# Muon flux and muon-induced neutron yield measurement at China Jinping underground laboratory

Bin Zhang on behalf of JNE Collaboration , zhangb20@mails.tsinghua.edu.cn
Department of Engineering Physics &
Center for High Energy Physics, Tsinghua University, Beijing, China

Jinping Neutrino Experiment

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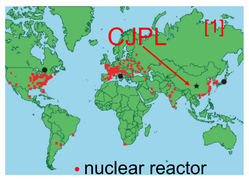
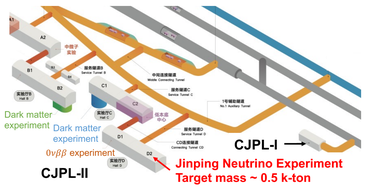
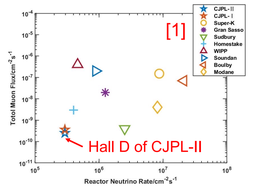
## 1. China Jinping Underground Laboratory (CJPL)

- **Deepest** lab with vertical rock overburden (6720 m.w.e.);
- **Lowest** cosmic-ray and reactor neutrino backgrounds;
- **Ideal** place for experimental studies including **MeV-scale neutrino, dark matter and 0$\upsilon\beta\beta$.**

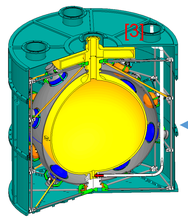


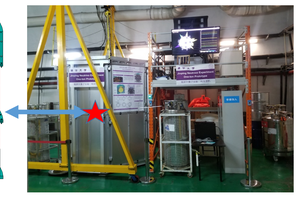




## 2. Jinping 1-ton prototype detector

- A 1.2 m spherical acrylic detector at CJPL-I.
- To measure cosmic-ray, neutron, and radon backgrounds.
- To demonstrate the background reduction techniques:
  - Nitrogen purge and sealing
  - Liquid scintillator distillation
- To test the performance of the Cherenkov liquid scintillator [2].

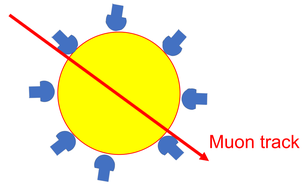


## 3. Muon direction reconstruction

**Time-Based Template Reconstruction in liquid scintillation :**

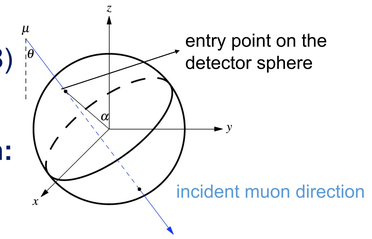
- How to extract the muon direction from time?




*The smaller the distance from the muon track, the earlier the arrival time of PMT*

**Template *i* is tagged with :**
- $\boldsymbol{p}_i$ = (cos$\theta$,$\phi$) and $R_i$ =(cos$\alpha$,$\beta$)
- $t_{ji}$: arrival time at PMT *j*

**Incident muon registered with:**
- $t_j$: arrival time at PMT *j*
- $\boldsymbol{p}$ : reconstructed direction




**Reconstruction process:**

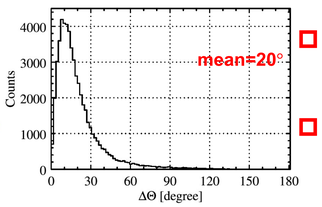
$$\boldsymbol{P} = \frac{\sum_{i=1}^{k} \frac{1}{d_i}\boldsymbol{p}_i}{\sum_{i=1}^{k} \frac{1}{d_i}} \qquad d_i := \sqrt{\sum_{j=0}^{29} \left(\tilde{t}_{ji} - \tilde{t}_j\right)^2}$$

$$\tilde{t}_{ji} = t_{ji} - \bar{t}_{ji} \qquad \bar{t} = \frac{1}{30}\sum_{j=0}^{29} t_j$$

$$\tilde{t}_i = t_i - \bar{t}_i \qquad \bar{t}_i = \frac{1}{30}\sum_{j=0}^{29} t_{ji}$$

**Find *k* templates with the smallest *d*.**

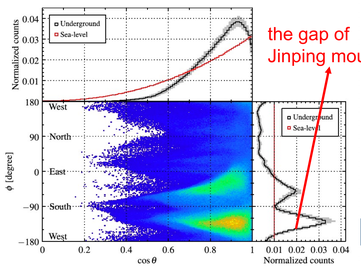
**Performance of the reconstruction method:**




- ΔΘ is included angle between the truth and reconstructed directions.
- Mean of ΔΘ is close to the minimum when *k*=50

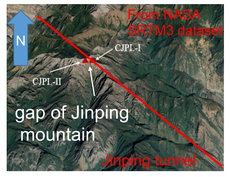
## 4. Muon measurement at CJPL-I

**Underground muon distribution prediction with:**
- Input 1: Modified Gaisser's formula [4], which describes muon distribution at sea level.
- Input 2: Jinping mountain's terrain.





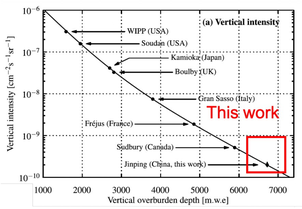


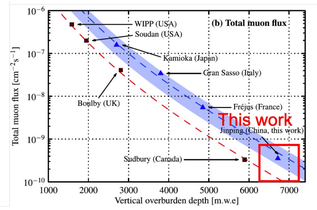



**Mean energy = 340 GeV**

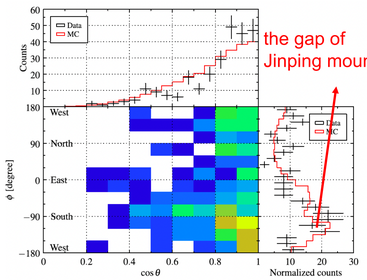
**Flux measurement:**
- ✓ Detected 343 muon events from 820.28 live-days
- ✓ Separated vertical and total fluxes.
- ✓ Total flux = $\left(3.61 \pm 0.19_{\text{stat.}} \pm 0.10_{\text{sys.}}\right)\times 10^{-10}\ \text{cm}^{-2}\text{s}^{-1}$

**Compared with other labs:**




**Direction measurement:**

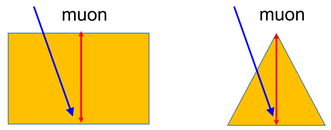






**Flux: under mine VS under mountain:**

At the same vertical depth, muon flux of laboratory situated under mountains is **(4 ± 2)** times that of laboratory situated down mine shafts, due to leakage through mountain.



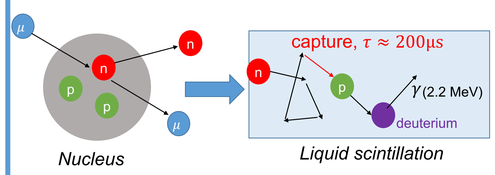

*Muon leaks into laboratory through the mountain.*

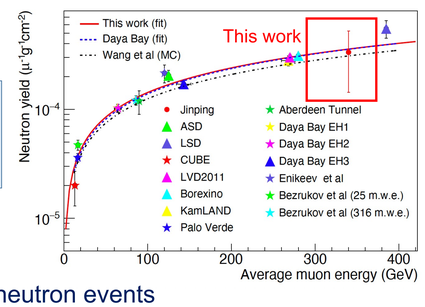
**Flux prediction at JNE site of CJPL-II:**
- Input 1: Jinping mountain's terrain
- Input 2: Cosmic-ray measured at CJPL-I.

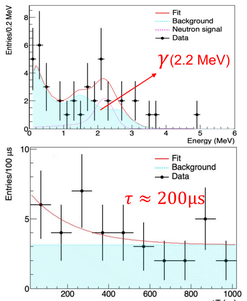
- Total flux predicted ≈ 2.5 $\times 10^{-10}\ \text{cm}^{-2}\text{s}^{-1}$
- **The lowest cosmic-ray muon flux** of all underground laboratories so far!
- Jinping Neutrino Experiment will be carried out here! see poster 131 for details.

## 5. Study of muon-induced neutrons

**Neutrons: From Creation to Capture**




**Yield measurement:**
- ✓ Found 7.36 ± 3.97 cosmic-ray induced neutron events
- ✓ Yield in liquid scintillation: $\left(3.44 \pm 1.86_{\text{stat.}} \pm 0.76_{\text{sys.}}\right)\times 10^{-4}\ \mu^{-1}\text{g}^{-2}\text{cm}^{-2}$

*ΔT is the time difference between the neutron event and the mother muon event*

## 6. Summary

- We have measured the cosmic-ray muon flux and muon-induced neutron yield and reconstructed various muon directions through the mountain at CJPL-I.
- We extrapolate the measured muon flux from CJPL-I to the JNE site at CJPL-II and find it **the lowest among** all the underground laboratories.

**References:**
1. Beacom, John F., et al. "Physics prospects of the Jinping neutrino experiment." Chinese Physics C 41.2 (2017): 023002.
2. Guo, Ziyi, et al. "Slow liquid scintillator candidates for MeV-scale neutrino experiments." Astroparticle Physics 109 (2019): 33-40.
3. Wang, Zongyi, et al. "Design and analysis of a 1-ton prototype of the Jinping Neutrino Experiment." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 855 (2017): 81-87.
4. Guan, Mengyun, et al. "A parametrization of the cosmic-ray muon flux at sea-level." arXiv preprint arXiv:1509.06176(2015).