Cosmic Muon Flux Measurement using the 1-ton Prototype Detector of Water Phase in CJPL-I

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Outline

1. Introduction
2. Detector & Data Taking
3. Data Analysis
4. Muon Flux Measurement
5. Direction Reconstruction
6. Summary

Motivation & Previous Results

- cosmic ray background estimation
- mountain imaging with muons

Previous Result: $\Phi = (3.56 \pm 0.16_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.(Zhang et al. 2024)

Data-Taking Periods

	Phase I	**Phase II**
Dates	Oct 15 – Nov 30, 2024	Jul 8 – Sep 19, 2025
Trigger	10 ch, 5 mV	10 ch, 5 mV
Light shielding	No	Yes (black shielding)
PMT set	Set A	Set B (replaced)
T_{DAQ} (valid)	75.25 days	69.88 days

- PMT replacement $\rightarrow$ independent time & gain calibration per period
- Shielding: blocks external Cherenkov light $\rightarrow$ better S/B in Phase II

Good-Run Selection

- Data subdivided into ~200 MB files
- Baseline: mean ADC in 20–120 ns of 900 ns waveform

Bad channel criteria (any one):

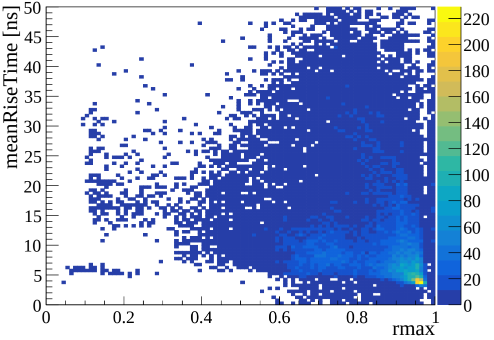
1. Baseline variance > 0.5 mV
2. Mean baseline deviates $> 5\sigma$ from channel average
3. Occupancy $> 5\sigma$ above mean or $< 1\%$ of mean

Result

File rejected if > 4 bad channels $\rightarrow$ **95% data retained**

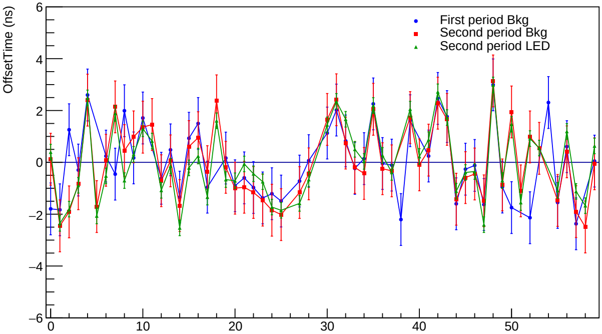
Flasher Rejection

- Background from PMT flashers and electronic noise
- Two discriminating variables:
  - $r_{\max}$: max PE in single channel / total PE
  - mrt: average rise time over triggered channels
- Flashers: $r_{\max} > 0.25$, $\mathrm{mrt} > 10$ ns
- **Muon candidates**: $r_{\max} < 0.25$, $\mathrm{mrt} < 30$ ns



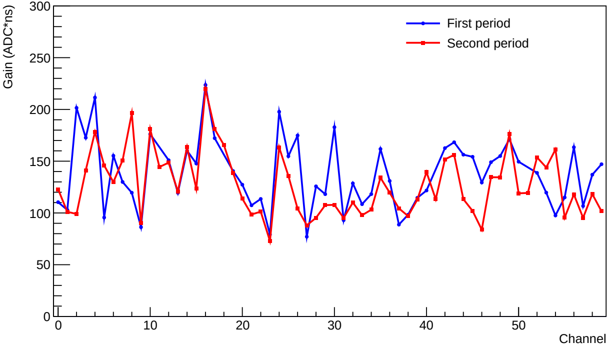
Time Calibration

- Independent calibration per period (PMTs replaced)
- Phase II: LED-based, avg. time resolution ~ 0.3 ns
- Phase I (no LED): environmental background, uncertainty ~ 1 ns



Gain Calibration

- PMT gain from dark noise charge spectrum (SPE spectrum)
- Fit SPE peak → extract PMT gain



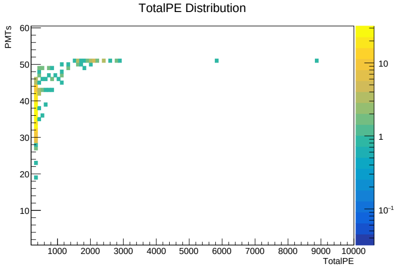
Muon Event Selection

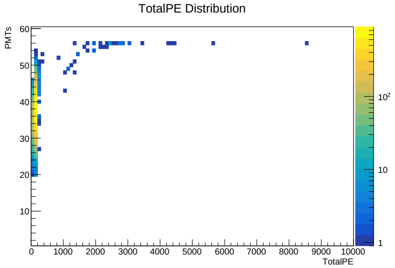
Phase I (no shielding)

- Energy overlap with radioactive BG
- Select by # of triggered PMTs
- **Cut:** $N_{\mathrm{PMT}} > 51$

Phase II (with shielding)

- Clear energy separation
- **Cut:** $E > 500$ **PE**
- Energy scale: χ^2 minimization





Selected events

Flux Calculation

The muon flux for each period:

$$\phi_{\mu,i} = \frac{N_{\mu,i}}{\varepsilon_i \, T_{\mathrm{DAQ},i} \, S_i} \tag{1}$$

- $N_{\mu,i}$: selected muon events
- ε_i: detection efficiency (from simulation)
- $T_{\mathrm{DAQ},i}$: effective live time
- S_i: effective area (from muon angular distribution)

$$\phi_{\mu,1} = (3.60 \pm 0.71_{\mathrm{stat}}) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{2}$$

$$\phi_{\mu,2} = (3.53 \pm 0.53_{\mathrm{stat}}) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{3}$$

Systematic Uncertainties

Source	**Phase I**	**Phase II**
Latitude, Longitude (± 100 m)	1.2%	2.7%
Elevation (± 100 m)	2.0%	2.0%
Acrylic sphere (± 0.5 cm)	0.3%	1.4%
PMT position & angle	1.3%	1.5%
Water absorption length	**16.4%**	1.3%
Shielding sphere (holes, radius)	—	5.7%
Rock thickness (± 50 cm)	2.2%	0.6%
Hadronic physics model	0.6%	1.3%
Muon generator	2.0%	1.7%
Energy scale ($\pm 10\%$)	—	0.8%
Total systematic	**16.9%**	**7.1%**

Combined Result

Two independent measurements combined via BLUE (uncorrelated systematics):

$$w_i \propto \frac{1}{\sigma^2_{\mathrm{stat},i} + \sigma^2_{\mathrm{sys},i}} \tag{4}$$

Combined muon flux (water phase)

$$\boxed{\Phi = (3.55 \pm 0.42_{\mathrm{stat}} \pm 0.25_{\mathrm{syst}}) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}} \tag{5}$$

- Consistent with Zhang et al. (2024) liquid scintillator result
- First water-phase measurement at CJPL

Template Method

Principle: Compare PMT hit pattern & charge of data events with simulation templates.

1. Generate templates: sample muon positions & angles over acrylic vessel
2. Record per-template: PMT hit times $\mathbf{T}_m$, charges $\mathbf{Q}_m$
3. Record direction information: $\mathbf{P}_m = (\theta_m, \phi_m)$
4. Match: minimize distance function between data event and template

Template Method

Distance function:

$$d^2(m,n) = \sum_{i=0}^{N} \left[f_i(\bar{\mathbf{T}}_{mi} - \bar{\mathbf{T}}_{ni})^2 + g_i(\bar{\mathbf{Q}}_{mi} - \bar{\mathbf{Q}}_{ni})^2 \right] \tag{6}$$

Weights f_i, $g_i \propto$ inverse variance of time/charge fluctuations.

Reconstruction with k nearest events

$$\mathbf{P}_{n,Recon} = \sum_{i=1}^{k} \frac{1}{d_i} \mathbf{P}_i \tag{7}$$

Template Method —Weight Functions

Time weight:

$$f(m,n,i) = \left(\frac{T_s^2}{q_{mi}} + \frac{T_s^2}{q_{ni}}\right)^{-1} \tag{8}$$

Charge variance:

$$\sigma_q^2 = q\left(1 + \frac{\sigma_{\mathrm{SPE}}^2}{\mu_{\mathrm{SPE}}^2}\right) \tag{9}$$

With calibration uncertainties (σ_{TCali}, η):

$$\frac{1}{f(m,n,i)} = \frac{T_s^2}{q_{mi}} + \frac{T_s^2}{q_{ni}} + \sigma_{\mathrm{TCali}}^2, \quad \frac{1}{g(m,n,i)} = (q_{mi} + q_{ni} + q_{mi}\eta^2)\left(1 + \frac{\sigma_{\mathrm{SPE}}^2}{\mu_{\mathrm{SPE}}^2}\right) \tag{10}$$

Marginal Likelihood Extension

Problem: Water phase $\rightarrow$ sparse, non-uniform channel hits.

Direct template matching requires identical triggered channels.

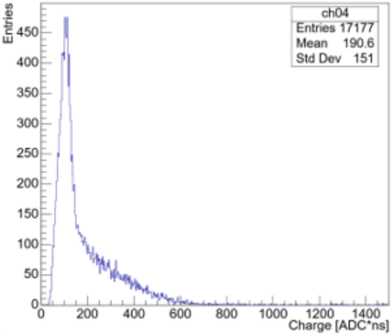
Solution: Marginal likelihood for channels with $Q = 0$ in muon candidates or templates, $Q \neq 0$ in the other:

$$\mathcal{L}(0|Q) = \int_0^{+\infty} \sum_{n=0}^{\infty} \pi(0,k)\,\pi(n,k)\,P(Q,n)\,\mathrm{d}k = \sum_{n=0}^{\infty} \frac{P(Q,n)}{2^{n+1}} \tag{11}$$

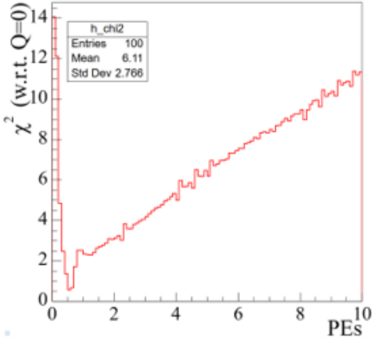
Likelihood ratio $\rightarrow$ χ^2 contribution:

$$\chi^2(0|Q) = -2\ln\frac{\mathcal{L}(0|Q)}{\mathcal{L}(0|0)} \tag{12}$$

Marginal Likelihood Extension



an example for SPE spectrum

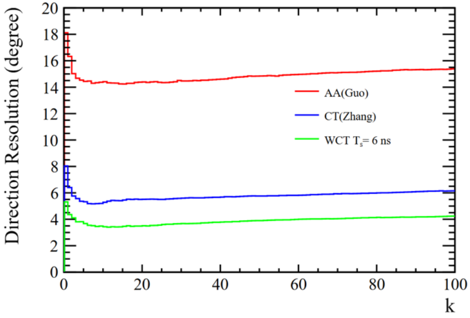


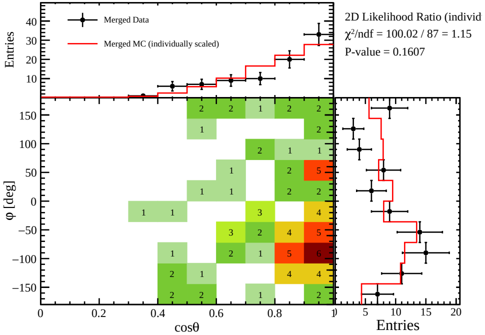
χ^2 calculated by the eaxmple spectrum

$$\chi^2(0|Q) \approx \mathrm{PE} + 1$$

If $Q > 5$ PE $\rightarrow$ template rejected (incompatible).

Reconstruction Resolution & Results





Summary

- **First water-phase** muon flux measurement at CJPL-I
- Upgraded 1-ton prototype operated for 66 days in pure water mode
- **Muon flux:**

$$\Phi = (3.55 \pm 0.42_{\mathrm{stat}} \pm 0.25_{\mathrm{syst}}) \times 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{13}$$

- Consistent with previous liquid scintillator measurement
- **Direction reconstruction:** template method + marginal likelihood extension
  - Optimized for sparse-hit water phase
  - Zenith/azimuth distributions match simulation
- Provides essential background input for future JNE water-phase detectors

Thank you!