中山大學
SUN YAT-SEN UNIVERSITY

物理学院
SCHOOL OF PHYSICS

Cosmic-ray muon polarization and atmospheric neutrino

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Platform for Muon Science and Technology

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- **Atmospheric Neutrino Flux Uncertainty**
- **Measurement of Muon Polarization**
- **Simulation about Cosmic-ray Muon Polarization**
- **Conclusion & Outlook**

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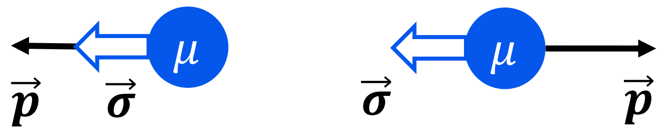
What is Muon Polarization

- What is Muon Spin Polarization?

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



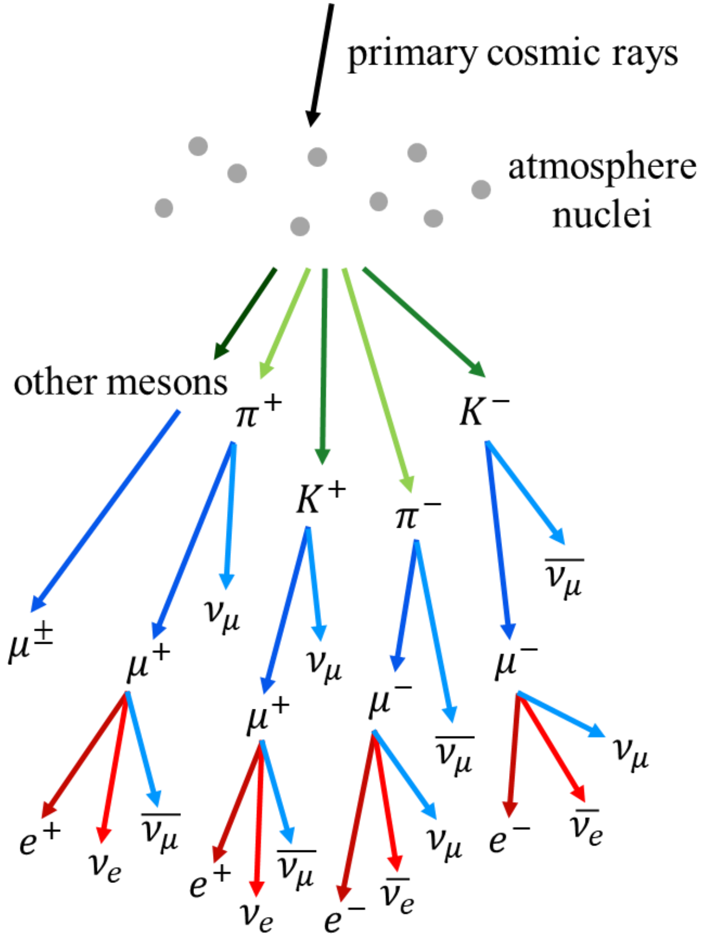
- Muon Production

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

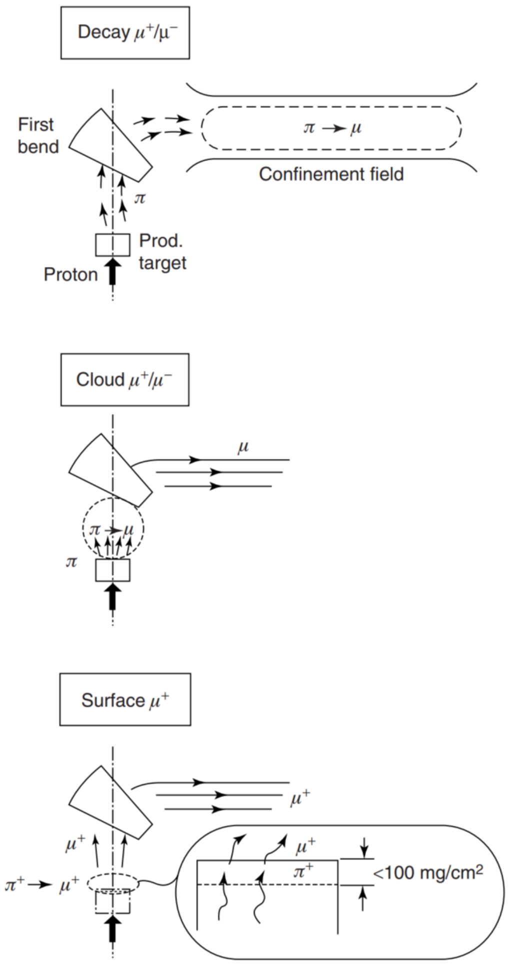
100% polarized

(center-of-mass frame)

Cosmic-ray muon



Accelerator muon



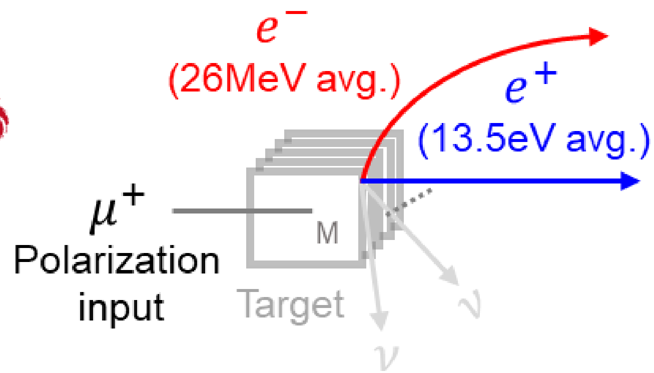
Nagamine, Kanetada. *Introductory muon science*. Cambridge University Press, 2003.

Why Muon Polarization Important?

Future experiments

$P_\mu \rightarrow$ Michel $e^\pm$ distribution

- Muonium-to-Antimuonium Conversion Experiment (MACE)



- MEG II: $\mu \rightarrow e\gamma$
- Mu3e: $\mu \rightarrow eee$
- COMET & Mu2e: $\mu N \rightarrow eN$

Application

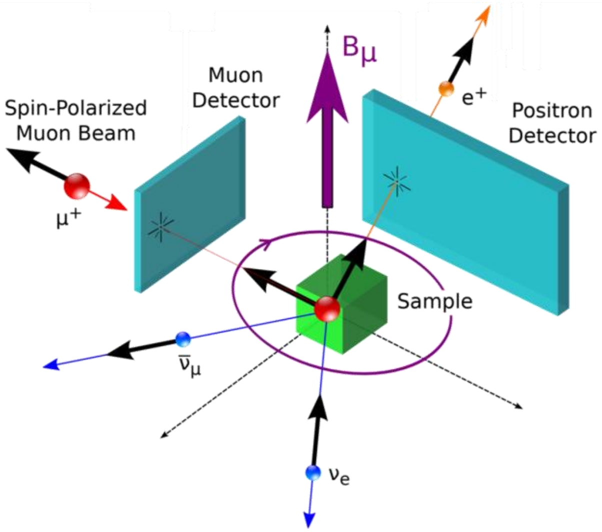
- Muon spin rotation/relaxation/resonance techniques (**μSR**) technique

  Using polarized muons as sensitive probe

  Magnetic order
  Spin dynamics
  Superconductivity
  ……

  Studying muon properties

  Hyperfine structure
  Diffusion phenomena
  Muonium
  ……



Amato, A. "Physics with muons: from atomic physics to solid state physics." *Lecture PHY* 432 (2018): 11-17.

Cosmic-ray studies

- **Atmospheric neutrino: next section**

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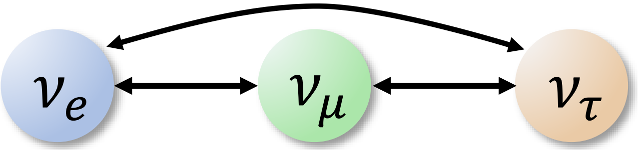
Atmospheric Neutrino

- **Neutrino oscillation**:



- **Atmospheric neutrino (ATN)**

  Wide energy range
  Long travel distance → Sensitive to θ_{23} and Δm^2_{32}

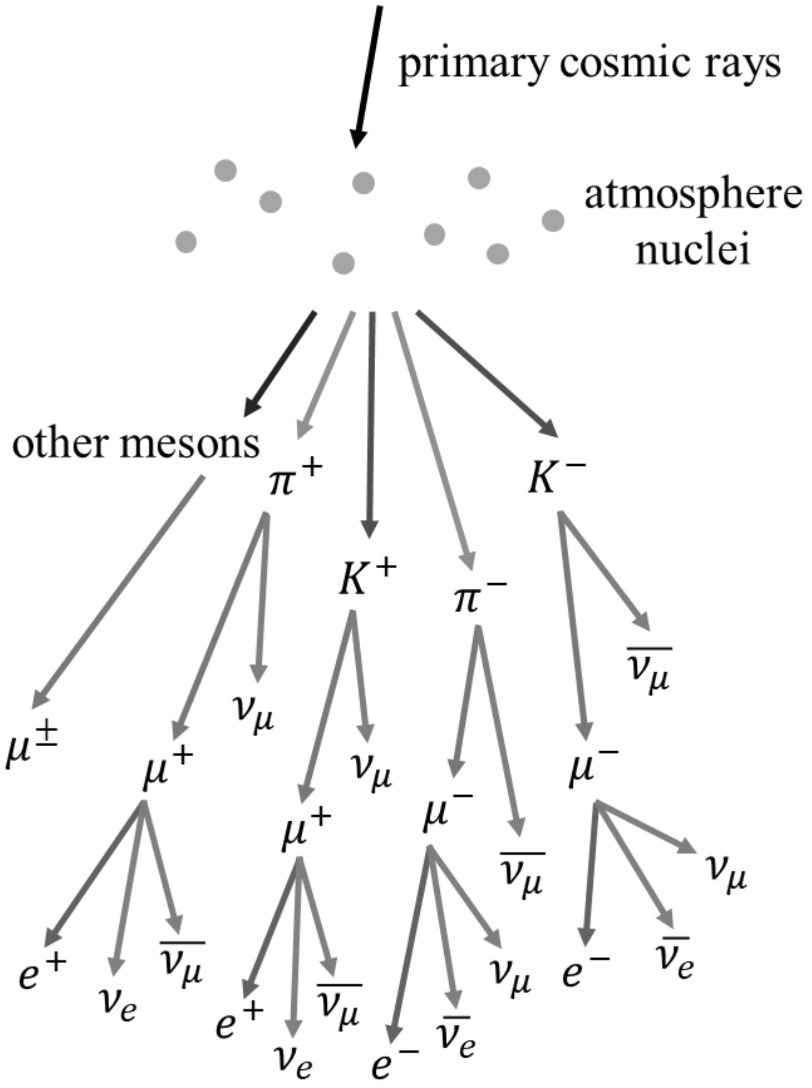
- ATN production process

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

- **Simulation toolbox: 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



Flux Uncertainties

- Simulation settings:

Detector	Event rate	Model	Energy range	Energy bin number	Direction resolution	Energy resolution
LS (4000 kt · yr)	34.7/kt · yr	HKKM	0.1-100 GeV	100 (log-scaled)	—	$\sigma_E^{\nu_\mu}/\text{GeV} = 0.011 + 0.043\sqrt{E/\text{GeV}}$ $\sigma_E^{\bar{\nu}_\mu}/\text{GeV} = 0.006 + 0.049\sqrt{E/\text{GeV}}$

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).

- θ_{23} & δ_{CP} varies while other parameters fixed to PDG values

  θ_{23}: remain ambiguous

  δ_{CP}: depends on the neutrino mass ordering

- Systematic uncertainties

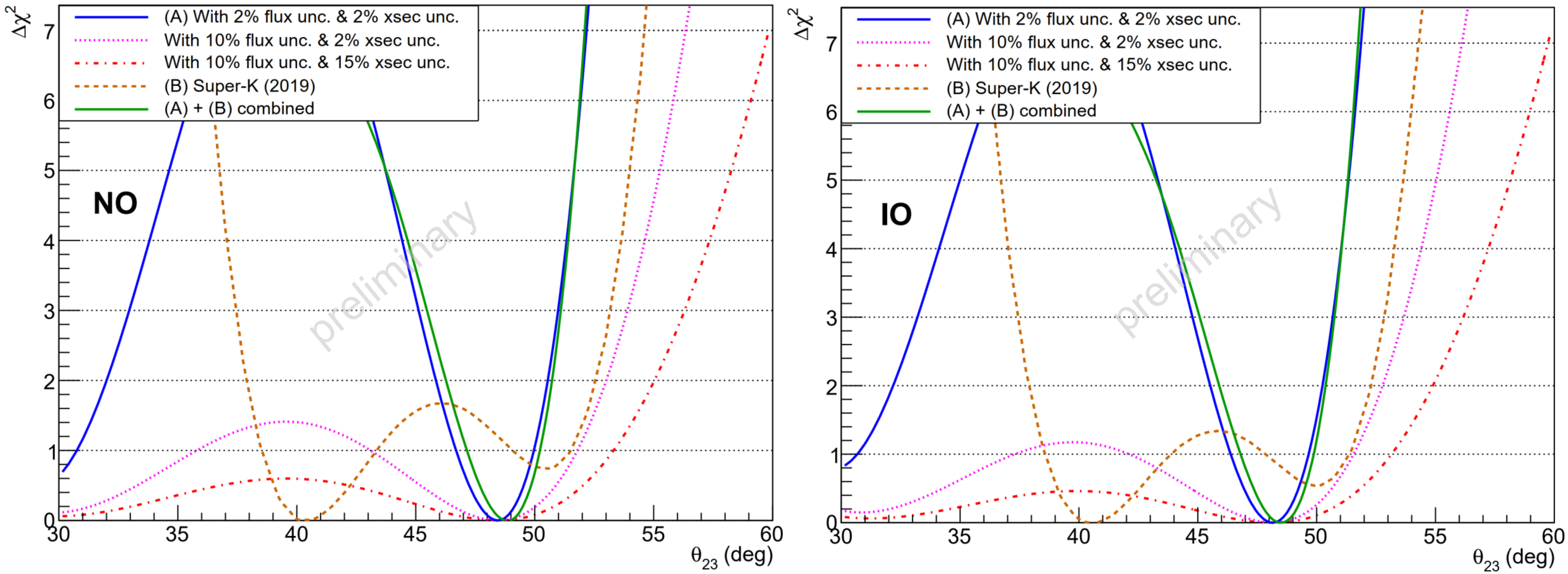
Asimov dataset — Fast simulation dataset

$$\chi^2(\theta_{23}, \delta_{\text{CP}}) = \sum_{k=1}^{100} \frac{\left(n_k - \mu_k(\theta_{23}, \delta_{\text{CP}})\right)^2}{\left(\sigma_{n_k}\right)^2 + \left(\sigma_k^{\text{flux}}\right)^2 + \left(\sigma_k^{\text{xsec}}\right)}$$

Uncertainties: statistical + flux + cross-section

Sensitivity with Different Flux Uncertainties

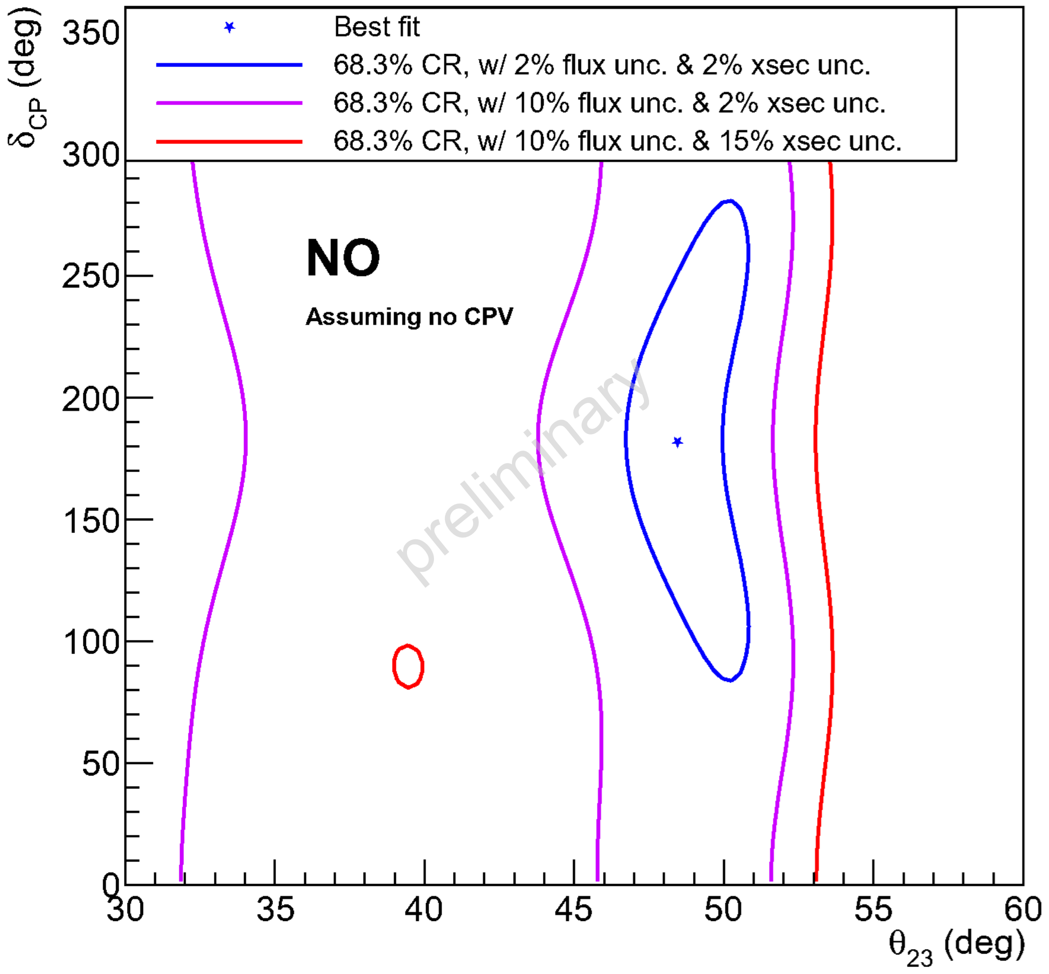
- Reducing flux uncertainties significantly improves the sensitivity to $\boldsymbol{\theta_{23}}$

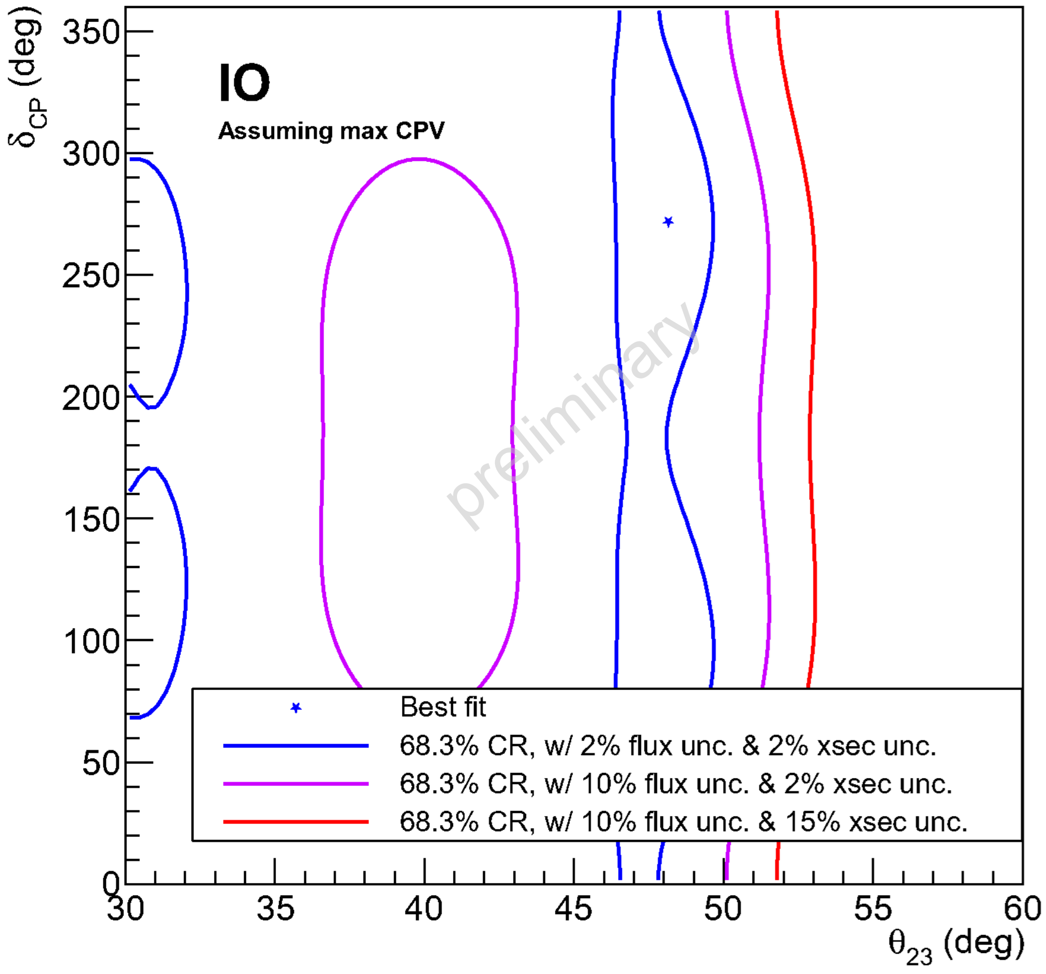


Precision measurement of θ_{23} with different flux and cross-section uncertainties

Sensitivity with Different Flux Uncertainties

- Reducing flux uncertainties significantly improves the sensitivity to $\boldsymbol{\theta_{23}}$ and $\boldsymbol{\delta_{CP}}$





62.8% confidence regions of θ_{23} and δ_{CP} parameters

ATN Flux Modeling

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

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

primary proton/nuclei flux ⊗ geomagnetic field selection effect ⊗ neutrino yield per primary particle

- **Main uncertainties**

- $\phi_{p(A)}$: energy spectrum and composition

  Primary cosmic-ray measurements (AMS-02, PAMELA, etc.)

- $\boldsymbol{Y_{p(A)\to\nu_i}}$: cross section of strong interaction

  Still Challenging

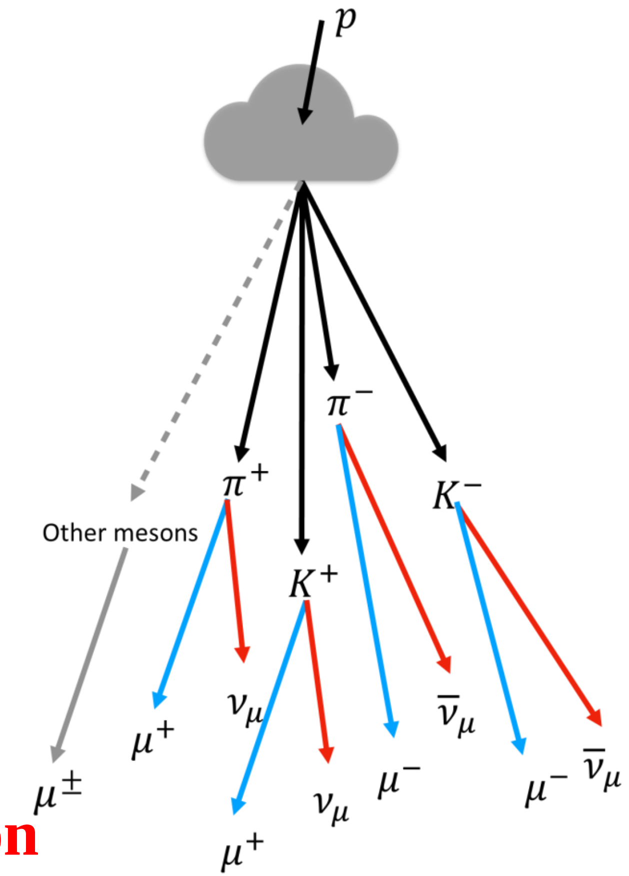
  Can be reduced with:

  - Accelerator experiment & **Cosmic ray measurement**

↓

Especially cosmic-ray muon:

energy spectrum, zenith distribution, **spin polarization**



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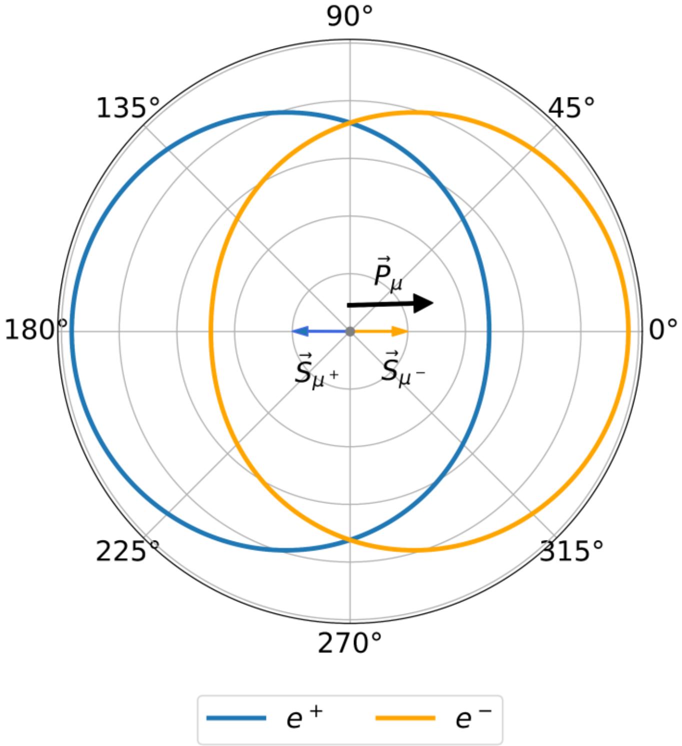
Muon Polarization Measurement: Accelerator

- How to measure:

  angular distribution of Michel electrons

$$d\Gamma = \frac{1}{4\pi\tau_\mu}\left(1 \pm \frac{1}{3}\cos\theta\right)\sin\theta\, d\theta d\phi$$

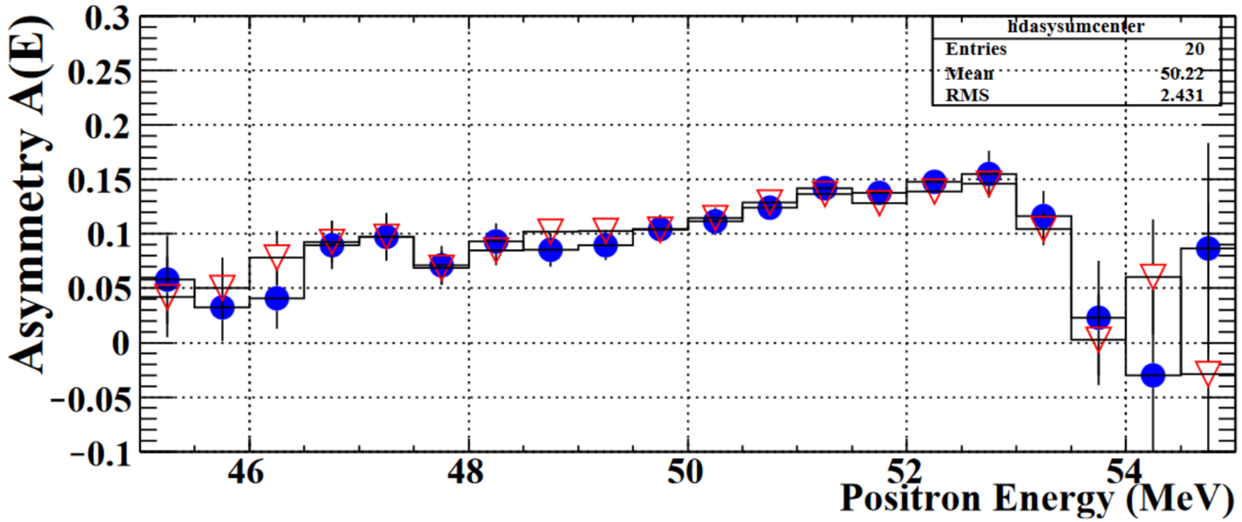


- Accelerator muon polarization

  Good uniformity in direction

  ↓

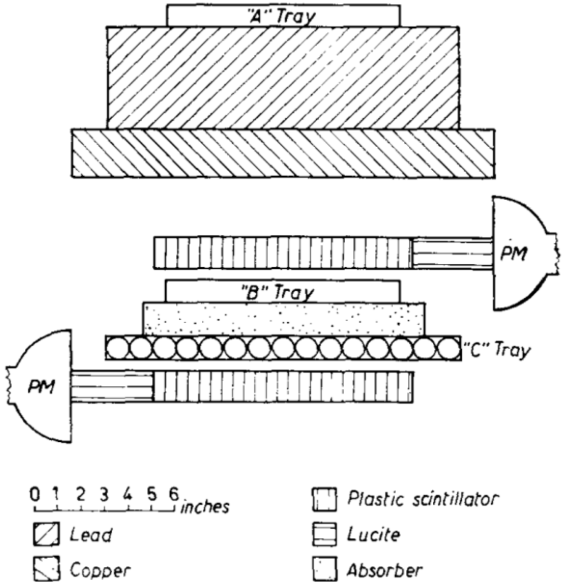
  Up-down asymmetry $\frac{N_u - N_d}{N_u + N_d}$ is enough



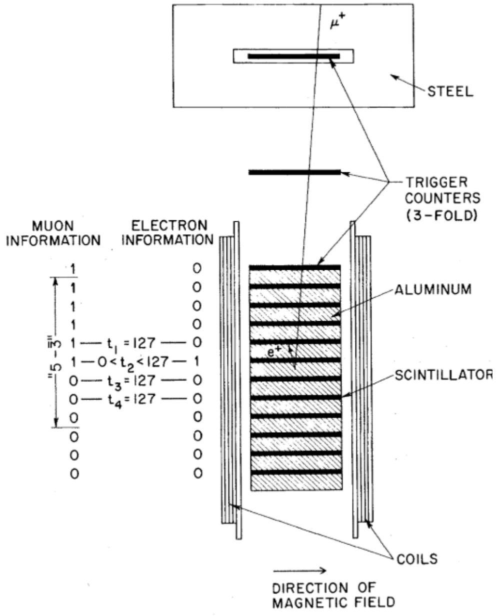
Baldini, A. M., et al. "Muon polarization in the MEG experiment: predictions and measurements: The MEG Collaboration." *The European Physical Journal C* 76 (2016): 1-12.

Muon Polarization Measurement: Cosmic Ray

- Cosmic-ray muon polarization
  Different zenith angle
- Measurement in history: low energy CR muon
  Up-down asymmetry $\frac{N_u - N_d}{N_u + N_d}$ of electron

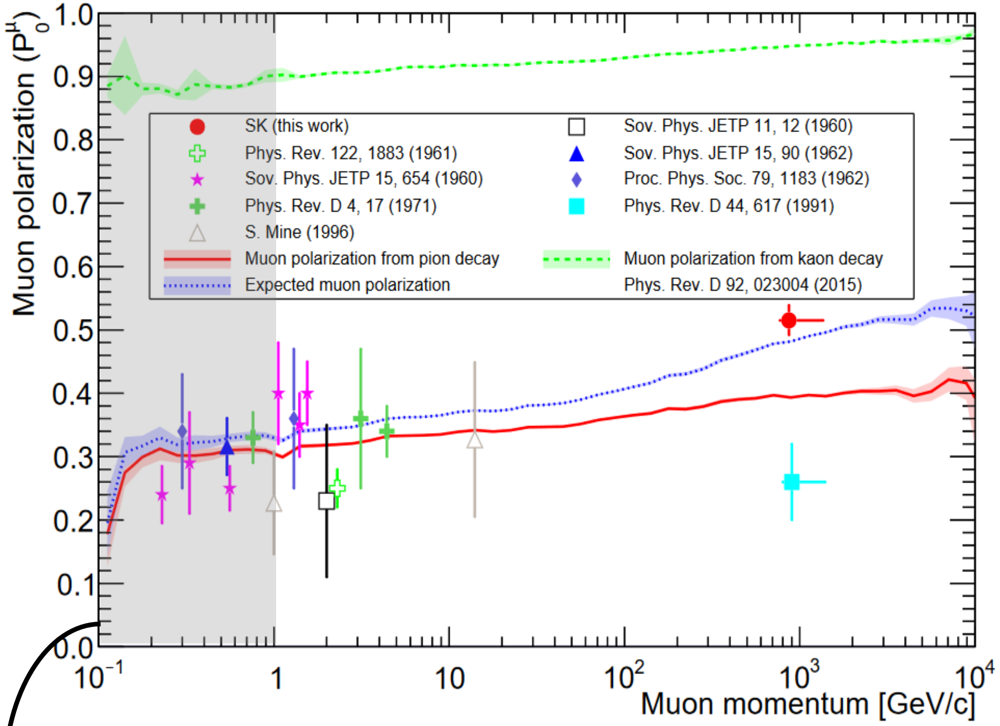


Fowler, J. M., H. Primakoff, and R. D. Sard. "The polarization of cosmic ray muons." *Il Nuovo Cimento (1955-1965)* 9.6 (1958): 1027-1045.



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

- Recent Measurement: Super-Kamiokande
  High precision but only TeV muon



Kitagawa, Hussain, et al. "Measurements of the charge ratio and polarization of cosmic-ray muons with the Super-Kamiokande detector."

sub-GeV P_μ: need more precise measurement

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Mustard-based Air shower Simulation program (MusAirS)

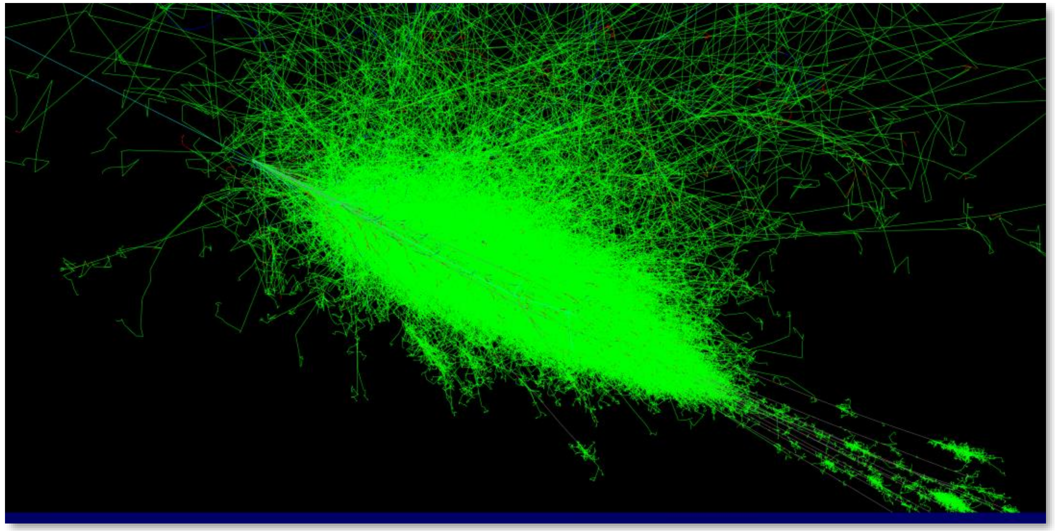
- **MusAirS simulation settings:**

  Physics list: FTFP_BERT

  Atmosphere: International Standard Atmosphere (ISA)

  Magnetic field: Zhaoqing, Guangdong (37.6382μT North, 26.120μT Down)

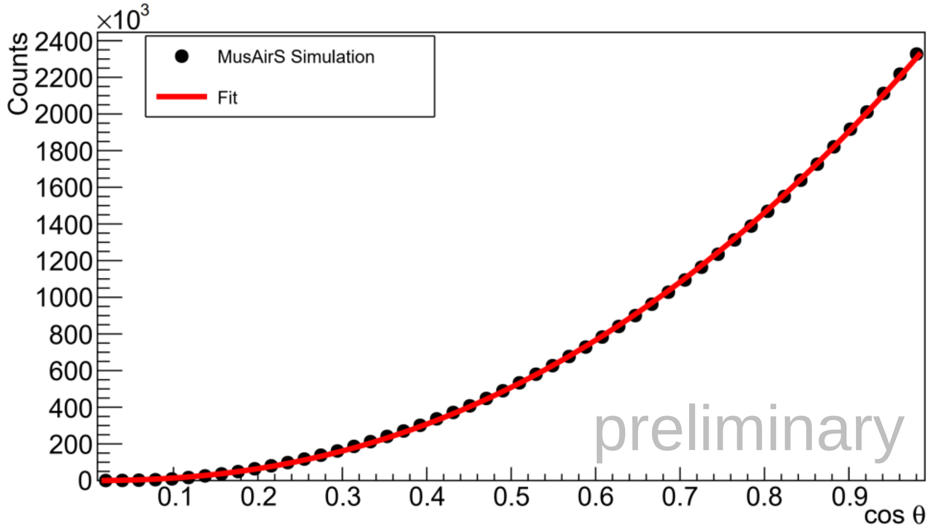
  Primary Particle Spectrum: based on AMS-02 (proton & helium > 99.9%)

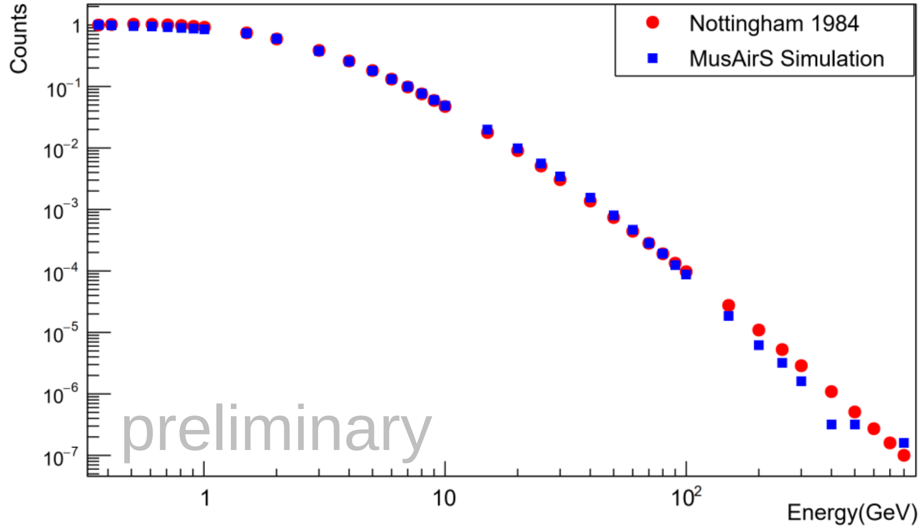


MusAirS: https://github.com/zhao-shihan/MusAirS

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

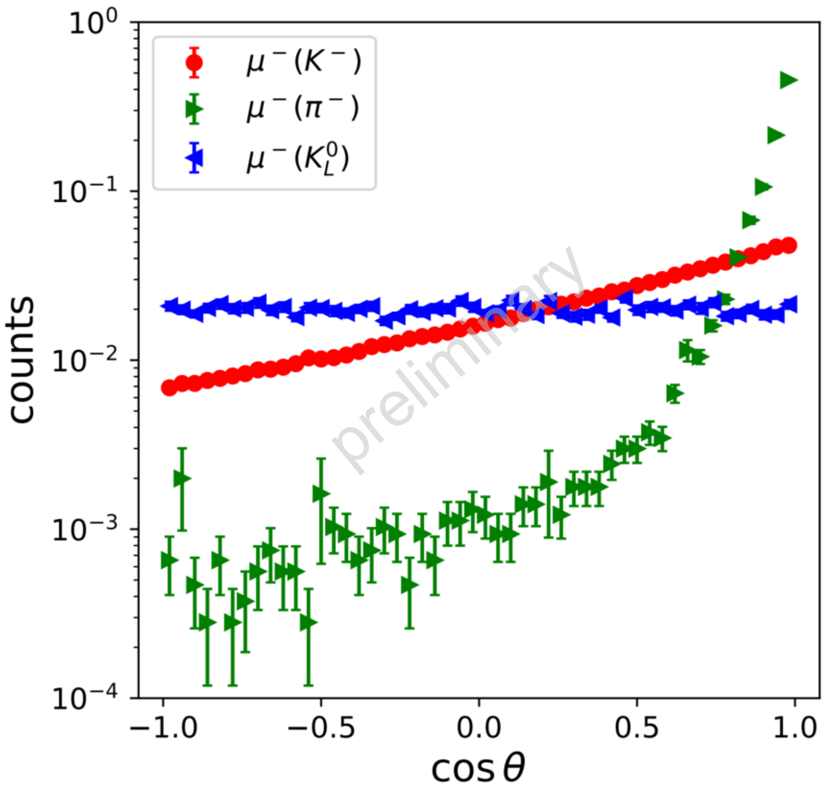
- Validation



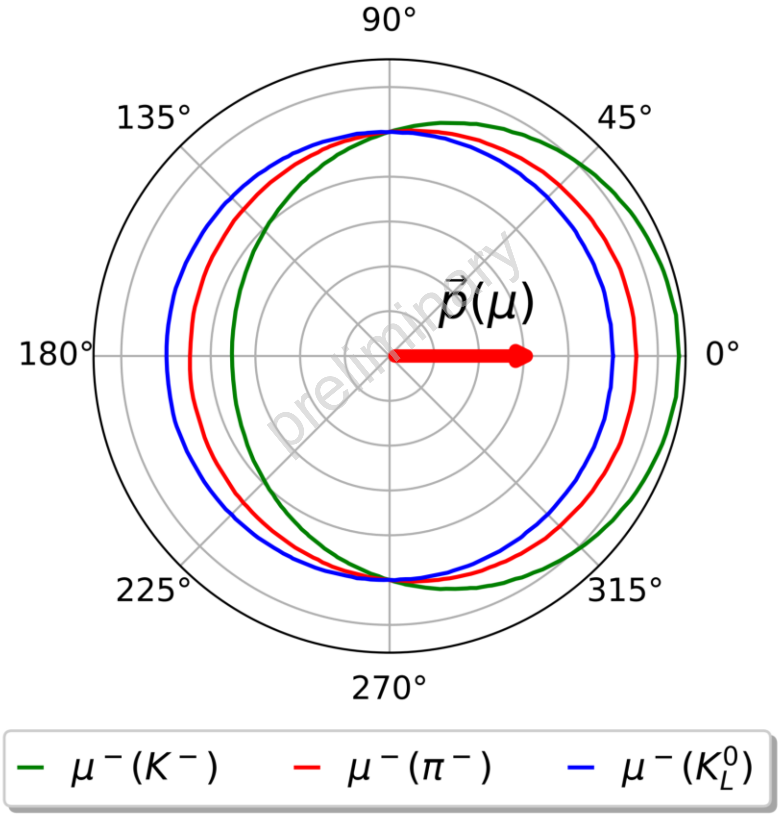


From Polarization Measurement to K-π ratio

CR muon polarization: sensitive to parent particle's K-π ratio



Distribution of cosmic-ray muon polarization



Distribution of Michel electron

- First stage:

Excluding (3σ) the hypothesis:

all parent particle is pion

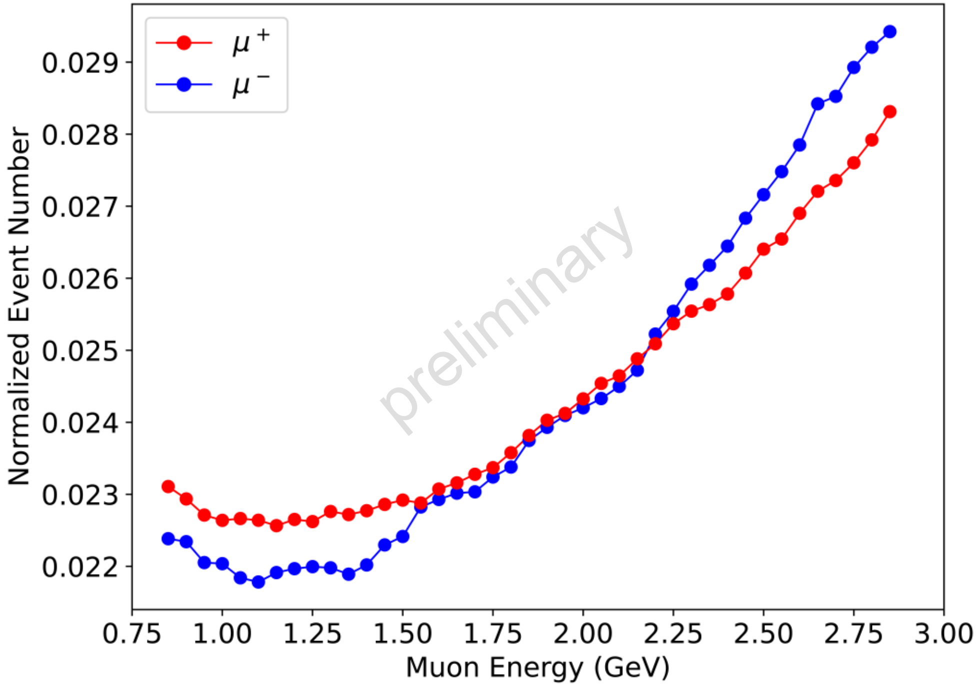
(K-π ratio = 0)

Influence of:

1. Muon energy
2. Altitude

Estimation of Minimum Event Number Required

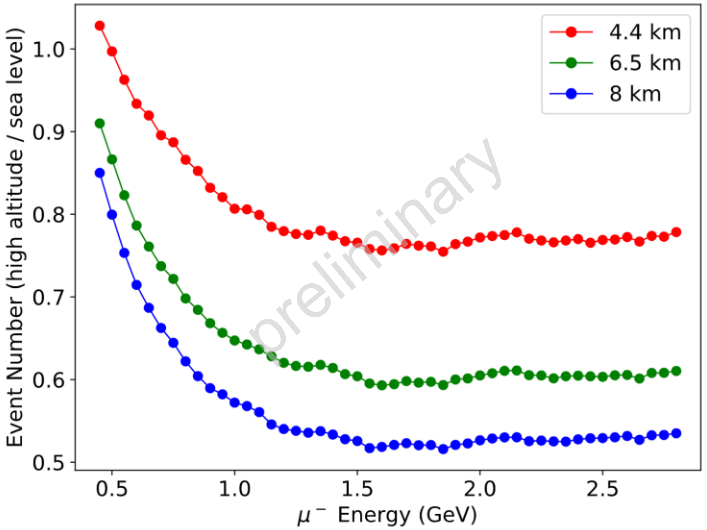
➢ **Influence of muon energy**

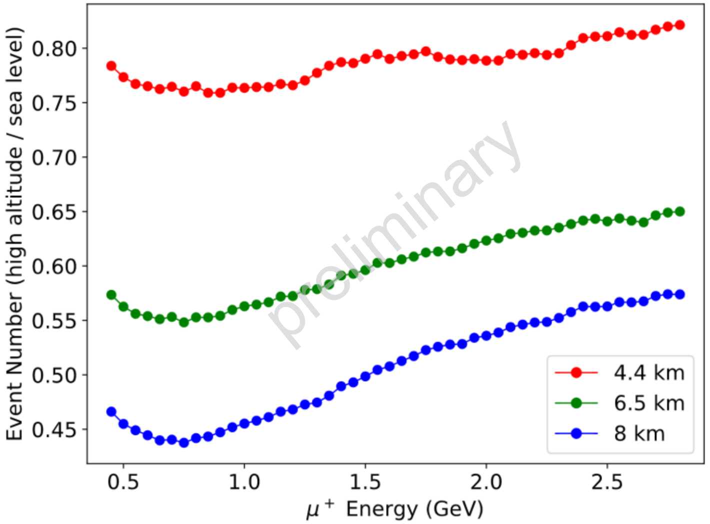


- Energy bin width: 500 MeV
- K-π ratio is given by MusAirS
- $E_\mu \uparrow \quad \phi_\mu \downarrow \quad K$-$\pi \uparrow$

Optimal energy range : 850-1350 MeV

➢ **Influence of altitude**

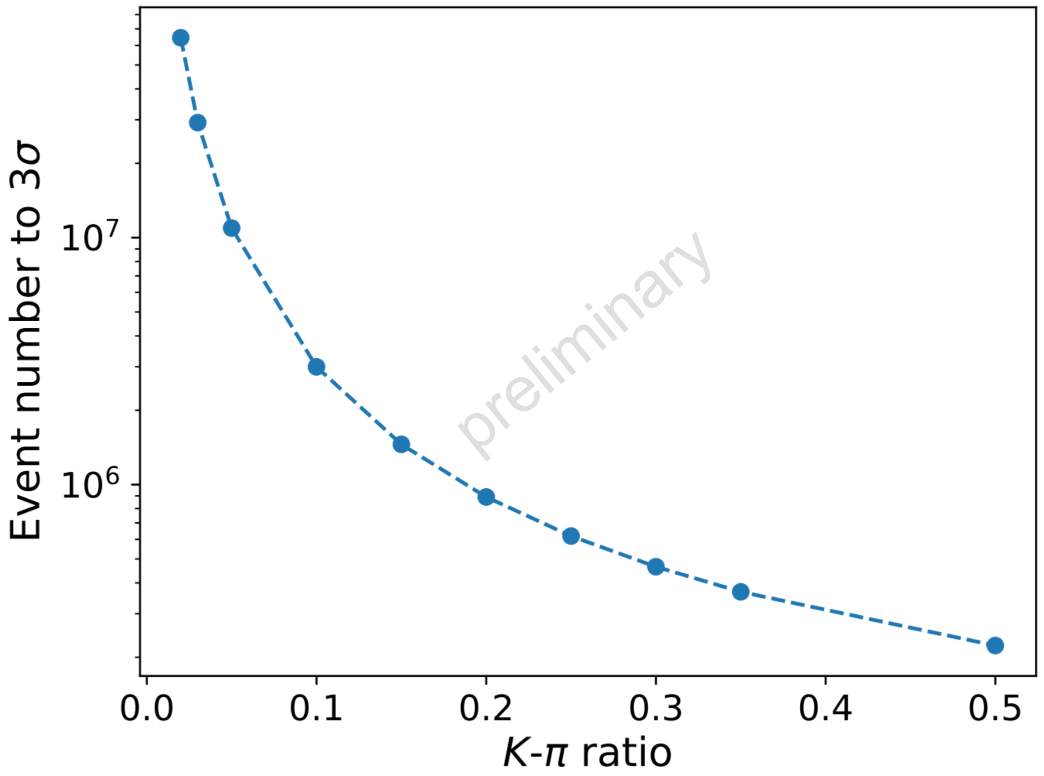


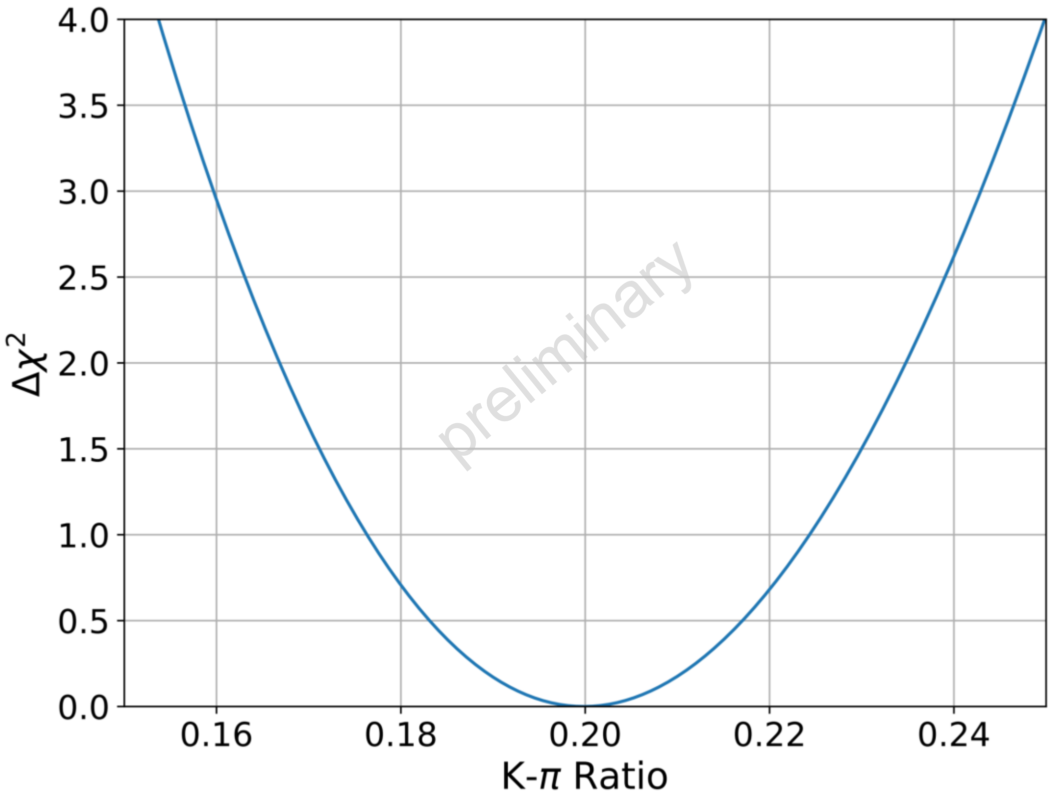


- Altitude ↑

  K-π ↓ flux ↑
- Event number ↓
- significant change but not enough
- **Constructing detector array is necessary**

Estimation with Detector Array





- **Estimation of required measuring time**

  about 10^6 events

  100 events / ($m^2 \cdot$ day) Not acceptable

  → 10000 days (30 years)

- Assuming K-π ratio = 0.2 & 1 year
- 10 m^2 detector area & $\boldsymbol{\mu^+/\mu^-}$ **identification**

  → K-π ratio in 1σ range: [0.176, 0.224]

Cosmic-Ray muon Spin polarization detectoR (CRmuSR)

for Sub-GeV Cosmic-ray Muon polarization Measurement

Prototype

- **Momentum Direction Detector (MDD)**

  Reconstructing the direction of muon momentum $\vec{p}/|\vec{p}|$

- **Positron/Electron Detector Ring (PDR)**

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

- **Muon-stopping Target**

- **Veto**

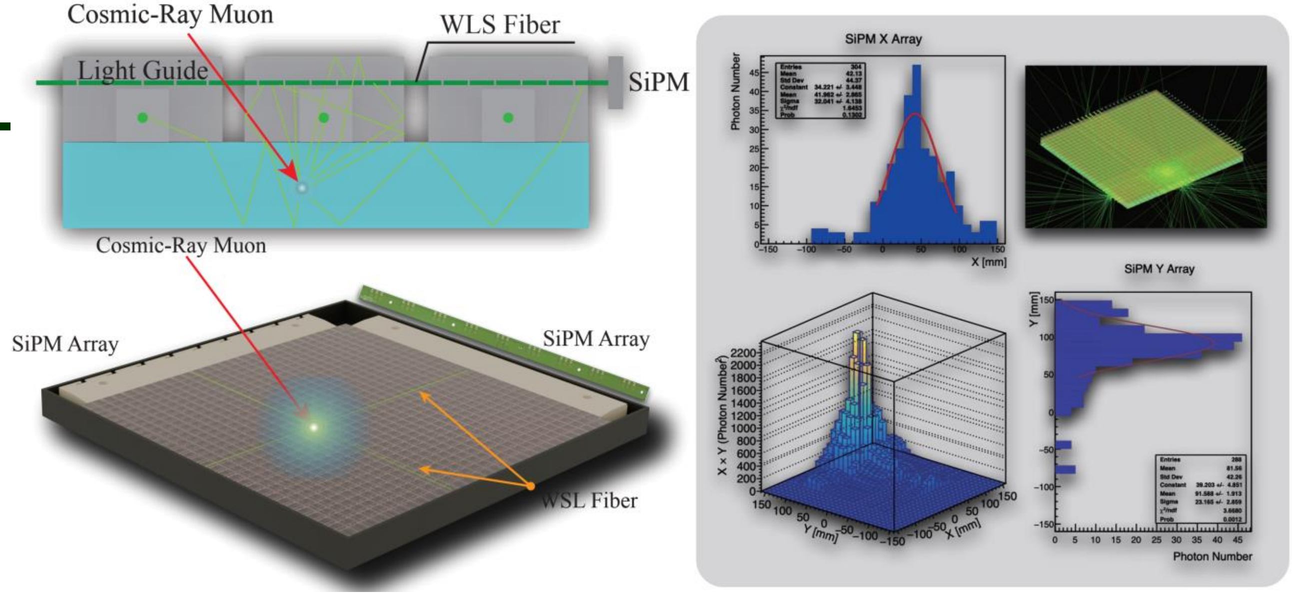
  Filter out high zenith cosmic-ray muon events

- More detail: Mingchen Sun's talk last year (MIP 2024)

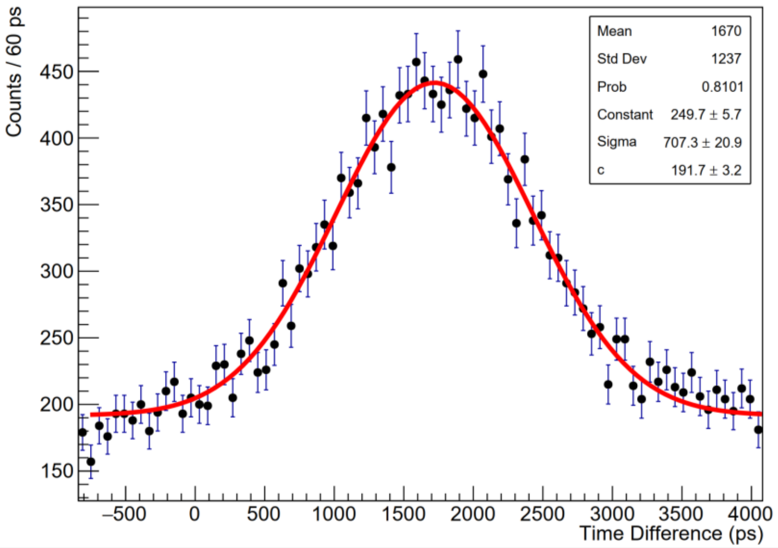
https://indico.cern.ch/event/1356341/contributions/5799615/attachments/2841517/4967096/3.MingchenSUN.pdf

Status of CRmuSR

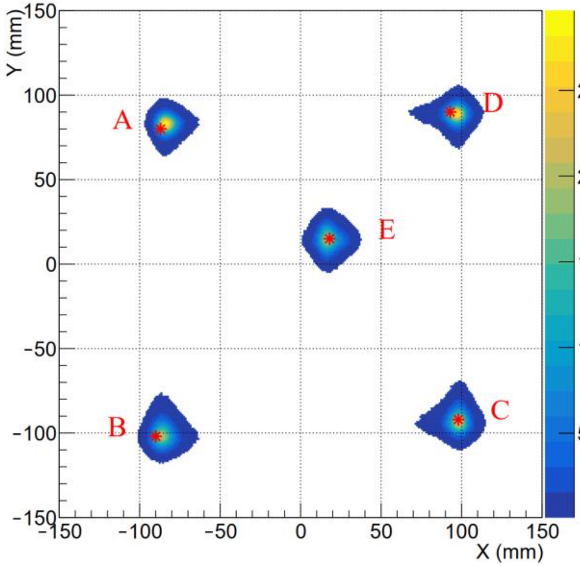
Current status: stable data acquisition



MDD design and simulation

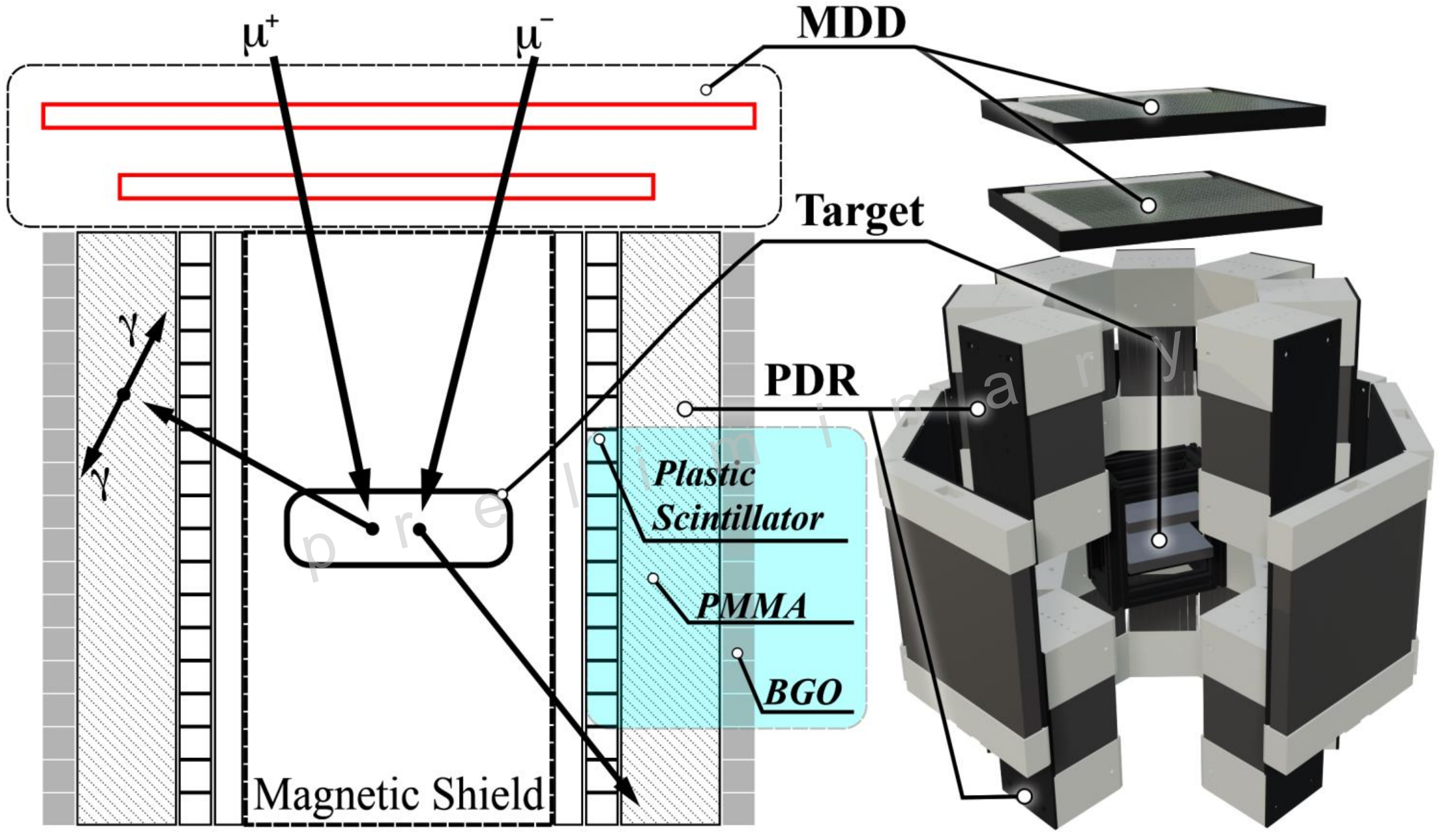


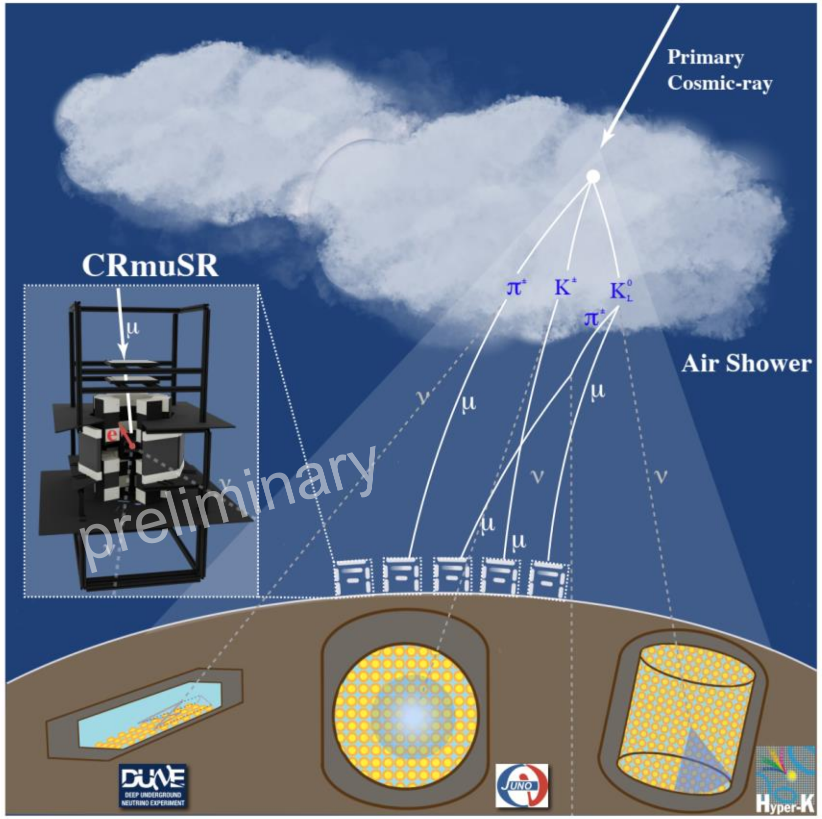
PDR time resolution



MDD calibration

CRmuSR Upgrade Plan





- **μ^+/μ^- identification**
  - Time difference of μ^+/μ^- decay
  - e^+e^- annihilation

- **Detector array**
  - More compact structure

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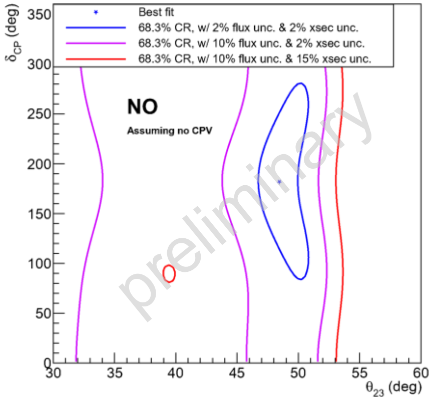
Conclusion & Outlook

Motivation

ATN flux model constraint



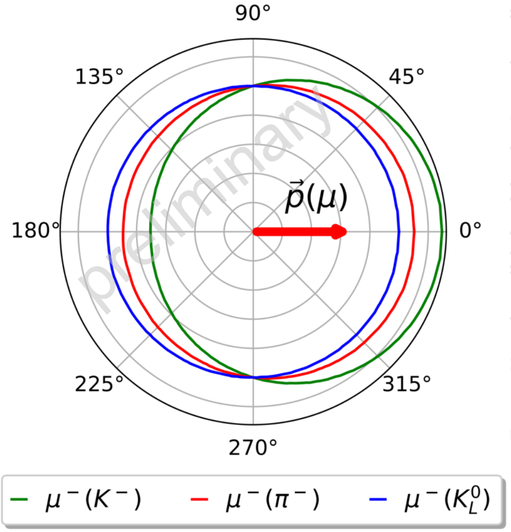
Measurement of CR muon polarization

A brief review of history

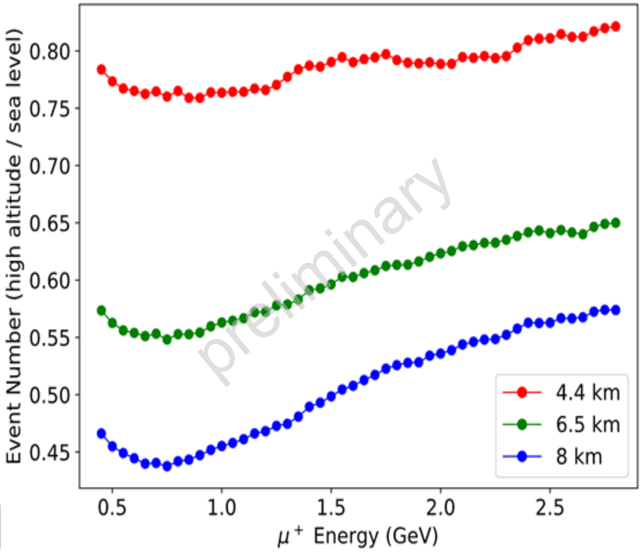
The necessity of sub-GeV muon polarization measurement

Simulation about P_μ

Hint to K-π ratio



Event number required

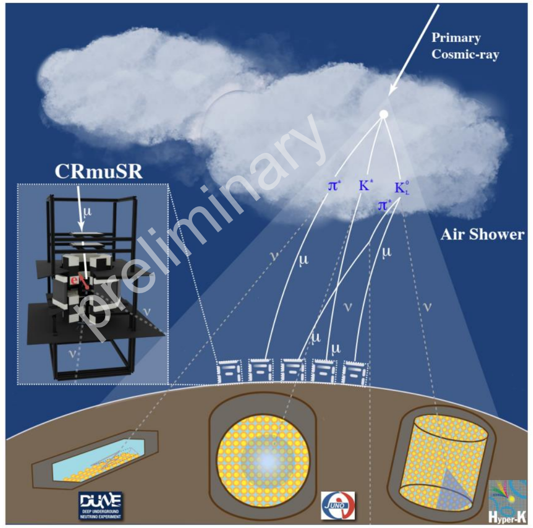


Estimation of detector array outcome

CRmuSR upgrade plan

μ^+/μ^- identification

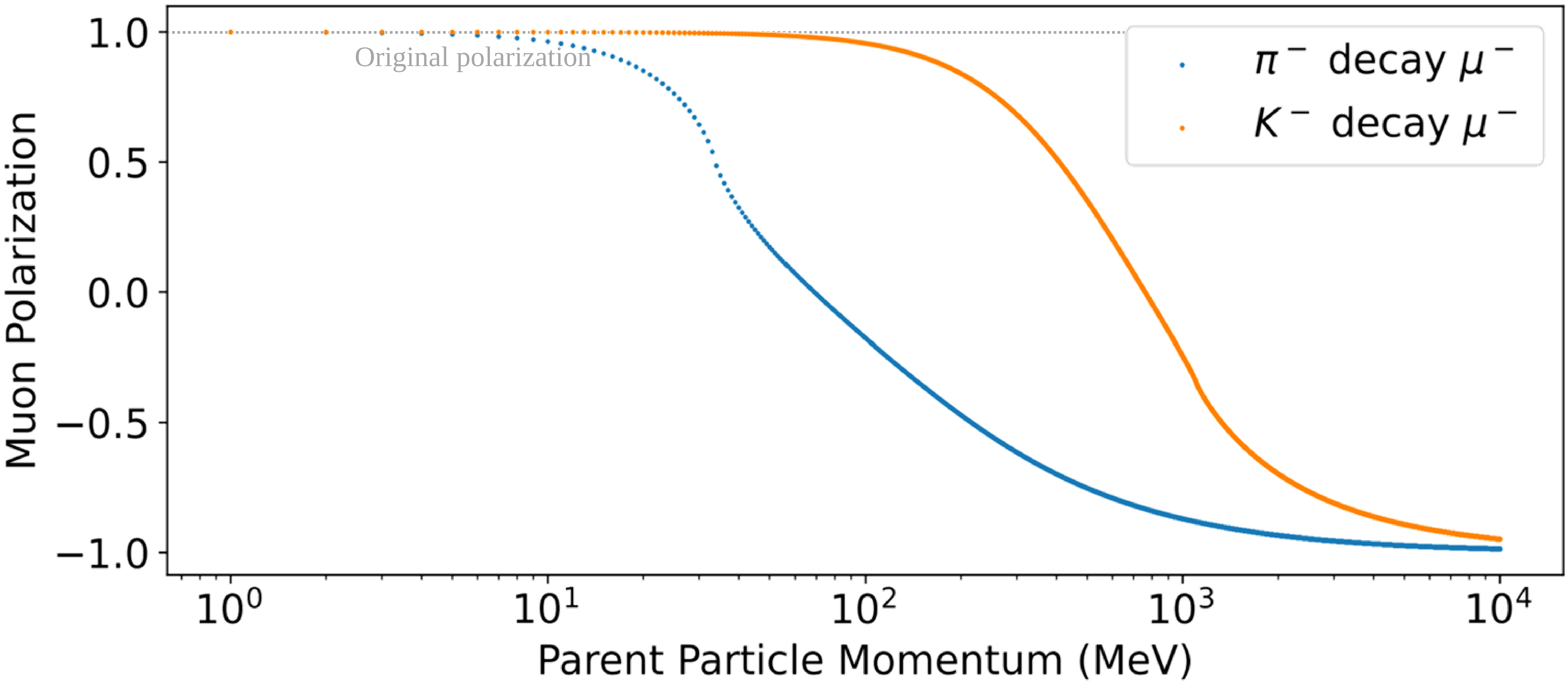
Array



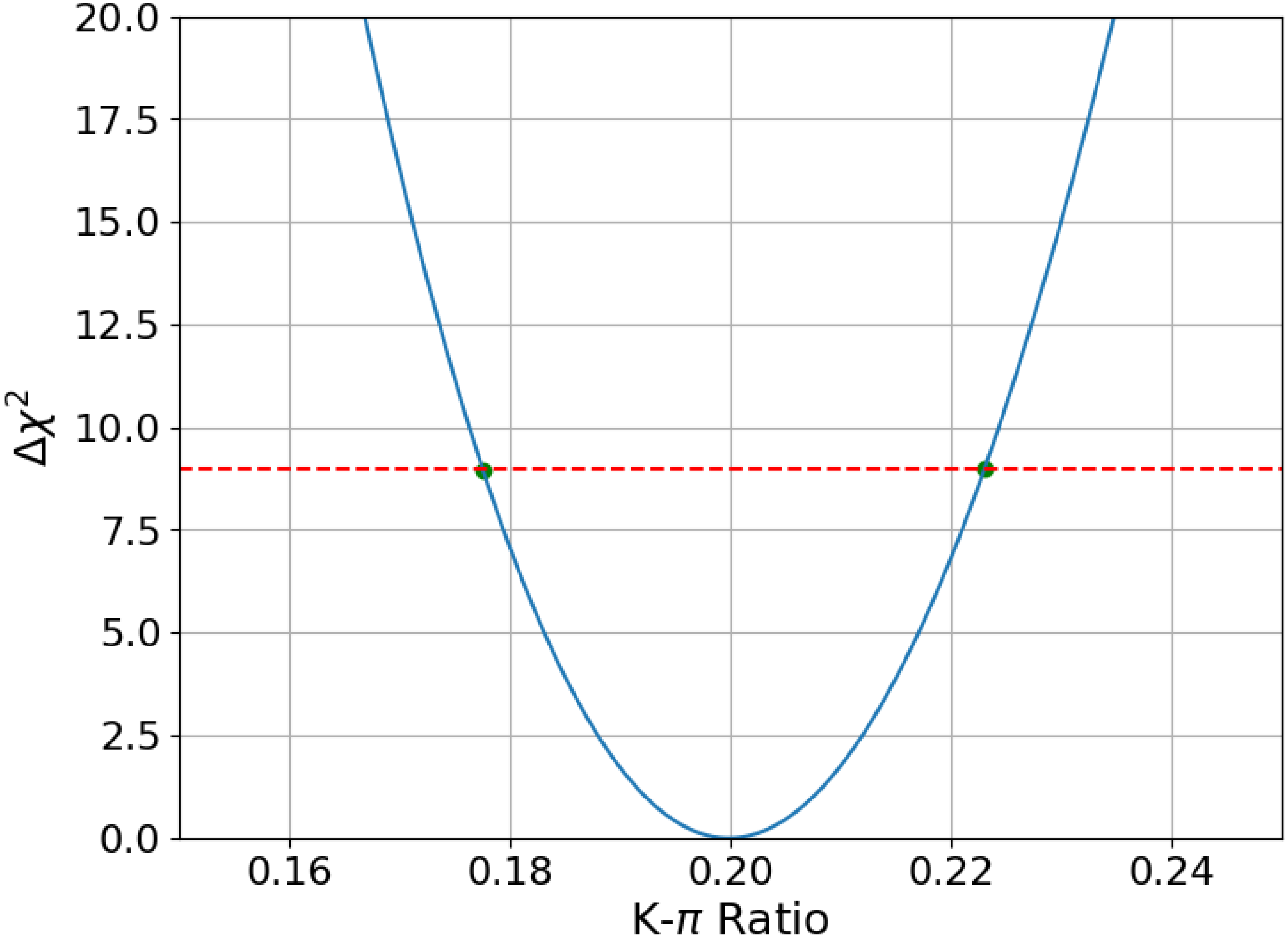
Thanks

Appendix

- CR muon polarization in laboratory frame



Appendix



- Estimation with detector array
- Assuming K-π ratio = 0.2 & 1 year
- 10 m^2 detector area
- $\boldsymbol{\mu}^+/\boldsymbol{\mu}^-$identification
- K-π ratio in 3σ range: [0.178, 0.223]