中山大學 物理学院
SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

Development of cosmic ray muon detector

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Sino-Thai International Summer School on High Energy Physics and Astrophysics in 2026

July 17th, 2026

References: https://www.smooth-sysu.cn/

① Design of a CsI(Tl) calorimeter for muonium-to-antimuonium conversion experiment, e-Print: 2408.17114, **Frontier of Physics** 20 (2025) 035202.

② Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE), 2410.18817, **Nucl. Sci. Tech.** 37 (2026) 4, 57. Selected as **Cover Paper**.

③ Development of portable cosmic-ray muon detector array for muography, e-Print: 2503.18800 **Journal of Applied Physics** 138, 074502 (2025) .

④ High-Precision Physics Experiments at Huizhou Large-Scale Scientific Facilities, e-Print: 2504.21050, **Chinese Physics Letter** 42 (2025) 11, 110102.

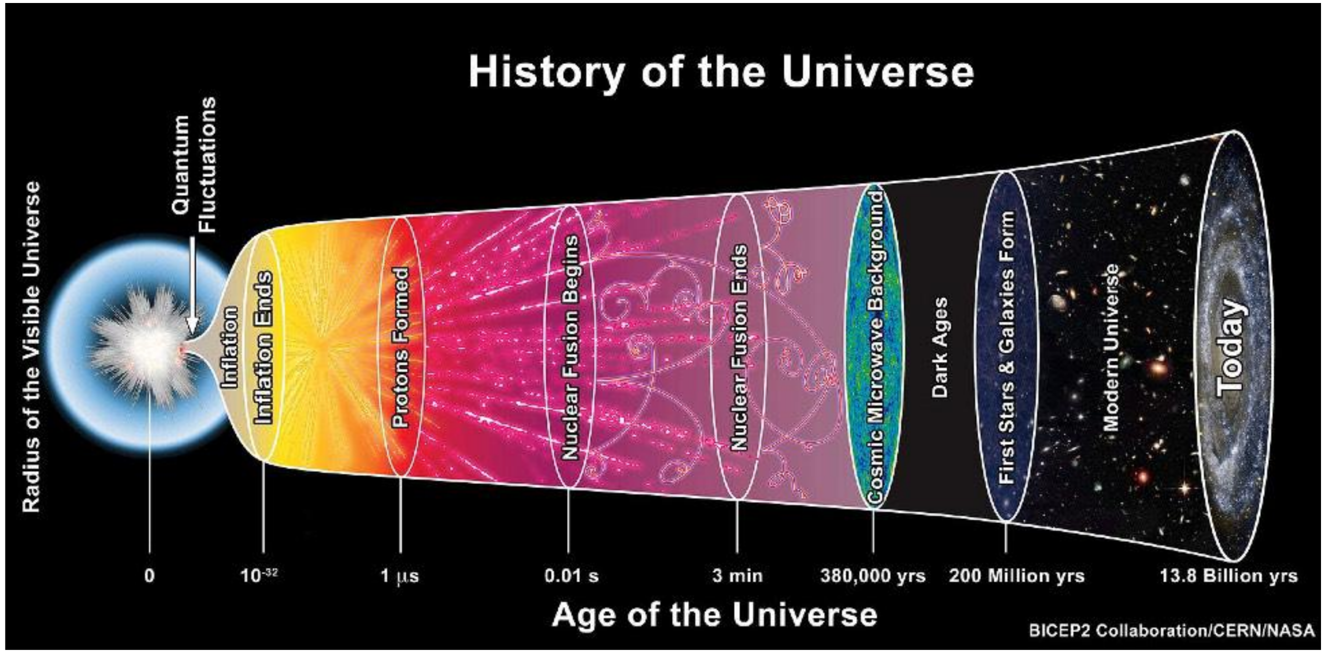
⑤ MuGrid-v2: A novel scintillator detector for multidisciplinary applications, e-Print: 2505.19777, **Journal of Applied Physics** 138, 024501 (2025).

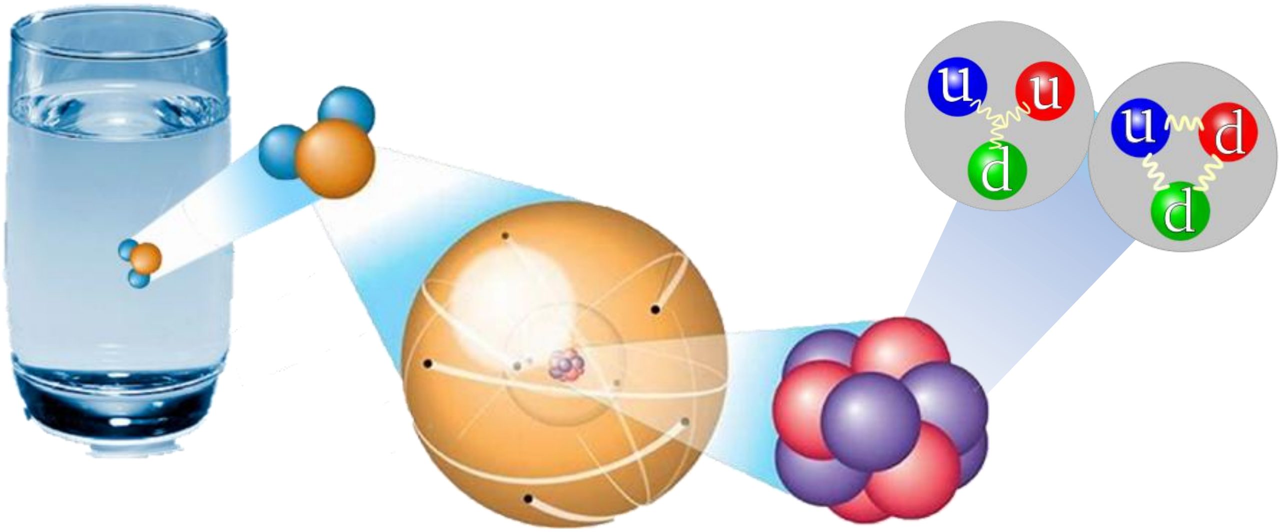
⑥ Positron Transport System for Muonium-to-Antimuonium Conversion Experiment, e-Print: 2508.07922, **Phys. Rev. Accel. Beams** 29 (2026) 3, 031602.

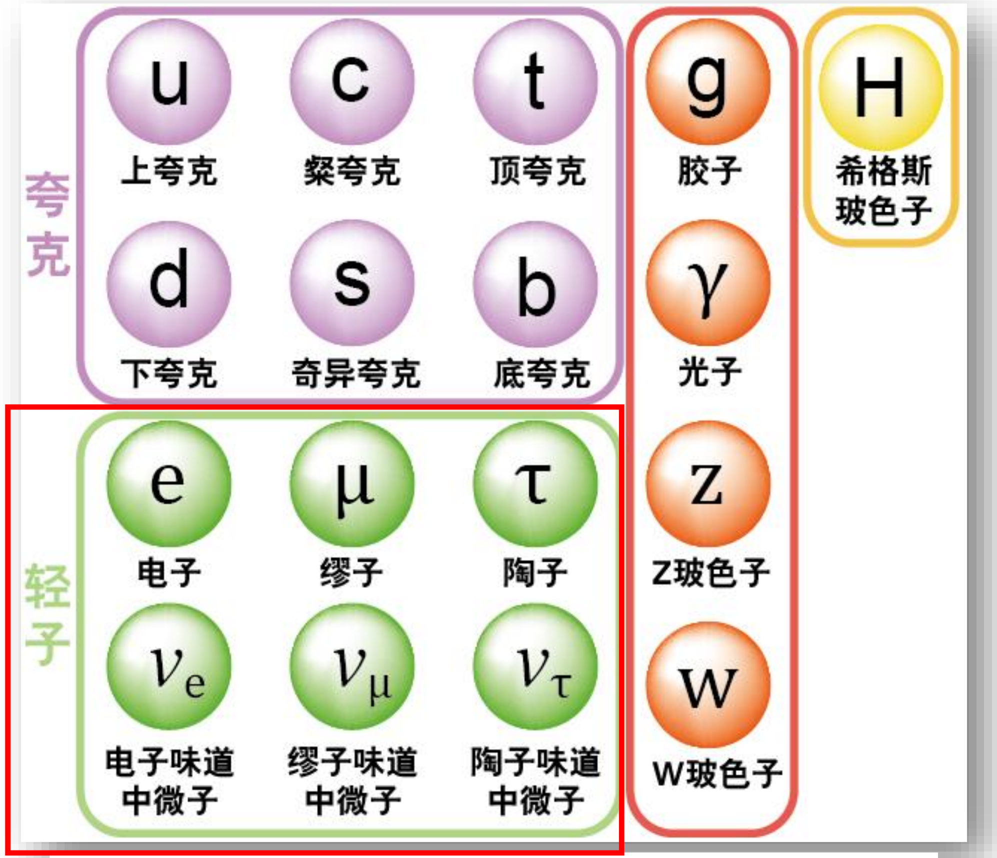
⑦ Muon beams towards muonium physics: progress and prospects, e-Print: 2601.15818. Review submitted to **Progress in Particle and Nuclear Physics**.

Table of contents

Review of standard model in particle physics





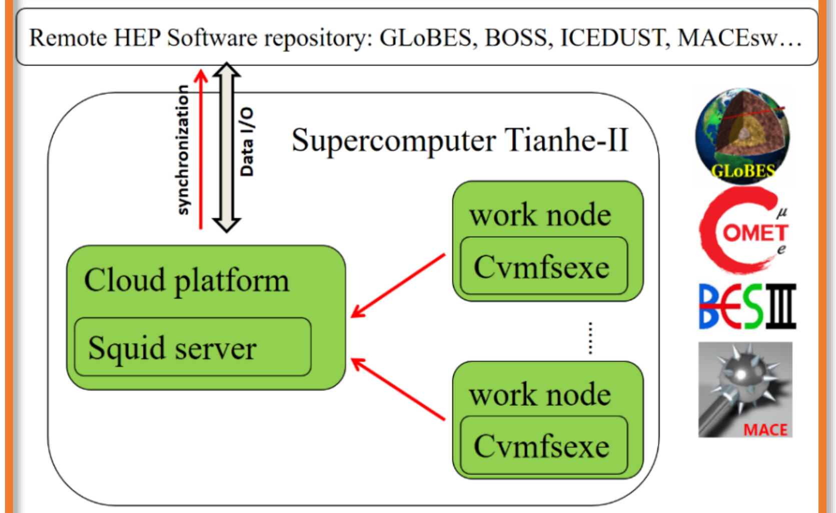


$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

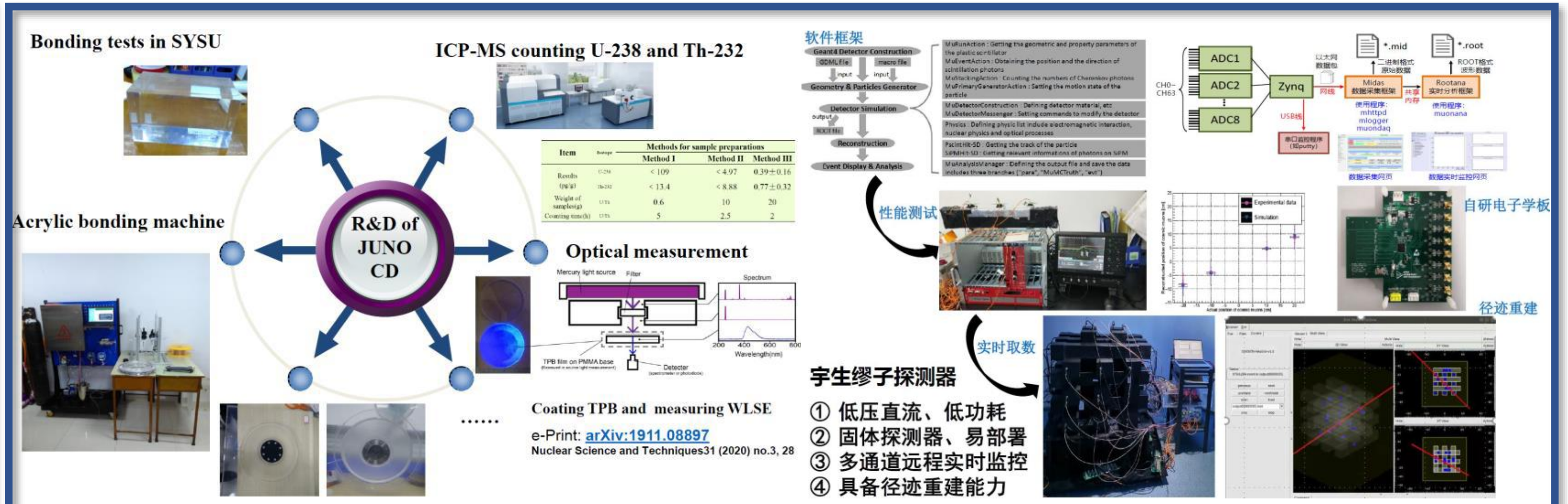
(Strong Interaction)

(Unification of Weak and Electromagnetic)

Lepton flavor physics and new physics



Build a big data platform
Based on supercomputer



Break through key technologies of low-background detectors in JUNO

Muon Science Frontier & Technological Applications

Both hardware and software are good for experiments.

Big data platform based on supercomputer

Application of a supercomputer Tianhe-II in an electron-positron collider experiment BESIII*

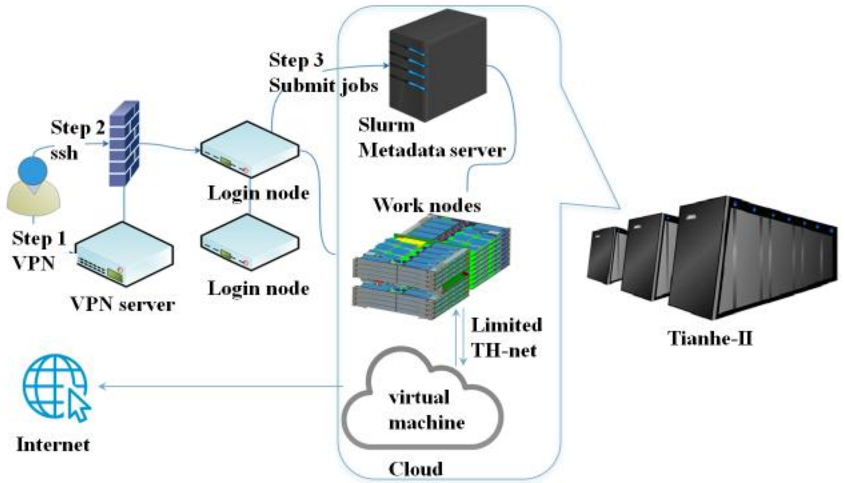
Jing-Kun Chen,[1] Bi-Ying Hu,[2] Xiao-Bin Ji,[3] Qiu-Mei Ma,[3,†] Jian Tang,[2,‡] Ye Yuan,[3,4] Xiao-Mei Zhang,[3] Yao Zhang,[3] Wen-Wen Zhao,[2] and Wei Zheng[3]

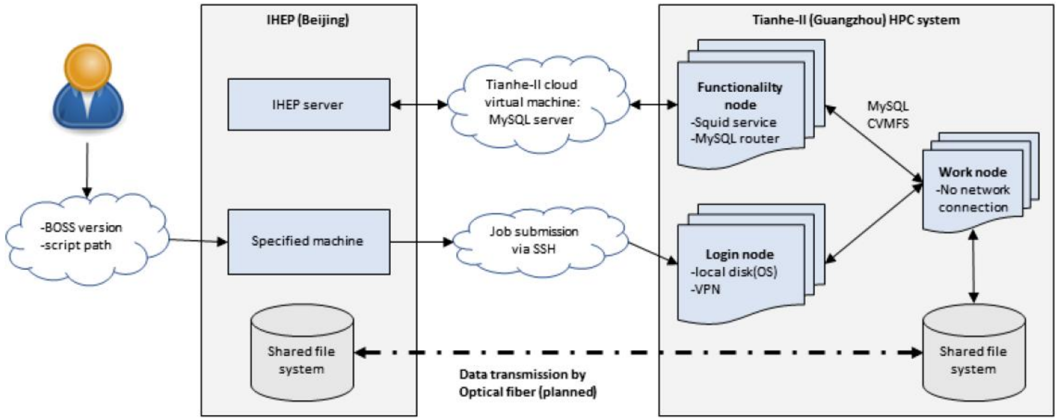
[1] *School of Computer Science and Engineer, Sun Yat-sen University, Guangzhou, 510006, China*
[2] *School of Physics, Sun Yat-sen University, Guangzhou, 510275, China*
[3] *Institute of High Energy Physics, Beijing, 100049, China*
[4] *University of Chinese Academy of Sciences, Beijing, 100049, China*

Precision measurements and new physics searches require massive computation in high energy physics experiments. Supercomputer remains one of the most powerful computing resources in various areas. Taking the BESIII experiment as an illustration, we deploy the offline software BOSS into the top-tier supercomputer "Tianhe-II" with the help of Singularity. With very limited internet connection bandwidth and without root privilege, we synchronize and maintain the simulation software up to date through CVMFS successfully, and an acceleration rate in a comparison of HPC and HTC is realized for the same large-scale task. We solve two problems of the real-time internet connection and the conflict of loading locker by a deployment of a squid server and using fuse in memory in each computing node. We provide a MPI python interface for high throughput (HT) parallel computation in Tianhe-II. Meanwhile, the program to deal with data output is also specially aligned so that there is no queue issue in the input/output (I/O) task. The acceleration rate in simulation reaches 80%, as we have done the simulation tests up to 15K processes in parallel.

Keywords: High Performance Computer, Collider experiment, IO solutions

JINST 18 (2023) 03, T03003



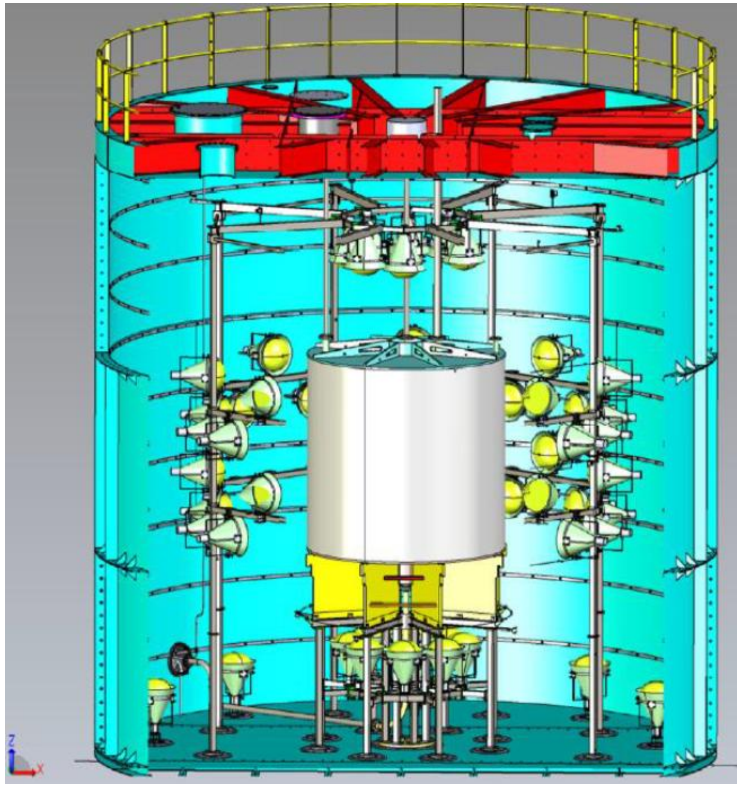


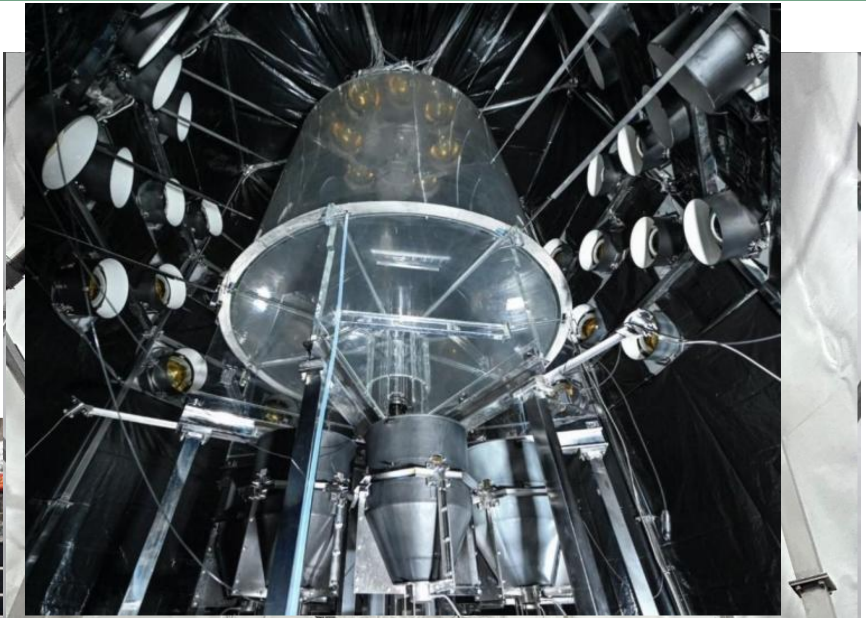
Breakthrough of key PMMA techniques in JUNO

- **Technical Applications:**

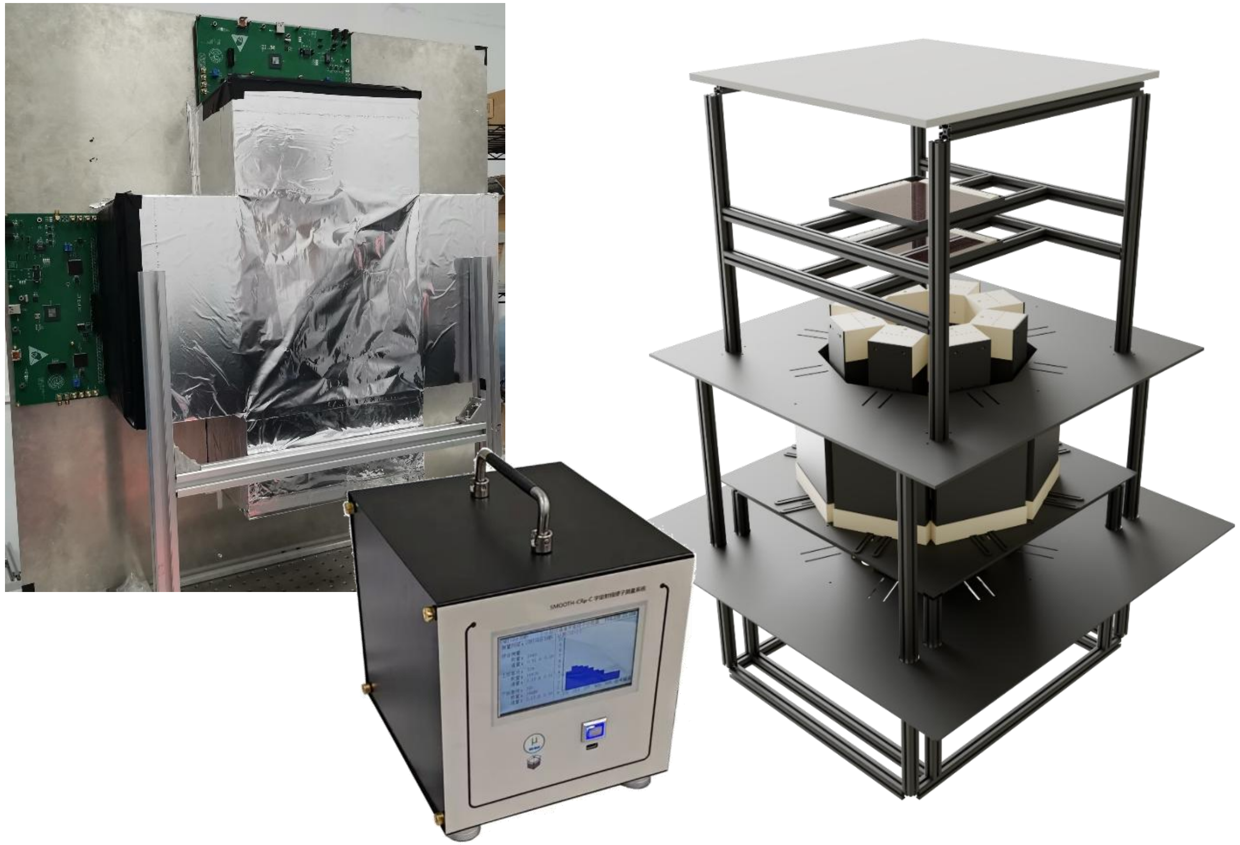
(1) Develop the PMMA bonding techniques for JUNO detector.

(2) Extend it to OSIRIS to monitor trace-level radioactive isotope Rn-222 in liquid scintillator.





Research Platforms and Teams



- 6 PhD students + 6 Master students + 1 research assistant,
- About 10 bachelor students to join the research training
- On-campus partners: Testing center, Supercomputer center
- Off-campus partners in China: USTC, CSNS, IMP&IHEP
- International collaborators: Mainz U., Osaka U., KEK, CU

- SMOOTH: ~100 m^2, Teaching → Research
- Supercomputer: a big data platform for particle physics
- Initialize a muon intensity experiment: MACE
- Participation into others: JUNO, COMET, MuCol…

Table of contents

Platform for Muon Science & Technology

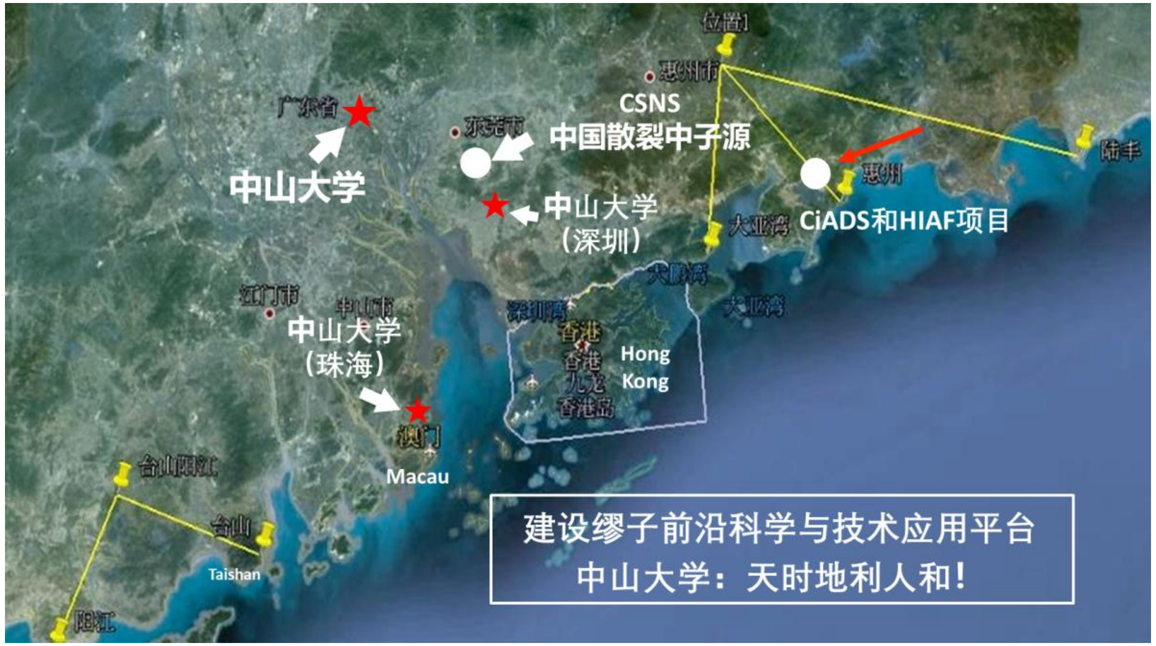
Platform established on Dec. 26, 2024.

Construction Units
School of Physics @ SYSU
School of Physics and Astronomy @ SYSU
Sino-French nuclear engineering @ SYSU
School of Science @ SYSU
School of Chemistry @ SYSU
SYSU Huizhou Research Institute
Institute of Modern Physics, Chinese Academy of Sciences
Institute of High Energy Physics, Chinese Academy of Sciences
Hunan University

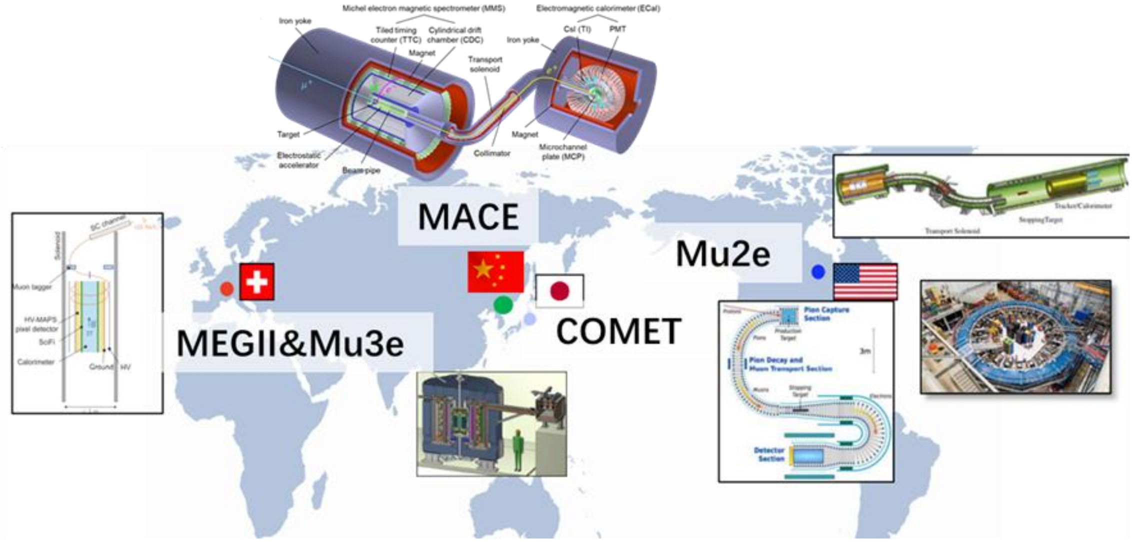
Platform for Muon Science & Technology

- The SMOOTH team consists of approximately 20 researchers. MACE, a frontier muon science experiment initiated by Sun Yat-sen University, aims to search for the conversion process of muonium to antimuonium. conceptual design report has been finalized. There are around 50 domestic and international collaborators participating in the MACE experiment.
- The SMOOTH Laboratory has successfully developed cosmic muon detector for educations, cosmic muon track detection systems, muon beam monitors, a prototype muon spin resonance spectrometer (μSR), and other related devices.

Great Bay Area is a hub of high intensity accelerators
粤港澳大湾区是强流加速器的聚集地



2024	2025	2026	2027	2028	2030
MACE实验 概念设计	MACE第一期 工程设计	MACE第一期 建设和调试	MACE第一期运行 发布首批物理结果	MACE第二期 建设和调试	MACE第二期运行 发布最终物理结果



SMOOTH homepage in Chinese https://www.smooth-sysu.cn

MACE: Muonium to Antimuonium Conversion Experiment

Credits:
Weizhi Xiong
Guihao Lu
Changlin Chen

MACE CDR was released and published!

Conceptual Design of the Muonium-to-Antimuonium Conversion Experiment (MACE)

Ai-Yu Bai,[1,2] Hanjie Cai,[3,4] Chang-Lin Chen,[5] Siyuan Chen,[1,2] Xurong Chen,[3,4,6] Yu Chen,[1,2] Weibin Cheng,[7] Ling-Yun Dai,[5,8] Rui-Rui Fan,[9,10,11] Li Gong,[7] Zihao Guo,[12] Yuan He,[3,4] Zhilong Hou,[9] Yinyuan Huang,[1,2] Huan Jia,[3,4] Hao Jiang,[1,2] Han-Tao Jing,[9] Xiaoshen Kang,[7] Hai-Bo Li,[9,4] Jincheng Li,[3,4] Yang Li,[9] Daming Liu,[13] Shulin Liu,[9,4,14] Guihao Lu,[1,2] Han Miao,[9,4] Yunsong Ning,[1,2] Jianwei Niu,[3,15] Huaxing Peng,[9,4,14] Alexey A. Petrov,[16] Yuanshuai Qin,[3] Mingchen Sun,[1,2] Jian Tang,[1,2,*] Jing-Yu Tang,[17] Ye Tian,[3] Rong Wang,[3,4] Xiaodong Wang,[18,19] Yi Wang,[13] Zhichao Wang,[1,2] Chen Wu,[9,10] Tian-Yu Xing,[20,21] Weizhi Xiong,[22] Yu Xu,[23] Baojun Yan,[9,14] De-Liang Yao,[5,8] Tao Yu,[1,2] Ye Yuan,[9,4] Yi Yuan,[1,2] Yao Zhang,[9] Yongchao Zhang,[12] Zhilv Zhang,[3] Guang Zhao,[9] and Shihan Zhao[1,2]

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[15] *School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*
[16] *Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208, USA*
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[20] *INFN Sezione di Milano, Milano 20133, Italy*
[21] *Universita degli Studi di Milano, Milano 20122, Italy*
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[23] *Advanced energy science and technology Guangdong laboratory, Huizhou 516007, China*

The spontaneous conversion of muonium to antimuonium is one of the interesting charged lepton flavor violation phenomena offering a sensitive probe of potential new physics and serving as a tool to constrain the parameter space beyond the Standard Model. The Muonium-to-Antimuonium Conversion Experiment (MACE) is designed to utilize a high-intensity muon beam, a Michel electron magnetic spectrometer, a positron transport system, and a positron detection system, to either discover or constrain this rare process with a conversion probability of $\mathcal{O}(10^{-13})$. This article presents an overview of the theoretical framework as well as a detailed description of the experimental design for the search for muonium-to-antimuonium conversion.

Keywords: Muonium; Lepton flavor violation; Muon beam; Drift chamber; Microchannel plate; Electromagnetic calorimeter

arXiv 2410.18817

Nucl. Sci. Tech. 37 (2026) 4, 57

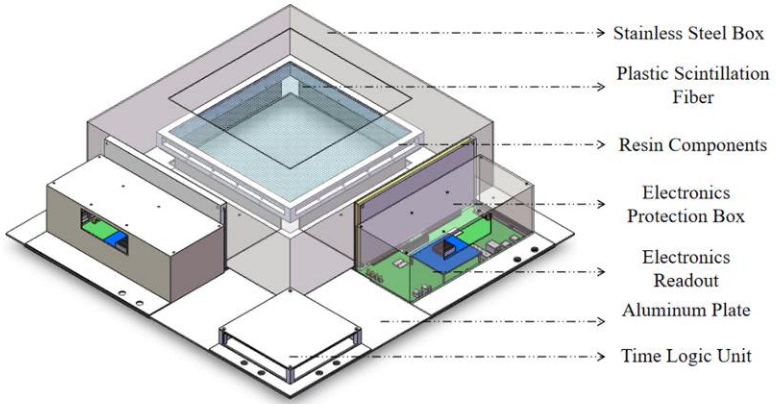
Technical Design of MACE

Welcome to joining our efforts!

Progress of various muon detector development

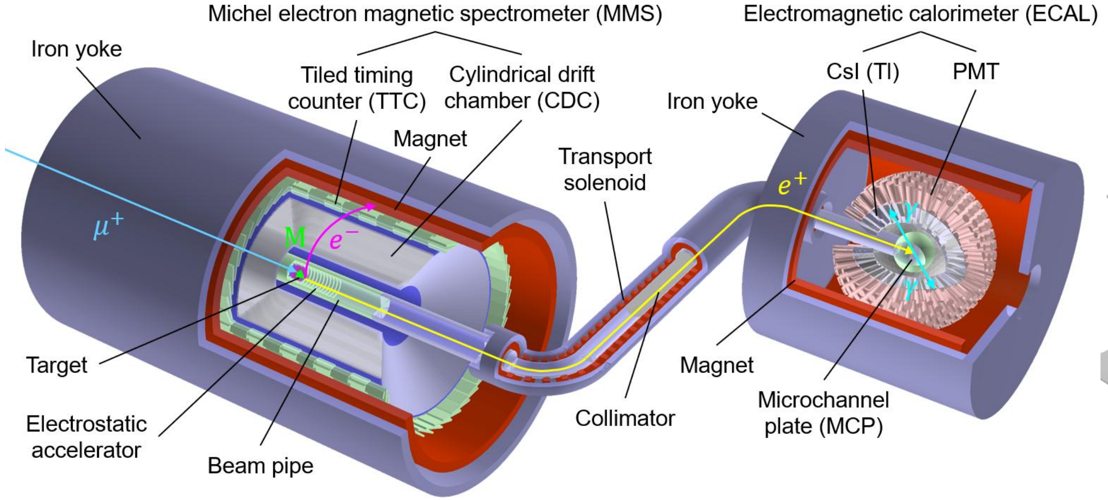
COMET muon beam monitor

Yu Xu et al, Nucl.Sci.Tech. 35 (2024) 4, 79



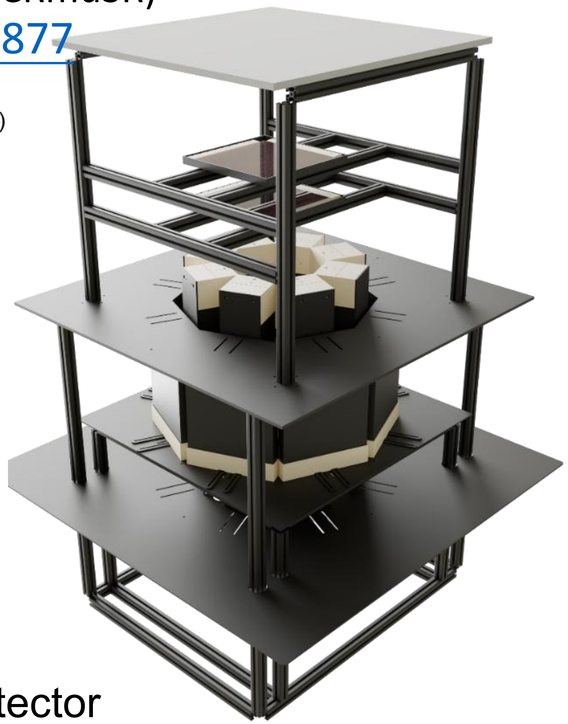
Conceptual Design Report of **MACE**

arXiv: 2410.18817 [hep-ex]

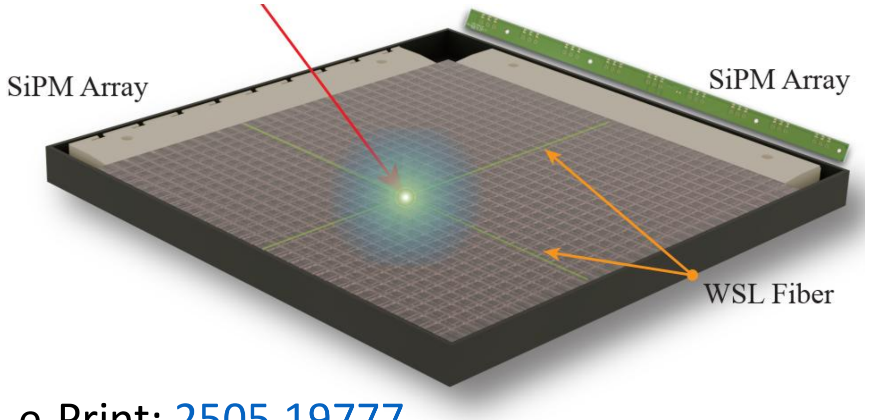


Cosmic-Ray muSR(CRmuSR)

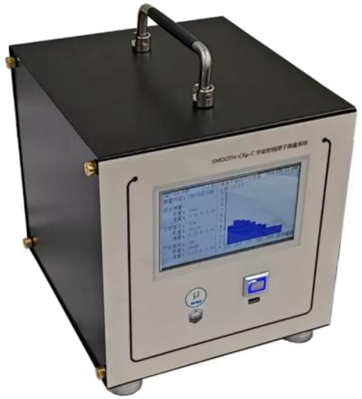
e-Print: 2505.13877



MuGrid-v2 for muography

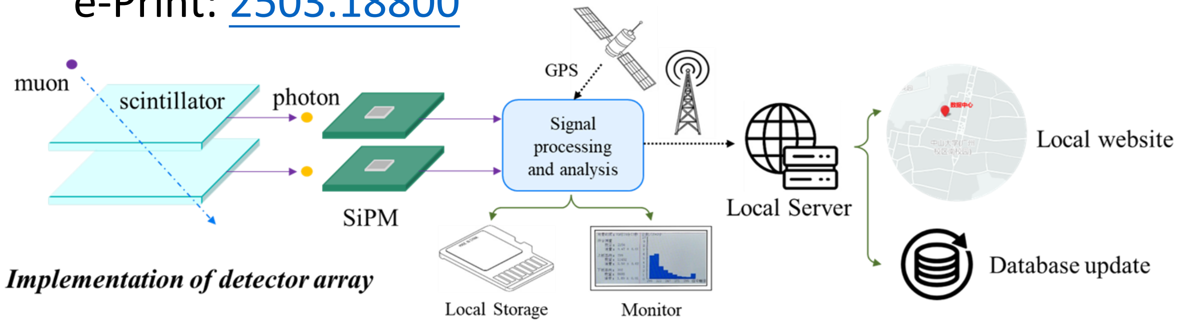


e-Print: 2505.19777

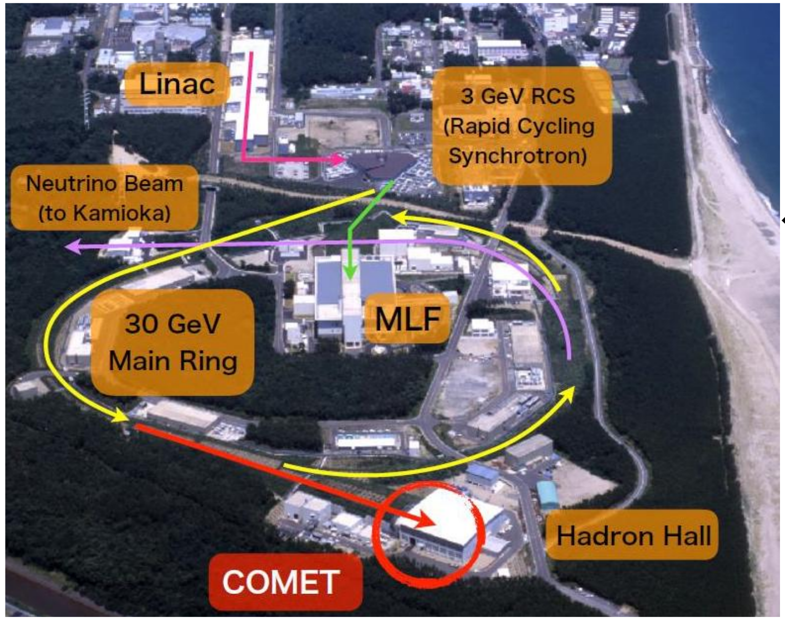


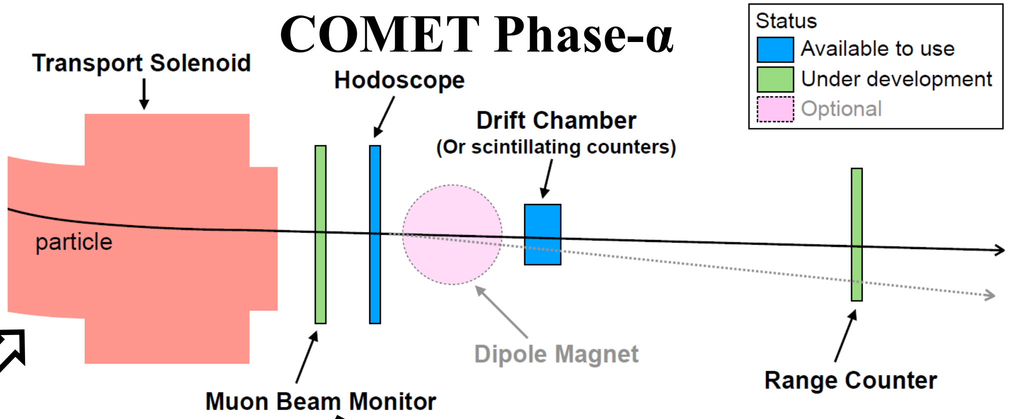
Portable cosmic-ray muon detector

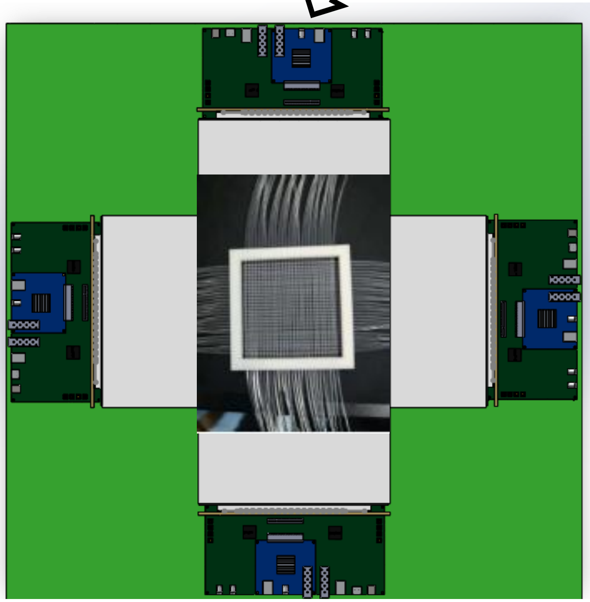
e-Print: 2503.18800

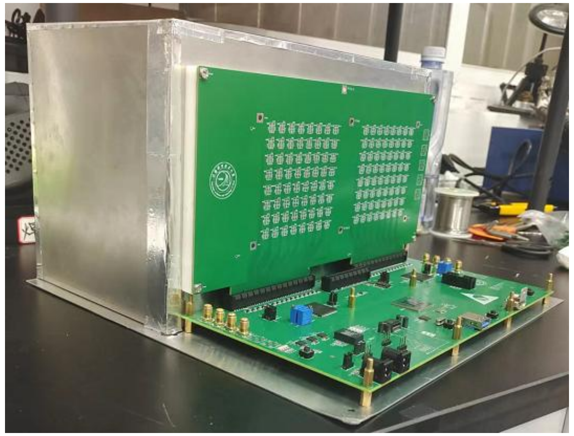


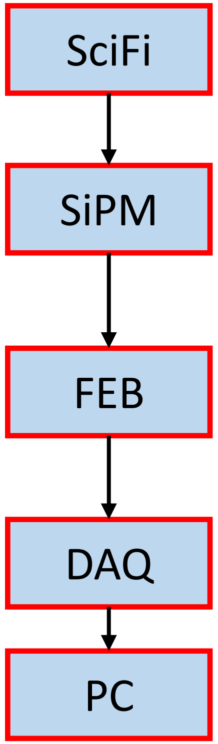
Muon beam monitor for COMET











e-Print: 2308.15253 [physics.ins-det]

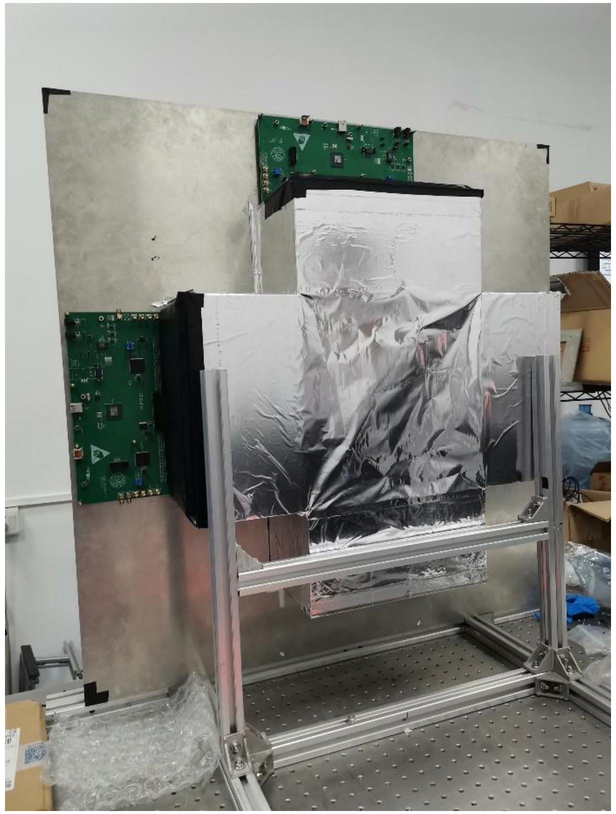
Nuclear Science and Techniques 35 (2024) 4, 79

Credits： SciFi contributions from KEK.
Thanks to Satoshi Mihara and KEK's accelerator crew.

Muon beam monitor for COMET

- CSNS proton beam time: 2022/7/20
- Beam window:
  - 1cm×1cm
  - Energy: 30 MeV, 35 MeV, 40 MeV, 45 MeV, 50 MeV, 55 MeV, 60 MeV
  - Time: 90s per point
  - Beam rate: 1.7×10^{7} protons/s/cm^{2}

Acknowledgment: CSNS proton beamline



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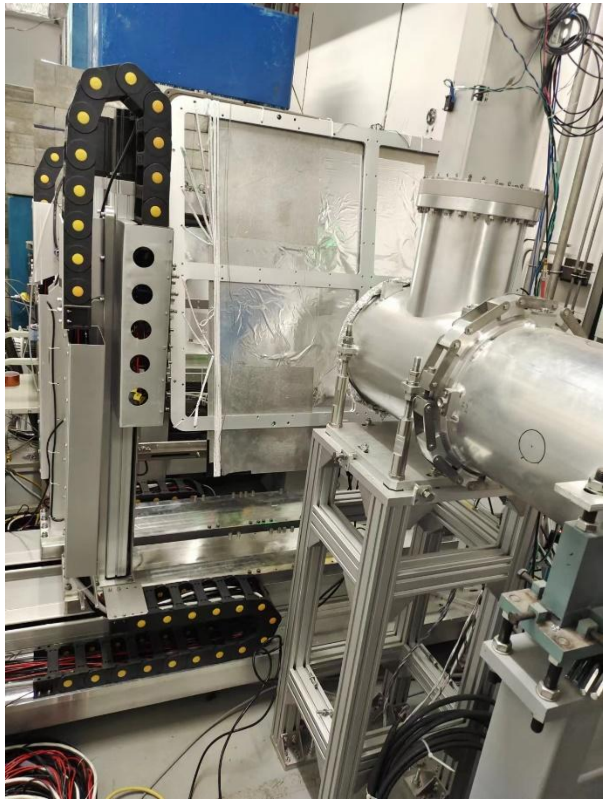
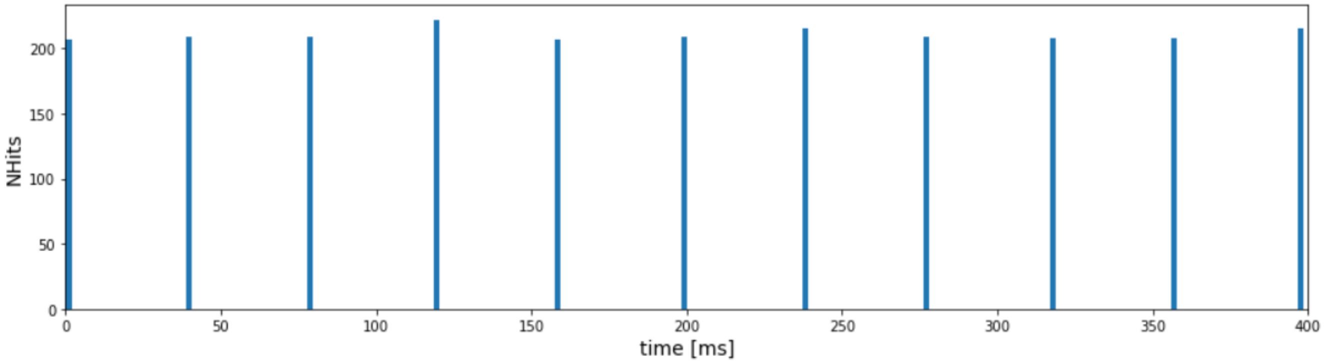
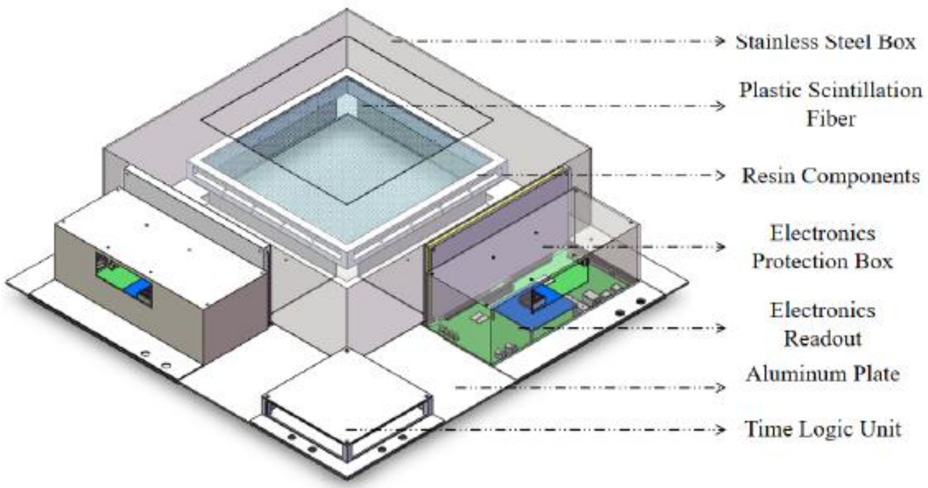
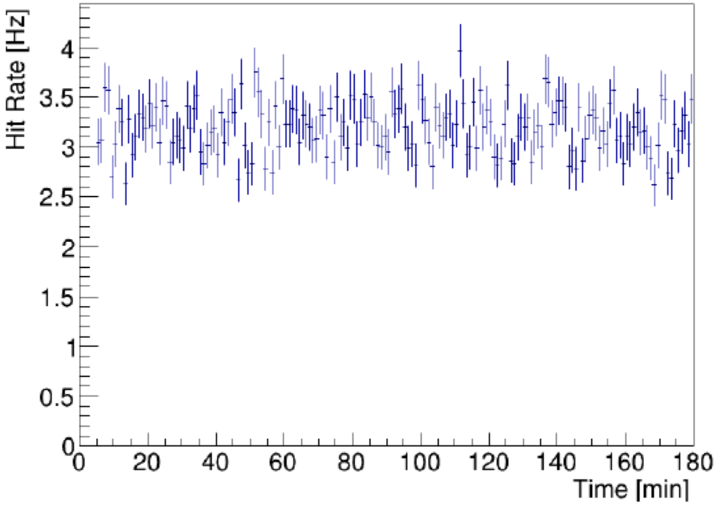
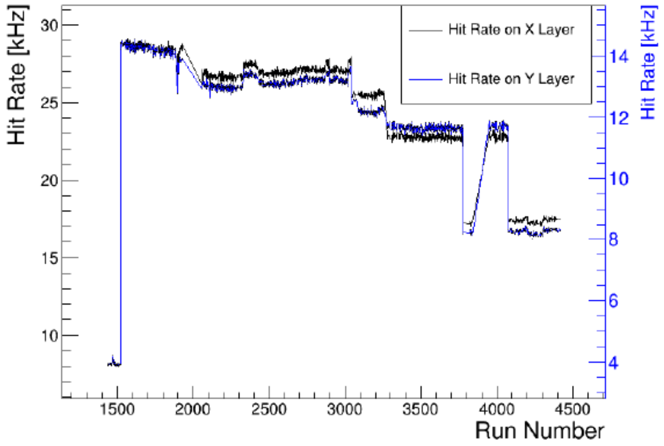


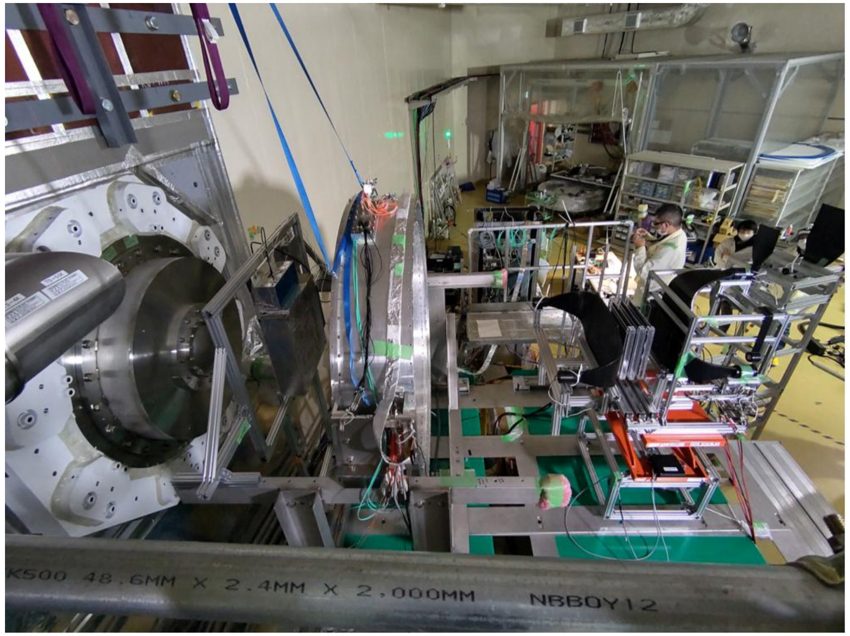


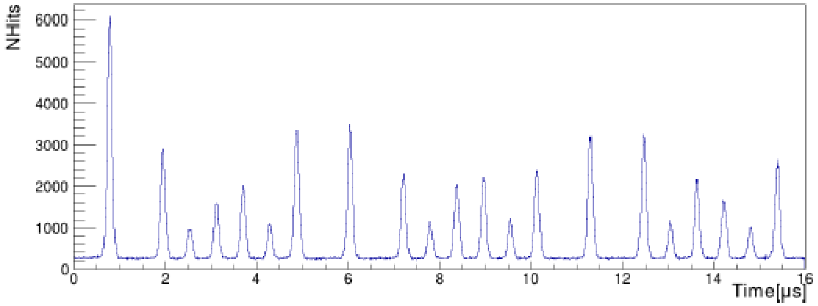
Muon beam monitor for COMET

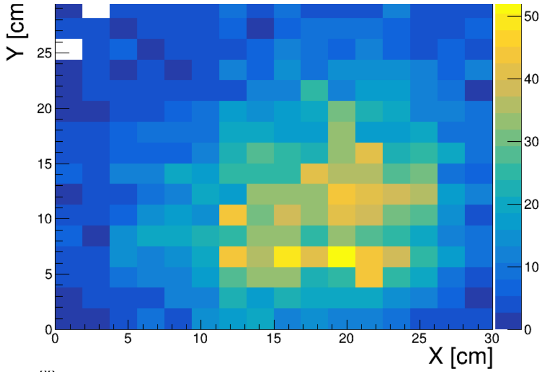


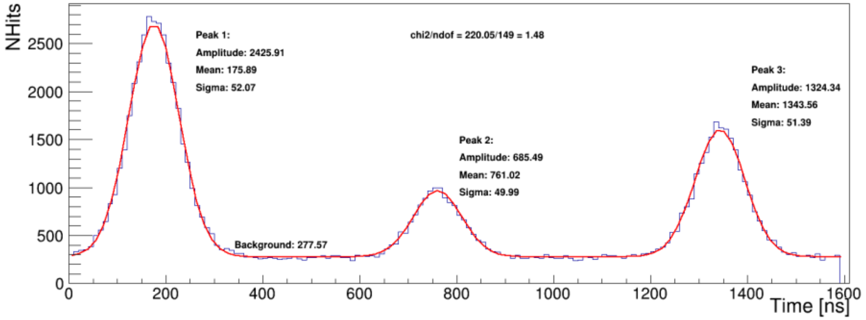


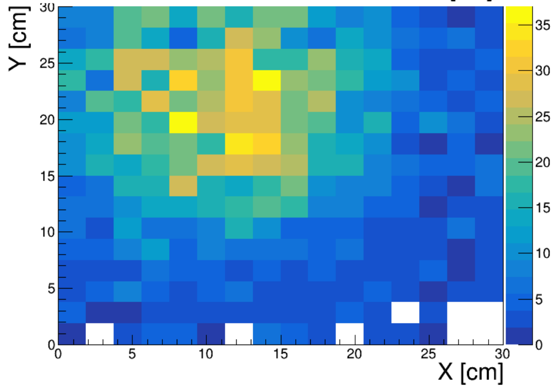






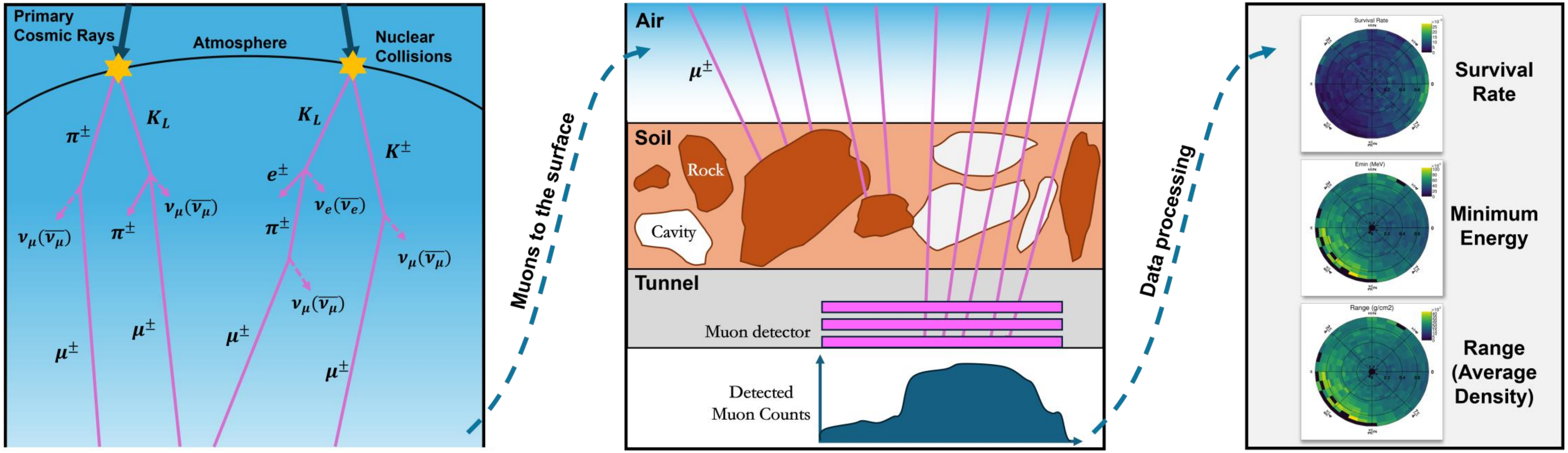






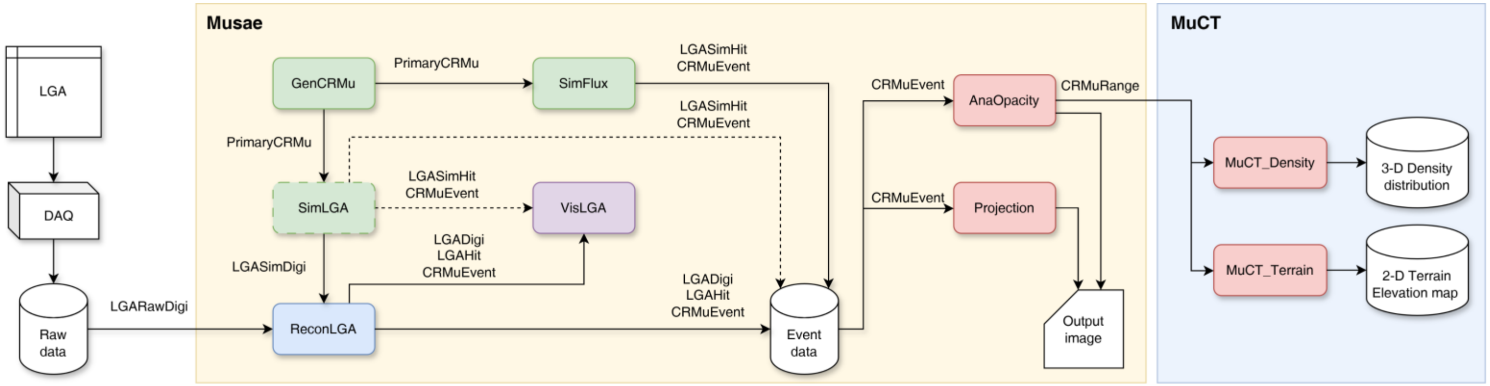
Muography

Cosmic-ray muon production | **Muon detection** | **Data analysis**



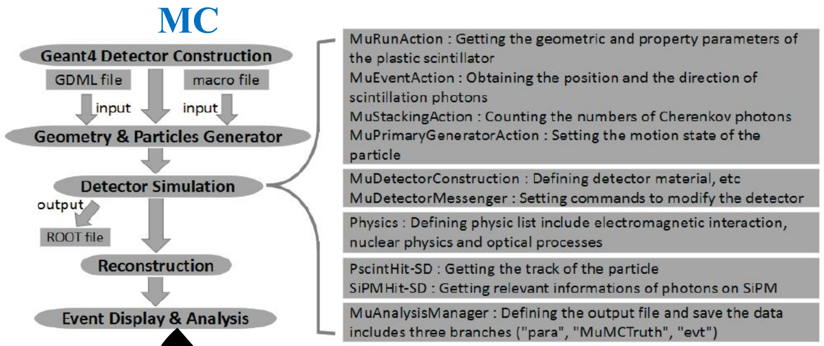
https://github.com/HcupSuki/Musae

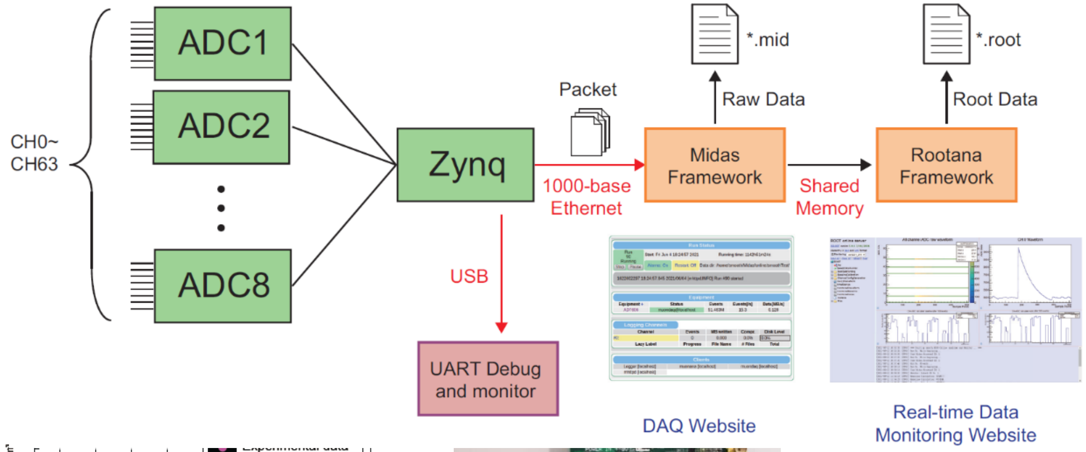
https://arxiv.org/abs/2606.03397



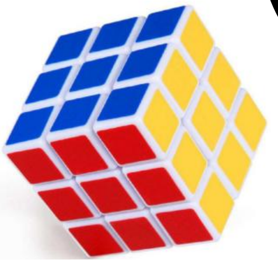
Detector R&D with cosmic muons: MuGrid-v1

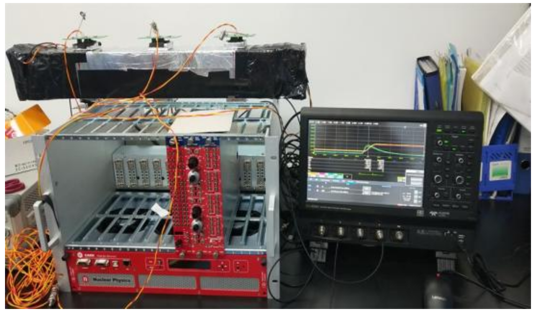
MC

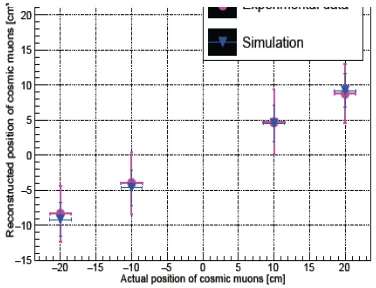




Module test





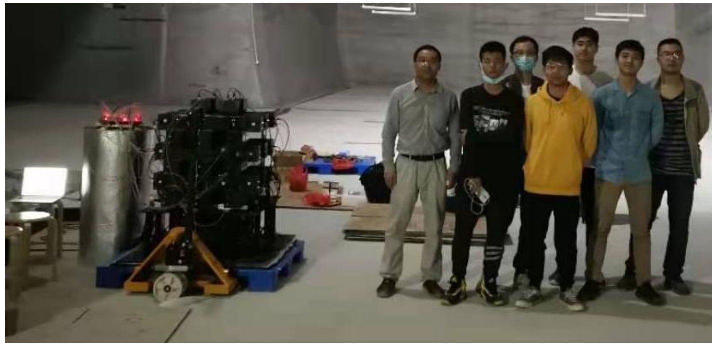


Customized electronics

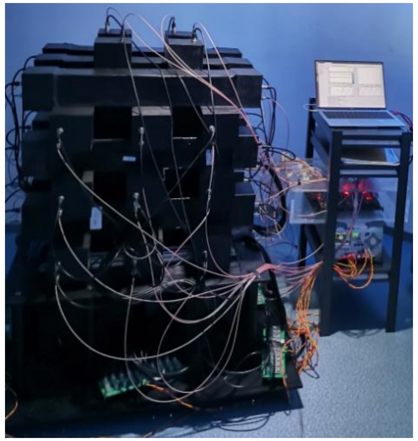
Track reconstruction

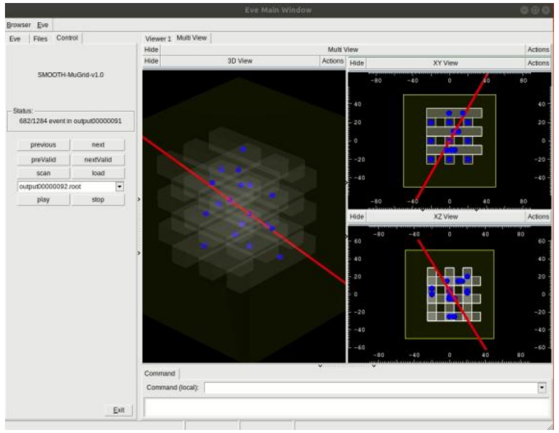
(a)

(b)



Online monitor

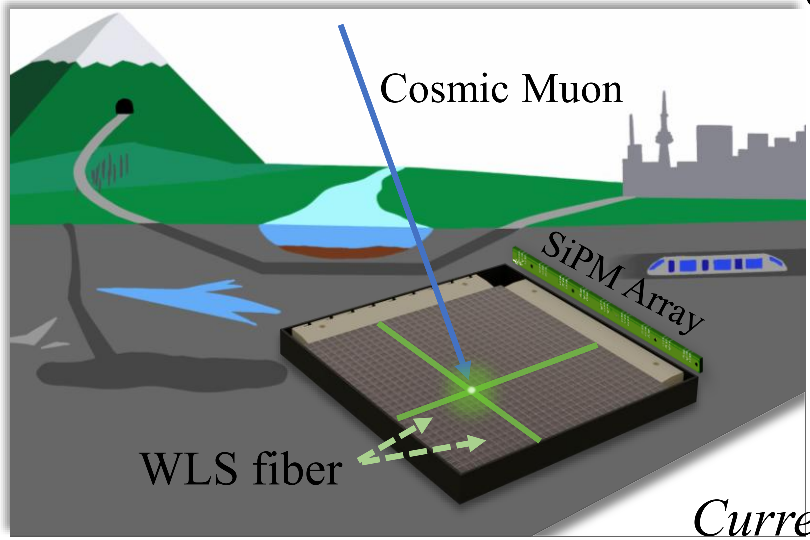




Nuclear Inst. and Methods in Physics Research, A1042 (2022) 167402

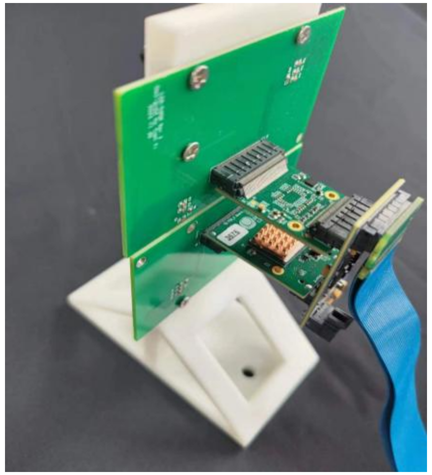
Detector R&D with cosmic muons: MuGrid-v2

e-Print: 2505.19777, **Journal of Applied Physics** 138, 024501 (2025).



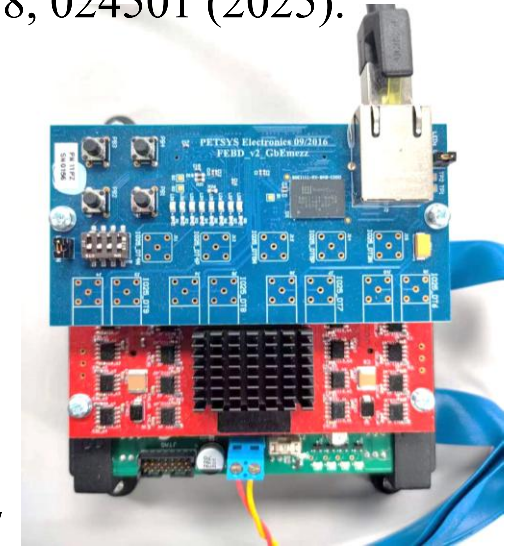
MuGrid-v2 detector

Current signal



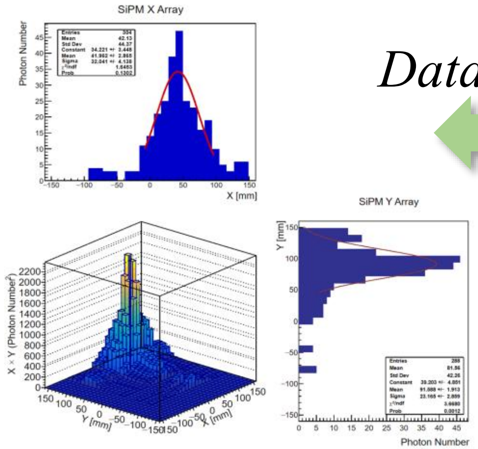
FEB module&
TOFPET2 ASIC

Digital signal



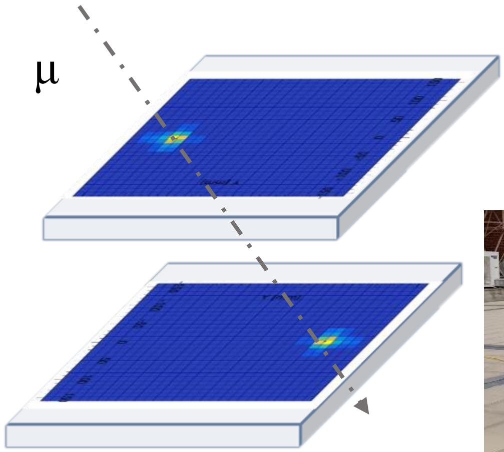
Upper computer

Data acquisition



Hit position reconstruction

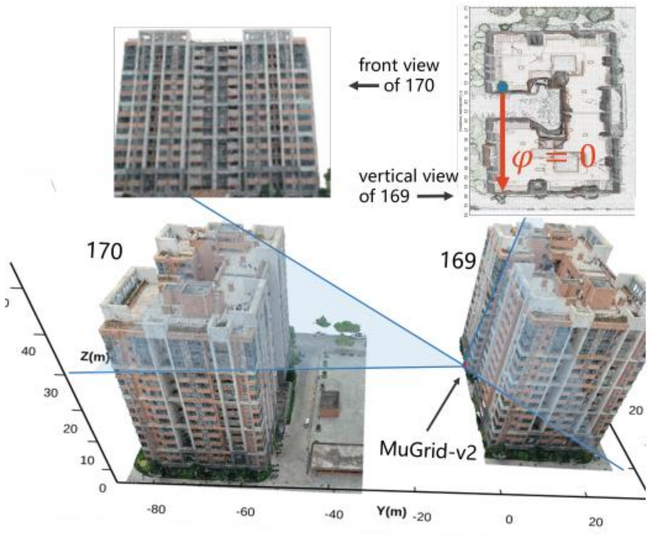
Analysis



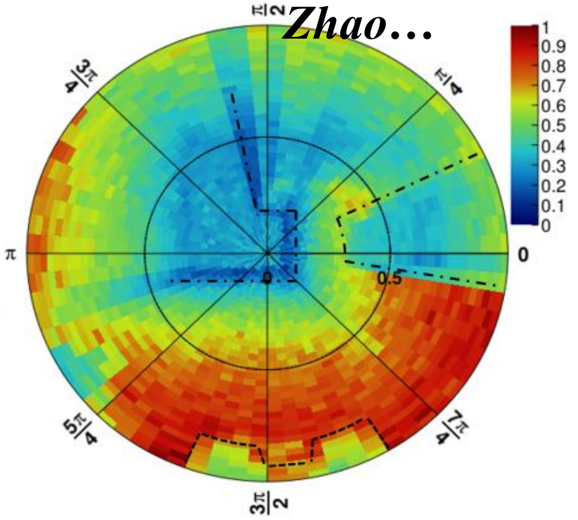
Track reconstruction

Upgrade: MuGrid-v2

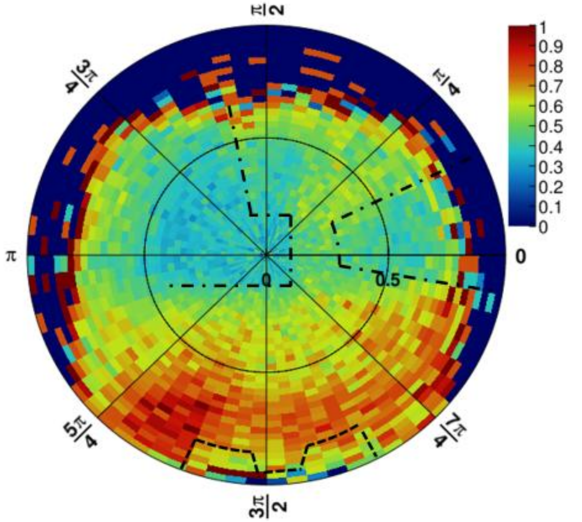
Credits: Tao Yu, Songran Qi, Shihan Zhao…



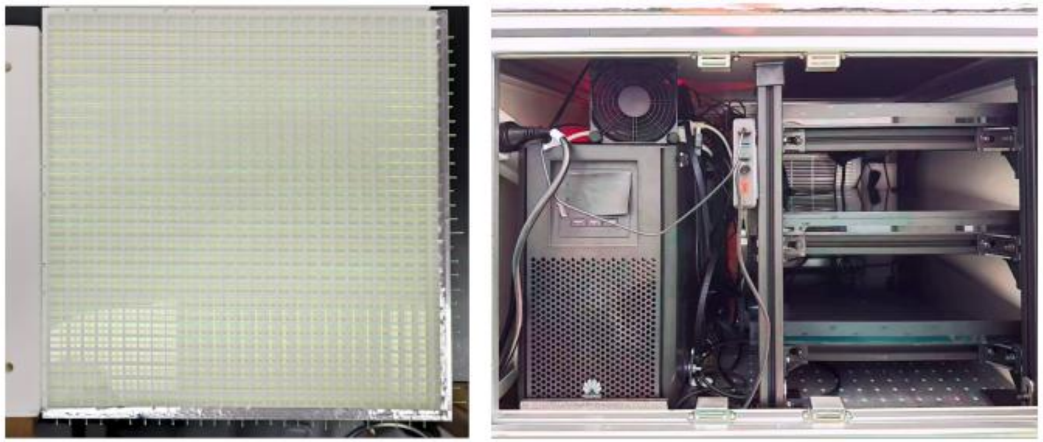
(a) An illustration of experimental setup.



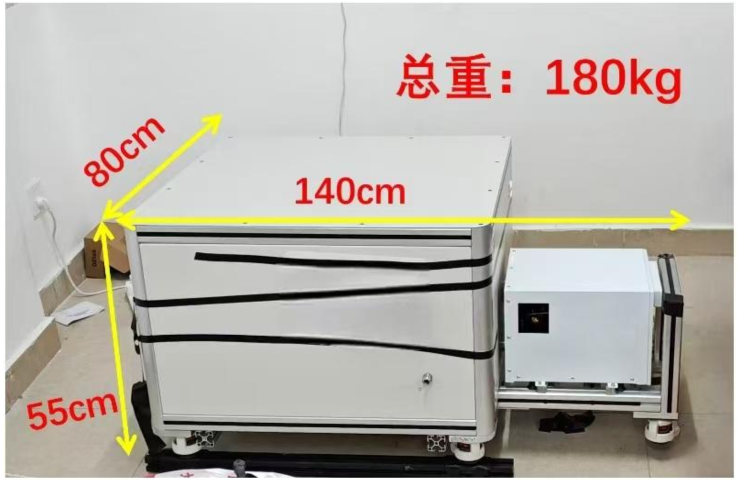
(b) Muon survival ratio in simulation.

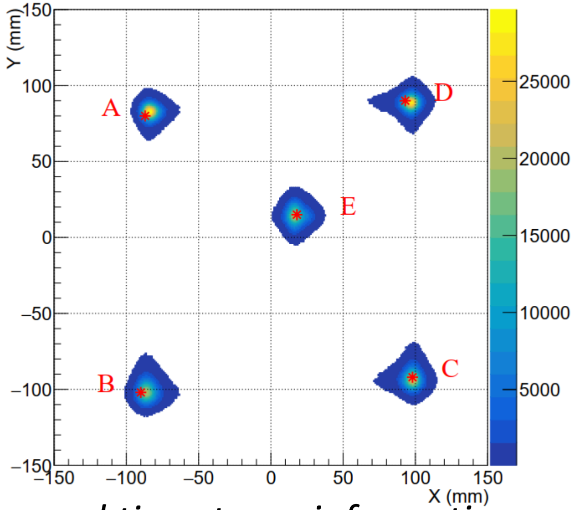


(c) Muon survival ratio in experiment.



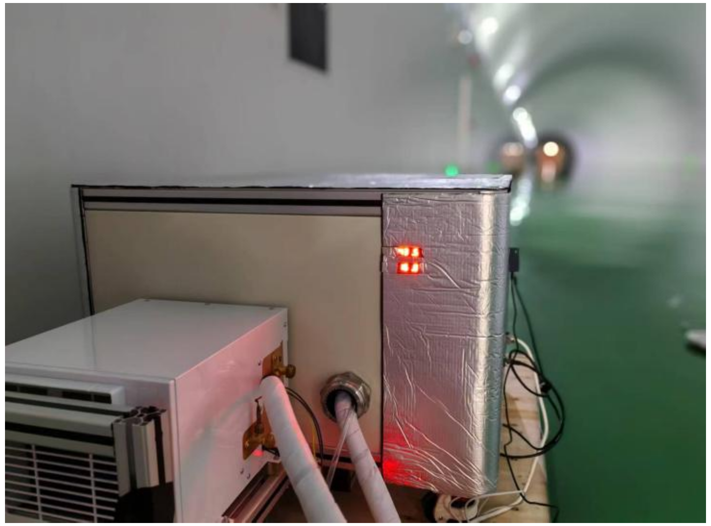
The detector MuGrid-v2 after assembly.

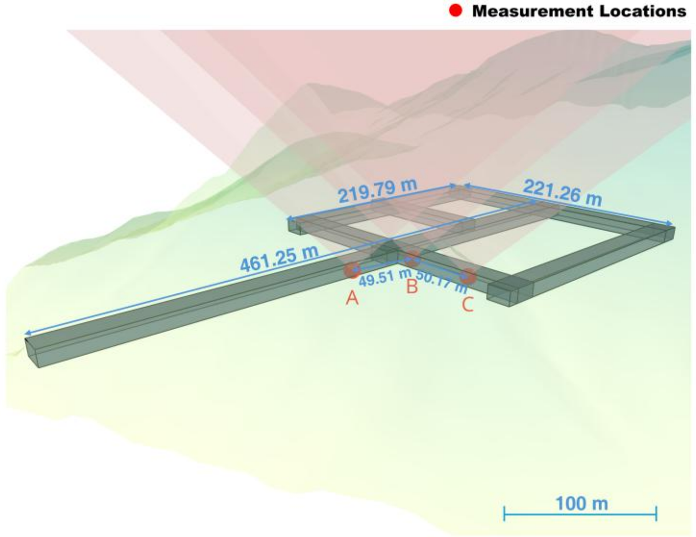




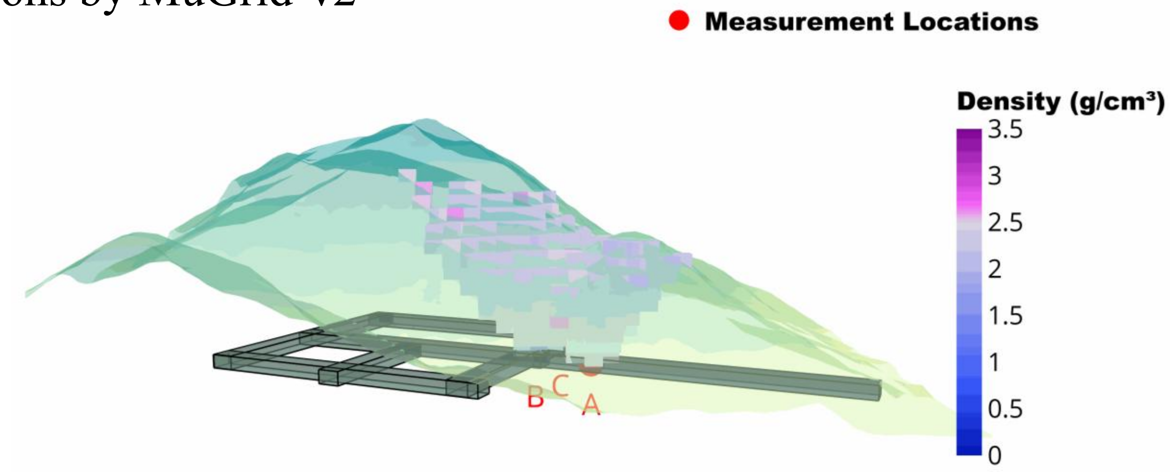
Calibrations with the energy and timestamp information.

Applications in Tianqin tunnel

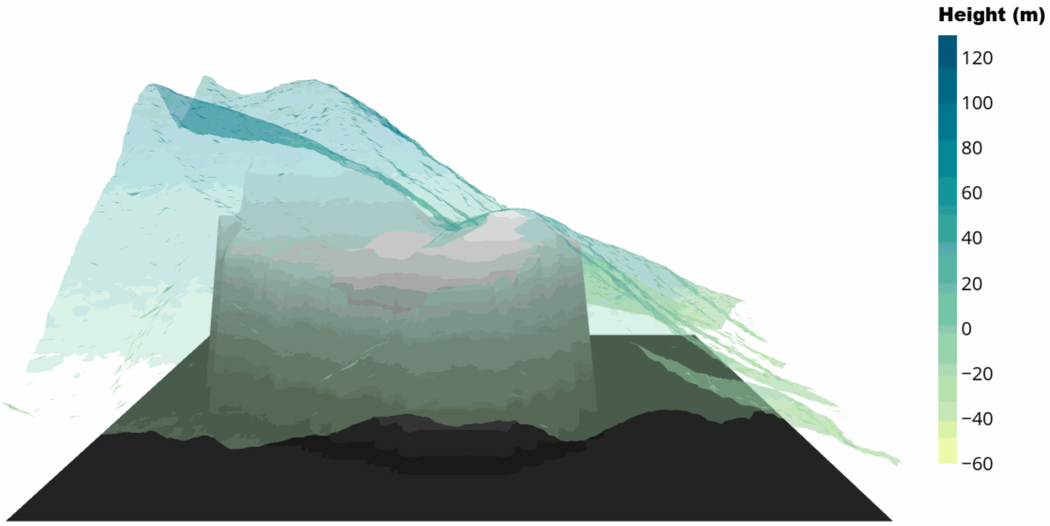




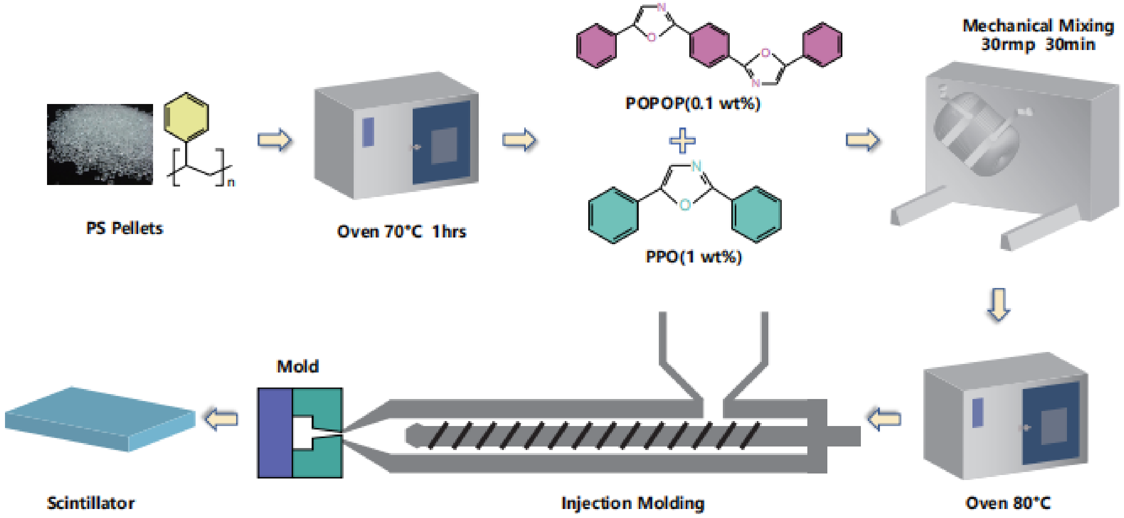
- 3D density reconstructions by MuGrid-v2

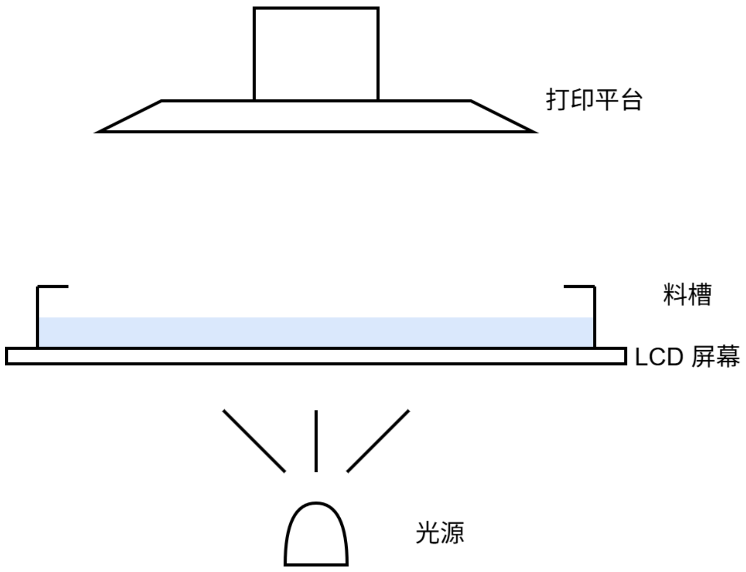


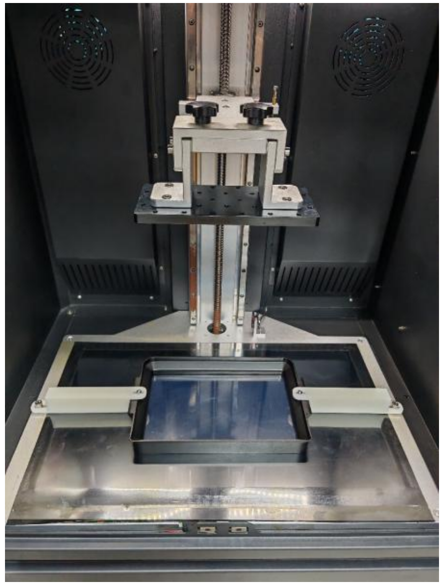
- 3D air-rock interface reconstructions by MuGrid-v2

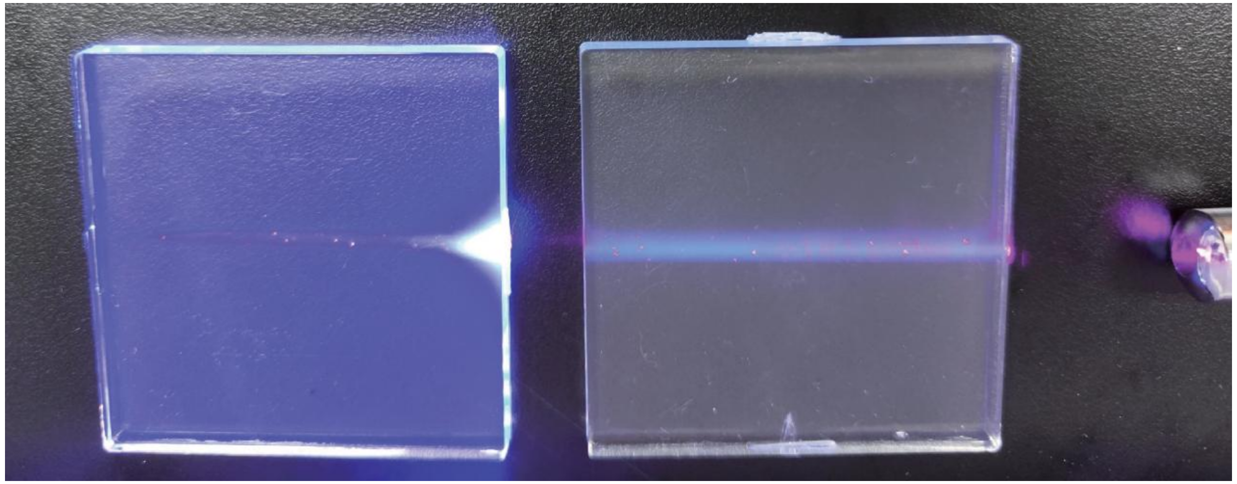


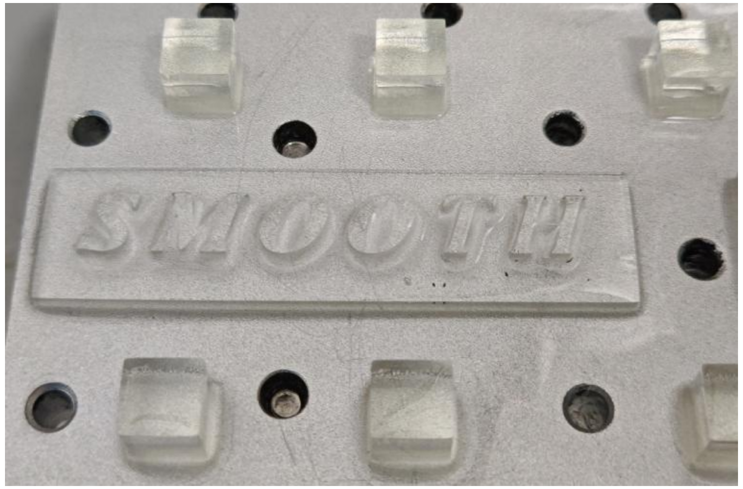
R&D of new plastic scintillators for muon detections

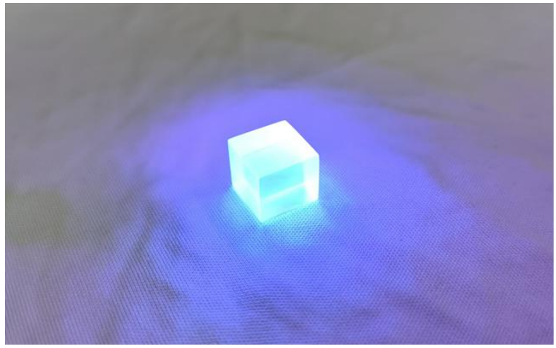




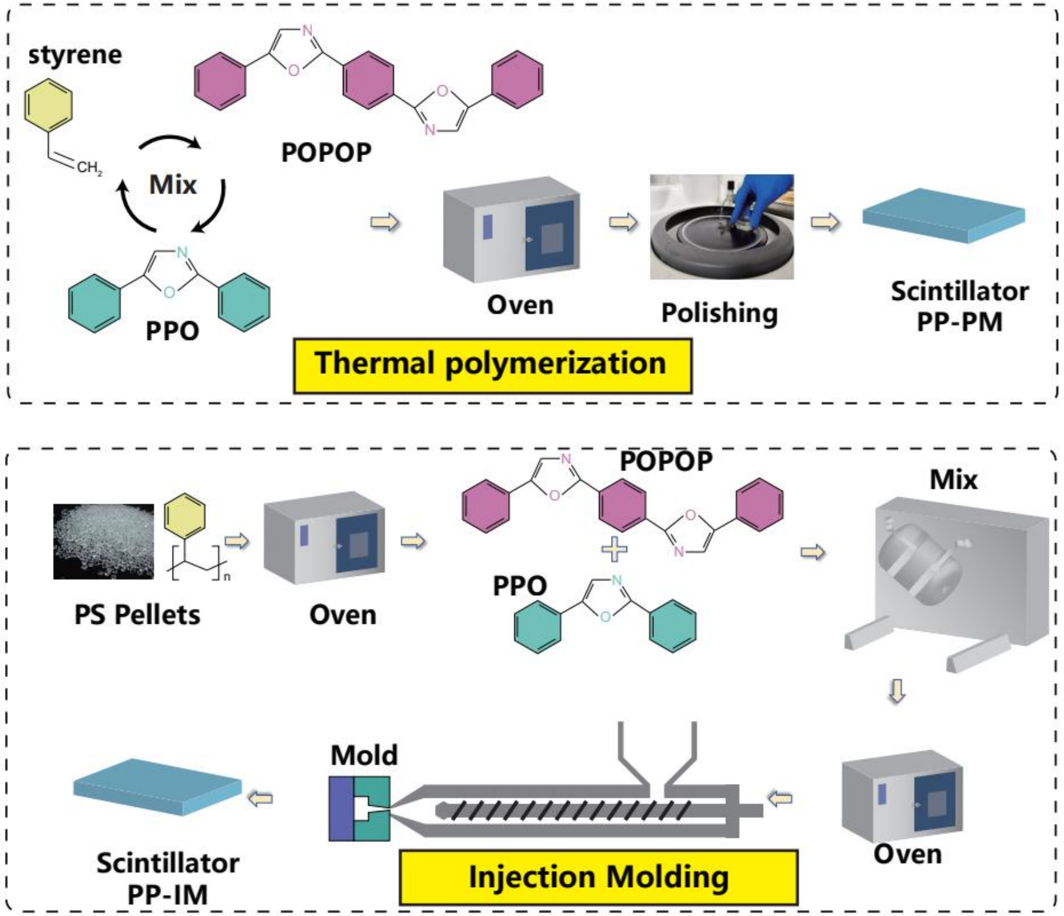


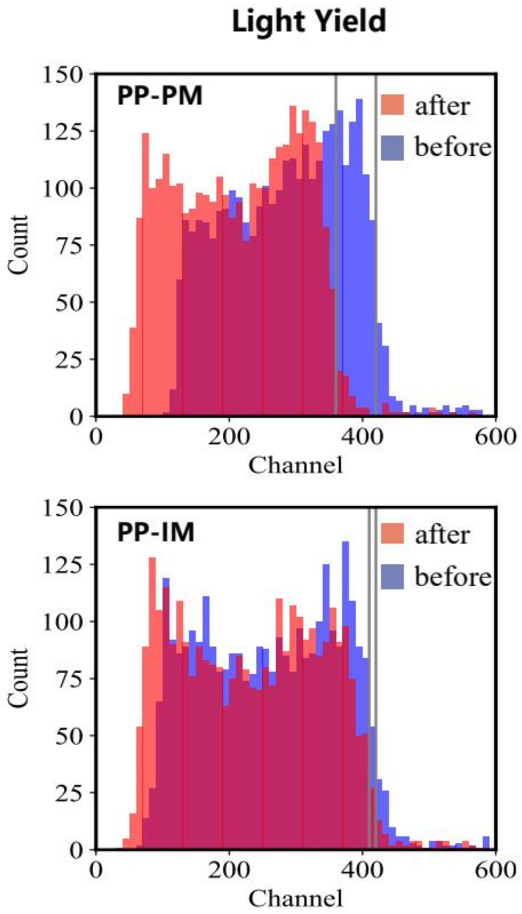


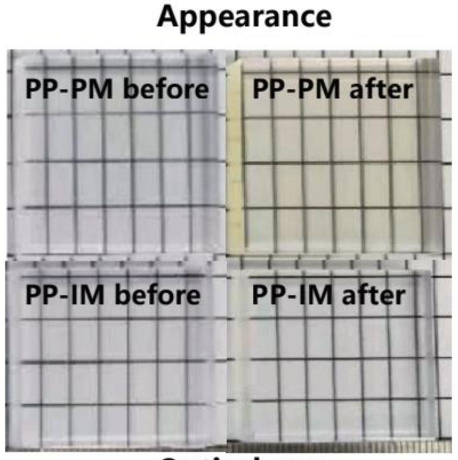


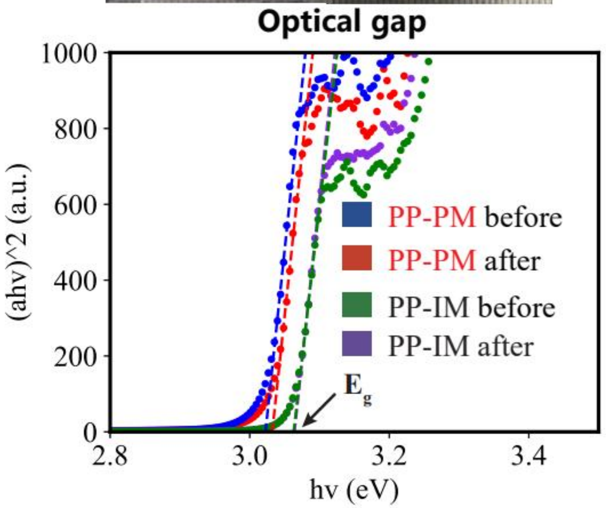


R&D of new plastic scintillators for muon detections





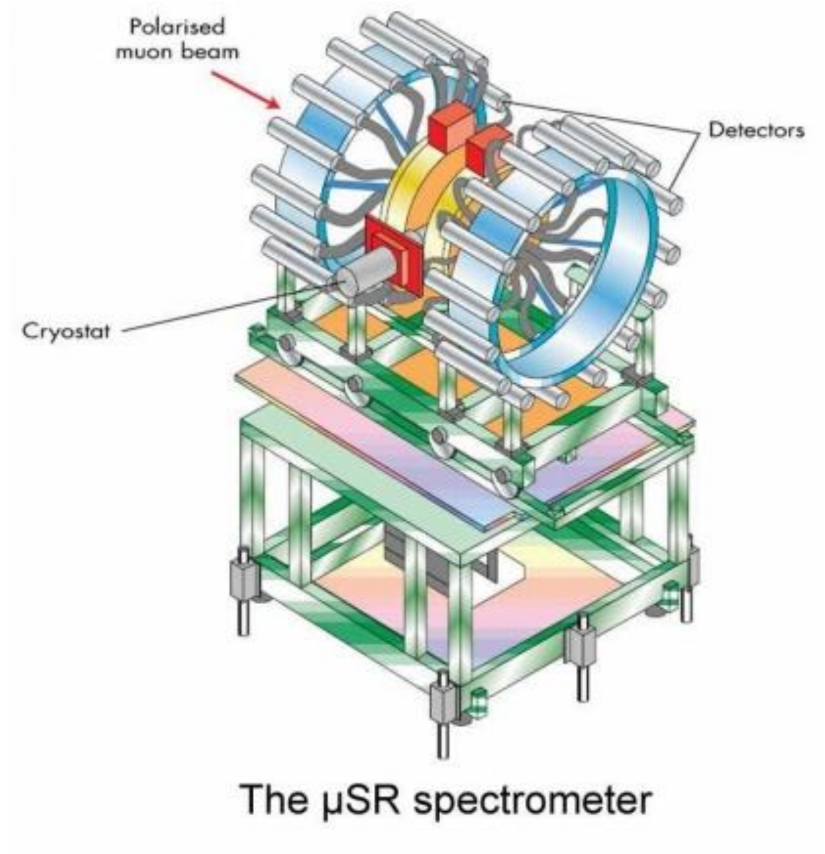




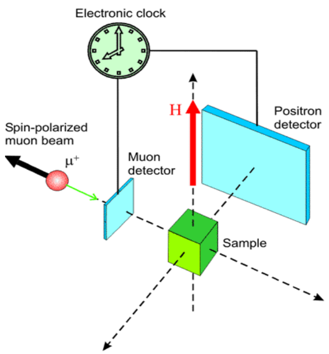
Enhancing plastic scintillator performance through advanced injection molding techniques

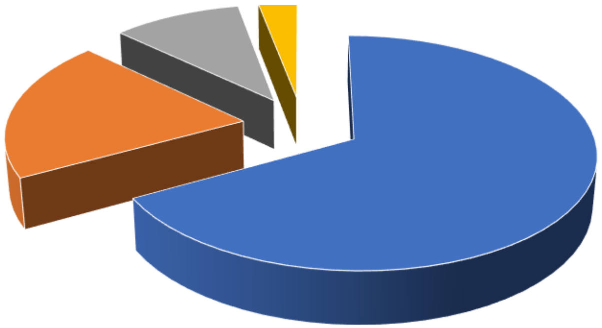
Credits: Jiahao Zhong, Nouman, Jian Zhou
Radiation Physics and Chemistry *226 (2025) 112193*

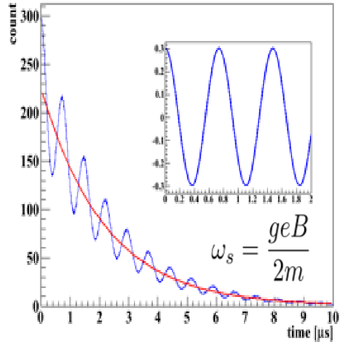
Muon Spin Relaxation, Rotation and Resonance (μSR)



Nature Materials 16, 467–473 (2017)



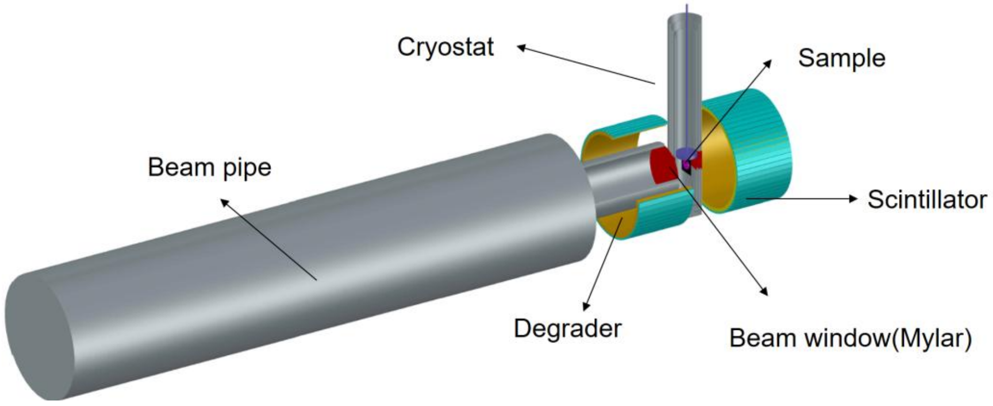




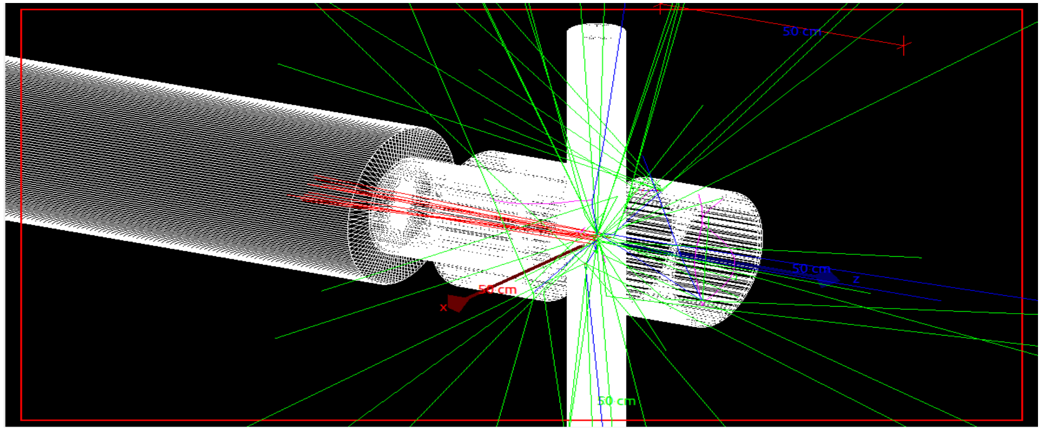
- Physics → *Magnetism*, *Superconductivity*, *Surface physics*, *Fundamental physics*
- Chemistry → *Molecular dynamics*, *Oxides*, *Muonium in materials*
- Materials → *Polymers*, *Semiconductors*, *Hydrogen storage material*
- Biology → *proteins*, *DNA*

Design and simulation of μSR

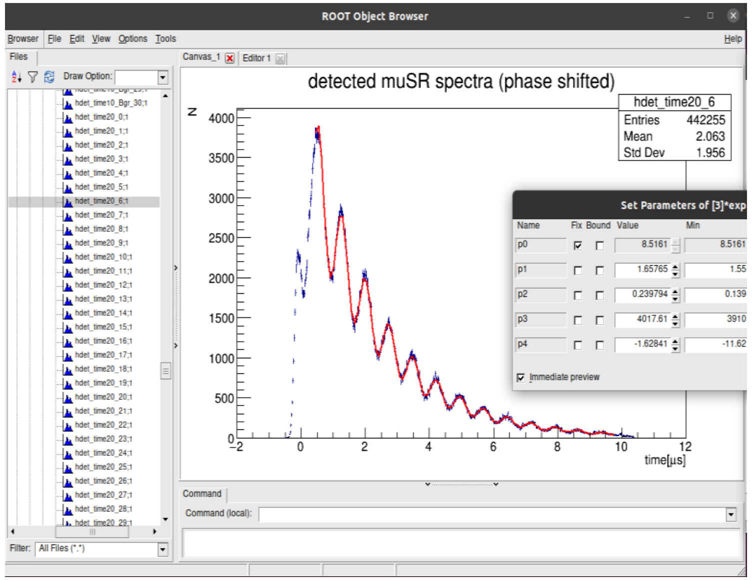
- Two detector rings, degraders, a cryostat, and a beam pipe.



CAD design

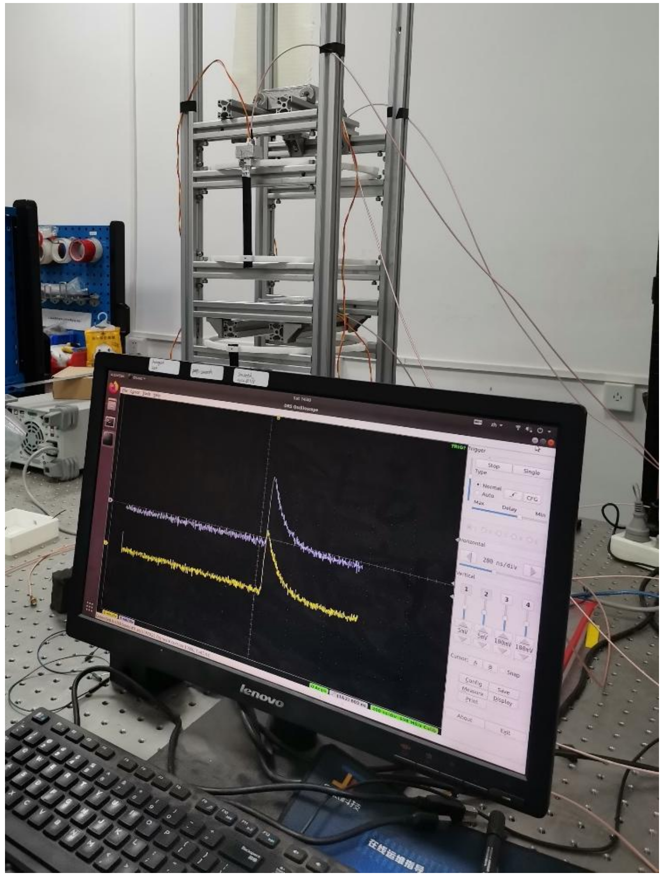


MC simulations



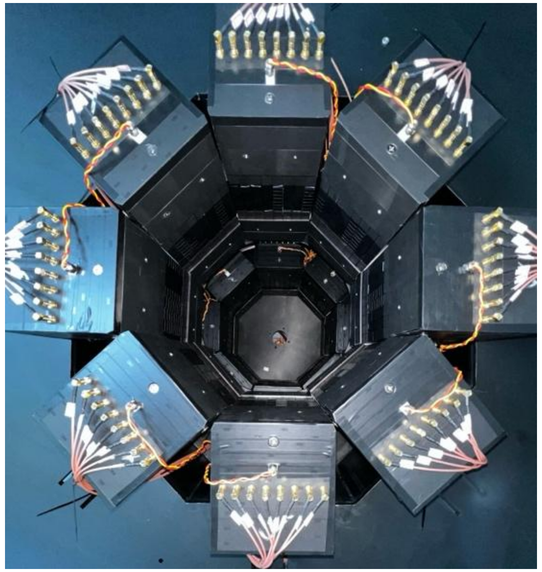
Mock data analysis and fit

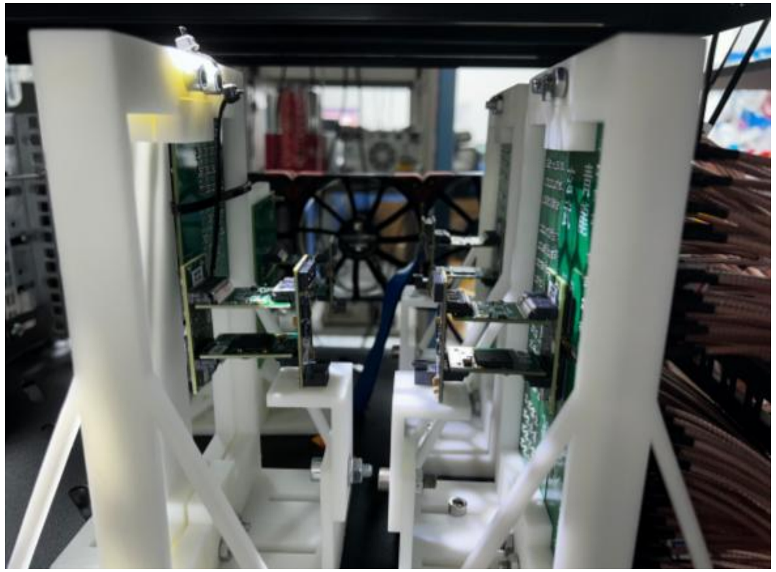
Credits： Yi-Xing Zhou

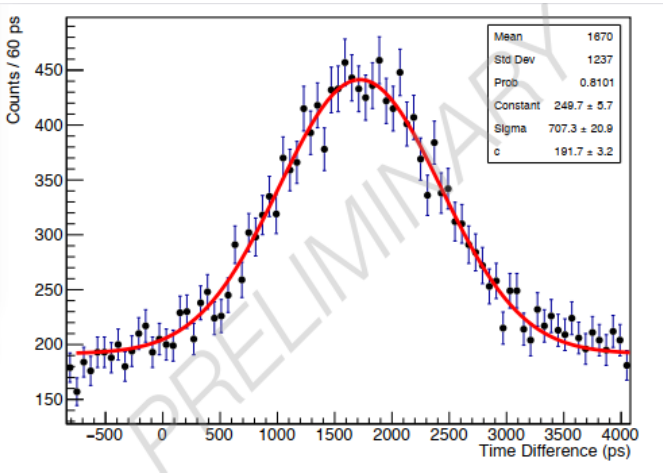


Prototype tests by CRμ

R&D of μSR







Time resolution: ~1 ns

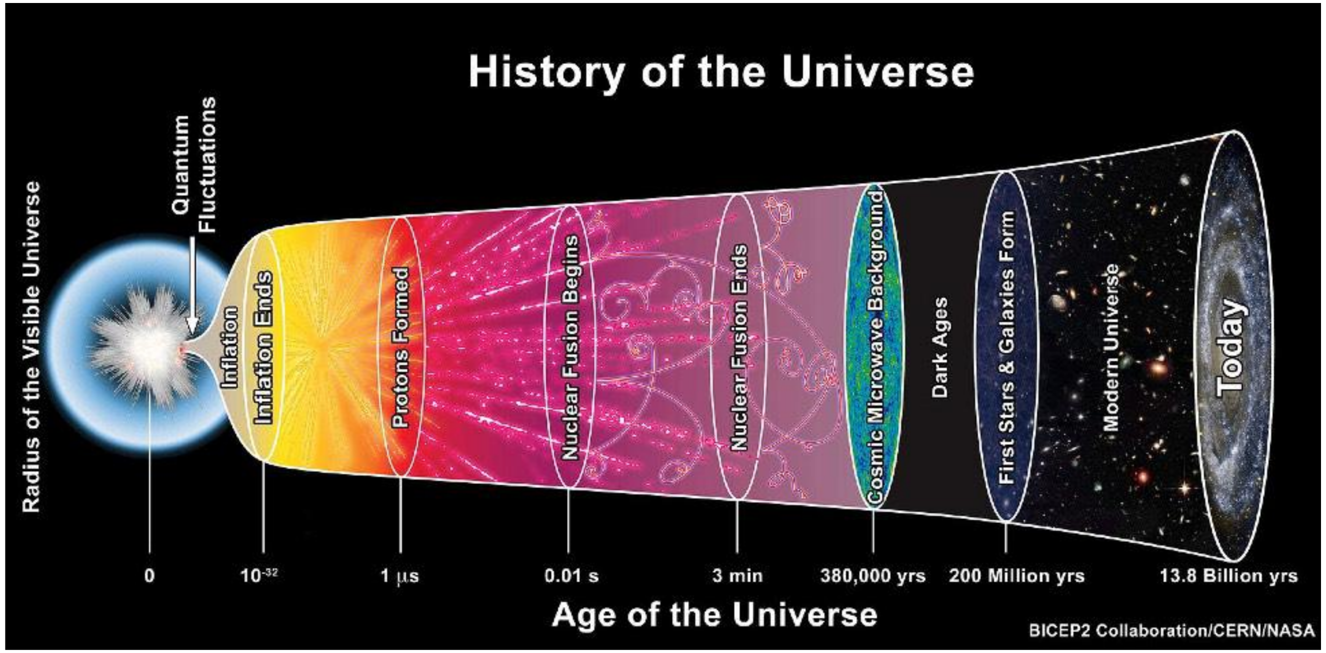
“The best engineer should reserve a redundancy.”

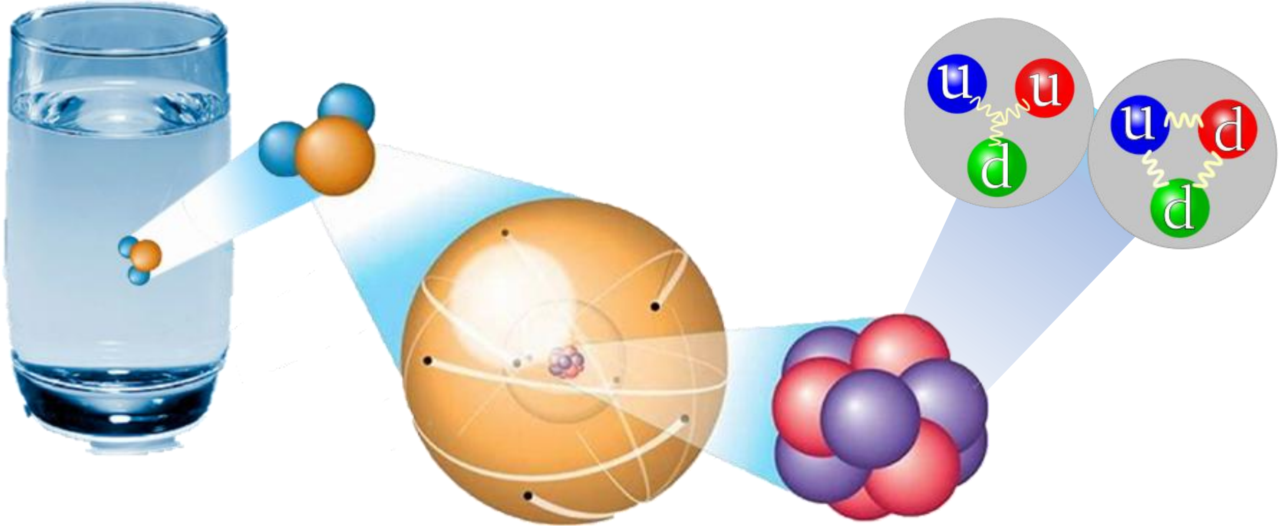
-- by Yun-Song Ning

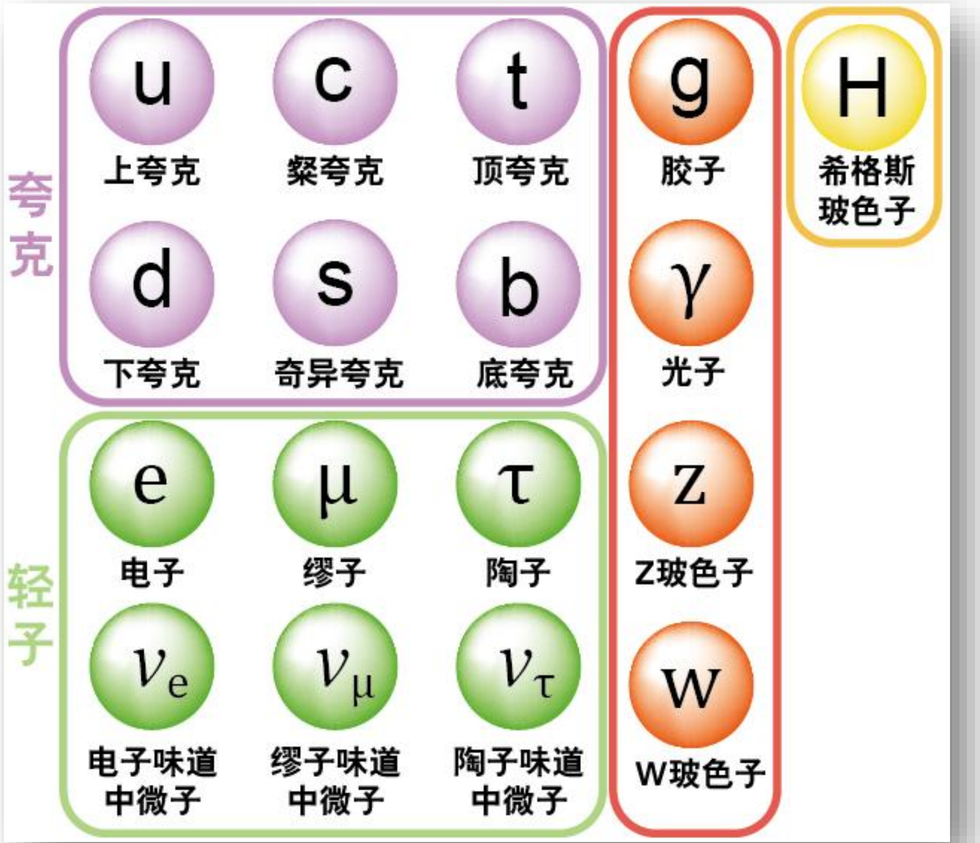
Table of contents

- Self-introduction and review
- Platform for muon science and technology
- Working principle for a cosmic ray muon detector
- How to build such a detector

Review of standard model in particle physics







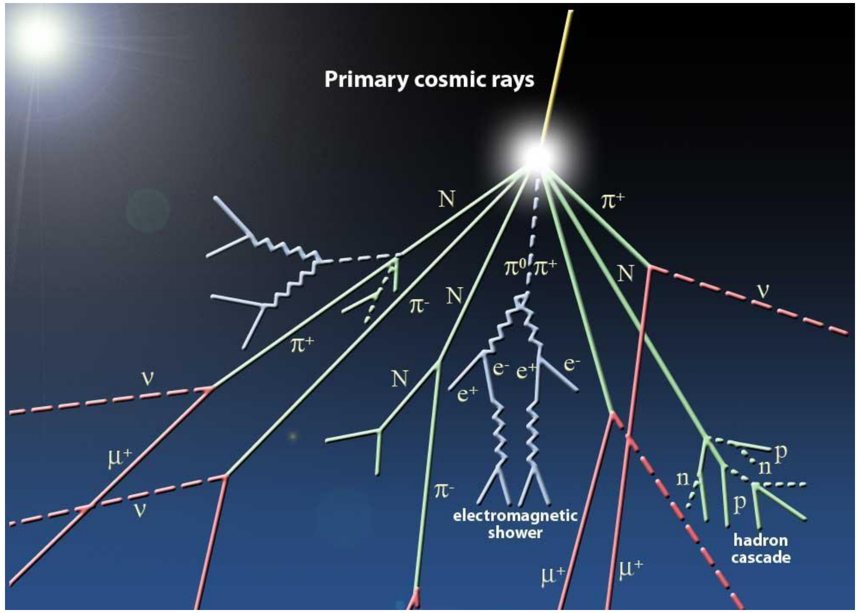
$\underbrace{SU(3)_{Color}}_{\text{QCD}} \otimes \underbrace{SU(2)_{Left} \otimes U(1)_{Hyper\ charge}}_{\text{WEAK} \oplus \text{QED}}$

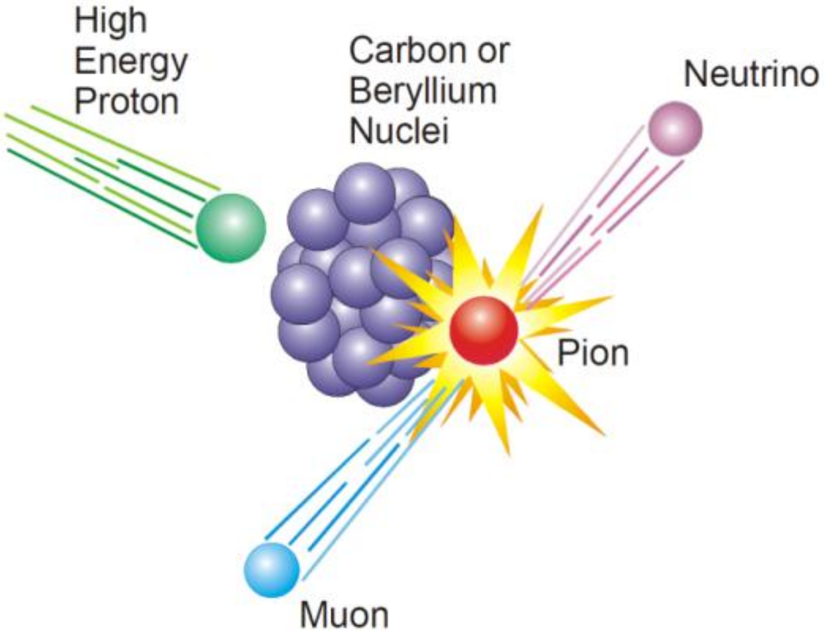
QCD (Strong Interaction)

WEAK ⊕ QED (Unification of Weak and Electromagnetic)

Basic properties of charged muons

- Muon (μ): a charged lepton that participates in electromagnetic and weak interactions
- Muon mass: 105 MeV; lifetime: 2.2 microseconds (μs)
- Muon sources: cosmic muon source v.s accelerator muon source

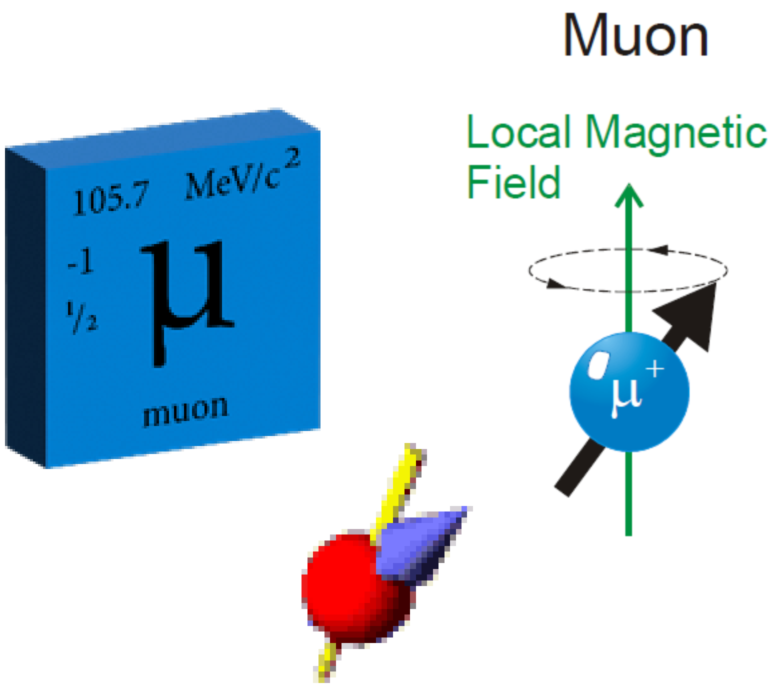




What is a muon or a muonium?

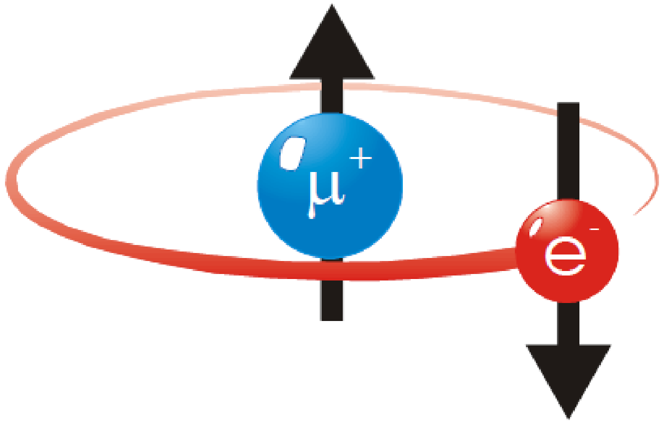
Muon:

- The polarised subatomic particle which has not interacted with its environment yet.
- It is either positively or negatively charged.



Muonium:

- A complex in which an electron orbits a positive muon. Muonium generally results from muons implanting themselves into an insulating sample.
- Hence, muonium is never seen in metallic samples.
- Muonium is considered as a light isotope of hydrogen.
- Their similar structures mean they have qualitatively similar chemical behaviour.
- However, muonium has a mass approximatively 9 times smaller than hydrogen, which results in quantitative differences.
- Muonium is frequently used to learn about hydrogen behaviour in a material.



History of muon and its spectrometer

1910

Theodore Wulf notices more radiation at the top of the Eiffel tower than on the ground – later to be identified as muons from cosmic rays.

1912

Using Wulf's electrometers, Victor Hess shows there is a relationship between observed radiation and altitude in a series of ballooning experiments. He found that at 5300 meters altitude, the ionization rate increased approximately fourfold over the rate at ground level

1936

Carl Anderson and Seth Neddermeyer discover the "meson" particle and its properties while studying cosmic rays.

Anderson and Hess share a Nobel prize, Hess for his discovery of cosmic radiation and Anderson for discovering the positron

1947

Conversi, Pancini and Piccioni show the discovered particle is actually the muon, and establish the lifetime of 2.2μs for the positive muon.

1957

Garmin, Lederman and Weinrich predict muons as a tool for research. In *Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays* they write: "it seems possible that polarised positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei".

1970s

Muon spectroscopy is used to investigate materials. The rapid development of muon spectroscopy as a tool for chemistry and solid state physics research began with the construction of three "meson factories".

1970 – Present day

During the last several decades muon spectroscopy has become recognized as an established local probe in condensed matter physics and chemistry.

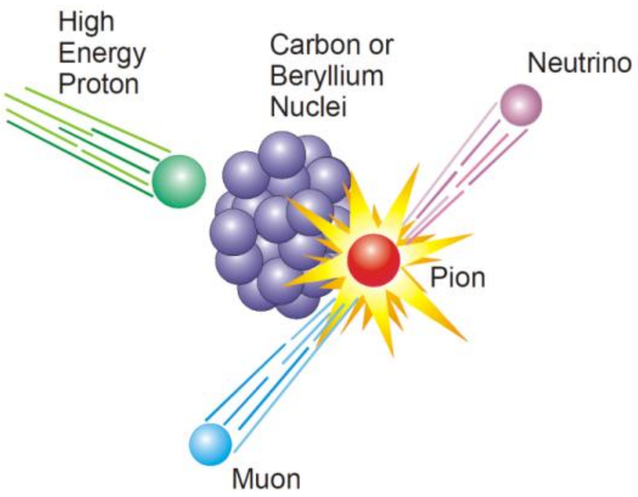
Thriving muon spectroscopy communities have been developed around the facilities at the PSI (Switzerland), TRIUMF (Canada), J-PARC (Japan), MuSIC (Japan) and ISIS (UK).

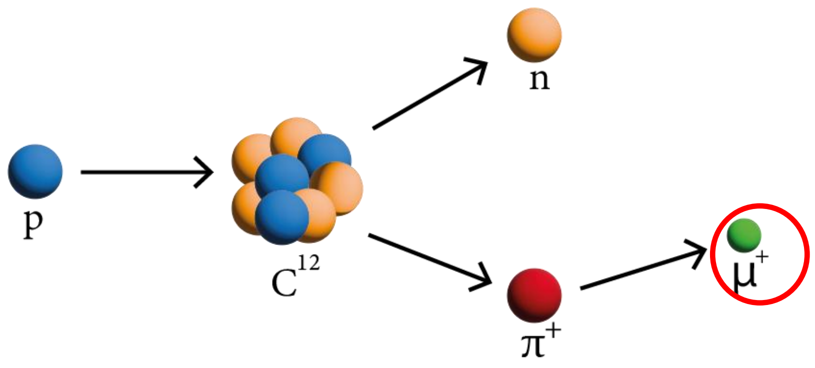
Present day

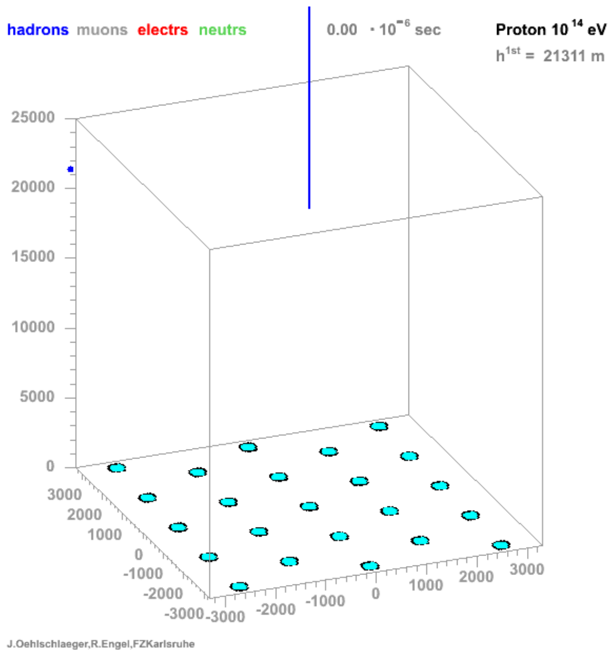
Recent technological achievements include the development of ultra-low background, high-statistics pulsed muon beams and spectrometers, fast timing spectrometers for high applied magnetic fields, and ultra low-energy muon beams for near surface and thin film studies.

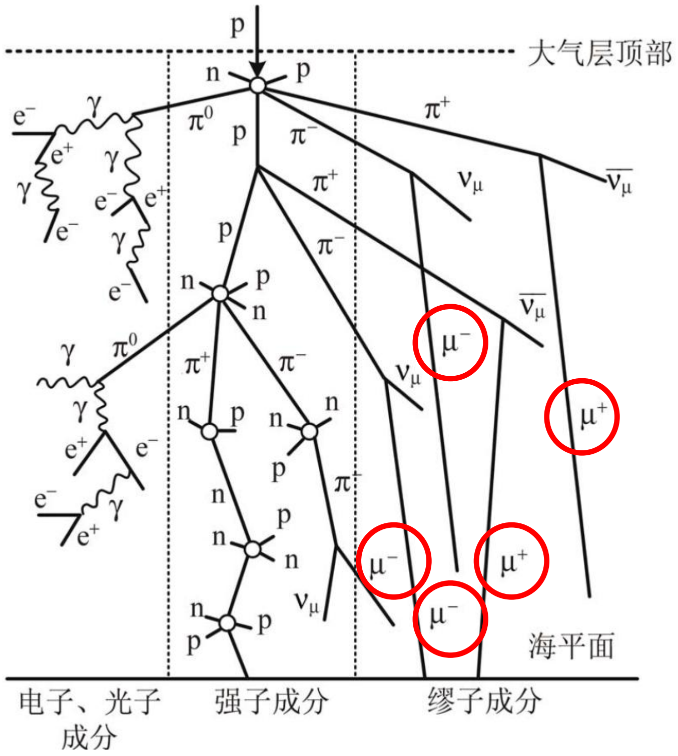
Many of the world's muon facilities also provide spallation neutron beams, exploiting the close synergy between muon spectroscopy and neutron scattering.

Where does a muon come from?





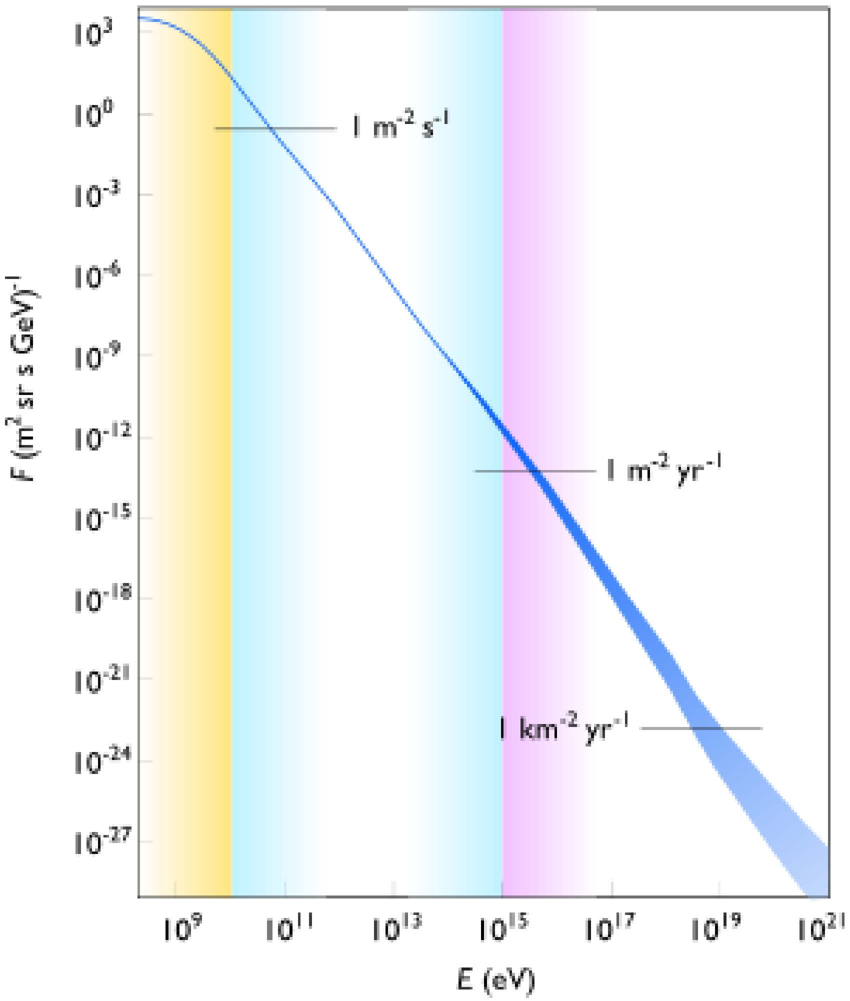


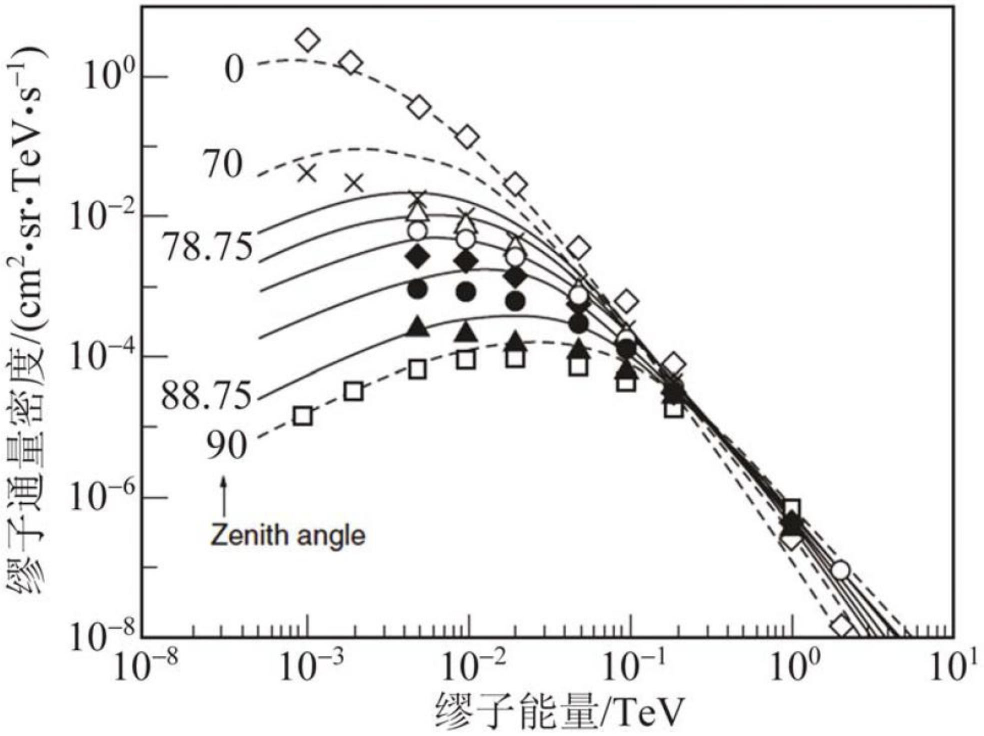


Accelerator muon source

Cosmic ray muon source

Flux of cosmic ray muons



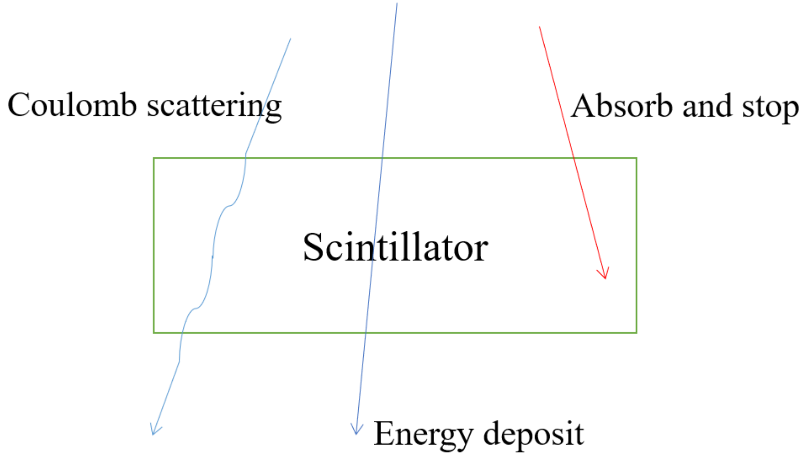


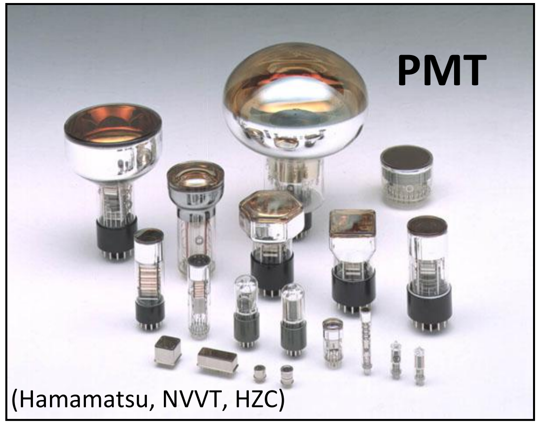
- Cosmic ray muon rate at the sea level: ~1 $\mu^{\pm}/cm^2/sr/min$

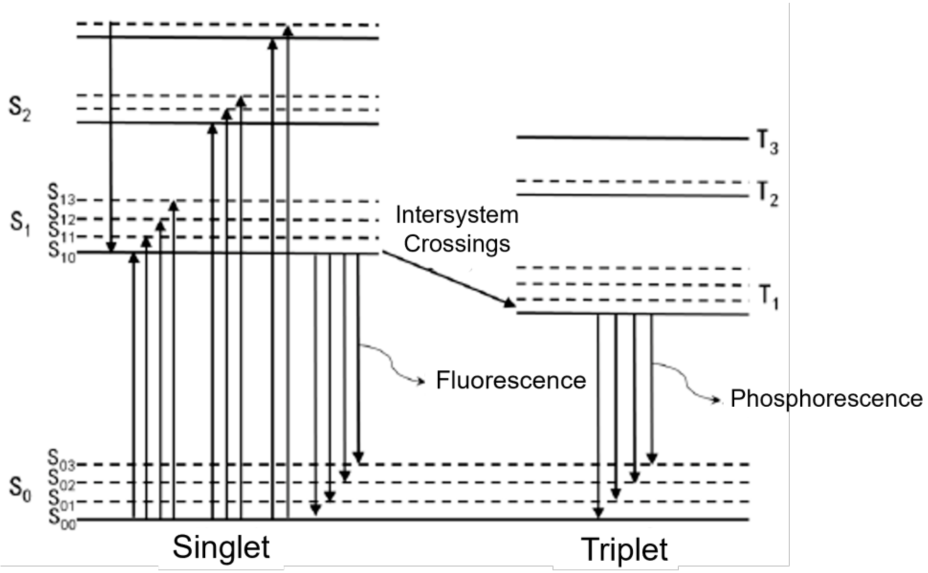
Table of contents

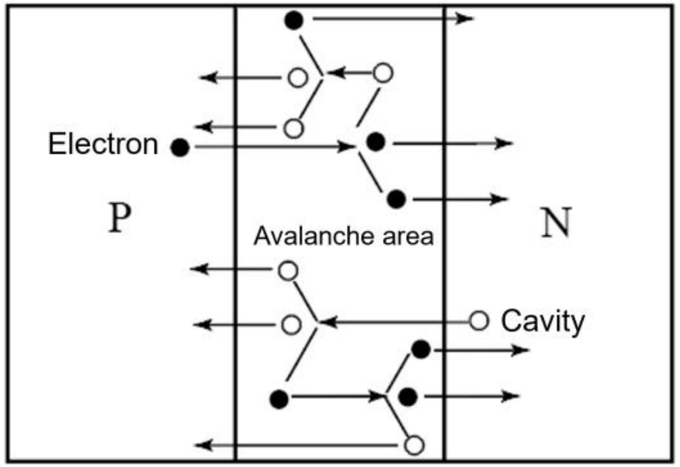
How to detect a muon?

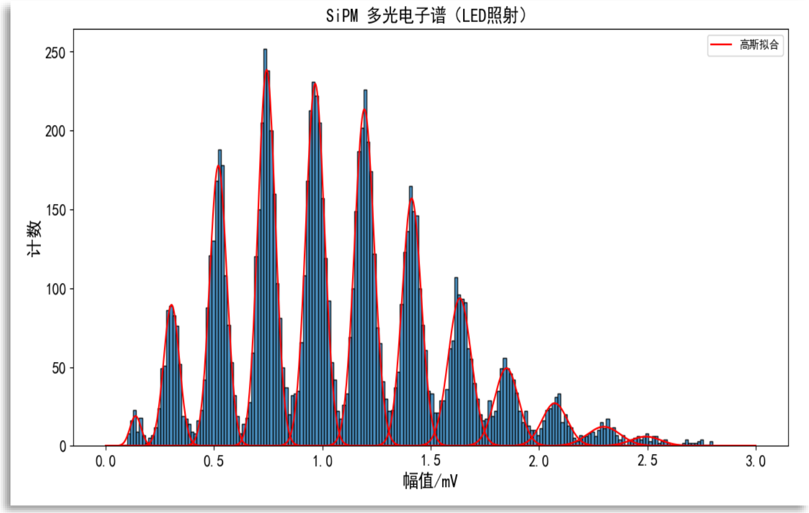
- Scintillator detector to identify a muon





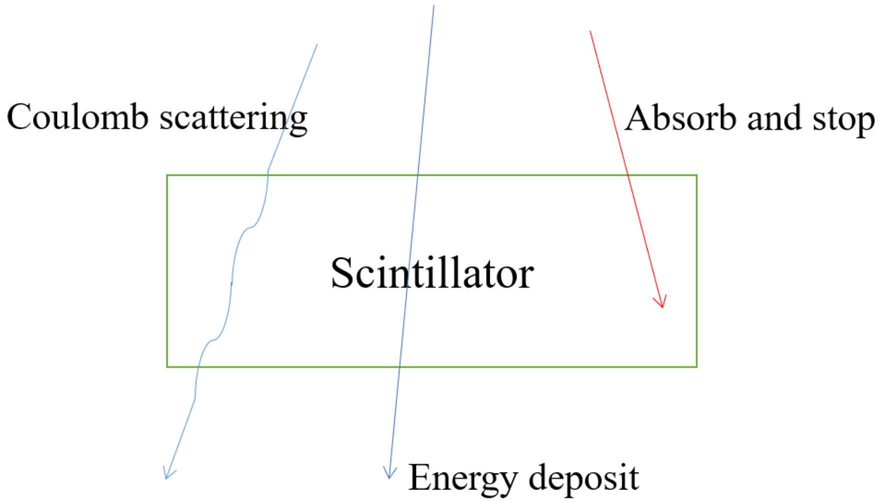


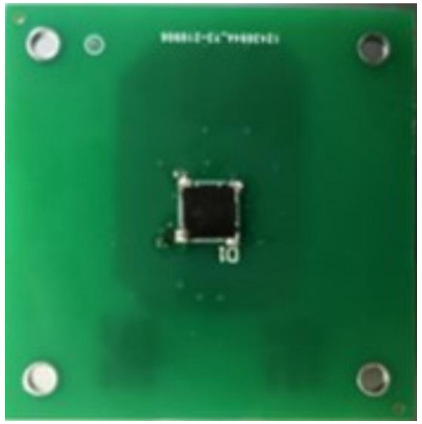


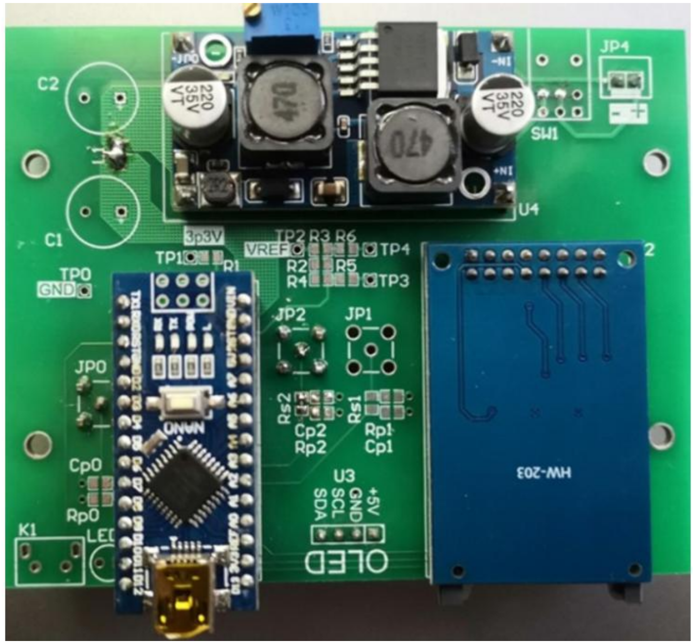


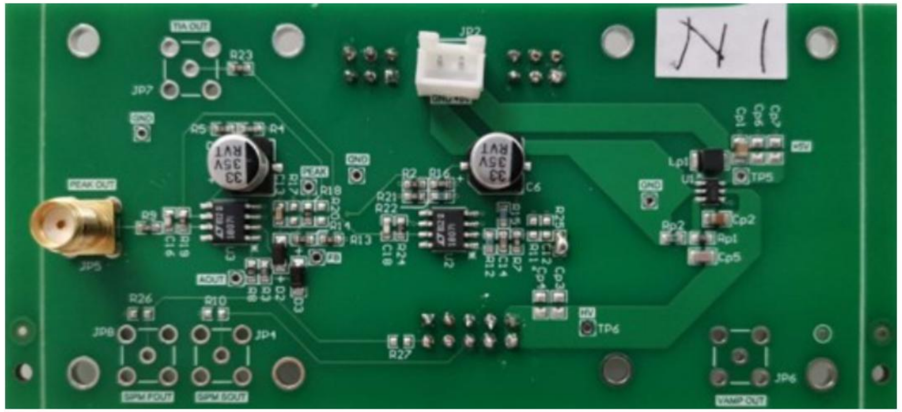
How to detect a muon?

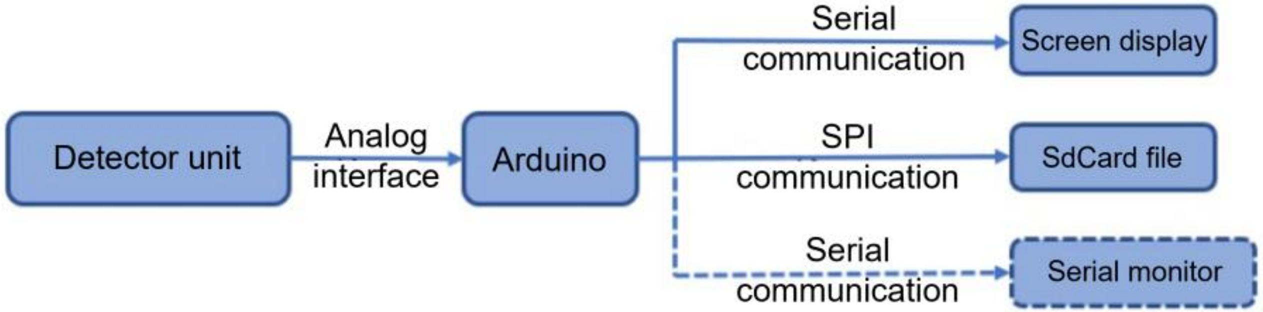
- Scintillator detector to identify a muon



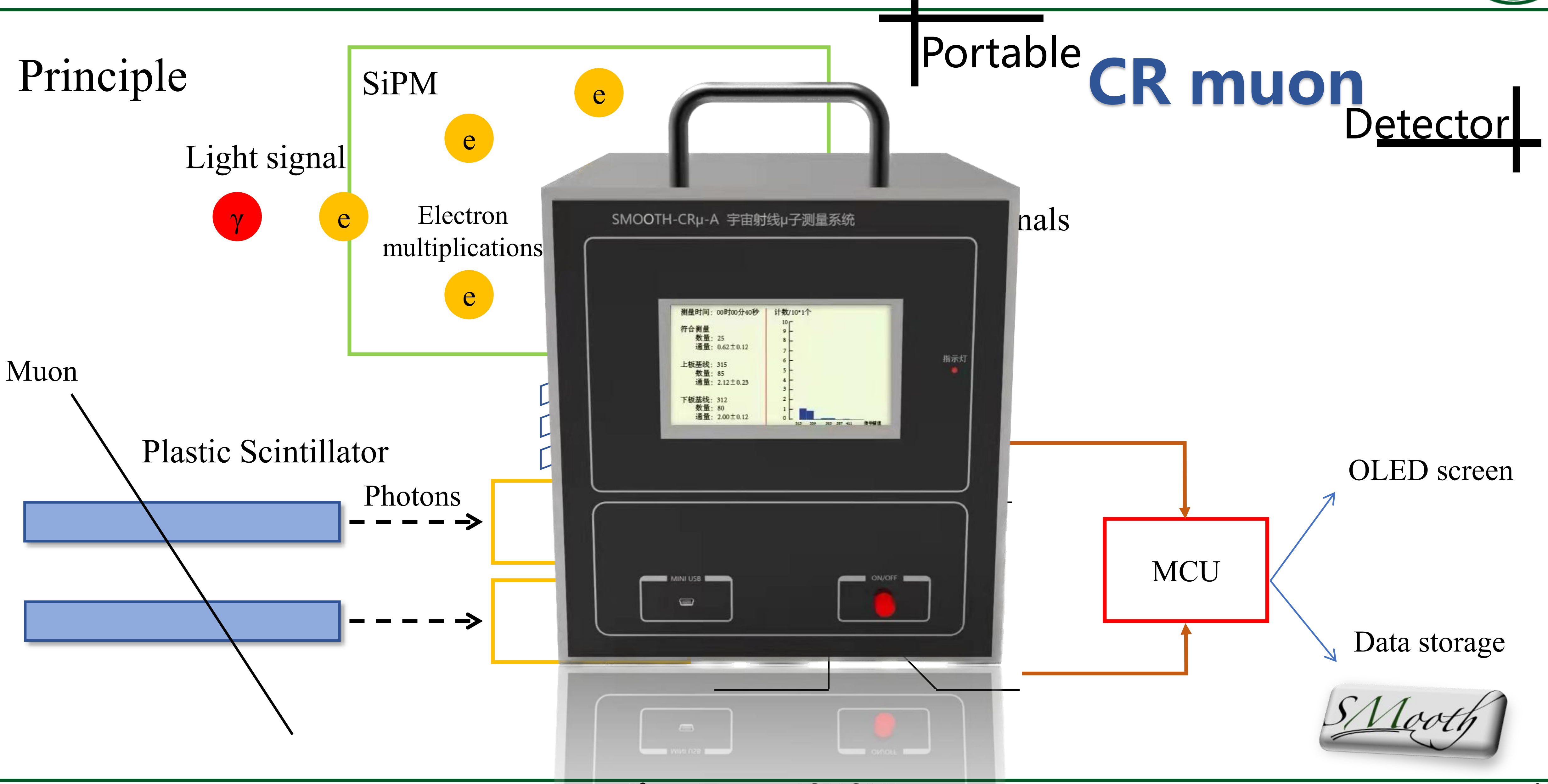








Development of a portable cosmic ray muon detector



Development of a portable cosmic ray muon detector

Remote data transmission

Portable **CR muon** Detector

2023-08-03 11:11:38.506701	NULL	NULL	NULL	NULL	NULL	2306N	11317E
2023-08-03 11:11:41.480237	NULL	341	387	NULL	NULL	NULL	NULL
2023-08-03 11:11:45.182682	NULL	320	377	NULL	NULL	NULL	NULL
2023-08-03 11:11:49.388721	4383	NULL	NULL	1059	0	NULL	NULL
2023-08-03 11:11:50.310038	NULL	341	314	NULL	NULL	NULL	NULL
2023-08-03 11:11:54.474593	NULL	330	385	NULL	NULL	NULL	NULL
2023-08-03 11:11:58.308499	NULL	372	321	NULL	NULL	NULL	NULL
2023-08-03 11:12:00.905770	4394	NULL	NULL	1062	0	NULL	NULL
2023-08-03 11:12:04.170956	NULL	396	307	NULL	NULL	NULL	NULL
2023-08-03 11:12:06.767346	NULL	311	334	NULL	NULL	NULL	NULL
2023-08-03 11:12:10.852105	NULL	318	386	NULL	NULL	NULL	NULL
2023-08-03 11:12:11.634761	4405	NULL	NULL	1065	0	NULL	NULL
2023-08-03 11:12:14.666927	NULL	321	324	NULL	NULL	NULL	NULL
2023-08-03 11:12:18.927260	NULL	373	303	NULL	NULL	NULL	NULL
2023-08-03 11:12:22.830663	4416	NULL	NULL	1067	0	NULL	NULL
2023-08-03 11:12:24.109443	NULL	304	381	NULL	NULL	NULL	NULL
2023-08-03 11:12:27.898041	NULL	361	394	NULL	NULL	NULL	NULL
2023-08-03 11:12:32.374202	NULL	323	381	NULL	NULL	NULL	NULL
2023-08-03 11:12:33.980902	4427	NULL	NULL	1070	0	NULL	NULL
2023-08-03 11:12:36.625741	NULL	371	329	NULL	NULL	NULL	NULL
2023-08-03 11:12:40.069296	NULL	308	340	NULL	NULL	NULL	NULL
2023-08-03 11:12:44.746863	NULL	372	309	NULL	NULL	NULL	NULL
2023-08-03 11:12:44.969175	4438	NULL	NULL	1073	0	NULL	NULL

Database

GPS positioning

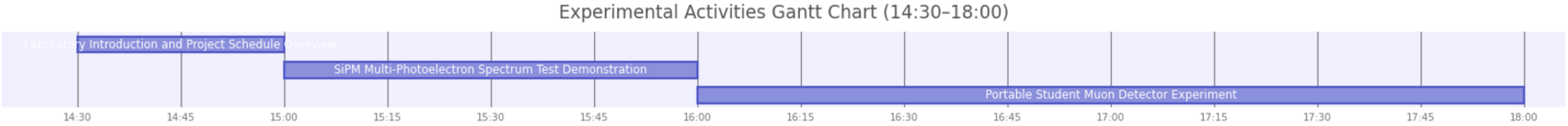
Data uploading

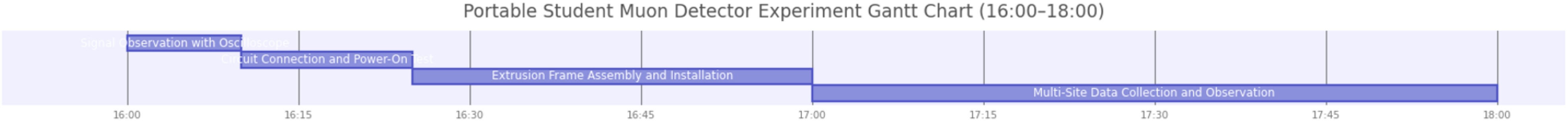
Muon

Base station

Cloud server

Summer School Experimental Course Schedule (14:30–18:00)





Summer school experimental course schedule (14:30-18:00, totaling 3.5 hours):

1. Introduction to the laboratory and project arrangement, 14:30-15:00, lasting 0.5 hours;
2. Demonstration of SiPM multi-photoelectron spectrum test experiment, 15:00-16:00, lasting for 1 hour;

   Experimental instruments: Lecory oscilloscope, DC power supply, SiPM test kit, MAXHUB;

   Experimental content: Demonstrate the experimental steps and results of SiPM signal and multi-photoelectron spectrum analysis on MAXHUB;

3. Portable cosmic muon detector experiment, 16:00-18:00, lasting for 2 hours;

   Experimental instruments : encapsulated scintillator unit, welded mainboard and kit, several wires;

   Experimental content:

   16:00—16:10 Observe the scintillator signal using an oscilloscope;

   16:10—16:25 Connect the various components of the detector using wires and conduct a power-on test;

   16:25—17:00 Construct a self-made frame using aluminum alloy profiles and proceed with the installation of the detector structure;

   17:00—18:00 Conduct multi-location data collection testing using detectors;

Total number of students in the experimental class:

29 (including 21 international students)

Anticipated course grouping:

4-5 groups

Course duration:

14:30—18:00, totaling 3.5 hours

Course content:

SiPM principle and multi-photoelectron spectrum measurement

Construction of portable cosmic muon detector

Summer School Experimental Course Schedule (14:30–18:00)

① Lab Introduction & Project Schedule Briefing, 14:30–15:00 (0.5 hours)

② Demonstration of SiPM Multi-photoelectron Spectrum Measurement Experiment, 15:00–16:00 (1 hour)

- Experimental Equipment: Lecroy Oscilloscope, DC Power Supply, SiPM Test Kit, MAXHUB Interactive Panel
- Experiment Content: Explain and demonstrate SiPM signal processing, multi-photoelectron spectrum analysis procedures and measurement results on the MAXHUB panel

③ Portable Cosmic Muon Detector Experiment, 16:00–18:00 (2 hours)

- Experimental Equipment: Pre-encapsulated scintillator units, pre-soldered main circuit boards & accessory kits, assorted connecting wires

- Breakdown of Experimental Procedures:
  - 16:00–16:10: Observe scintillator output signals with an oscilloscope
  - 16:10–16:25: Connect all detector components with wires and perform power-on verification
  - 16:25–17:00: Fabricate a support frame using aluminum alloy extrusions and complete detector structural installation
  - 17:00–18:00: Laboratory tour and multi-site data acquisition tests with the assembled detector