中山大學 物理学院

SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

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缪子自旋谱仪的样机研制

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SMOOTH Lab, SCHOOL OF PHYSICS, SYSU

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第二届惠州大科学装置高精度物理研讨会－暨基于HIAF加速器集群的缪子科学与技术研讨会

目录

Index

- *Introduction*
- *CRmuSR design*
- *CRmuSR prototype*
- *Summary and outlook*

目录

Index

What is μSR ?

- *muSR is collection of muon spin rotation/relaxation/resonance techniques.*

Distribution of Michel electron produce by polarized muon

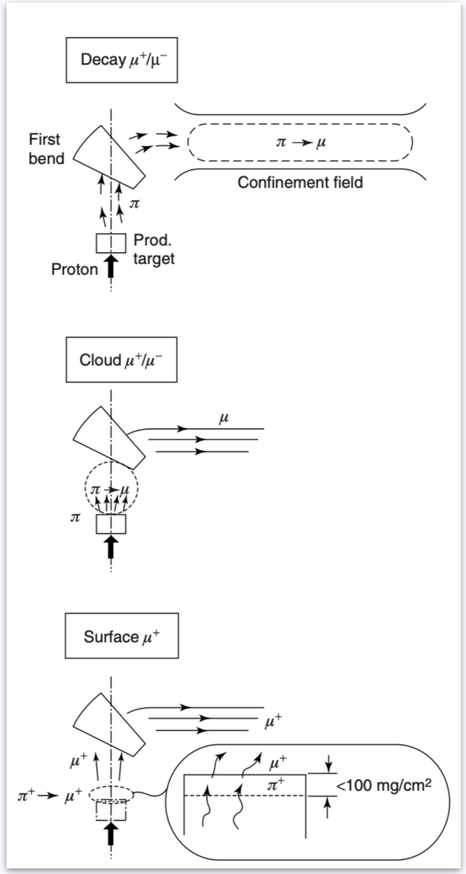


Figure: muon produced by accelerator.

Muon decay Mode

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e (\mathrm{BR} \rightarrow 100\%)$$

Michel electron distribution

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

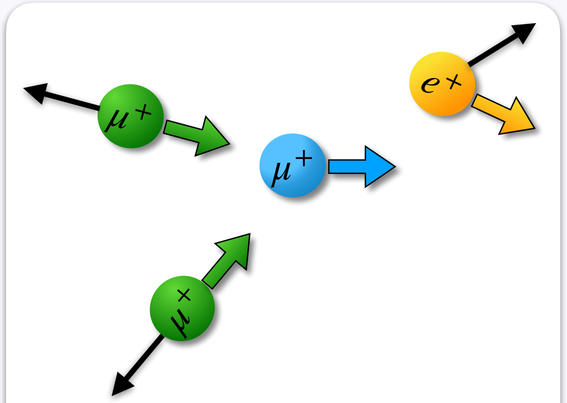
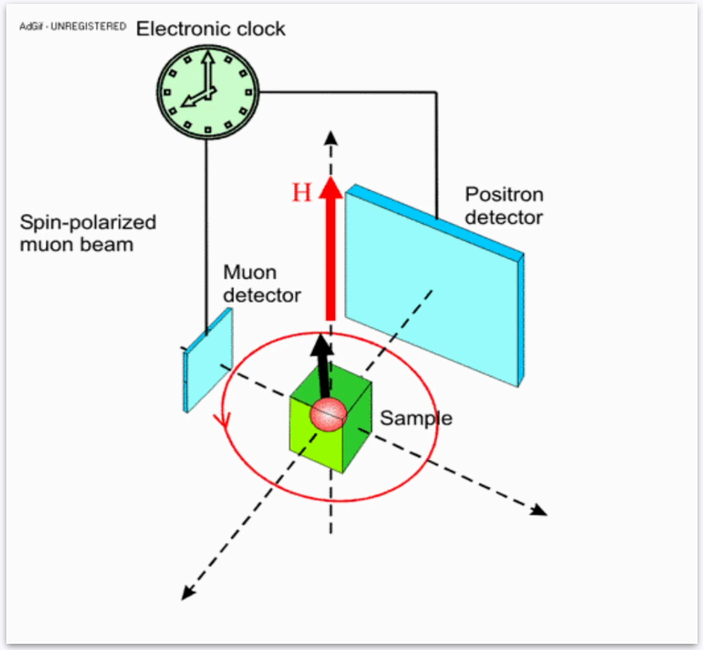


Figure: muon three body decay mode.

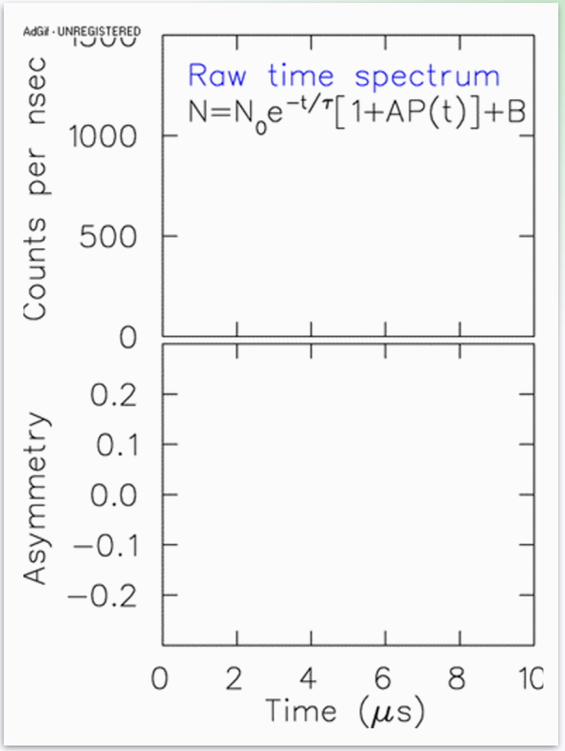
Spin procession in magnetic field

$$H = -\vec{\mu}_\mu \cdot \vec{B} = -\gamma \vec{B} \cdot \vec{\sigma}_\mu$$



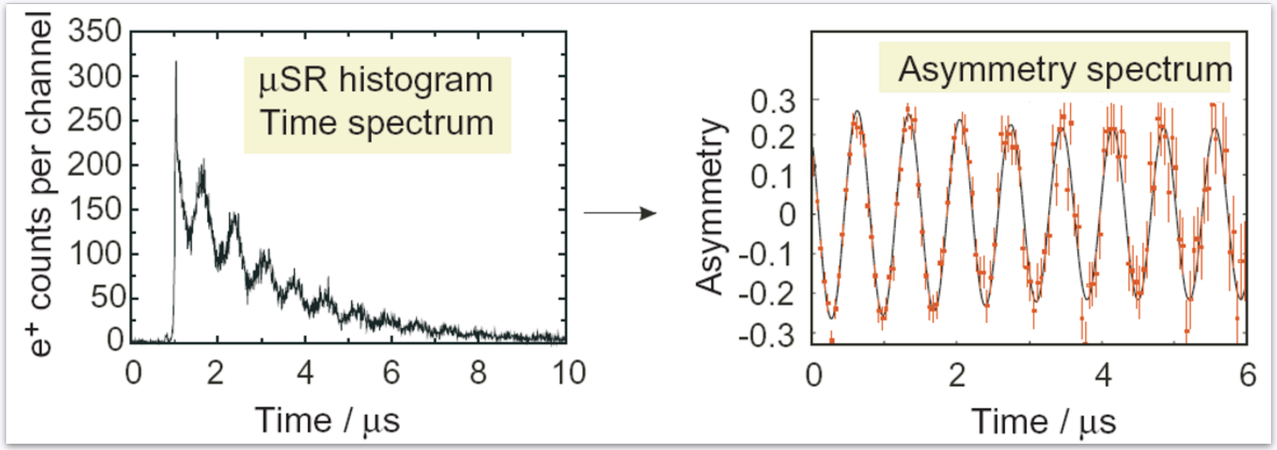
http://neutron.magnet.fsu.edu/muon_relax.html

muSR spectrum



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

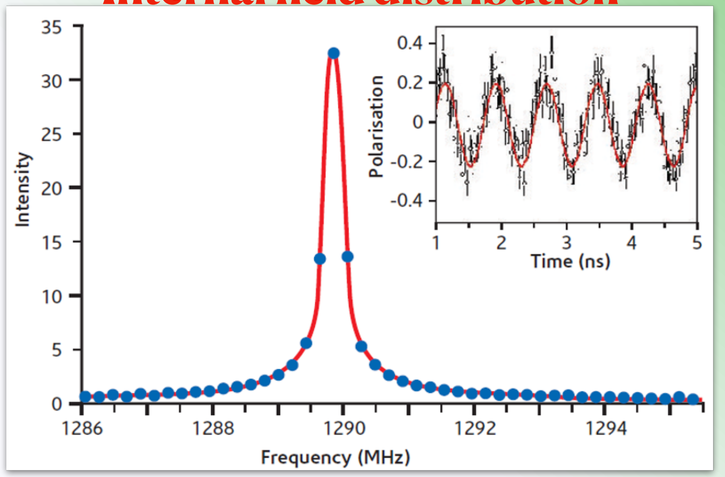
Advantages of μSR spectroscopy



Fourier transformation

Maximum entropy analysis

Internal field distribution



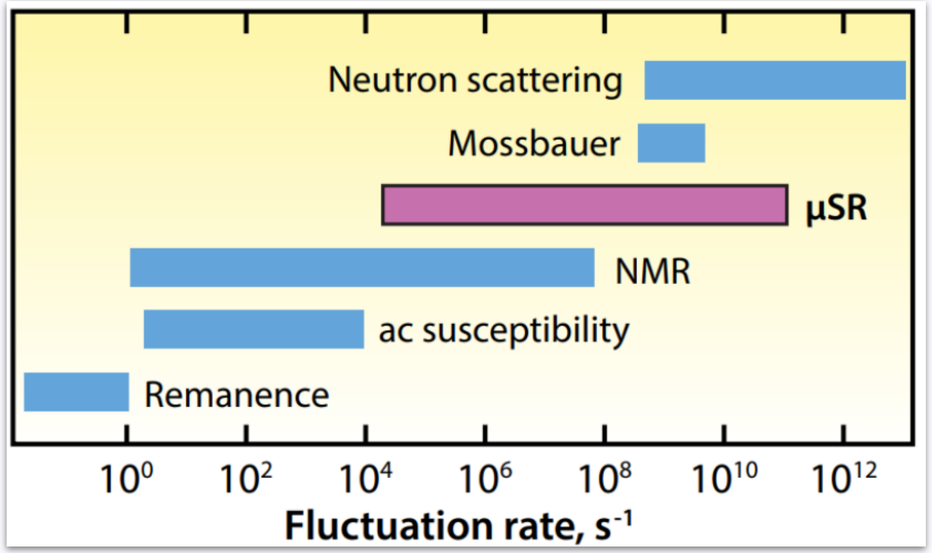


Figure: Fluctuation rate of several techniques.

- ***Unique & wide time scale (complementary to NMR/neutron scattering)***
- ***Non-Destructive($\mu \rightarrow e\nu\bar{\nu}$, the decay product are Non-Destructive)***
- ***High sensitivity(rely on the time resolution of spectrometer)***
- ***Local probing(no need to search reciprocal space)***
- ***Dynamic Information(μSR spectrum analysis)***
- ***Wide Applicability(superconducting, magnetic materials etc.)***

Development of a Chinese muSR apparatus[EB/OL]. 2023[2024-08-26]. https://indico-tdli.sjtu.edu.cn/event/1465/contributions/6915/attachments/2873/4399/Development_of_Chinese_muSR_apparatus-V2.pdf.

Applications of μSR

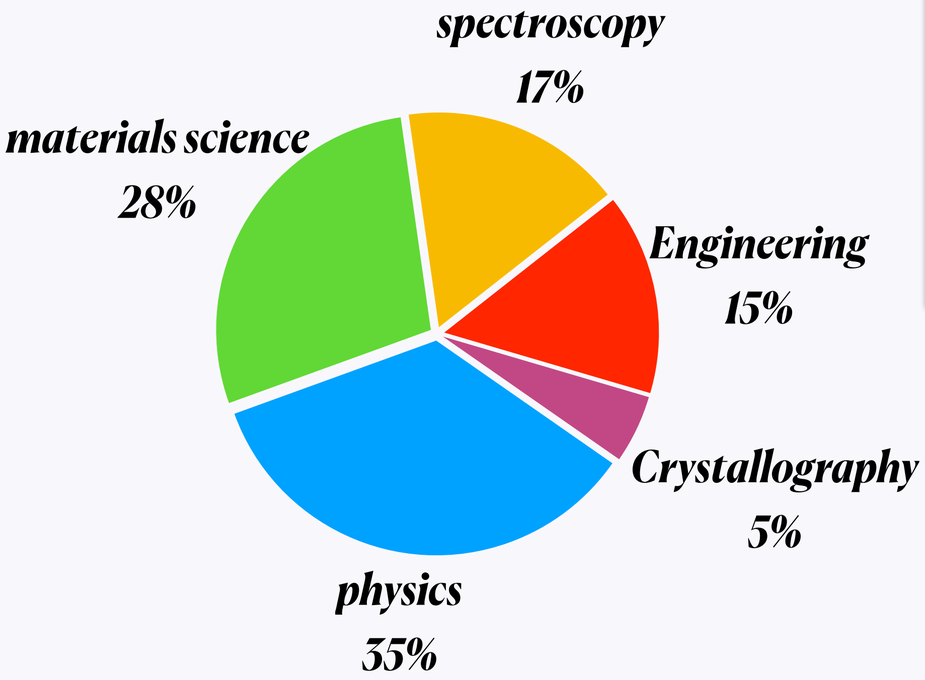


Figure: muSR-related research field.
(data from https://webofscience.clarivate.cn/wos/alldb/analyze-results/be8f2164-bfa3-4c4d-8c20-25840d776843-0103667d9d)

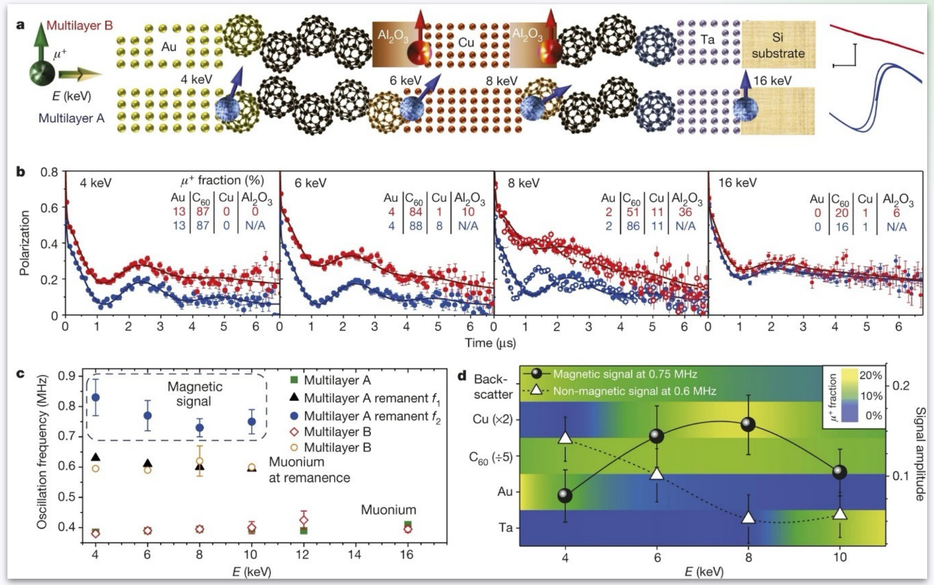


Figure: Bulk-boundary correspondence research using muSR.
F. Al Ma'Mari et al., **Nature** 524, 69 (2015).

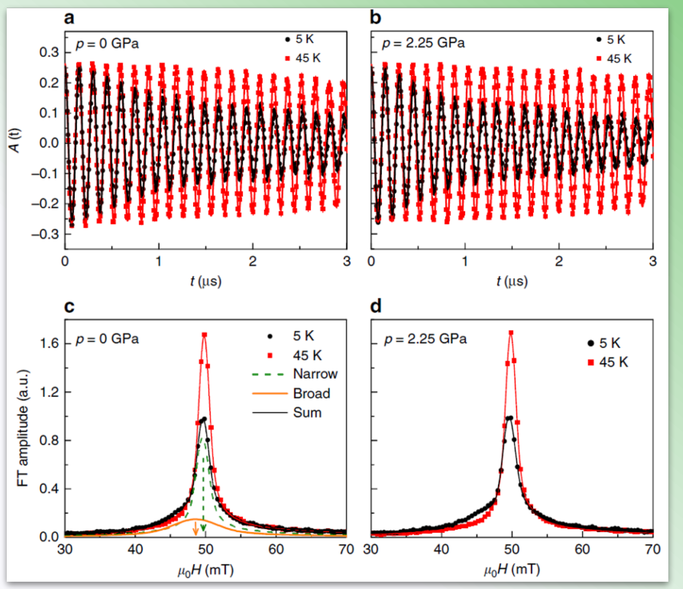


Figure: Measurement of spontaneous fields in superconductors using muSR.
Z. Guguchia et al., Nature Communications 6, 9863 (2015).

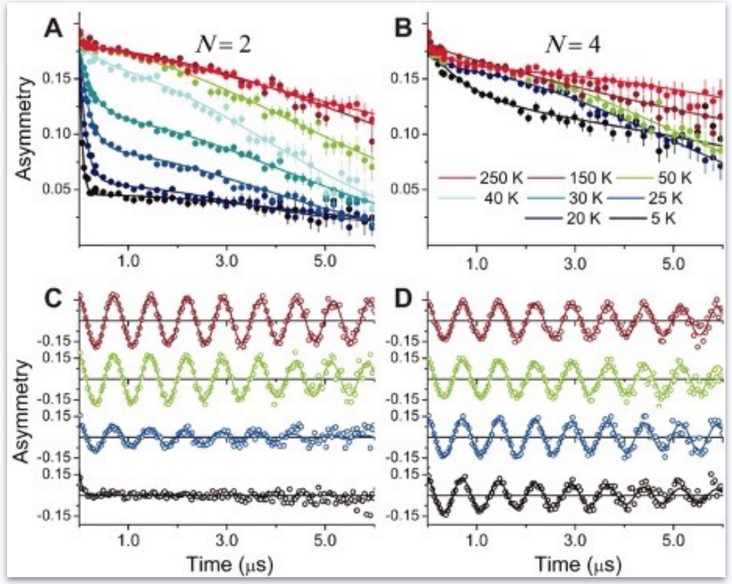


Figure: muSR application on the nano scale structure research.
A. Boris et al., **Science** 332, 937 (2011)

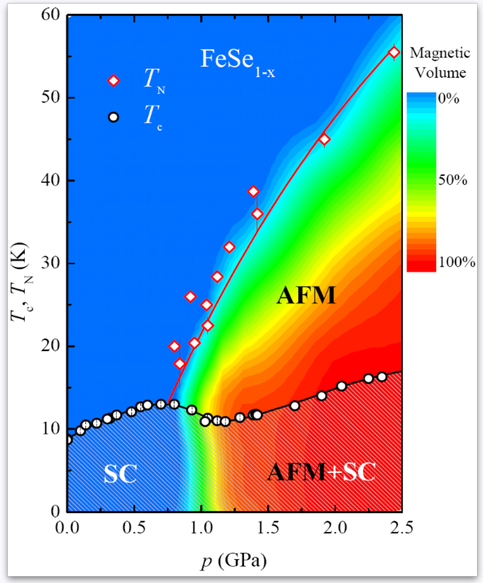
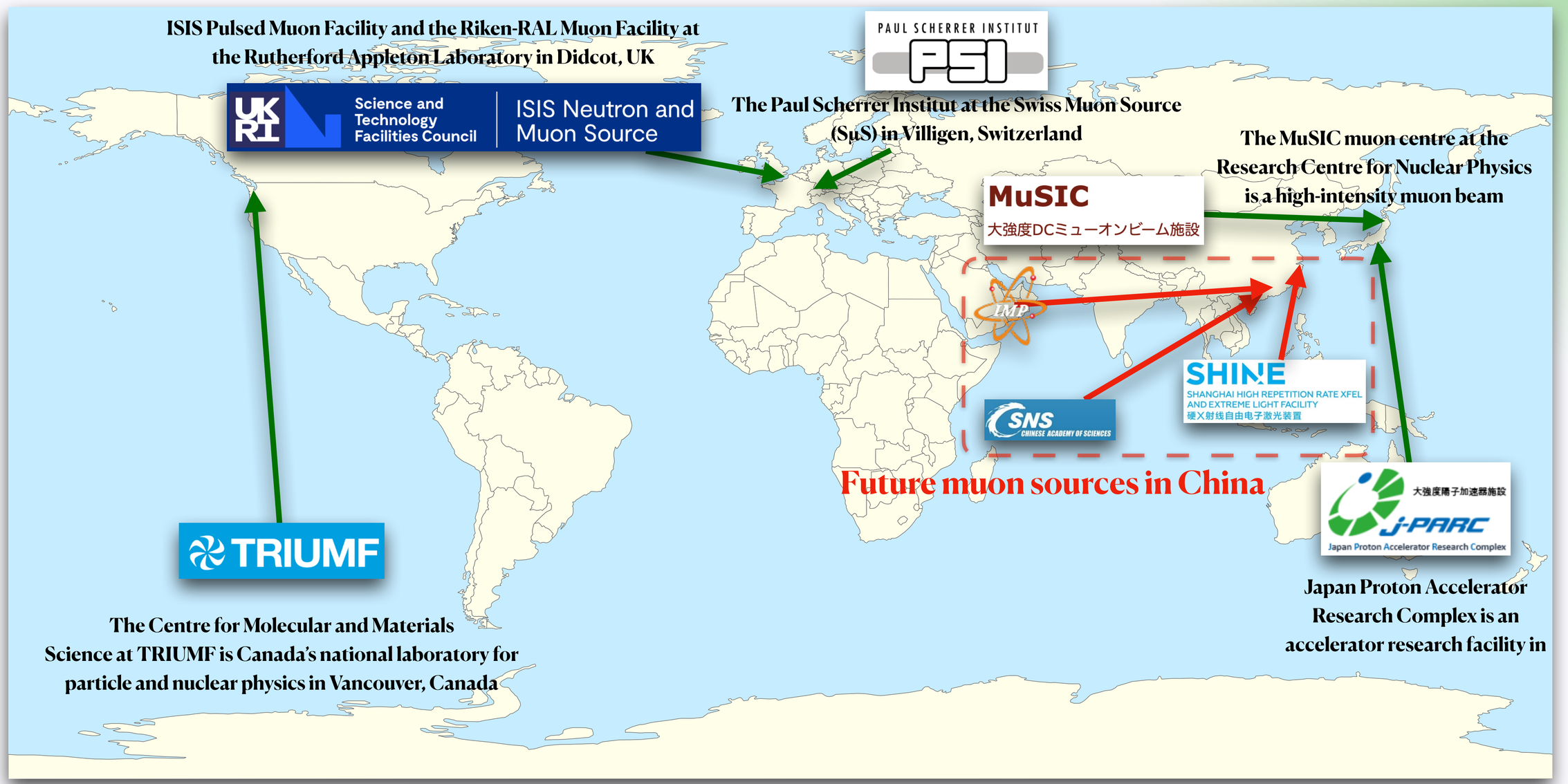


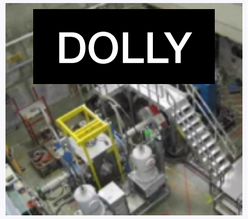
Figure: muSR application on the collective electronic phase.
M. Bendele et al., **Phys. Rev. Lett.** 104, 087003 (2010)

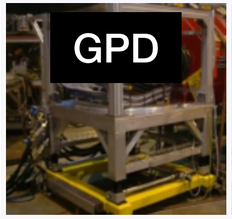
Muon sources for μSR measurements

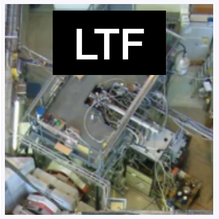


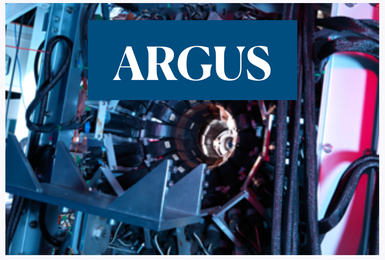
In the future, accelerator muon sources in China will require muSR techniques.

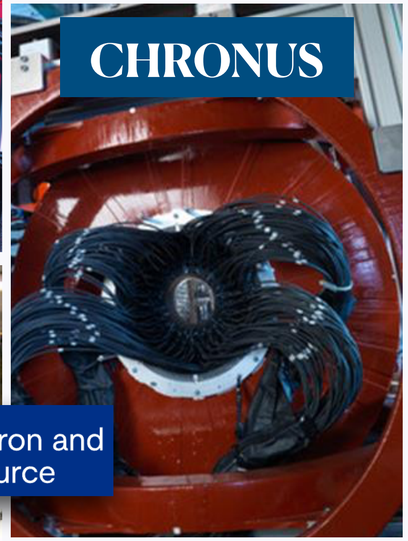
Existing μSR apparatus

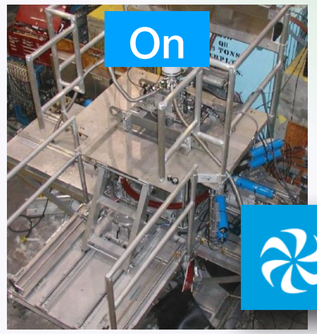


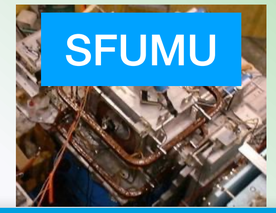












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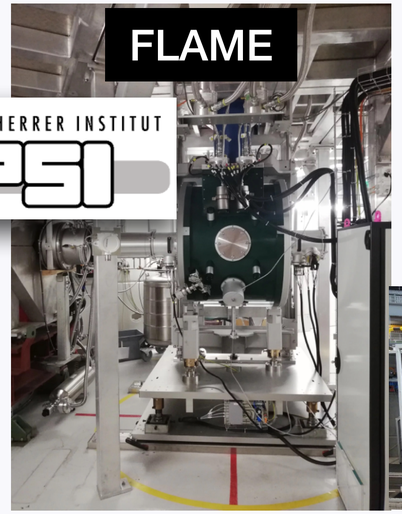
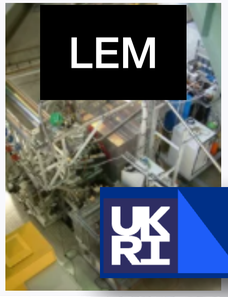
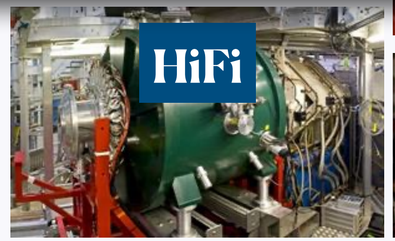
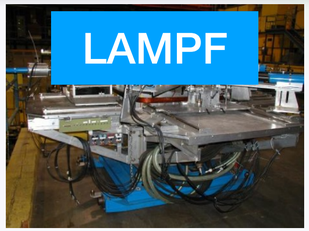


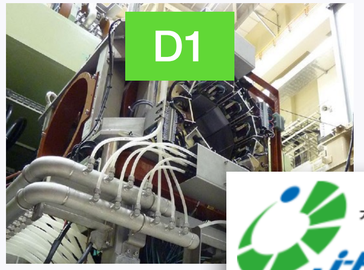


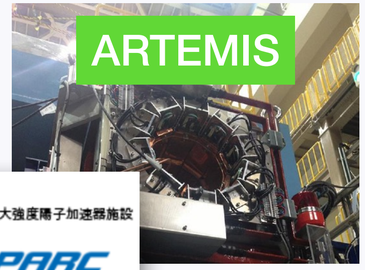
PAUL SCHERRER INSTITUT PSI

UKRI Science and Technology Facilities Council | ISIS Neutron and Muon Source







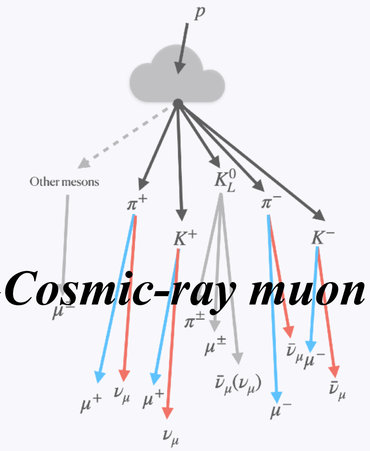


大強度陽子加速器施設 J-PARC Japan Proton Accelerator Research Complex

Muon sources in china also require muSR spectrometers

and the associated experimental techniques !!!

How to develop a muSR without a muon source?



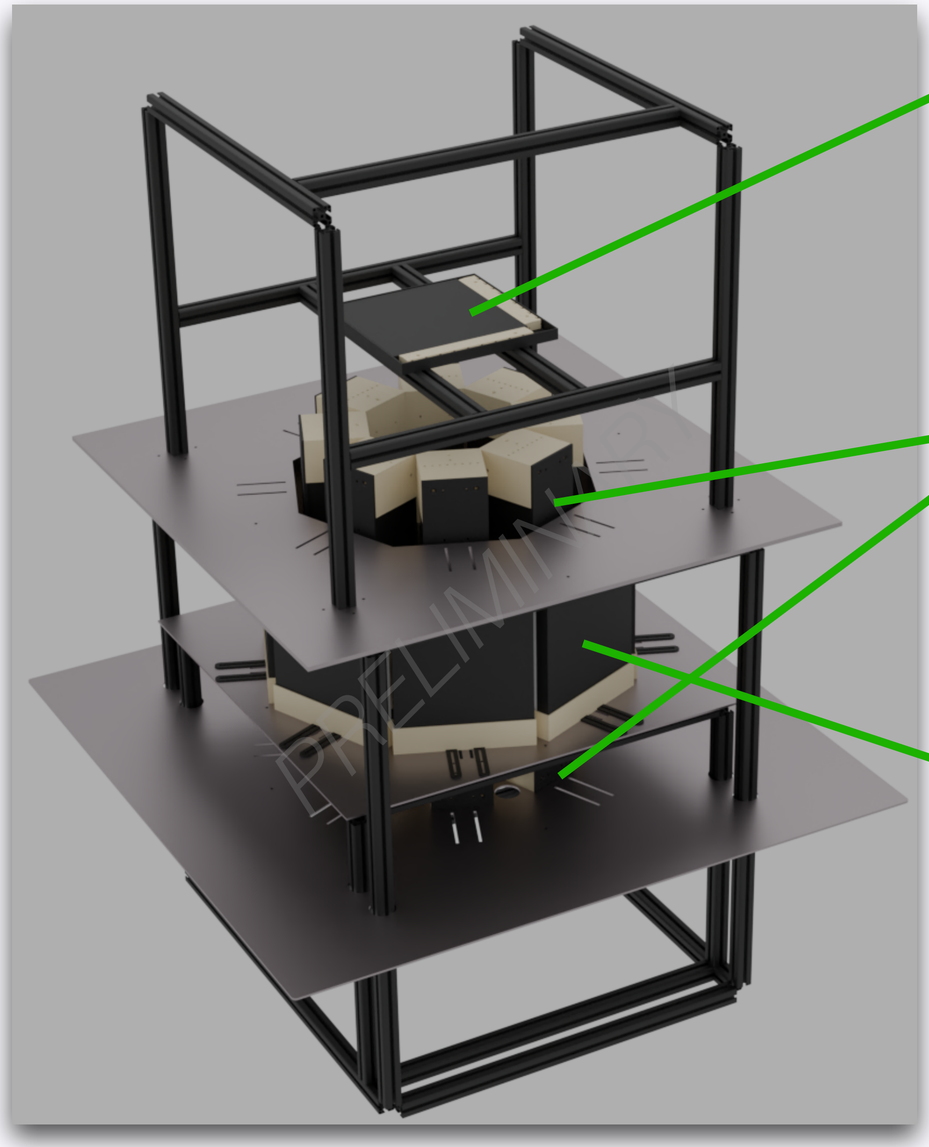
Cosmic-ray muon

目录

Index

- *Introduction*
- *CRmuSR design*
- ***CRmuSR prototype***
- *Summary and outlook*

Cosmic-Ray muSR(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):

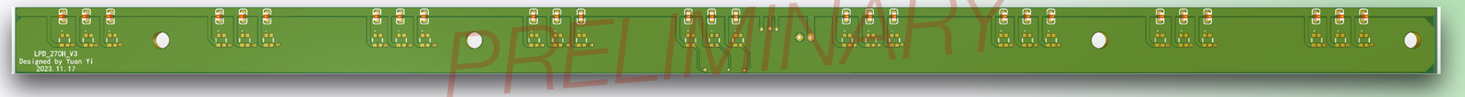
Filter out parallel cosmic-ray muon events.

Requirement: high detection efficiency.

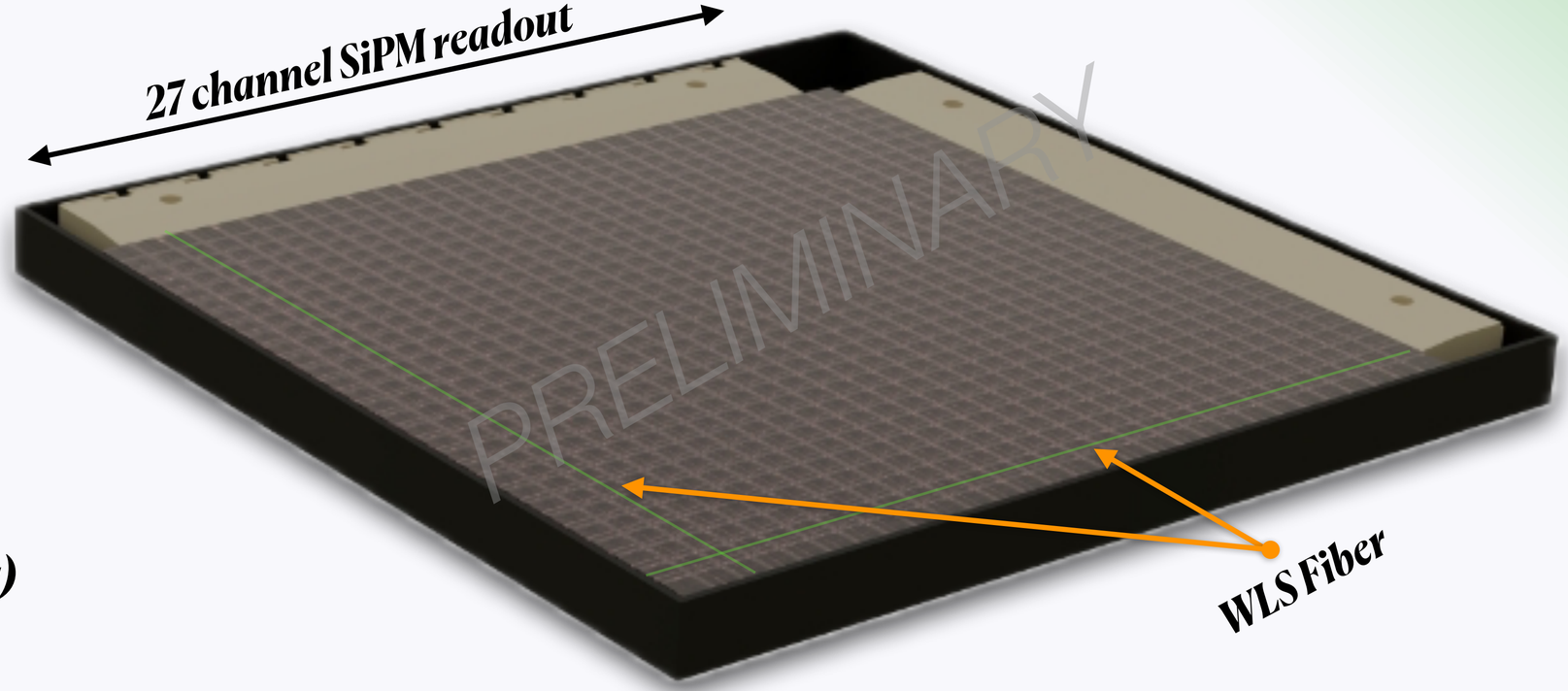
CRmuSR Module: Light Guide detector Array (LGA)

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)



LGA single layer design (27 channels version).

Size of scintillator

- $32 \times 32 \times 1\text{cm}$ ***(27 channels layer)***
- $64 \times 64 \times 1\text{cm}$ ***(54 channels layer)***

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.

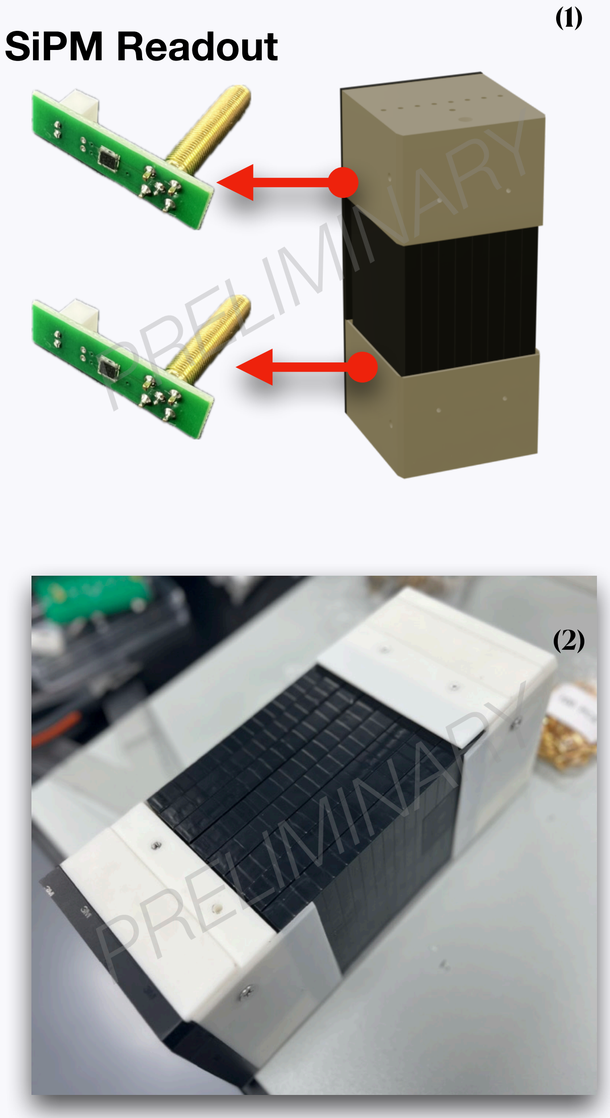


Figure: (1) The design of single unit in PDR and the location of SiPM readout. (2) Single PDR unit detector.

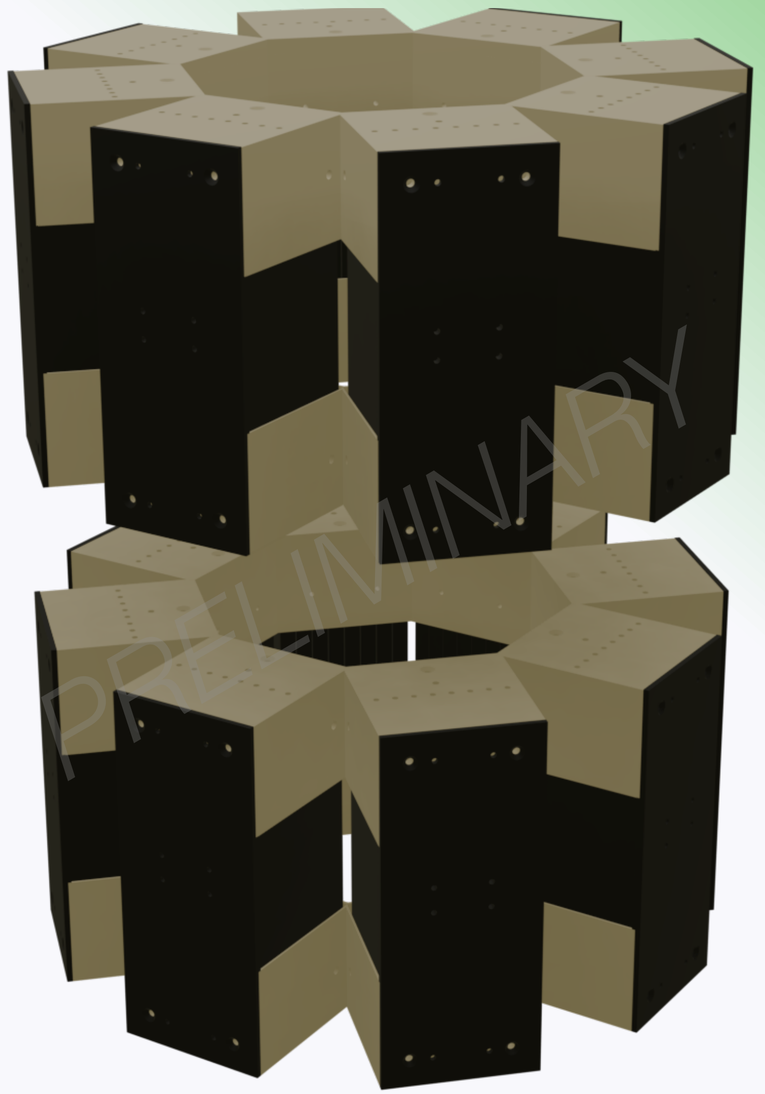


Figure: Two PDR arrangement in CRmuSR detector.

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*** $320 \times 300 \times 30\text{mm}^3$

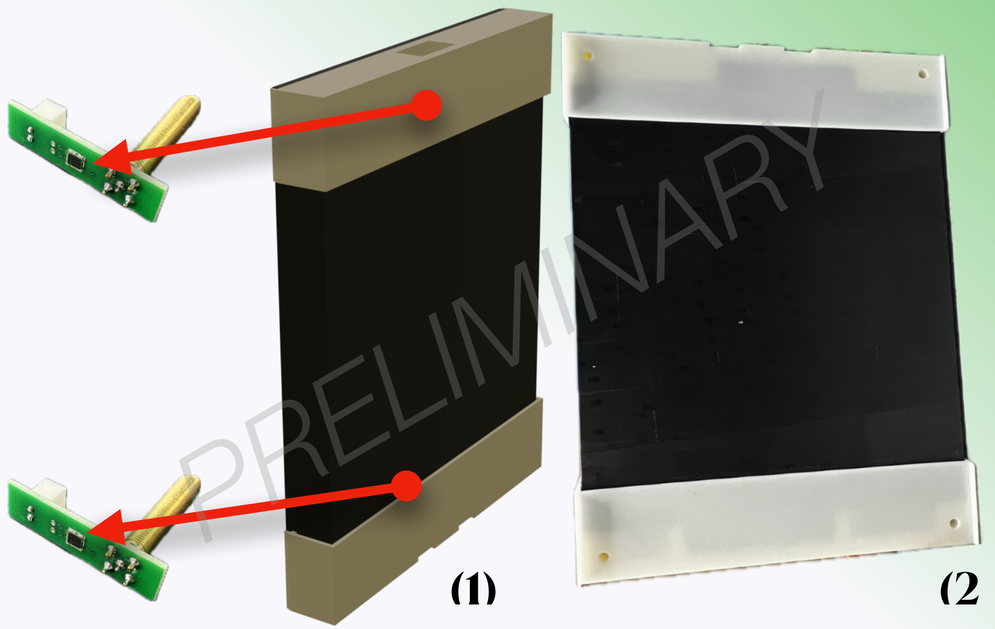


Figure1: (1)Design of a single unit of Veto; (2)Veto single unit finished.

Each Veto have 8 units(16 channels)

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

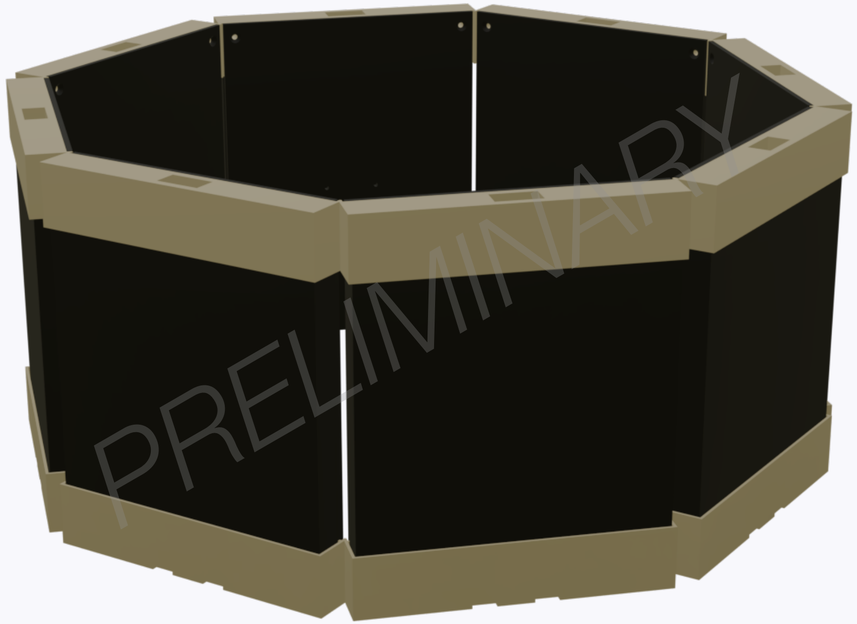


Figure2: Design of entire Veto modular (by Hesheng Liu and Mingchen Sun).

CRmuSR electronic and work flow

We use TOFPET2 ASIC chips as our electronic readout.

- TOFPET2 ASIC features
  - 64 independent channels
  - Max channel hit rate: 600 kHz
  - TDC time binning: 30 ps.
  - Dynamic range: 1500 pC.

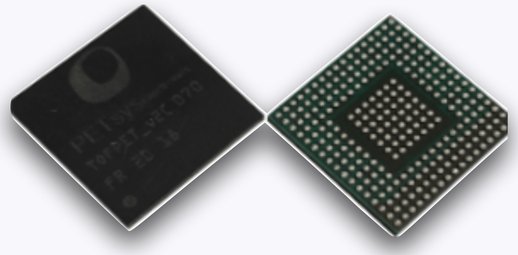
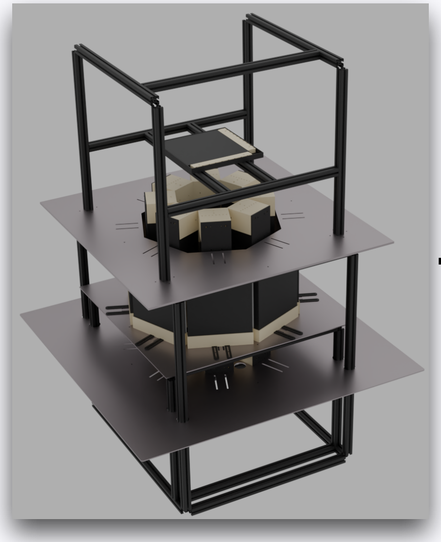


Figure: TOFPET ASIC chip.



Final design of CRmuSR

Current Signal

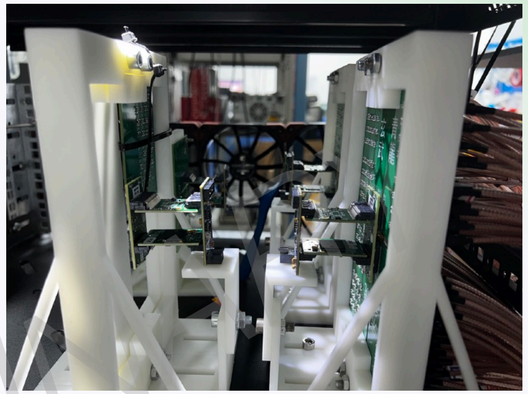


Figure: FEB modular and TFPET ASIC.

Digital Signal

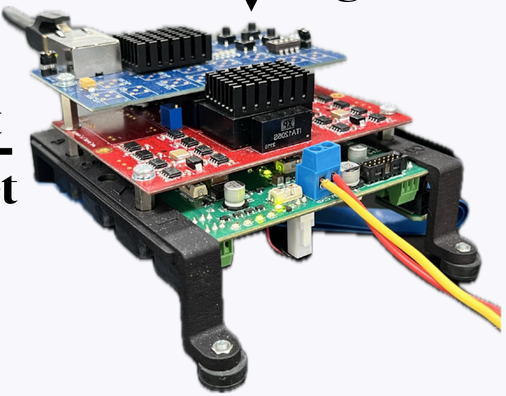
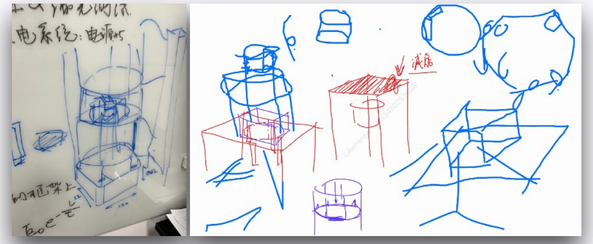


Figure: Mother Board

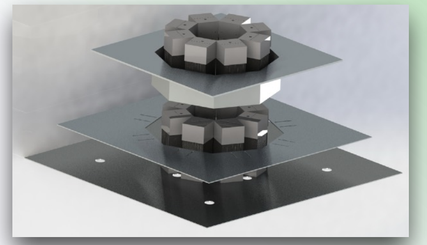
Gigabit Ethernet

Upper computer

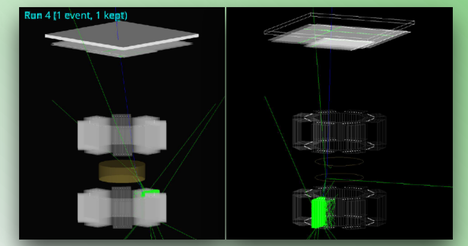
CRmuSR detector system



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

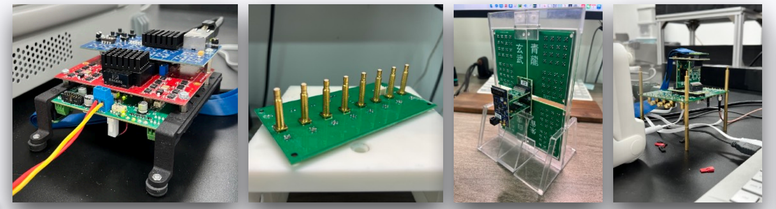


First design for 2 PDR

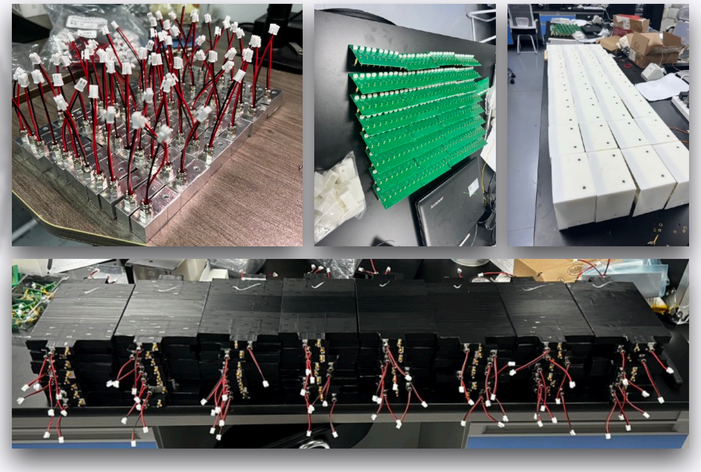


Signal and background simulation .
(Mainly by Aiyu Bai)

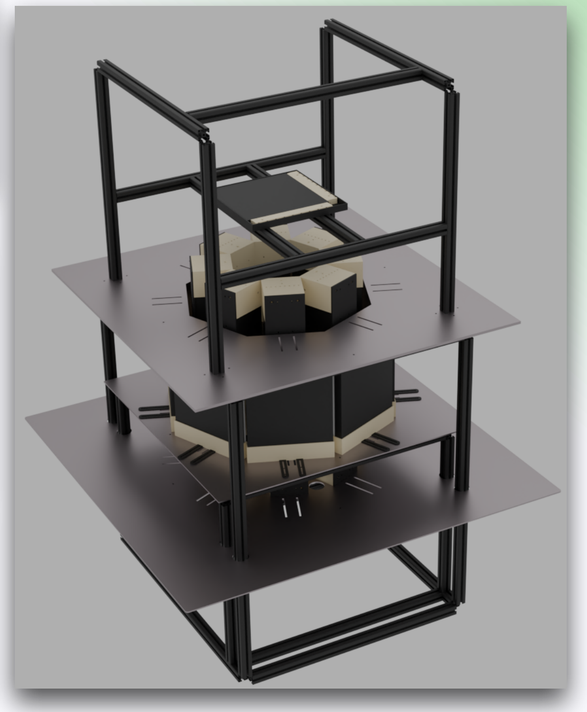
CRmuSR during data acquiring process.



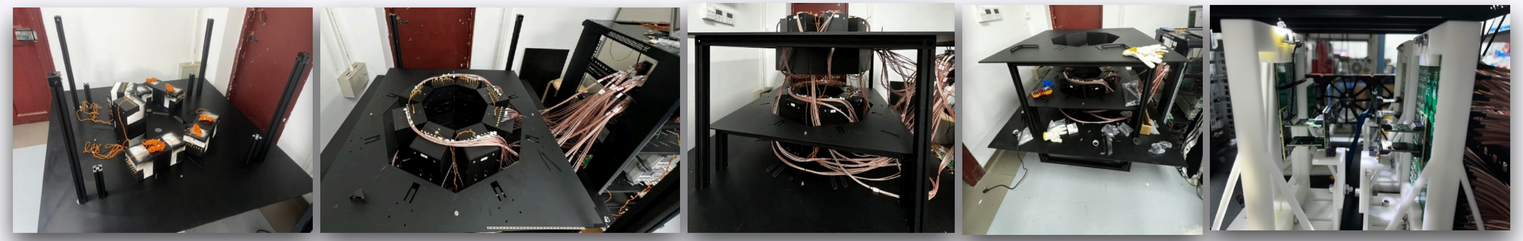
Develop and testing the electronic. (Mainly by Yi Yuan and Yu Chen)



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.

- ***Muon spin rotation signal,***
- ***Cosmic-ray muon stop and decay signal.***

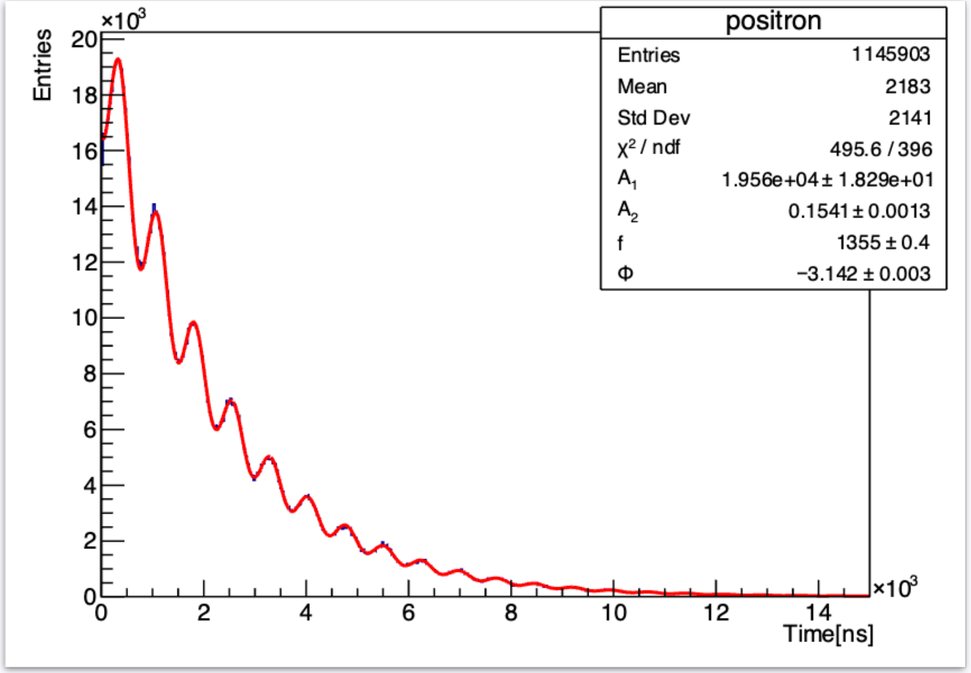
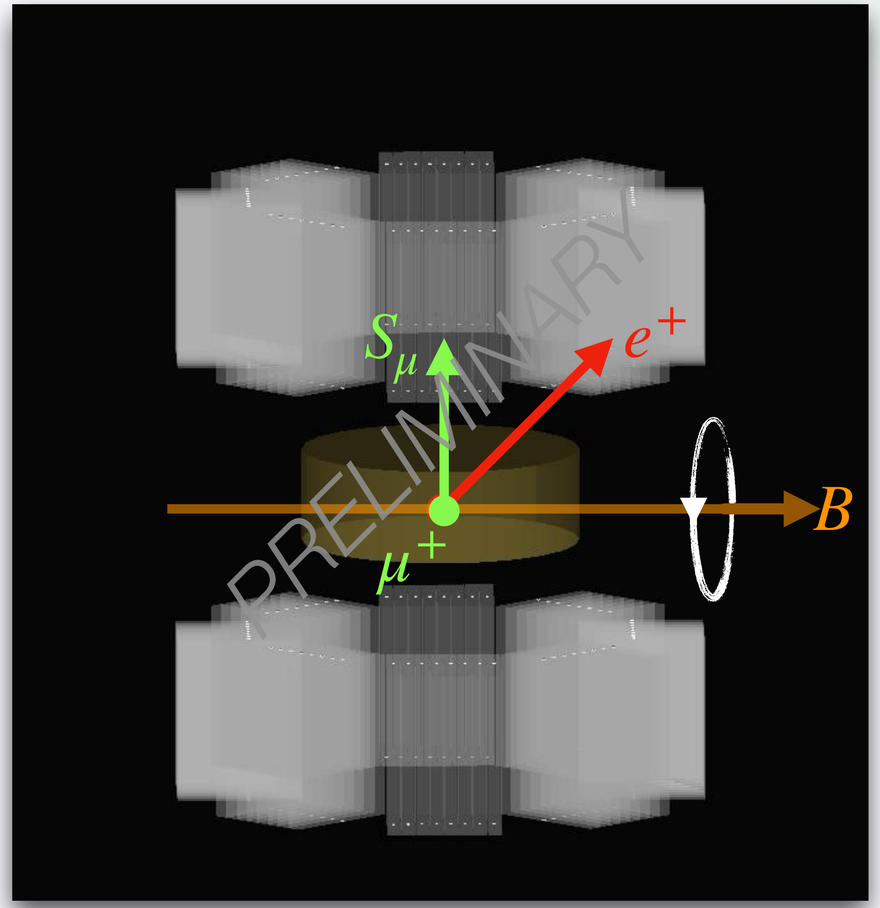


Figure: GEANT4 simulated muSR Spectrum $B_{sim} = 100 \pm 0.02$Gs.



GEANT4 simulation geometry of CRmuSR

Typical signal:

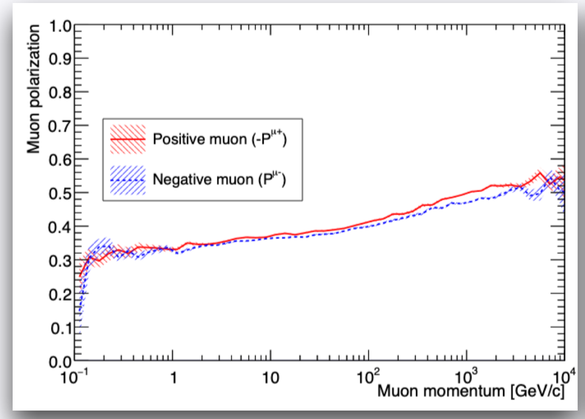
Michel electron decay from the muon precession in the magnetic field.

- $B_z = 100$Gs

CRmuSR Simulation

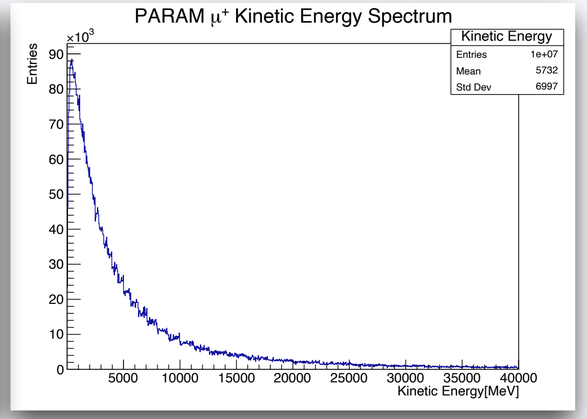
We use GEANT4 to simulate the detector respond of different events.

- *Muon spin rotation signal,*
- ***Cosmic-ray muon stop and decay signal.***



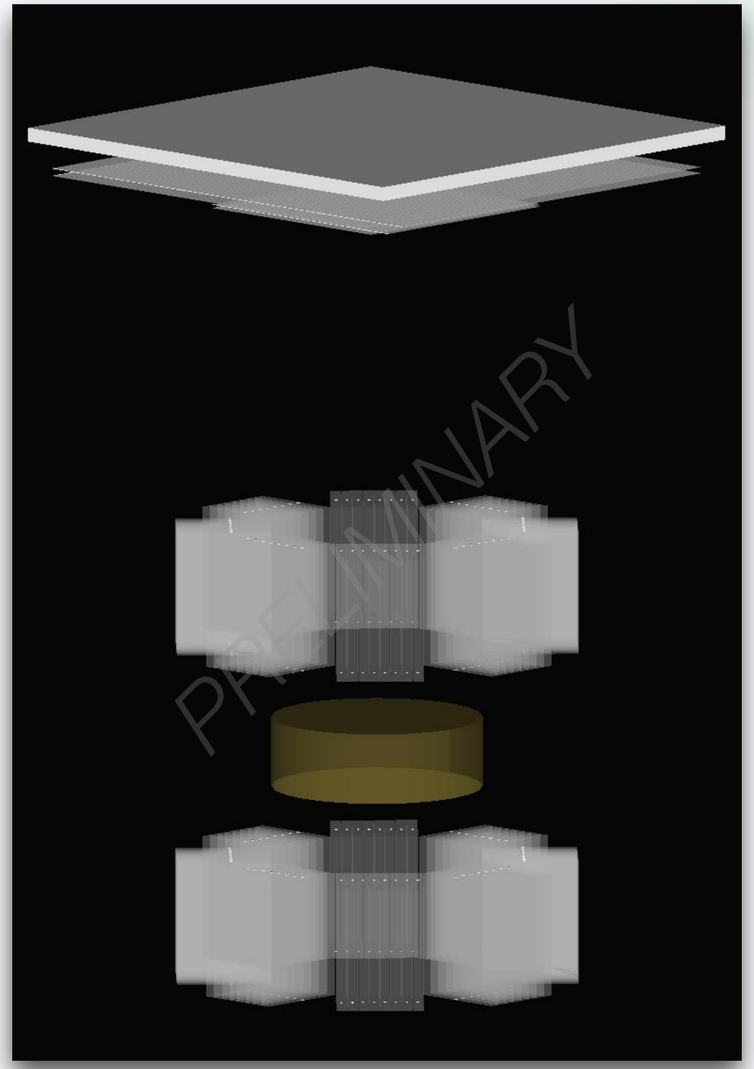
The expected polarization as a function of muon momentum based on Honda flux simulation.

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.



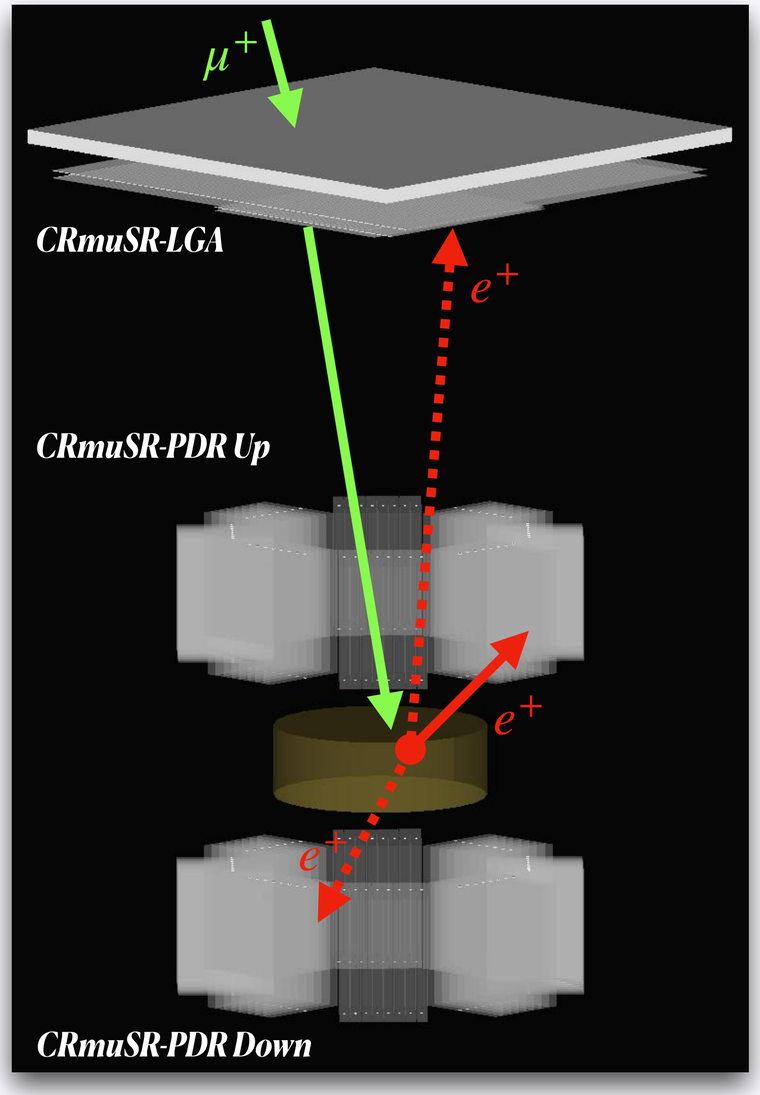
GEANT4 simulation geometry of CRmuSR

Typical signal:

Cosmic-ray muon

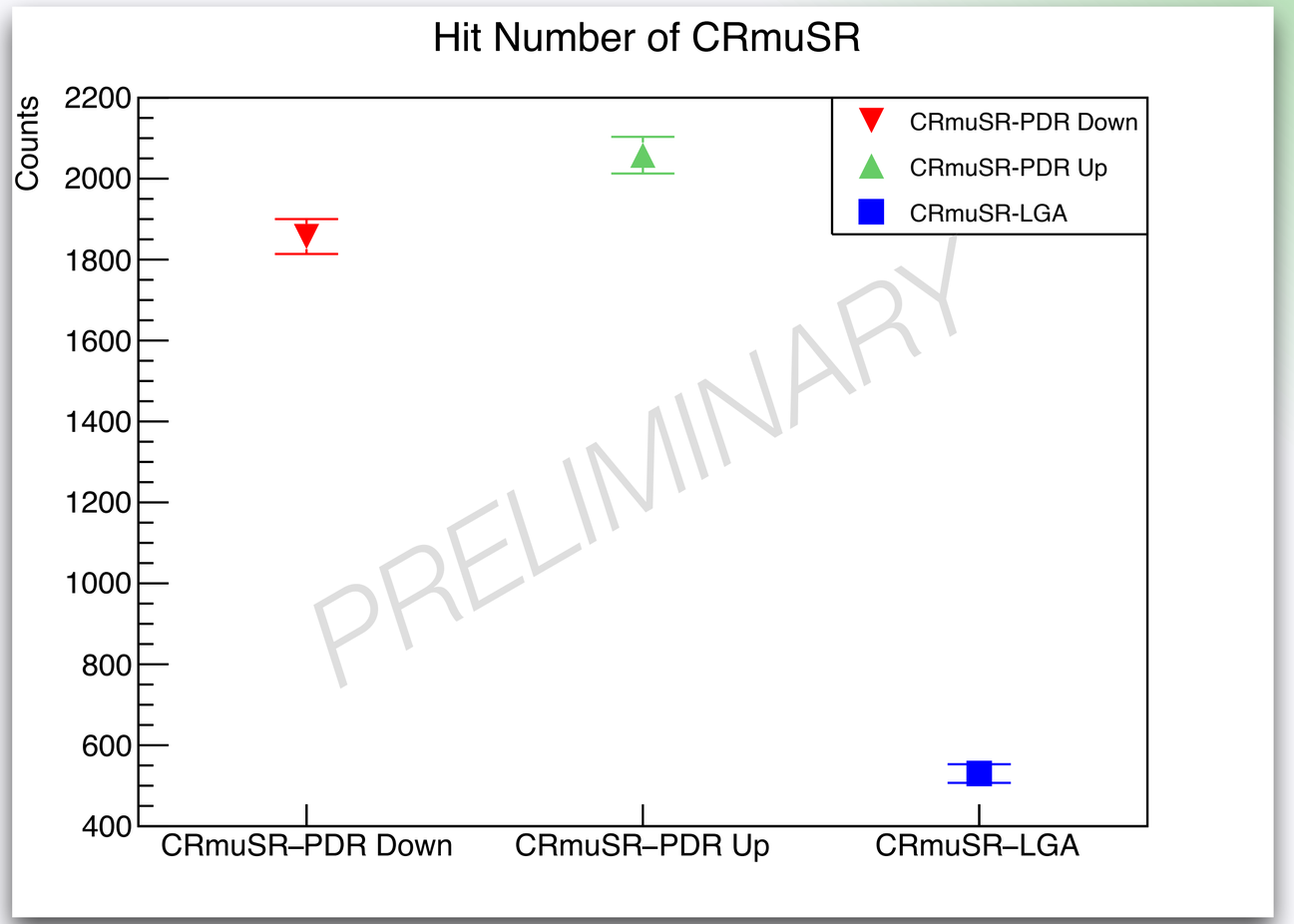
- *two layer of LGA* ($\vec{p}_\mu$ / $|\vec{p}_\mu|$)
- *stop in the target and decay*
- *two PDR* ($\vec{\sigma}$)

Decay Asymmetry of Cosmic-ray Muon



GEANT4 simulation geometry of CRmuSR

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



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

目录

Index

CRmuSR performance

Detector efficiency for cosmic-ray muon

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

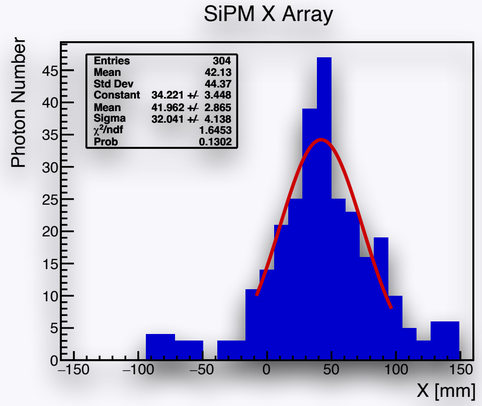
Total solid angle coverage >70%(for target)

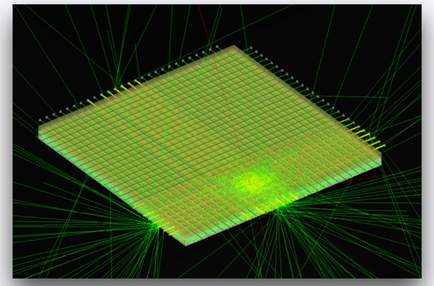
There are overlaps between modules.

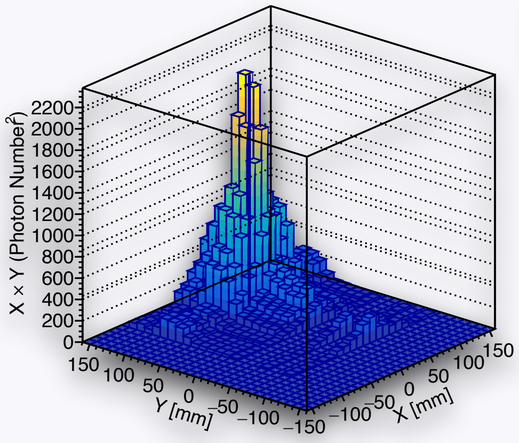
- ***40% (PDR),***
- ***>29% (LGA),***
- ***>30% (Veto).***

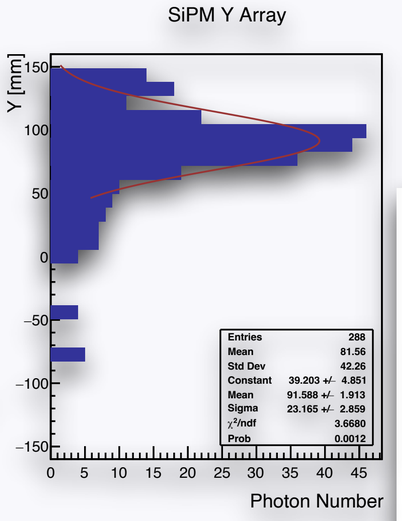
Azimuth angular resolution of PDR better than 6°.

Spatial resolution is about 3mm.



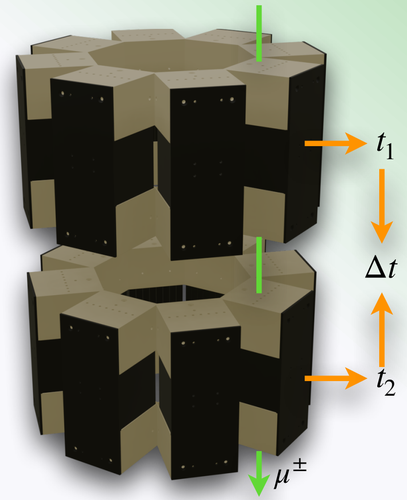




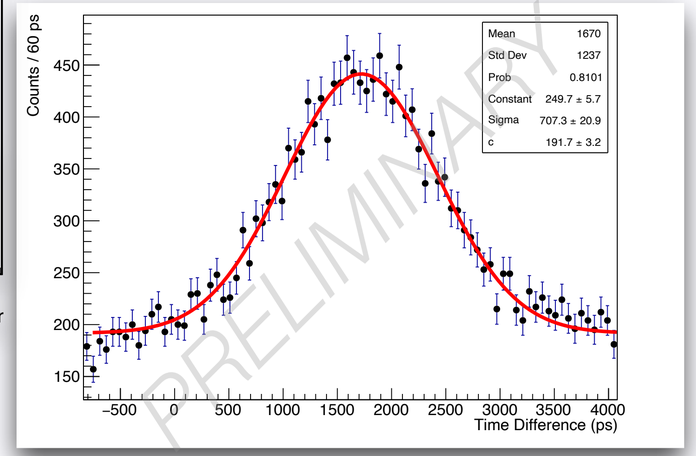


Simulation results for single layer of LGA.

Time resolution of PDR is about 1ns.

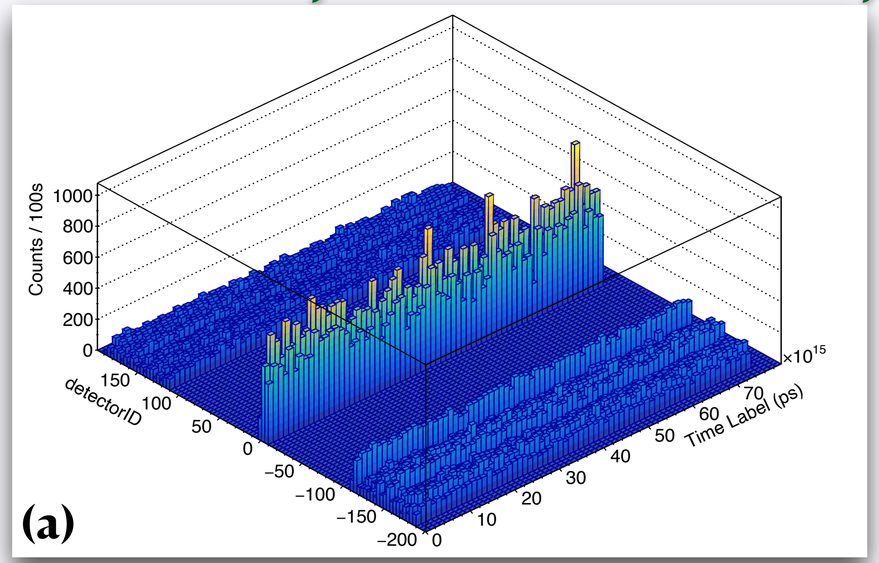


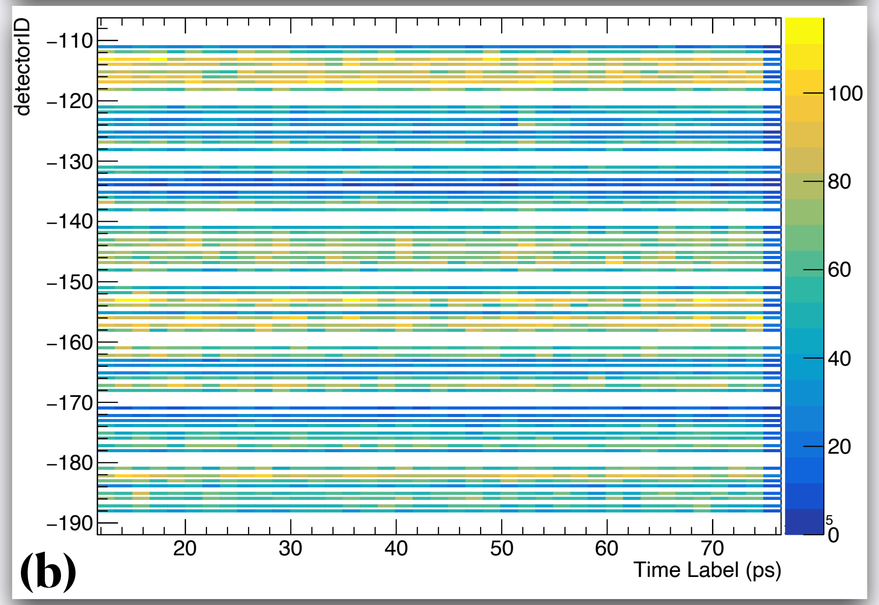
Using penetrate cosmic-ray muon test PDR time resolution.



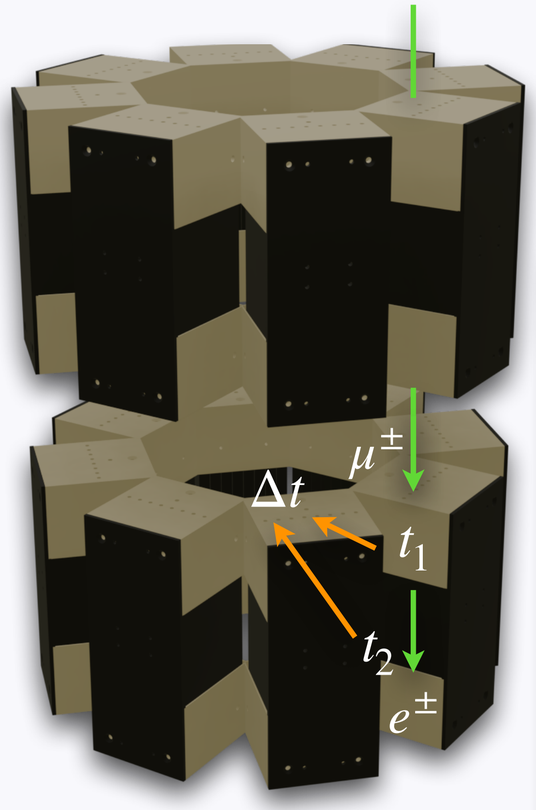
Preliminary analysis for time resolution of PDR.

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.

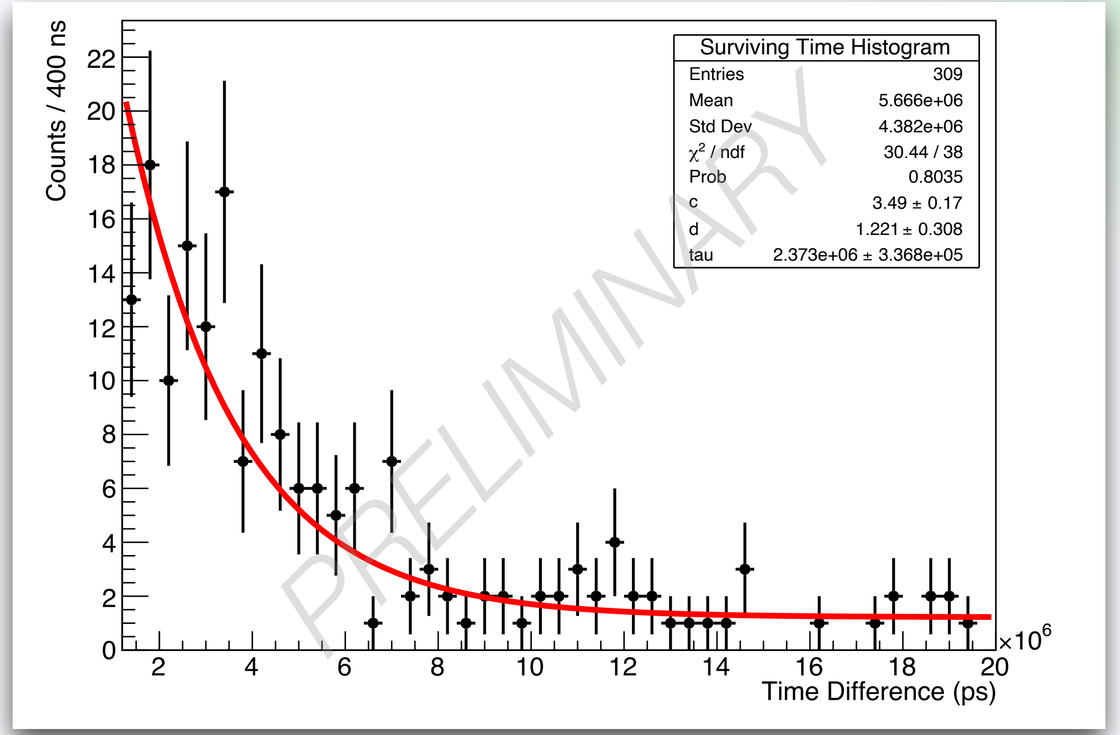


Lifetime of cosmic-ray muon decay in PDR.

Using Coincident time difference Δt

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

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

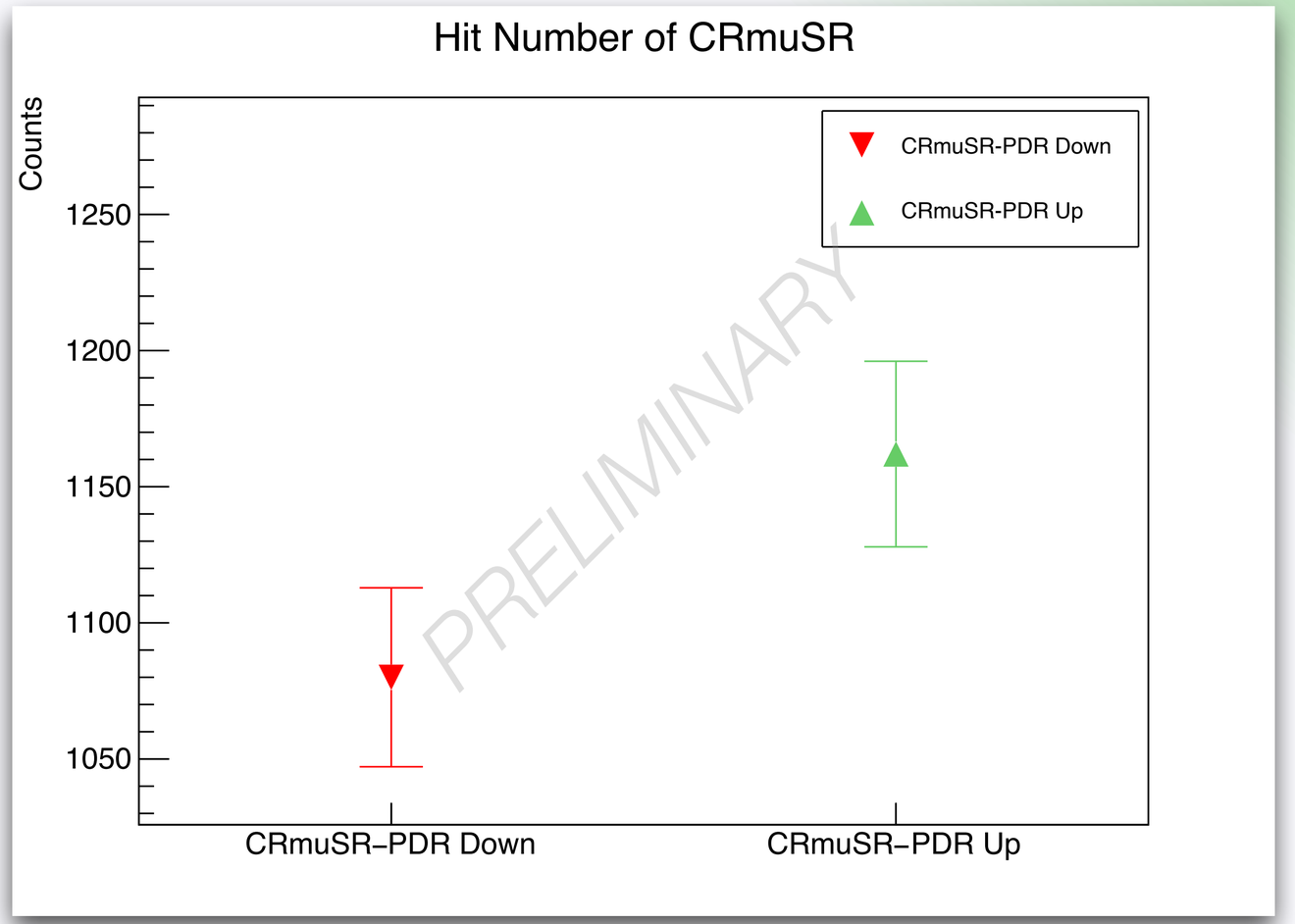


Preliminary analysis for cosmic-ray muon lifetime with PDR.

Decay Asymmetry of Cosmic-ray Muon

CRmuSR testing target in the present.

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



Rough analysis of Michel electron hits in CRmuSR experiment.

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

目录

Index

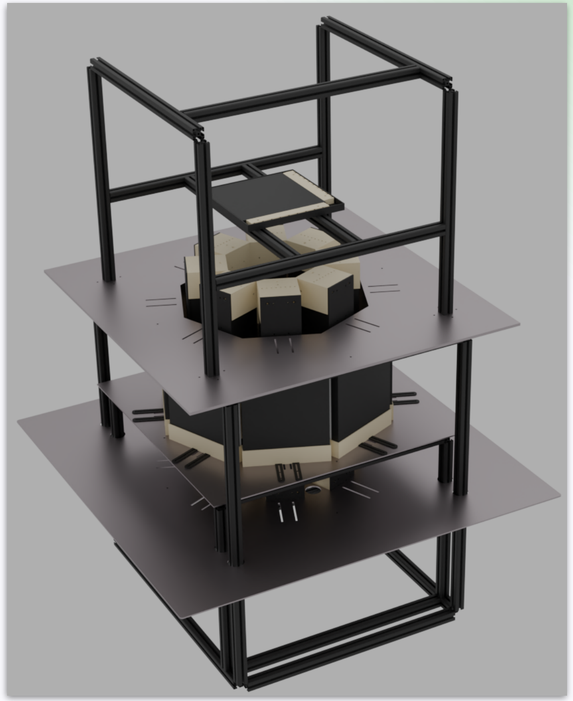
Future plan

Data Acquiring for CRmuSR

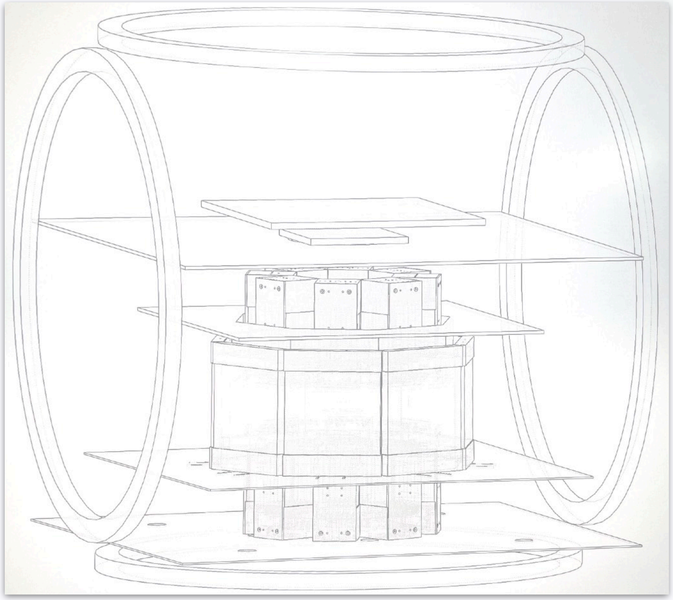
- Complete the installation of the LGA,
- complete the design and the set up for target,
- continue the data acquiring and the analysis of cosmic-ray muon.

Upgrade the CRmuSR to CRmuSR-II

- Upgrade the electronic for high intensity muon source,
- Upgrade the physical environment (no magnetic field → Zero field, low temperature environment, ...),
- Complete muSR spectrum analysis program for the detector system.

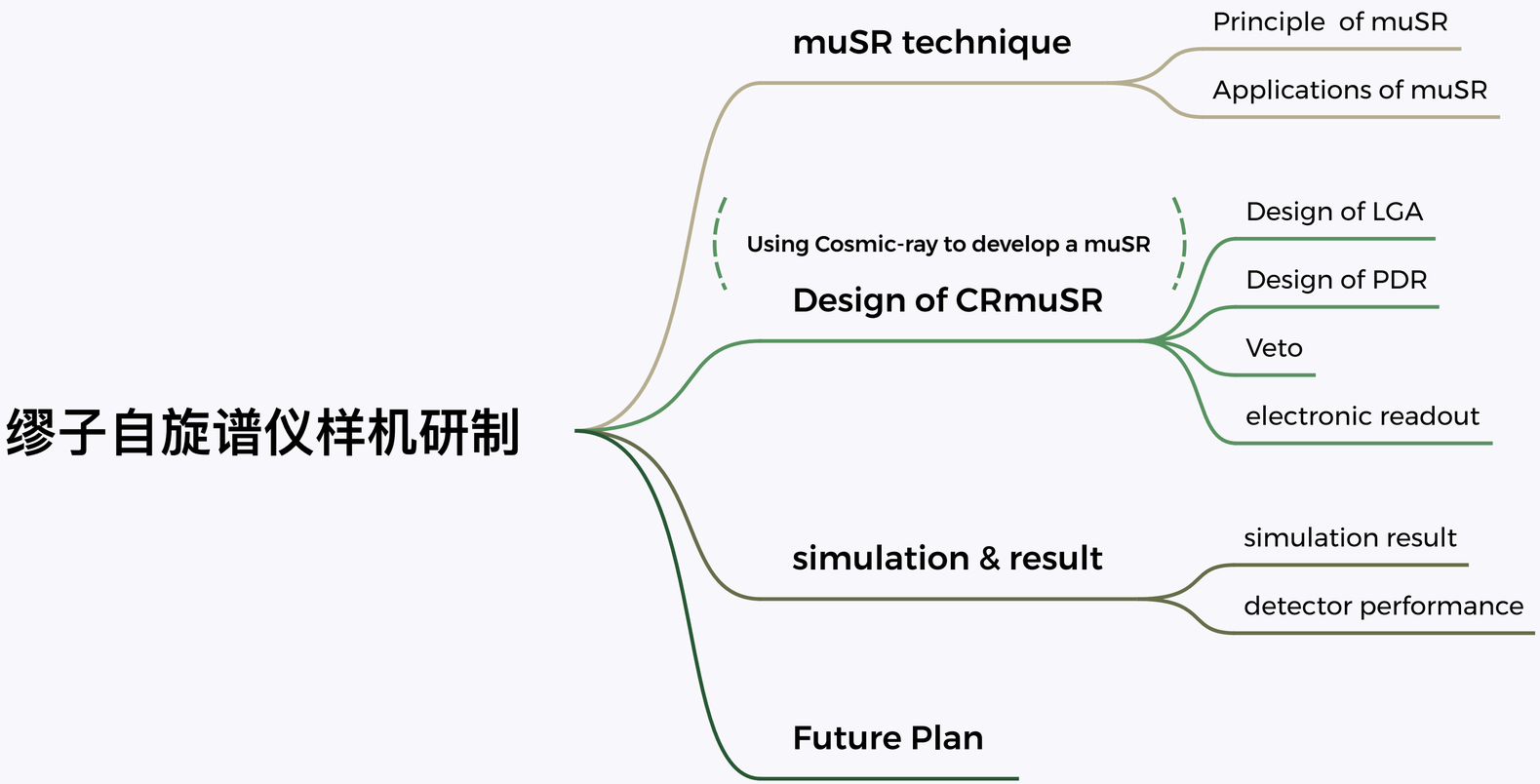


Final design of CRmuSR



Rough design of CRmuSR-II

Summary


缪子自旋谱仪样机研制
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electronic readout
simulation & result
simulation result
detector performance
Future Plan

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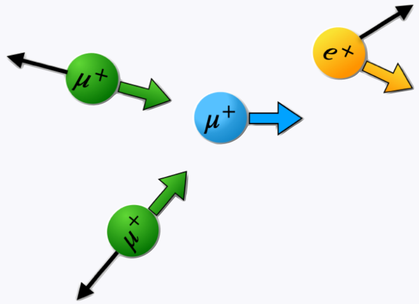
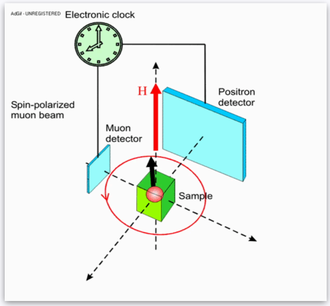
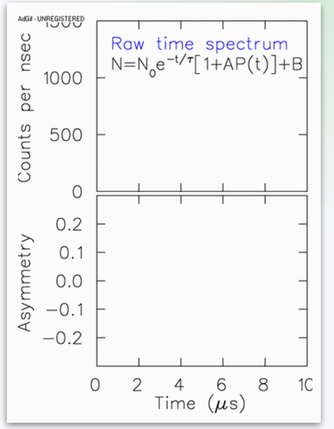
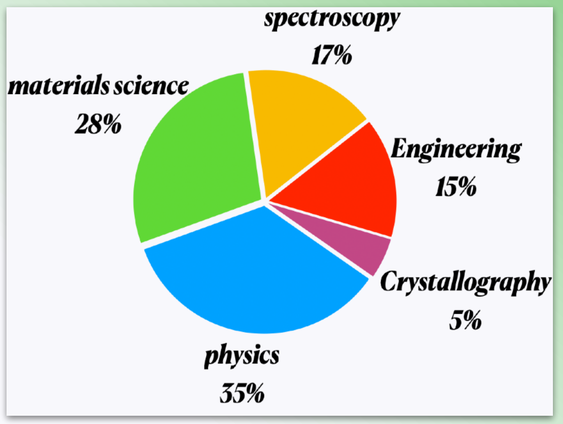
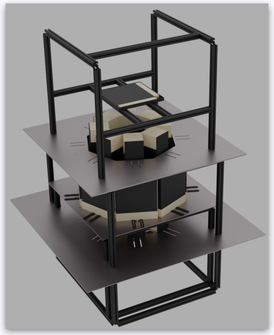


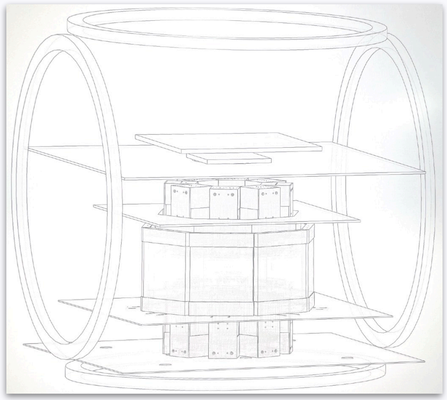








缪子自旋谱仪样机研制



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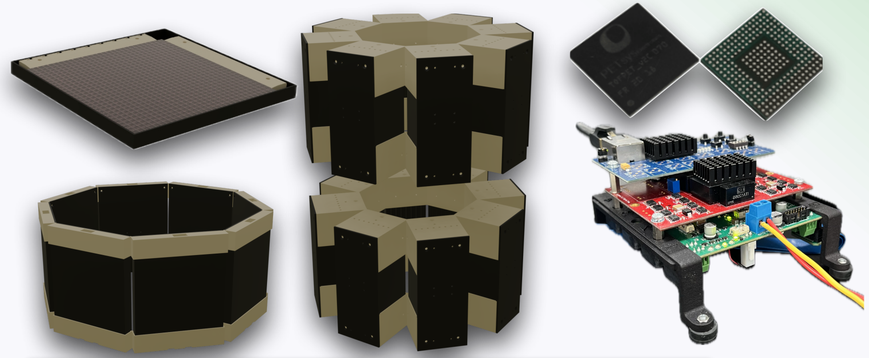
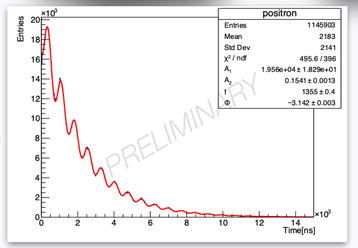
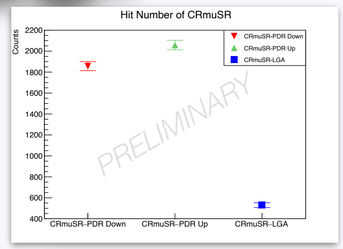
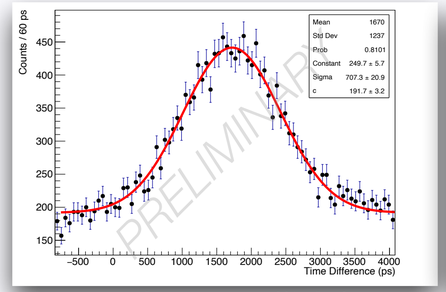


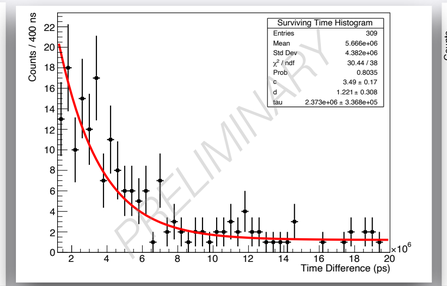
- simulation & result
  - simulation result
  - detector performance

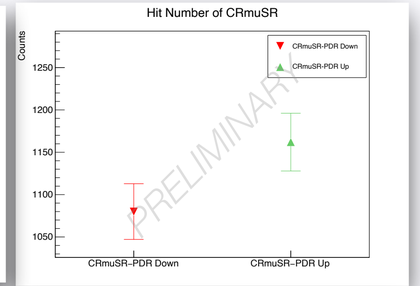




- Future Plan







中山大學 物理学院

SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS

Thanks!

Welcome Collaborations!