中山大學 物理学院

SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

Study of Low Energy Cosmic-ray muons with a Spin Spectroscopy Array

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

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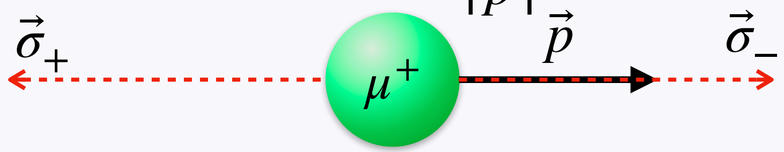
Polarization of muon

- Muon spin polarization is important property.

$$P_\mu = \vec{\sigma} \cdot \frac{\vec{p}}{|\vec{p}|}$$



- Muon produced in accelerator is mainly from

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$ 100% polarized

- Cosmic-ray muon are mainly produced by

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

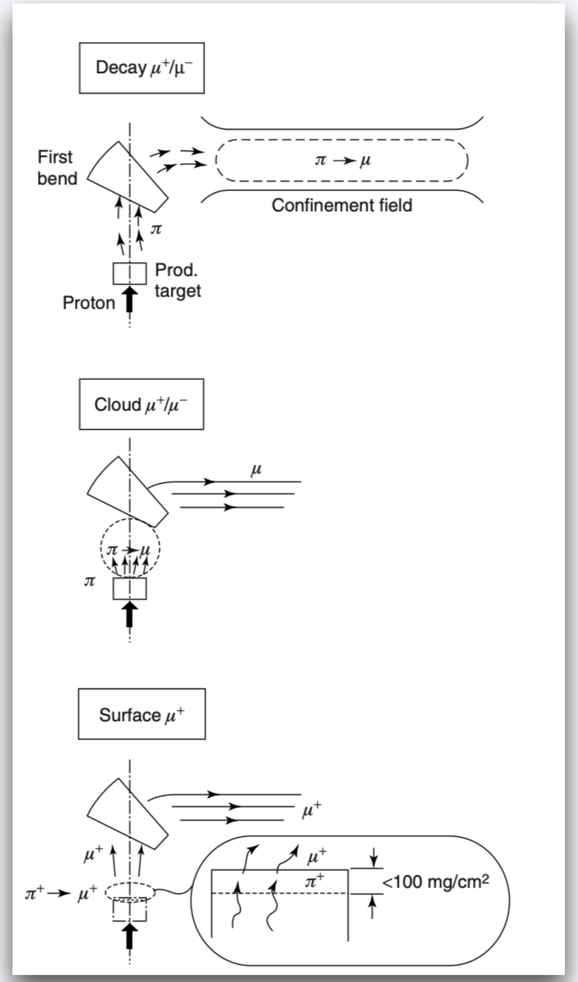


Figure1: muon produced by accelerator.

Nagamine, Kanetada. *Introductory muon science*. Cambridge University Press, 2003.

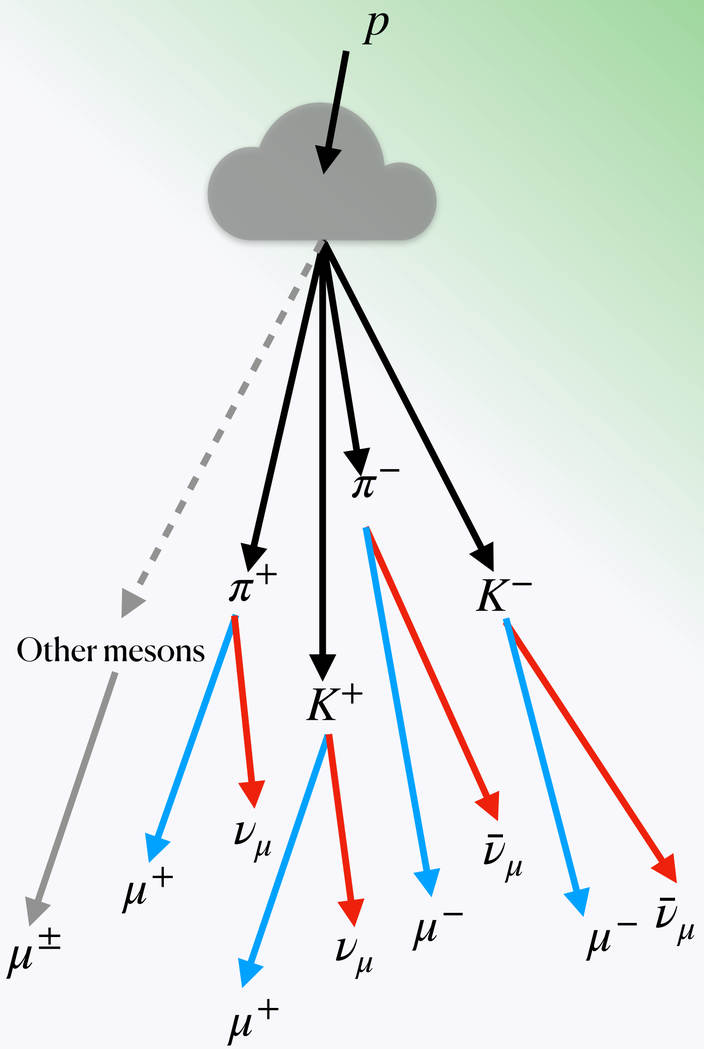


Figure2: production of cosmic-ray muon.

What is the polarization of cosmic-ray muons and what are its applications?

Atmospheric Neutrino Energy Spectrum

- $\pi - K$ ratio will improve precision of atmospheric neutrino model.

Muon polarization effect by the initial momentum

- $m(\pi^{\pm}) \simeq 139\text{MeV}, m(K^{\pm}) \approx 493\text{MeV}.$

$$|\vec{p}_{\mu,K}| > |\vec{p}_{\mu,\pi}|$$

Measuring the magnitude of cosmic-ray muon polarization helps constrain the $\pi - K$ ratio to the muon flux.

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}), \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

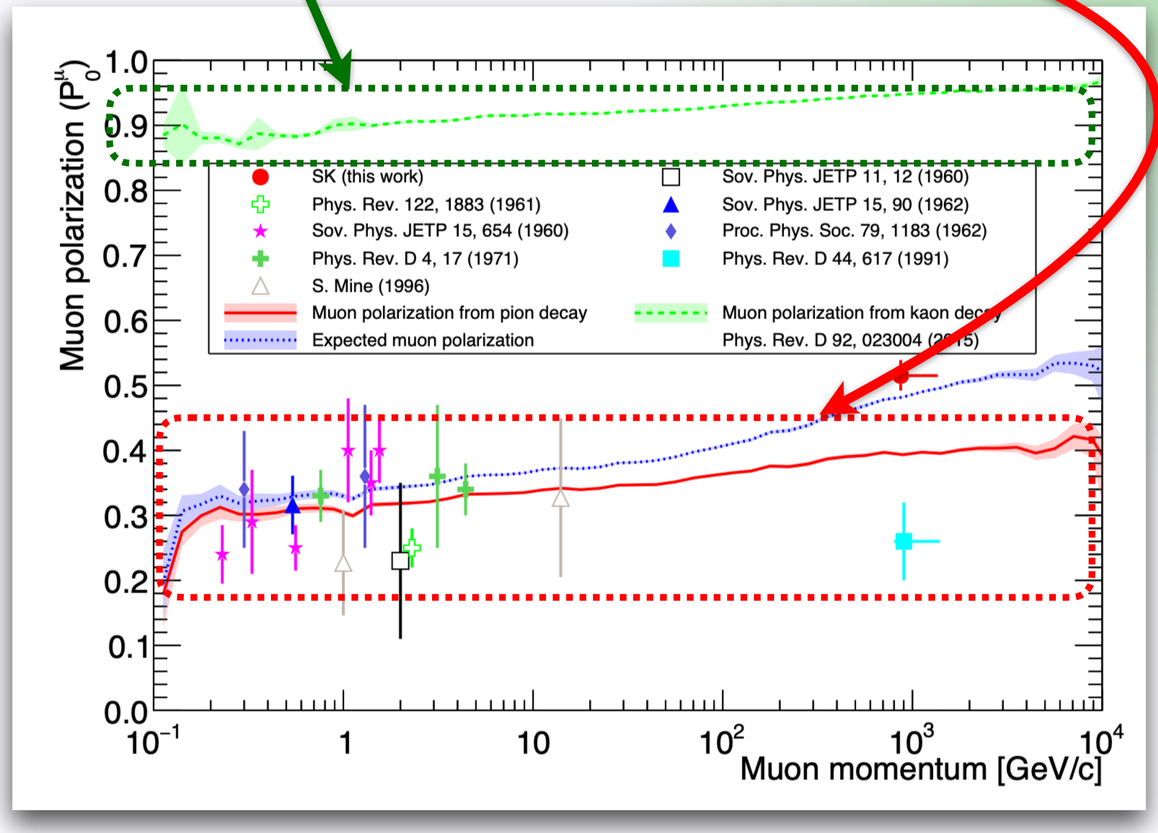


Figure: Historical experiment result of cosmic-ray muon polarization.

Measurements of the charge ratio and polarization of cosmic-ray muons with the Super-Kamiokande detector Super-Kamiokande Collaboration • H. Kitagawa (Okayama U.) et al.e-Print: 2403.08619 [hep-ex]

Application of Muon Polarization Measurement

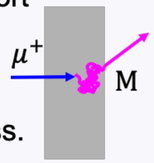
Important !!!

Future Experiments

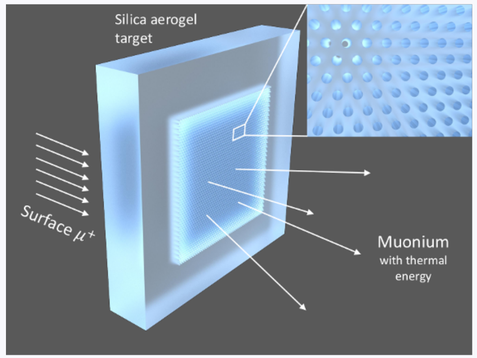
Polarization input

μ^+ (~1MeV) scattering
↓
Electron capture (~1keV)
↓
Muonium (~100eV)
Epithermal scattering
↓
Random walk (room temp.)
↓
Emission to vacuum

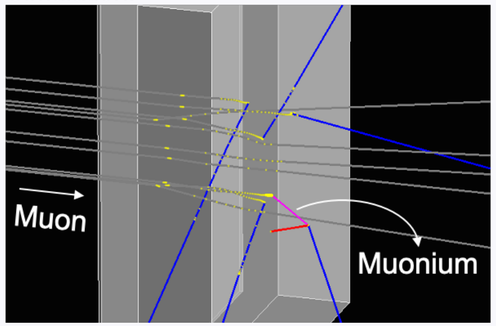
MC simulation for muonium transport has been developed under the MACE offline software framework.



① Geant4 low-energy EM process.
② Geant4 AtRest process, modeled phenomenologically.
③ Random walk approach to thermal muonium tracking.



Simulation:



Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406
Zhao S, Tang J. Optimization of muonium yield in perforated silica aerogel[J]. arXiv preprint arXiv:2401.00222, 2023.

Shihan Zhao's talk this afternoon.

Muon related application

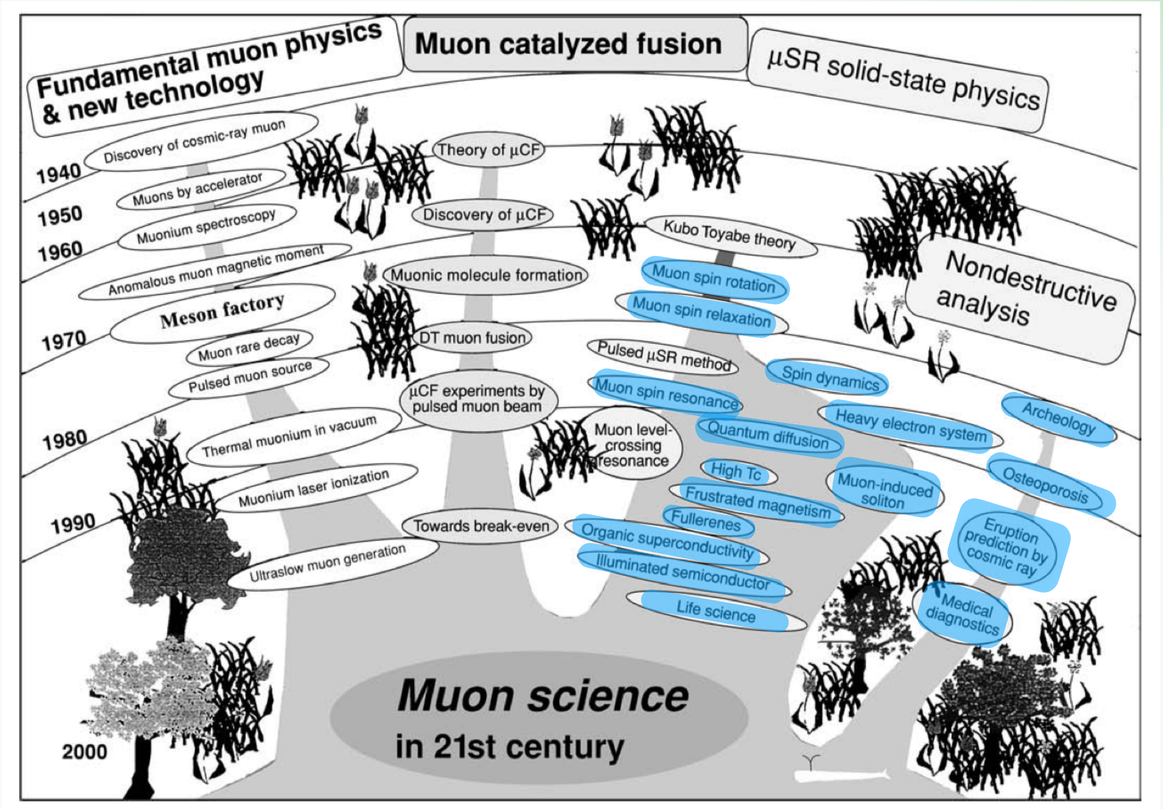
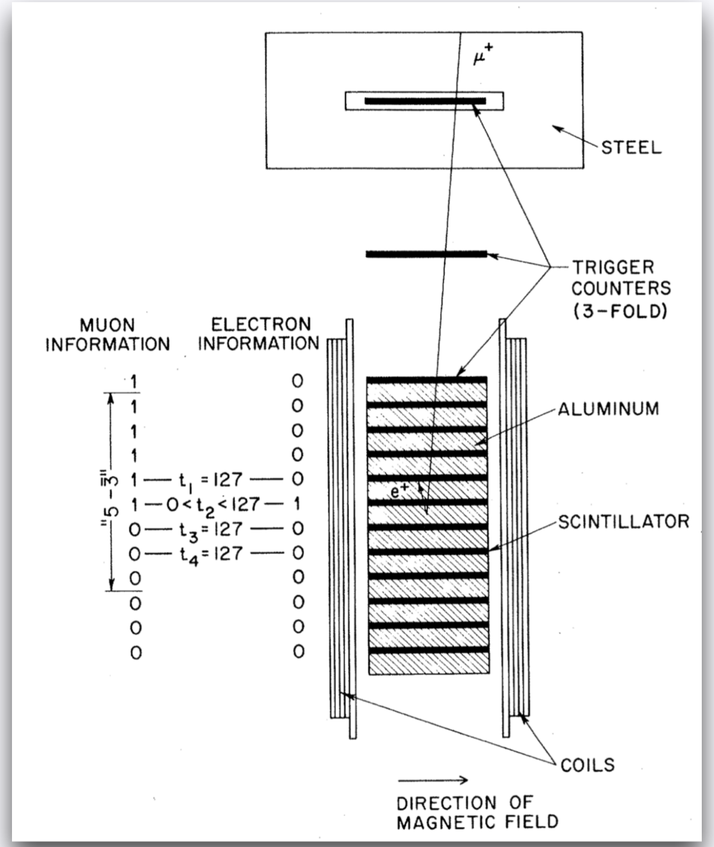


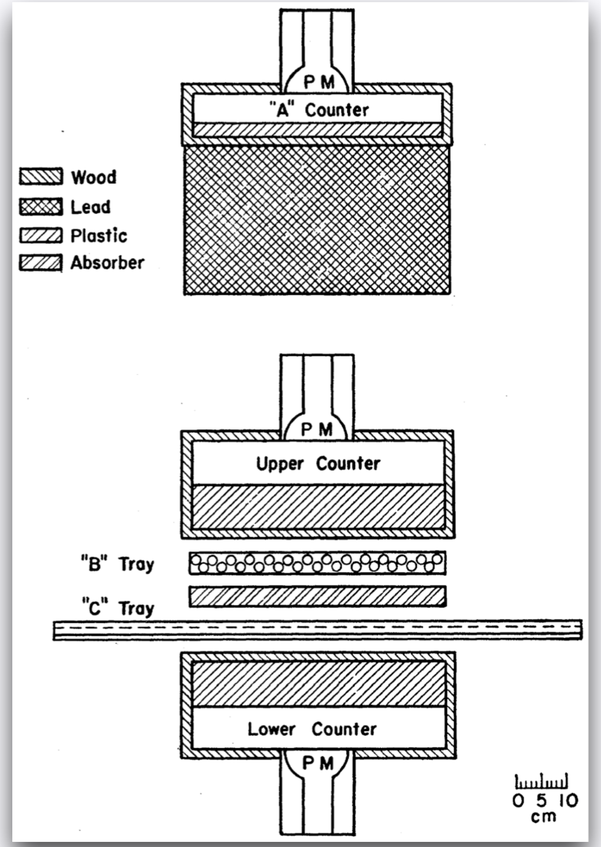
Figure: Historical development of muon science towards the 21st century. Cosmic-ray muon polarization measurement can improve the application which marked blue.

Nagamine K. Introductory muon science[M]. Cambridge University Press, 2003.

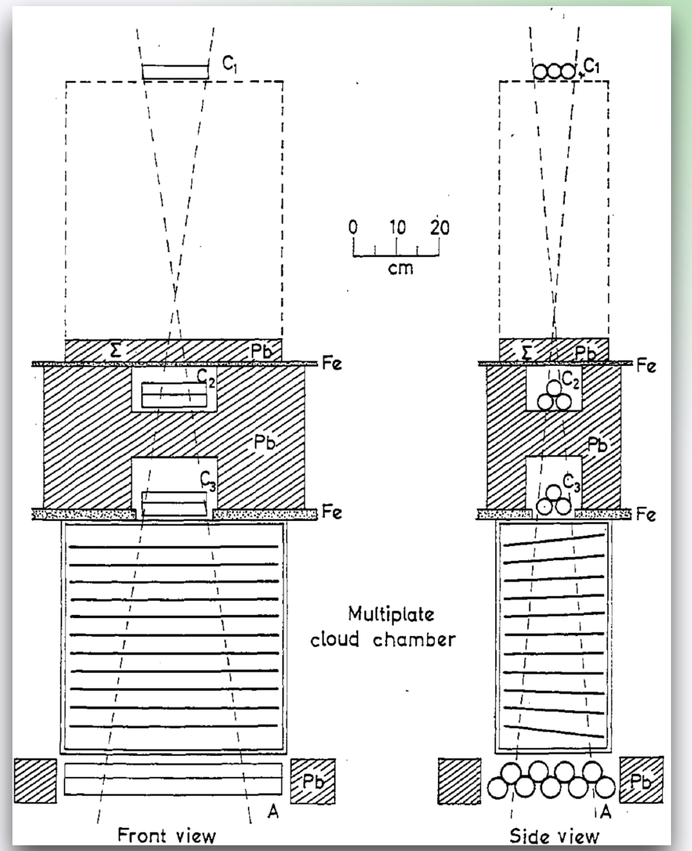
Low energy cosmic-ray muon polarization experiments in history



Turner R, Ankenbrandt C M, Larsen R C. Polarization of cosmic-ray muons[J]. Physical Review D, 1971, 4(1): 17.



Johnson C S. Polarization of cosmic-ray muons at sea level[J]. Physical Review, 1961, 122(6): 1883.



Johnson C S. Polarization of cosmic-ray muons at sea level[J]. Physical Review, 1961, 122(6): 1883.

$$\text{Asymmetry of Micheal electron } \alpha_e = \frac{N_u - N_d}{N_u + N_d} \text{ equal to muon polarization?}$$

Motivation of cosmic-ray muon spin rotation spectroscopy (CRmuSR)

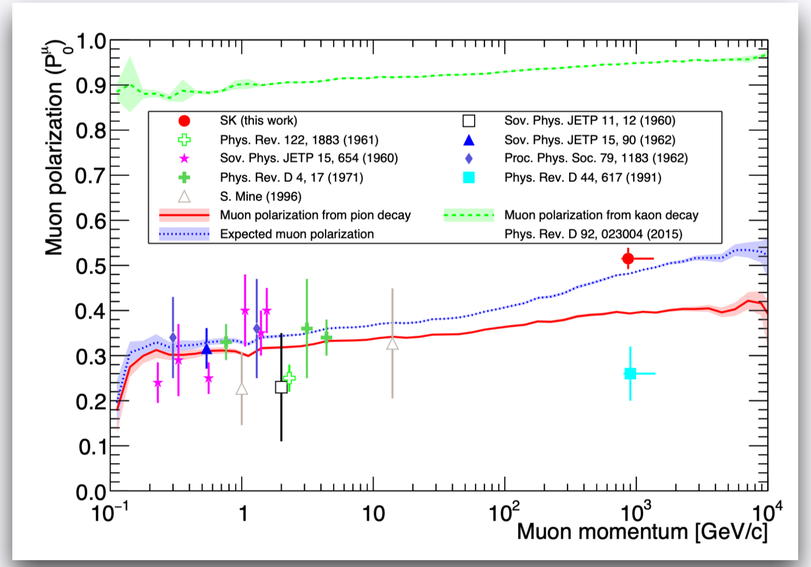
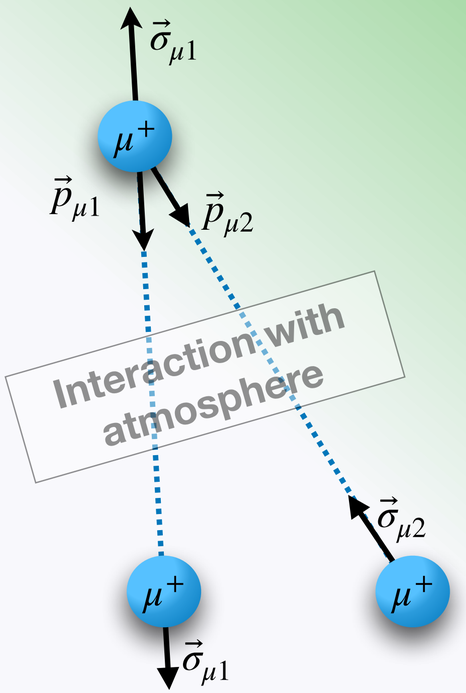


Figure: Historical experiment result of cosmic-ray muon polarization.
Measurements of the charge ratio and polarization of cosmic-ray muons with the Super-Kamiokande detector Super-Kamiokande Collaboration • H. Kitagawa (Okayama U.) et al.e-Print: 2403.08619 [hep-ex]

- Michel electron distribution

$$d\Gamma = \frac{G_F^2 m_\mu^2}{192\pi^3}\left(3 - 2x + (1-2x)\frac{\vec{\sigma}_\mu \cdot \vec{p}_e}{|\vec{p}_e|}\right) d\Omega$$

Measurement for angular distribution will improve the polarization precision.



cosmic-ray muon polarization

- **high energy** P_μ
  - Michel electron distribution (update 2024 by Super-K)
- **low energy** P_μ
  - Michel electron up-down asymmetry (update before 1980s)
  - angular distribution reconstruction
  - $P_\mu, (\vec{p}_\mu/|\vec{p}_\mu|)$ correlation

CRmuSR

- Michel electron angular resolution (CRmuSR-PDR)
- muon momentum direction resolution (CRmuSR-LGA)

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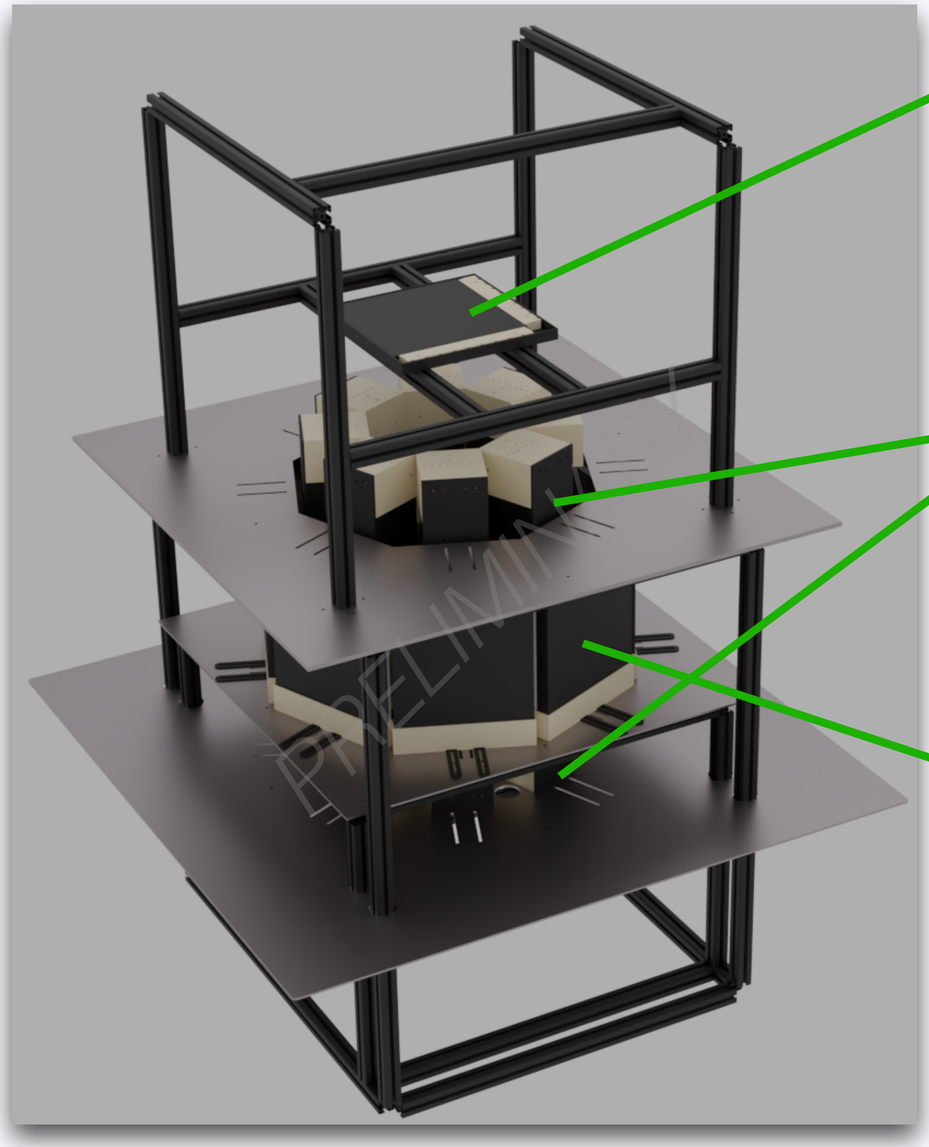
CRmuSR Design



Final design of CRmuSR

- Light Guide Array detector (CRmuSR-LGA):

  Reconstructing the $\vec{p}/|\vec{p}|$ of cosmic-ray muon.

  Requirement: good spatial resolution.

- Positron/electron detector Ring (CRmuSR-PDR):

  Reconstructing the azimuth angular distribution of Michel $e^{\pm}$.

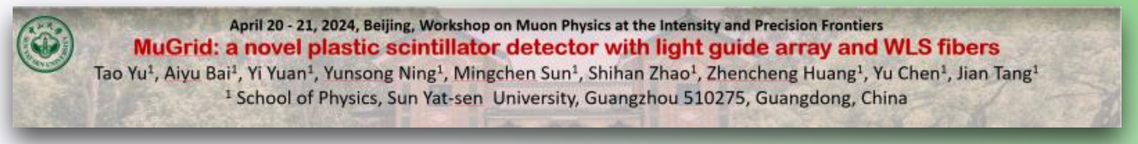
  Requirement: good azimuth angular resolution.

- Veto (CRmuSR-Veto):

  Filter out parallel cosmic-ray muon events.

  Requirement: high detection efficiency.

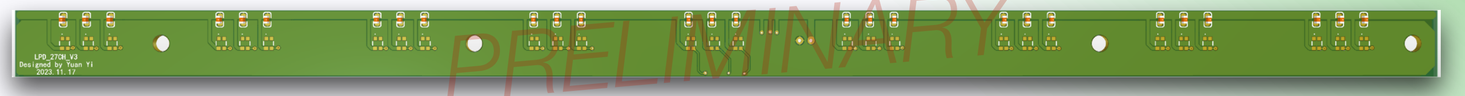
CRmuSR Module: Light Guide detector Array (LGA)



Tao yu's poster

Single layer of LGA has 27/54 SiPMs readout

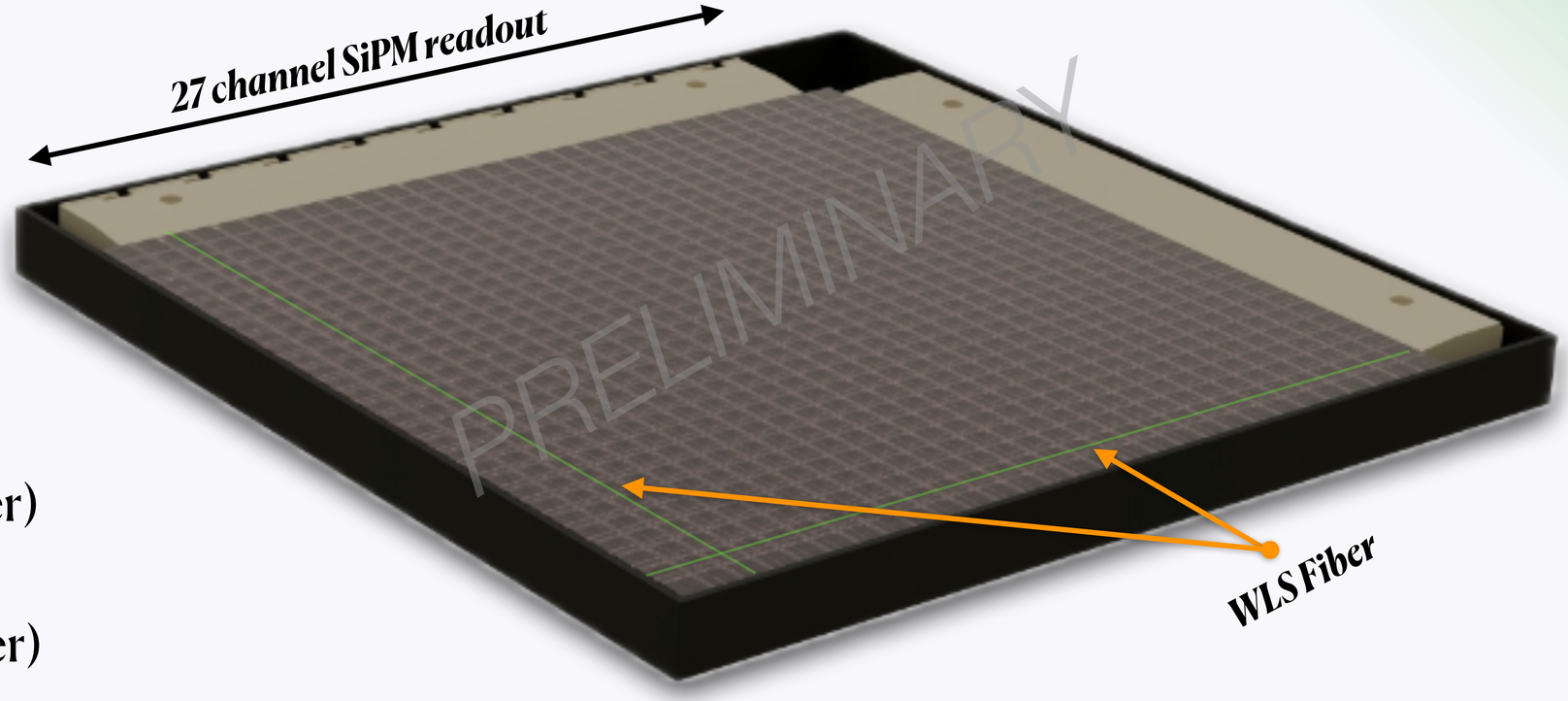
- Each SiPM coupling with a wave length shift (WLS) fiber
- Distance between two Layer is 5cm



27 channels SiPM readout PCB board. (By Yi Yuan)

Size of scintillator

- $32 \times 32 \times 1$cm (27 channels layer)
- $64 \times 64 \times 1$cm (54 channels layer)



LGA single layer design (27 channels version).

CRmuSR Module: Positron/electron Detector Ring (PDR)

Each unit in PDR (16 channels)

- 8 scintillator detector with SiPMs readout in both side.

Each PDR have 8 units (128 channels)

- Covers 2π azimuth angle with nearly no dead body.

CRmuSR has 2 PDR for Michel electron detection.

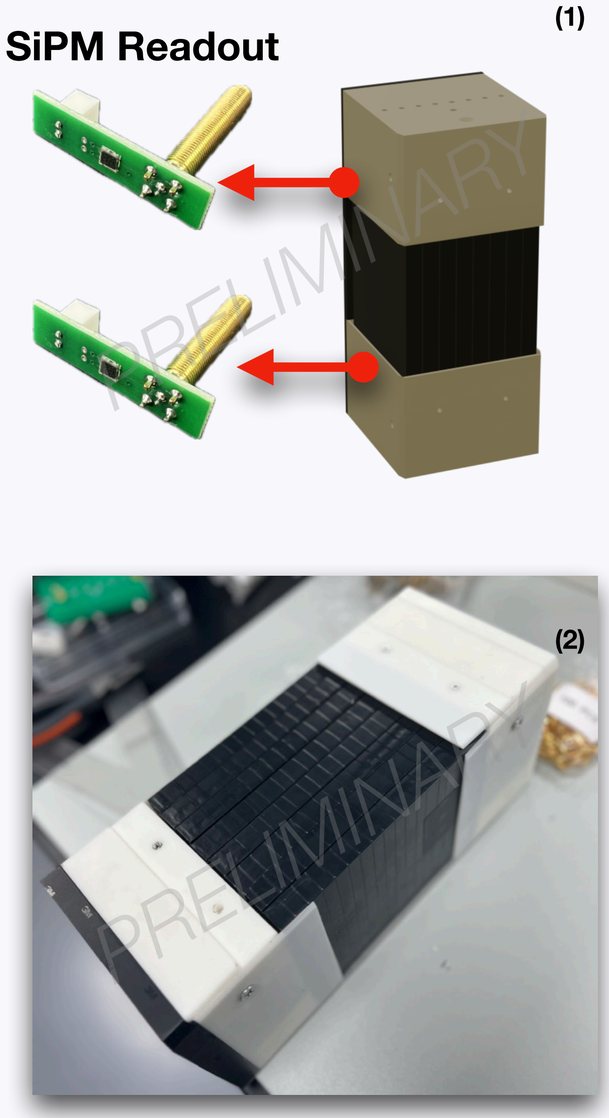


Figure: (1) The design of single unit in PDR and the location of SiPM readout. (2) Single PDR unit detector.

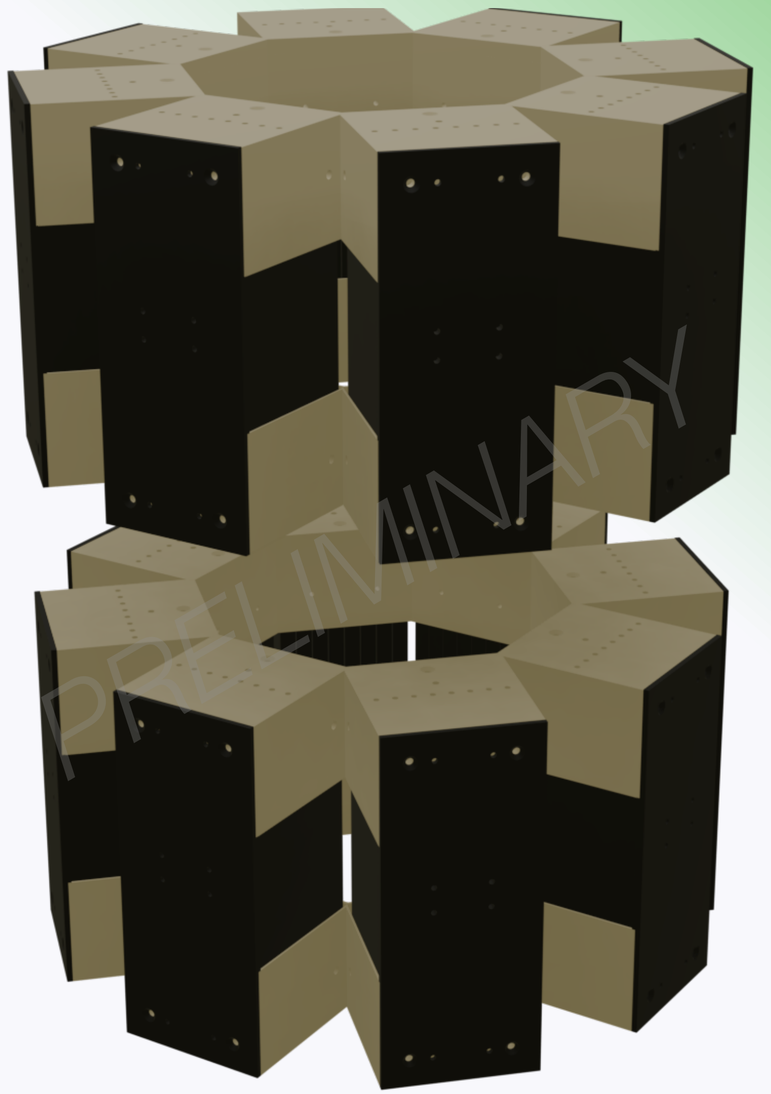


Figure: Two PDR arrangement in CRmuSR detector.

CRmuSR Module: Veto

Each unit of Veto (2 channels)

- Each Veto have 2 SiPM readout place in both side of the scintillator.
- Each scintillator size $320 \times 300 \times 30\text{mm}^3$

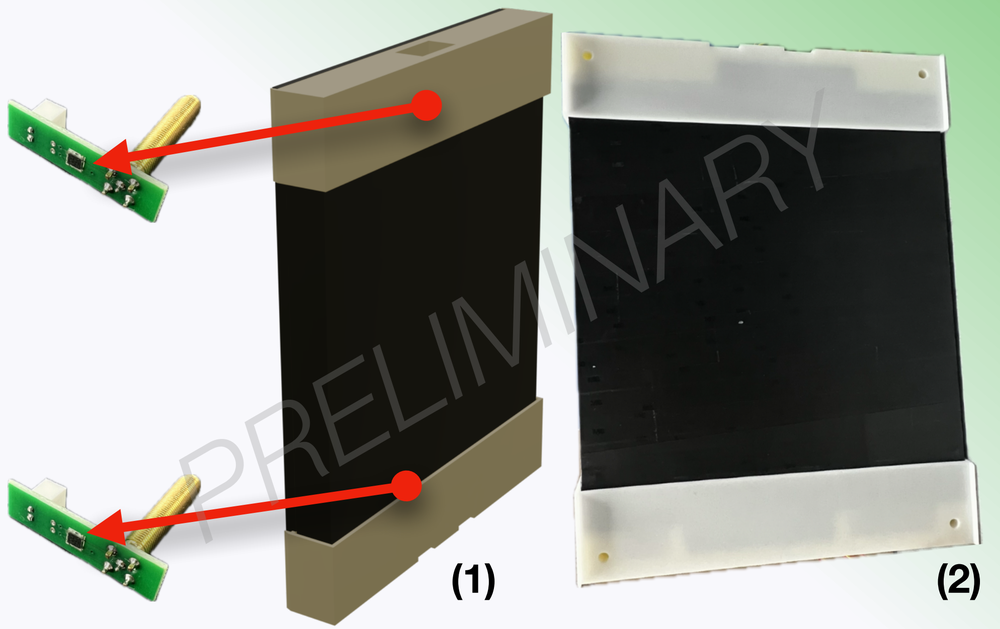


Figure1: (1)Design of a single unit of Veto; (2)Veto single unit finished.

Each Veto have 8 units(16 channels)

- Covers 2π azimuth angle with nearly no dead body.
- Cover the rest solid angle between two PDR.

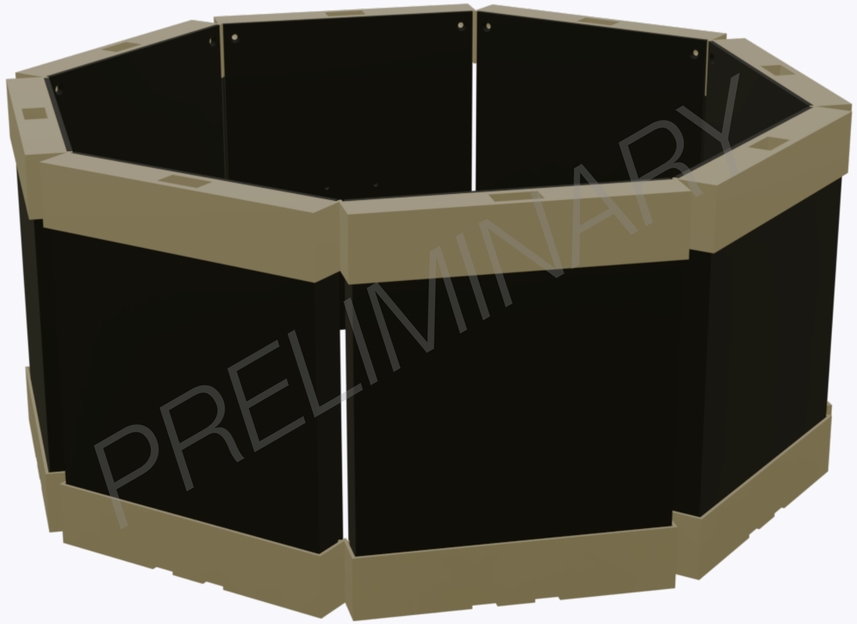
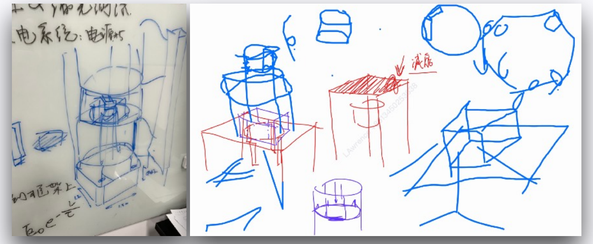
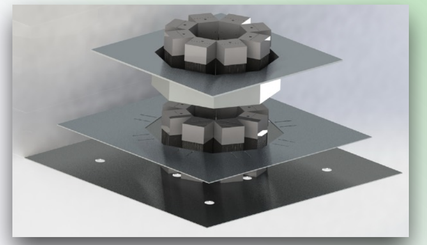


Figure2: Design of entire Veto modular (by Hesheng Liu and Mingchen Sun).

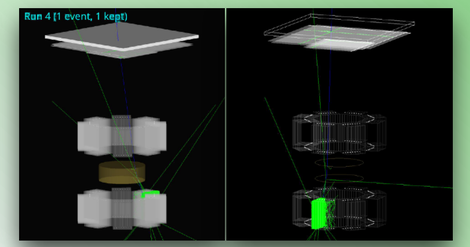
CRmuSR detector system



Strange thought during the nucleic acid for Covid .
(Mainly by Mingchen Sun, Tao Yu, Yunsong Ning)

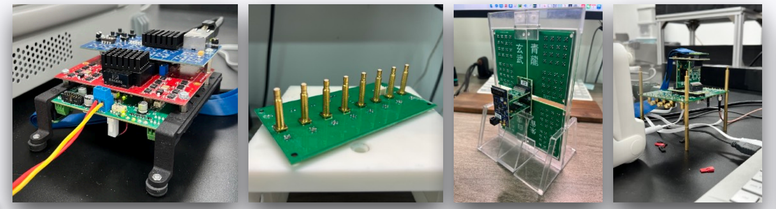


First design for 2 PDR

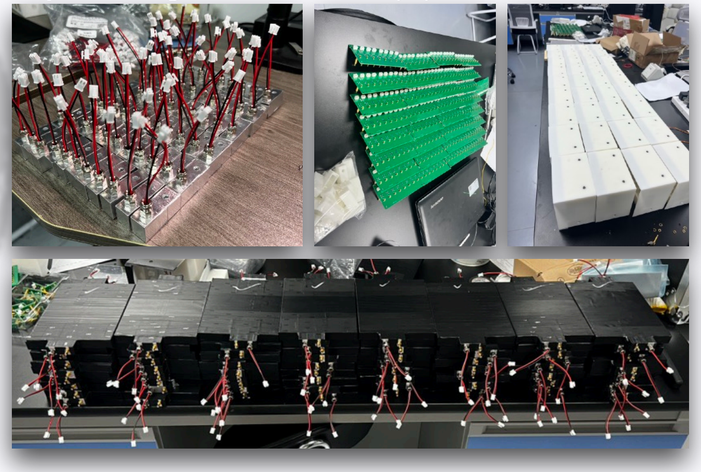


Signal and background simulation .
(Mainly by Aiyu Bai)

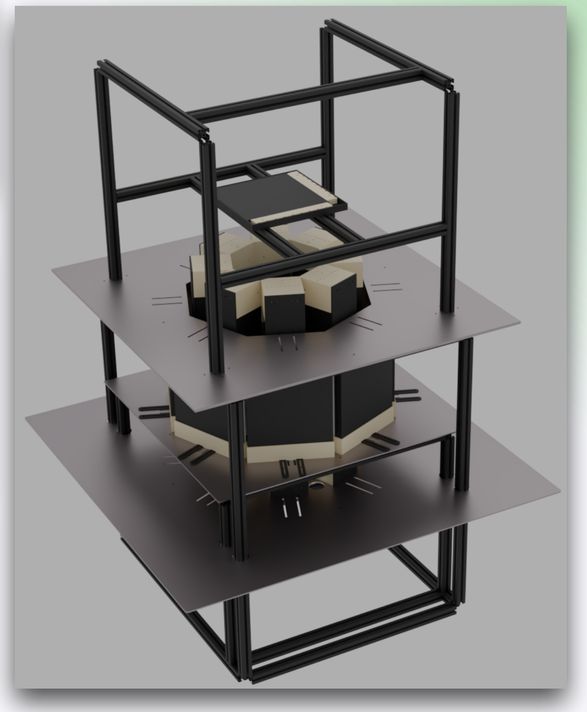
CRmuSR during data acquiring process.



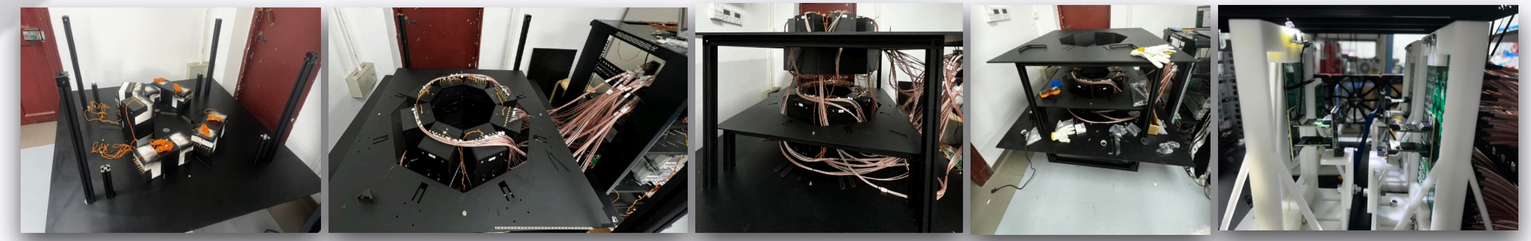
Develop and testing the electronic. (Mainly by Yi Yuan and Yu Chen)



Encapsulation progress. (By SMOOTH lab)



Final design of CRmuSR

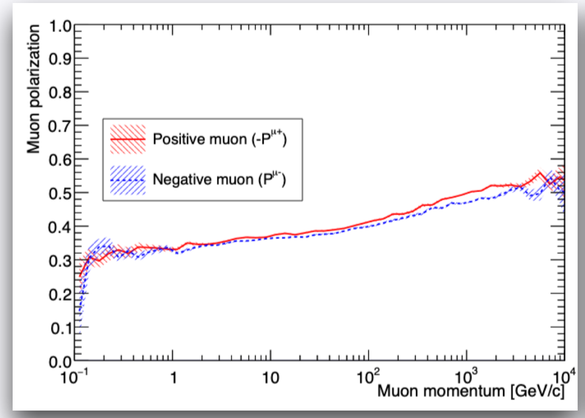


CRmuSR assembly process (By SMOOTH lab)

CRmuSR Simulation

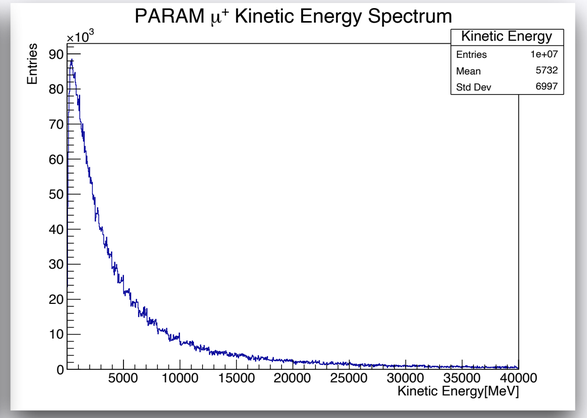
We use GEANT4 to simulate the detector respond of different events.

- Cosmic-ray muon generator is PRAMA.
- Cosmic-ray muon polarization is same as Honda muon flux simulation.



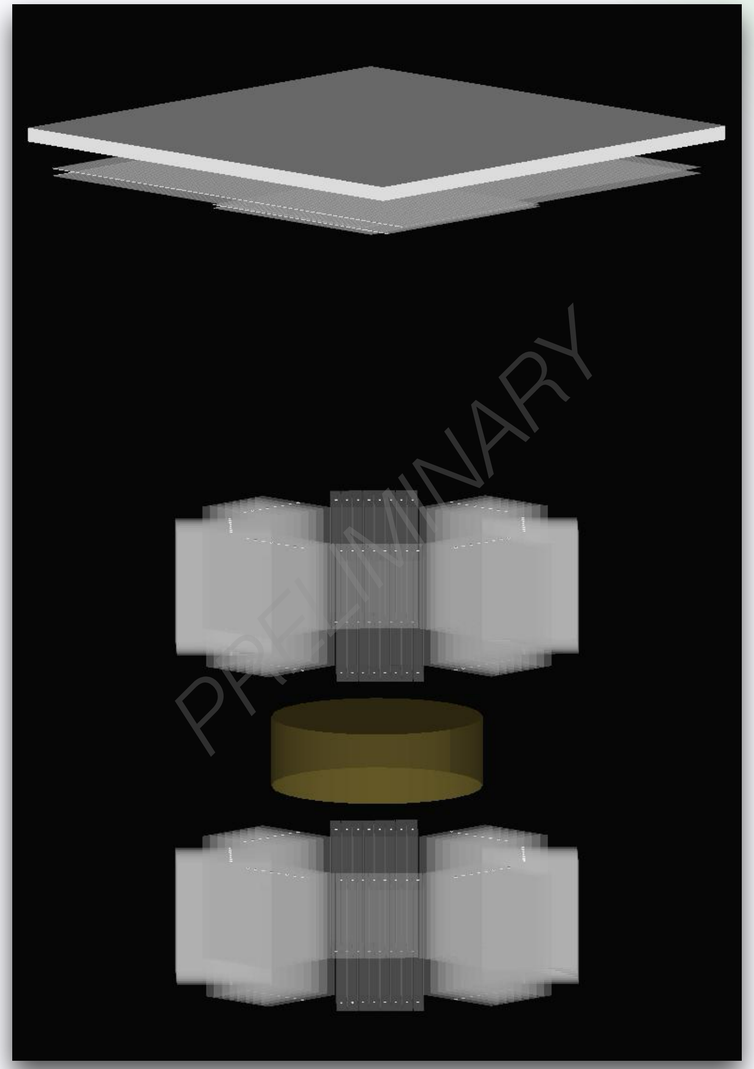
The expected polarization as a function of muon momentum based on Honda flux simulation.

Measurements of the charge ratio and polarization of cosmic-ray muons with the Super-Kamiokande detector Super-Kamiokande Collaboration • H. Kitagawa (Okayama U.) et al.e-Print: 2403.08619 [hep-ex]



PRAMA μ^+ energy spectrum.

Sato T. Analytical model for estimating terrestrial cosmic ray fluxes nearly anytime and anywhere in the world: Extension of PARMA/EXPACS[J]. PloS one, 2015, 10(12): e0144679.



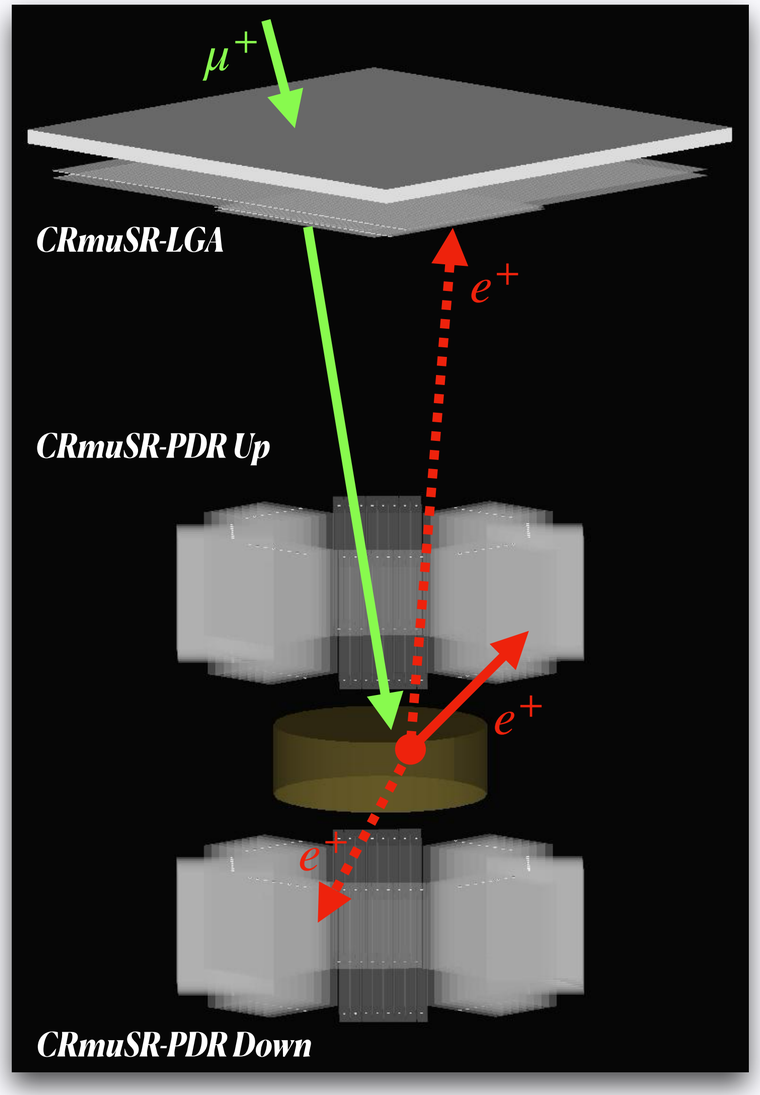
GEANT4 simulation geometry of CRmuSR

Typical signal:

Cosmic-ray muon

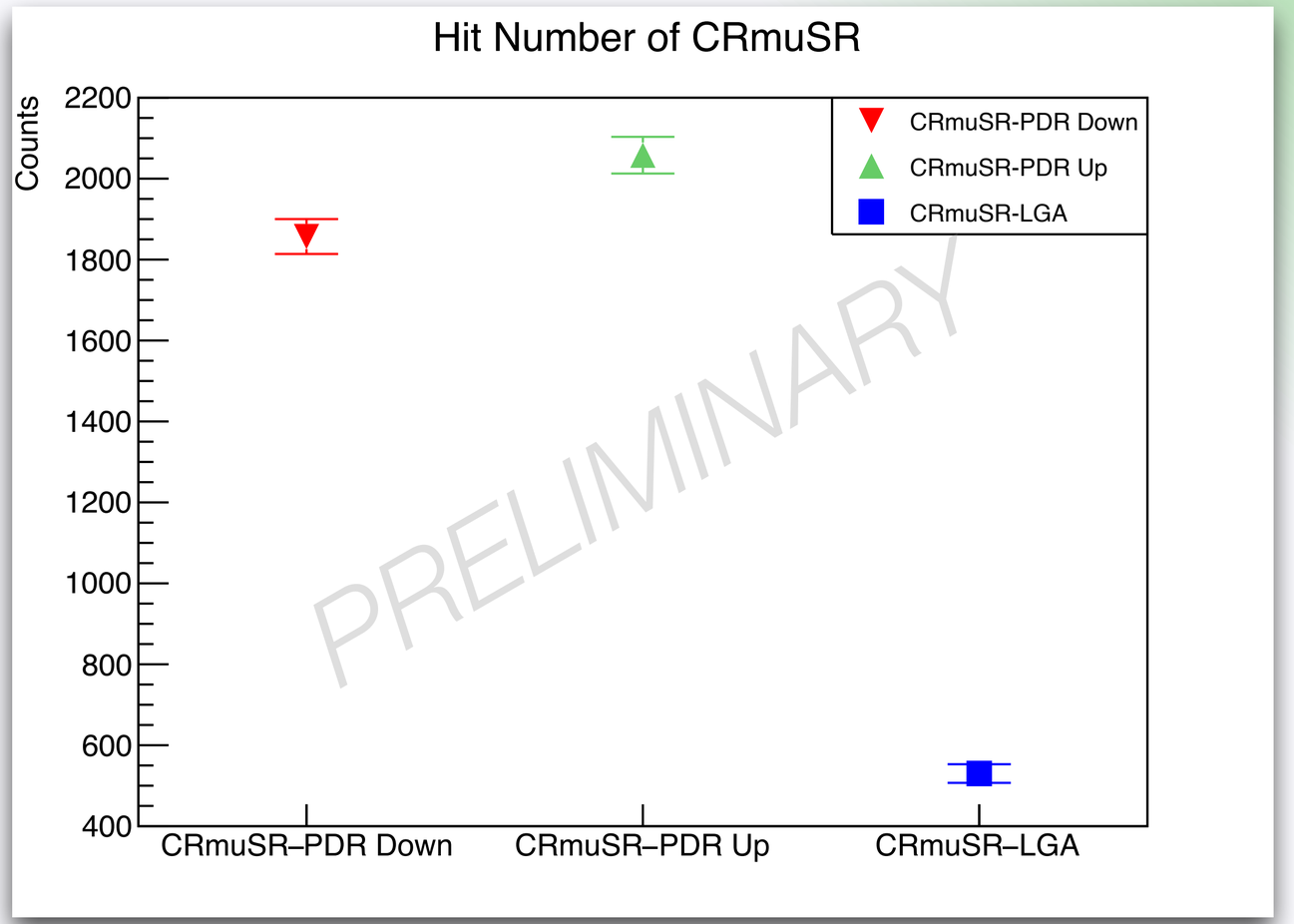
- *two layer of LGA* ($\vec{p}_\mu / |\vec{p}_\mu|$)
- *stop in the target and decay*
- *two PDR* ($\vec{\sigma}$)

Decay Asymmetry of Cosmic-ray Muon



GEANT4 simulation geometry of CRmuSR

$\sim 3 \times 10^6$ cosmic-ray muons generated = 60 days data taking



$$\text{Up-down Decay asymmetry } \alpha_e = \frac{N_u - N_d}{N_u + N_d} = 0.051 \pm 0.015$$

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CRmuSR performance

Detector efficiency for cosmic-ray muon

- Single scintillator in PDR unit $\geq$ 97 %
- Single unit in Veto $\geq$ 95 %

Total solid angle coverage >70%(for target)

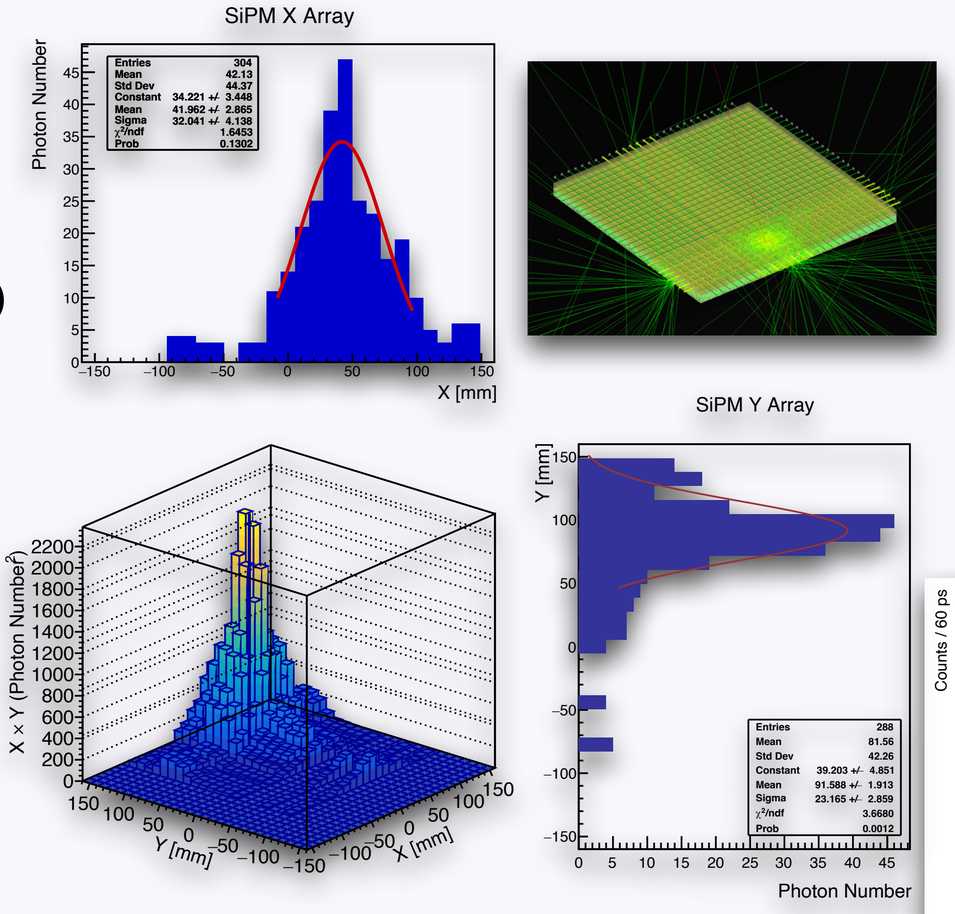
There are overlaps between modules.

- 40% (PDR),
- >29% (LGA),
- >30% (Veto).

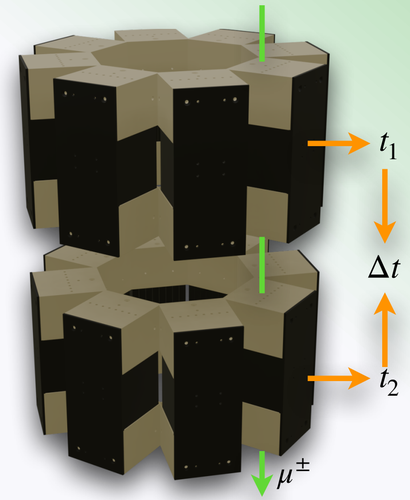
Azimuth angular resolution of PDR better than 6°.

Spatial resolution is about 3mm.

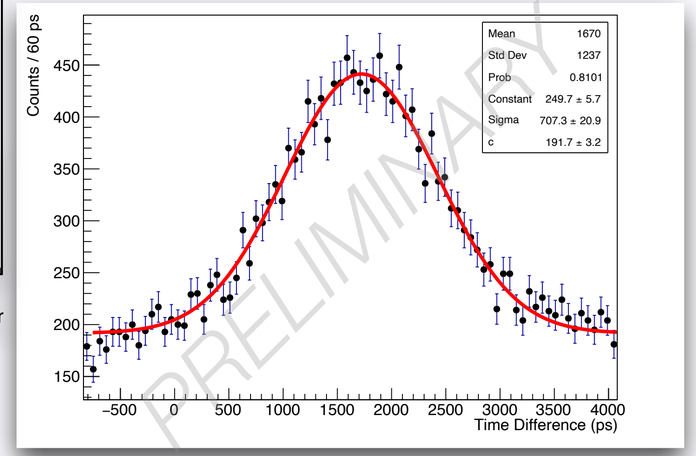
Time resolution of PDR is about 1ns.



Simulation results for single layer of LGA.

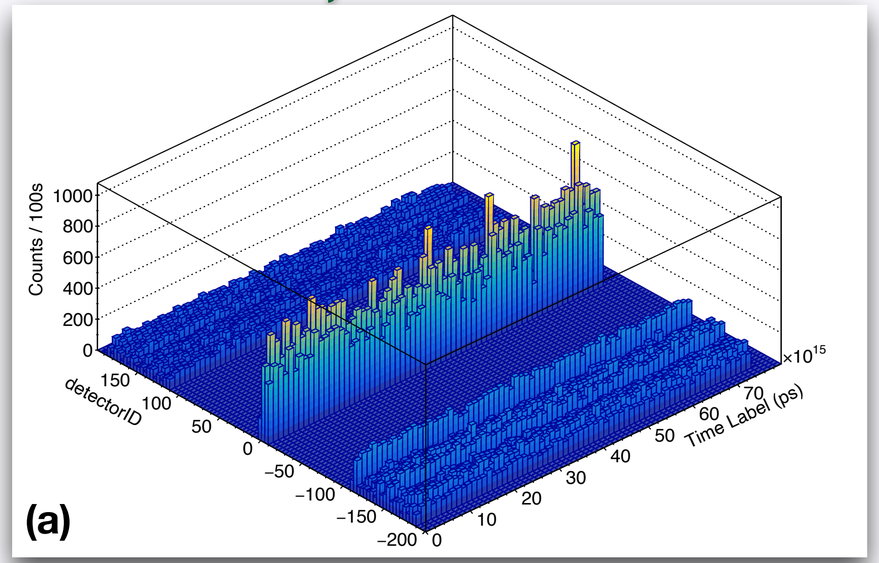


Using penetrate cosmic-ray muon test PDR time resolution.

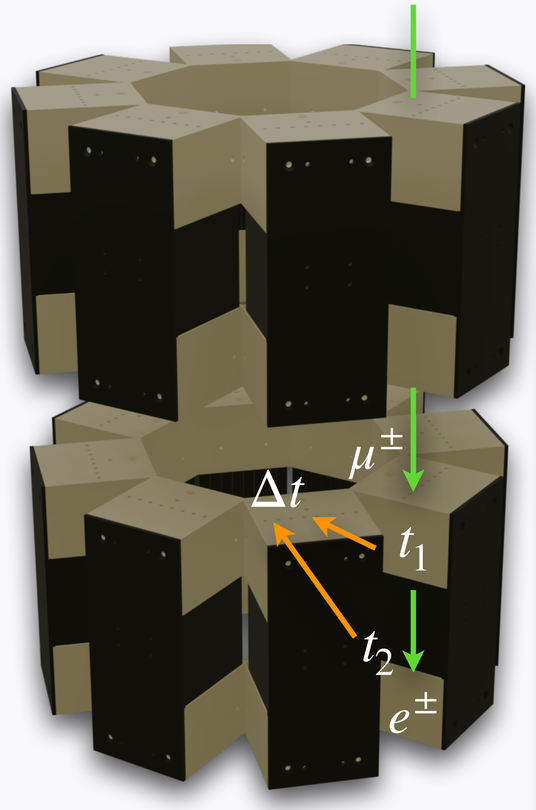


Preliminary analysis for time resolution of PDR.

Cosmic-ray Muon Measurement by CRmuSR



(a)Double trigger rate in 12h. Detector ID > 100 are CRmuSR-PDR Up, detector ID < -100 are CRmuSR-PDR Down, detector ID in [−8,0) are Veto, detector ID 1 and 2 are scintillator target. (b) Double trigger rate for CRmuSR-PDR Down in 12h.

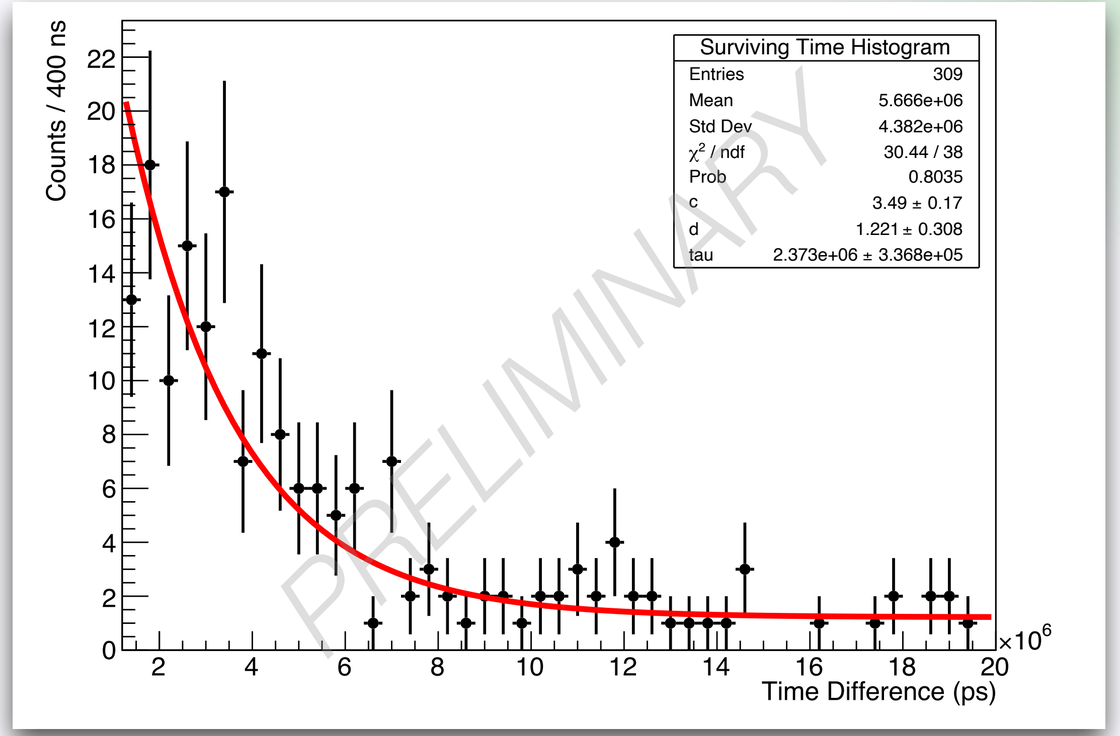


Lifetime of cosmic-ray muon decay in PDR.

Using Coincident time difference Δt

Fitting with $\exp(-t/\tau_\mu + c) + d$

$\tau_\mu = 2.37 \pm 0.34 \mu s$

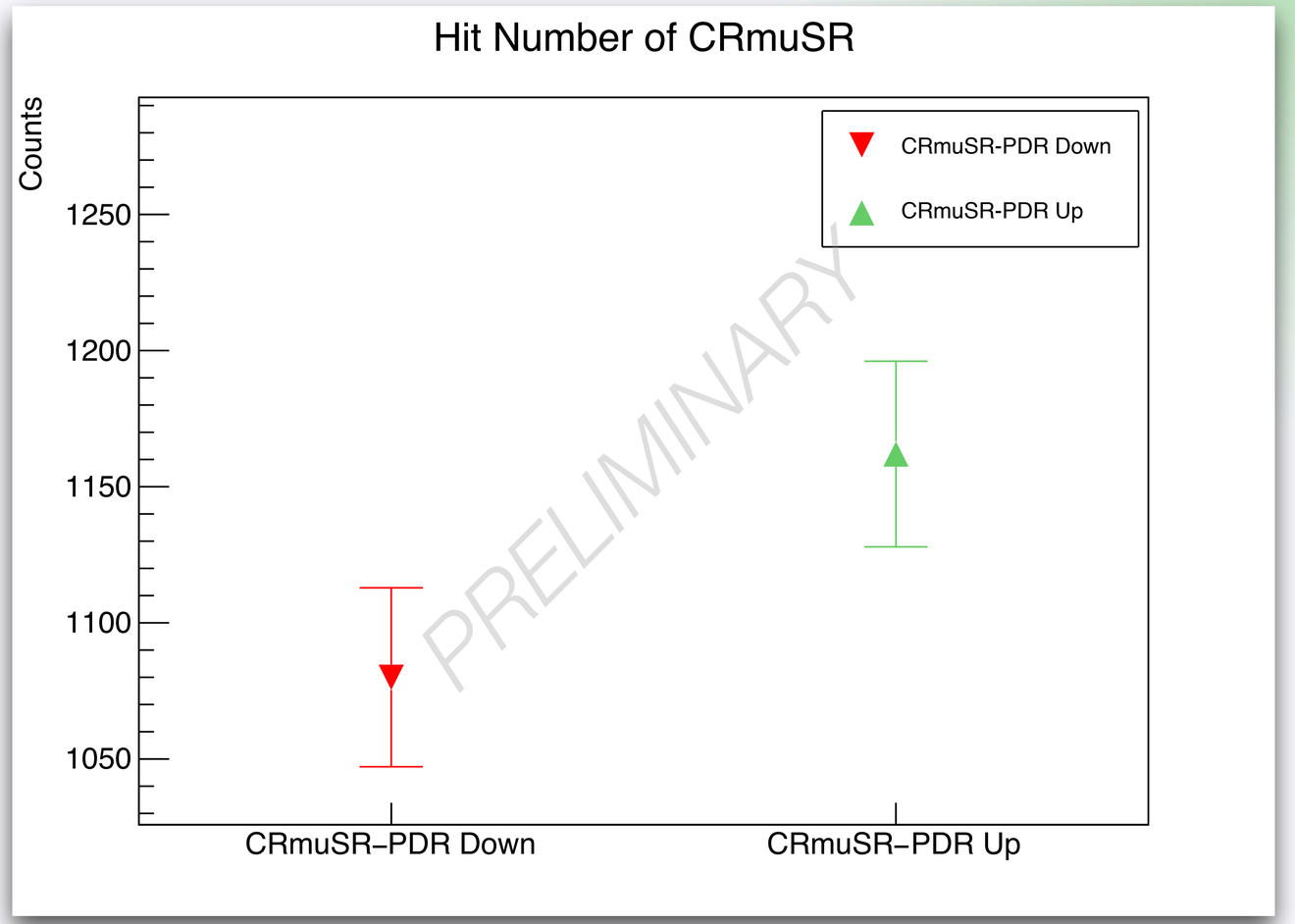


Preliminary analysis for cosmic-ray muon lifetime with PDR.

Decay Asymmetry of Cosmic-ray Muon

CRmuSR testing target in the present.

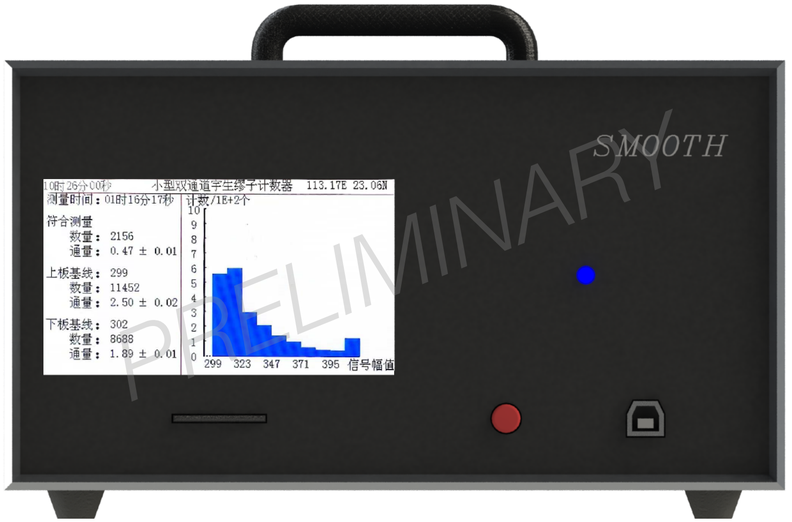
$$\text{Up-down Decay asymmetry } \alpha_e = \frac{N_u - N_d}{N_u + N_d} = 0.036 \pm 0.021$$



Rough analysis of Michel electron hits in CRmuSR experiment.

For the study of cosmic ray muon polarization, our dataset is still insufficient.

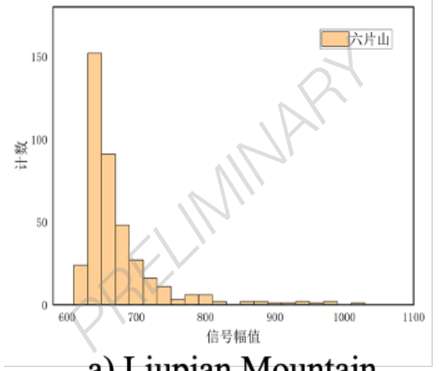
Prototype of CRmuSR array system



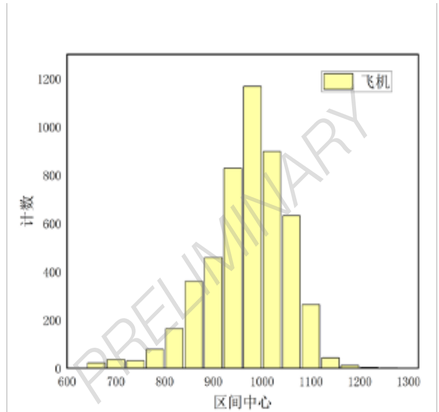
SMOOTH Portable Cosmic-ray Muon detector (SMOOTH-PCμ)

SMOOTH Portable cosmic-ray muon detector

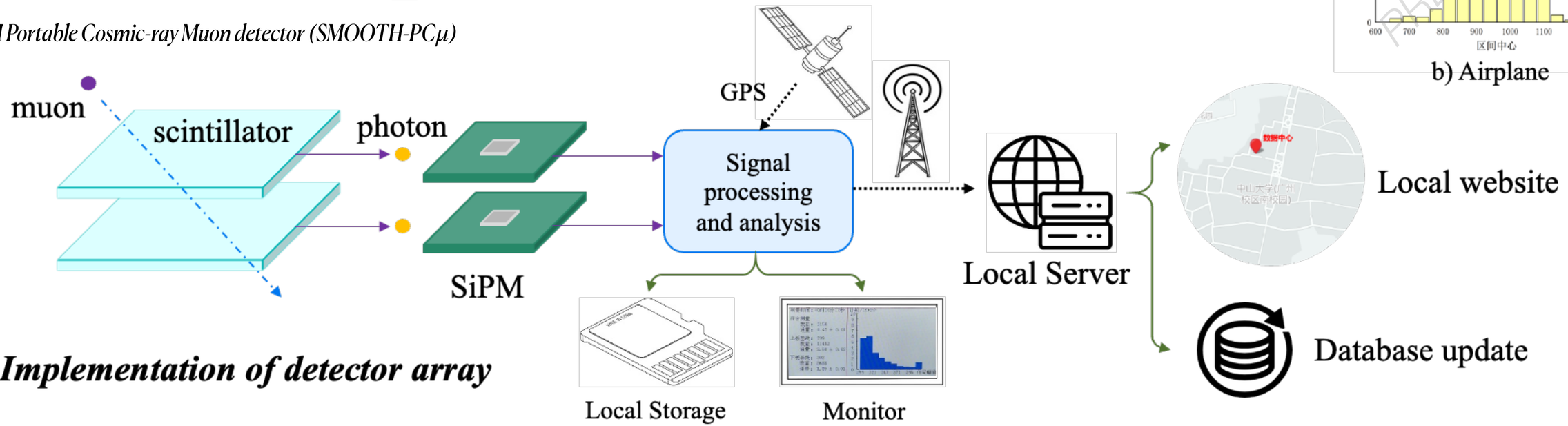
- Contains location information, signal magnitude and flux.
- Implementing data backhaul using base stations.
- Successfully completed field test.



a) Liupian Mountain



b) Airplane



Implementation of detector array

Prototype of CRmuSR array system

A map consisting of detector arrays.

Detector 1:

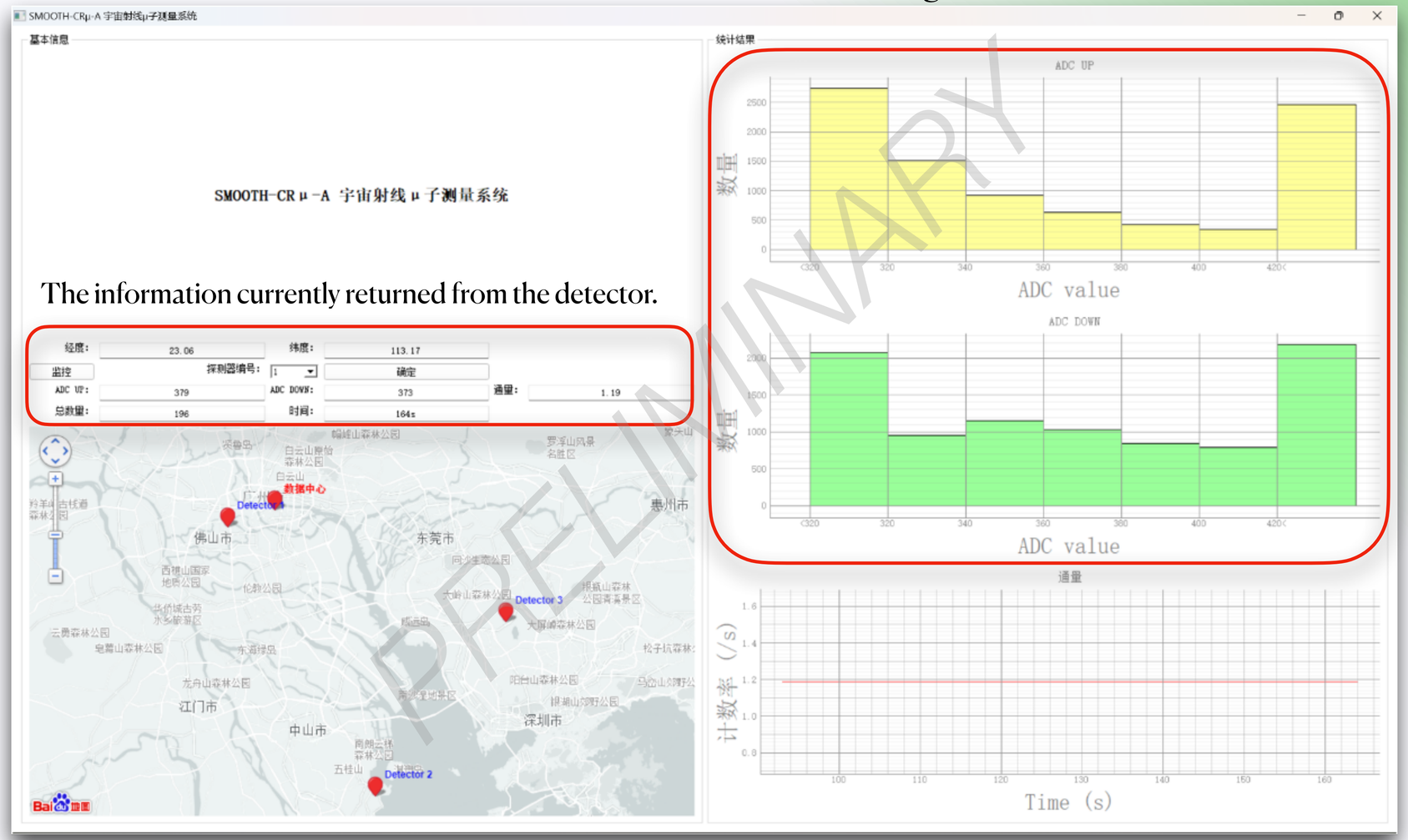
SYSU(Guangzhou)

Detector 2:

SYSU(Zhuhai)

Detector 3:

SYSU(Shenzhen)



Statistics of detector results

(including database historical data)

Remote monitoring UI interface for detectors

Multiple times the original data volume achieved, eliminating location dependence for conclusions.

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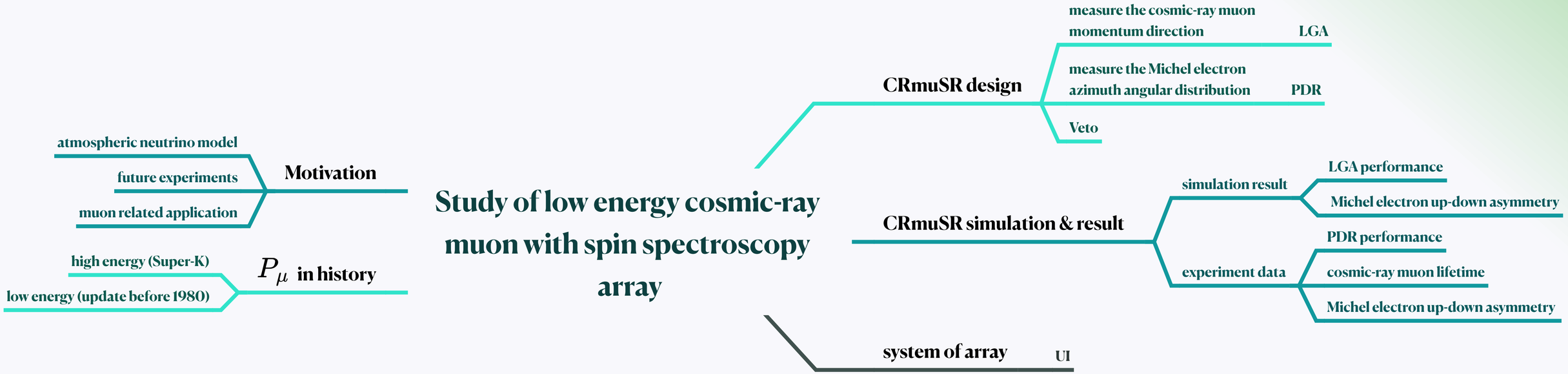
Summary


Study of low energy cosmic-ray muon with spin spectroscopy array
Motivation
atmospheric neutrino model
future experiments
muon related application
P_μ in history
high energy (Super-K)
low energy (update before 1980)
CRmuSR design
measure the cosmic-ray muon momentum direction
LGA
measure the Michel electron azimuth angular distribution
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simulation result
LGA performance
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cosmic-ray muon lifetime
Michel electron up-down asymmetry
system of array
UI

Summary

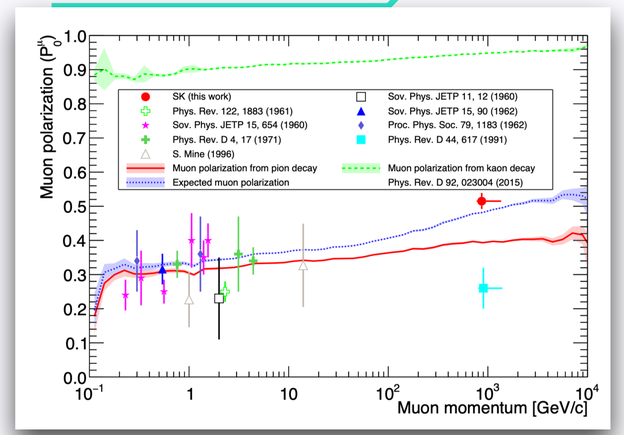
Study of low energy cosmic-ray muon with spin spectroscopy array

Motivation

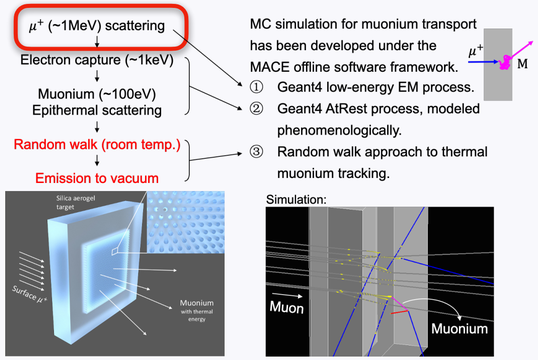
- atmospheric neutrino model
- future experiments
- muon related application

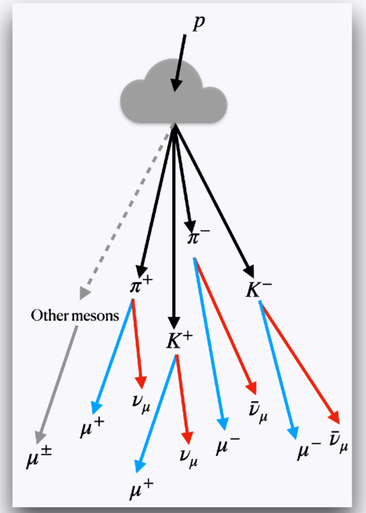
P_μ in history

- high energy (Super-K)
- low energy (update before 1980)



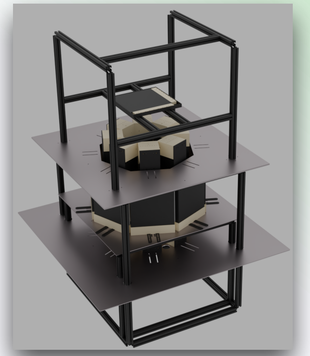
Polarization input

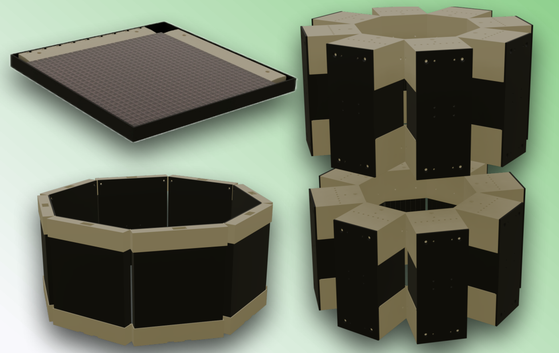


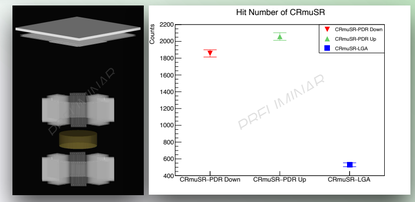


CRmuSR design

- measure the cosmic-ray muon momentum direction — LGA
- measure the Michel electron azimuth angular distribution — PDR
- Veto



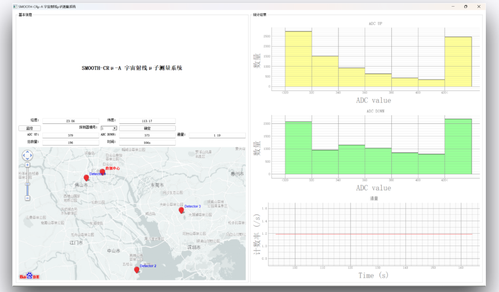


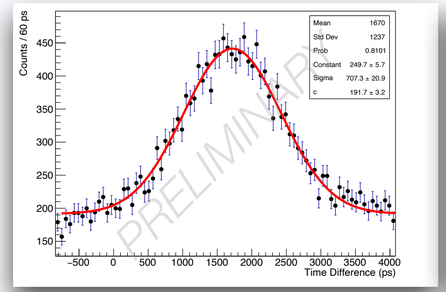


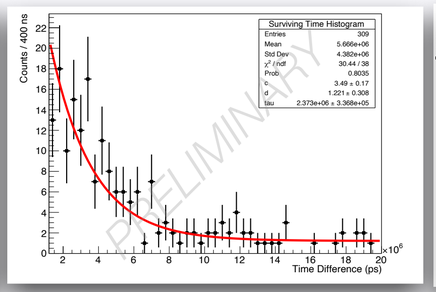
CRmuSR simulation & result

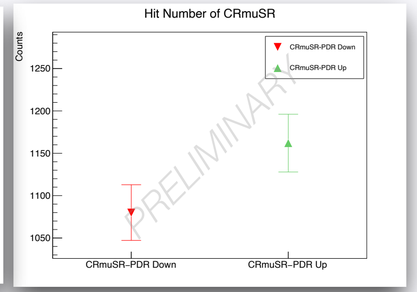
- simulation result
  - LGA performance
  - Michel electron up-down asymmetry
- experiment data
  - PDR performance
  - cosmic-ray muon lifetime
  - Michel electron up-down asymmetry

system of array — UI









Future plan

Data Acquiring for CRmuSR

- Complete the installation of the LGA,
- complete the design and the set up for target,
- continue the data acquiring for CRmuSR and reconstruct the cosmic-ray muon polarization.

Upgrade the CRmuSR to CRmuSR-II

- Increase the amount of stopped cosmic-ray muons,
- Upgrade the physical environment (no magnetic field →Zero field, low temperature environment, ...),
- Complete the system of array and the establishment of the data server.

中山大學 物理学院

SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

Thanks!

Welcome Collaborations!

21st April 2024, Beijing (PKU)

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