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Study of Annual Modulation at Soudan Mine Using a Liquid Scintillation Detector

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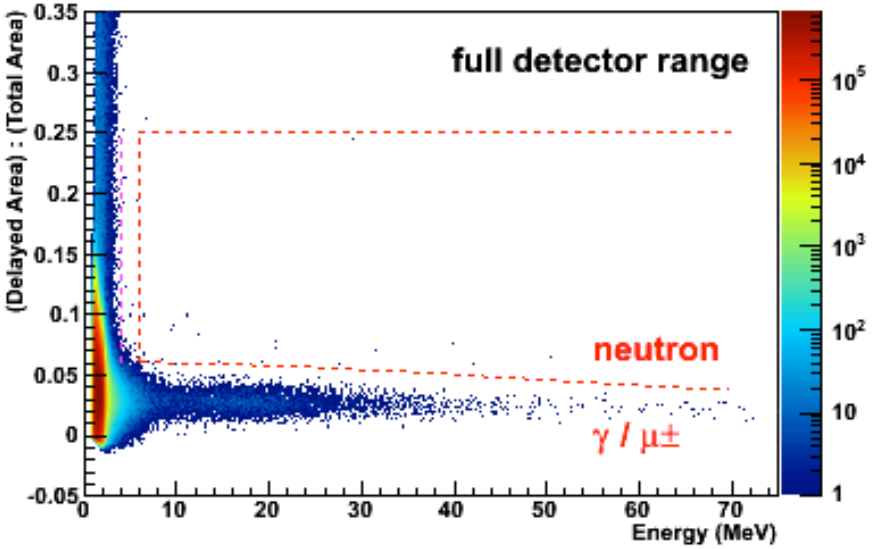
Motivation

- The phenomenon of annual modulation is believed to be one of keys to direct dark matter searches in favor of WIMPs scenario.
- DAMA and CoGeNT experiments observed the annual modulation which interpreted as dark matter signature. However, the source which caused the annual modulation in both is still under investigation.
- We have a liquid scintillation detector running at Soudan Mine (1.95 km.w.e) for over 3 years. Clearly annual modulation patterns are also observed for muons.

Liquid Scintillation Detector at Soudan

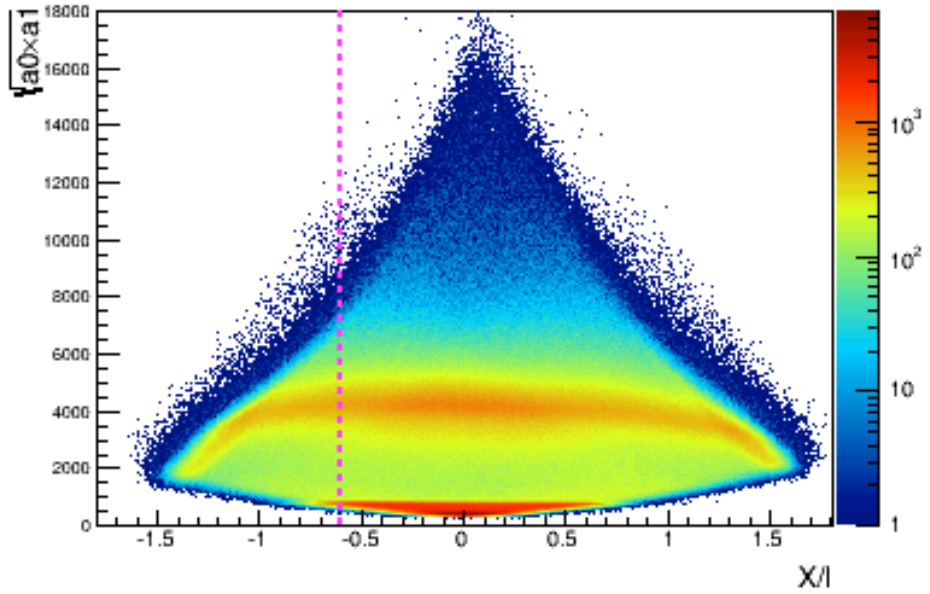
Detector Design

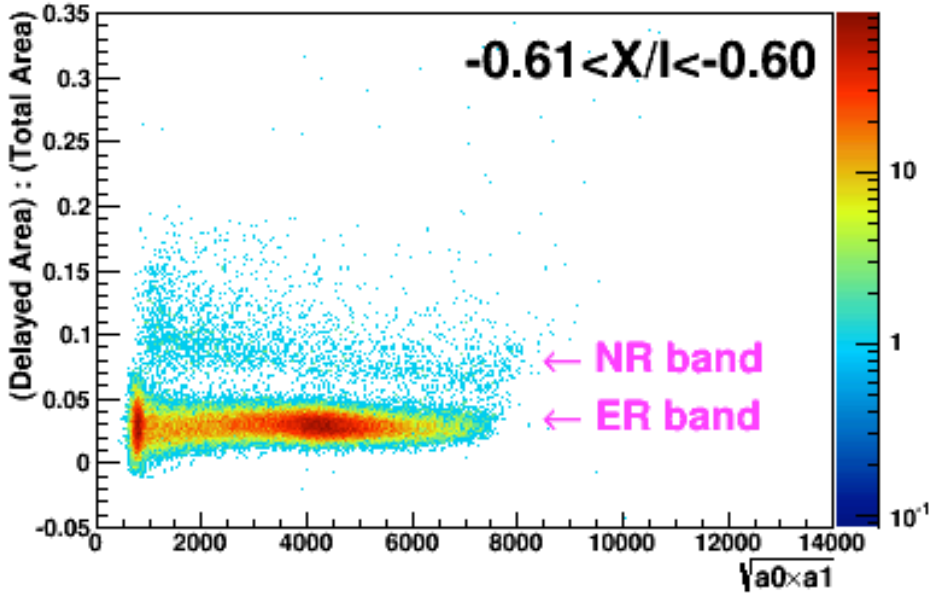
- 1m long LS neutron detector filled with 12 liters LS EJ301.
- Internally covered with diffusive paint EJ520.
- 2 Hamamtsu 5” PMTs(R4144) attached to the detector through Pyrex glass windows.



- Detector performance and measurement results please refer
  1) NIMA 729(2013)138
  2) PRD 90 (2014) 122003

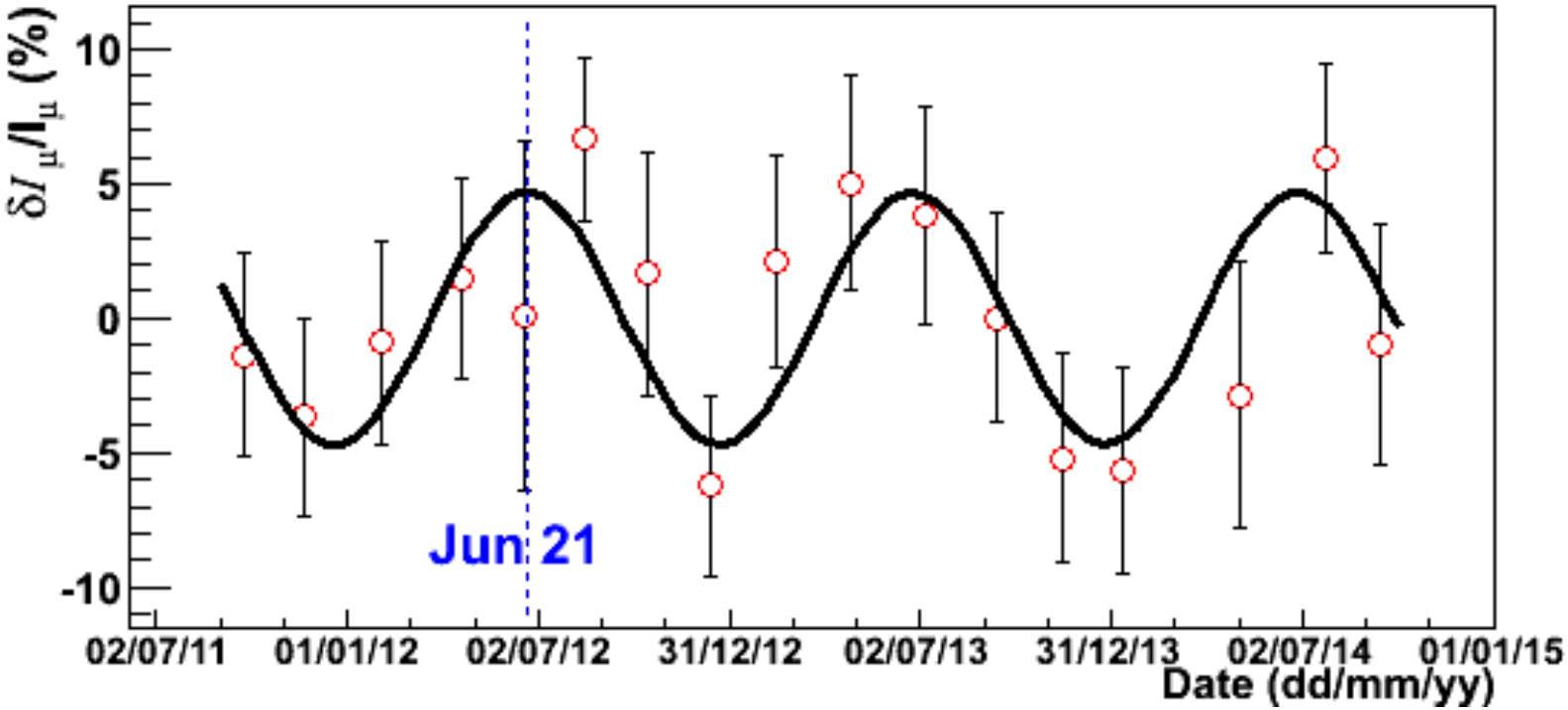
Neutrons at Surface





- Surface background data: 19.16 days.
- Muon minimum ionization peak is about ~20 MeV in terms the size of the detector.

Muon Modulation (E_{vis}>10MeV)

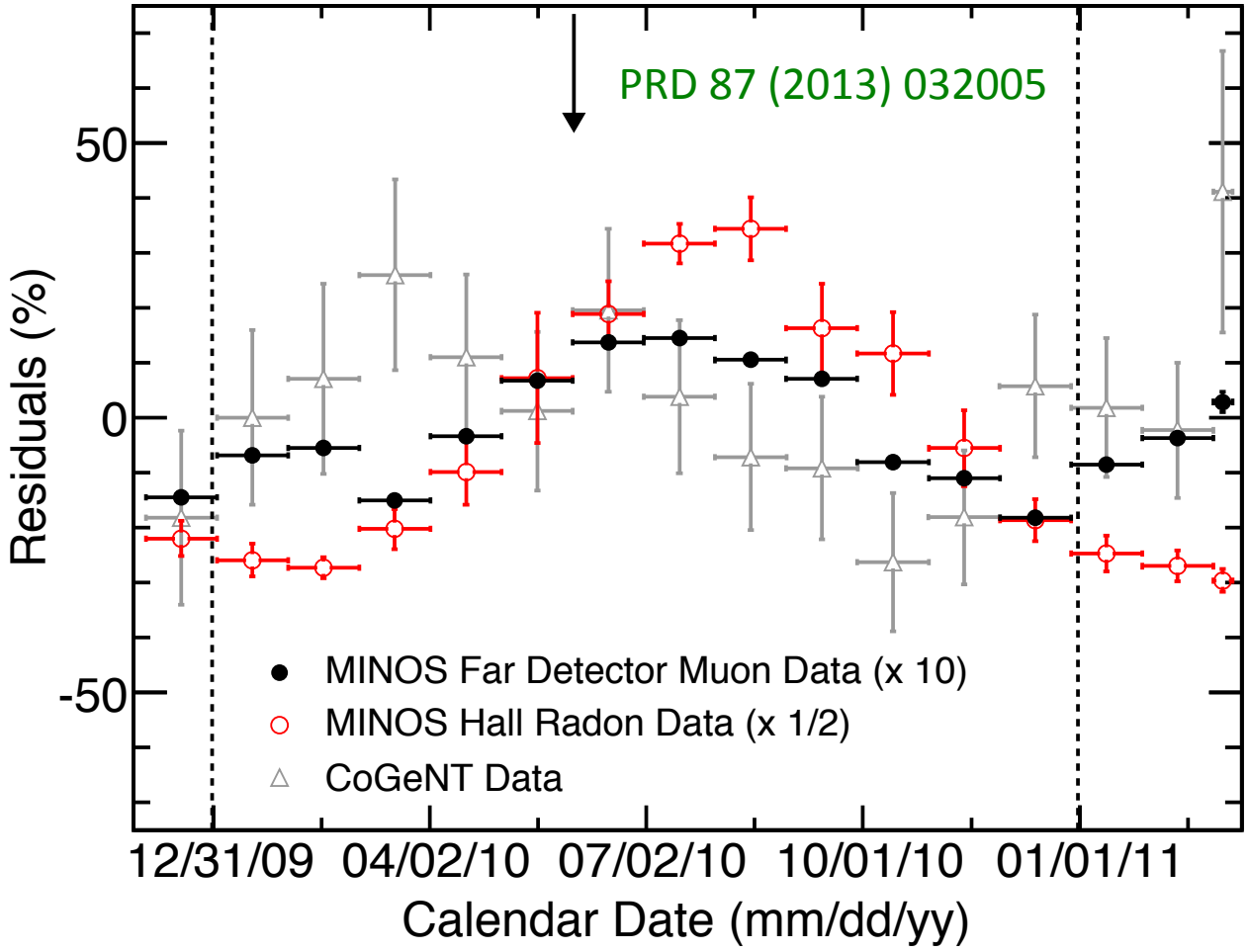


$$I_\mu = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

$$\bar{I_\mu} = 1.31 \times 10^{-4}\, s^{-1}$$
$$\delta I_\mu = 6.15 \times 10^{-6}\, s^{-1}$$
$$T = 367.98\, days$$
$$t0 \rightarrow Jun\, 21$$

Bin size is about 2 months:
Modulation Amplitude: (4.68 ± 1.35)%.
Phase t0: (Jun 21 ± 21.3) days
Period T: (367.98 ± 14.32) days

MINOS and CoGeNT

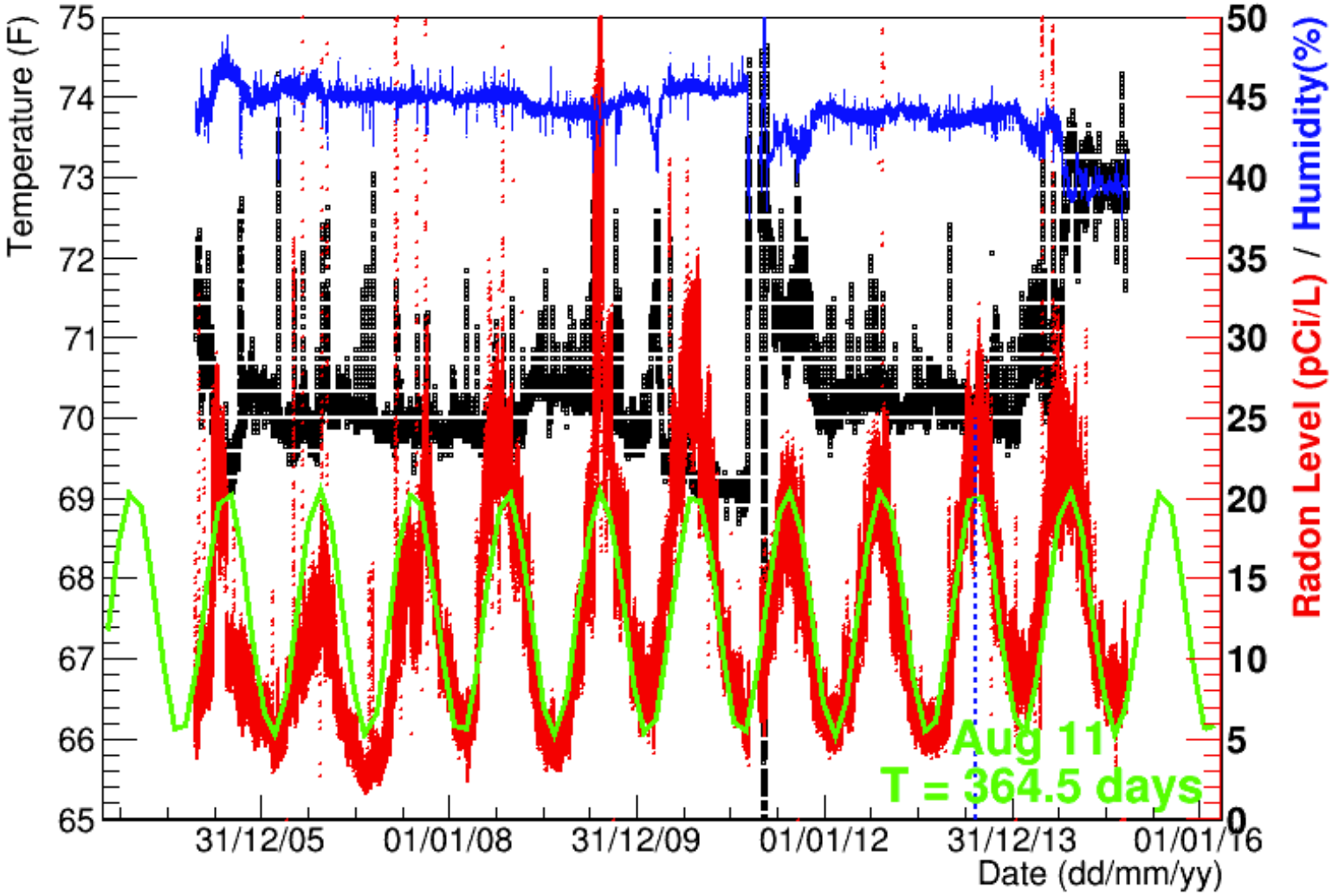


Comparison with Other Experiments

Site	Soudan-A	Soudan-B	Soudan-C	LNGS-A	LNGS-B	LNGS -C
Detector	ours	CoGeNT	MINOS	LVD	Borexino	DAMA
E^{μ}_{thr} [GeV]	730	730	730	1833	1833	1833
$I_{\mu}[10^{-4}/m^2/s]$	16.5		16.5	3.31	3.41	
Modul. Ampl.	4.68%	16.6%	1.37%	1.5%	1.3%	2%
Period (days)	368±14	347±29	317±3.2	367±15	366±3	365±7
Phase (days)	Jun $21^{th} \pm 21$	Apr $25^{th} \pm 12$	Jul $6^{th} \pm 1.4$	Jul $4^{th} \pm 15$	Jun $28^{th} \pm 6$	Jun $2^{th} \pm 7$
			Radon			
mean(pCi/L)	14.0±0.1	12.0±0.1	12.0±0.1			
Modul. Ampl.	47.0%	57.7%	57.7%			
Period (days)	364.5±0.6	367.4±3.5	367.4±3.5			
Phase (days)	Aug 10±0.4	Aug 3±1.1	Aug 3 ±1.1			

Note: the modulation signals from CoGeNT and DAMA are not from direct Muons.

Yearly Environmental Data at Soudan



NO obvious correlation between Radon level and Temperature/Humidity.

Thanks Prisca, Anthony and Jeff (UMN) for providing those data.

Summary

- Over three years of background data have been collected at Soudan Mine. Clearly annual modulation signals from Muon(E>10MeV) are observed.
- The modulation phases of Muon is at Jun 21st ± 21.3 days with the period of 367.98 ± 14.32 days.
- Secondary particle from muons should also have similar modulation patterns but with different amplitude which need further investigation. Muon veto + NaI array would be help to tag these secondary particles with our current detector.
- Radon has obvious modulation pattern in the cavern. Radon could impact large energy range from a few MeV(alphas) down to keV (gamma or x-rays). This effect is still under study.
- Implications: Both Muon and Radon could affect low energy rates which cause low energy variations.