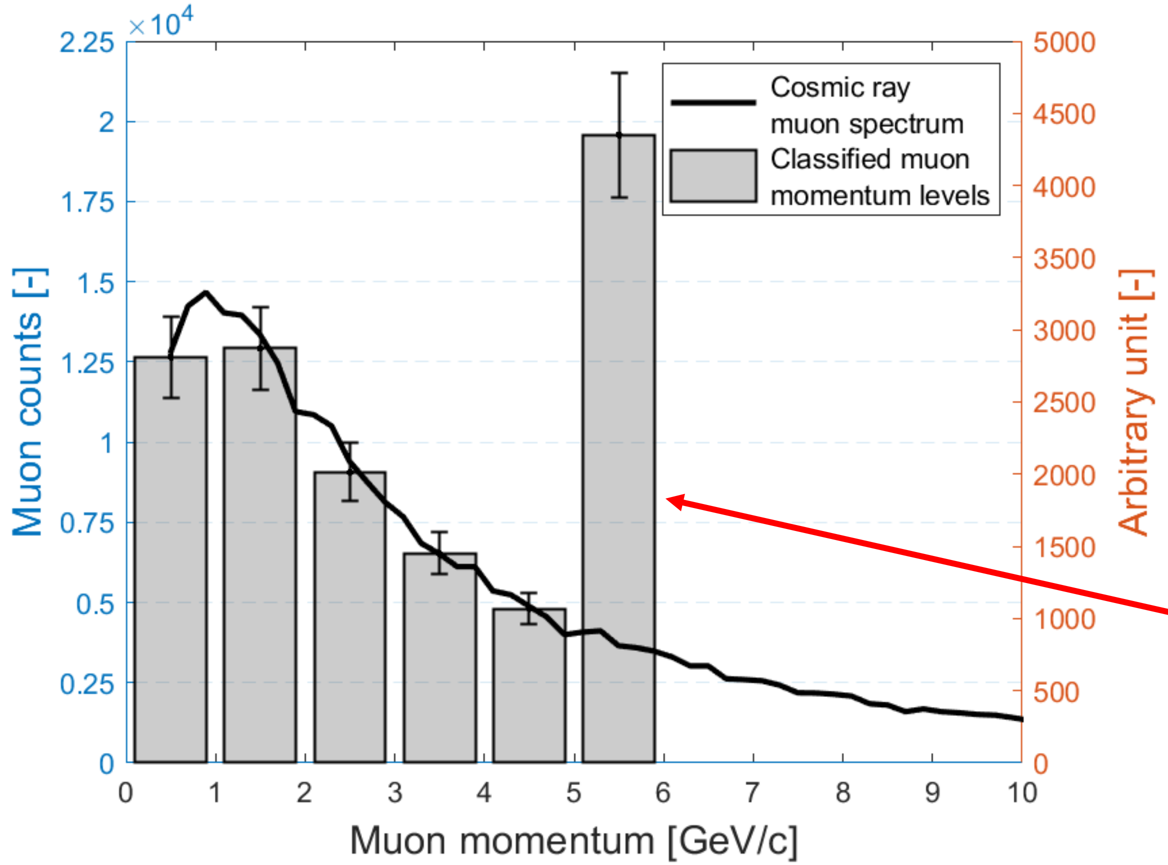

Fig. 2.10 Reconstructed cosmic ray muon spectrum using six radiators.

- Cosmic ray muon spectrum was successfully reconstructed using 6 radiators.
- All muons with $p_{\mu} > 5$ GeV/c are recorded and accumulated in the 6th bin.
- This problem can be easily resolved by increasing the number of radiators.

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

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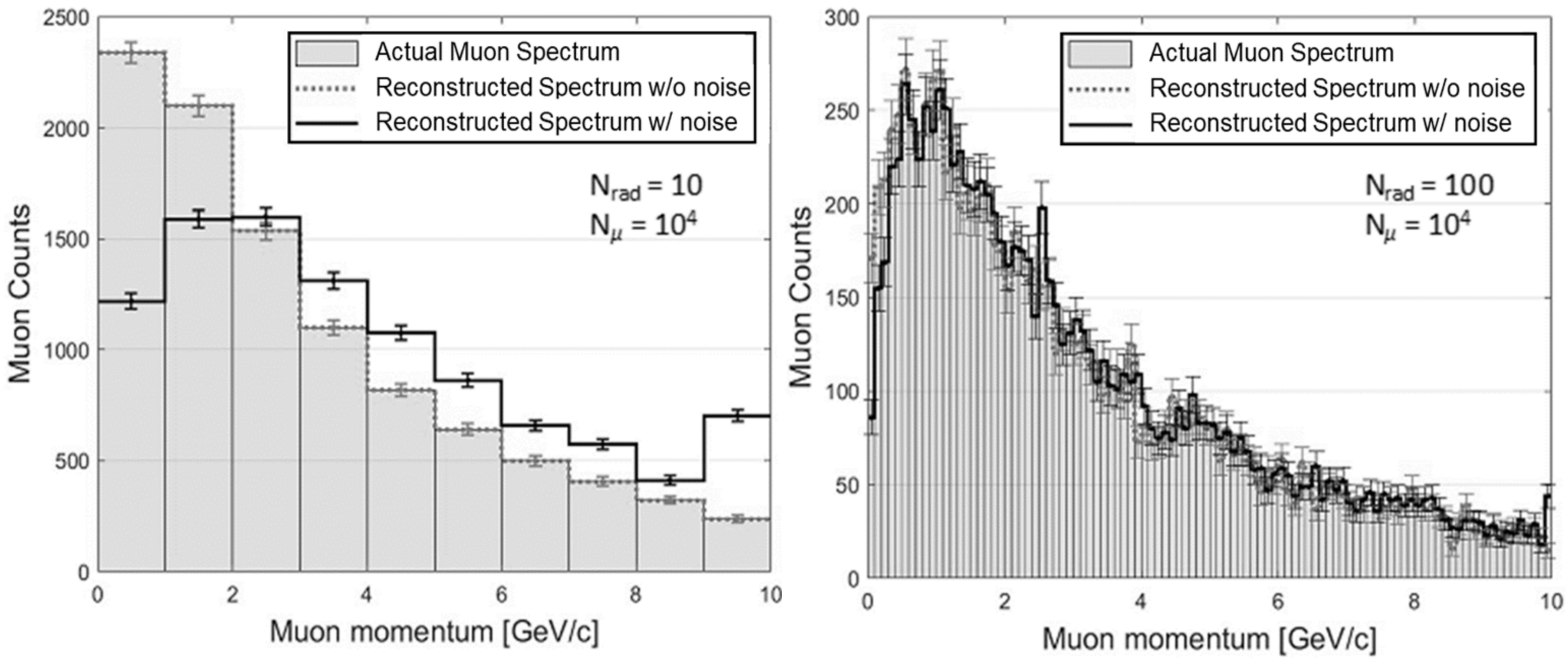
3. Results



- $N = 10$
- $\sigma_p = \pm 0.5\ GeV/c$
- $\sigma_p/p|_{mean} = 21.33\ \%$

- $N = 100$
- $\sigma_p = \pm 0.05\ GeV/c$
- $\sigma_p/p|_{mean} = 3.35\ \%$

Fig. 2.11 Reconstructed cosmic ray muon spectrum using extended number of radiators, 10 (left) and 100 (right)

J. Bae, S. Chatzidakis, *Fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications*, Scientific Reports **12**:2559 (2022)

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

GEN IV International Forum
Expertise | Collaboration | Excellence

III. MOMENTUM INTEGRATED IMAGING ALGORITHM

<table>
<tr><th>PoCA</th><th>mPoCA</th></tr>
<tr><td colspan="2">1. Voxelated the volume of interest.
2. Find a single scattering point using PoCA algorithm.
$\rightarrow P_{PoCA} = [P_x, P_y, P_z]$</td></tr>
<tr><td>3a. Compute a scattering angle, θ.
4a. Record θ with P_{PoCA}.
$\rightarrow V_{xyz} = [P_x, P_y, P_z, \theta]$
5a. Plot θ at P_{PoCA}.</td><td>3b. Compute M-value.
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</table>

Fig. 3.1 Simplified pseudocodes for PoCA and mPoCA algorithms for muon scattering tomography

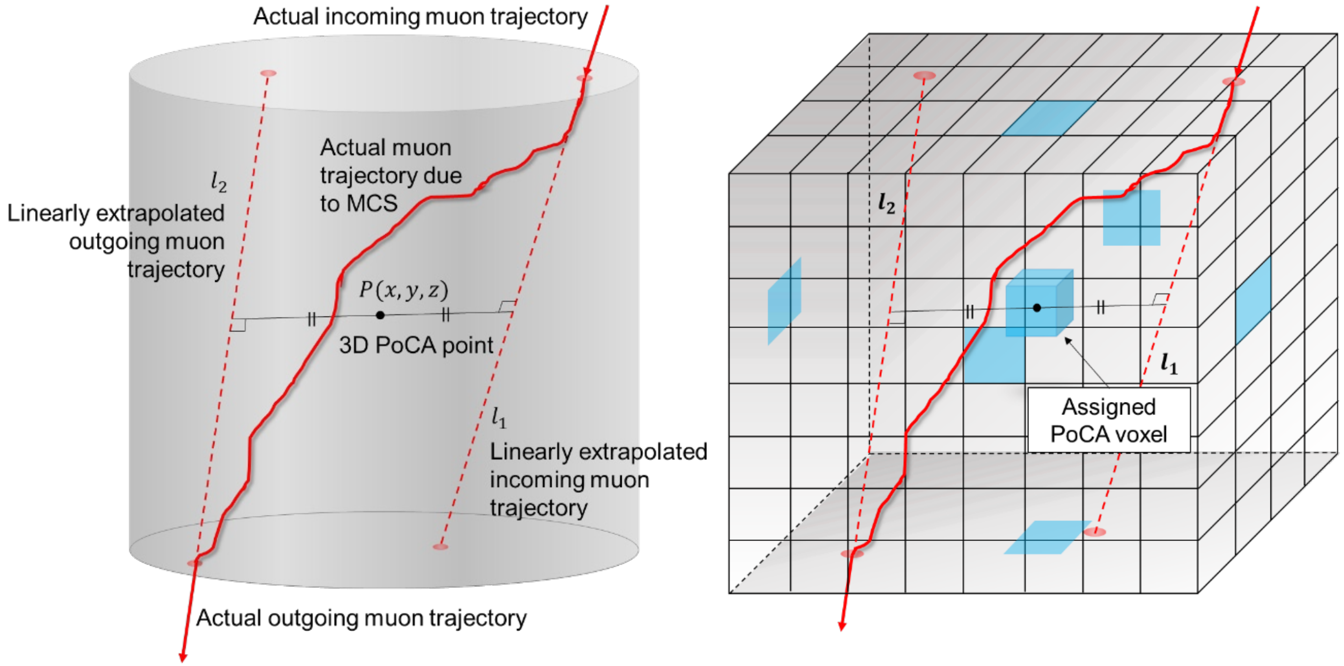

Fig. 3.2 Point of Closest Approach (PoCA) and voxelated volume of interest

J. Bae, S. Chatzidakis, "Momentum Integrated PoCA Algorithm for Muon Scattering Tomography", Journal of Imaging (under review)

III. MOMENTUM INTEGRATED IMAGING ALGORITHM

PoCA	mPoCA
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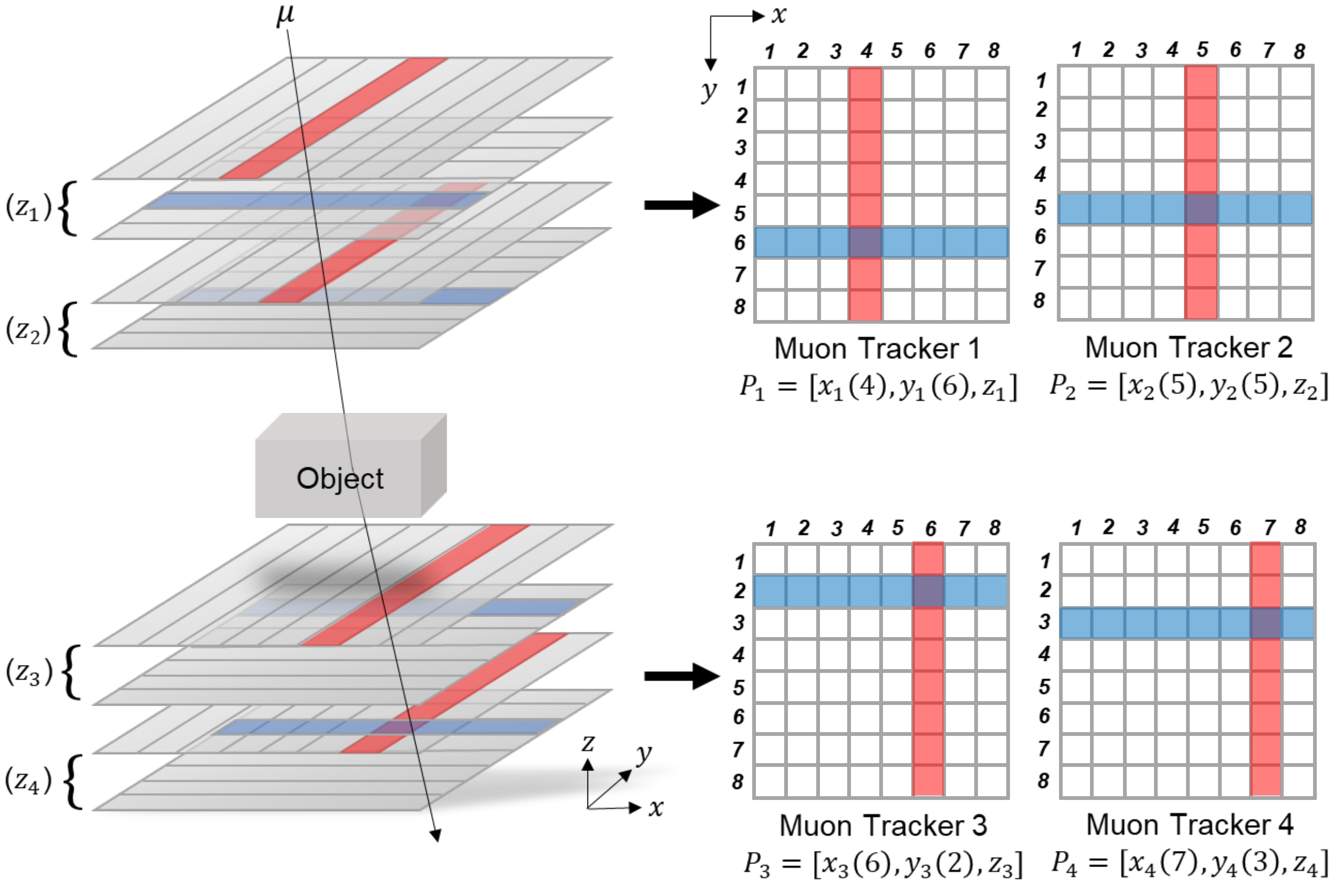

Fig. 3.3 Reconstruction of incoming and outgoing muon trajectories.

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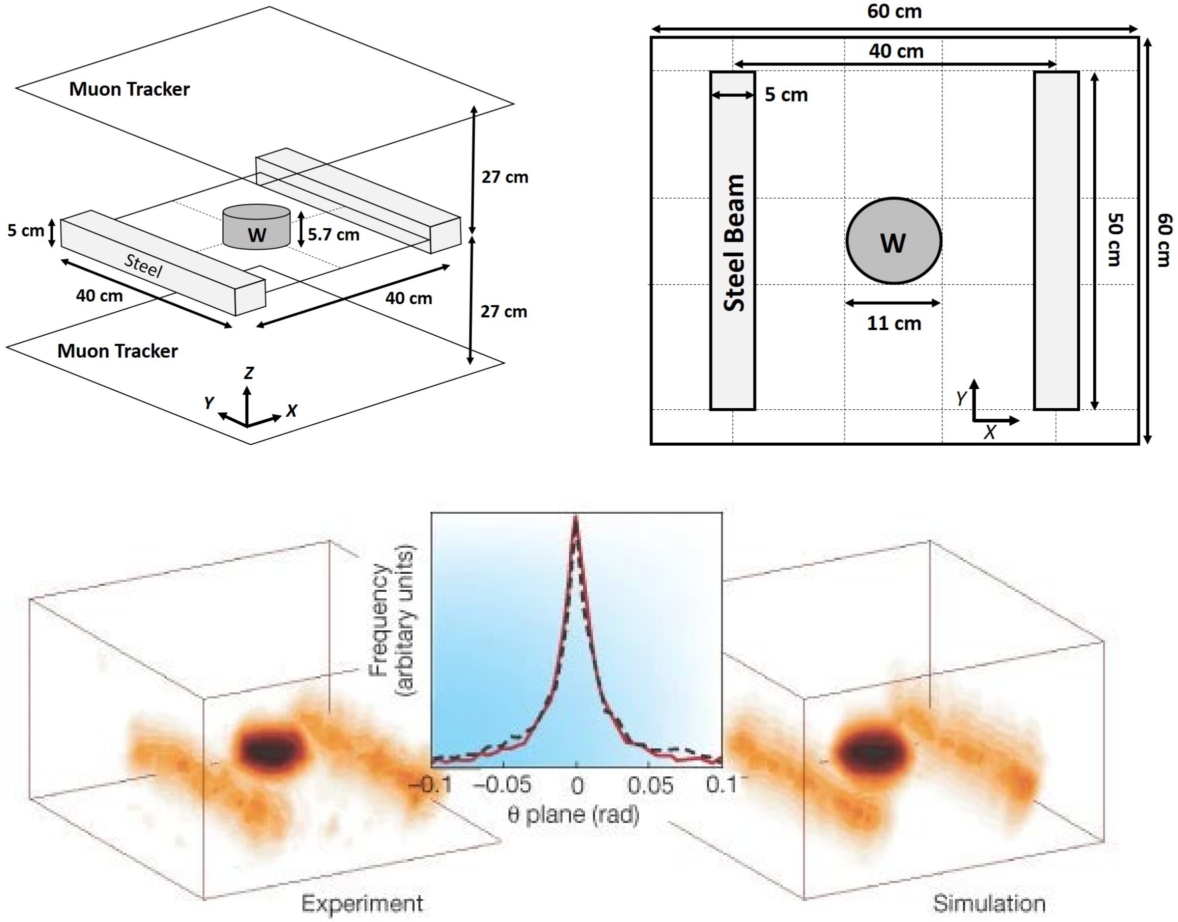

Fig. 3.4 Benchmarking experiment and simulation results by K. N. Borozdin et al.

Borozdin, K., Hogan, G., Morris, C. *et al.* Radiographic imaging with cosmic-ray muons. *Nature* **422,** 277 (2003).

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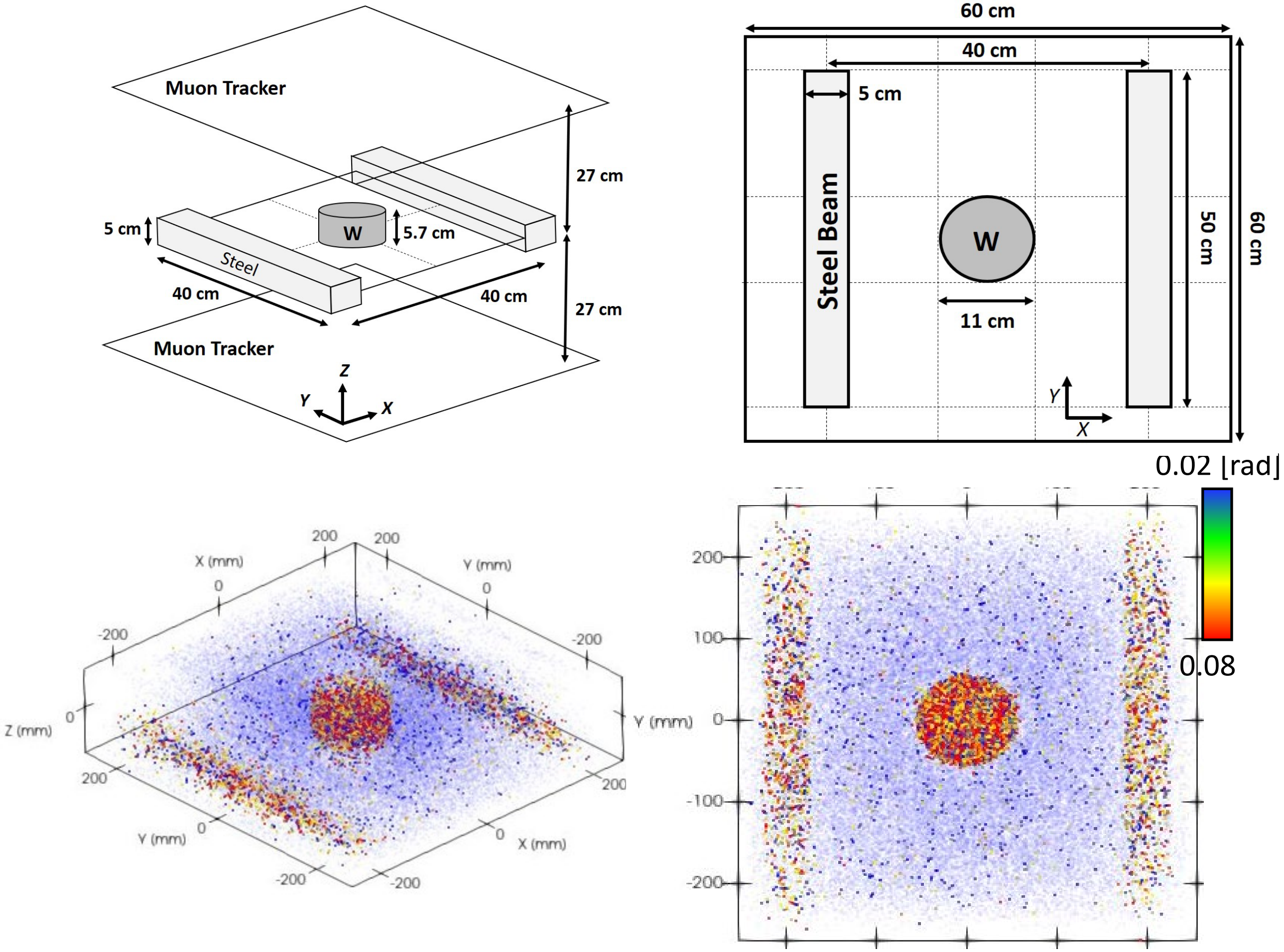

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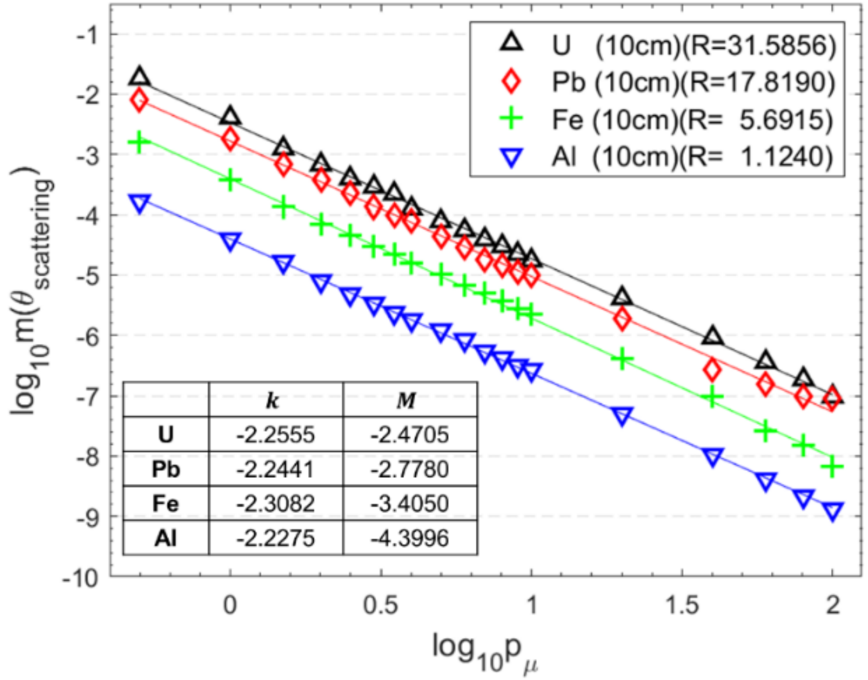


$$\log_{10} mod(\theta) = k \log_{10} p + M$$

$$M = \log_{10}\left(\theta\ [\mathrm{rad}] \times p\ [\mathrm{GeV/c}]^{2.24}\right)$$

Fig. 3.5 Correlation between $\log_{10} \mathrm{mod}(\theta)$ and $\log_{10} p$

J. Bae, S. Chatzidakis, "Generalized mPoCA imaging algorithm for Muon Radiography" (in preparation)

III. MOMENTUM INTEGRATED IMAGING ALGORITHM

PoCA	mPoCA
1. Voxelize the volume of interest. 2. Find a single scattering point using PoCA algorithm. $\rightarrow P_{PoCA} = [P_x, P_y, P_z]$	
3a. Compute a scattering angle, θ. 4a. Record θ with P_{PoCA}. $\rightarrow V_{xyz} = [P_x, P_y, P_z, \theta]$ 5a. Plot θ at P_{PoCA}.	3b. Compute M-value. 4b. Record M with P_{PoCA}. $\rightarrow M_{xyz} = [P_x, P_y, P_z, M]$ 5b. Plot M at P_{PoCA}.

Fig. 3.1 Simplified pseudocodes for PoCA and mPoCA algorithms for muon scattering tomography

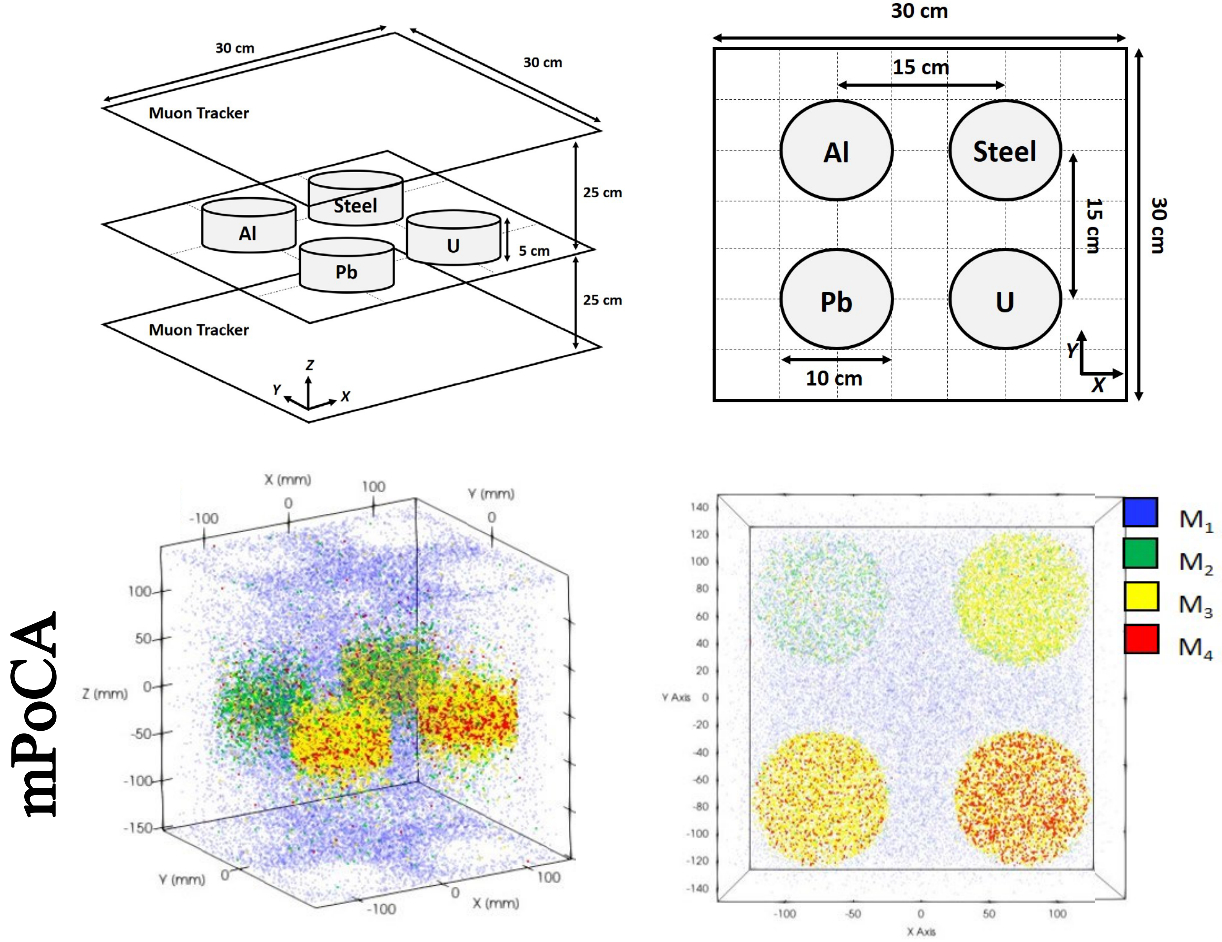


Fig. 3.6 Muon scattering tomography using mPoCA algorithm for aluminum, steel, lead, and uranium

J. Bae, S. Chatzidakis, “Momentum Integrated PoCA Algorithm for Muon Scattering Tomography”, IEEE Transactions on Nuclear Science (under review)

III. MOMENTUM INTEGRATED IMAGING ALGORITHM

<table>
<tr><th>PoCA</th><th>mPoCA</th></tr>
<tr><td colspan="2">1. Voxelize the volume of interest.
2. Find a single scattering point using PoCA algorithm.
$\rightarrow P_{PoCA} = [P_x, P_y, P_z]$</td></tr>
<tr><td>3a. Compute a scattering angle, θ.
4a. Record θ with P_{PoCA}.
$\rightarrow V_{xyz} = [P_x, P_y, P_z, \theta]$
5a. Plot θ at P_{PoCA}.</td><td>3b. Compute M-value.
4b. Record M with P_{PoCA}.
$\rightarrow M_{xyz} = [P_x, P_y, P_z, M]$
5b. Plot M at P_{PoCA}.</td></tr>
</table>

Fig. 3.1 Simplified pseudocodes for PoCA and mPoCA algorithms for muon scattering tomography

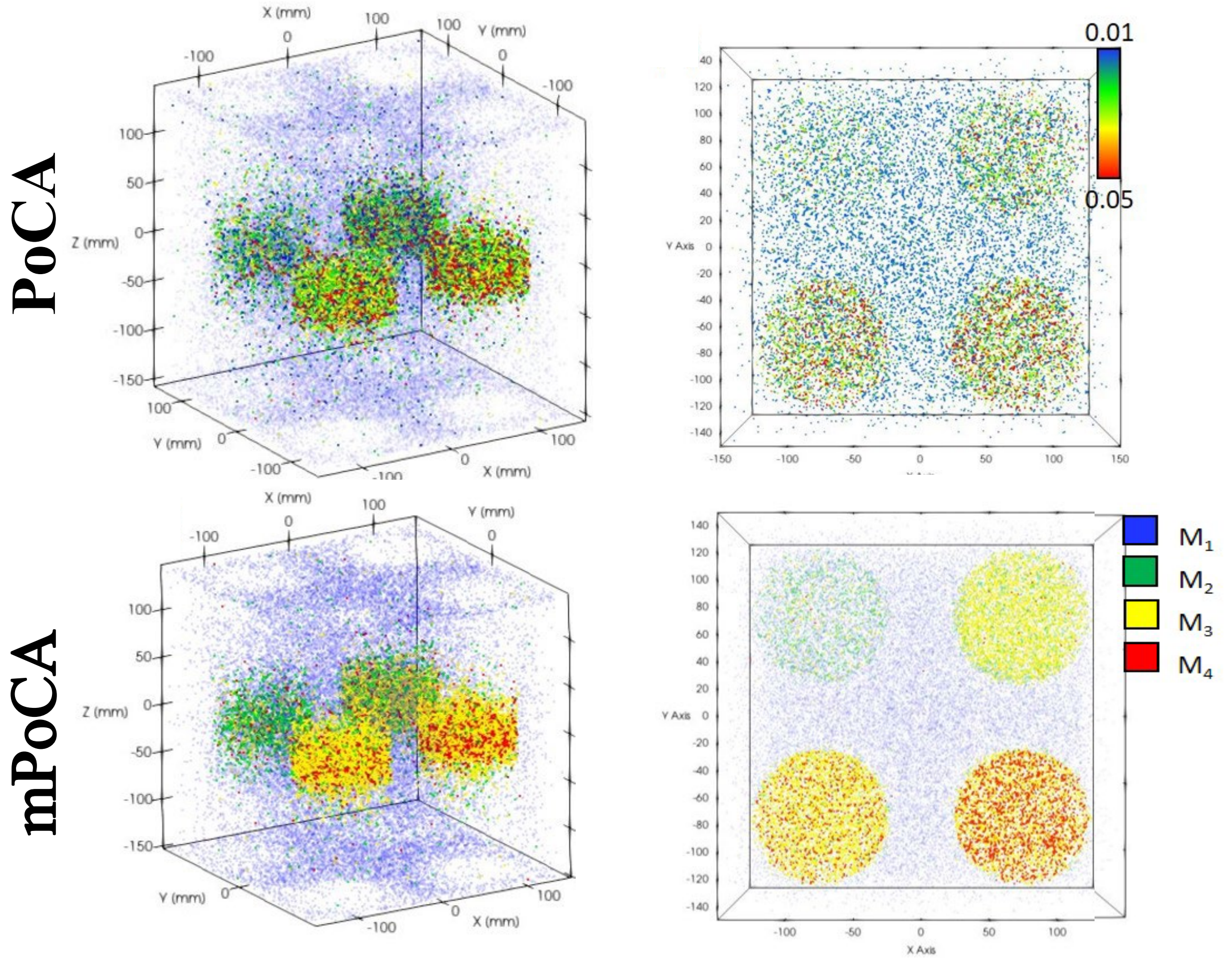


Fig. 3.7 PoCA and mPoCA algorithms for imaging aluminum, steel, lead, and uranium

J. Bae, S. Chatzidakis, "Momentum Integrated PoCA Algorithm for Muon Scattering Tomography", IEEE Transactions on Nuclear Science (under review)

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

GEN IV International Forum
Expertise | Collaboration | Excellence

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

1. Implementation of Cherenkov muon spectrometer in SNF monitoring

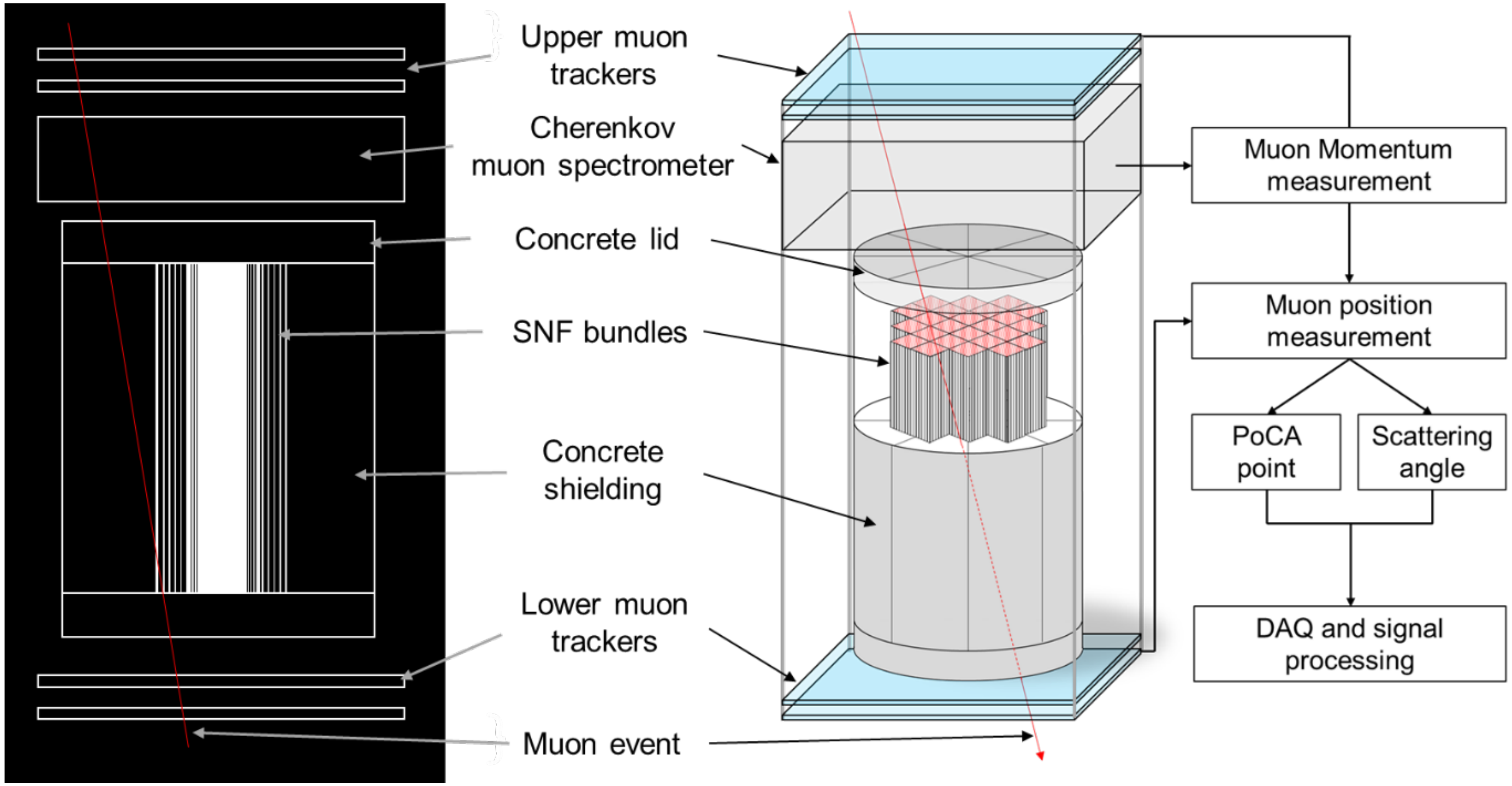


Fig. 4.1 Overview of the momentum integrated muon tomography system using the Cherenkov muon spectrometer for SNF dry cask imaging (right) and the visualized Geant4 model (left).

J. Bae, S. Chatzidakis, “Momentum Integrated Muon Tomography for Spent Nuclear Fuel Monitoring” (in preparation)

2. Results

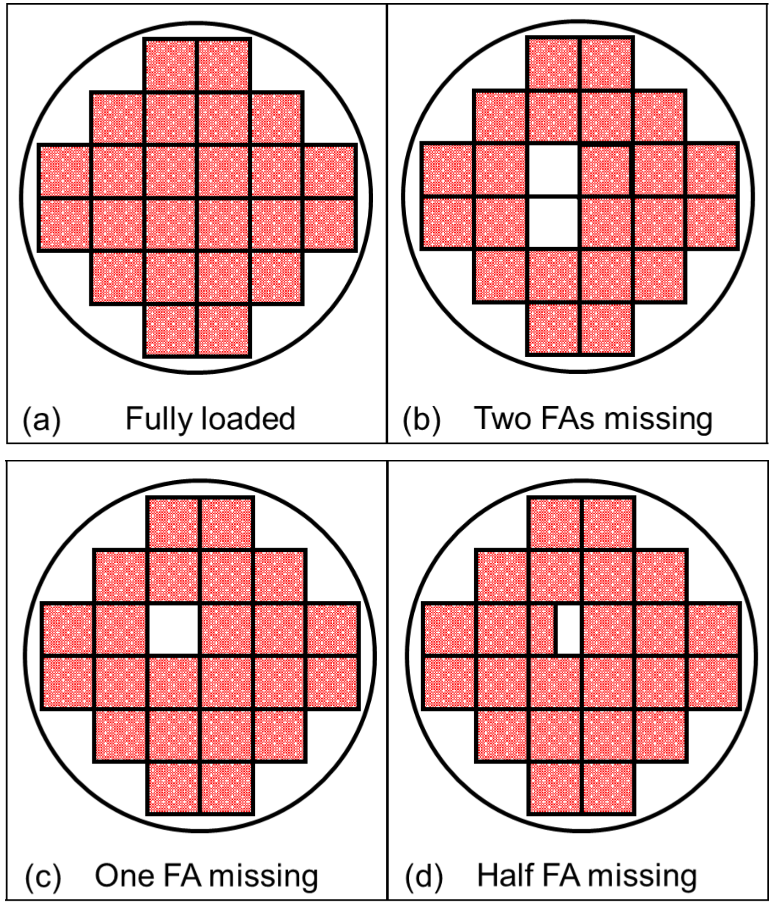


Fig. 4.2 Overview of four scenarios in SNF cask monitoring

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

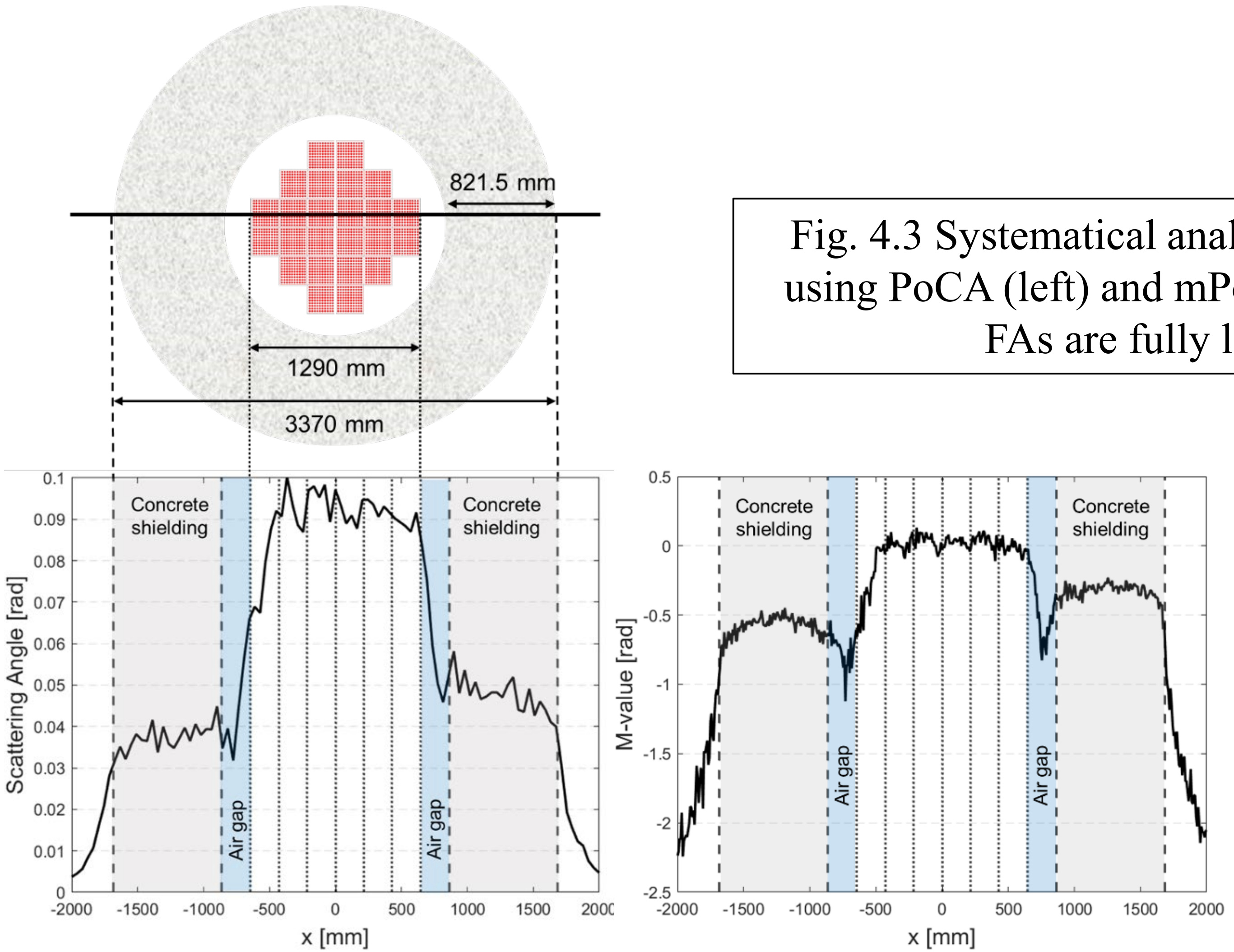


Fig. 4.3 Systematical analysis of SNF cask using PoCA (left) and mPoCA (right) when FAs are fully loaded

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

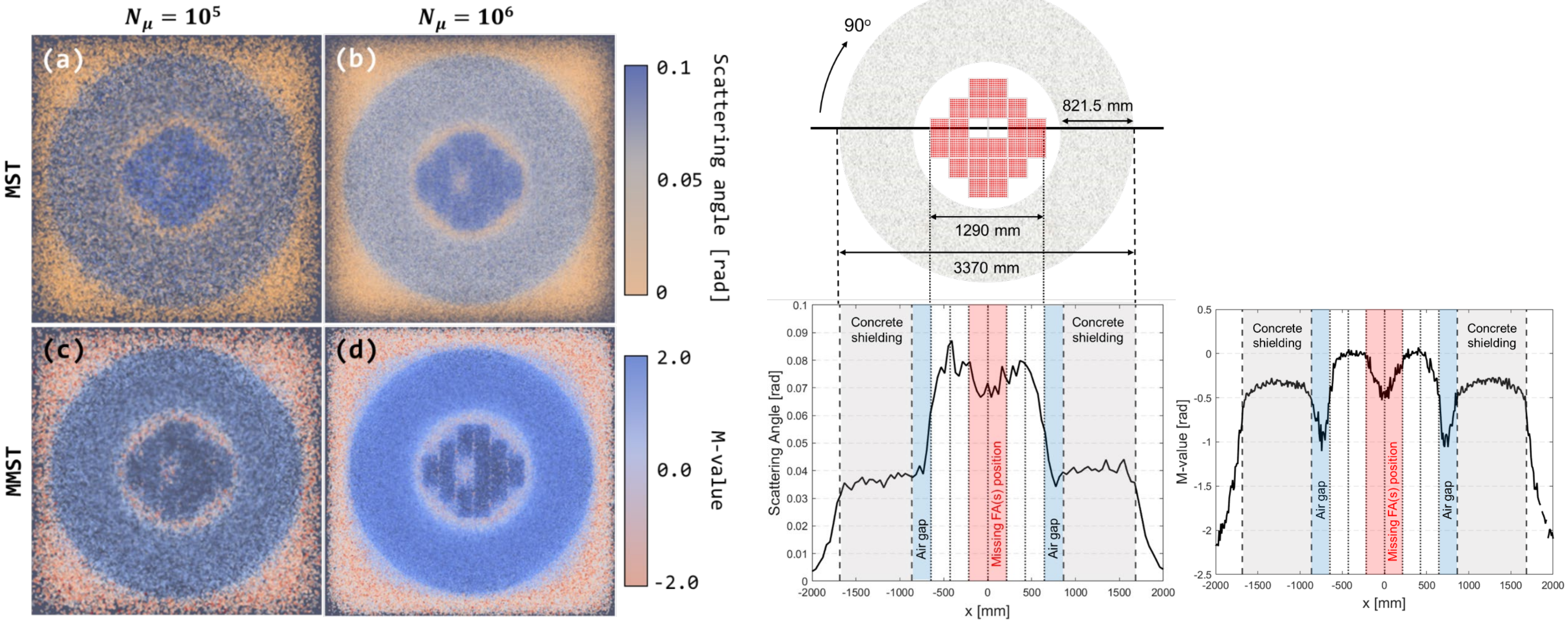


Fig. 4.4 Reconstructed images (left) and systematical analysis of SNF cask using PoCA and mPoCA (right) when two middle FAs are missing

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

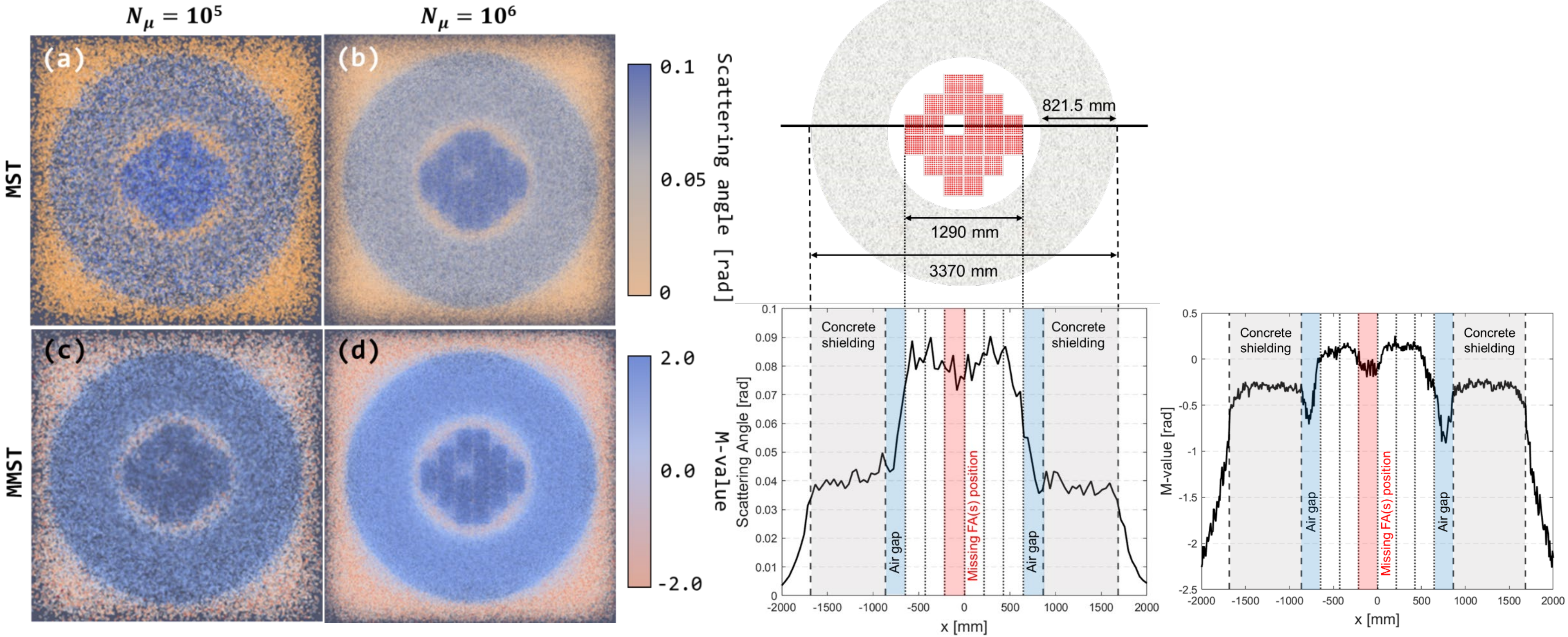


Fig. 4.5 Reconstructed images (left) and systematical analysis of SNF cask using PoCA and mPoCA (right) when one middle FA is missing

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

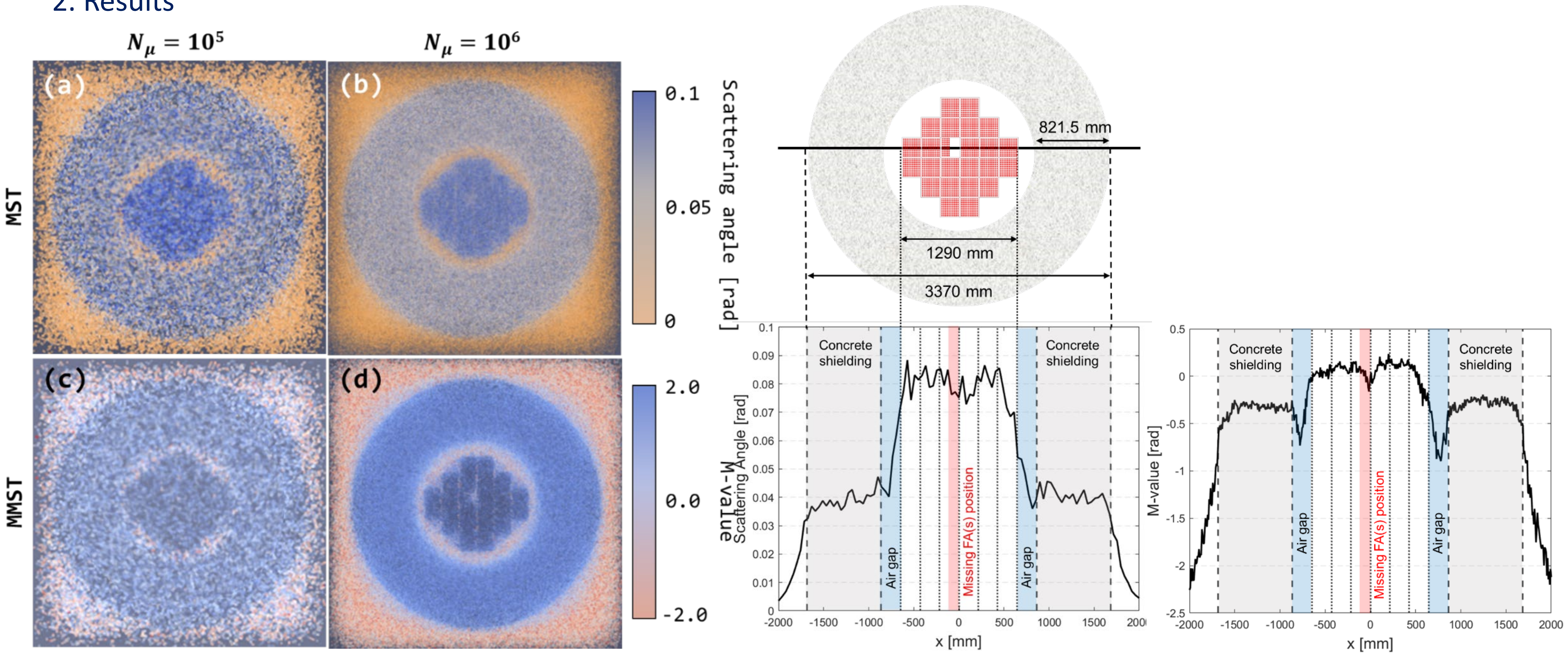
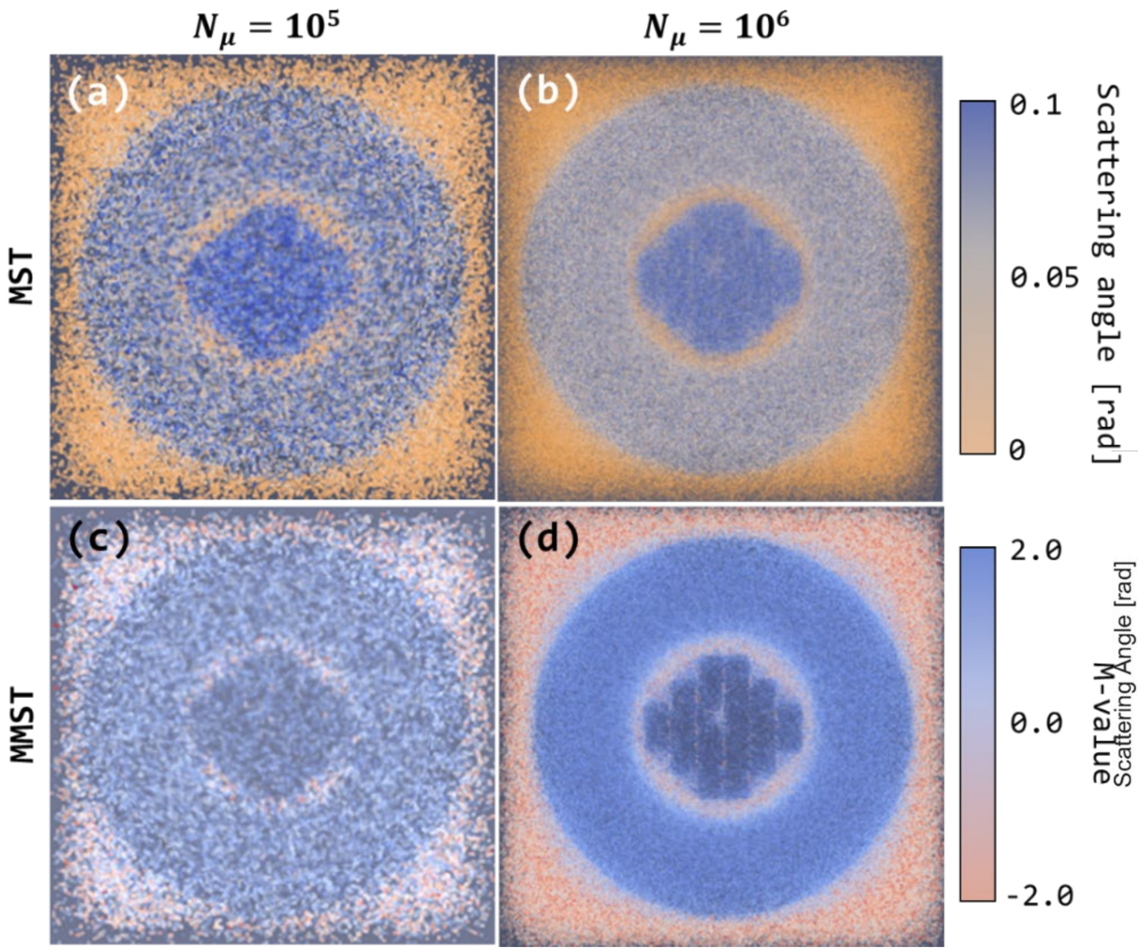


Fig. 4.6 Reconstructed images (left) and systematical analysis of SNF cask using PoCA and mPoCA (right) when a half of middle FA is missing

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results



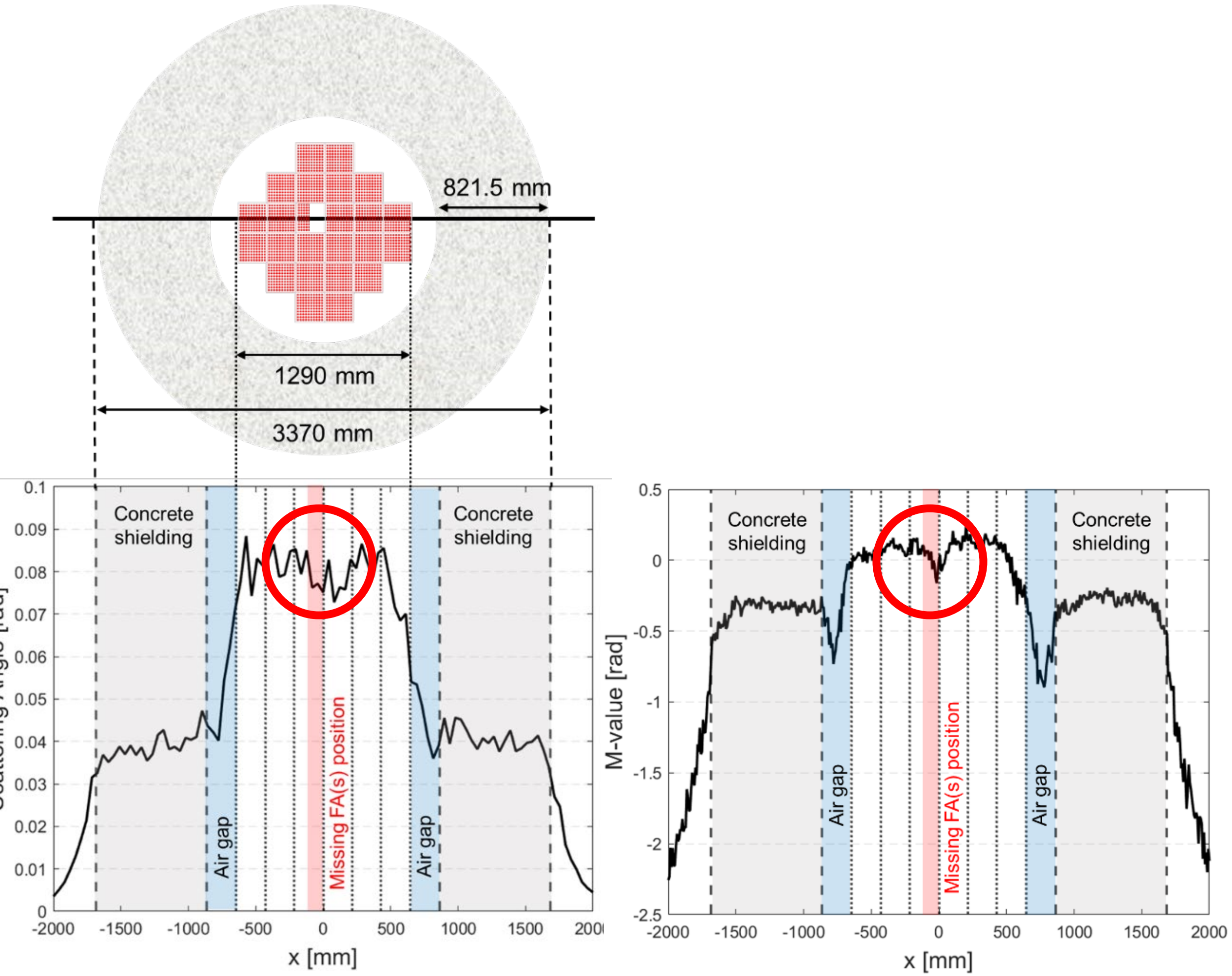


Fig. 4.6 Reconstructed images (left) and systematical analysis of SNF cask using PoCA and mPoCA (right) when a half of middle FA is missing

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

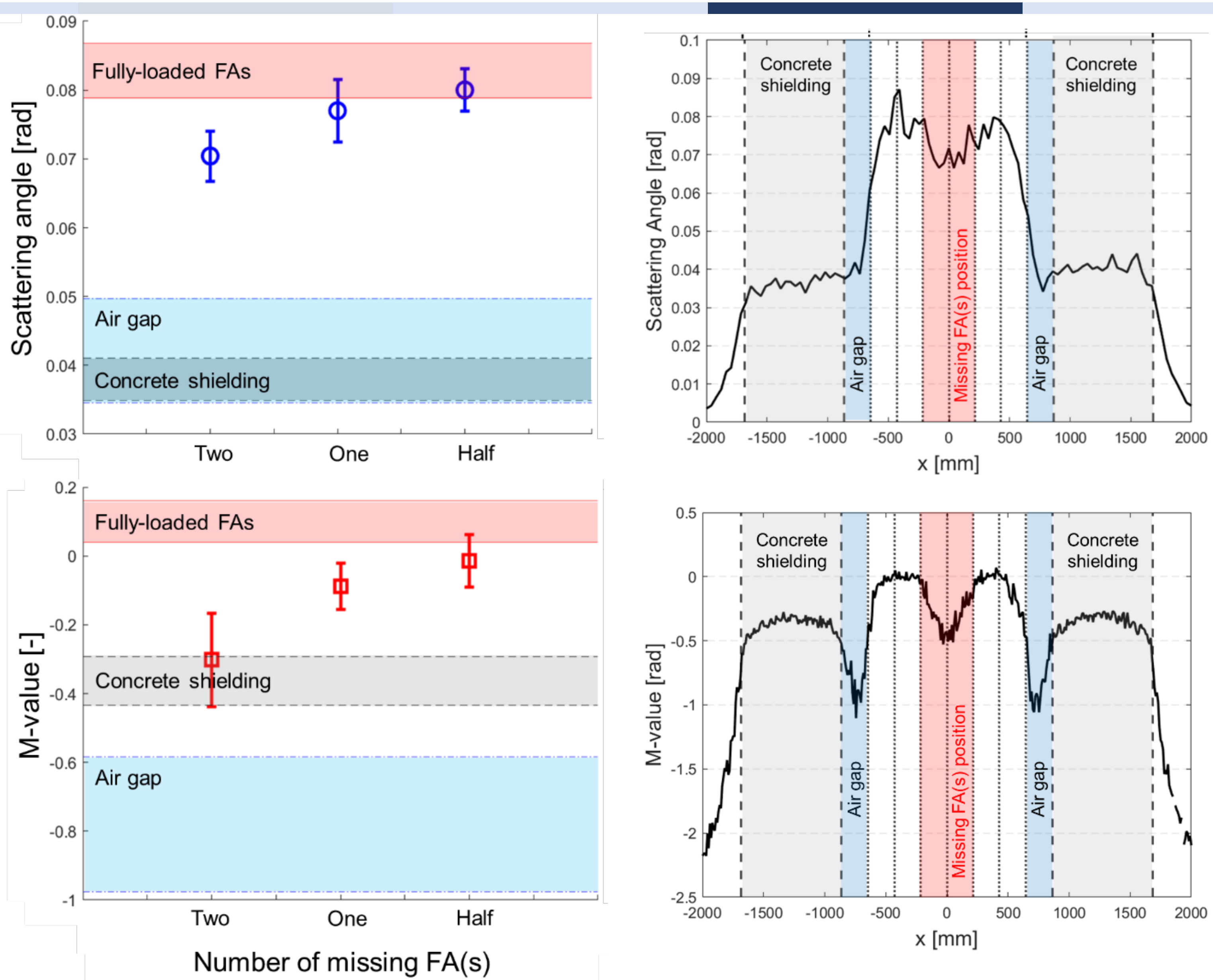
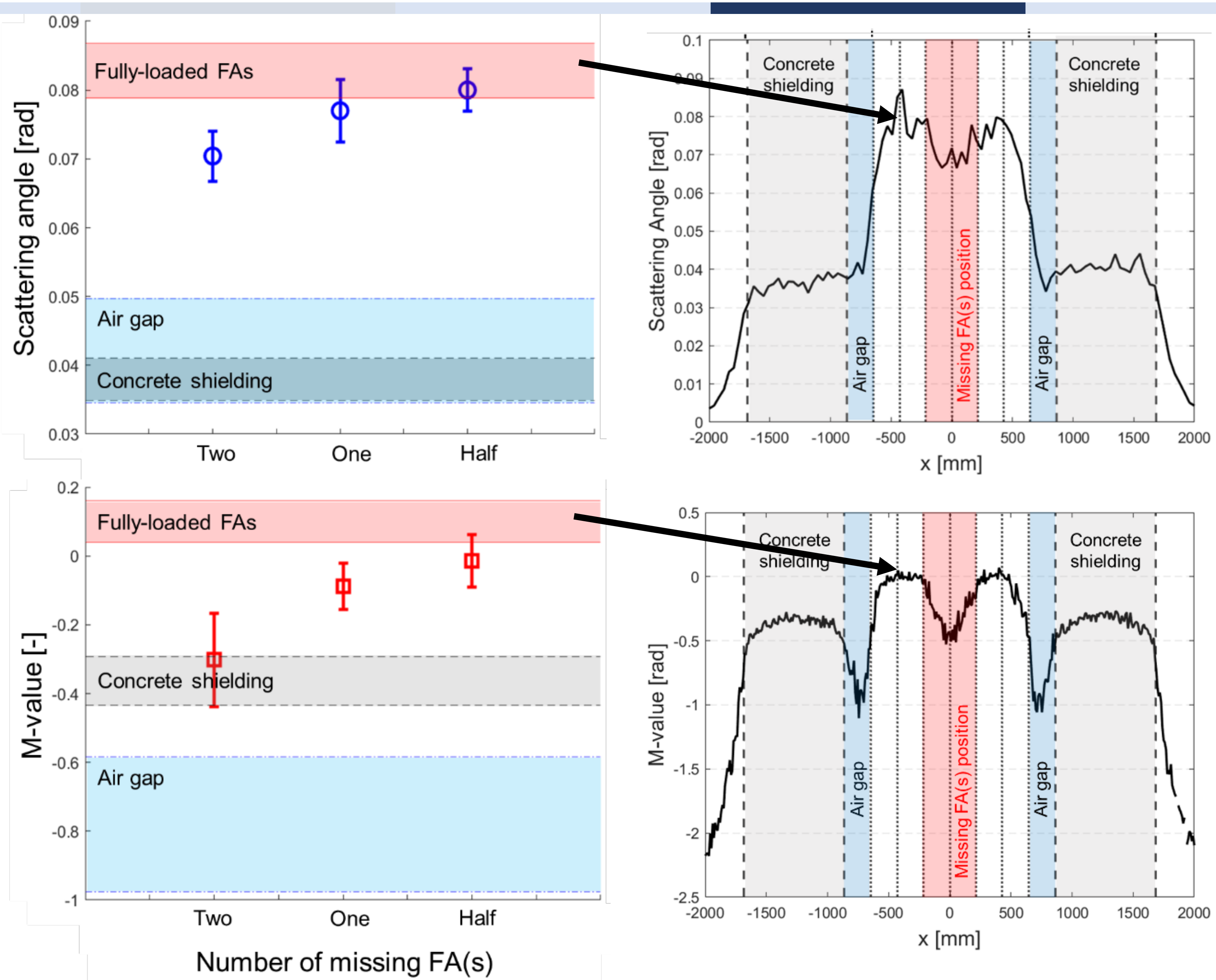


Fig. 4.7 Analysis of missing FA separation capability using PoCA (top) and mPoCA (bottom) algorithms.

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results



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IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

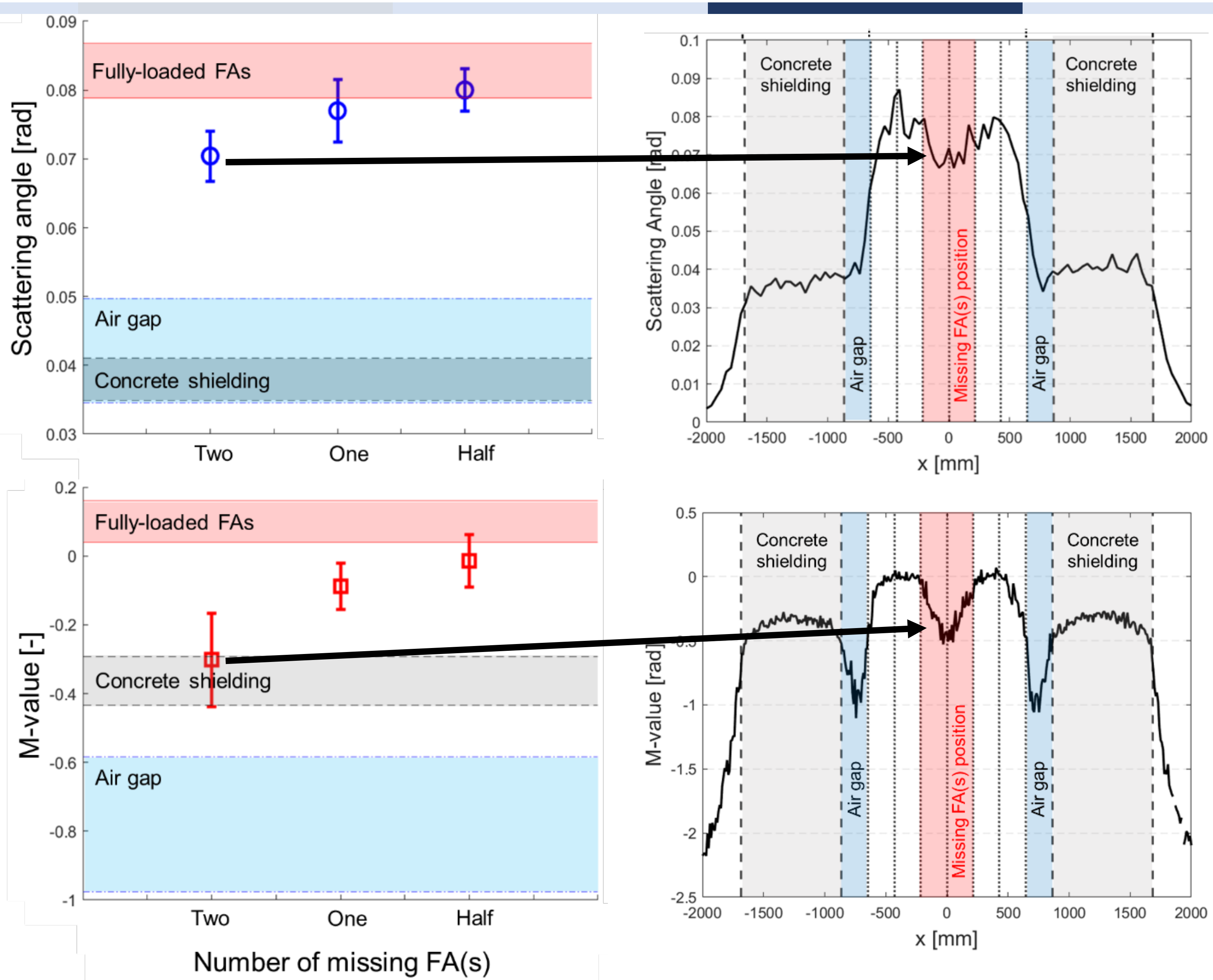

Fig. 4.7 Analysis of missing FA separation capability using PoCA (top) and mPoCA (bottom) algorithms.

IV. MOMENTUM INTEGRATED MUON TOMOGRAPHY

2. Results

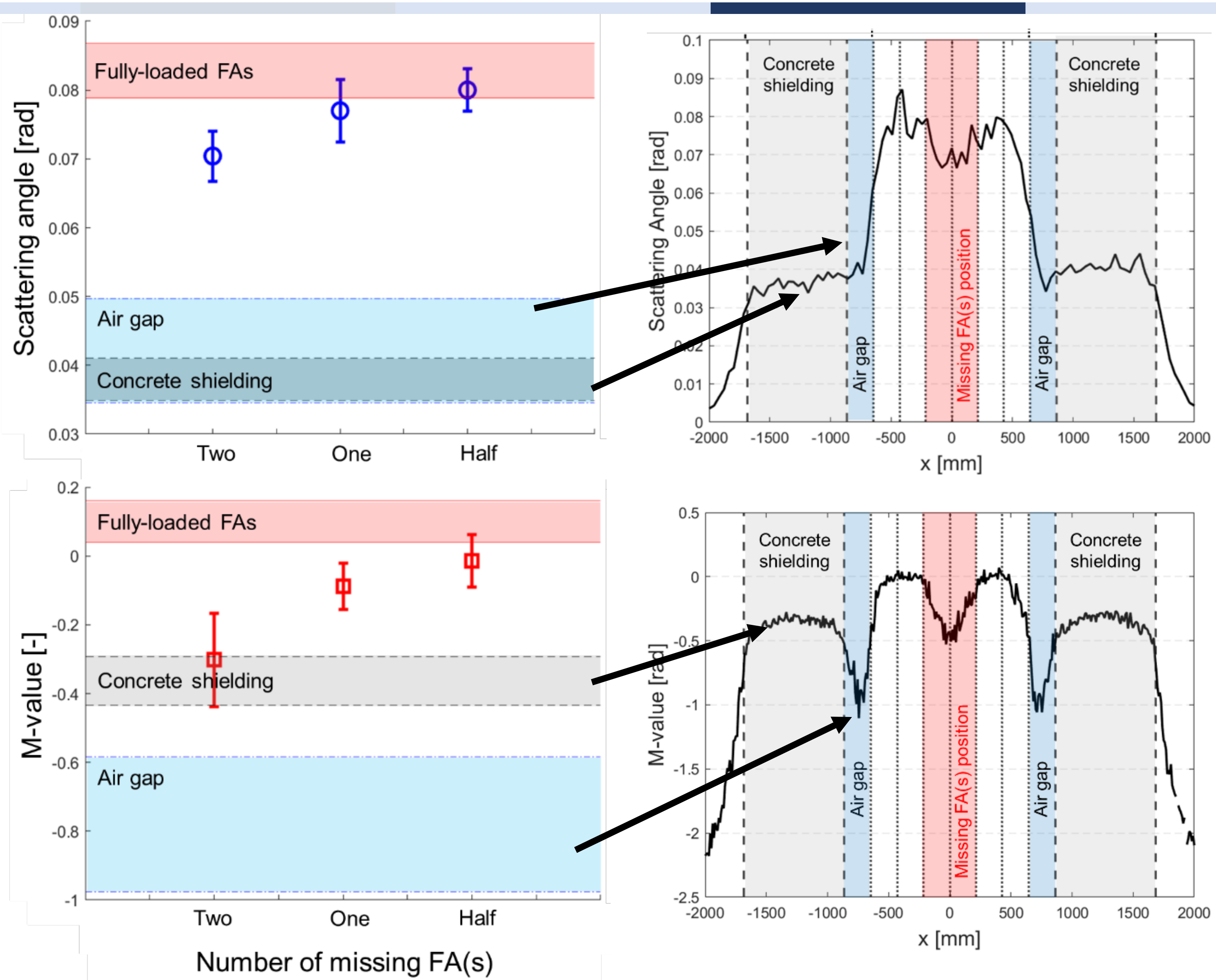

Fig. 4.7 Analysis of missing FA separation capability using PoCA (top) and mPoCA (bottom) algorithms.

A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

TABLE OF CONTENTS

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V. SUMMARY AND CONCLUSION

Muon Spectrometer Using Gas Cherenkov Radiators

1. A glass (SiO_2) and five pressurized gas (CO_2) radiators are used in the prototype.

* Requirements in design

- Easily coupled with existing muon tomography → Simply placed between target object and trackers
- Compact and portable → ~1 m^3
- Light-weight → < 10kg
- Compatible momentum measurement resolution → σ_p/p = 3.35%, 21.33% for N_{rad} = 100 and 10.
- High accuracy → Mean CR ~ 87%
- Preserve incoming and outgoing muon trajectories → Barely interferes initial muon trajectories

2. Although increased N_{rad} improves $\sigma_p/p|_{mean}$, it will negatively impact the SNR due to the decreased expected Cherenkov signals.
3. To measure energetic muon momentum (>100 GeV/c), very low gas pressure is required.

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V. SUMMARY AND CONCLUSION

Momentum Integrated PoCA Algorithm

1. Momentum integrated PoCA imaging algorithm and M-values.
   - A new algorithm does not increase the computational cost.
   - Materials can be classified using M-values which was challenging using muon scattering angles.
   - Imaging resolution is significantly improved.

Momentum Integrated Muon Tomography

1. It enables us to locate two, one, and a half missing FA(s) in a SNF dry cask.
   - Significantly improves the imaging resolution and reduced the required scanning time to find the missing FA by a factor of 10 or more.

List of Publications -- Peer-reviewed Journal Articles

1. J. Bae, S. Chatzidakis, "Momentum Integrated PoCA Algorithm for Muon Scattering Tomography", *Journal of Imaging* (under review) ← mPoCA
2. J. Bae, S. Chatzidakis, "Momentum Integrated Muon Tomography for Spent Nuclear Fuel Monitoring", *Nuclear Instruments and Methods in Physics Research A* ← Applications of mPoCA in nuclear material management
3. J. Bae, S. Chatzidakis, "Generalized mPoCA imaging algorithm for Muon Radiography" (in preparation) ← Generalized mPoCA
4. J. Bae, S. Chatzidakis, "Development of compact muon spectrometer using multiple pressurized gas Cherenkov radiators", *Results in Physics*, **39** (2022)
5. J. Bae and S. Chatzidakis, "Momentum-Dependent Cosmic Ray Muon Computed Tomography using a Fieldable Muon Spectrometer", *Energies,* **15(7)**, 2666 (2022).
6. J. Bae and S. Chatzidakis, "Fieldable Muon Spectrometer Using Multi-Layer Pressurized Gas Cherenkov Radiators and Its Applications", *Scientific Reports*, **12**, 2559 (2022).
7. J. Bae and S. Chatzidakis, "A New Semi-Empirical Model for Cosmic Ray Muon Flux Estimation", *Progress of Theoretical and Experimental Physics,* **ptac016** (2022).
8. J. Bae and R. Bean, "Investigation of Thermohydraulic Limits on Maximum Reactor Power in LEU Plate-Fueled, Pool Type Research Reactor", *Nuclear Science Engineering* (2022).
9. J. Bae, R. Bean, and R. Abboud, "CFD Analysis of Dry Storage Cask with Advanced Spent Nuclear Fuel Cask Additives", *Annals of Nuclear Energy*, **145** (2020).

List of Publications -- Oral/Poster Presentations and Conference Proceedings

1. J. Bae, S. Chatzidakis, "Spent Nuclear Fuel Dry Cask Monitoring Using Momentum Integrated Muon Tomography", International High Level Radioactive Waste Management Conference (embedded in ANS Winter Meeting), Nov 13-17, 2022, Phoenix, AZ.
2. J. Bae, S. Chatzidakis, "Development and Evaluation of Momentum Coupled Muon Scattering Tomography", IEEE NSS MIC RTSD conference, Nov 05-12, Milano, Italy.
3. J. Bae, S. Chatzidakis, "Non-Linear Cherenkov Muon Spectrometer Using Multi-Layer Pressurized C_3F_8 Gas Radiators", ANS Annual Meeting, June 12-16, 2022, Anaheim, CA.
4. J. Bae and S. Chatzidakis, "A High-Resolution Muon Spectrometer Using Multi-Layer Gas Cherenkov Radiators", American Physical Society (APS) March Meeting, Mar 14-18, 2022, Chicago, IL.
5. J. Bae, S. Chatzidakis, "Applied Gas Cherenkov Radiators to Measure Cosmic Ray Muon Momentum", UKC 2021, Dec 12–15, Anaheim, CA.
6. J. Bae and S. Chatzidakis, "Fieldable Muon Momentum Measurement using Coupled Pressurized Gaseous Cherenkov Detectors", Trans. Am. Nuc. Soc. 125 (1), 400-403 (2021).

Brauslau Travel Grant

Best Presentation Award

Winner of "Pitch your Thesis" competition

List of Publications -- Oral/Poster Presentations and Conference Proceedings

7. J. Bae and S. Chatzidakis, “Cosmic Muon Momentum Measurement Using the Multiple Pressurized Gaseous Cherenkov Detectors”, IEEE NSS-MIC Conf. Records (2021).
8. J. Bae and S. Chatzidakis, “The Effect of Cosmic Ray Muon Momentum Measurement for Monitoring Shielded Special Nuclear Materials”, INMM proceedings, (2021).
9. J. Bae, S. Chatzidakis, R. Bean, “Effective Solid Angle Model and Monte Carlo Method: Improved Estimations to Measure Cosmic Muon Intensity at Sea Level in All Zenith Angles”, ICONE28 proceedings, 4 (2021).
10. [INVITED] J. Bae, R. Bean, and R. Abboud, “A Critical and CFD Analysis of a Dry Storage Cask with Advanced Spent Nuclear Fuel Cask Additives”, Waste Management Symposium (WMS), March 2020, Phoenix, AZ, USA.
11. J. Bae and R. Bean, “Analytical Methods in Safeguards for Nuclear Nonproliferation and Complete, Verifiable, Irreversible Denuclearization (CVID) of North Korea”, INMM proceedings (2019).
12. J. Bae, R. Bean, and R. Abboud, “A Criticality Analysis of a Dry Storage Cask with Advanced Nuclear Fuel Cask Additive”, Trans. Am. Nuc. Soc. 118, 147-150 (2018).

IEEE Trainee grant (online)

Best Paper Award

Roy G. Post Scholarship

Discussion

Junghyun Bae, Ph.D.
School of Nuclear Engineering, Purdue University
Eugene P. Wigner Distinguished Staff Fellow, Oak Ridge National Laboratory
USA

27 July 2022

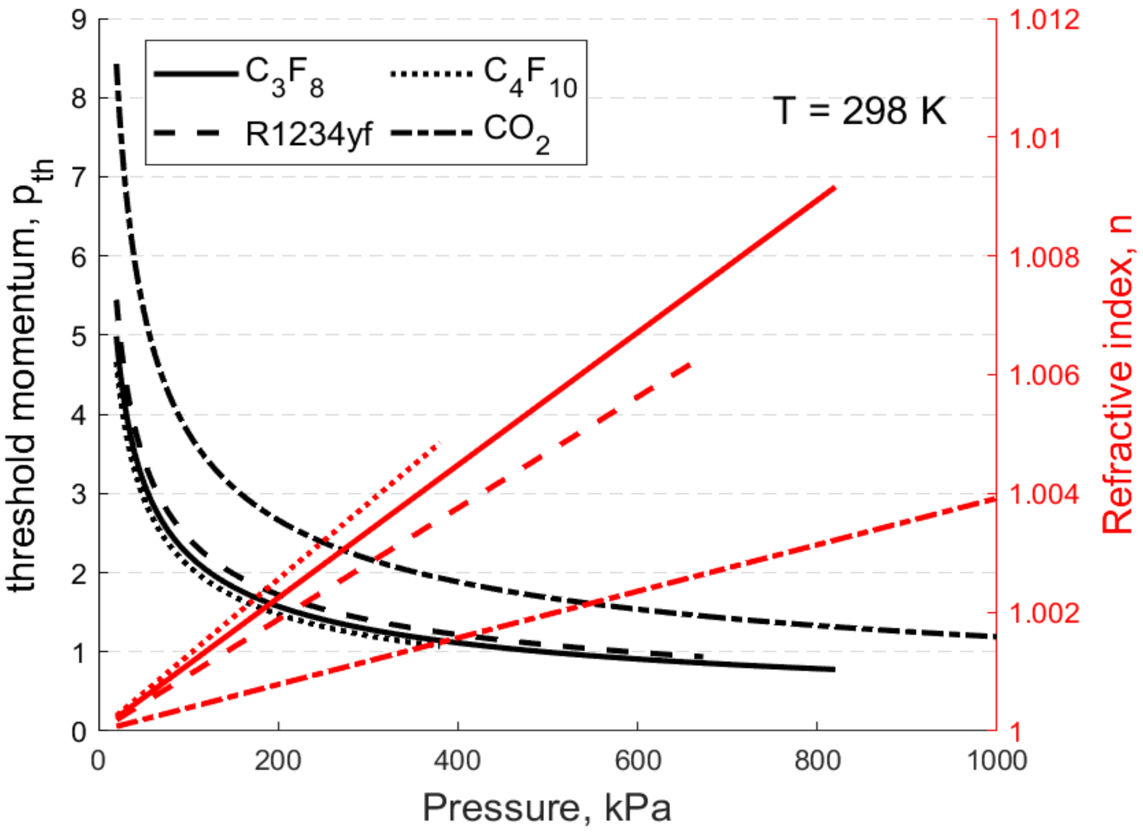
Upcoming Webinars

Date	Title	Presenter
31 August 2022	China's Multi-purpose SMR-ACP100 Design and Project Progress	Dr. Song Danrong, Nuclear Power Institute of China
28 September 2022	Development of In-Service Inspection Rules for Sodium-Cooled Fast Reactors Using the System Based Code Concept	Dr. Shigeru Takaya, JAEA, Japan
26 October 2022	Sodium Integral Effect Test Loop for Safety Simulation and Assessment (STELLA)	Dr. Jewhan LEE , KAERI, Republic of Korea
28 November 2022	Visualization Tool for Comparing Energy Options	Dr. Mark Deinert, Colorado School of Mines, USA

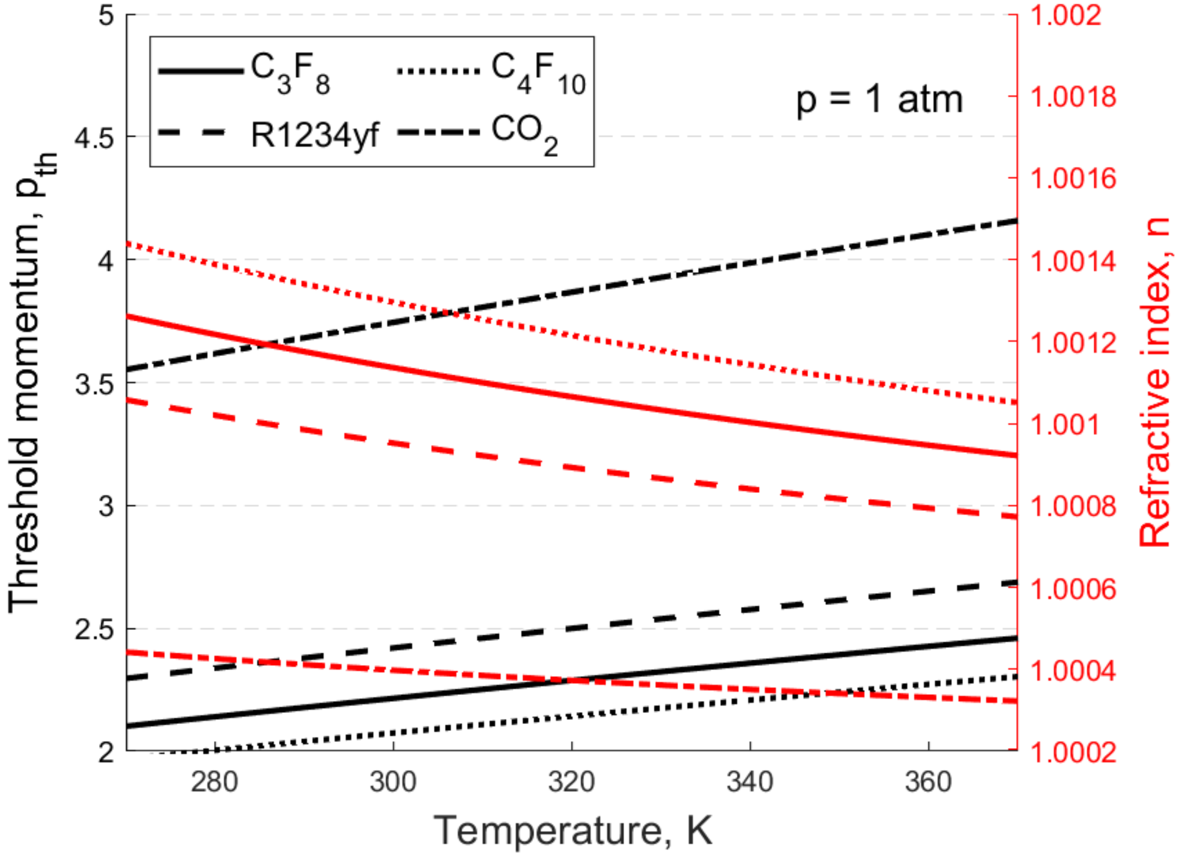
BACKUP SLIDES

II. MUON SPECTROMETER USING GAS CHERENKOV RADIATORS

1) Operational Principle



Pressure vs p_{th} & n



Temperature vs p_{th} & n

Method to differentiate Cherenkov radiation signal from scintillation