



Measurement of cosmic muon flux and cosmogenic neutron yield at CJPL

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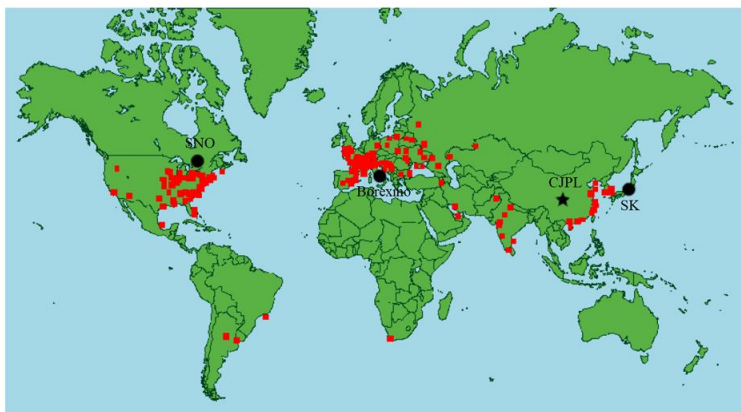
实验简介

- 中国锦屏地下实验室:

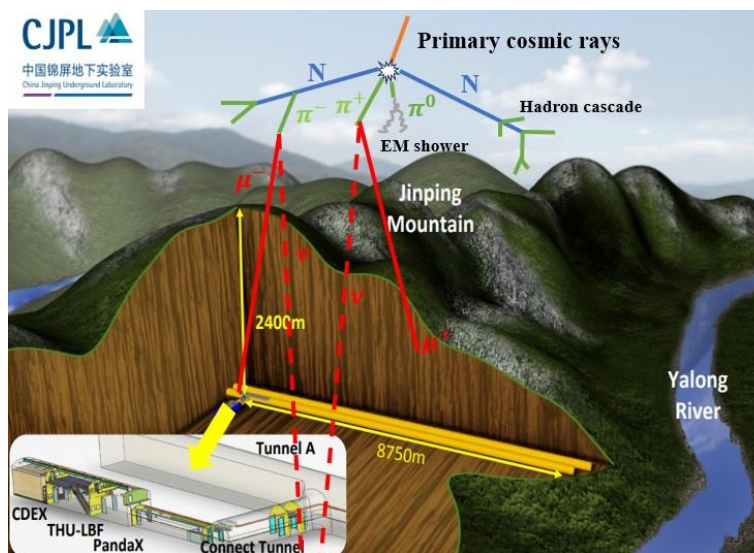
- 低宇宙线通量
- 低反应堆中微子本底
- 低岩石放射性

- 锦屏中微子实验:

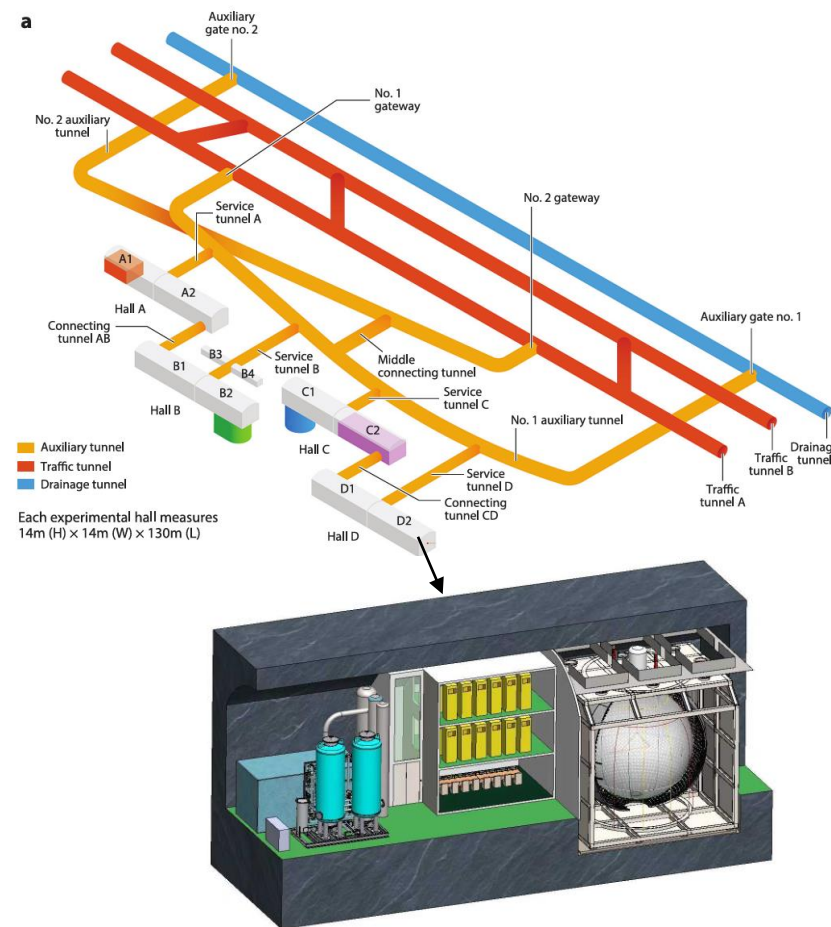
- 太阳中微子
- 地球中微子
- 超新星中微子
- $0\nu\beta\beta$



Chin. Phys. C 41, 023002(2017)



Ann. Rev. Nucl. Part. Sci. 67, 231(2017)

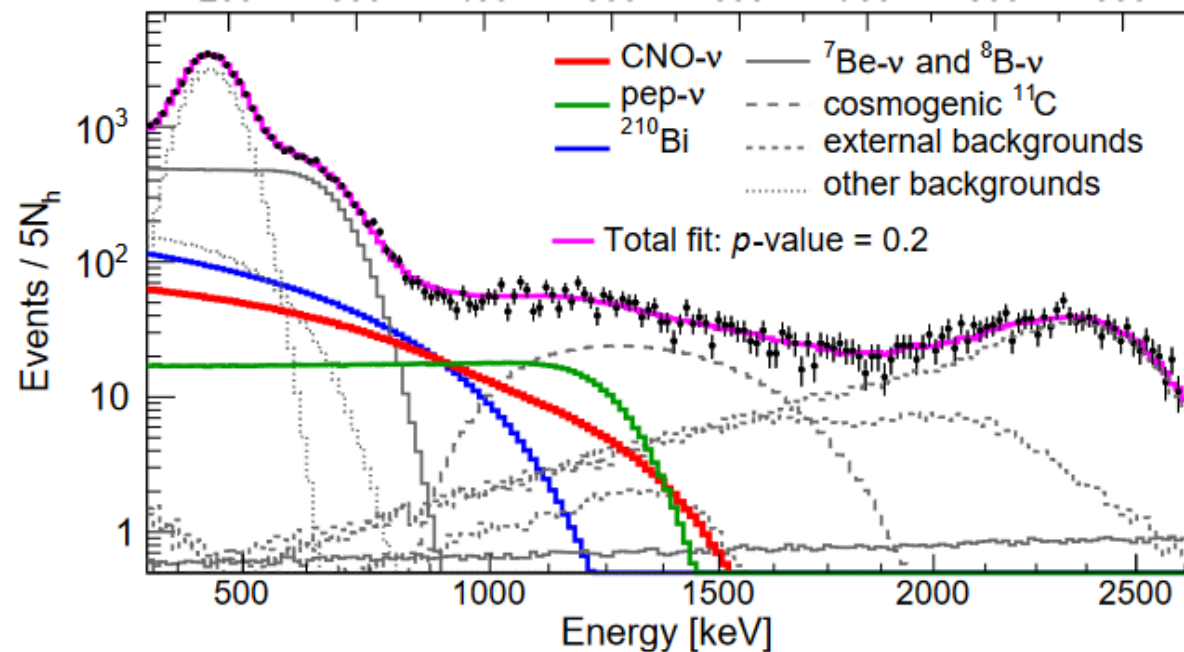
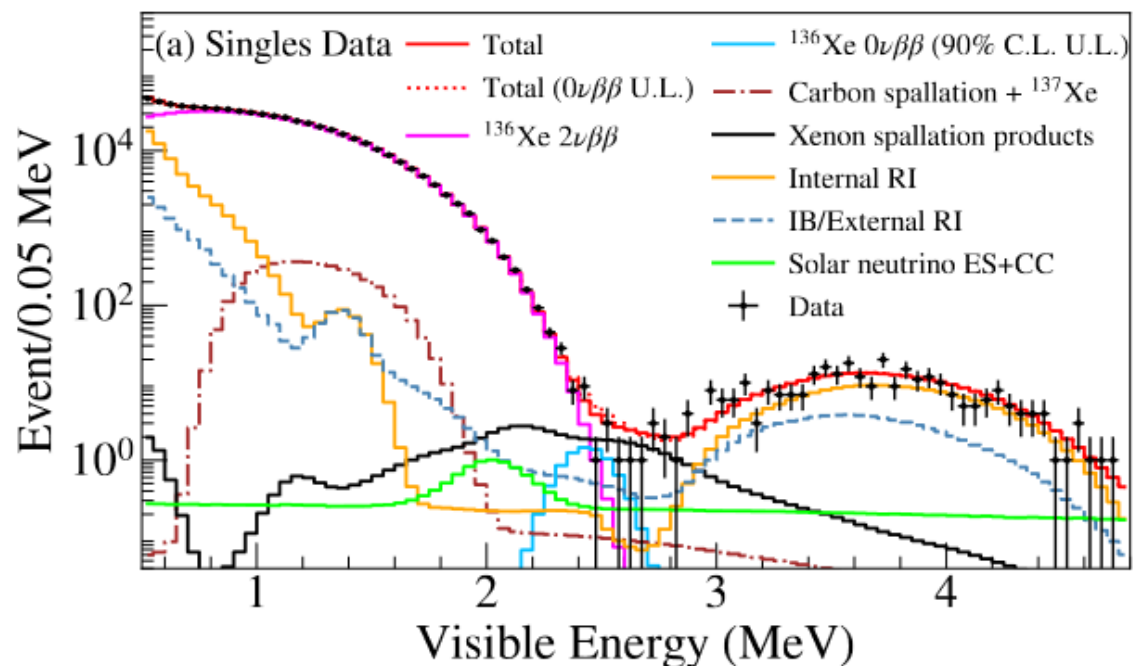


Site	^{238}U	^{232}Th	^{40}K
Jinping	$1.8 \pm 0.2 (^{206}\text{Rn})$	<0.27	<1.1
Sudbury	13.7 ± 1.6	22.6 ± 2.1	310 ± 40
Gran Sasso hall A	116 ± 12	12 ± 0.4	307 ± 8
Gran Sasso hall B	7.1 ± 1.6	0.34 ± 0.11	7 ± 1.7
Gran Sasso hall C	11 ± 2.3	0.37 ± 0.13	4 ± 1.9
Kamioka	~ 12	~ 10	~ 520

研究意义

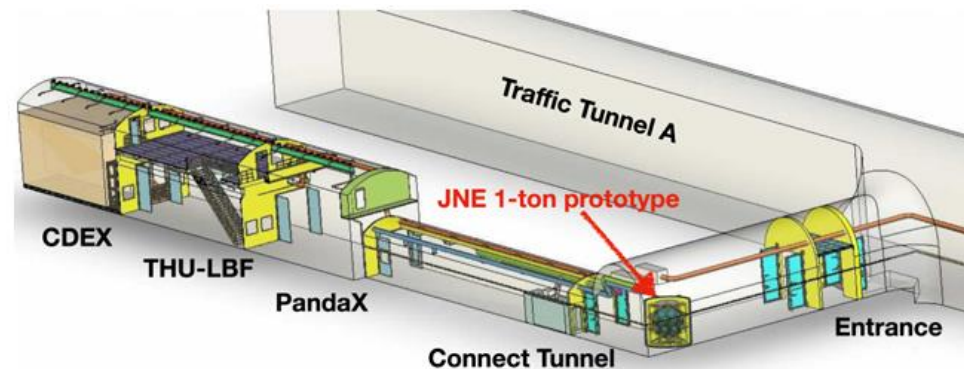
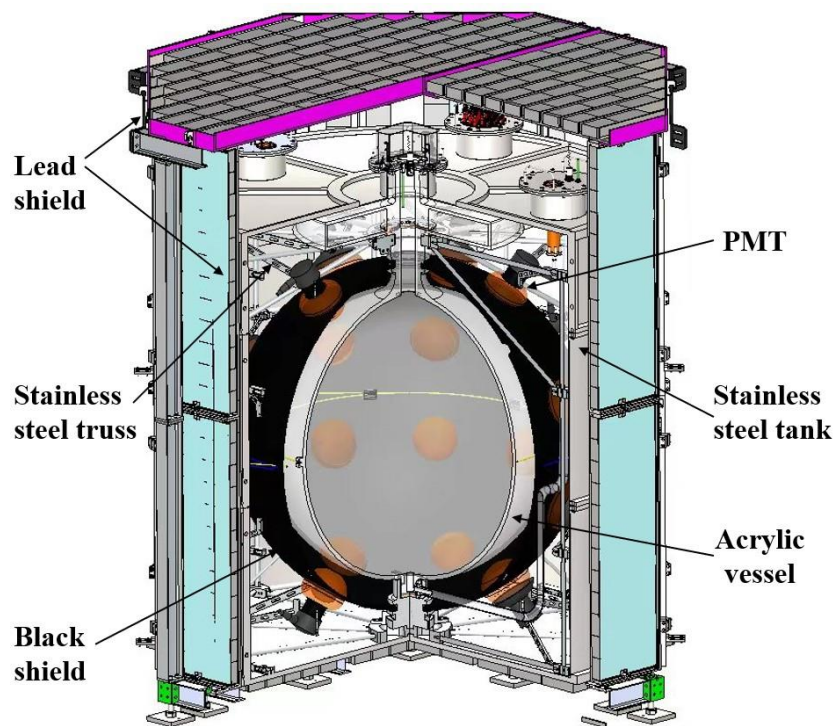
- 缪子及其散裂产物是寻找太阳中微子和 $0\nu\beta\beta$ 实验的主要本底
- 此本底的研究和测量对未来五百吨探测器的物理分析有重要作用

KamLAND-Zen $0\nu\beta\beta$ Phys. Rev. Lett. 130, 051801(2023) Borexino CNO solar neutrino Phys. Rev. Lett. 129, 252701(2022)



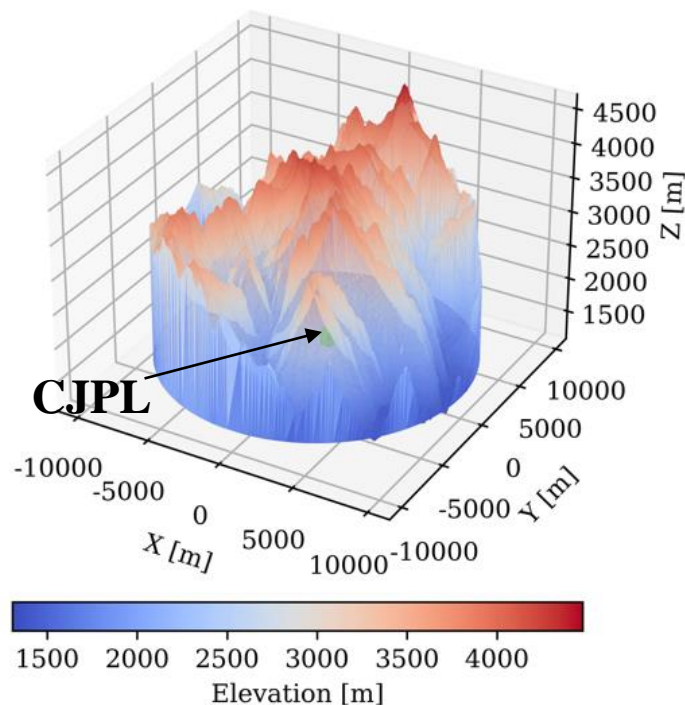
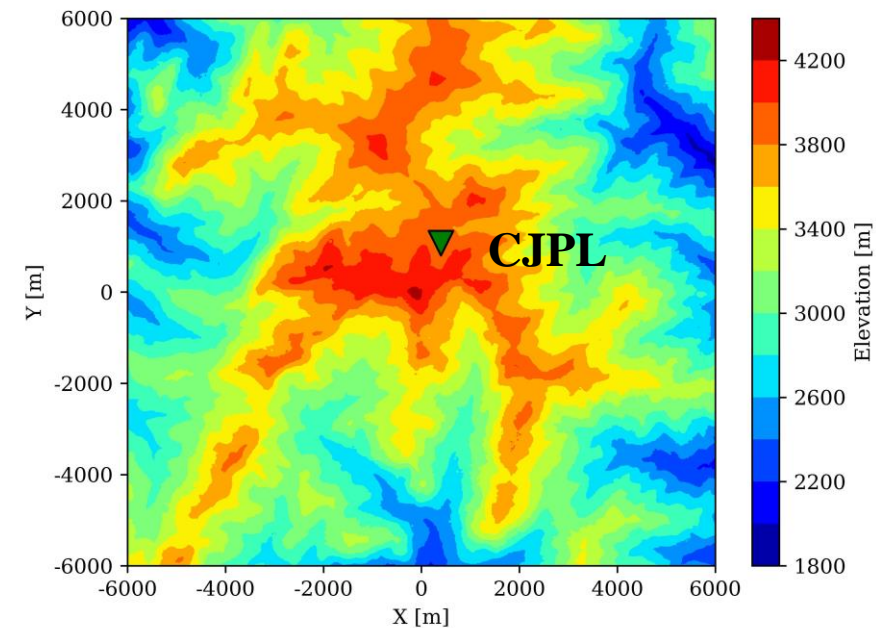
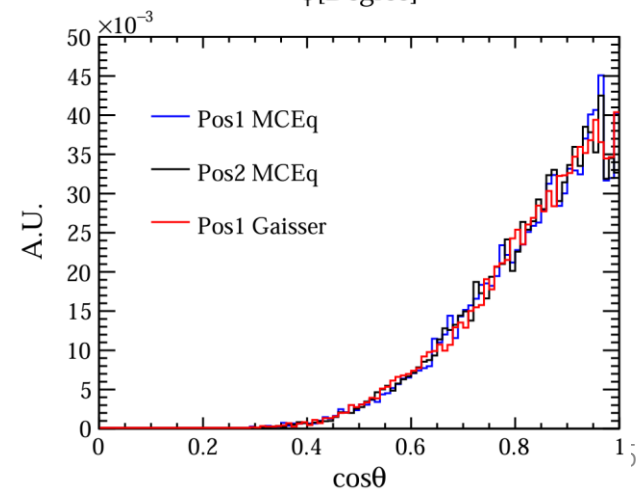
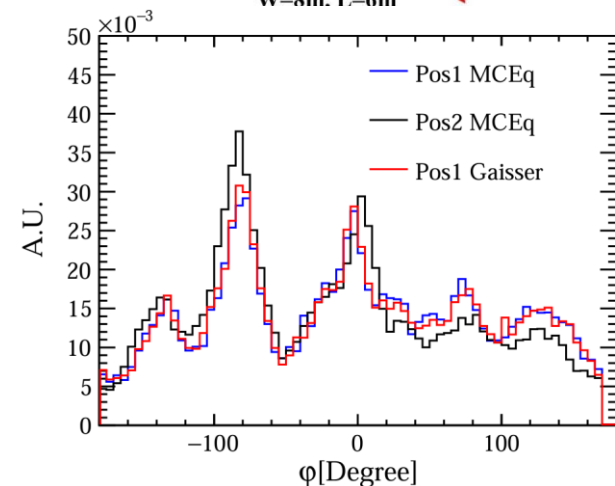
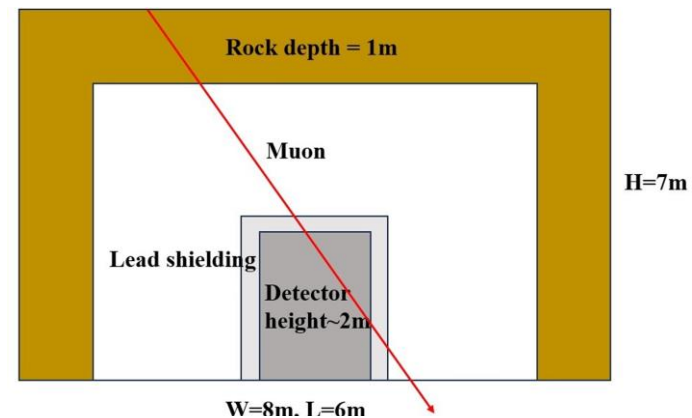
一吨原型机

- 2017年8月开始液闪相取数
- 2023年9月停止取数，共1289天数据



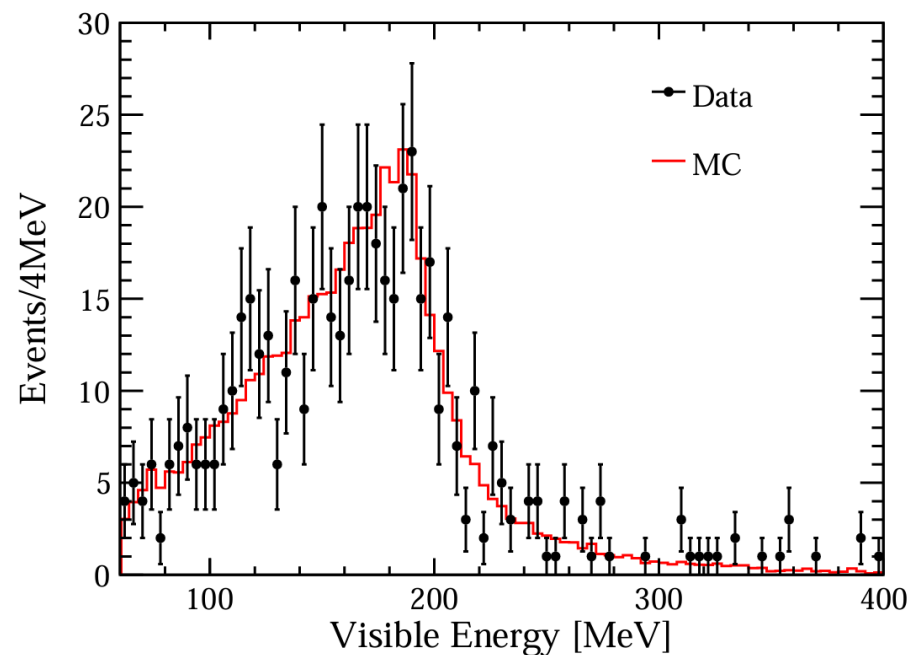
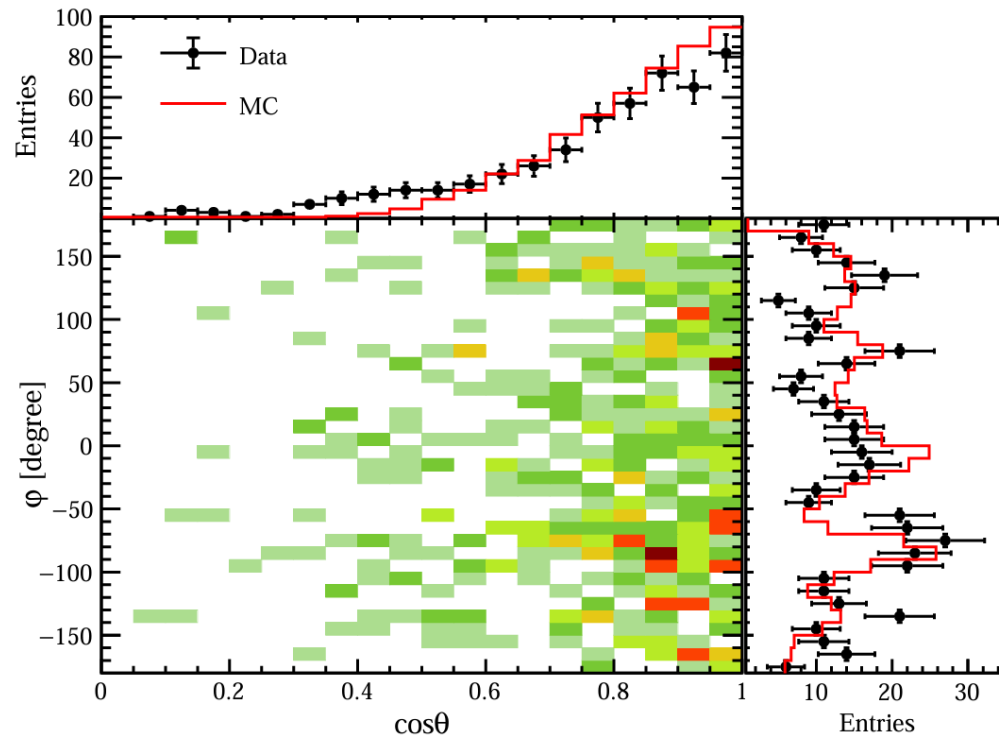
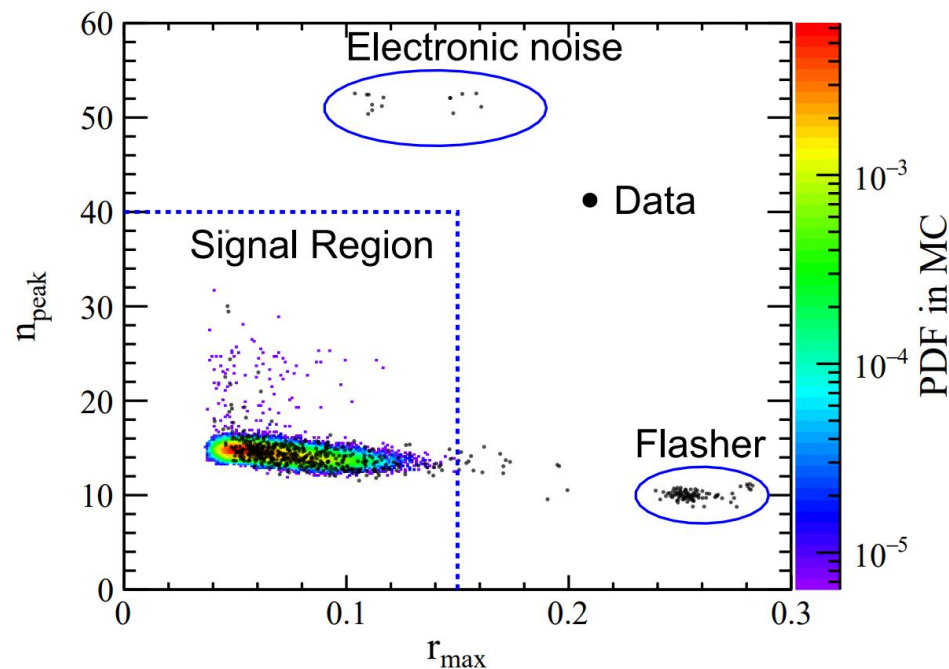
宇宙线缪子模拟

- 山体模拟：得到地下实验室的缪子分布
- 探测器模拟：得到缪子的探测器响应



繆子事例特征

- 选择条件：
 - 可见能量 > 60 MeV (天然放射性)
 - $r_{\max} < 0.15$ (flasher)
 - $n_{\text{peak}} < 40$ (电子学噪声)

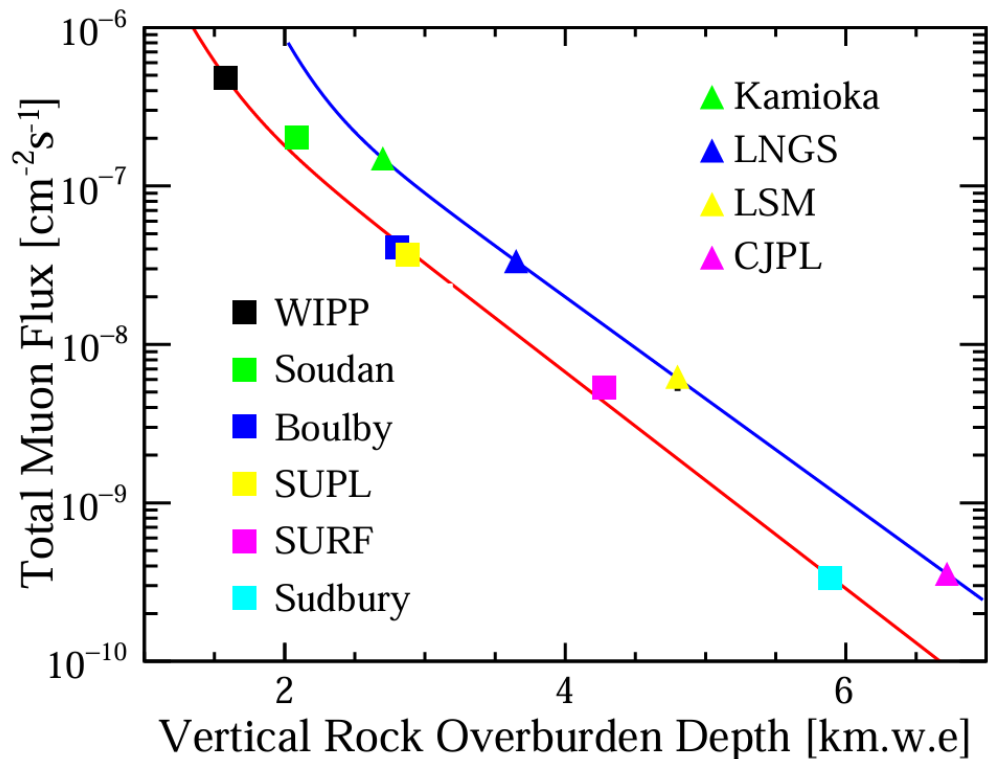


宇宙线缪子流强测量

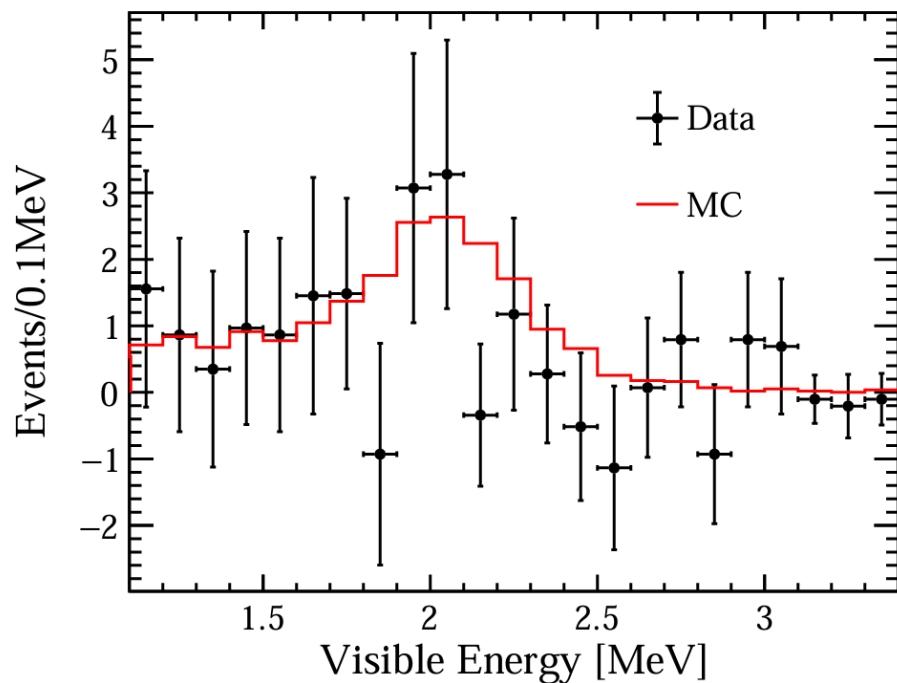
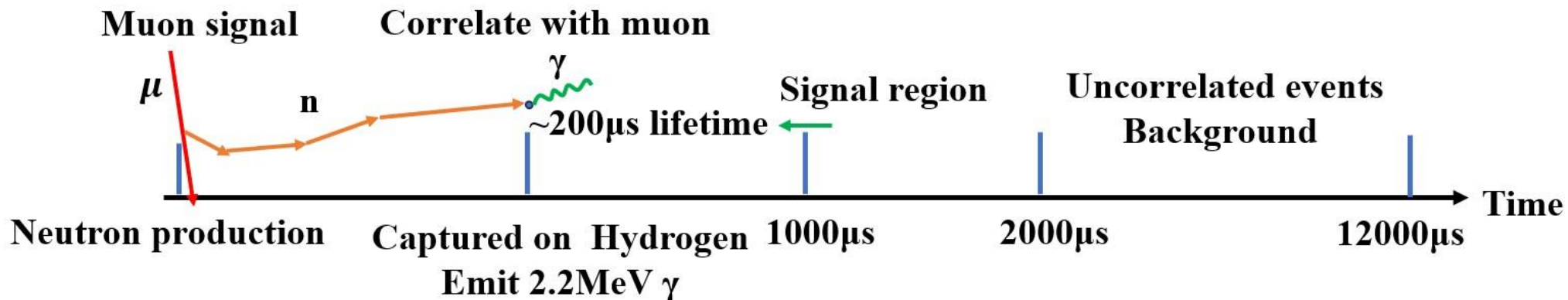
$$\phi_{\mu} = \frac{N_{\text{total}}}{T \times S} = \frac{N_{\mu}}{\epsilon \times S \times T} = [3.56 \pm 0.16(\text{stat.}) \pm 0.10(\text{syst.})] \times 10^{-10} \text{ cm}^{-2}\text{s}^{-1}$$

↗ 数据中满足选择条件的缪子总数
↘ 缪子选择效率 有效缪子入射面积 有效取数时间

Source	Uncertainty	Flux	Uncertainty
Energy scale	± 5 %		± 1.6 %
Acrylic vessel radius	± 0.5 cm		± 1.5 %
Lead shielding thickness	± 5 cm		± 0.2 %
Rock thickness	± 50 cm		± 0.7 %
Hadronic model	± 50 %		± 0.5 %
Muon generator			± 0.2 %
laboratory position			
latitude and longitude	± 100 m		± 1.1 %
elevation	± 100 m		± 0.6 %
Total systematic			± 2.7 %
statistical			± 4.5 %



繆致中子事例挑选与本底扣除



信号区间事例数 归一化因子 本底区间事例数

$$N_{\text{obs}} = N_{20-1020 \mu\text{s}} - k \times N_{2000-12000 \mu\text{s}}$$

结构俘获修正 繆子簇射修正 中子泄露修正

$$N_n = N_{\text{obs}} \times \frac{(1 - f_{\text{structure}}) \times (1 - f_{\text{shower}}) \times f_{\text{spill}}}{\epsilon_E \times \epsilon_t \times f_{\text{det}}}$$

能量选择效率 时间选择效率 探测器尺寸修正

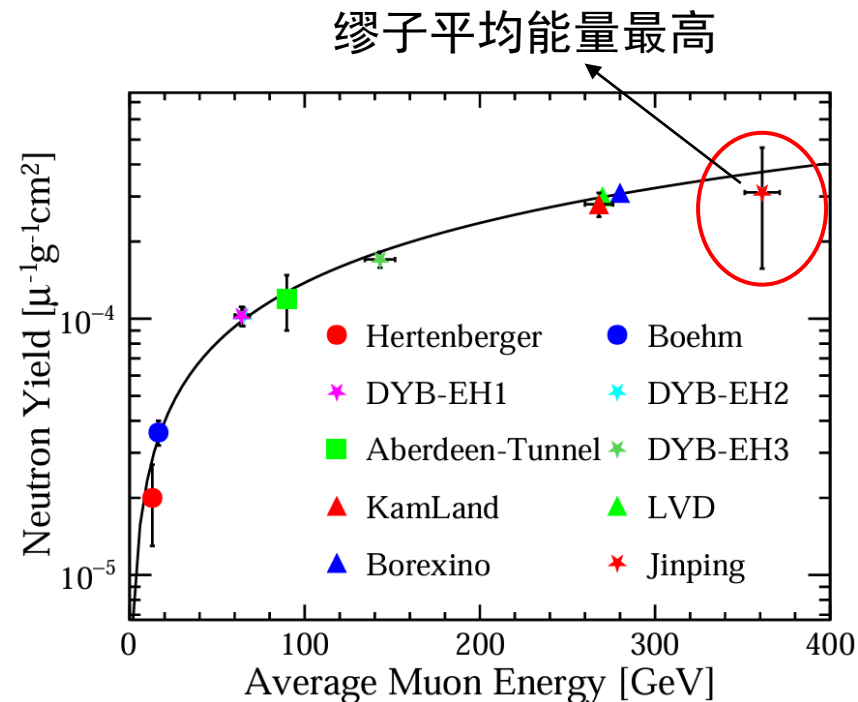
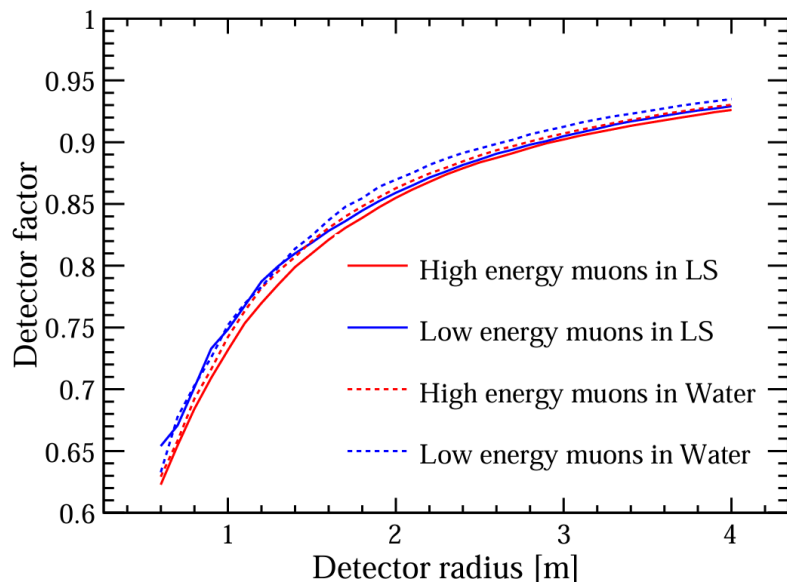
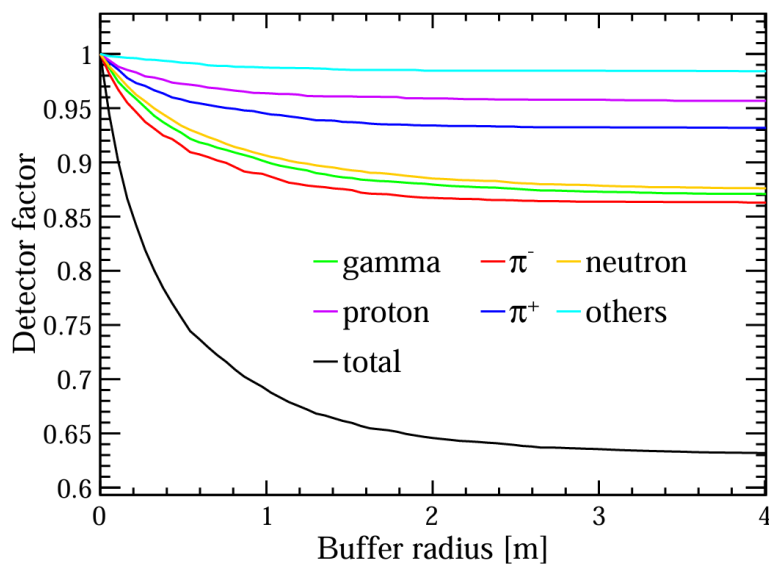
液闪中缪致中子产额测量

$$Y_n = \frac{N_n}{(\sum L_\mu) \times \rho} = \frac{N_n}{N_\mu \times L_{avg} \times \rho} = 3.11 \pm 1.46 \text{ (stat.)} \pm 0.50 \text{ (sys.)} \times 10^{-4} \mu^{-1} \text{g}^{-1} \text{cm}^2$$

穿过液闪缪子数
液闪中缪子平均径迹长度
液闪密度

缪子穿过液闪产生中子数

Parameter	Nominal value	Uncertainty	Dominant source
ϵ_E	57.0 %	± 2.8 %	Energy scale
ϵ_t	90.6 %	± 0.8 %	MC statistic
$f_{\text{structure}}$	0.24	± 9.2 %	Hadronic model
f_{shower}	0.21	± 9.8 %	Hadronic model
f_{spill}	0.61	± 7.9 %	Hadronic model
f_{det}	0.63	± 1.9 %	Hadronic model
L_{avg}	95.6 cm	± 1.5 %	Acrylic vessel radius
ρ	0.86 g/cm ³	/	/
N_{obs}	10.5	± 46.9 %	Signal statistic
Total	/	± 49.6 %	/





总结

- 本研究利用锦屏中微子实验一吨原型机1239天的数据，对其中的缪子信号进行了研究。
- 对探测器中的缪子信号和缪子的物质的相互作用进行了详细的模拟研究。
- 分别测量了锦屏地下实验室的宇宙线缪子流强，液闪中的缪致中子产额。