中山大學 SUN YAT-SEN UNIVERSITY

物理学院 SCHOOL OF PHYSICS

Cosmic Ray Muon Polarization to Facilitate Atmospheric Neutrino Physics

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SYSU MuOn and Optical TomograpHy

100 YEARS SPIN 2025

26th International Symposium on Spin Physics

A Century of Spin

arXiv:2505.13877

SMOOTH

- ***Muon Spin Polarization***
- ***How cosmic ray muon polarization measurement facilitates atmospheric neutrino physics?***
- ***Cosmic Ray Muon Polarization Detector (CRmuSR)***
- ***Summary and outlook***

- **Muon Spin Polarization**
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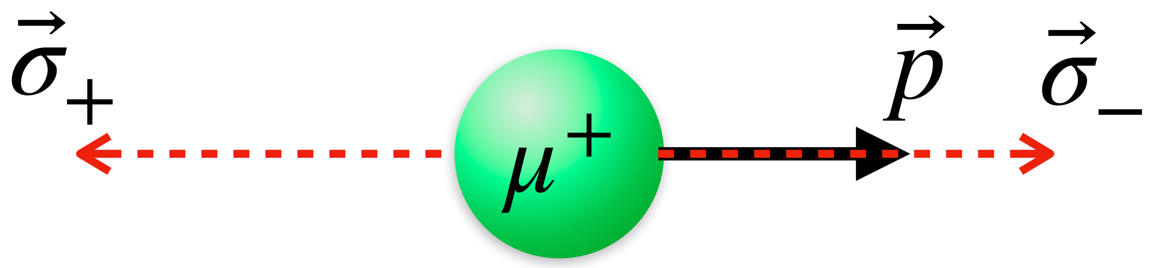
Muon Spin Polarization

Muon Polarization $P_\mu = \vec{\sigma} \cdot \dfrac{\vec{p}}{|\vec{p}\,|}$

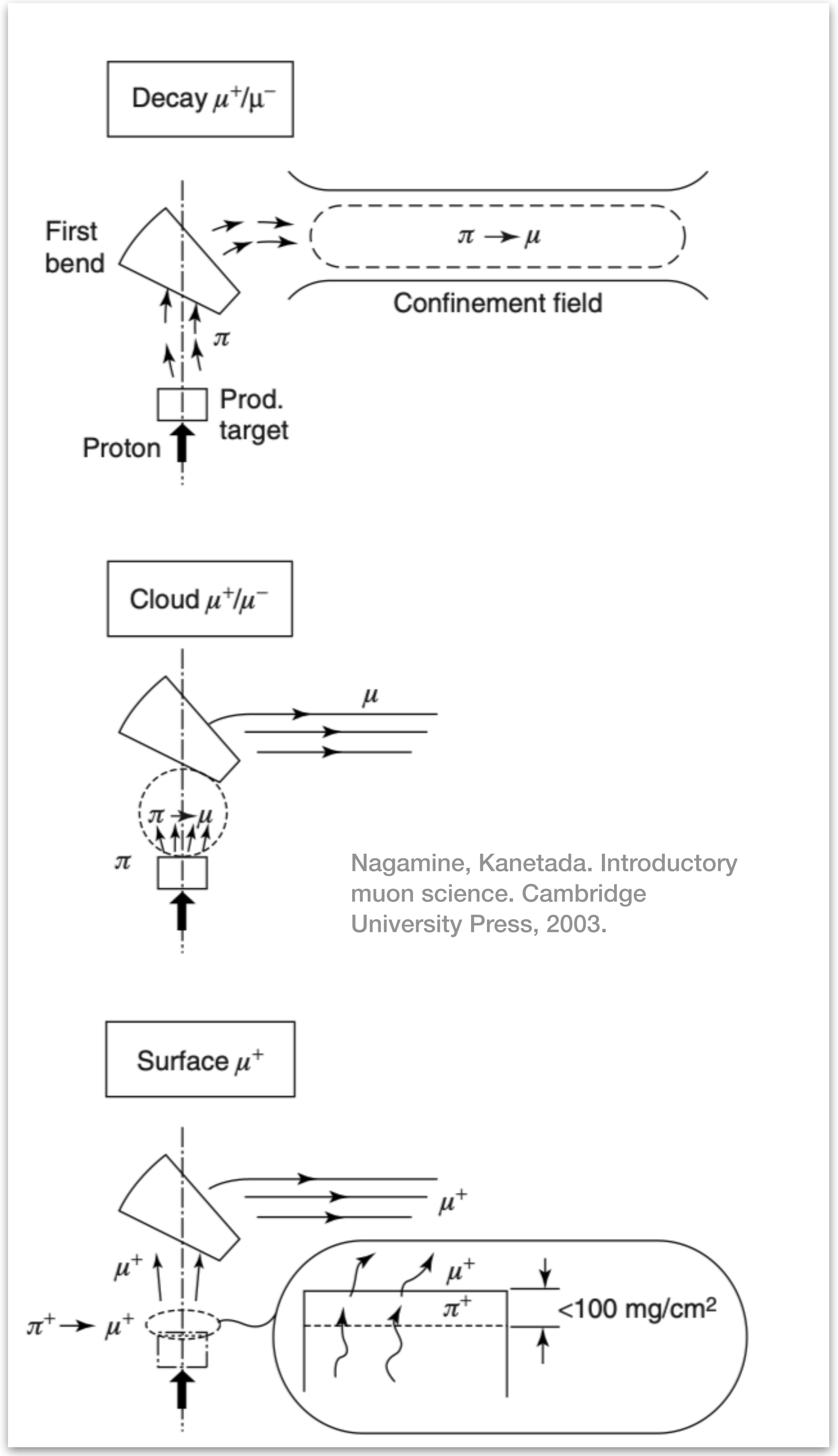
- **Accelerator Muon Beam**

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

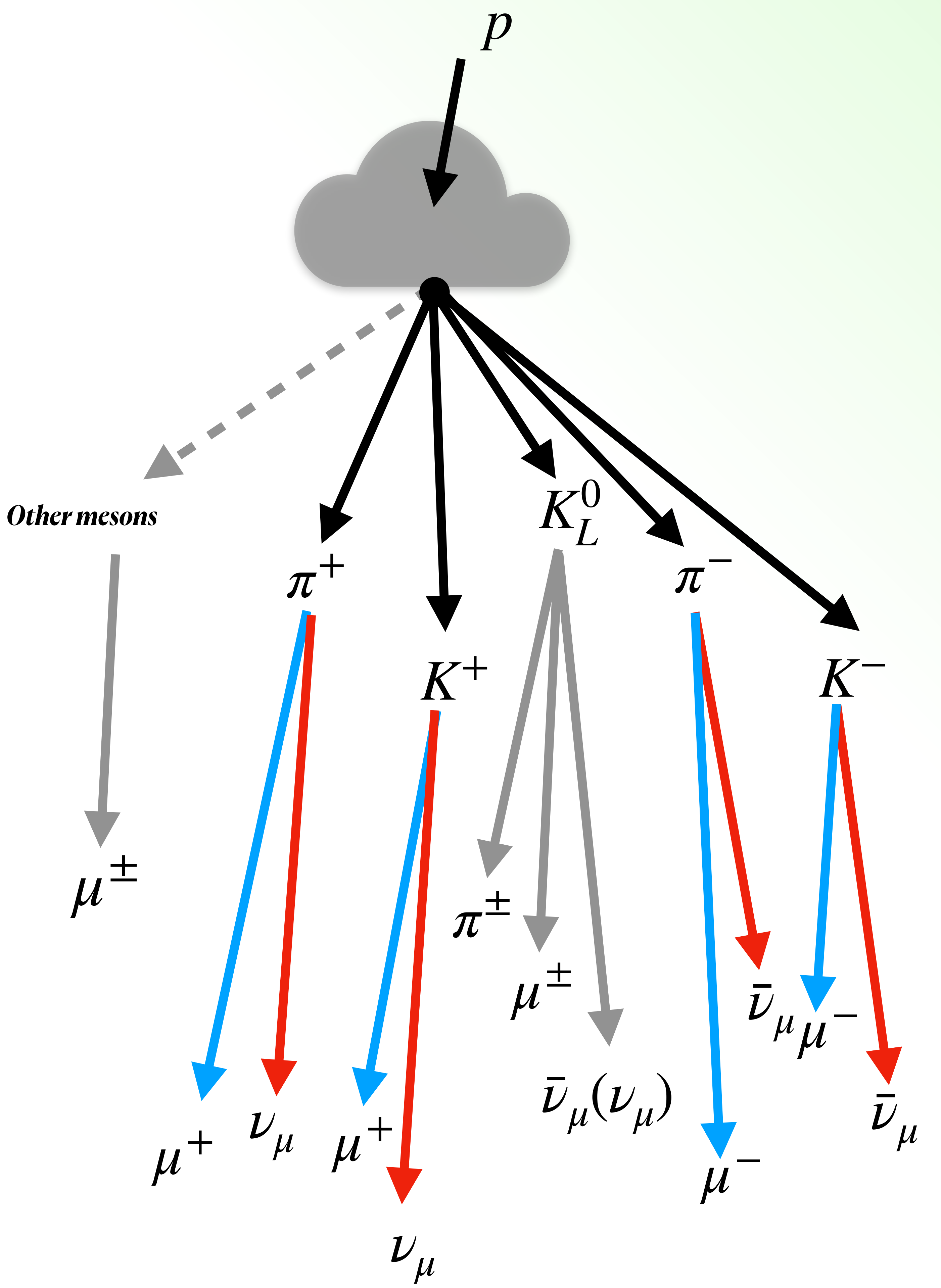


- **Cosmic-ray Muon Multi-production processes**

$$\begin{cases} \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K_L^0 \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu) \end{cases}$$



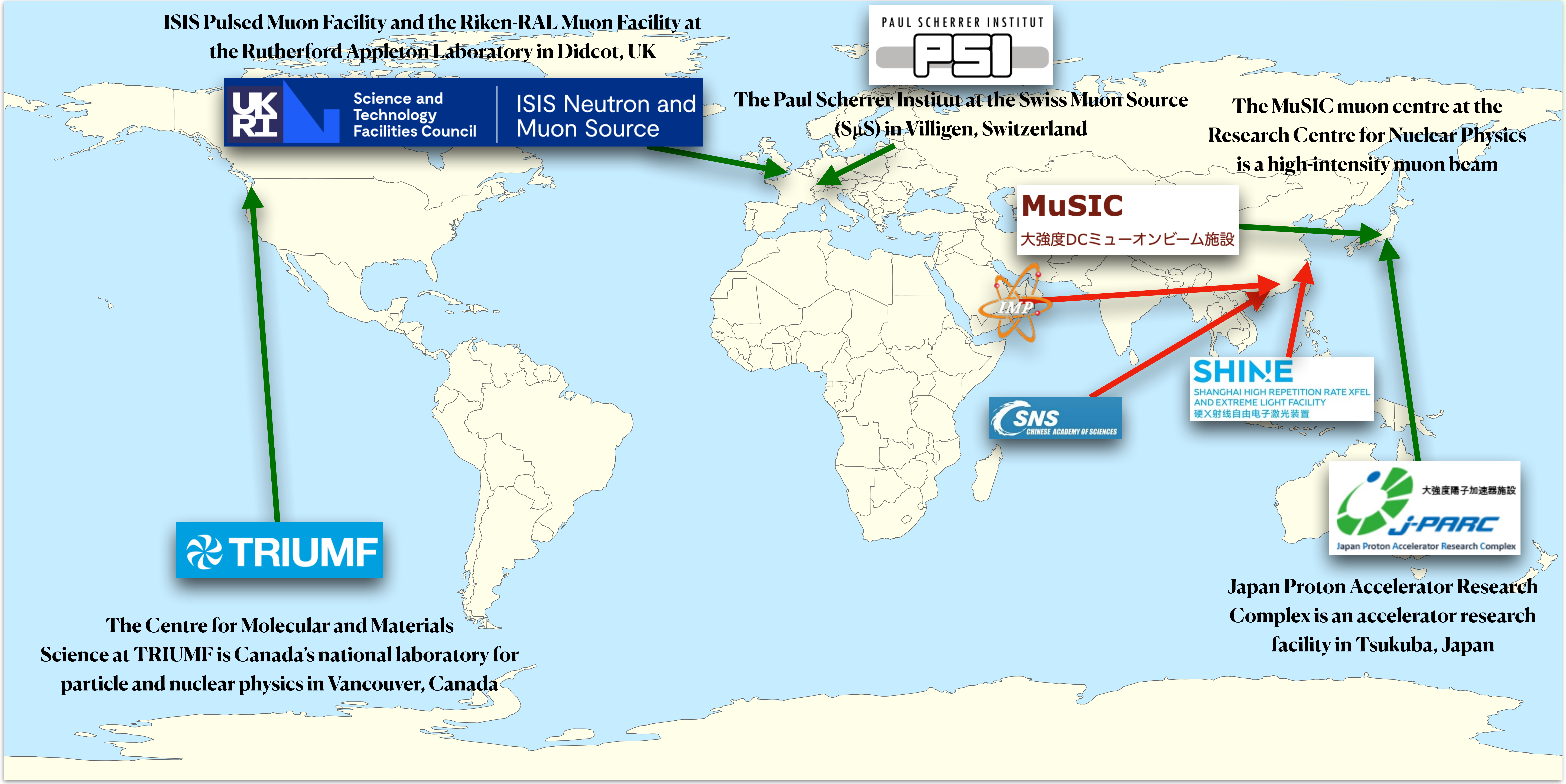
Muon produced by accelerator.



Production of cosmic-ray muon.

Cosmic-ray Muon should have a complicated nature polarization property.

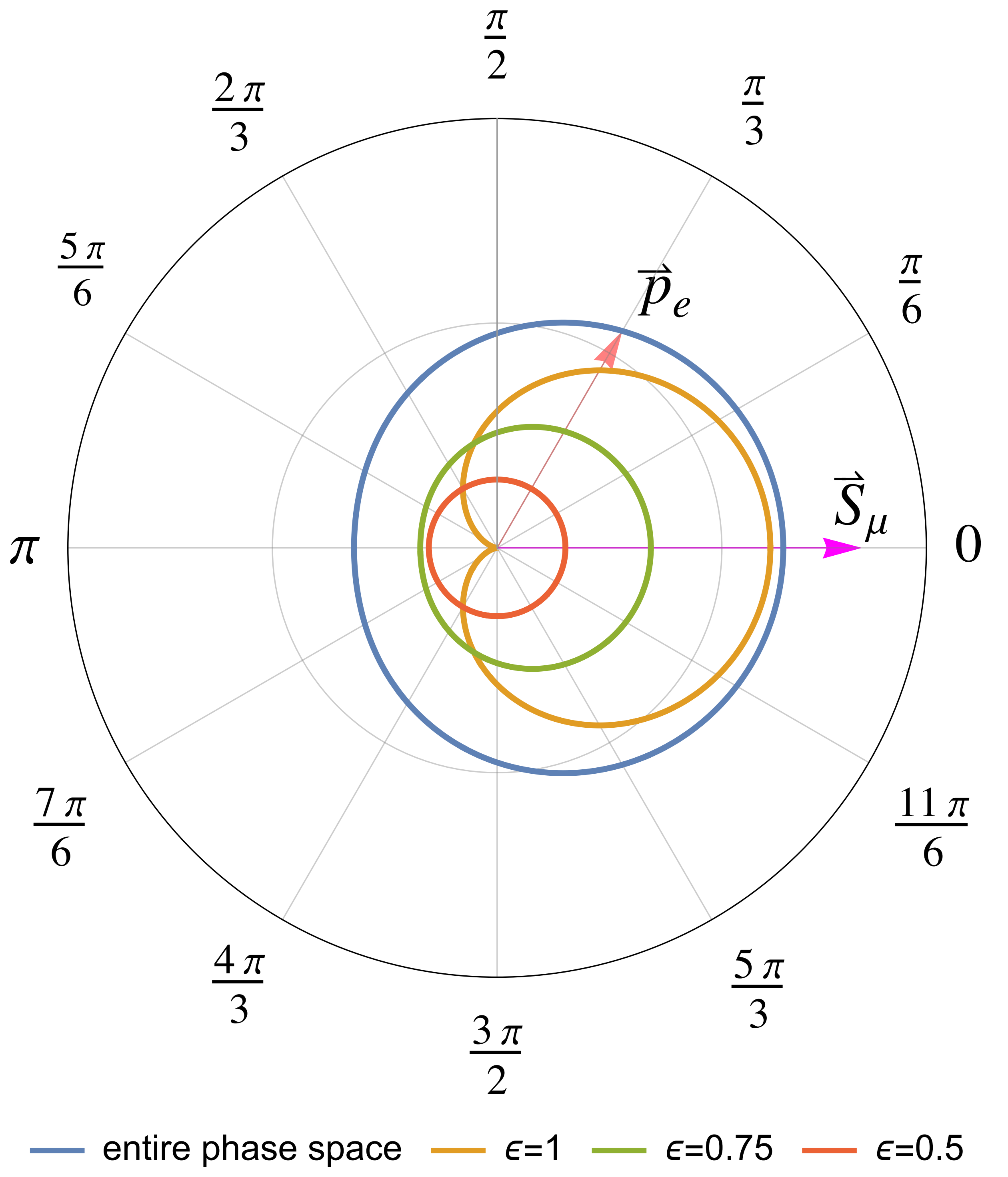
Accelerator Muon Beamline Around the World



Muon Polarization in Frontier Experiments

Muon Polarization →Michel electron distribution

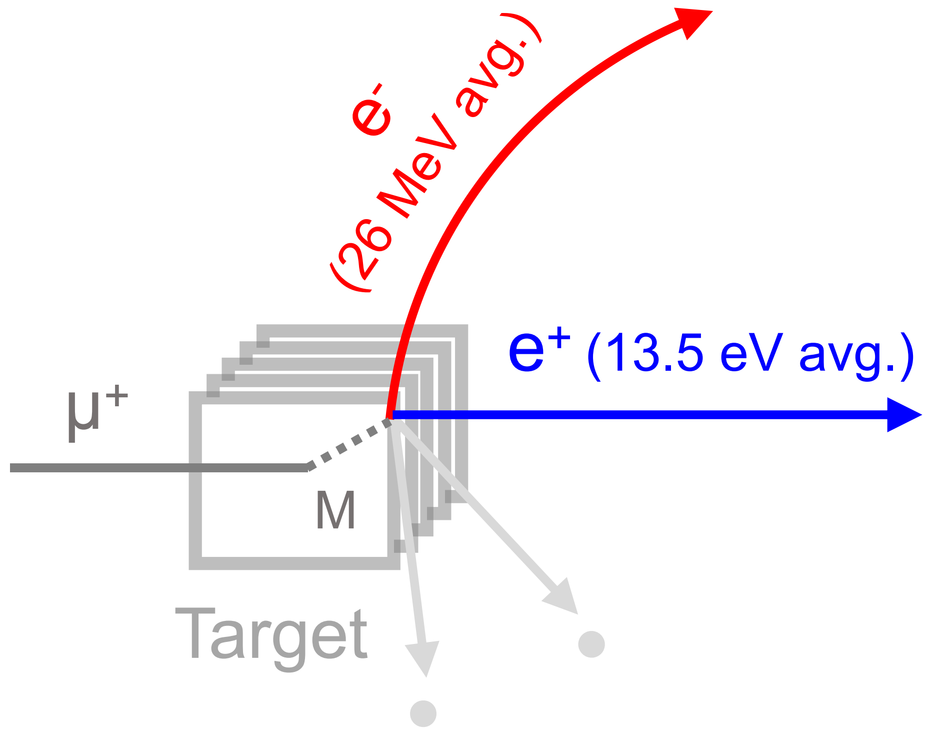
$$N_{\text{Michel}}(E_e) \propto 1 + \frac{1}{3} P_\mu \cos\theta_e$$



Michel electron spatial distribution dnder different ϵ

Mu2e *Mu3e* *MEGII*

Muonium-to-Antimuonium Conversion Experiment

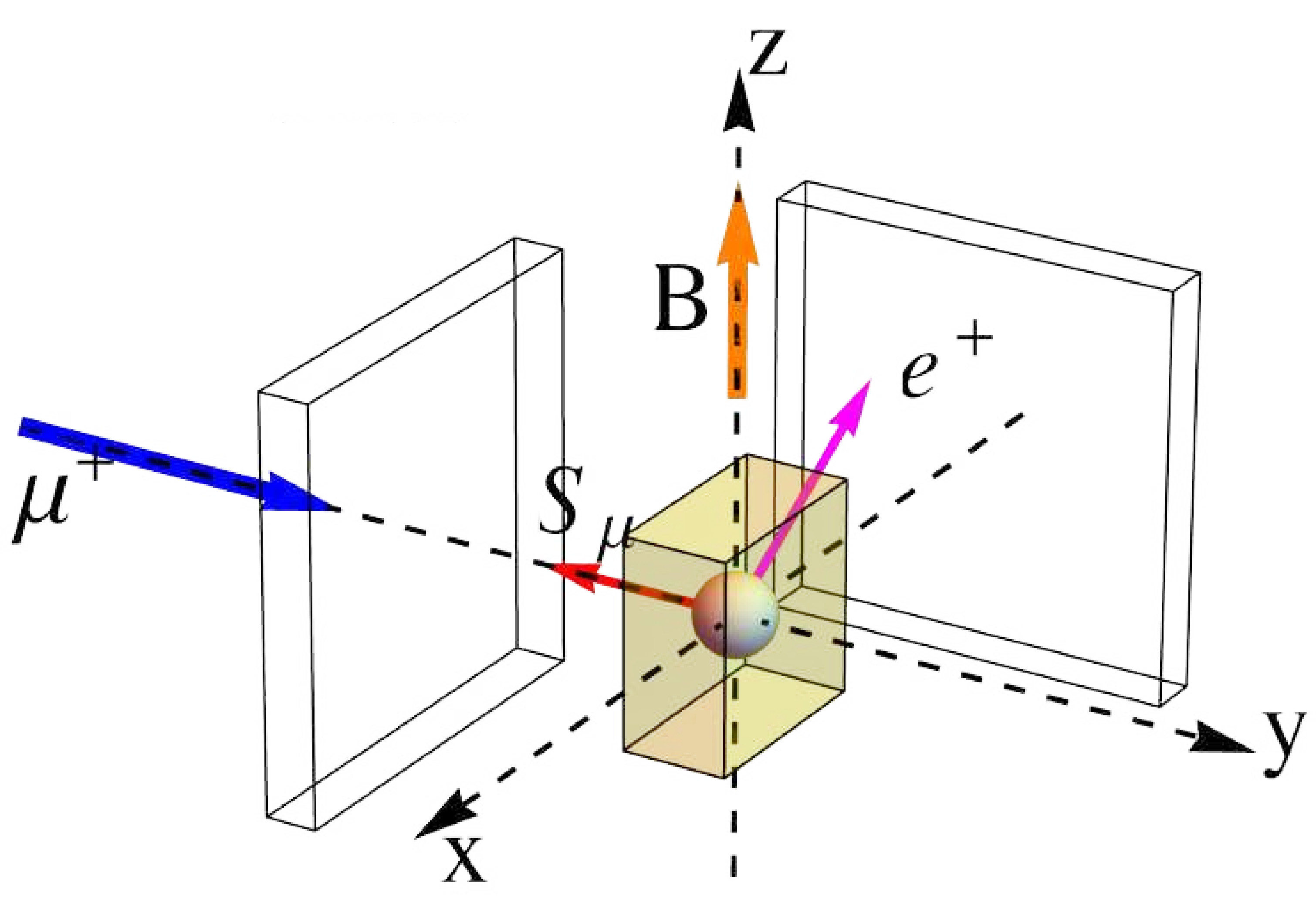


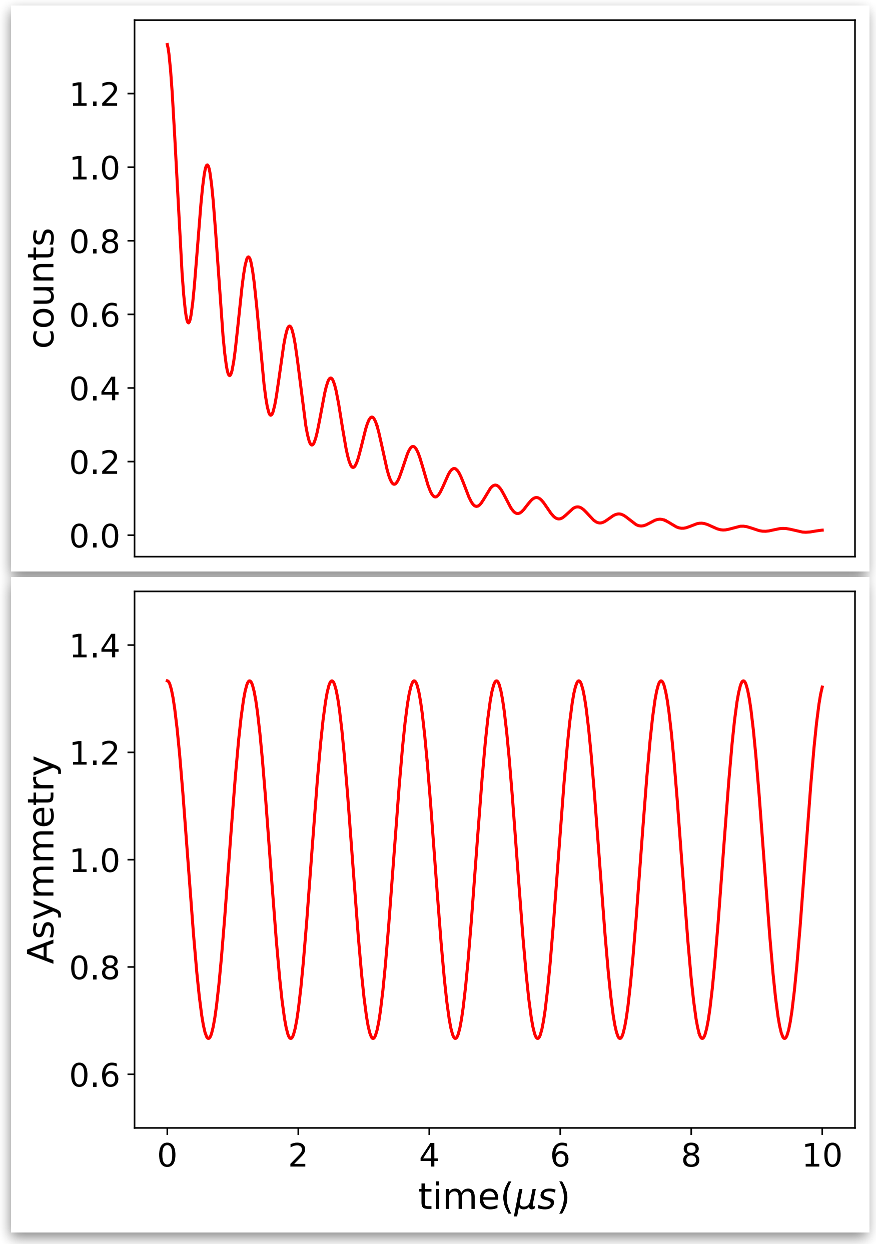
Michel electrons from muon decay constitute a significant background

Muon polarization calibration is essential on improving the accuracy for frontier experiments.

Muon Polarization in Applied Technologies

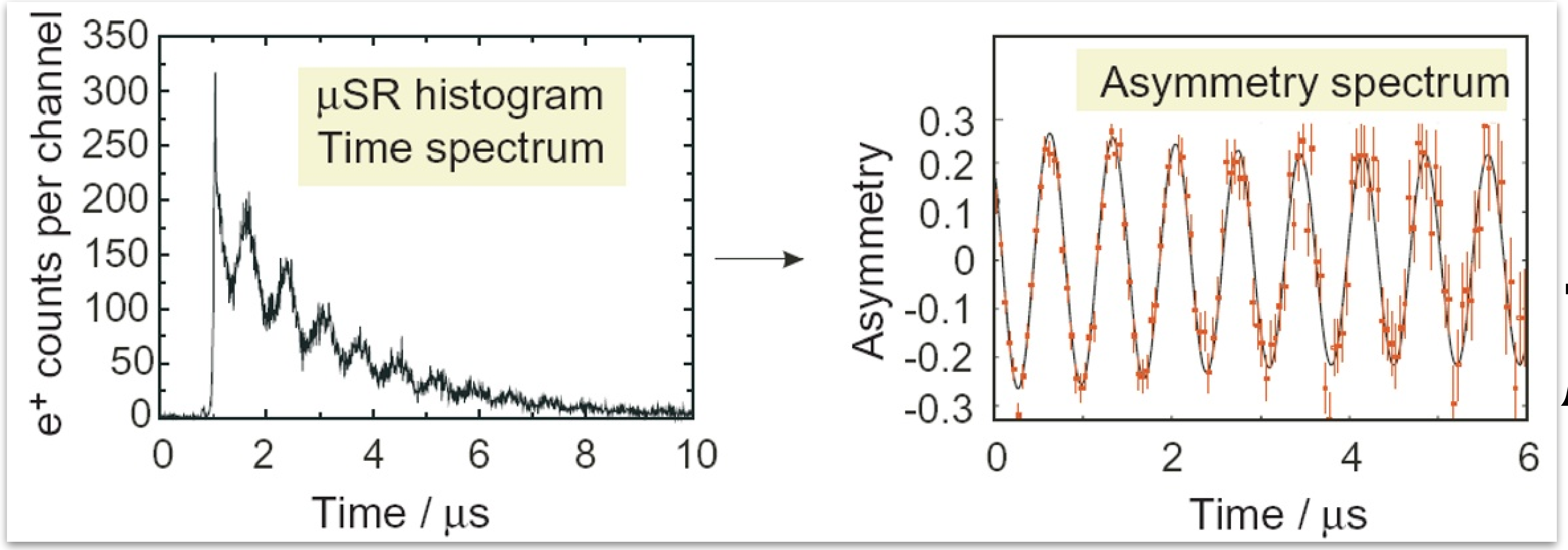
Muon spin rotation/relaxation/resonance (μSR) is an important application technology for muon beamlines.





μSR accuracy depends on

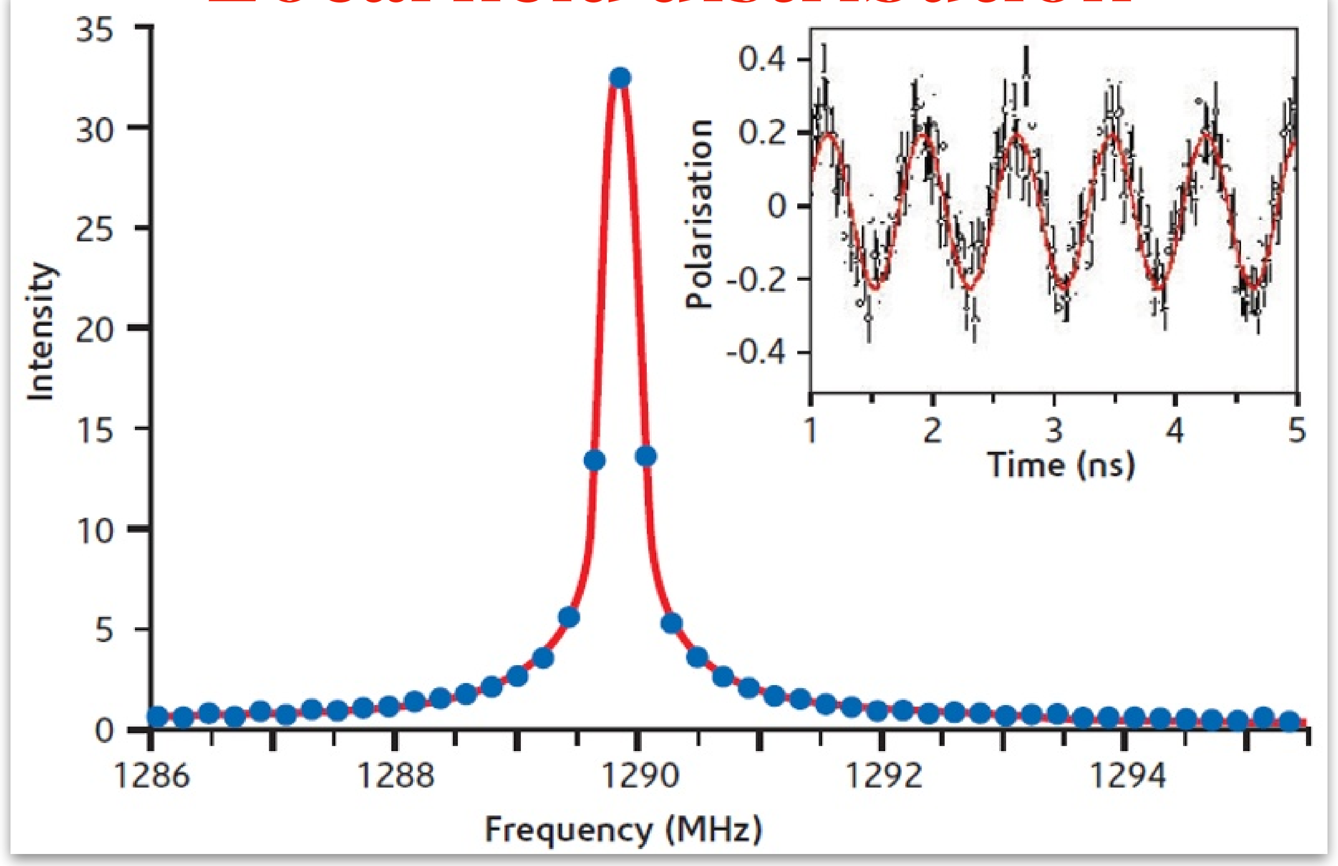
- ***Polarization of the muon beamline***
- ***Time resolution of μSR spectroscopy***
- ***Detection efficiency of μSR detector modules***



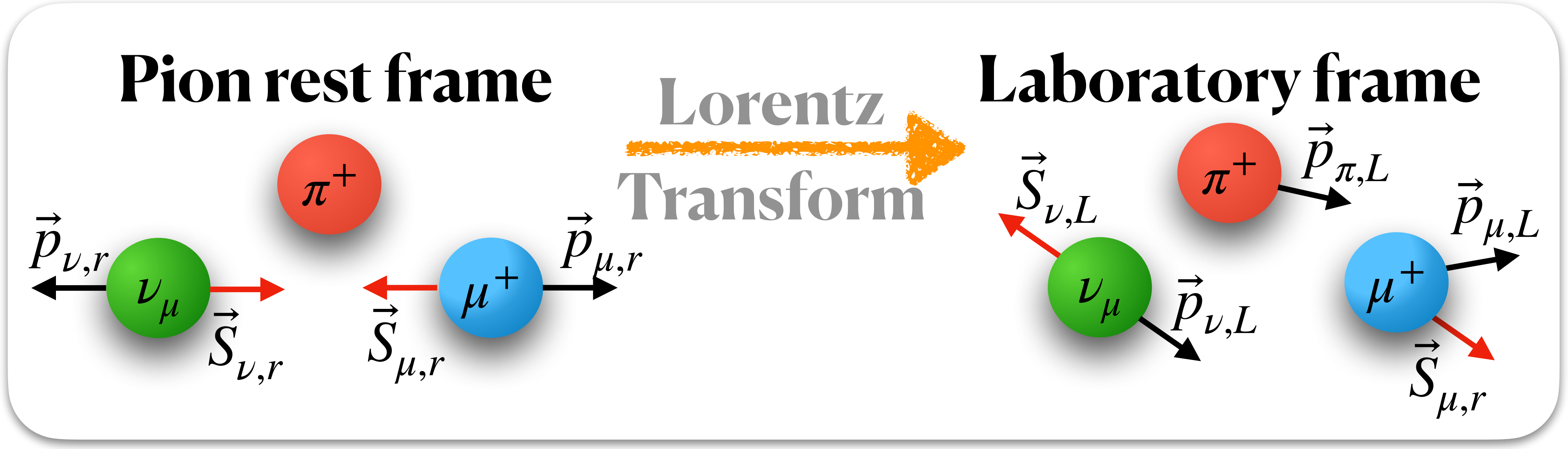
Fourier transformation

Maximum entropy analysis

Local field distribution



Cosmic-Ray Muon Polarization



$$\mathcal{P}_\mu = \vec{\sigma} \cdot \frac{\vec{p}}{|\vec{p}|}$$

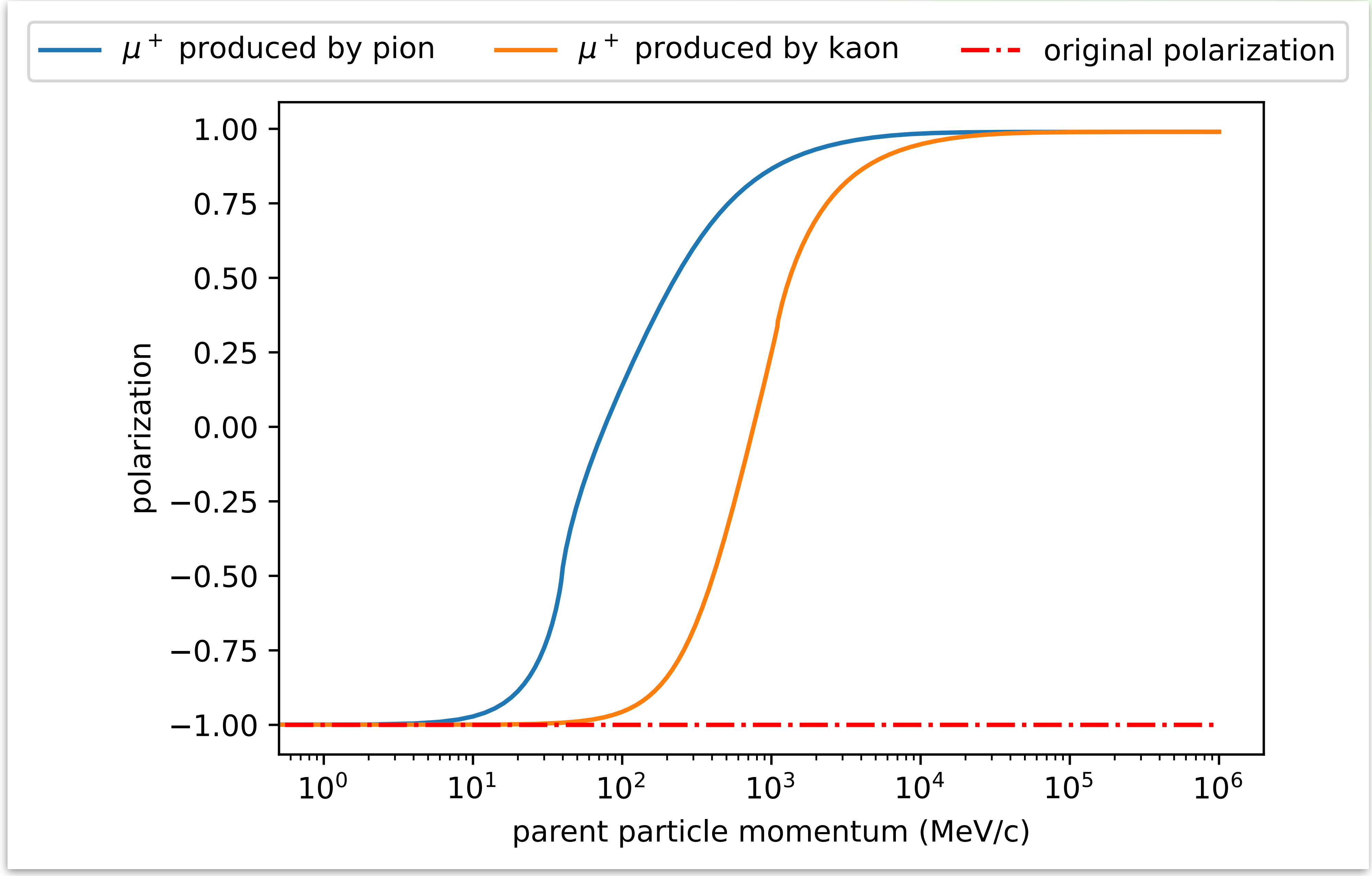
$$\mathcal{P}_\mu = \frac{\cos\alpha\sqrt{1+R_p^2} + R_p + g(\alpha, R_p, R_m)}{\sqrt{2R_p\cos\alpha\sqrt{1+R_p^2} + (1+\cos^2\alpha)R_p + 2\cdot\sqrt{1+g^2(\alpha, R_p, R_m)}}},$$

$$g(\alpha, R_p, R_m) = \frac{\cos\alpha\sqrt{1+R_p^2} + R_p + R_m}{\sqrt{1+R_m^2}\sqrt{2R_p\cos\alpha\sqrt{1+R_p^2} + (1+\cos^2\alpha)R_p + 2}}.$$

$R_m = m_\mu / m_M$ is the mass ratio between the muon and its parent particle

$R_p = p_M / E_M$ is the momentum-to-energy ratio of muon parent particles

α is the angle between the parent particle's momentum and the muon's momentum.



Average Polarization of muon produced by different particles.

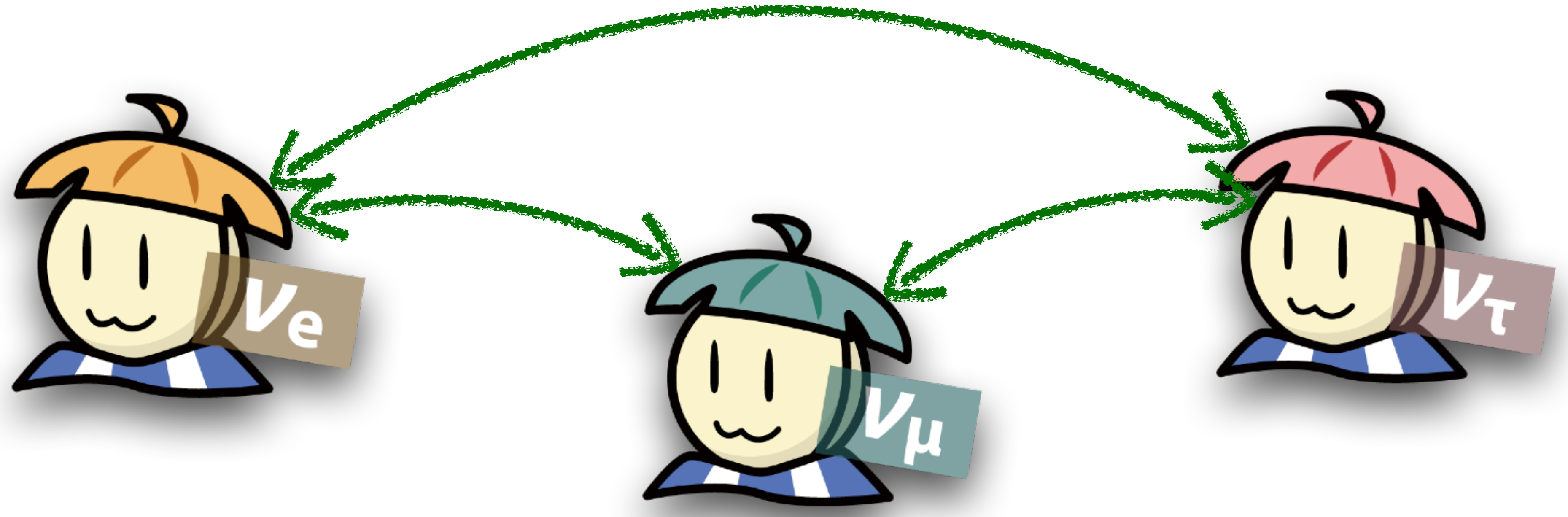
Cosmic-ray muons & Atmospheric neutrinos Share production process

$$\begin{cases} \pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K_L^0 \to \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu) \end{cases}$$

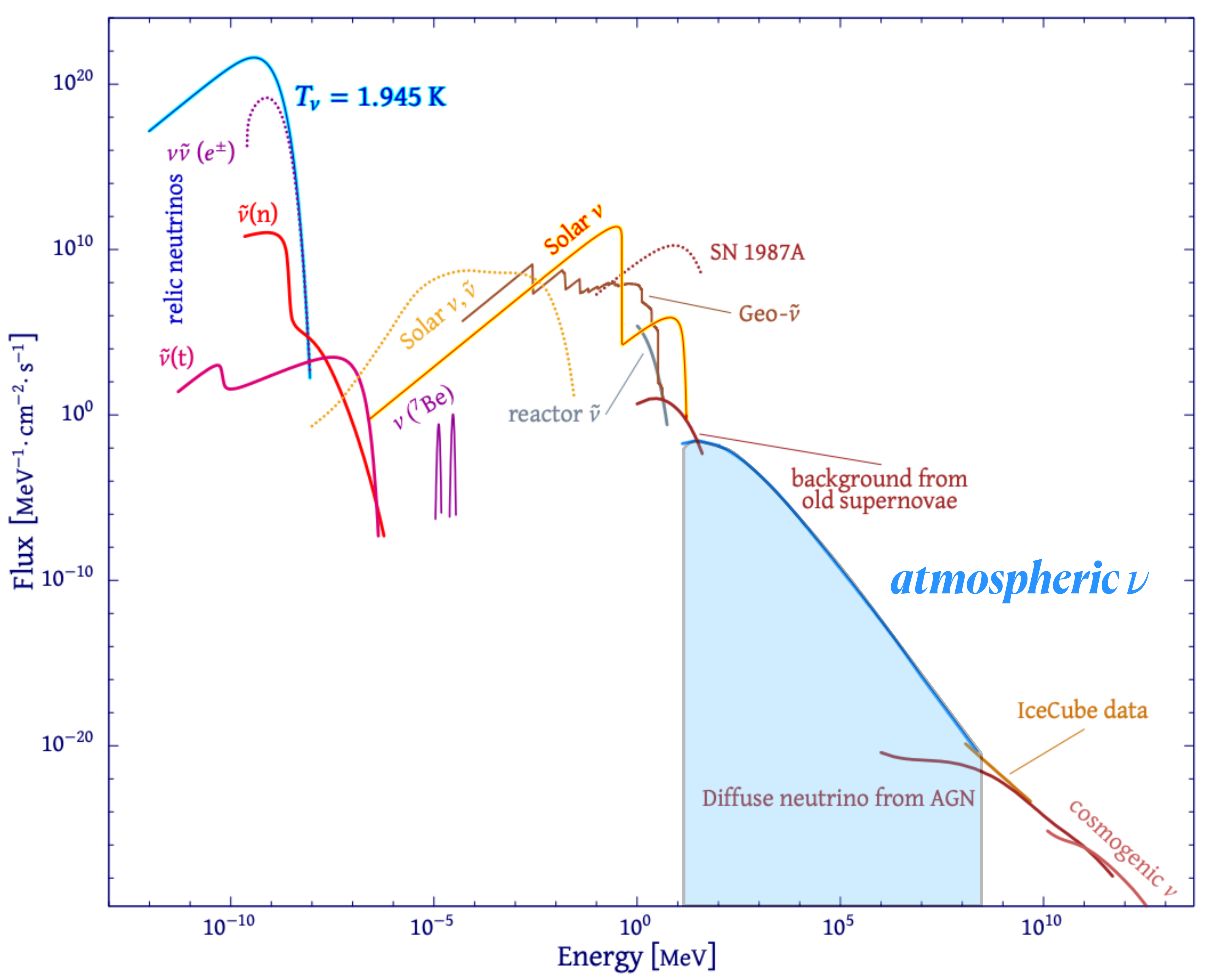
Cosmic-ray muon polarization may help understand atmospheric neutrino production.

- *Muon Spin Polarization*
- ***How cosmic ray muon polarization measurement facilitates atmospheric neutrino physics?***
- *Cosmic Ray Muon Polarization Detector (CRmuSR)*
- *Summary and outlook*

Atmospheric Neutrino Eperiment



https://higgstan.com/particle-image/



Ivanchik A V, Kurichin O A, Yurchenko V Y. Neutrino at different epochs of the Friedmann Universe[J]. Universe, 2024, 10(4): 169.

Current Experiments

ICECUBE NEUTRINO OBSERVATORY

SUPER K

KM3NeT

et. al.

Future Experiments

JUNO

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-K

TBC ...

Uncertianties of ATN flux

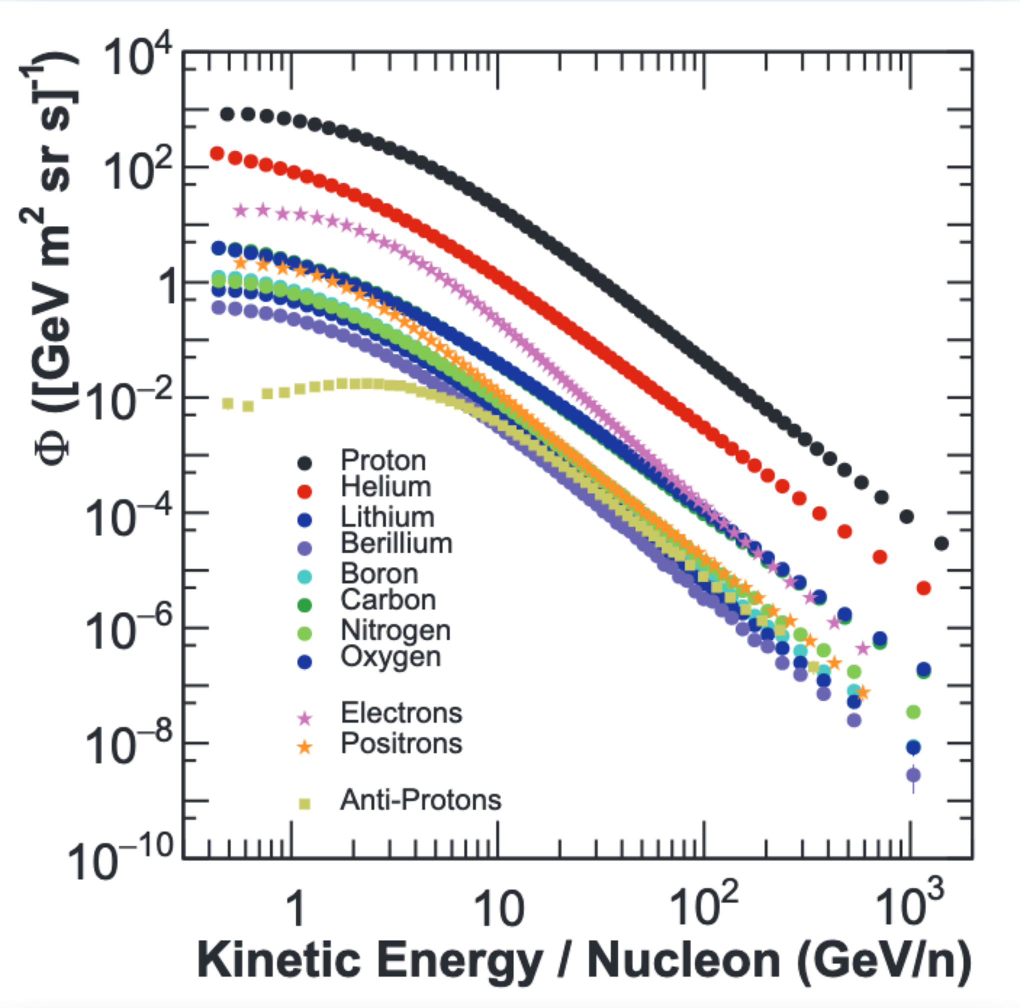
$$\phi_{\nu_i} = \phi_p \otimes R_p \otimes Y_{p\to\nu_i} + \sum_A \left\{ \phi_A \otimes R_A \otimes Y_{A\to\nu_i} \right\}$$

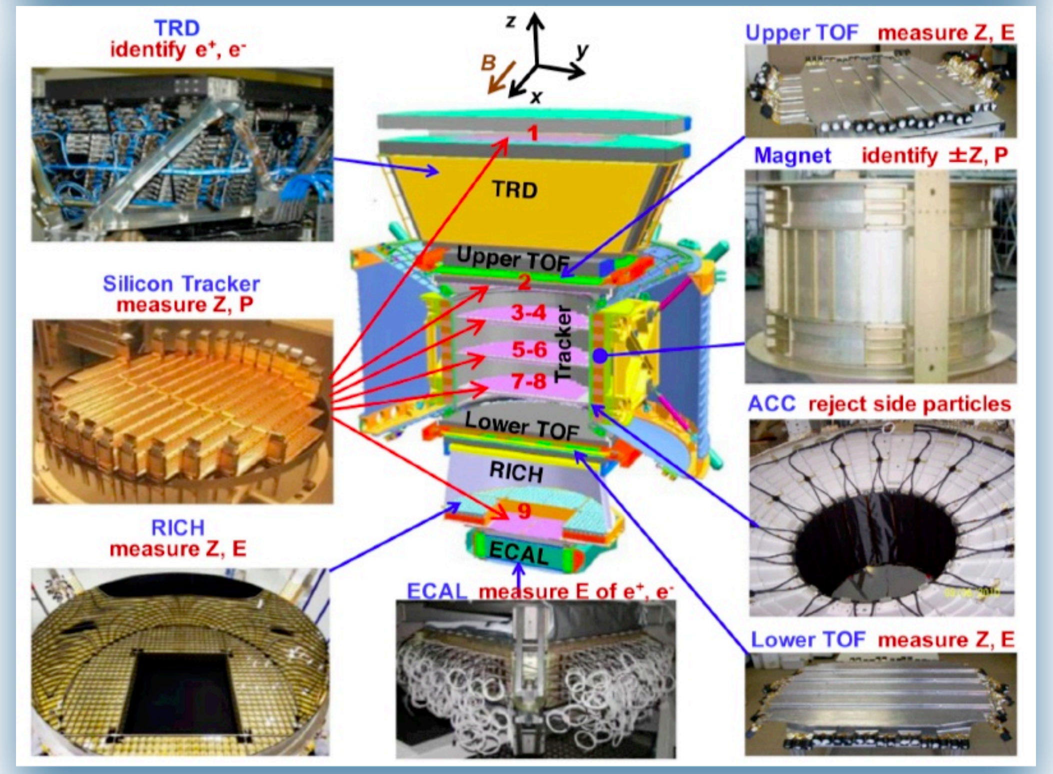
Gaisser, Th K., and M. Honda. "Flux of atmospheric neutrinos." Annual Review of Nuclear and Particle Science 52.1 (2002): 153-199

Vagelli V. Italian Physical Society: Results from AMS-02 on the ISS after 6 years in space[J]. Nuovo Cimento C, 2019, 42: 173.

primary proton/nucleon flux $\otimes$ geomagnetic selection effect $\otimes$ neutrino yield per primary particle

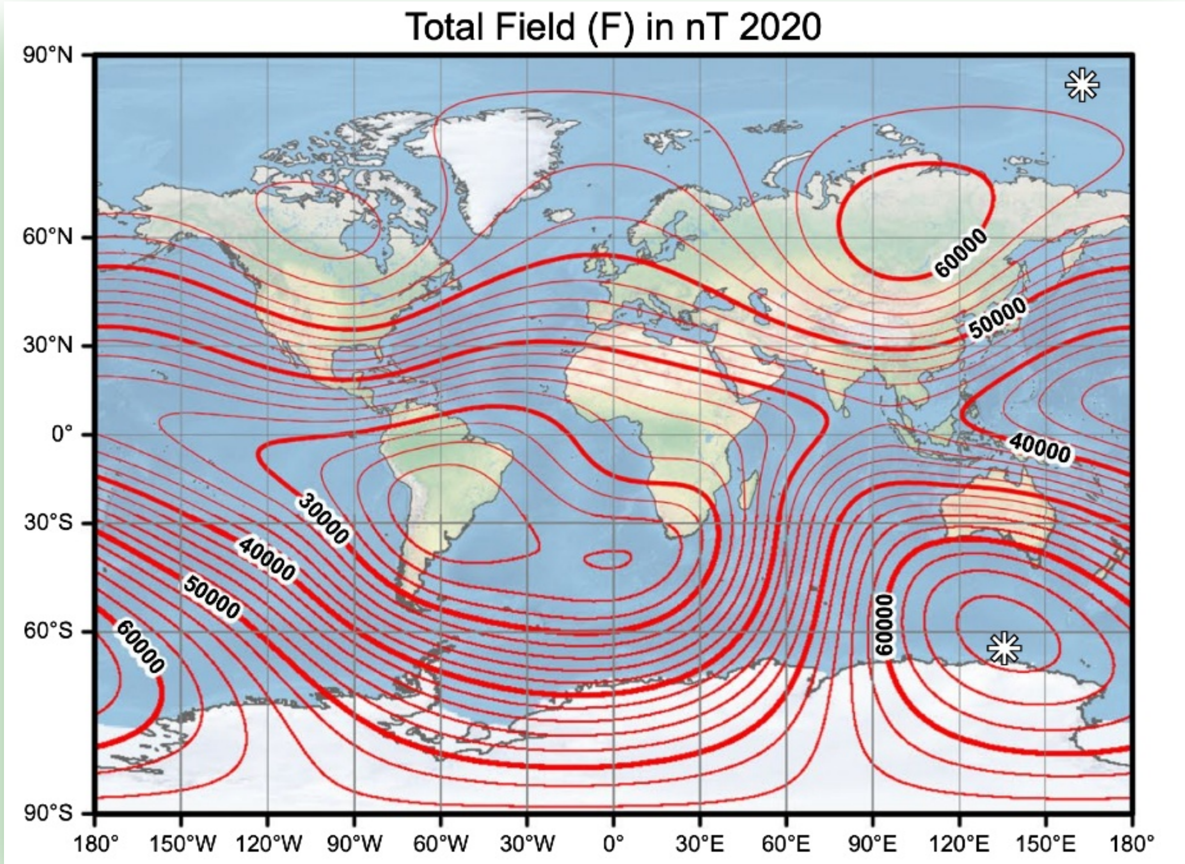
Cosmic Ray Experiments





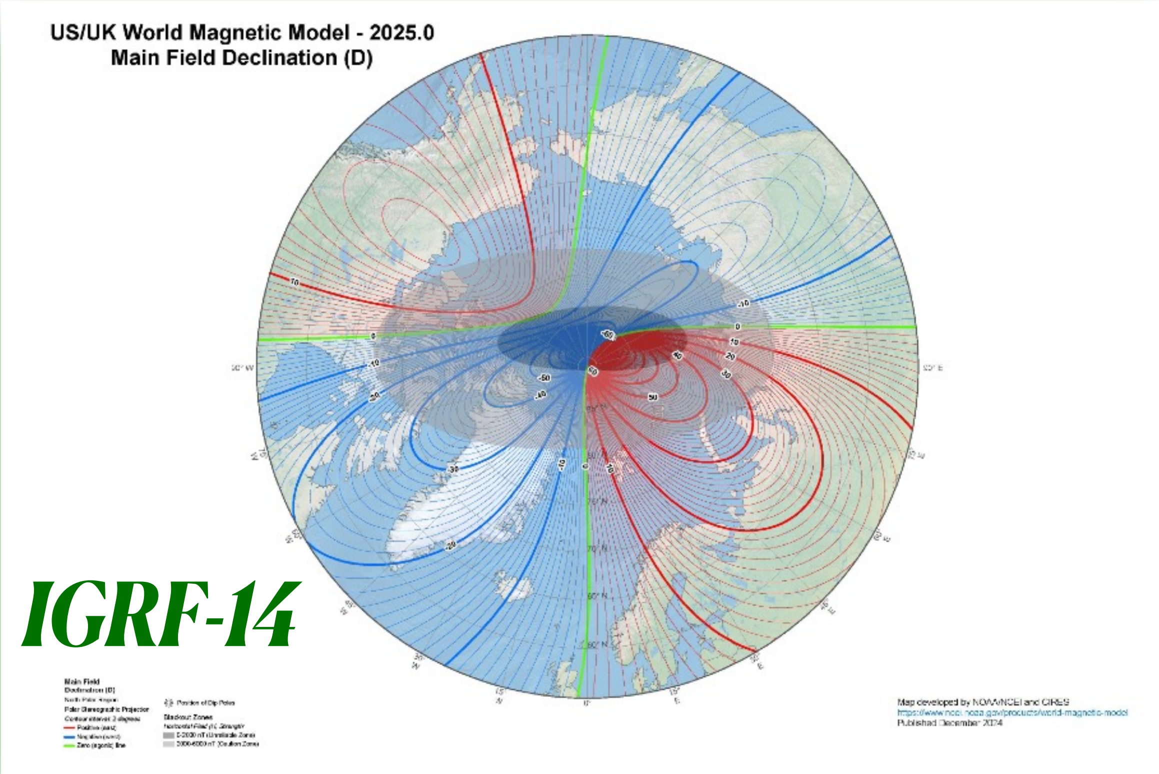
AMS-02 detector system

ground and satellie based measurements



IGRF-13

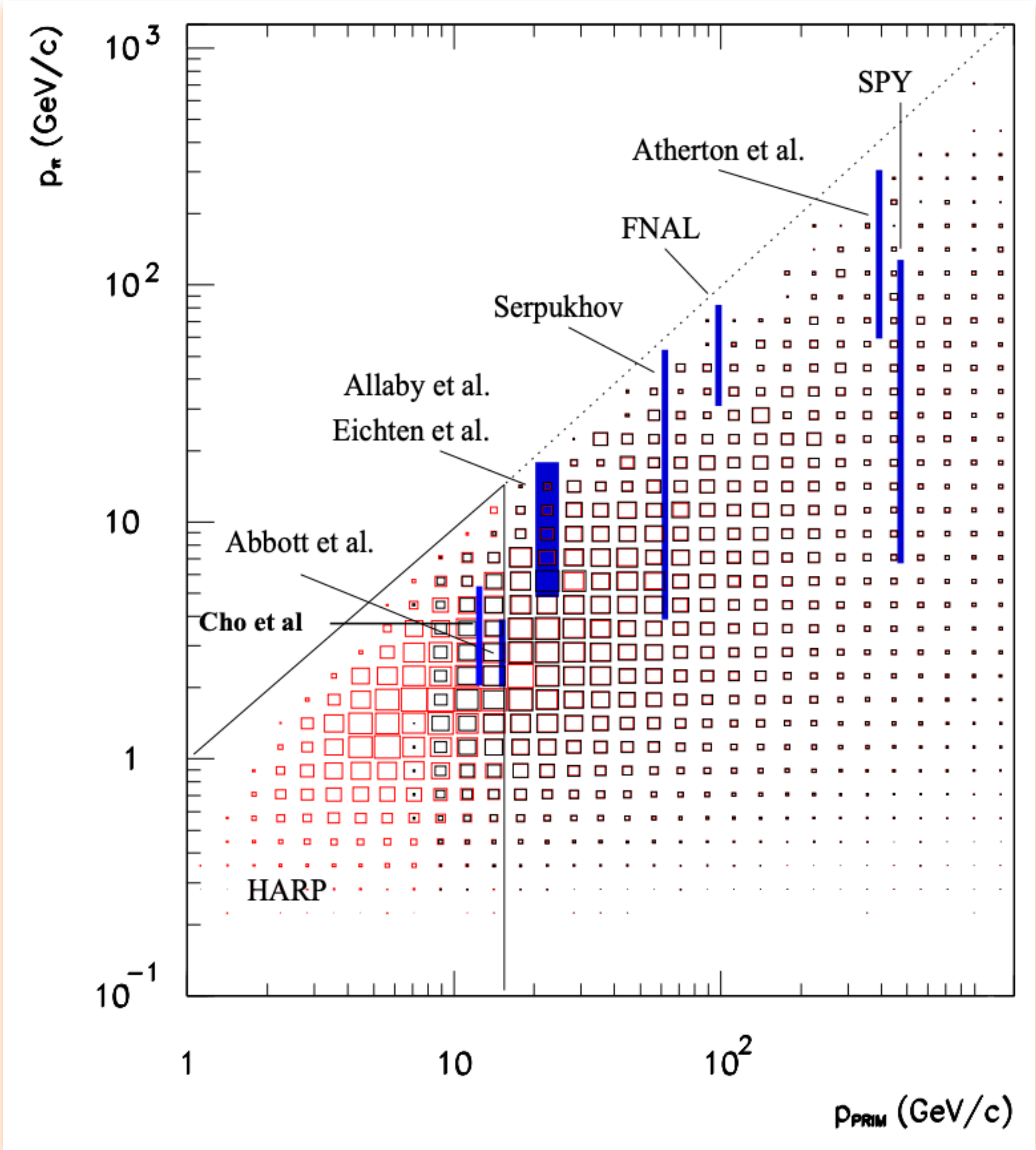
Alken P, Thébault E, Beggan C D, et al. International geomagnetic reference field: The thirteenth generation[J]. Earth, Planets and Space, 2021, 73: 1-25.



IGRF-14

International Geomagnetic Reference Field(IGRF) Model

Accelerator-based Experiments

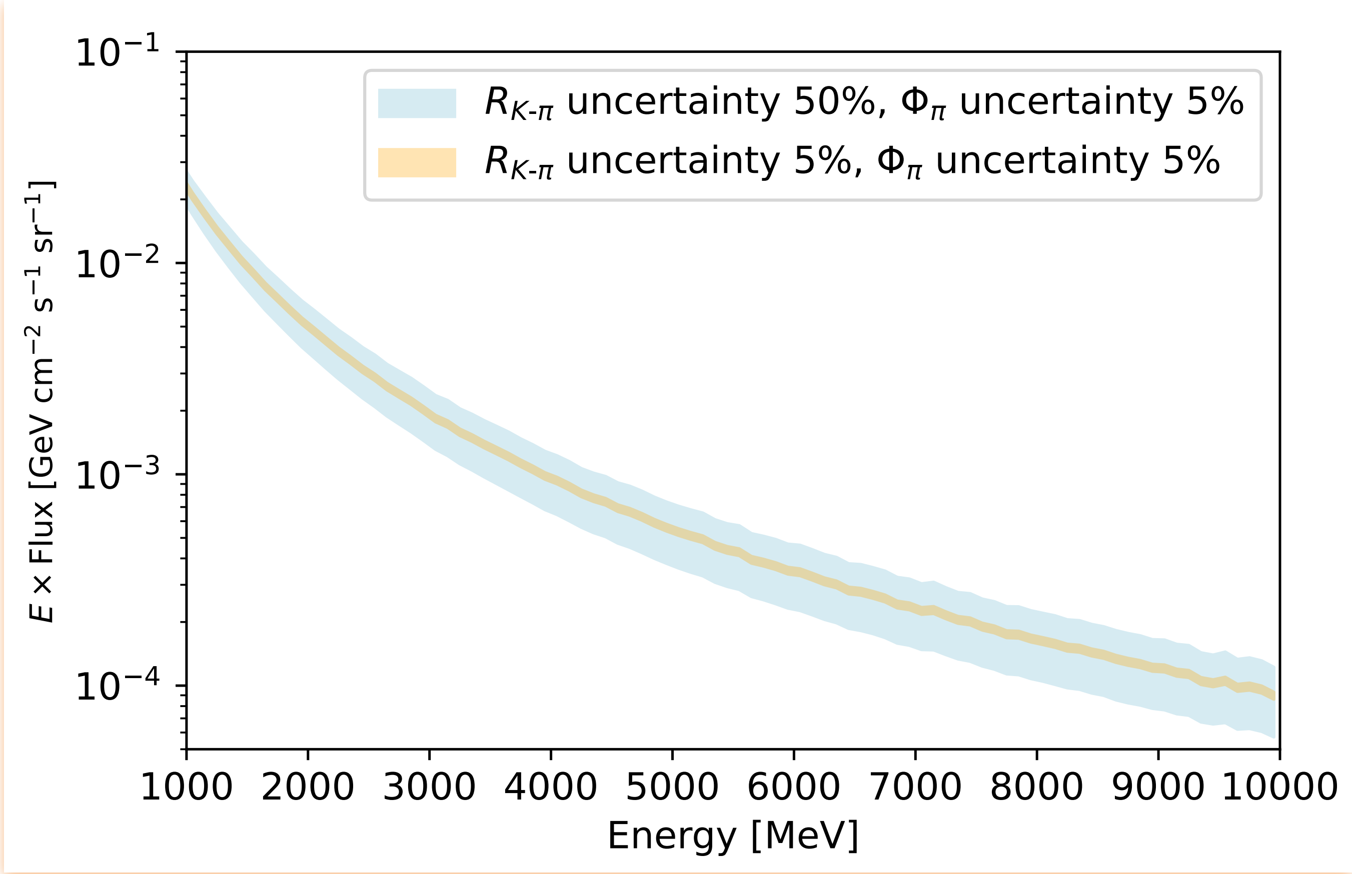


- Low-energy region is important but has not been measured
- Poses significant challenges to current accelerator technology

Indirect Measurements Through Cosmic-ray

$$\begin{cases} \pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ K_L^0 \to \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu) \end{cases}$$

- Constrain the ATN production process indrectly through CR measurements.



Cosmic-ray Muon Polarization Measurement

Gaisser T K, Honda M. Flux of atmospheric neutrinos[J]. Annual Review of Nuclear and Particle Science, 2002, 52(1): 153-199.

How ATN Flux Uncertainties Effect Sensetivity?

Detector	Event Rate	ATN Flux Model	Energy Range	Energy Bin Number	Energy resolution
LS $4000\,kt\cdot yr$	$34.7/kt\cdot yr$	*HKKM*	*0.1-100 GeV*	*100* *(Log-scaled)*	$\sigma_E^{\nu_\mu}/\mathrm{GeV} = 0.011 + 0.043\sqrt{E/GeV}$ $\sigma_E^{\bar{\nu}_\mu}/\mathrm{GeV} = 0.006 + 0.049\sqrt{E/GeV}$

Abusleme, Angel, et al. "JUNO sensitivity to low energy atmospheric neutrino spectra." The European Physical Journal C 81 (2021): 1-16.

Honda, M., et al. "Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model." Physical Review D 92.2 (2015): 023004.

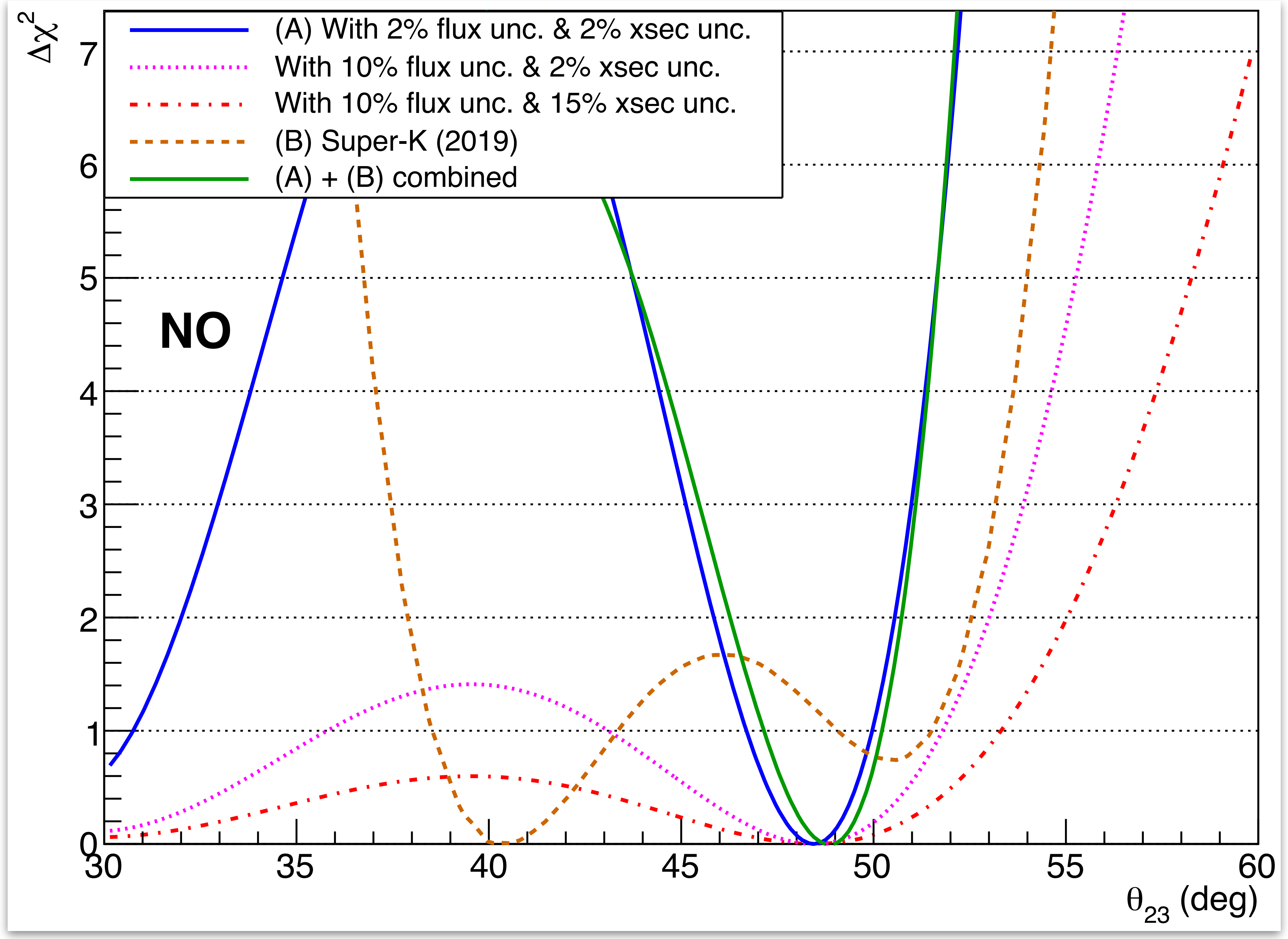
S.-F. Ge, Neutrino CPV, in Huizhou High Intensity Frontiers Conference, HHIF (2025).

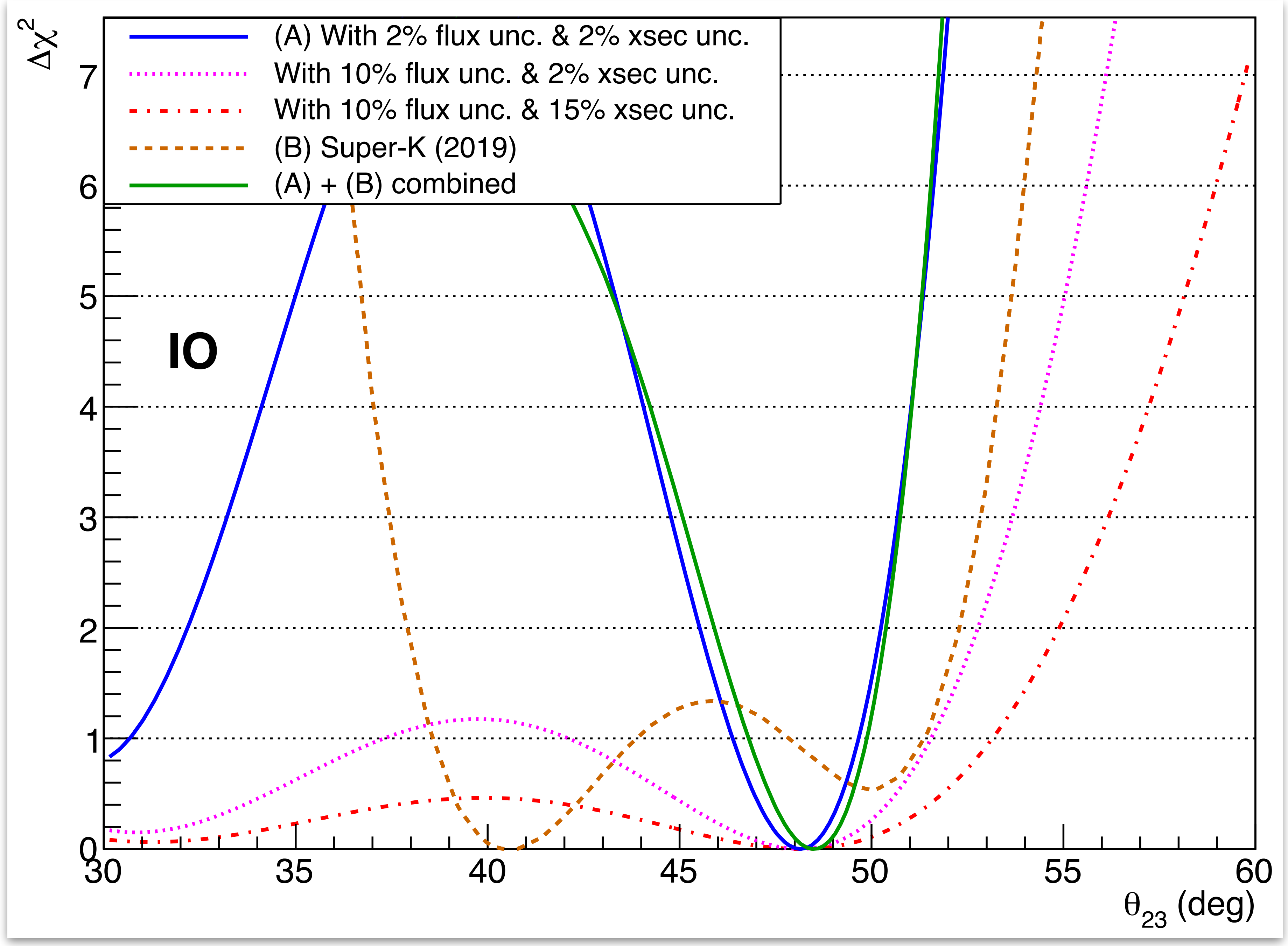
Simulation toolkit: nuSQuIDS

Argüelles, Carlos A., Jordi Salvado, and Christopher N. Weaver. "nuSQuIDS: A toolbox for neutrino propagation." Computer Physics Communications 277 (2022): 108346.

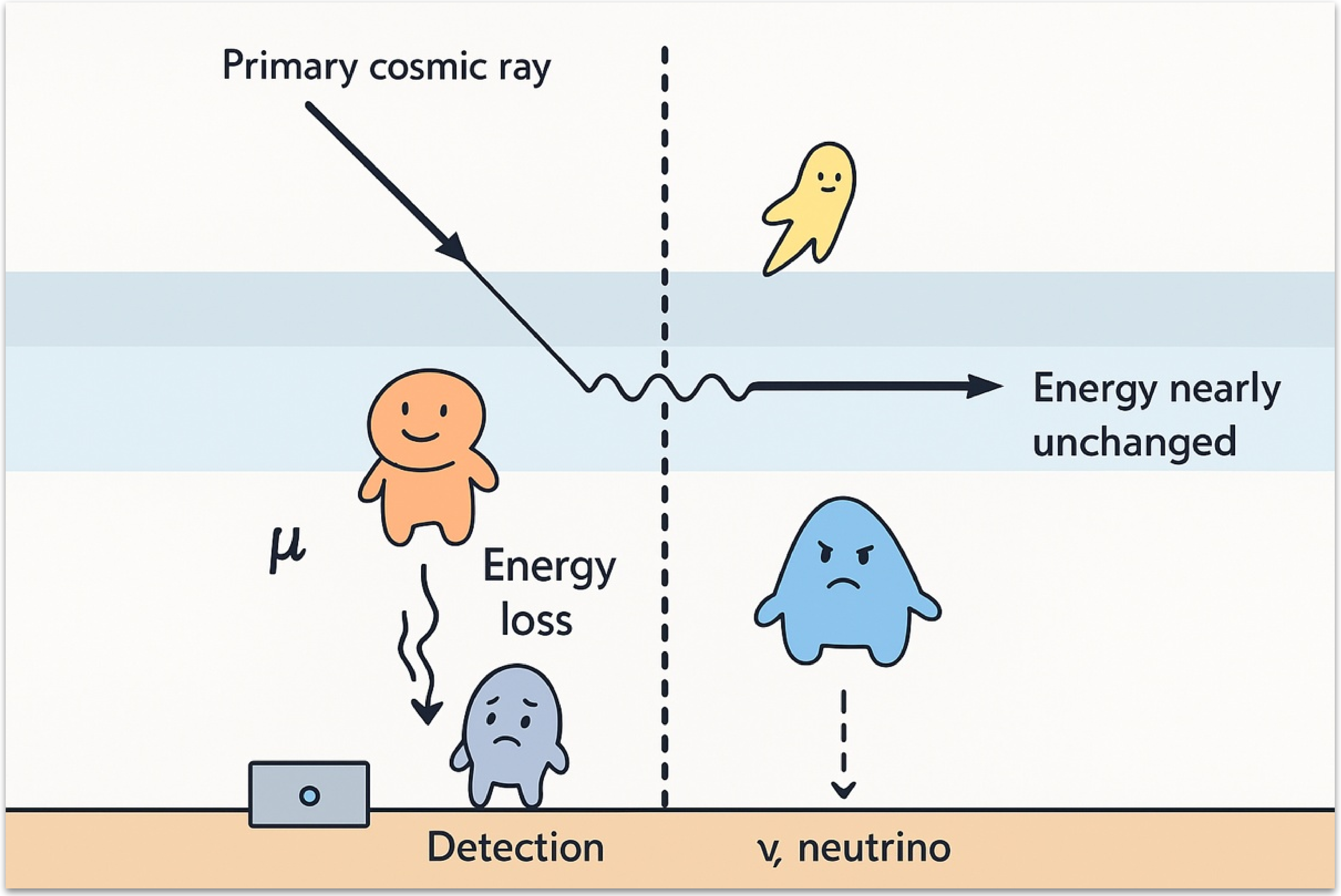
SQuIDS
Simple Quantum Integro Differential Solver

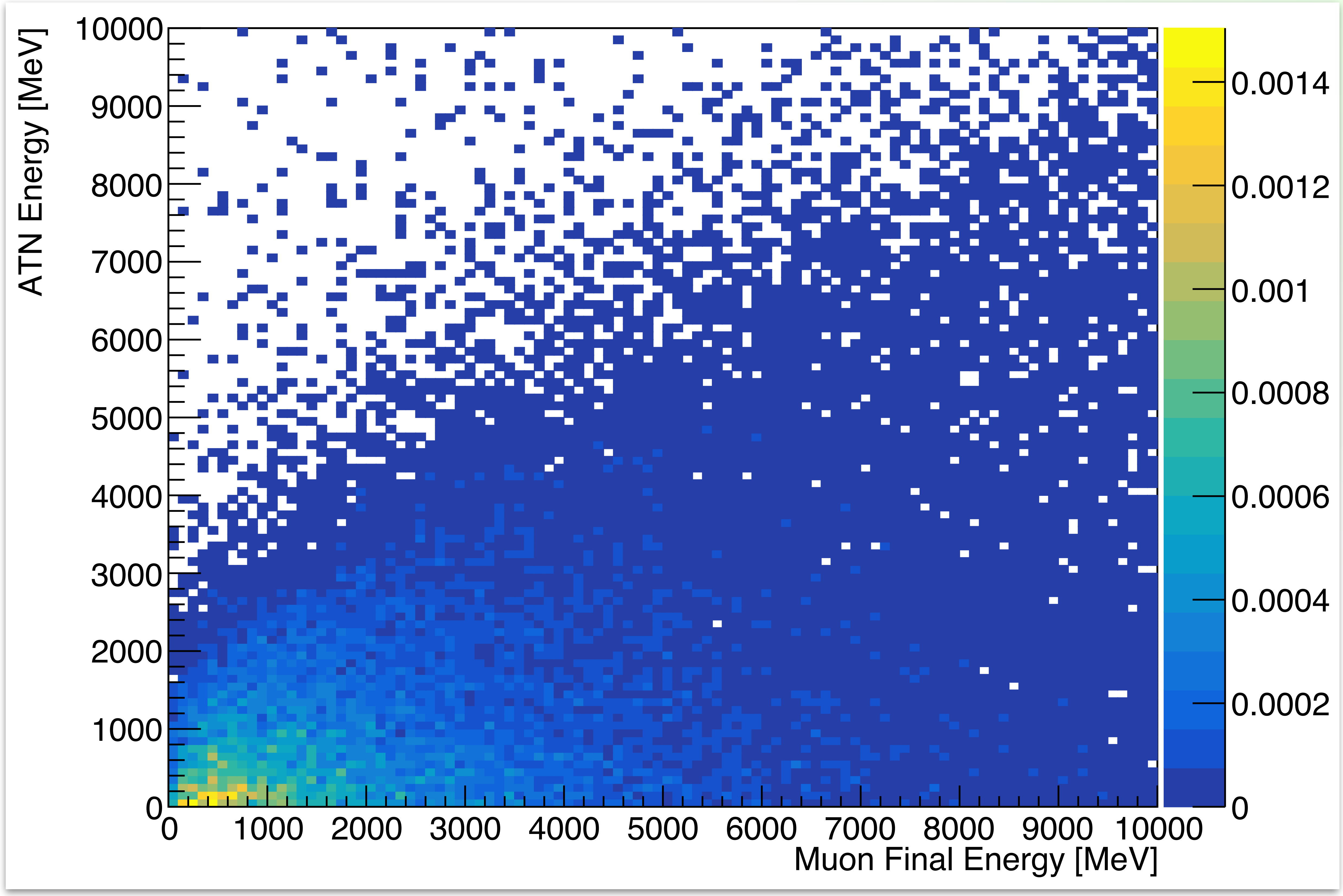
θ_{23} varies while other parameters fixed to PDG Values





C1: Which Energy region (Cosmic ray Muon) should we focus on?





Sub-GeV cosmic ray muons (sea level) are closely connected to GeV atmospheric neutrinos (golden signal region).

We need a dedicated high-precision detector system to measure low-energy cosmic ray muon polarization!

C2: How can we detect cosmic-ray muon polarization?

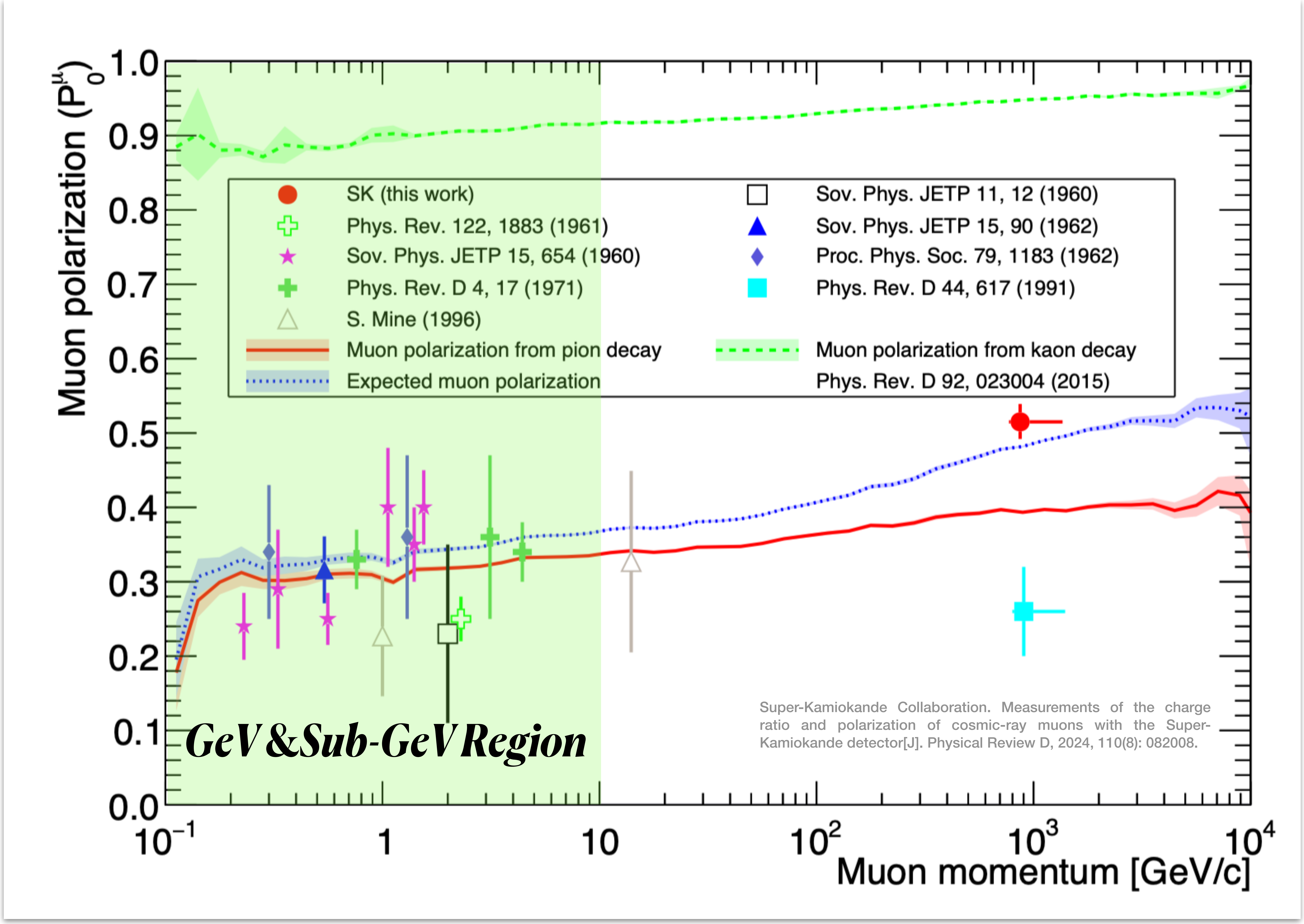
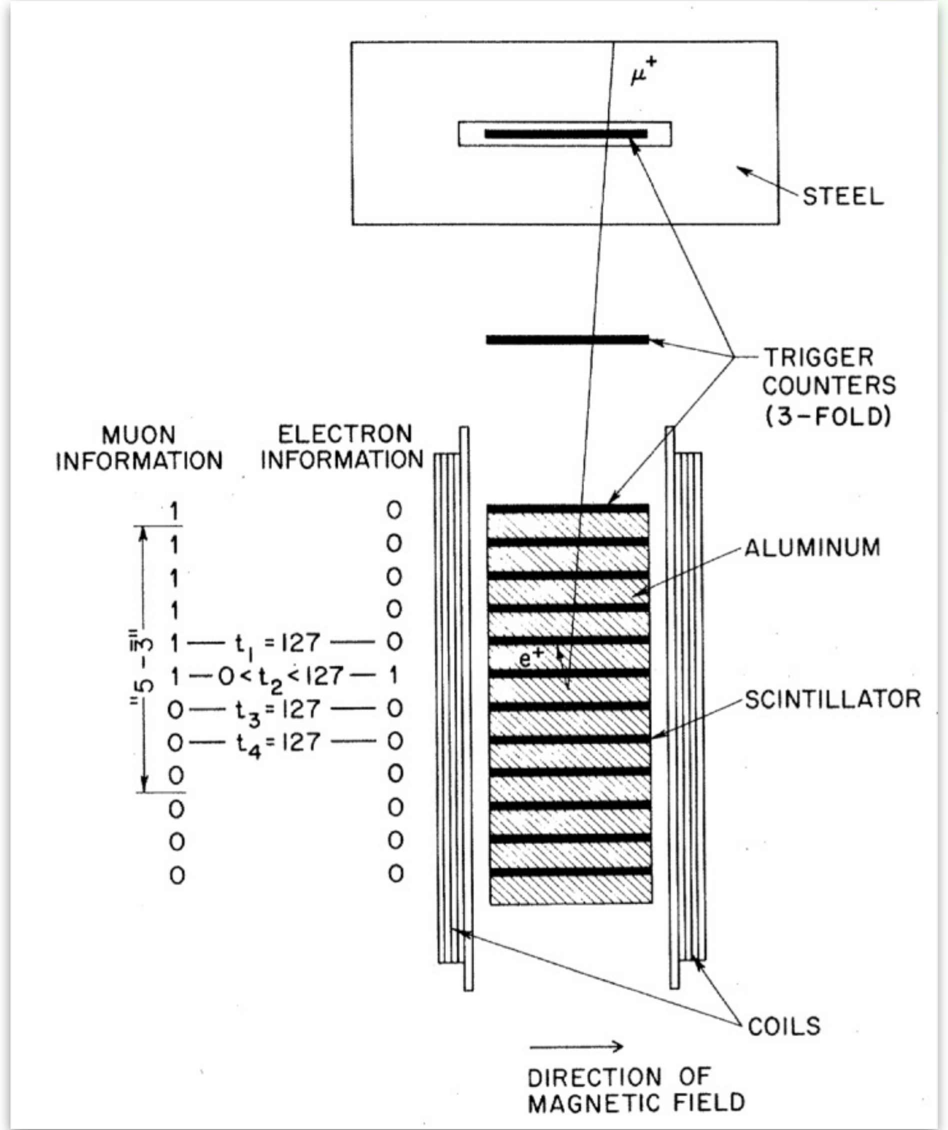
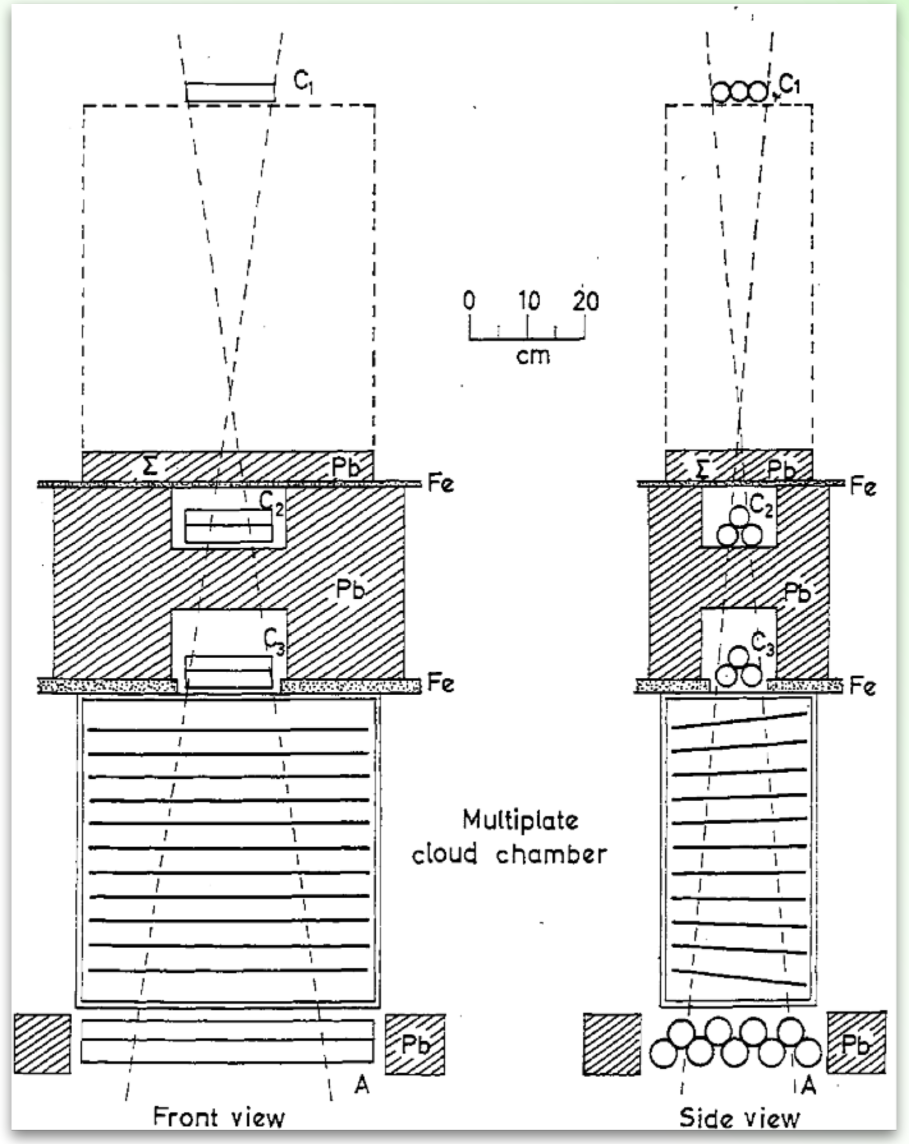


Figure: Historical experiment results of cosmic-ray muon polarization.



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.

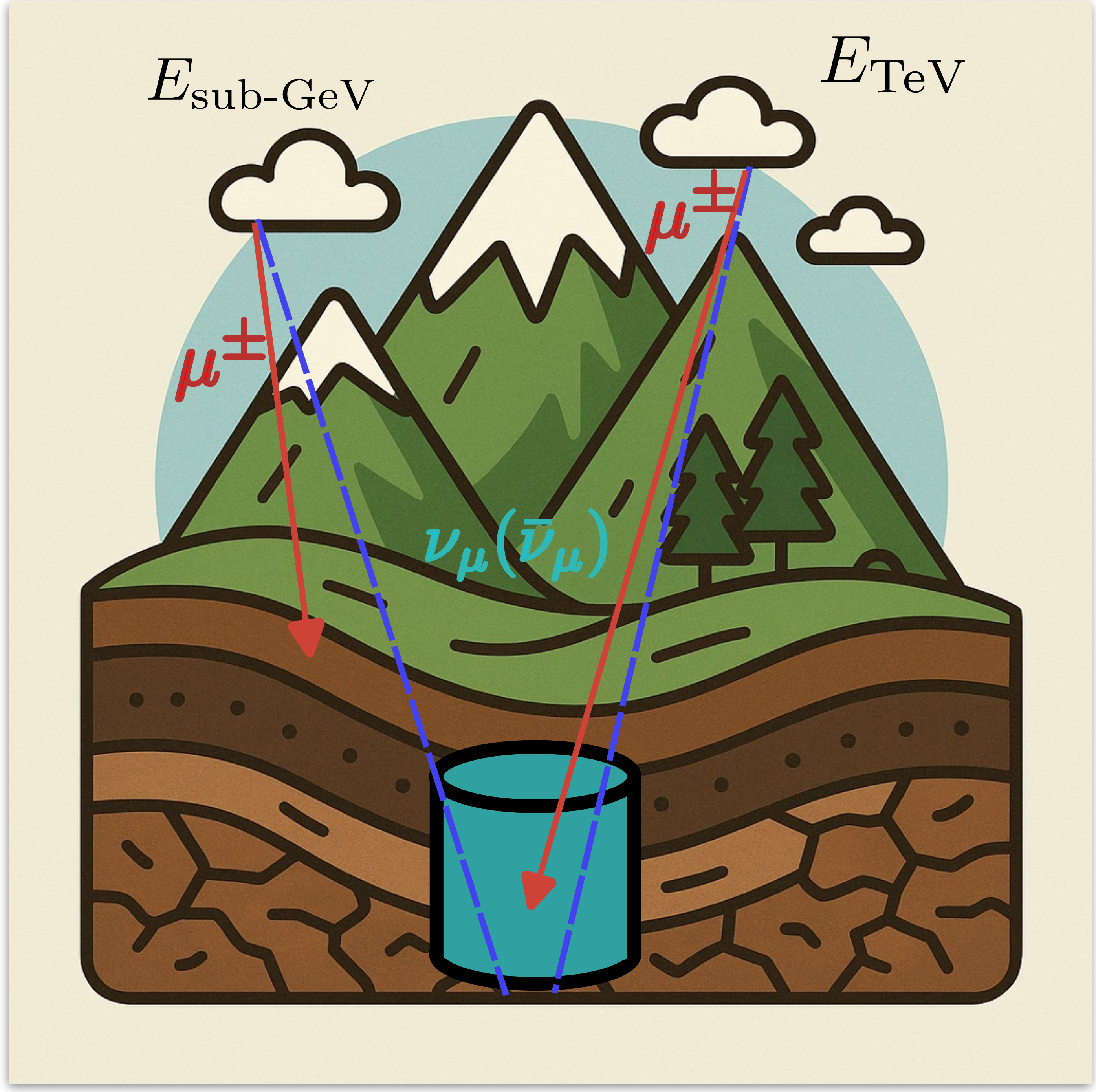


Figure2. Cosmic-ray muon polarization in deep underground

Cosmic-ray Muon Polarization Simulation

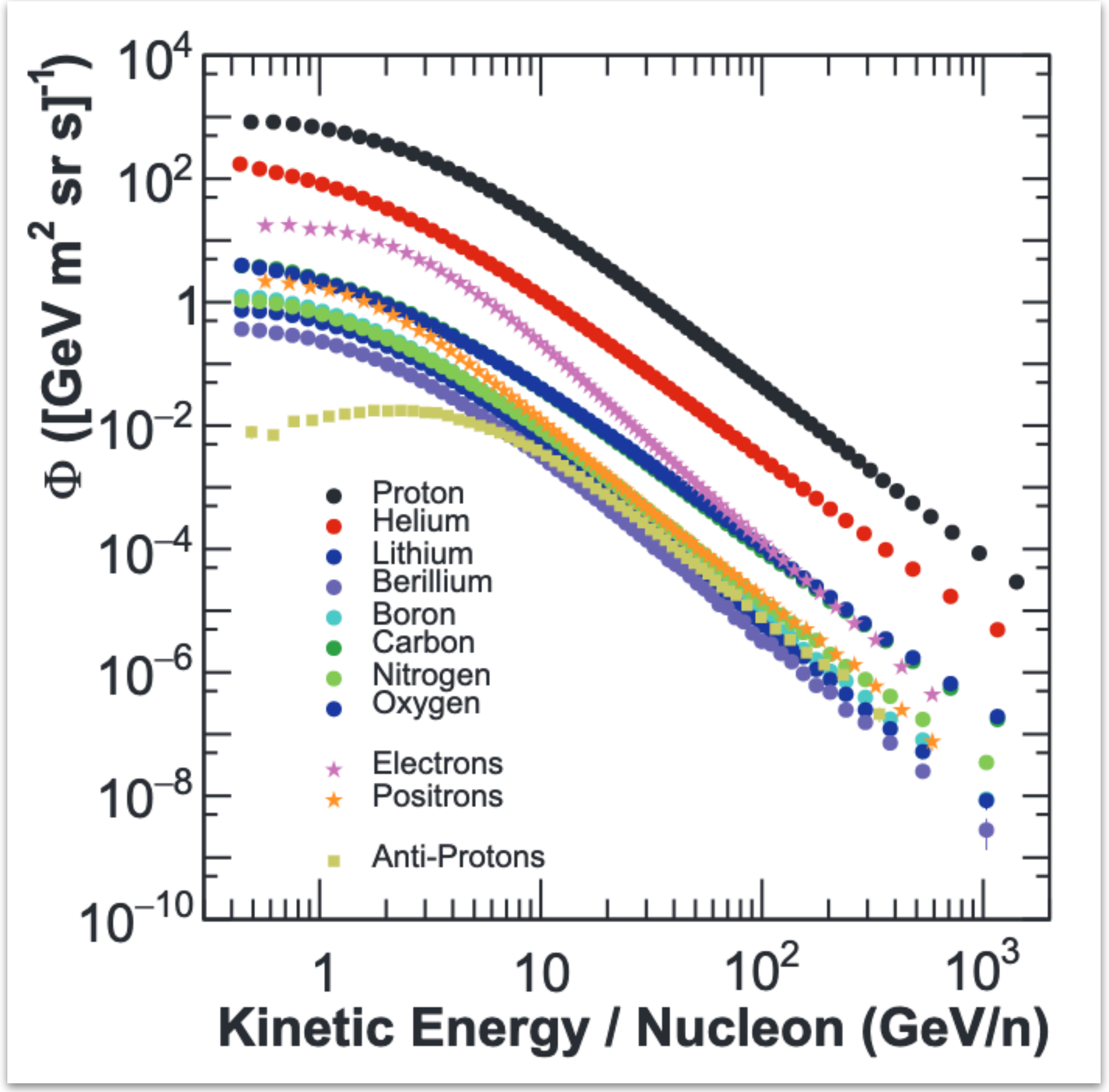
Mustard-based Air Shower Simulation toolkit (MusAriS)

https://github.com/zhao-shihan/Mustard

https://github.com/zhao-shihan/MusAirS

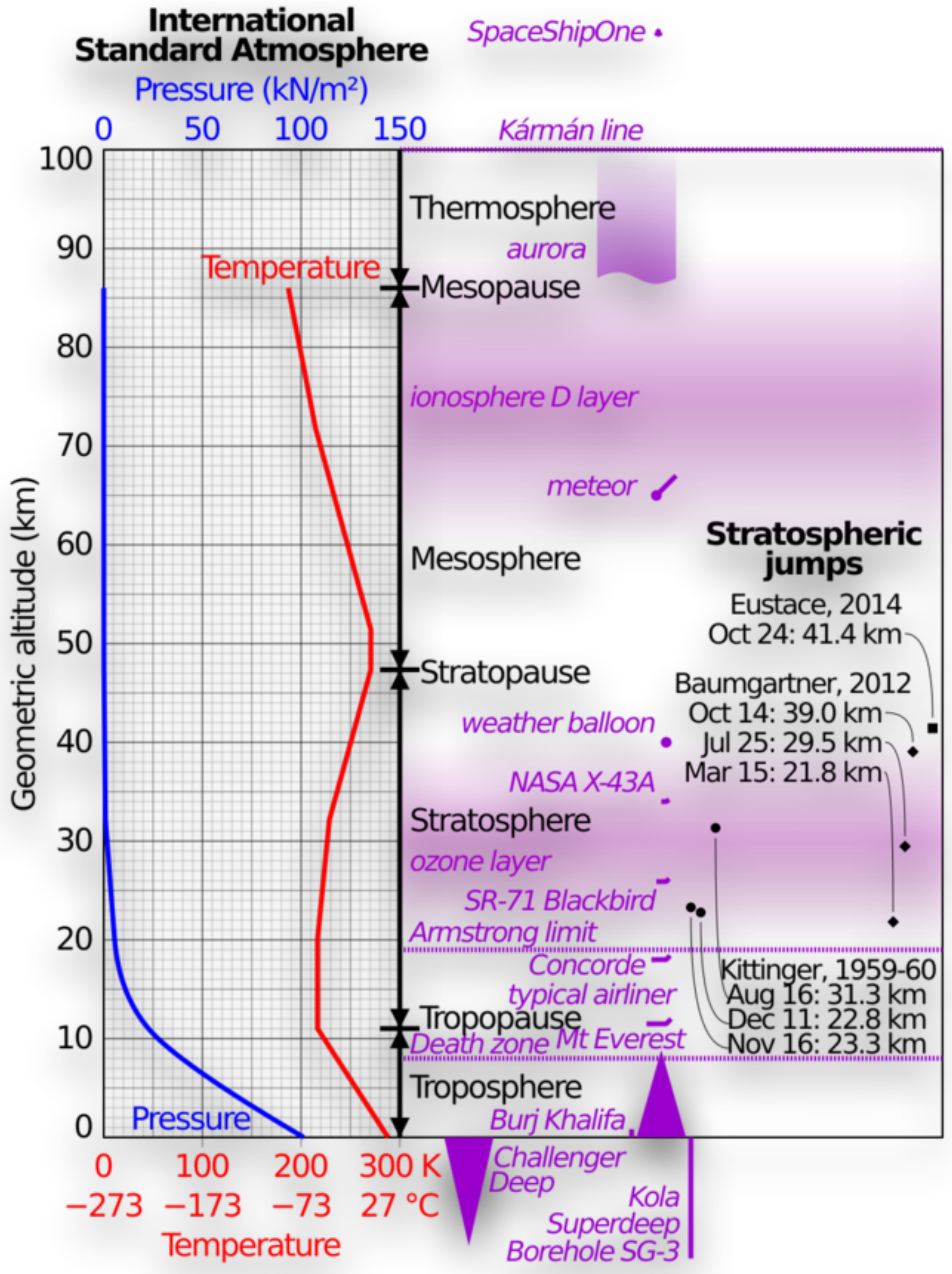
Primary Cosmic-ray:

AMS-02 Experimental Data

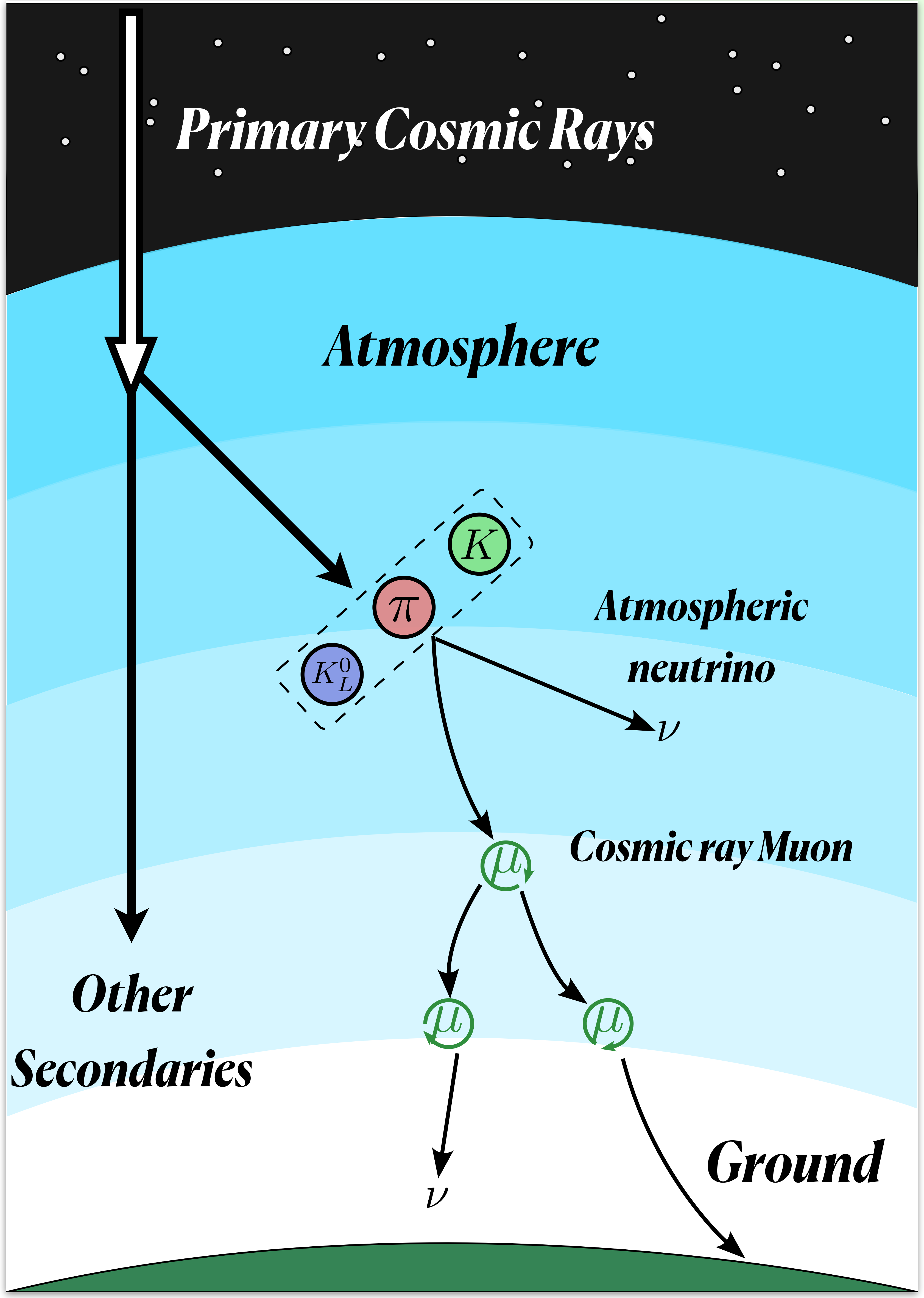


Atmosphere Modeling:

International Standard Atomsphere



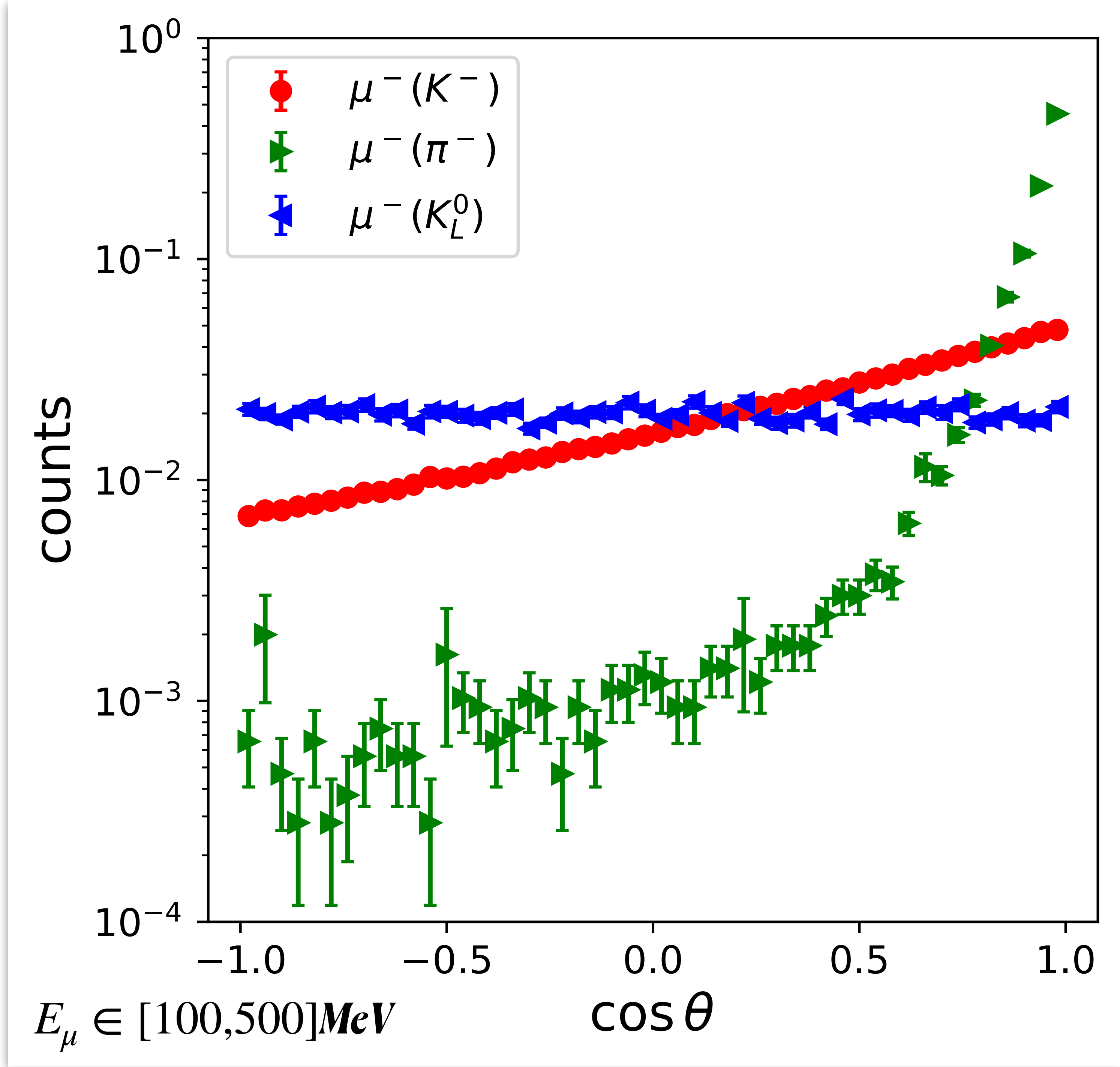
ISA Model



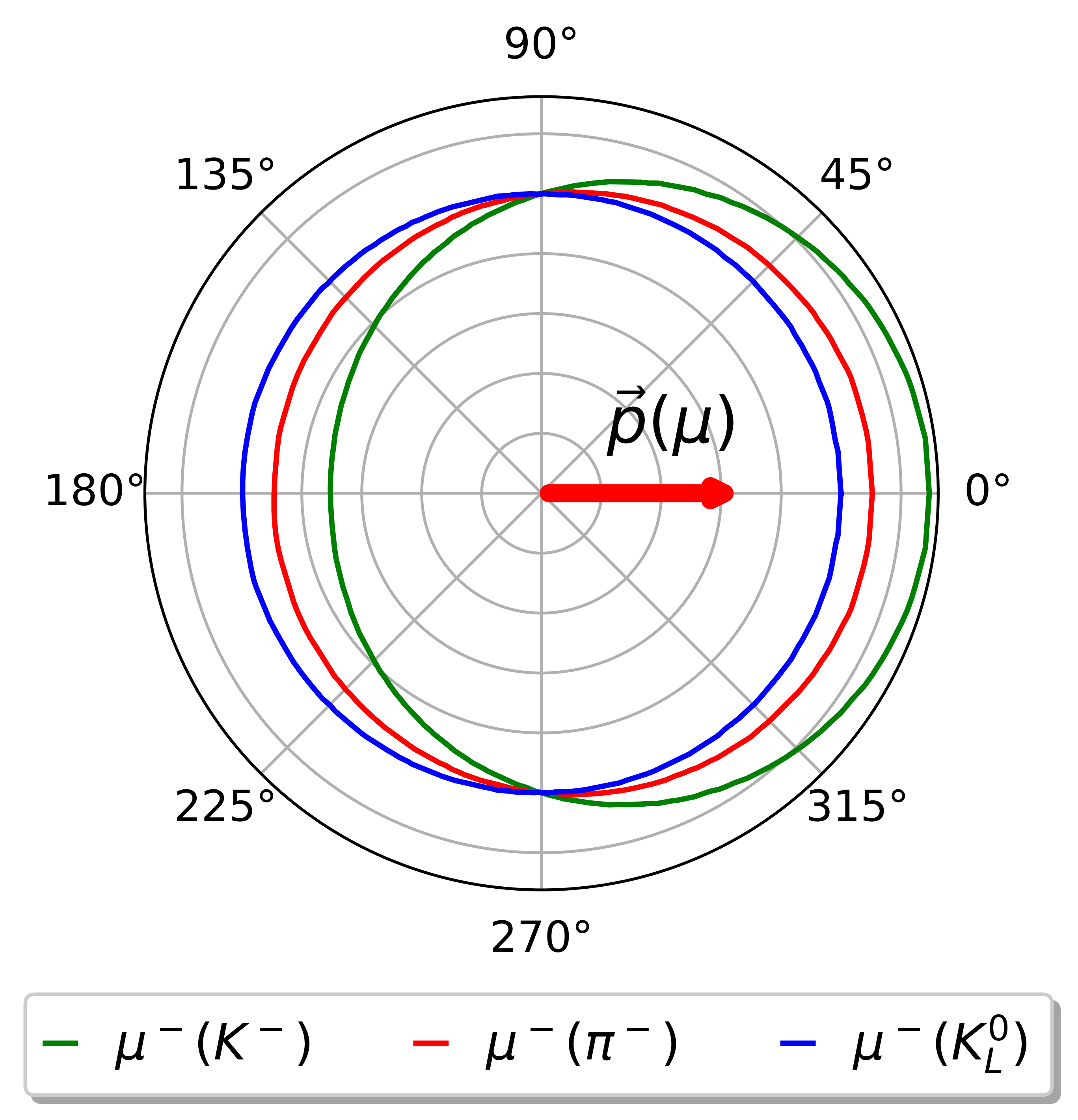
MusAirS Simulation Work Flow

Cosmic-ray Muon Polarization Measurements

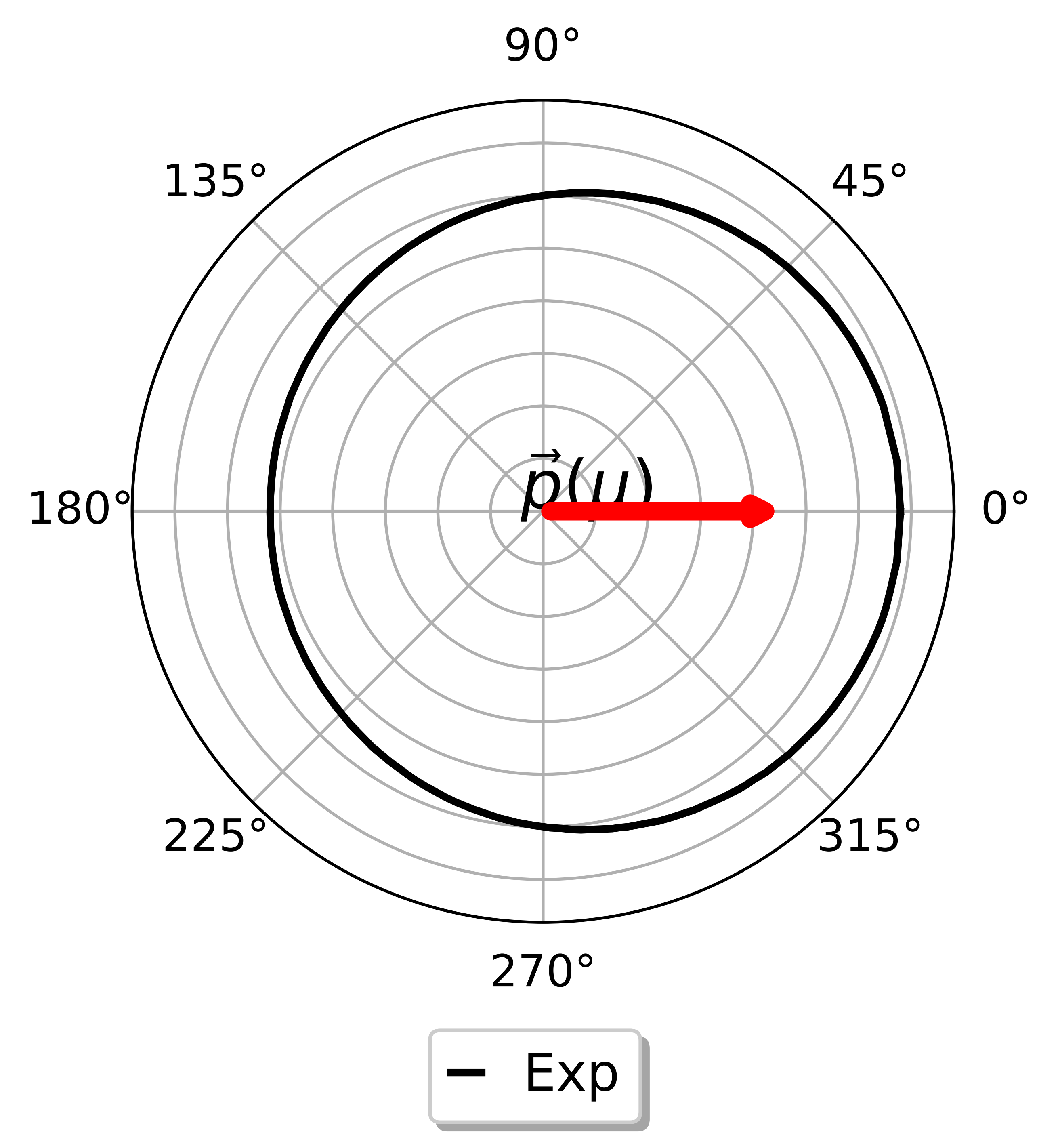
Polarization Distribution



Michel electron Distribution



Experiment



K-π Ratio

Unfolding the spectrum

Michel electron distribution

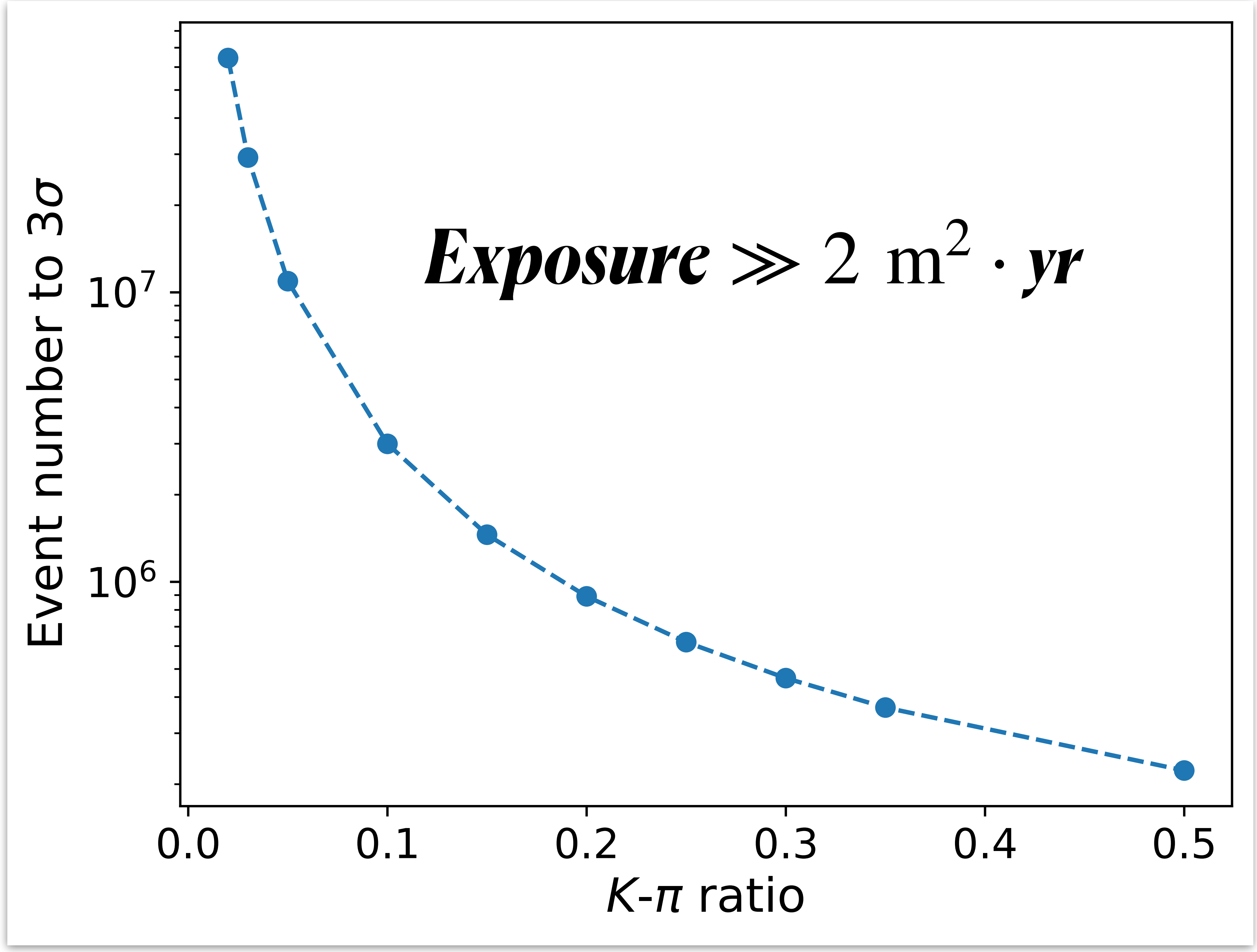
Key to reconstructing K-π Ratio:

- **Momentum Direction resolution**
- **The capability of reconstructing Michel electrons' distribution**

C3: How practical is the experiment?

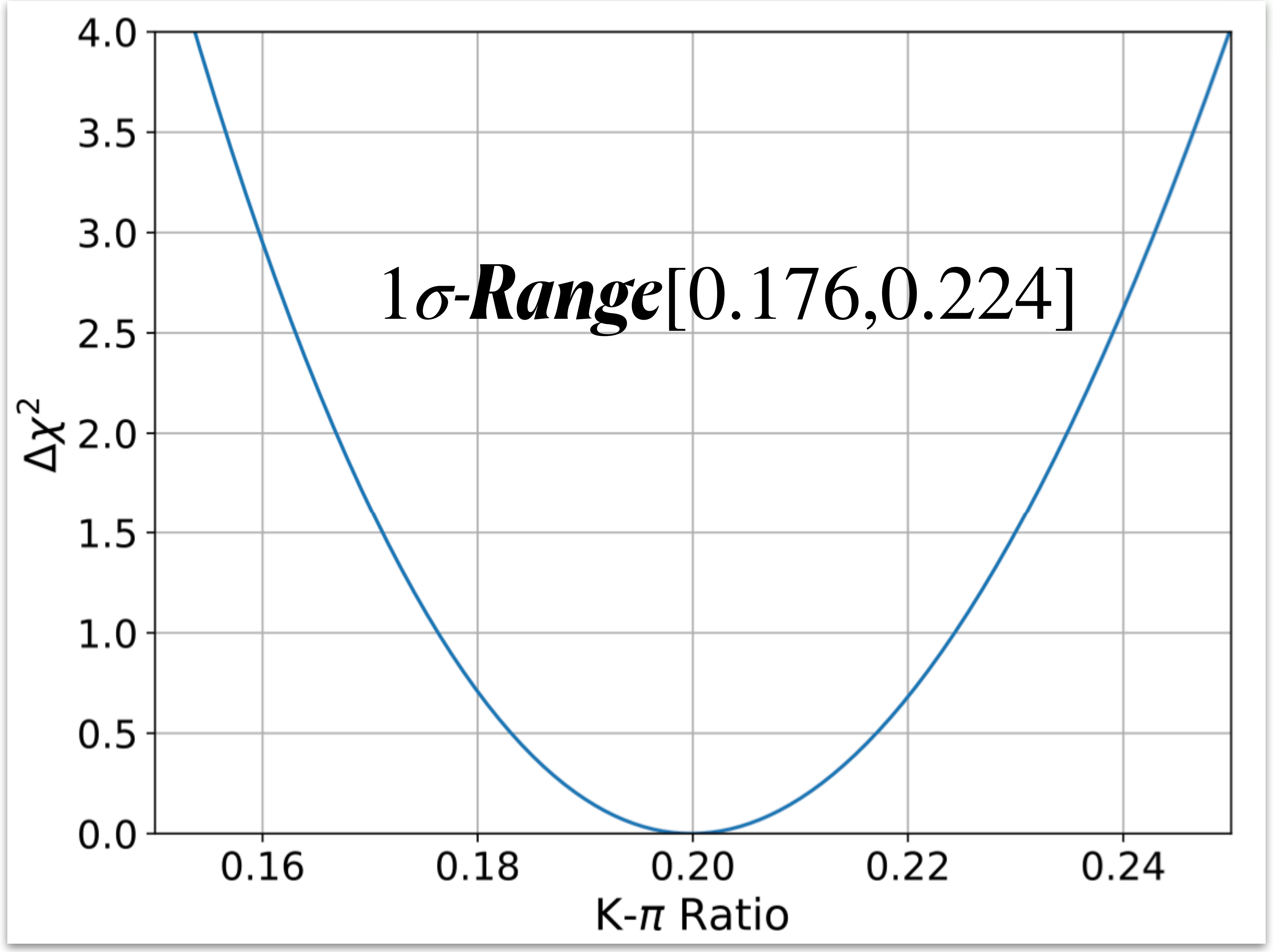
Phase I: Exclude "CR muons are only produced by pion"

- *Detector has prefect spatial resolution*
- *Michel $e^{\pm}$ event rate are $100\ day^{-1}$ for a 1 m^2 detector*



Phase II: Measure the K-π Ratio with detector array

- *K-π Ratio $= 0.2$*
- *Detector Array has effective area $\mathcal{O}(10)$ m²*



The detector should support modular and array-based deployment.

- *Cosmic Ray Muon Polarization Measurement*
- *How cosmic ray muon polarization measurement facilitates atmospheric neutrino physics?*
- ***Cosmic Ray Muon Polarization Detector (CRmuSR)***
- *Summary and outlook*

Cosmic-Ray muon Spin polarization detectoR (CRmuSR)

Momentum Direction Detector (MDD)

- *Reconstruct Muon Momentum Direction*

Muon Stopping Target (Target)

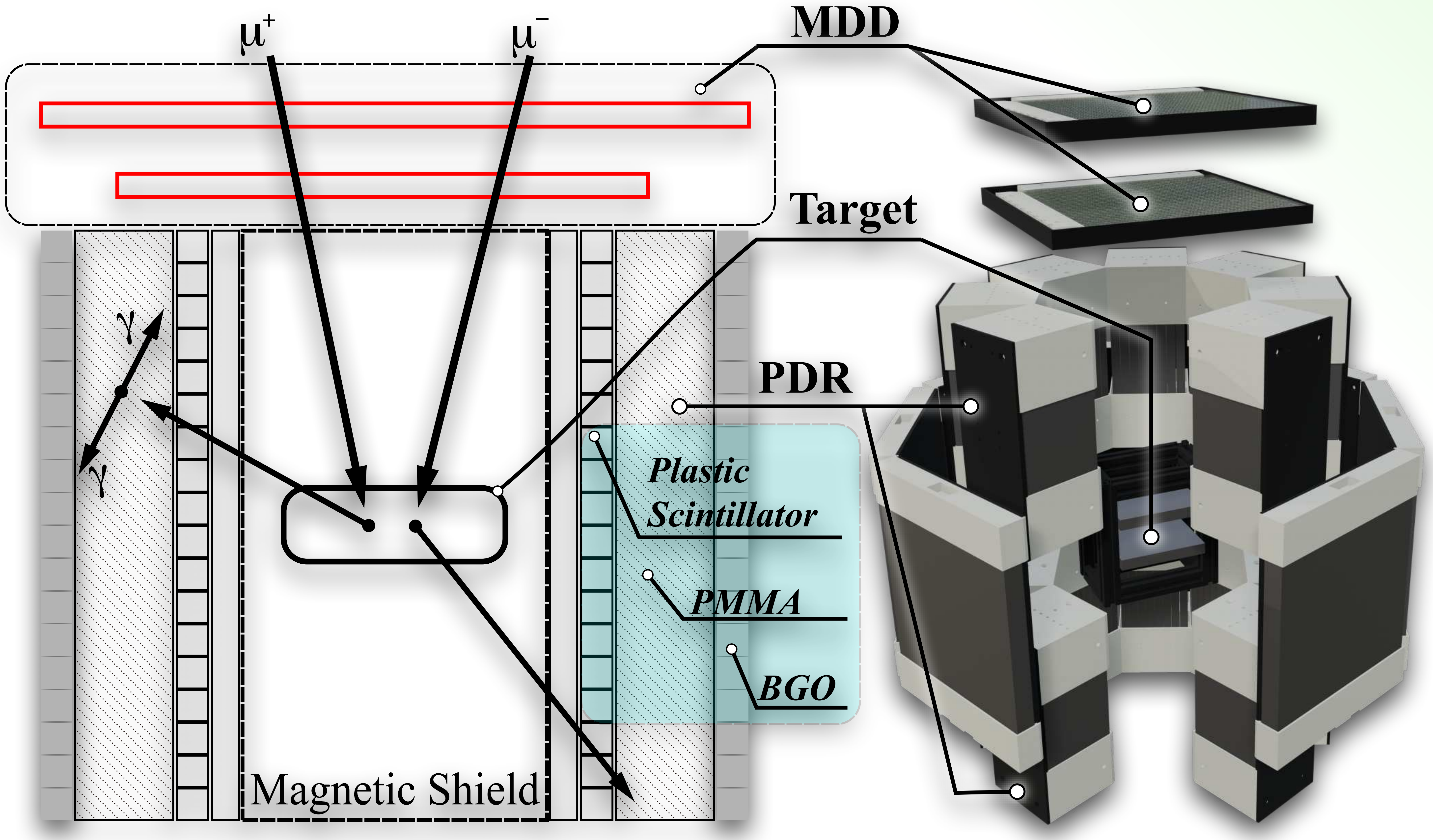
- *Stop the muon until it decay*

Positron/electron Detector Ring (PDR)

- *Reconstruct Michel $e^{\pm}$ Distribution*

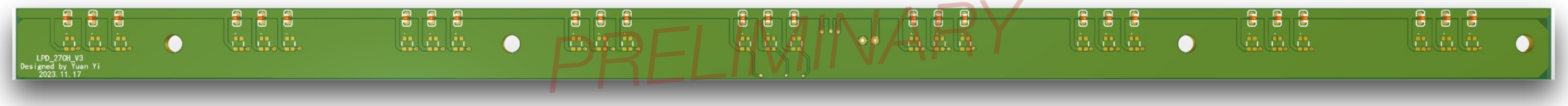
Magnetic Shield

- *Shielding the geomagnetic field*

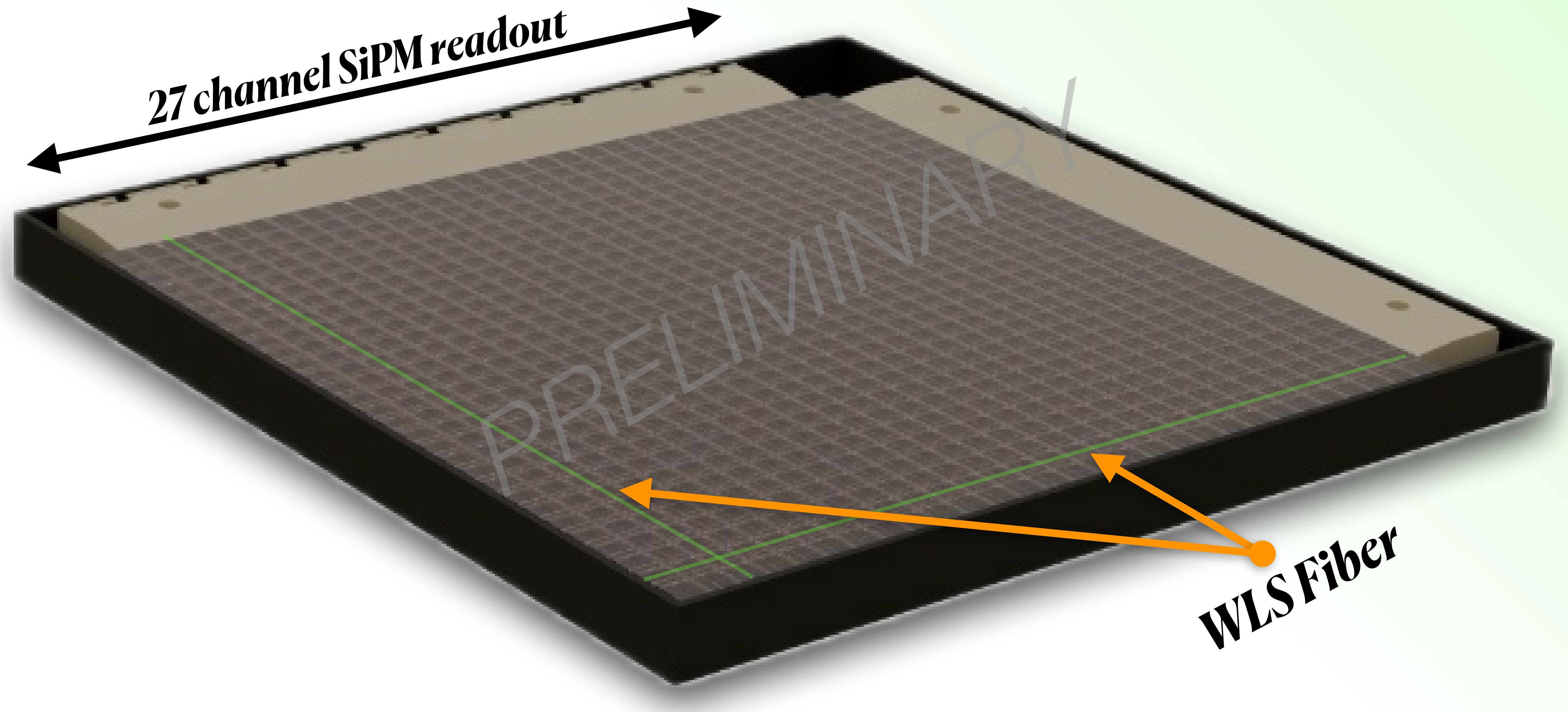


Conceptional Design *Prototype Design*

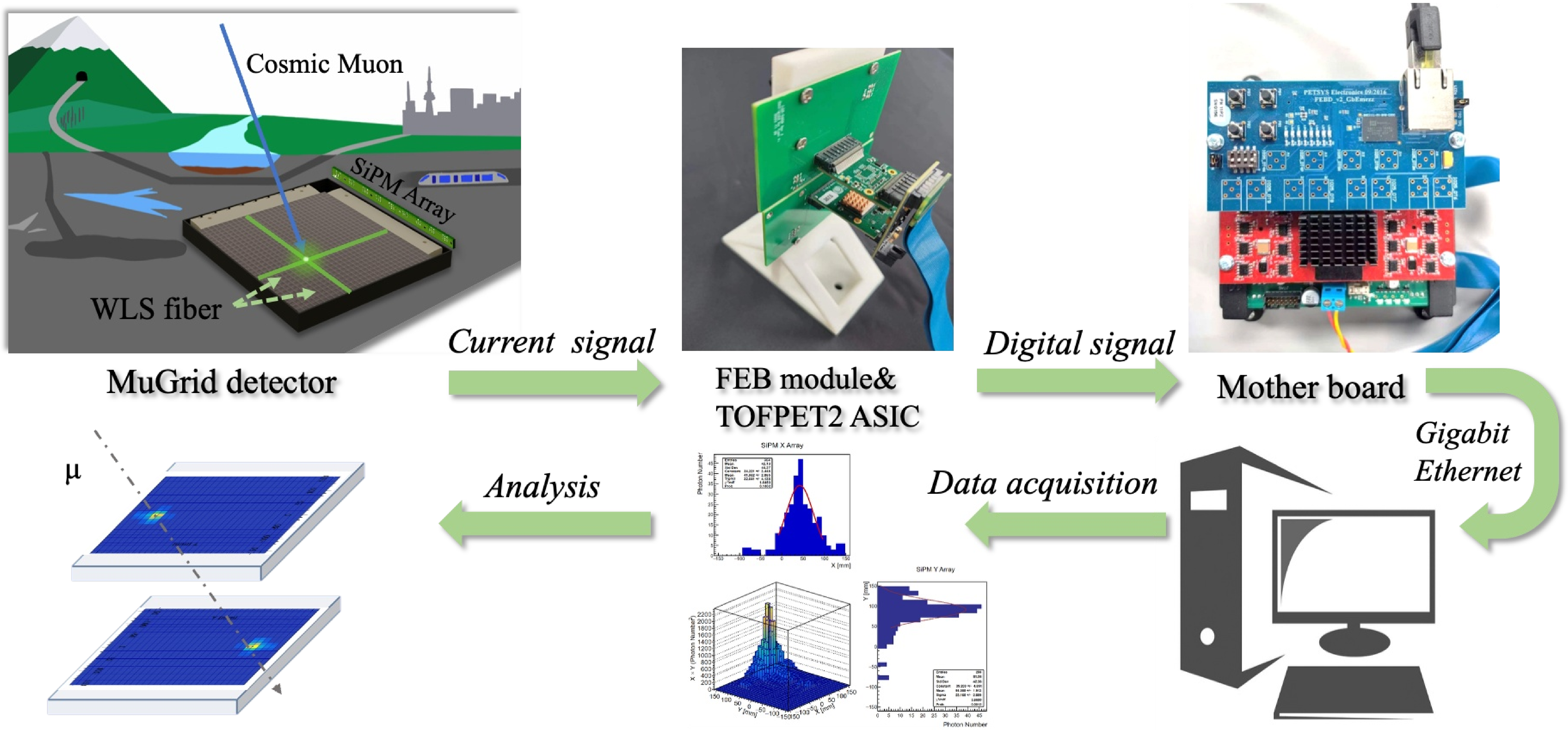
MDD In CRmuSR Prototype

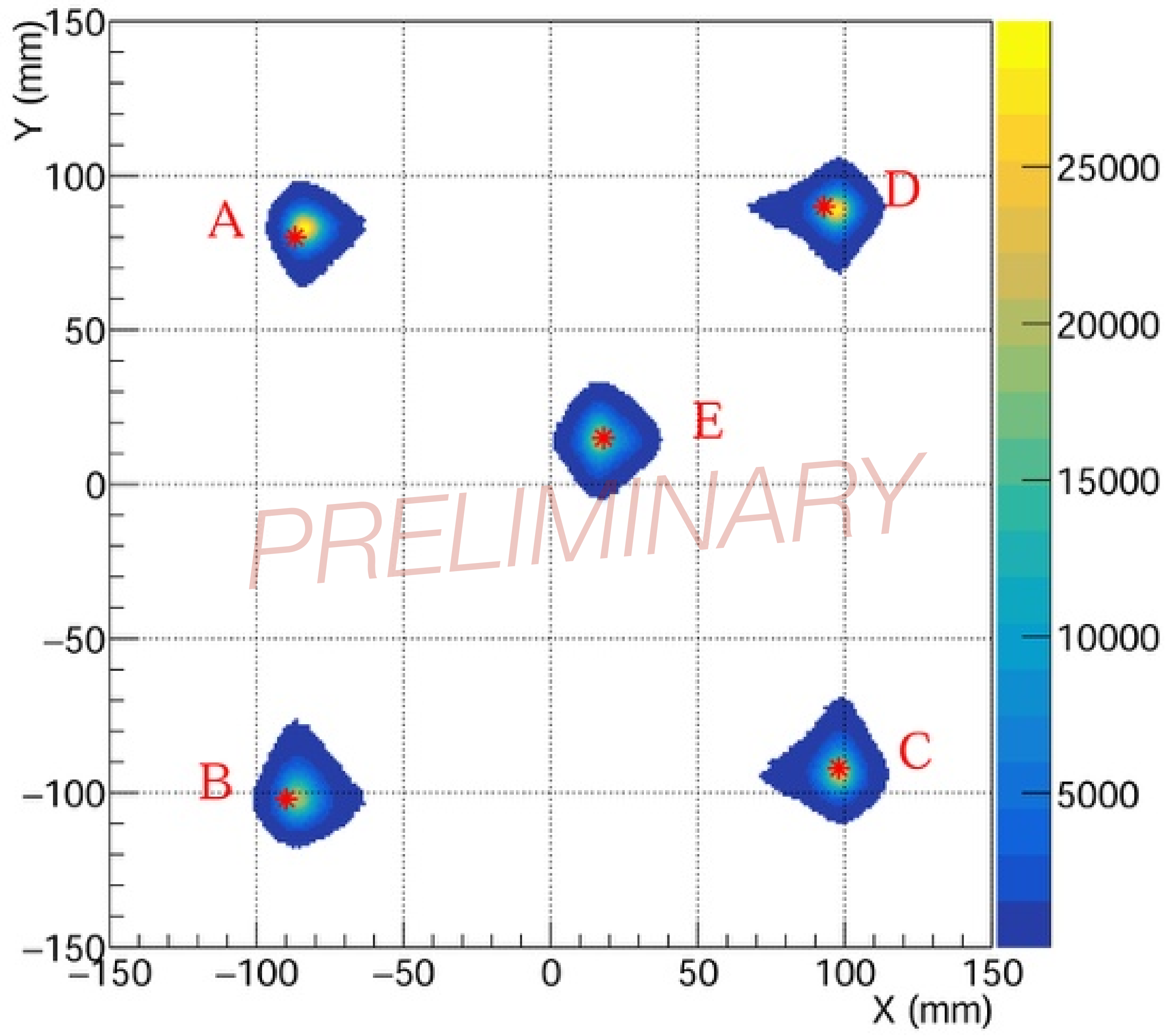


27 channels SiPM readout PCB board. (By Yi Yuan)



LGA single layer design (27 channels version).





PDR In CRmuSR Prototype

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.

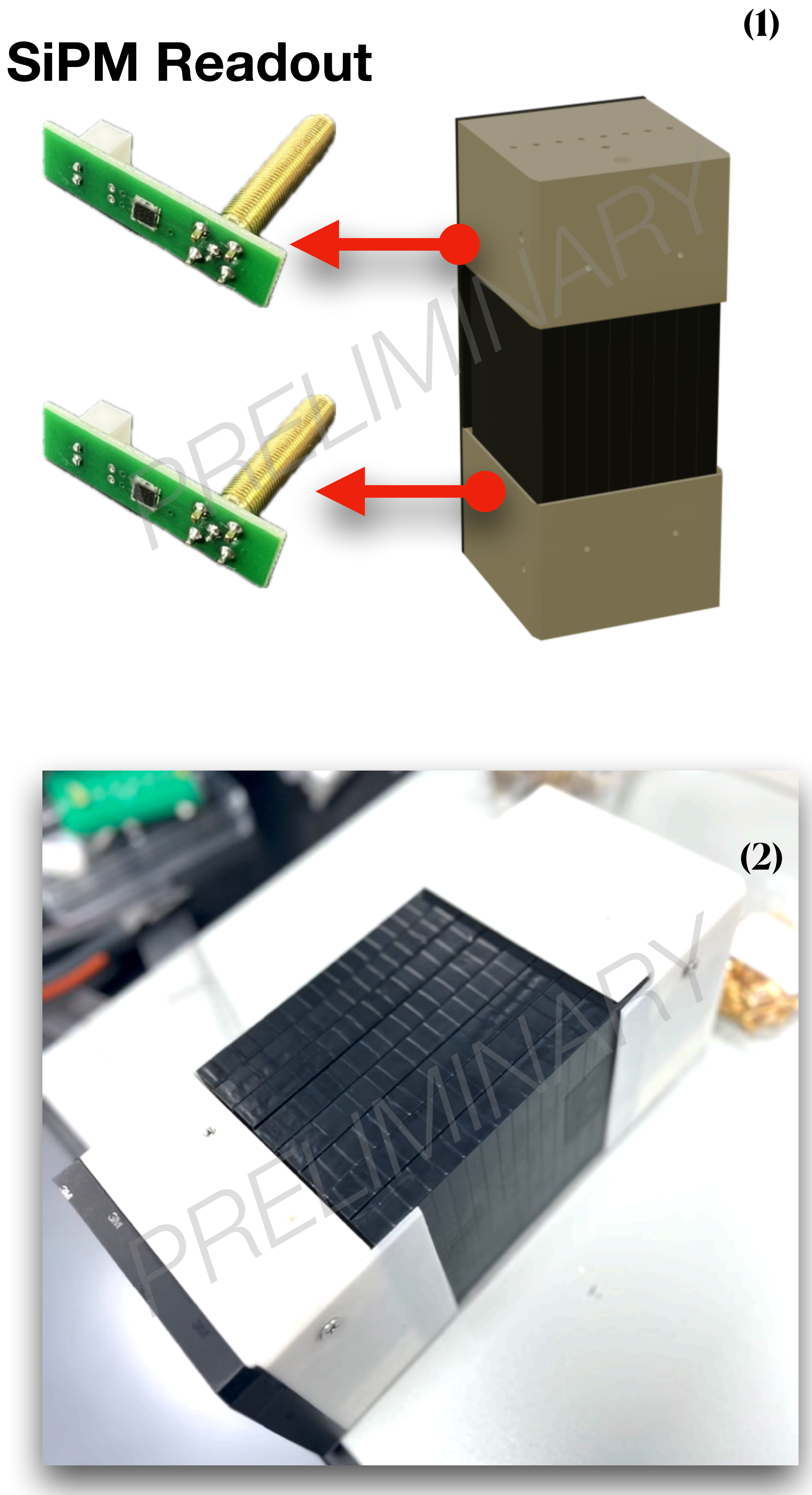


Figure: (1) The design of single unit in PDR and the location of SiPM readout. (2) Single PDR unit detector.

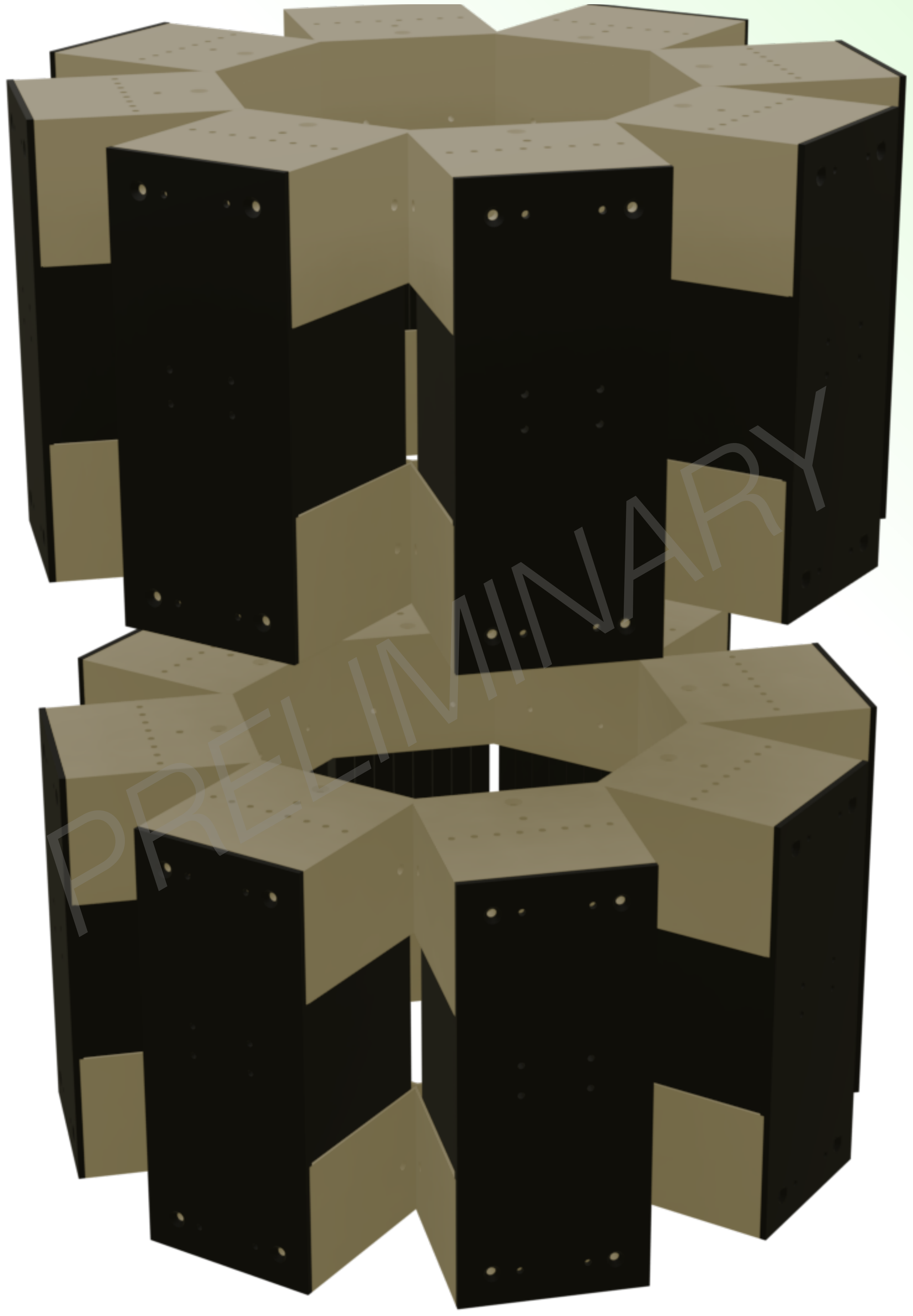
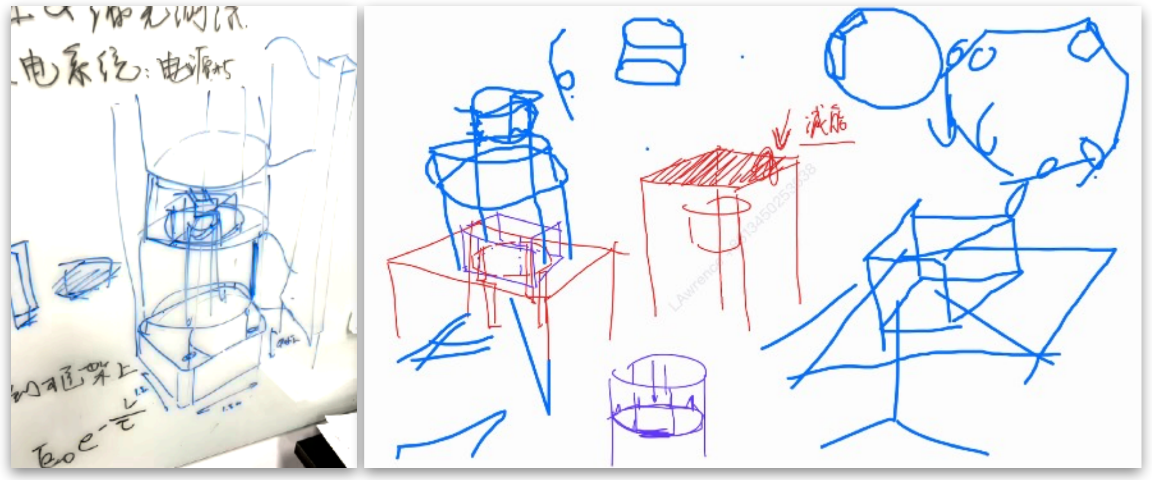
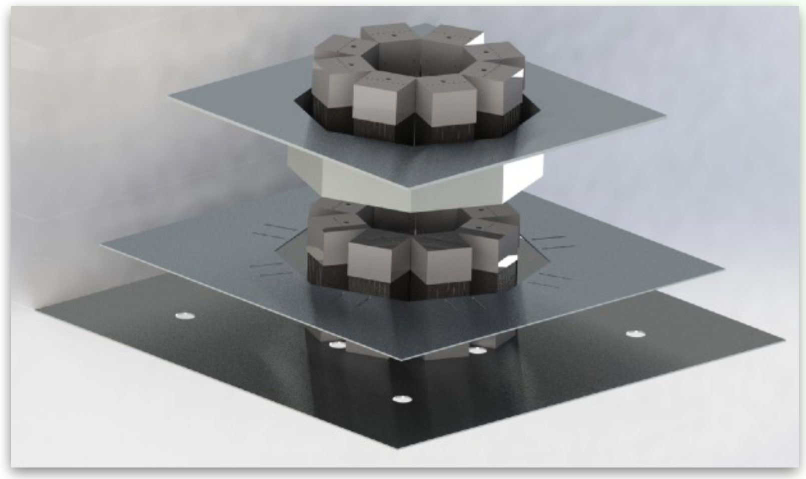


Figure: Two PDR arrangement in CRmuSR detector.

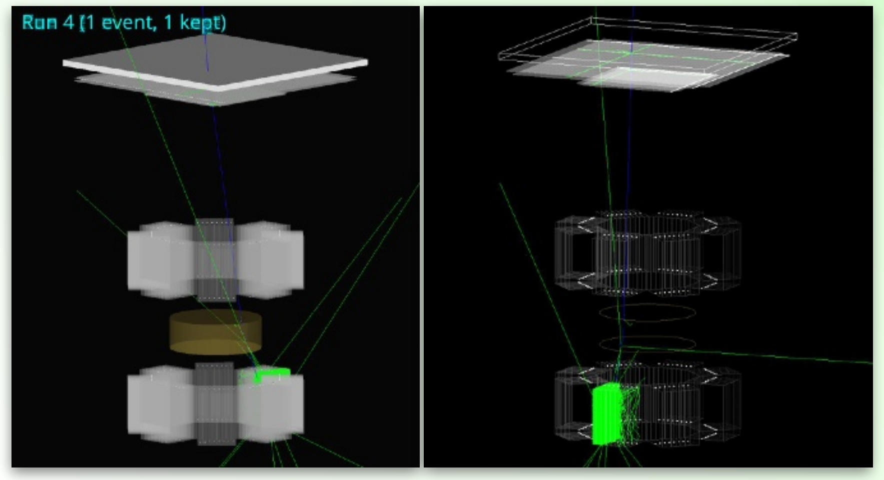
CRmuSR Prototype



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

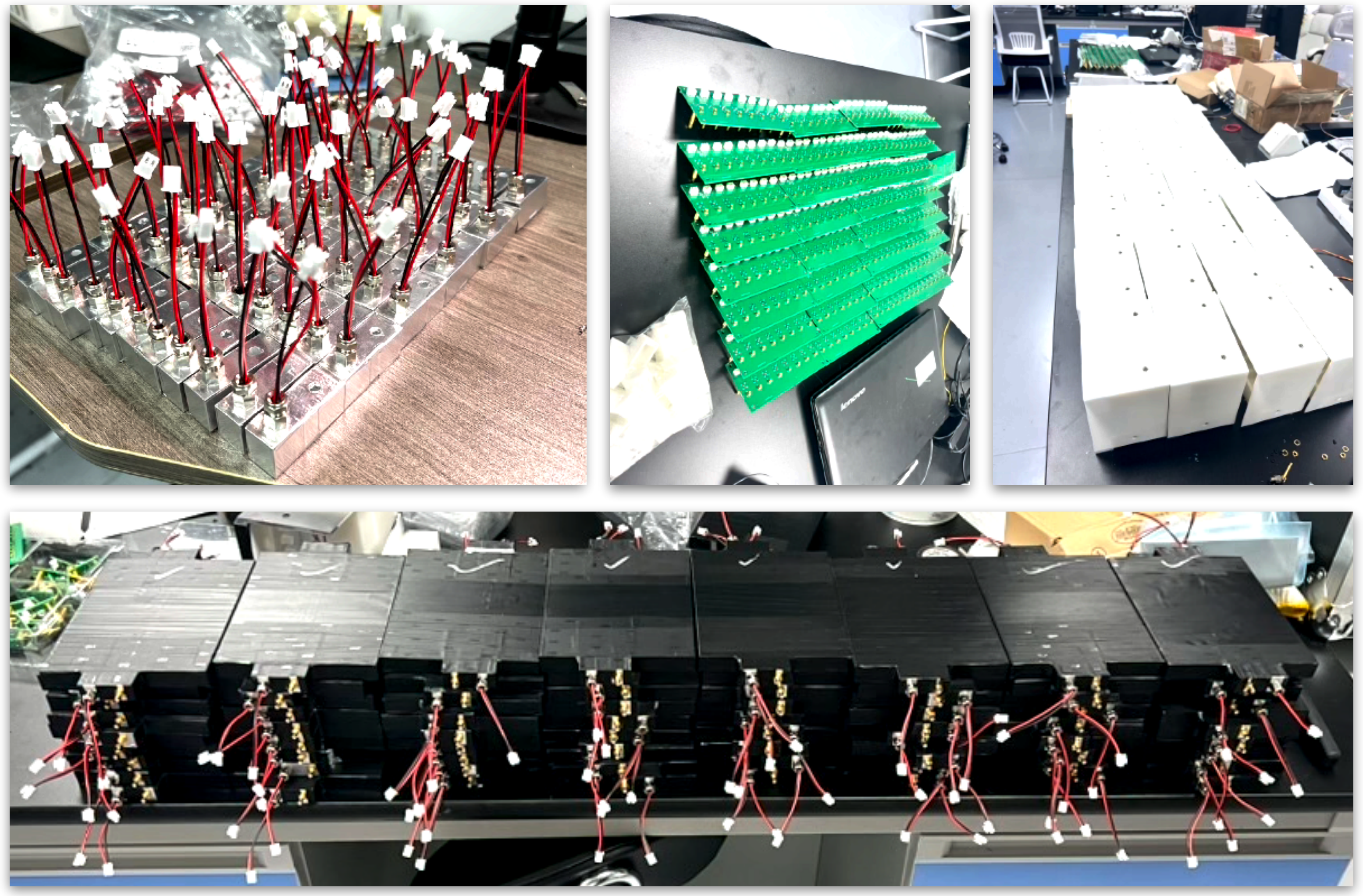


First design for 2 PDR

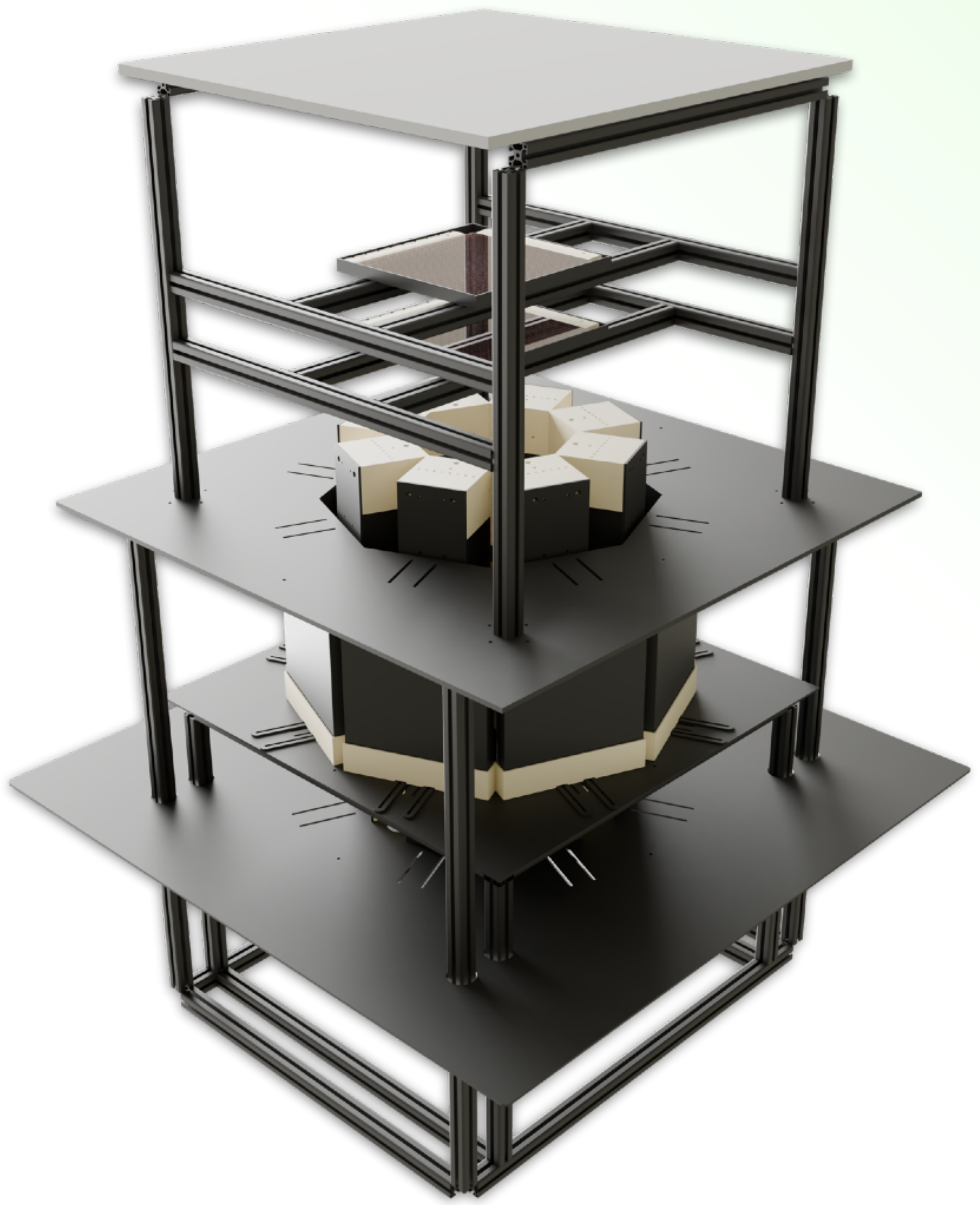


Signal and background simulation .
(Mainly by Aiyu Bai)

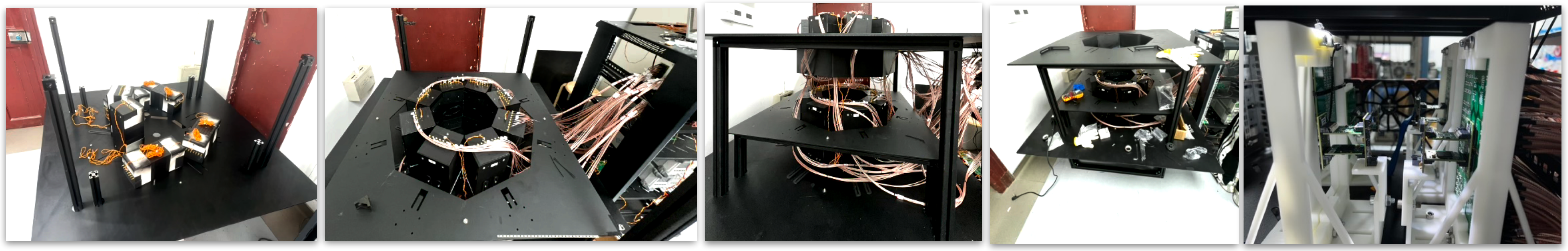
CRmuSR during data acquiring process.



Encapsulation progress. (By SMOOTH lab)



Final design of CRmuSR



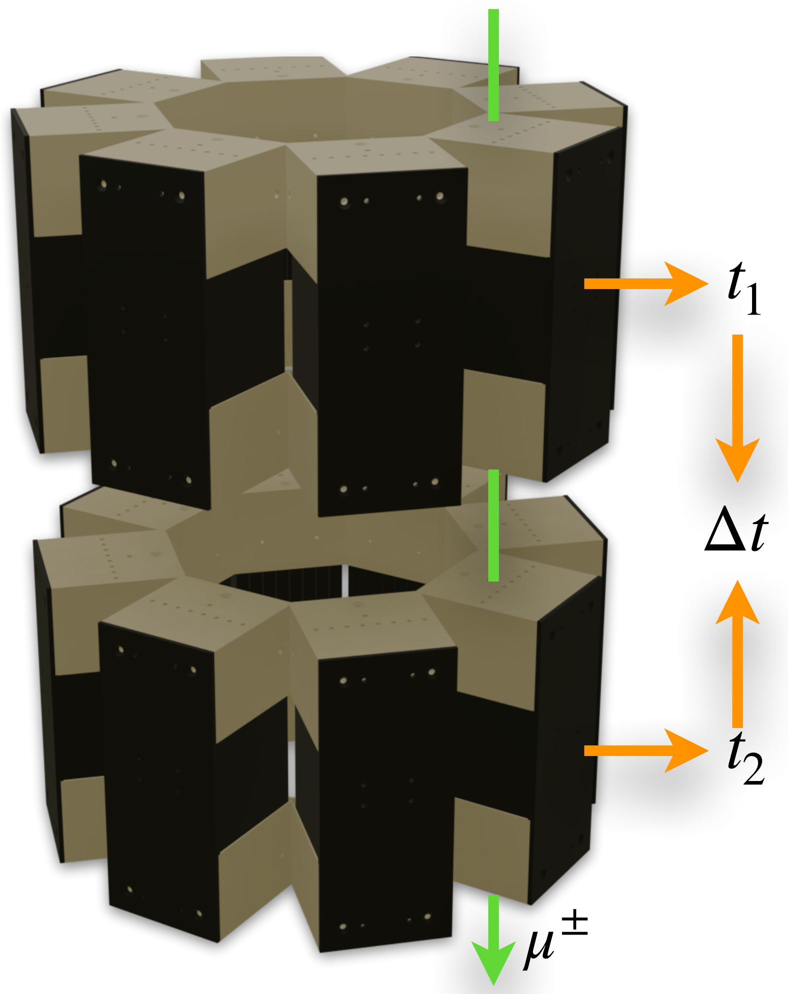
CRmuSR assembly process (By SMOOTH lab)

Preliminary Analysis

Up-down Decay asymmetry

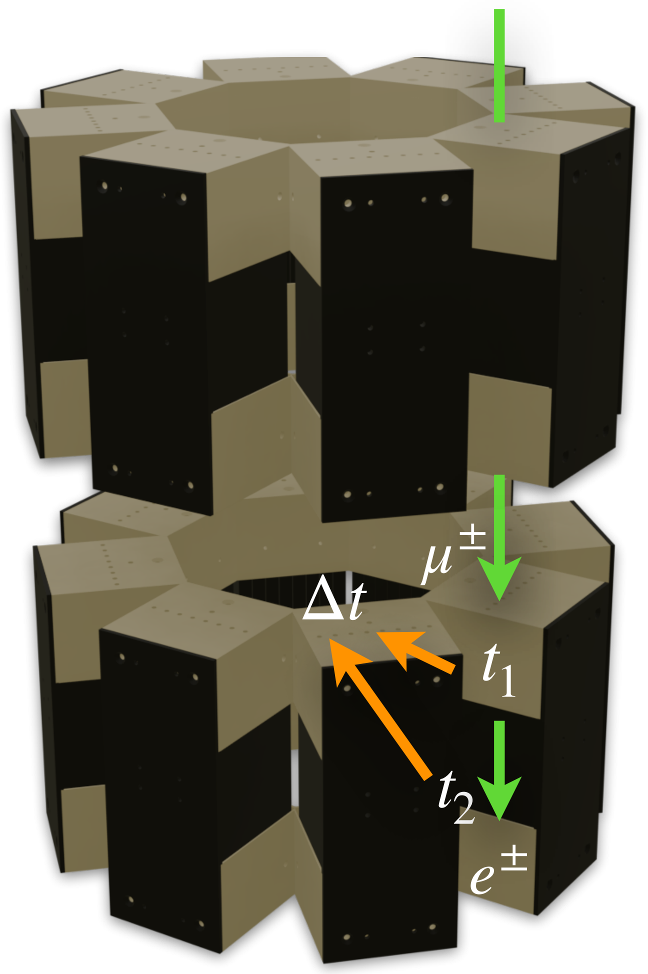
$$\alpha_e = \frac{N_u - N_d}{N_u + N_d} = 0.036 \pm 0.021$$

Time resolution of PDR is about 1ns.



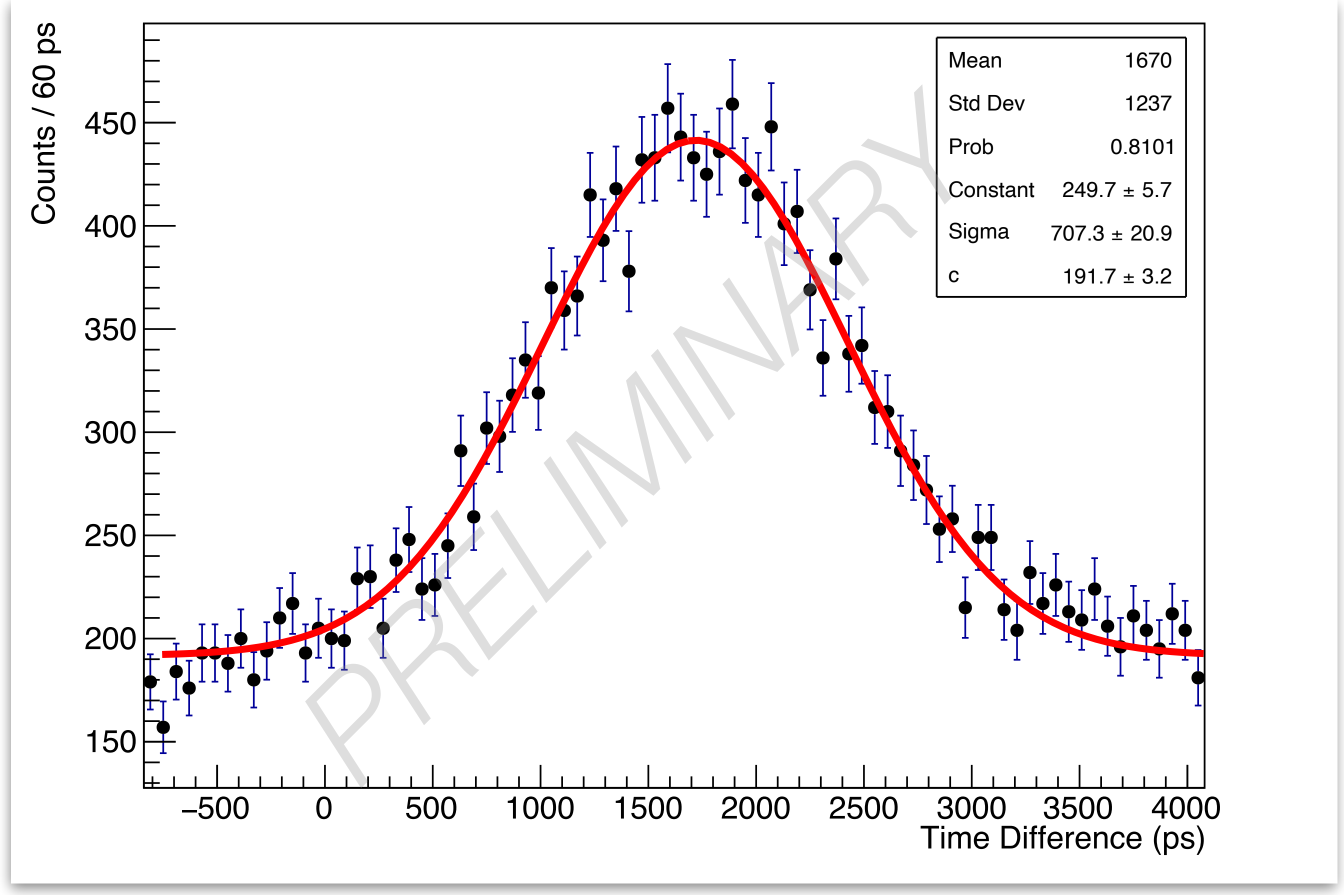
Using penetrate cosmic-ray muon test PDR time resolution.

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

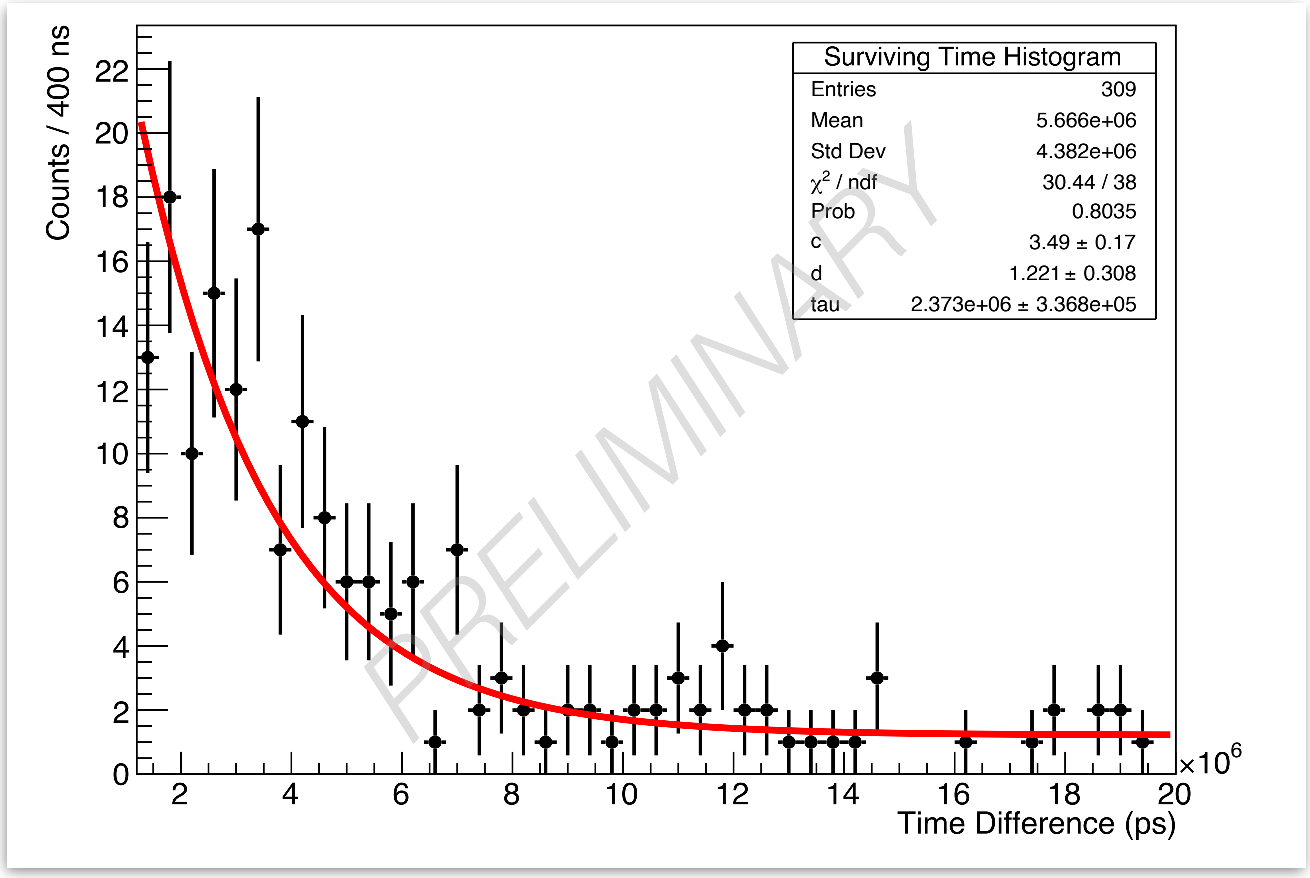


Lifetime of cosmic-ray muon decay in PDR.

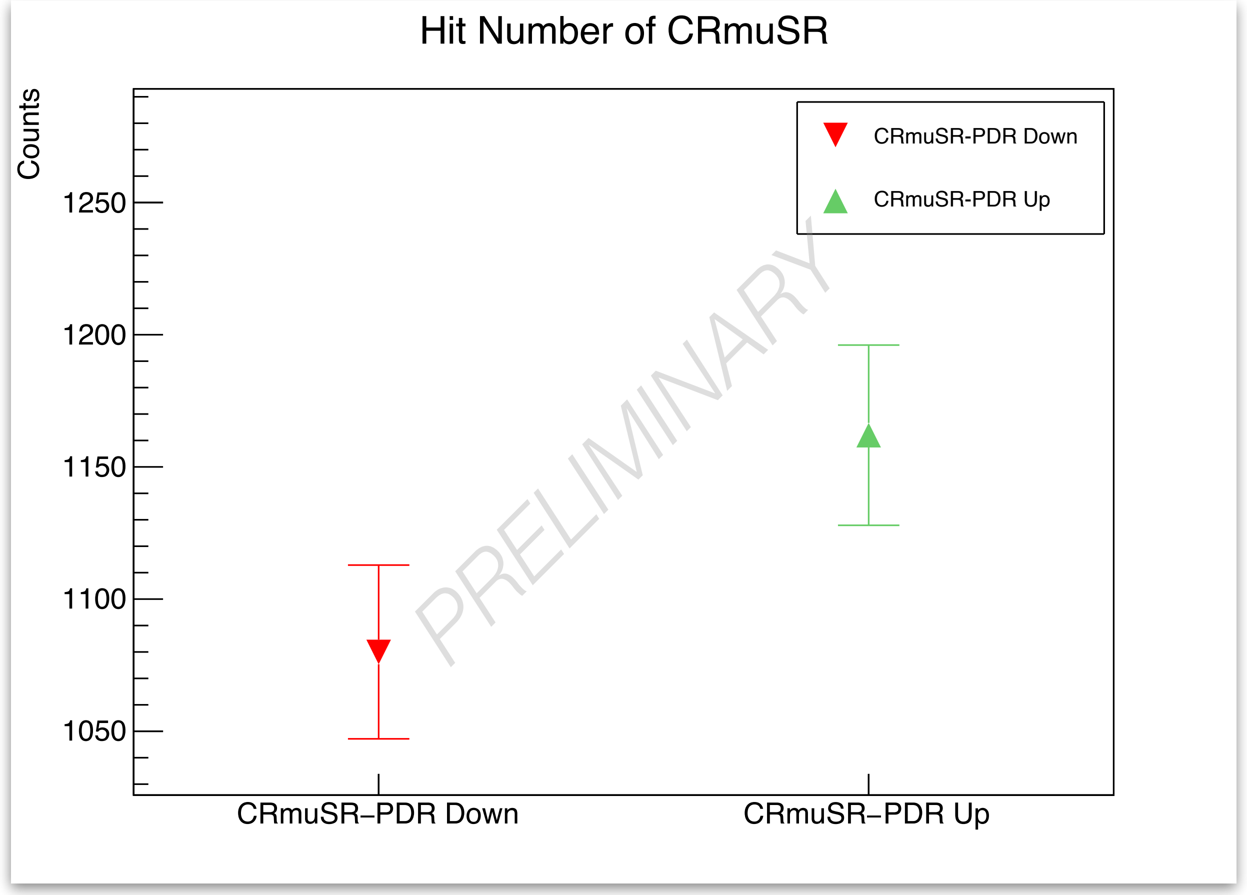
CRmuSR testing target in the present.



Preliminary analysis for time resolution of PDR.



Preliminary analysis for cosmic-ray muon lifetime with PDR.

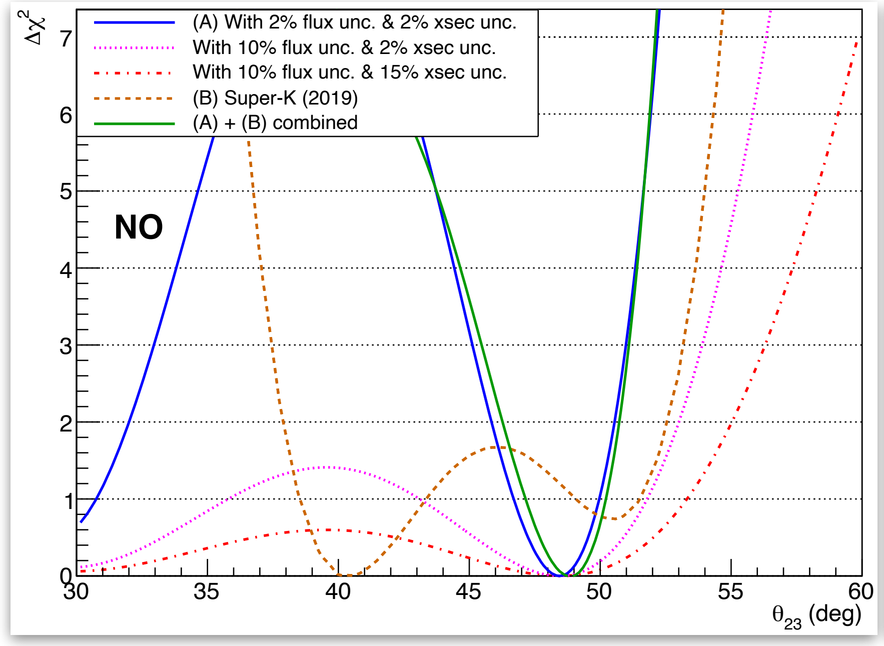


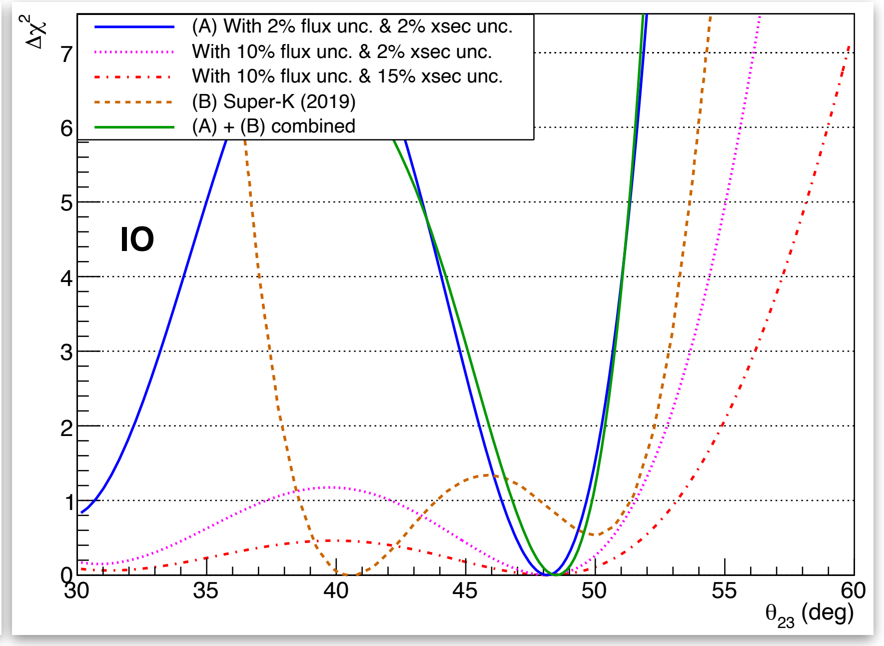
Rough analysis of Michel electron hits in CRmuSR experiment.

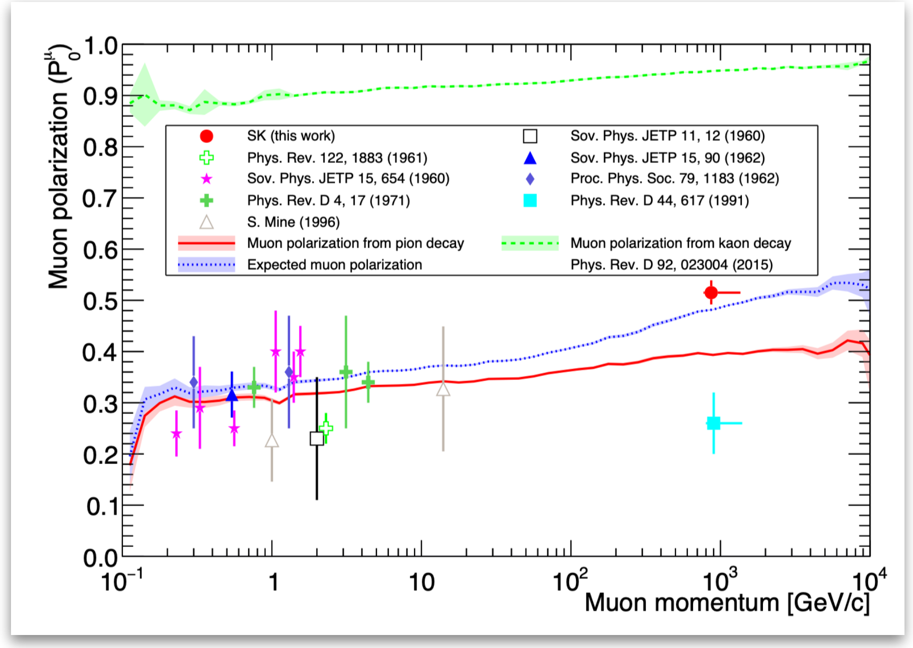
Further data acquisition and analysis are in progress ...

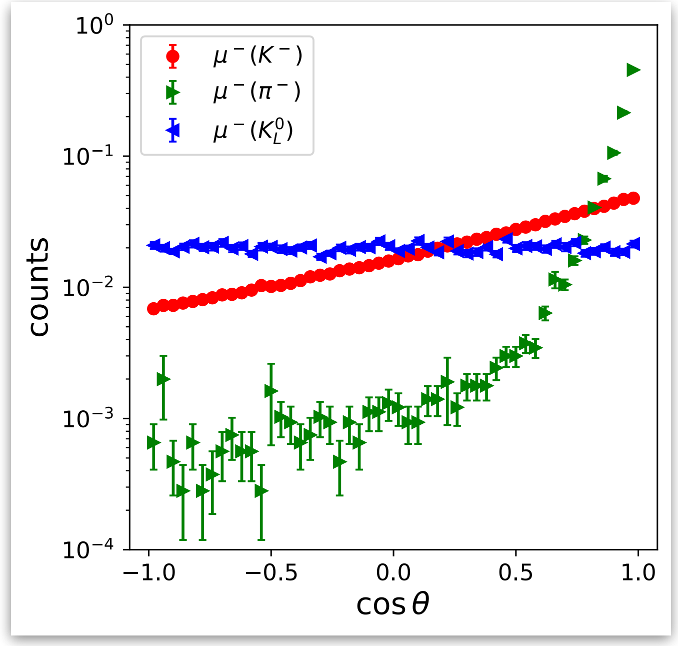
- Cosmic Ray Muon Polarization Measurement
- How Atmospheric Neutrino Uncertainty Affects the Sensitivity of Neutrino Experiments?
- Cosmic Ray Muon Polarization Detector (CRmuSR)
- **Summary and outlook**

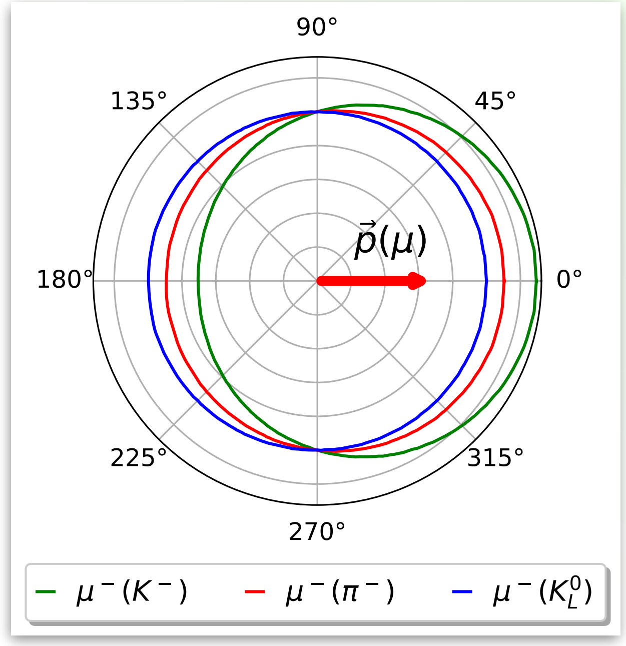
Summary and Global Network

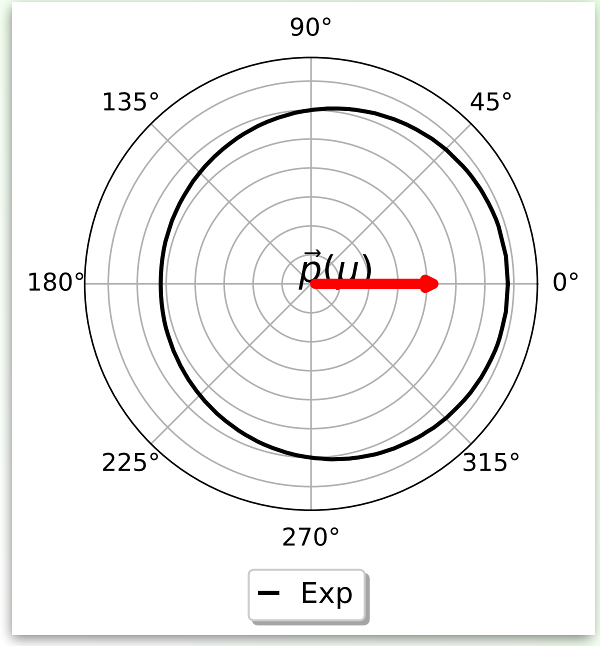












Constrain ATN flux uncertainty

Update the low energy cosmic ray muon polarization data

Motivation

arXiv:2505.13877

Cosmic ray muon polarization measurement

MusAirS Simulation

Estimation of Phase I & II

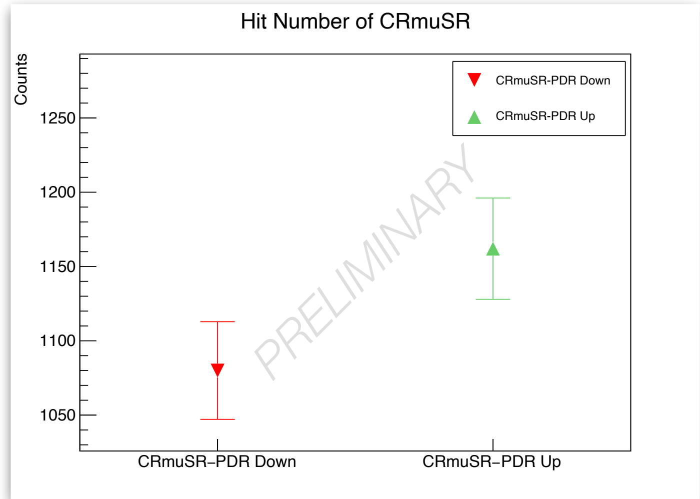
Validation of Atmospheric Neutrino Flux via CRmuSR

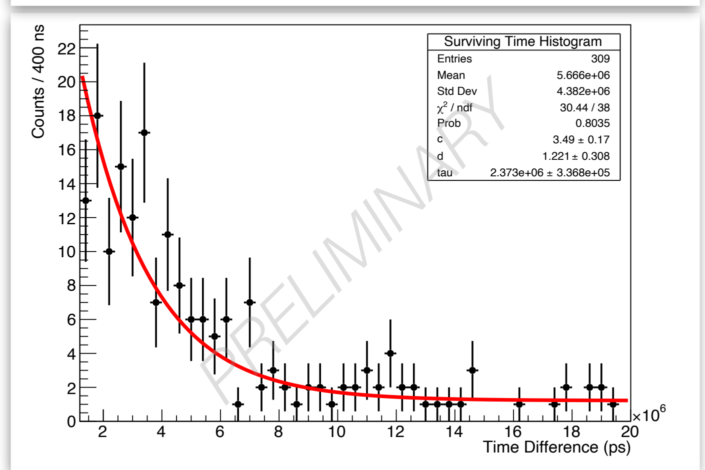
Detector development

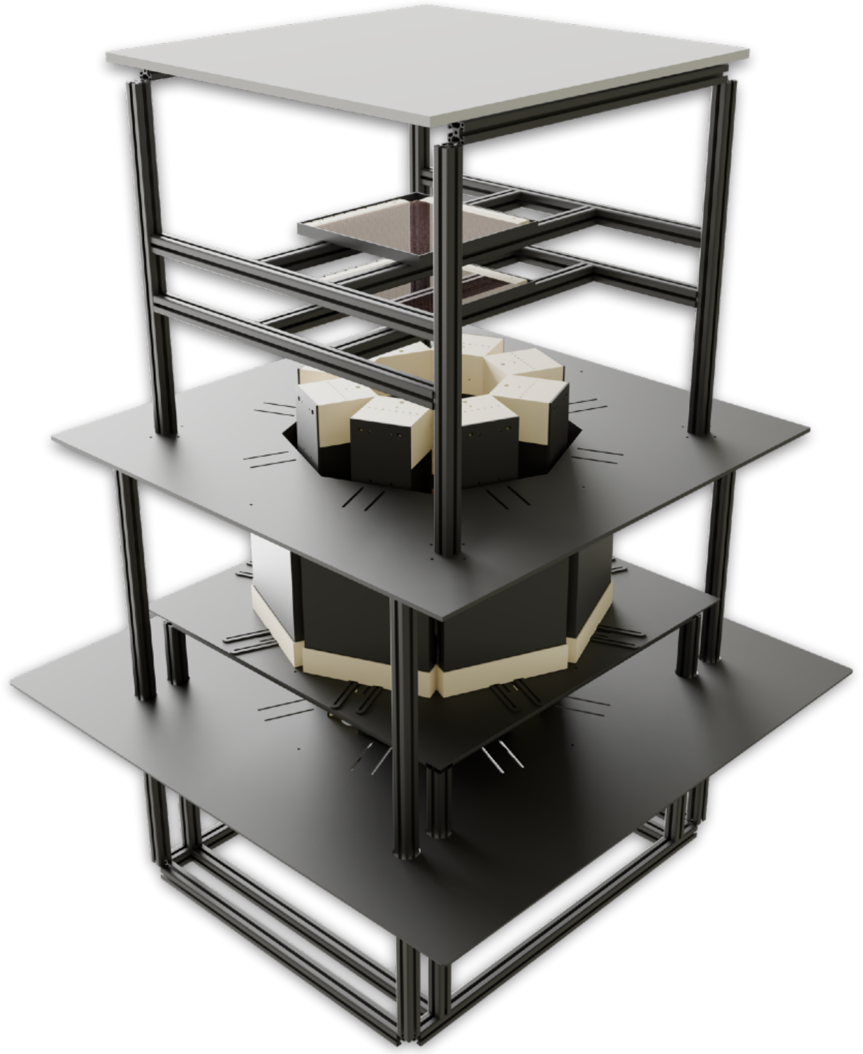
Preliminary analysis

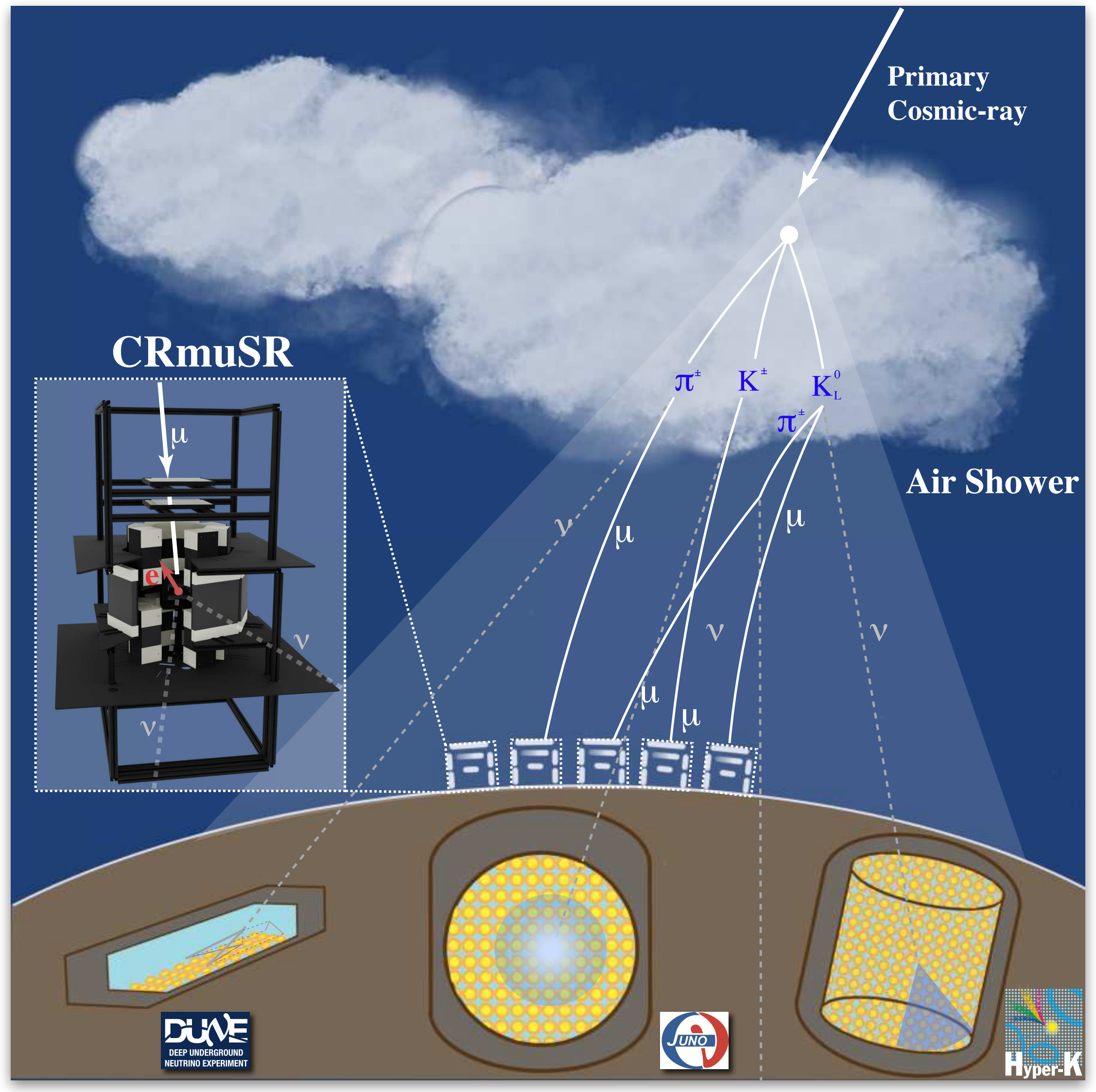
CRmuSR Prototype

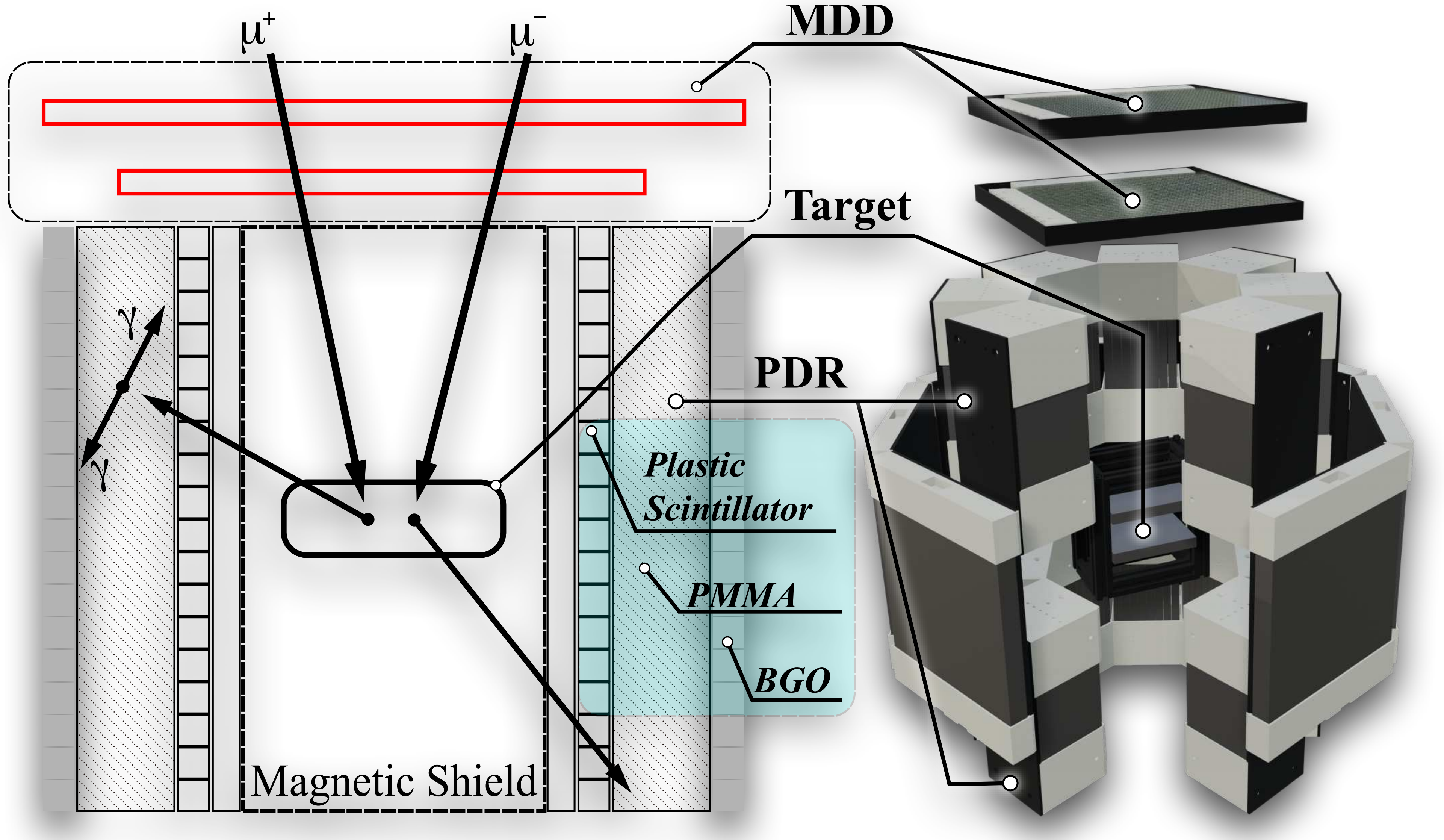
CRmuSR Design











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SMOOTH Team

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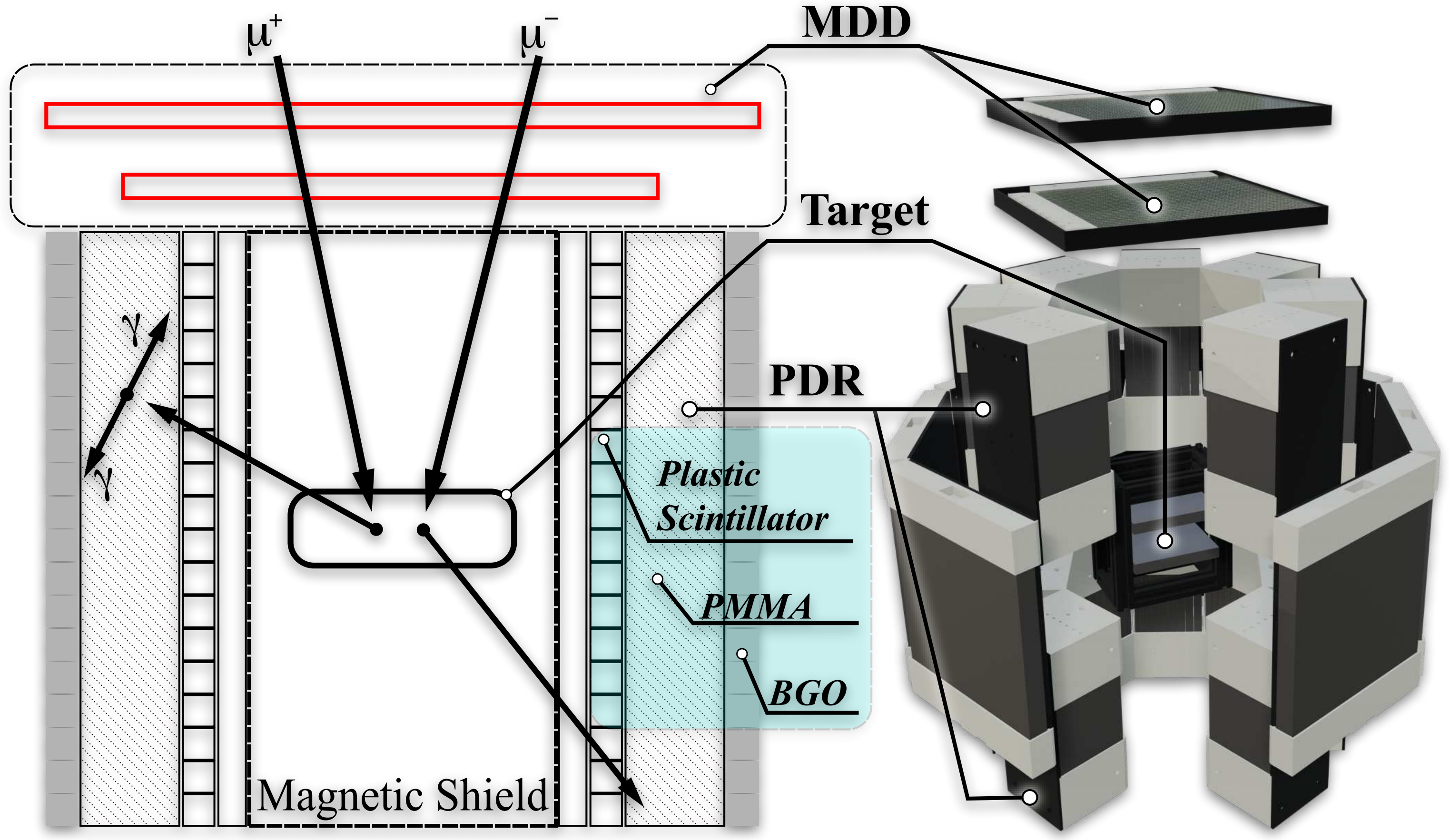
SYSU MuOn and Optical TomograpHy

Cosmic Ray Muon Experiment

CRμSR

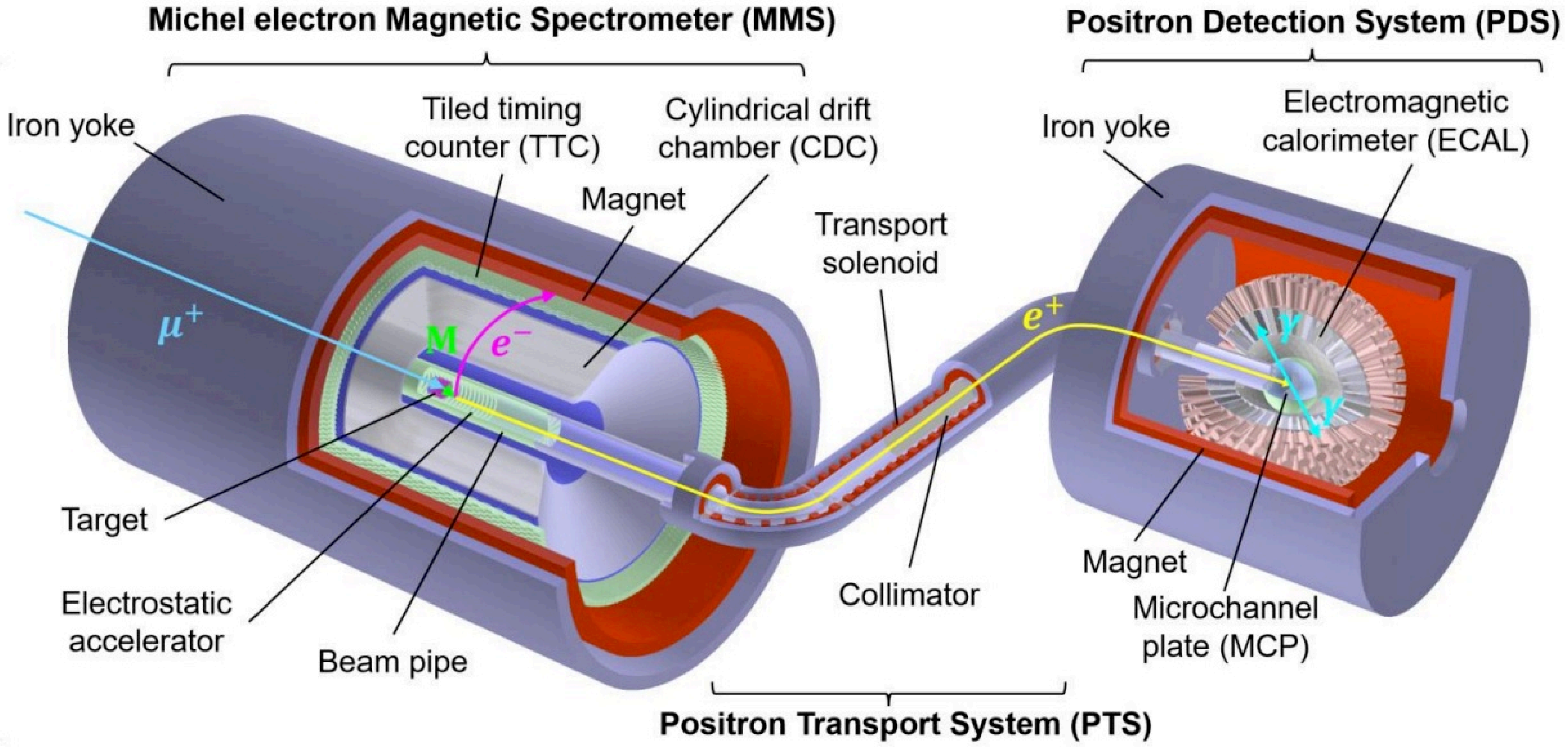
arXiv:2505.13877



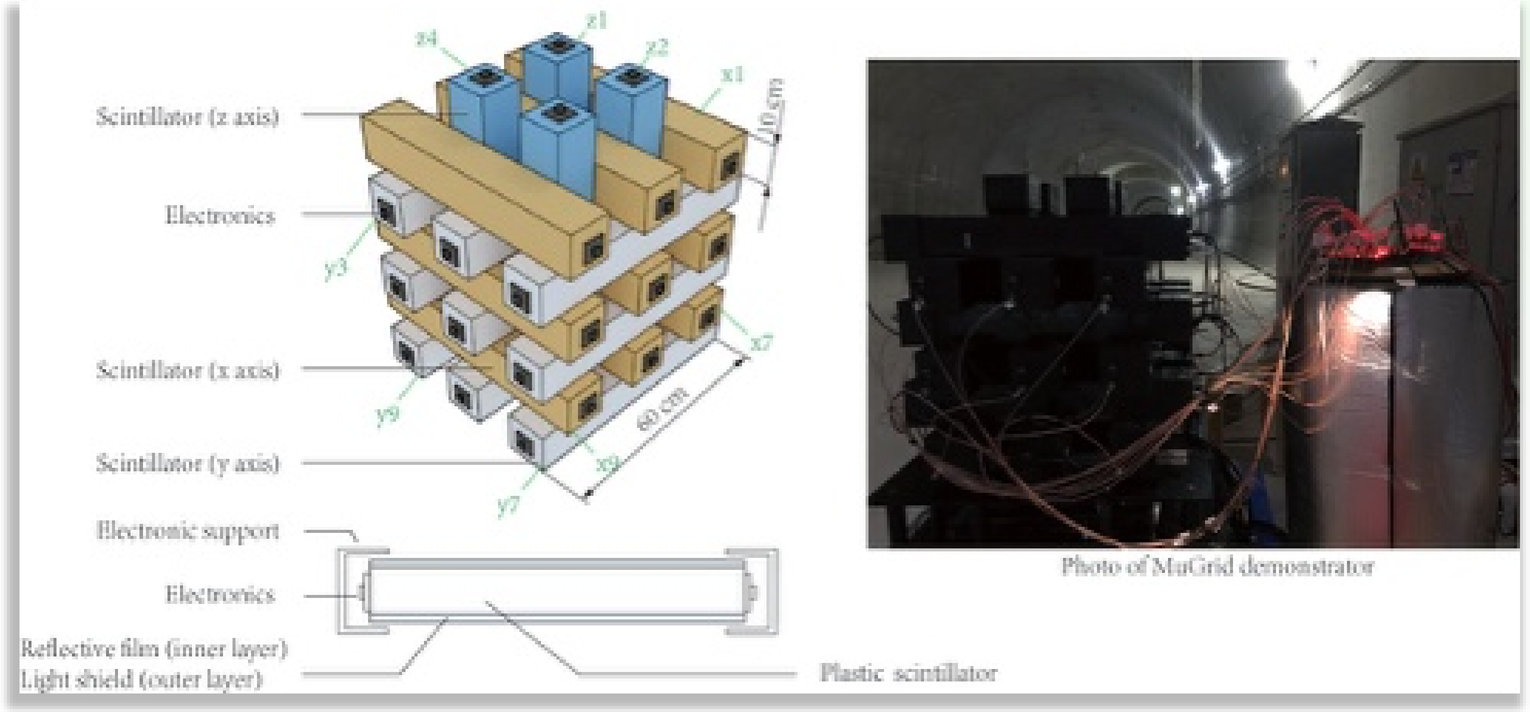
New Physics Experiment

Muonium-to-Antimuonium Conversion Experiment

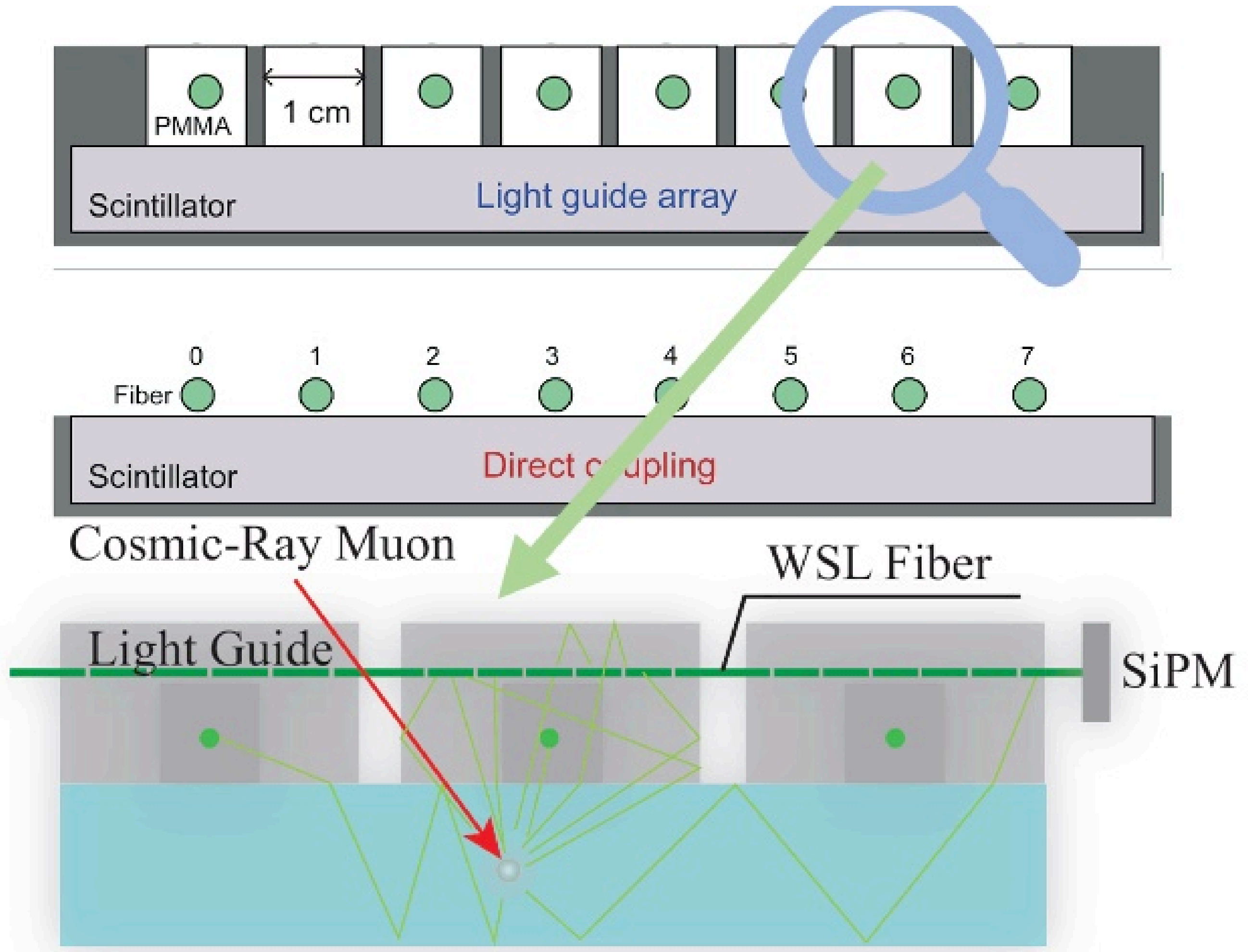
arXiv:2410.18817



Muon Related Application



arXiv:2505.19777



Thanks

Back Up

Average Polarization Calculation

$$\mathcal{P}_\mu = \frac{\cos\alpha\sqrt{1+R_p^2} + R_p + g(\alpha, R_p, R_m)}{\sqrt{2R_p\cos\alpha\sqrt{1+R_p^2} + (1+\cos^2\alpha)R_p + 2} \cdot \sqrt{1+g^2(\alpha, R_p, R_m)}},$$

$$g(\alpha, R_p, R_m) = \frac{\cos\alpha\sqrt{1+R_p^2} + R_p + R_m}{\sqrt{1+R_m^2}\sqrt{2R_p\cos\alpha\sqrt{1+R_p^2} + (1+\cos^2\alpha)R_p + 2}}.$$

$R_m = m_\mu / m_M$ **is the mass ratio between muon and its parent particle**

$R_p = p_M / E_M$ **is the momentum-to-energy ratio of muon parent particles**

α **is the angle between muon momentum direction and Michel electron momentum direction**