Variations in the cosmogenic neutron flux and the cosmic ray muon energy underground

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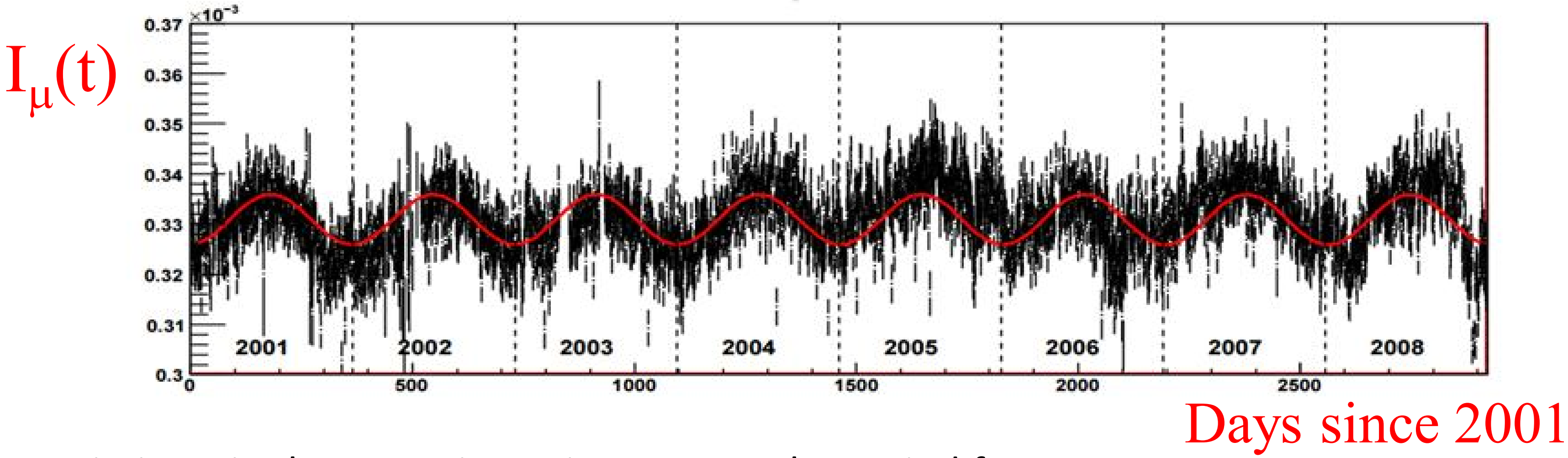
Outline

- Seasonal variations (modulation) in the muon intensity
- Variations of cosmogenic neutrons at the LVD depth
- Seasonal variations of the mean muon energy and the cosmogenic neutron flux at the LVD depth
- On the mechanism of seasonal variations of the mean muon energy deep underground

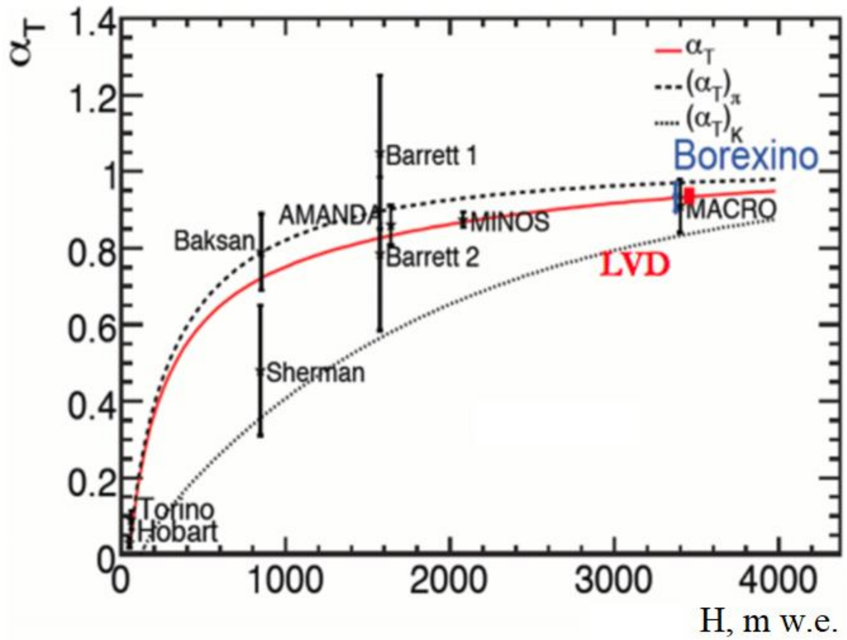
Muon Intensity Seasonal variations



Variations in the muon intensity on LVD, the period from 2001 to 2009

$$\boxed{\frac{\Delta I_\mu}{I_\mu} = \alpha_T \frac{\Delta T_{at}^{\mathrm{eff}}}{T_{at}^{\mathrm{eff}}}}$$

$$\frac{\delta I_\mu}{I_\mu^0} = 1.5\%$$

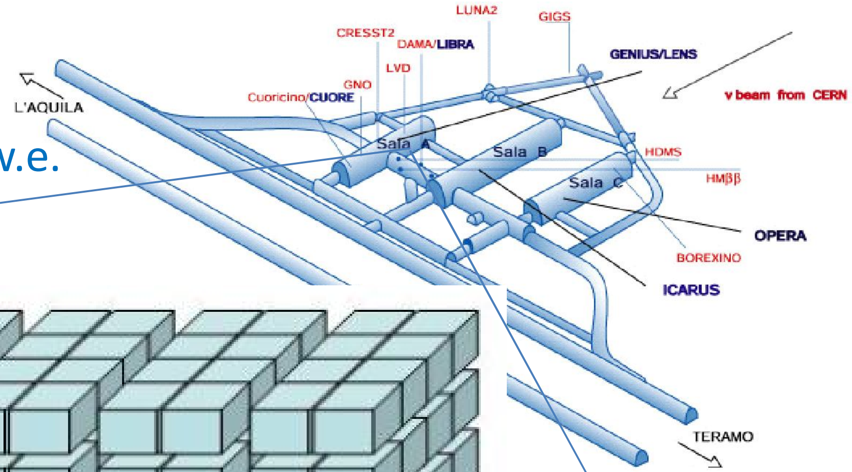


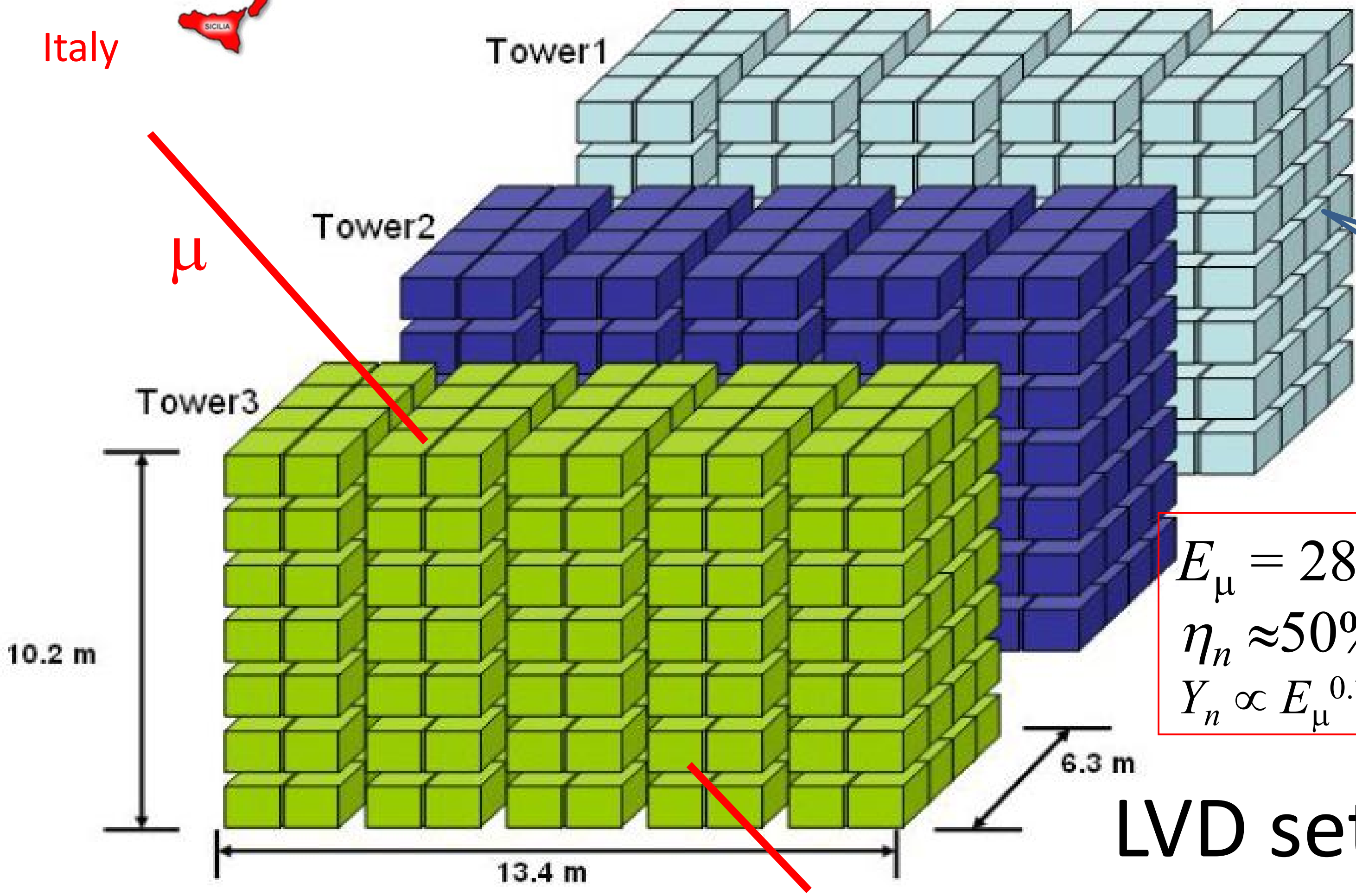
Dependence of temperature coefficient on depth

Large Volume Detector @ LNGS

Italy

H = 3.1 km w.e.



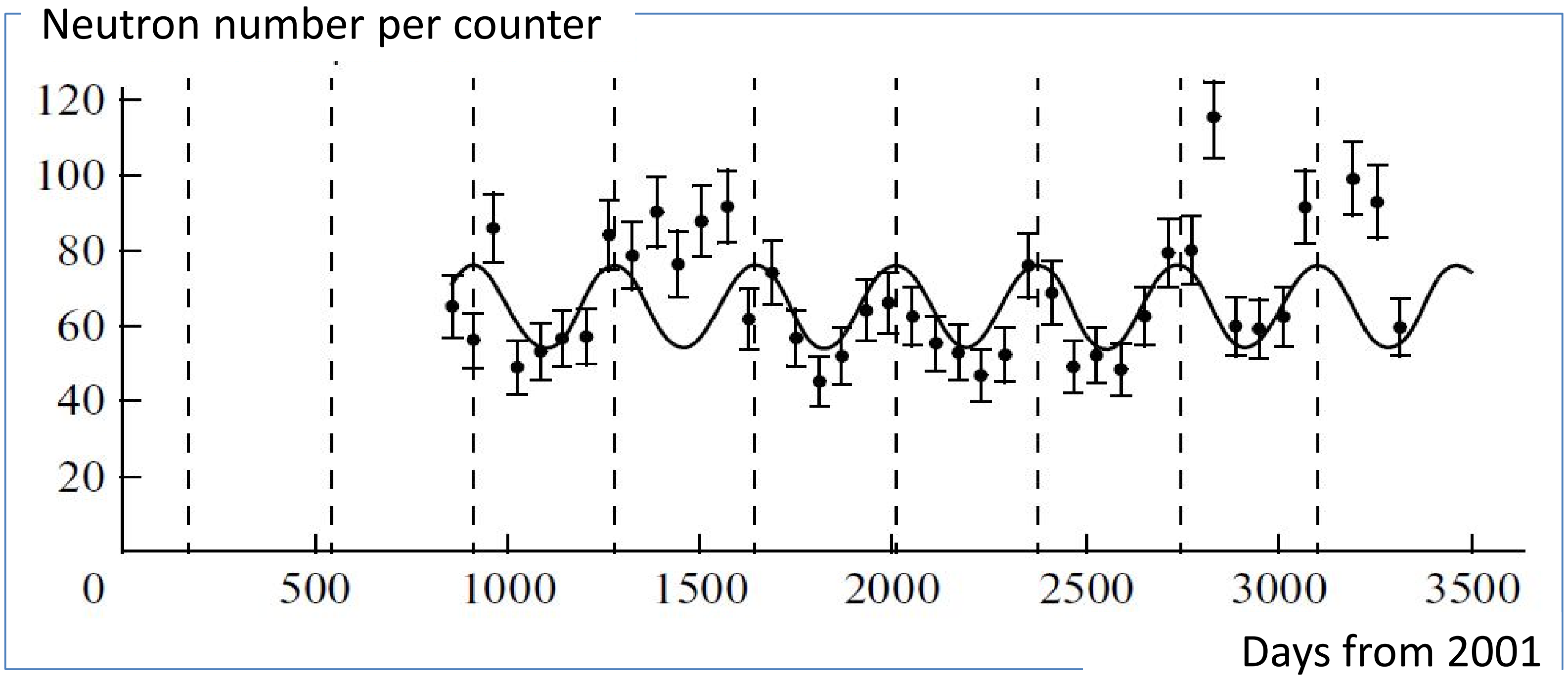


M(sc) = 330 t
M(Fe) = 340 t

$E_\mu = 280$ MeV
$\eta_n \approx 50\%$
$Y_n \propto E_\mu^{0.75} A^{0.95}$ n/μ(g/cm^2)$^{-1}$

LVD setup

Φ_n



$$\frac{\delta \Phi_n}{\Phi_n^0} = \frac{\delta N_n}{N_n^0} = 14.3\% \qquad \sigma \approx 40\%$$

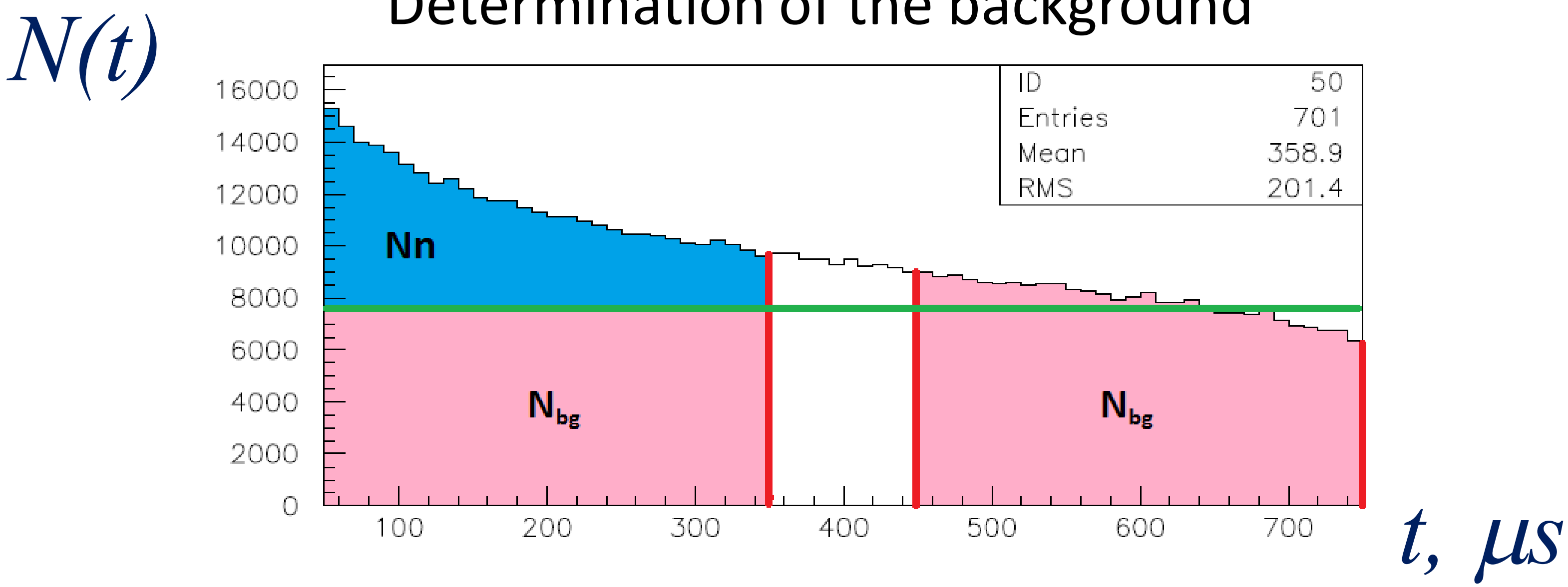
$$\Phi_n \propto I_\mu Y_n$$

$$\boxed{Y_n \propto \bar{E}_\mu^{0.78} A^{0.95}}$$

Variations of cosmogenic neutrons

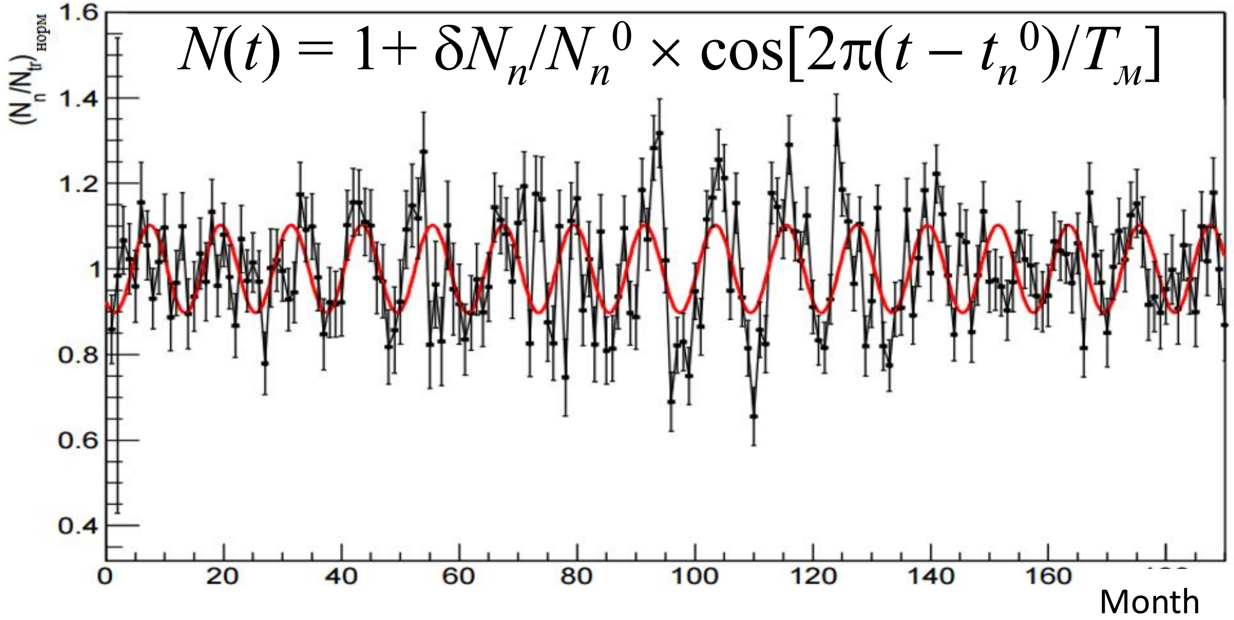
Epoch folding method

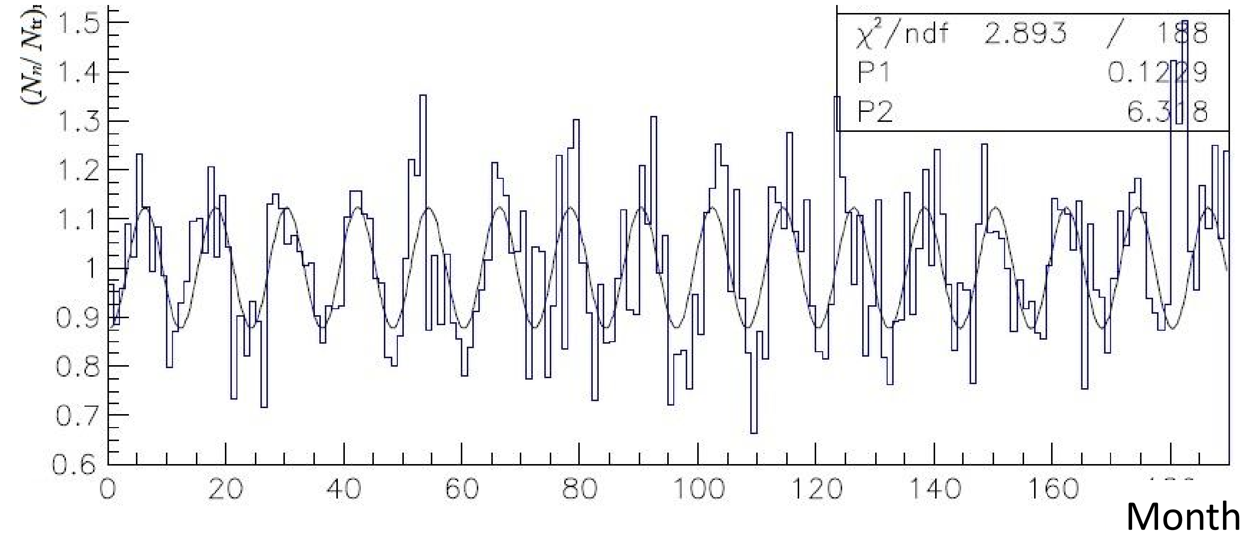
Determination of the background



$N_n / N_\mu = (N_{tot} - N_{bg}) / N_\mu$ (for each month of 180 months)

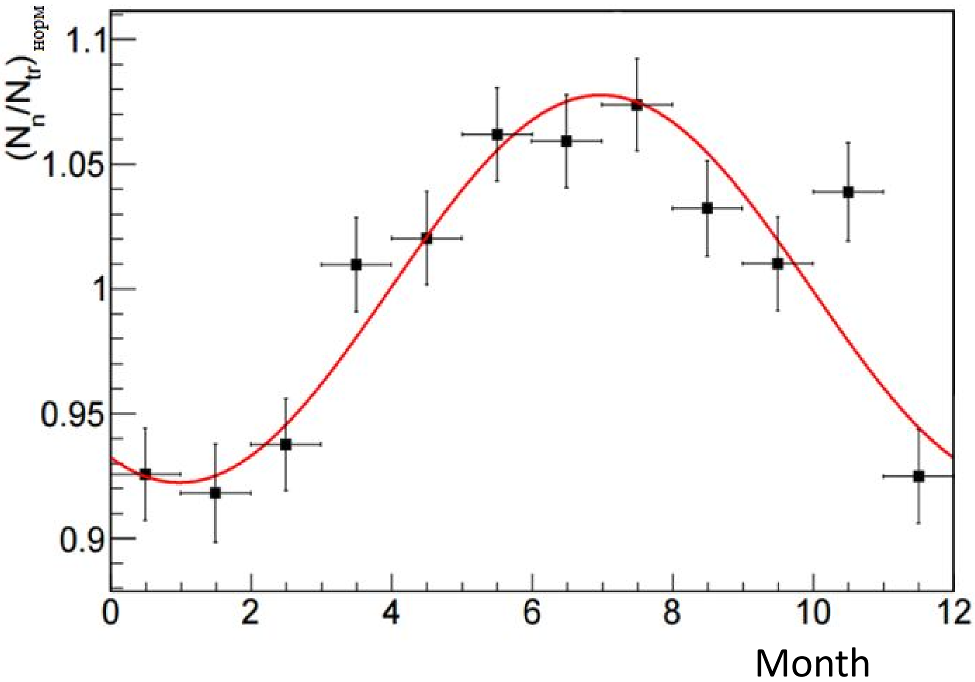
Epoch folding method





Variations of the specific number of neutrons N_n/N_μ on LVD for 15 years (2001 - 2016);
the statistical uncertainties of measurements are indicated in steps of 1 month, the curve is the best approximation of the data using a harmonic function

Epoch folding method



$(\delta N_n/N_n^{\,0}) = 0.077 \pm 0.008$

$t_n^{\,0} = 7.0 \pm 0.4$ (stat) $\pm\, 0.5$ (sys)

$T_M = 12$ months

$$\frac{\delta N_n}{N_n^0} = \frac{\delta Y_n}{Y_n^0} = 7.7\%$$

Determination of the parameters of the cg-neutron variations by epoch folding method.

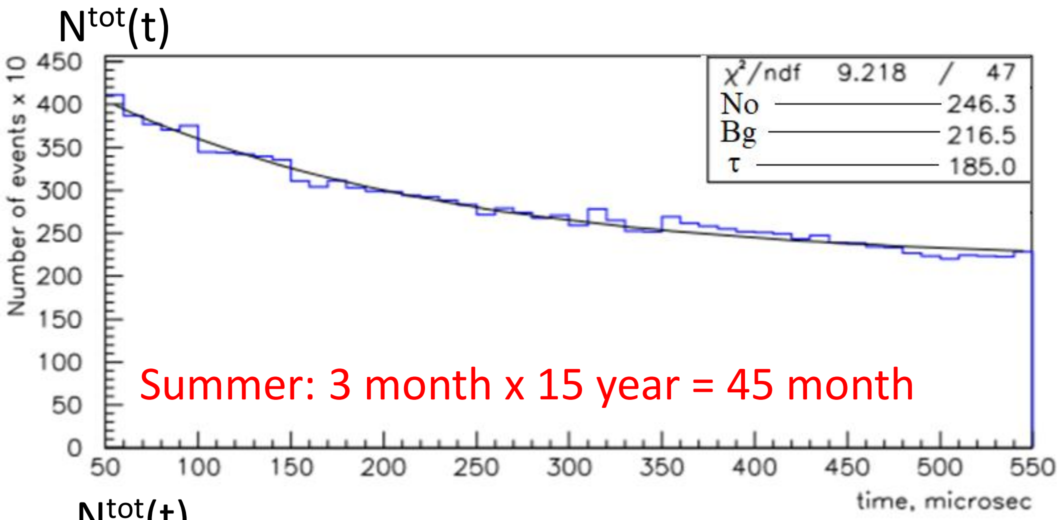
Residual method: «summer» – «winter»

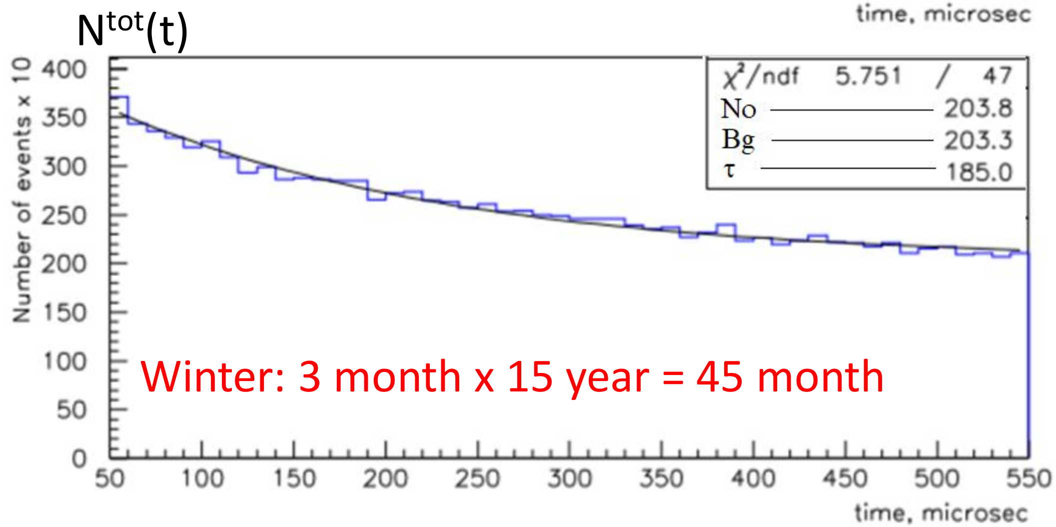
$$\delta N_n = (N^w_n - N^s_n)/(N^w_n + N^s_n)$$

$N^{tot}(t) = N_o \cdot \exp(-t/\tau) + Bg$

$N_n = N_o \cdot \tau$, $\tau = 185\ \mu s$

$$\frac{\delta N_n}{N_n^0} = \frac{\delta Y_n}{Y_n^0} = 7.7\%$$





Amplitude of the mean muon energy variations

$$Y_n(E_\mu) \propto E_\mu^{0.78}$$

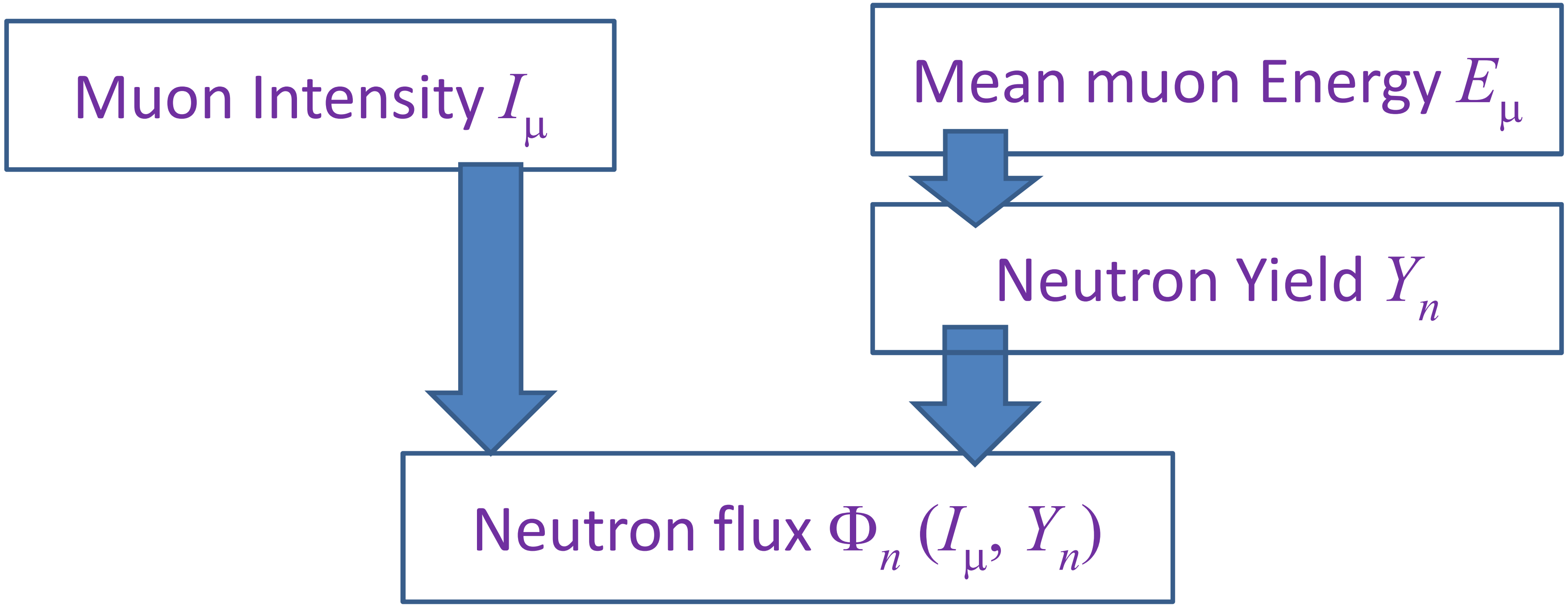
$$\frac{N_n+\delta N}{N_n}=\frac{Y_n+\delta Y_n}{Y_n}=\left(\frac{E_\mu+\delta E}{E_\mu}\right)^{0.78} \Rightarrow \frac{\delta E}{E_\mu} = \left(1+\frac{\delta N}{N_n}\right)^{1/0.78} - 1$$

$$\frac{\delta E}{E_\mu} = (1+0.08)^{1/0.78} - 1 = 0.10$$

$$E_\mu^{\mathrm{LVD}} = 280 \pm 28\ \text{ГэВ}$$

The 10% muon energy variations result in about 8 % variations in the muon-induced neutron yield.

Seasonal variations of the cosmogenic neutron flux



The variation amplitude of the cosmogenic neutron flux

$$1 + \delta\Phi_n/\Phi_n^0 = (1 + \delta I_\mu/I_\mu)\times(1 + \delta Y_n/Y_n) = 1.015 \times 1.077$$

$$\boxed{\delta\Phi_n/\Phi_n^0 = 9.3\ \%.}$$

Intensity

$$\frac{\delta I_\mu}{I_\mu^0} = 1.5\%$$

$\sigma \approx 4\%$

Energy

$$\frac{\delta \bar{E}_\mu}{\bar{E}_\mu^0} = 10\%$$

$\sigma \approx 11\%$

Yield

$$\frac{\delta Y_n}{Y_n^0} = 7.7\%$$

$\sigma \approx 11\%$

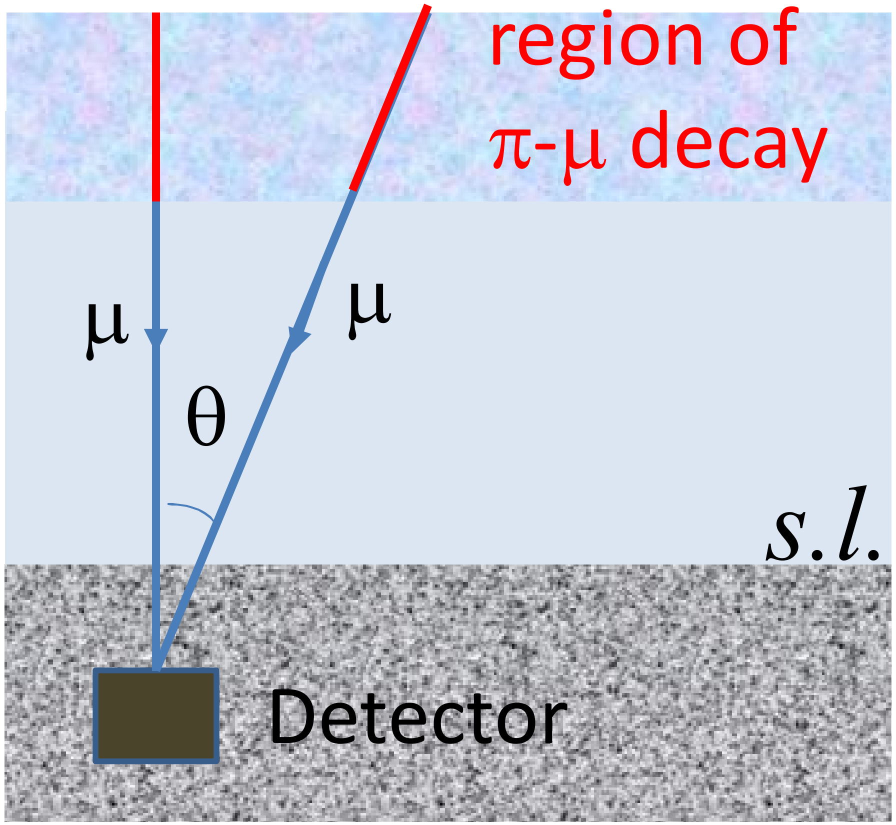
Flux

$$\frac{\delta \Phi_n}{\Phi_n^0} = 9.3\%$$

$\sigma \approx 12\%$

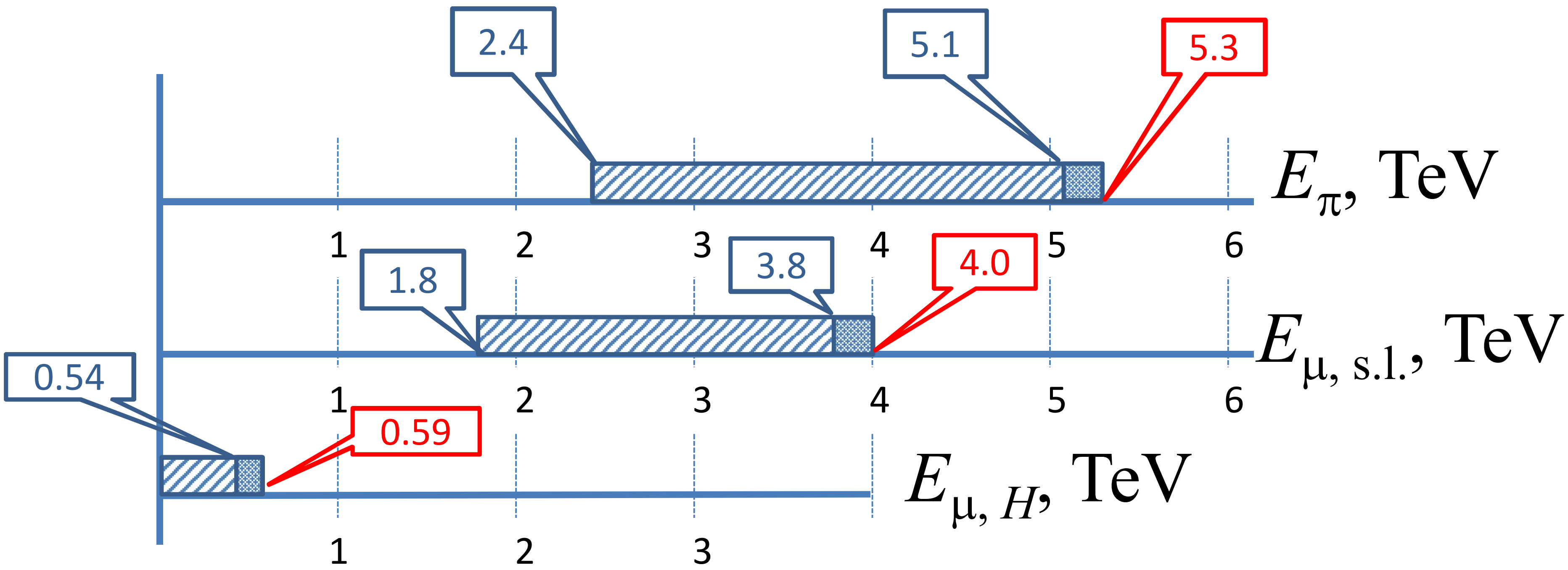
The origin of the mean muon energy variations

A: Increase (decrease) of a decay probability for the high energy pions – just as increasing (decreasing) of production of the high energy muons at rise (diminution) of θ



The origin of the mean muon energy variations

B: Variations (expansion or reduction) of the effective energy range of $\pi^{\pm}$ -decays

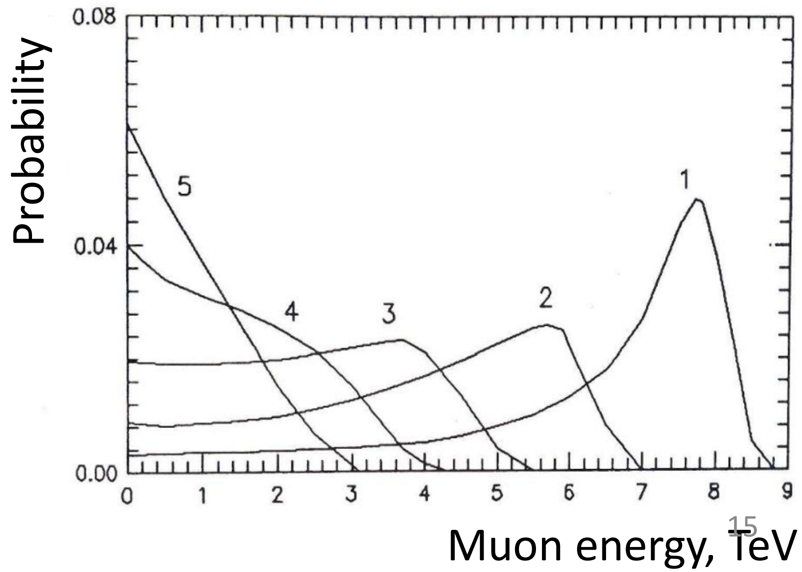


The origin of the mean muon energy variations

C: Peculiarities of transformation of the muon energy spectrum at s.l. ($P(E_\mu^{sl}) \propto E_\mu^{-3.75}$) to the muon energy spectrum deep underground (quasi-stepped $P(E_\mu) \propto (\epsilon_\mu + E_\mu)^{-3.75}$)

$$\boxed{E^{av}_{\mu,H} = (E_{\mu,\mathrm{sl}} + \epsilon_\mu)\, e^{-\mathrm{b}H} - \epsilon_\mu}$$

The distribution of probability for a muon with energy of 10 TeV at sea level to have energy from E to E + 0.1 TeV at a depth of 5, 4, 3, 2, 1 km w.e.



LVD parameters

$H^{\min} = 3.1$ km w.e.
$E^{\min}_{\mu,\,\mathrm{sl}} = 1.3$ TeV,
$E^{\mathrm{th}}_{\mu,\,\mathrm{sl}} = 1.8$ TeV

$\epsilon_\mu = a/\mathrm{b} = 667$ GeV
$a = 280$ GeV/km w.e.
$\mathrm{b} = 0.42$ / km w.e.

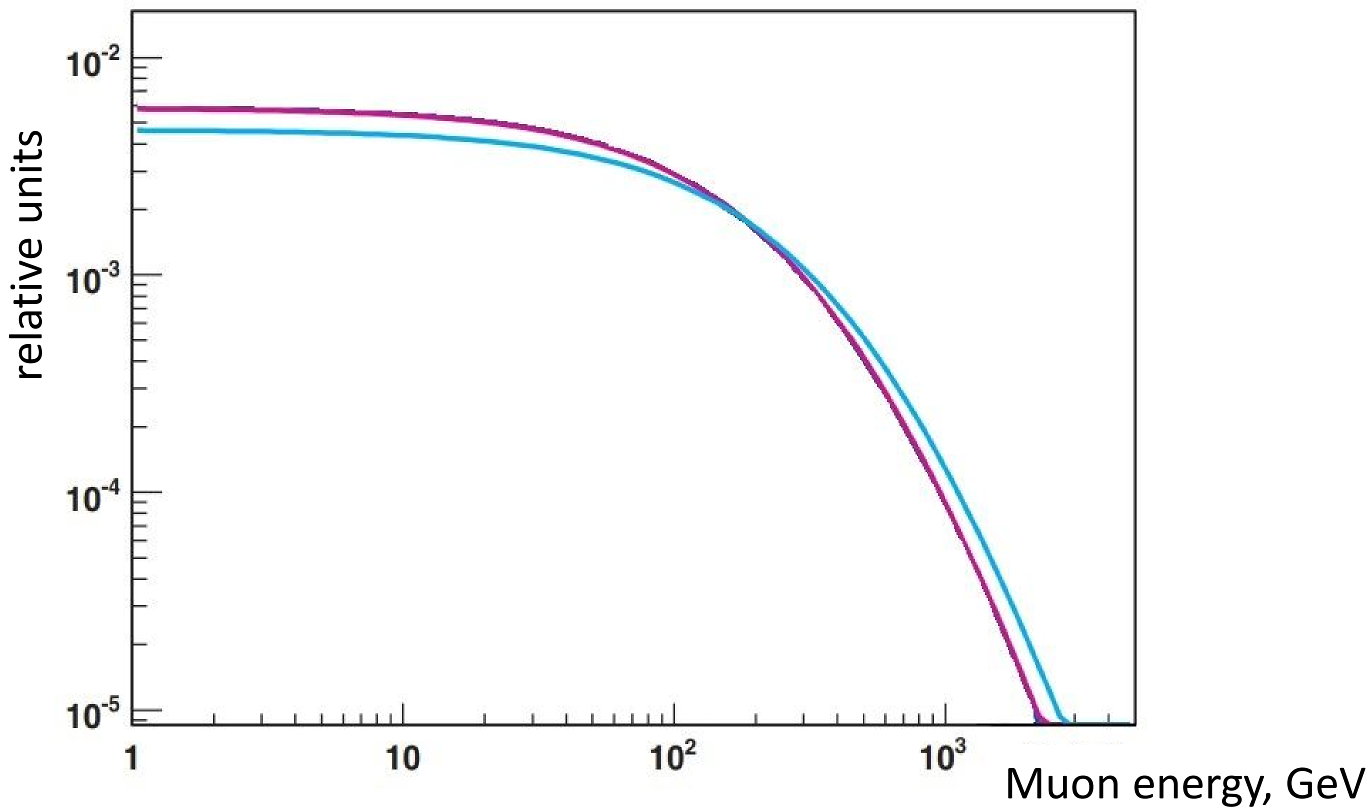
The origin of the mean muon energy variations

A Variations of a decay probability for the high energy pions.

B Variations of the effective energy range of $\pi^{\pm}$ -decays.

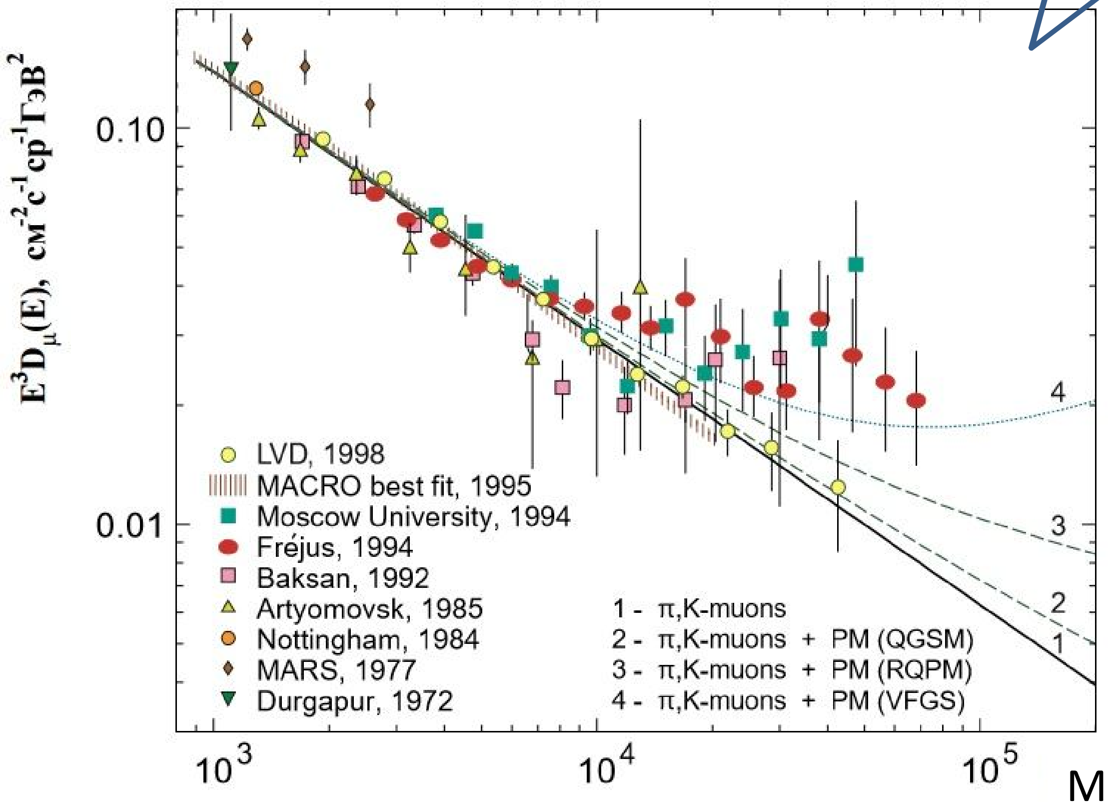
C Transformation of the muon energy spectrum at s.l. to the muon energy spectrum deep underground.

$$A + B \rightarrow \sim 4\%; \quad C \rightarrow \sim 6\%$$



Seasonal transformation of the muon spectrum shape at the LVD depth (a qualitative representation). The red curve is the average annual spectrum, the blue one is the summer spectrum.

E. V. Bugaev et. al.,
Phys. Rev. D., vol.58,
1998



Muon energy, GeV

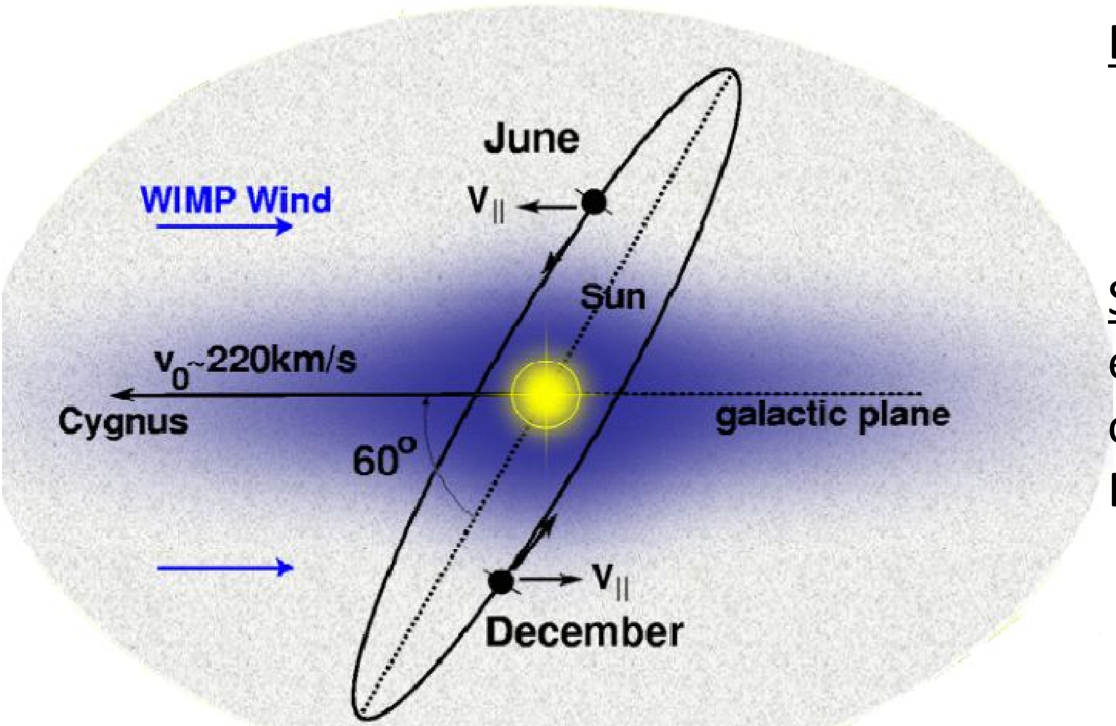
Differential muon spectra at sea level for the vertical.

Conclusion

- ✓ The seasonal variations of muon-induced neutrons per muon were found on the basis of data for 15 years. The measured characteristics of the neutron variations indicate seasonal variations in the average energy of muons at the LVD depth with amplitude of 10%, i.e. $E_\mu = 280 \pm 28$ GeV.
- ✓ The modulations of muons and neutrons are caused by a temperature effect, that is by the seasonal temperature and density variations of the upper atmospheric layers.
- ✓ The variations in the mean energy of the muon flux are the main source of underground cosmogenic neutron variations, because the muon energy is more sensitive to the temperature effect than muon intensity.
- ✓ Previously it was assumed that the flux of cosmogenic neutrons is proportional to the amplitude of muon intensity variations 1.5%. We have shown that the neutron flux has an amplitude of seasonal variations in 6 times more, because the mean muon energy deep underground also varies with amplitude of $\sim$ 10%.
- ✓ The mean muon energy variations increase role of cosmogenic neutrons in a background forming at searching for DM-particles (WIMPs) by the annual modulation method.

Thank you.

Direct search for Dark Matter particles

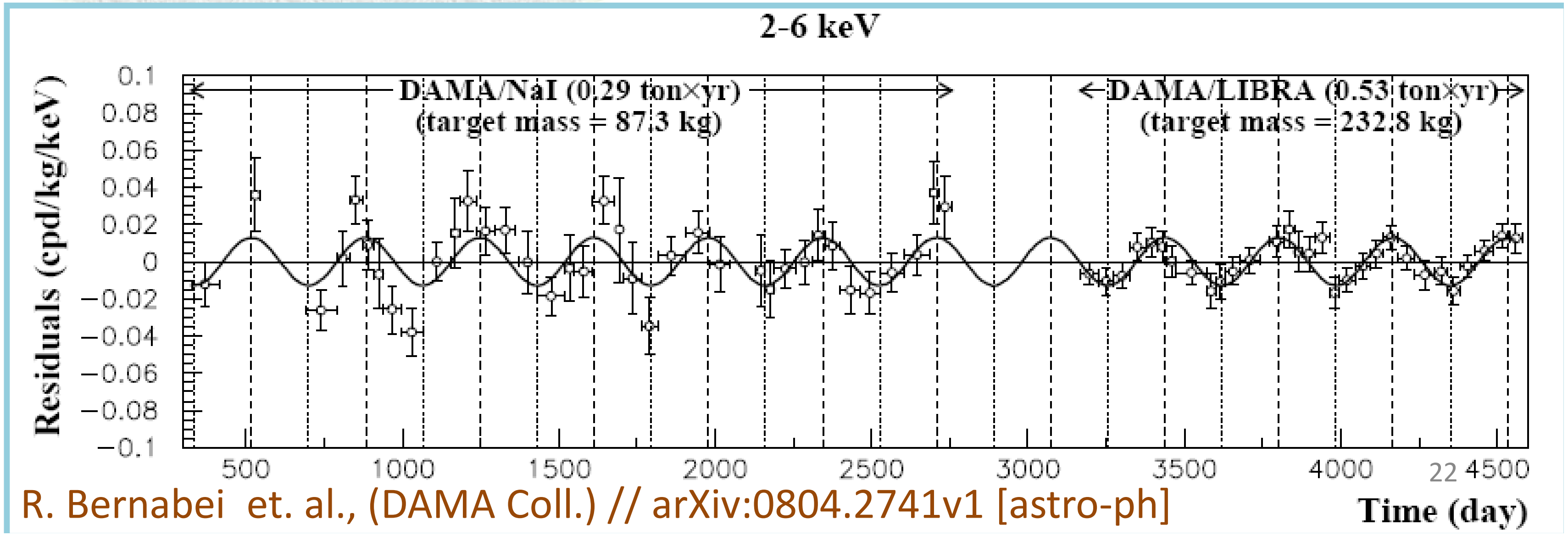


Experiments:

XENON
DAMA/LIBRA

Signal: periodic changes in the energy release in the detector caused by the rotation of the Earth around the Sun.

phase t_0 = 152.5 day (June 2nd).



R. Bernabei et. al., (DAMA Coll.) // arXiv:0804.2741v1 [astro-ph] mean annual global muon intensity (μ cm^{-2} s^{-1}) at depth H

the yield of neutrons (n/μ/g/cm^2) in a substance with a mass number A at the muon energy E_μ (GeV) corresponding to a given depth

$$\Phi_n^0(H) = I_\mu^0(H) \times Y(E_\mu) \times \lambda_n \quad (n\ \text{см}^{-2}\ \text{с}^{-1})$$

the attenuation length of neutrons with the energy spectrum of cg-neutrons (about 40 g/cm^2 for a standard rock).

$$Y(E_\mu, A) = b\, E_\mu^{0.78} A^{0.95}$$
$$(b = 4.4 \times 10^{-7}\ \text{cm}^2\text{g}^{-1}),$$

$$\boxed{\Phi_n^0(H,A) = b\, \lambda_n I_0^\mu(H) E_\mu^{0.78} A^{0.95}}$$

Annotation

The parameters of the seasonal modulations in the intensity of muons and cosmogenic neutrons generated by them at a mean muon energy of 280 GeV have been determined in the LVD (Large Volume Detector) experiment.

The modulations of muons and neutrons are caused by a temperature effect, the seasonal temperature and density variations of the upper atmospheric layers. The analysis performed here leads to the conclusion that the variations in the mean energy of the muon flux are the main source of underground cosmogenic neutron variations, because the energy of muons is more sensitive to the temperature effect than their intensity.

The parameters of the seasonal modulations in the mean energy of muons and the flux of cosmogenic neutrons at the LVD depth have been determined from the data obtained over 15 years of LVD operation.