Measurement of specific number of muon-induced neutron using Large Volume Detector

Measurement of the cosmogenic neutron seasonal variations with LVD

LVD collaboration

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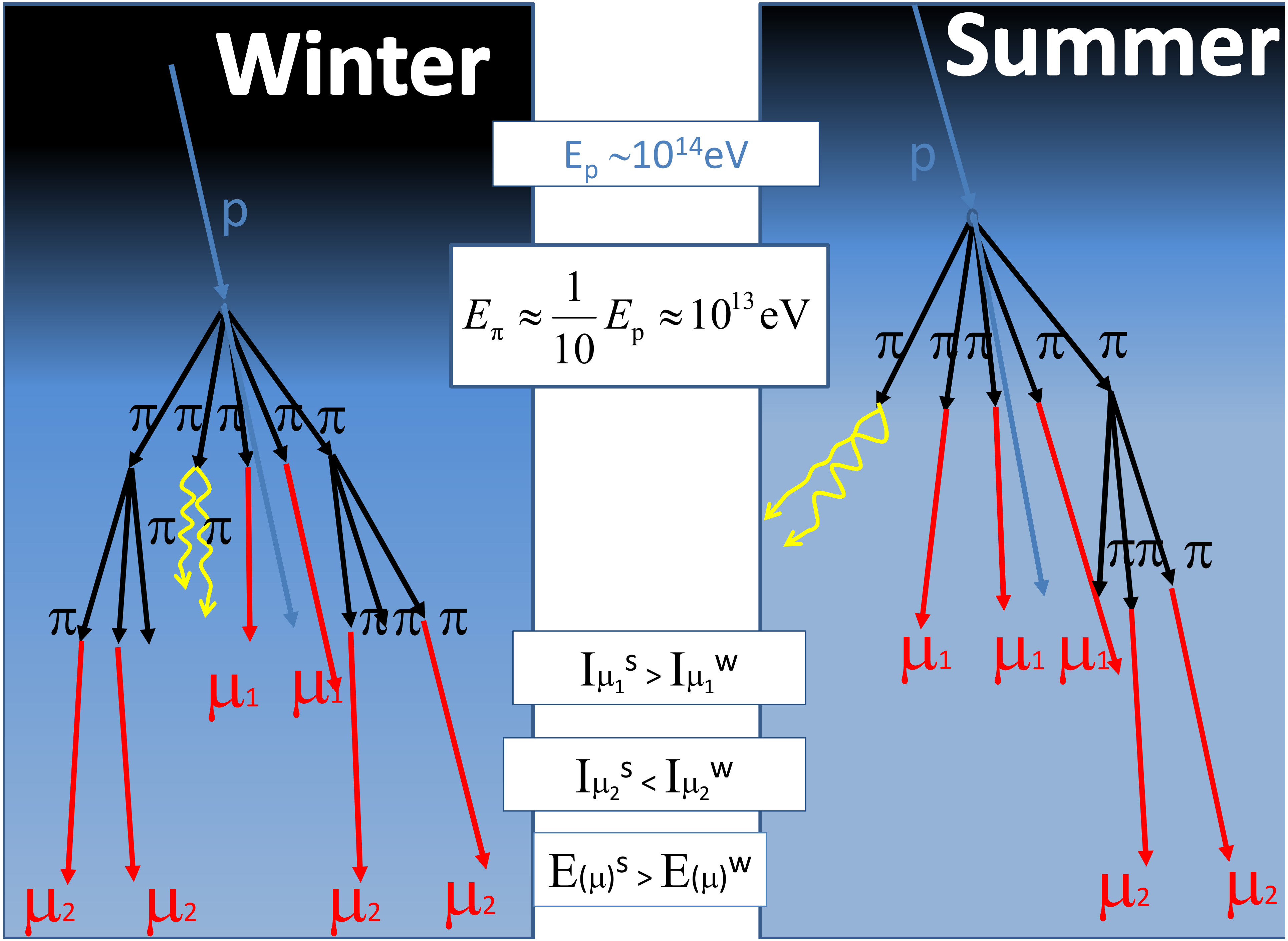
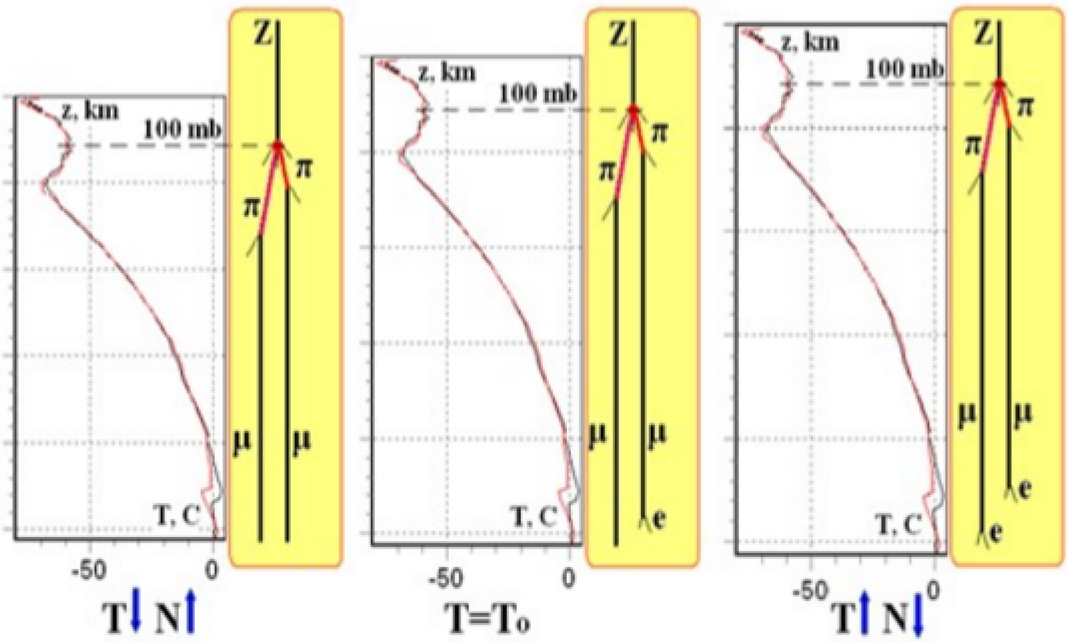
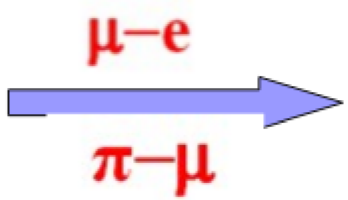


Winter
Summer
p
$E_p \sim 10^{14}$eV
$E_\pi \approx \frac{1}{10} E_p \approx 10^{13}$ eV
$I_{\mu_1}^{s} > I_{\mu_1}^{w}$
$I_{\mu_2}^{s} < I_{\mu_2}^{w}$
$E(\mu)^{s} > E(\mu)^{w}$
π
μ_1
μ_2

Temperature effect



The temperature effect of the muon component is caused by a competition between decay of π/κ and μ and their interaction with the atmospheric nuclei due to the change of geometric atmosphere dimensions.

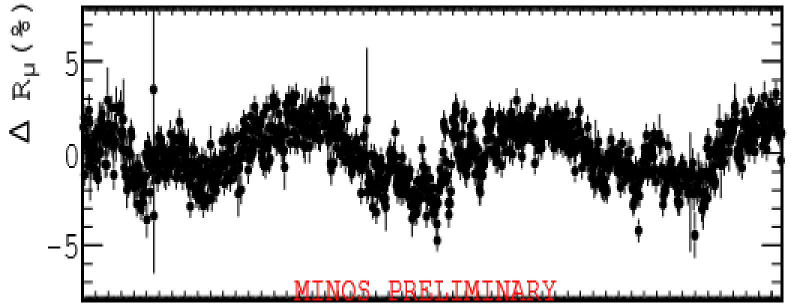


- negative temperature effect
- positive temperature effect

With atmosphere heating and its consequent expansion the number of π/k decays is increasing and this results in positive temperature effect. Simultaneously with the atmosphere expansion the μ path to the detector is increasing what results in the negative temperature effect as μ decay becomes more possible.

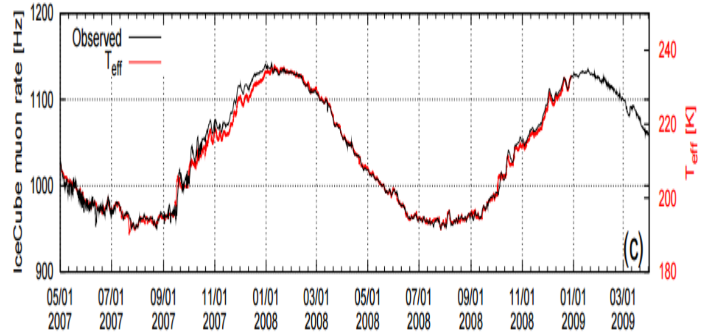
The set of the available muon intensity variation measurements:

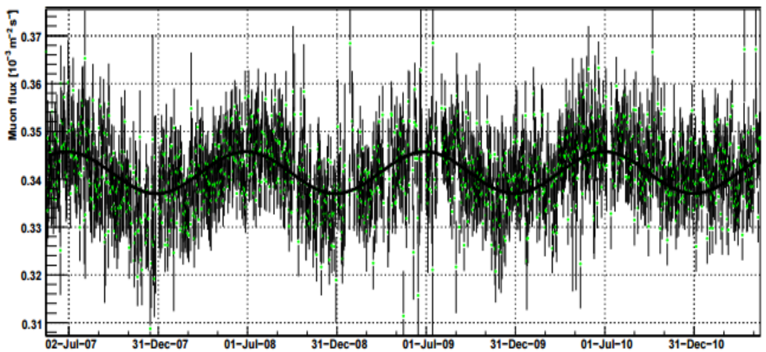
1. MACRO (1991 - 1994)
2. AMANDA (225 days 1997)
3. MINOS (1096 days)
4. LVD (2001 - 2008)
5. BOREXINO (2007 - 2011)
6. IceCube (18 month 2007-2008)



MINOS (E.W. GRASHORN for Minos coll., Observation of Seasonal Variations with the MINOS Far Detector, 30ICRC, arXiv:0710.1616)

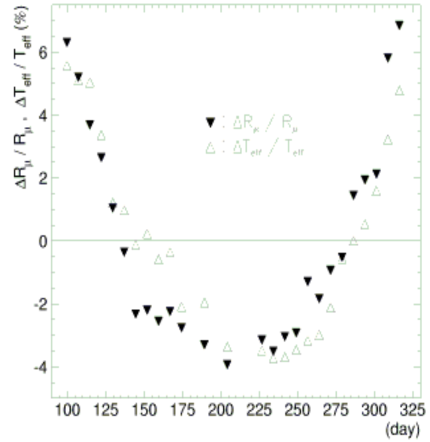
IceCube (Serap Tilav for IceCube coll., Atmospheric Variations as observed by IceCube, arXiv:1001.0776)

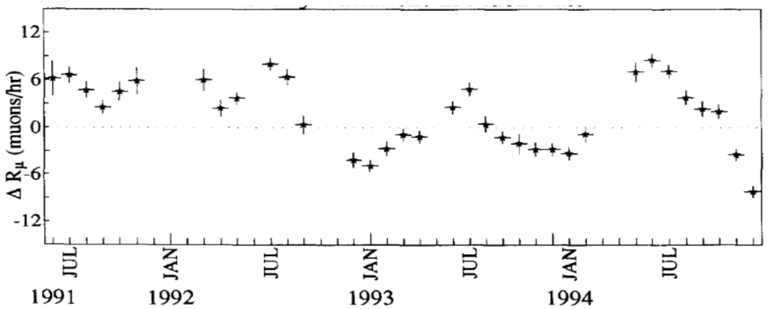




Borexino (Davide D'Angelo for Borexino coll. Seasonal modulation in the Borexino cosmic muon signal, arXiv:1109.3901)

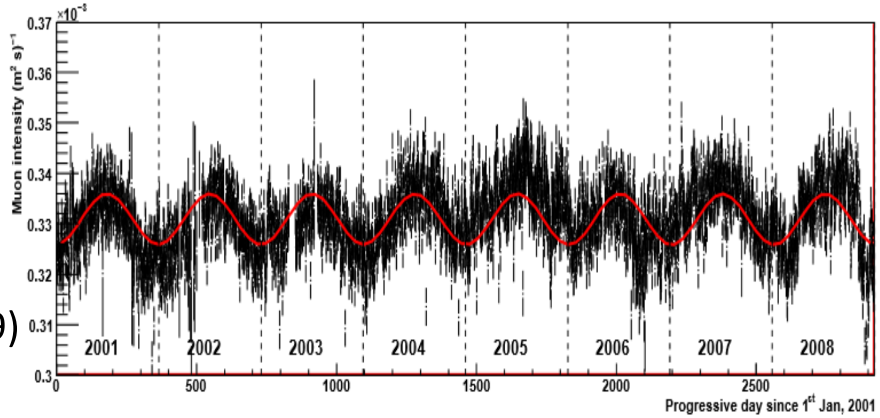
AMANDA Coll. (A. Bouchta for Amanda coll., Seasonal variation of the muon flux seen by Amanda, 26 ICRC, 1999



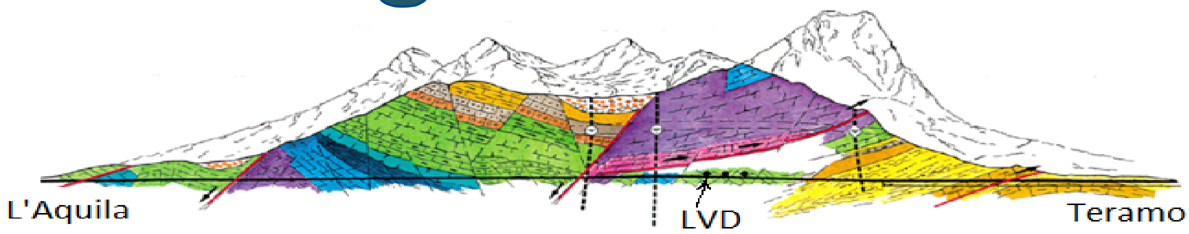


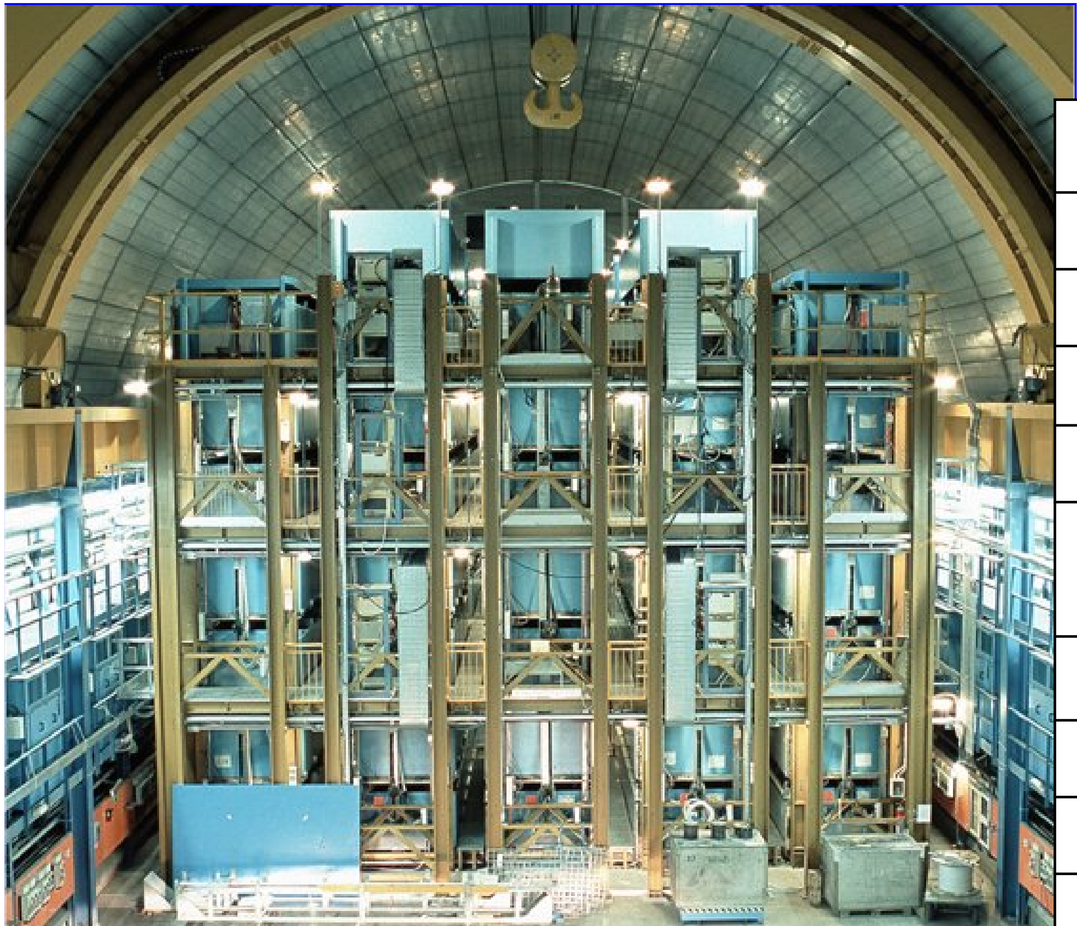
MACRO Coll (M. Ambrosio, Seasonal variations in the underground muon intensity as seen by MACRO, Astroparticle Physics, 7 (1997) 109-124)

LVD (M. Selvi for LVD Coll., Analysis of the seasonal modulation of the cosmic muon flux in the LVD detector during 2001-2008, 31 ICRC, 2009)



Large Volume detector LVD



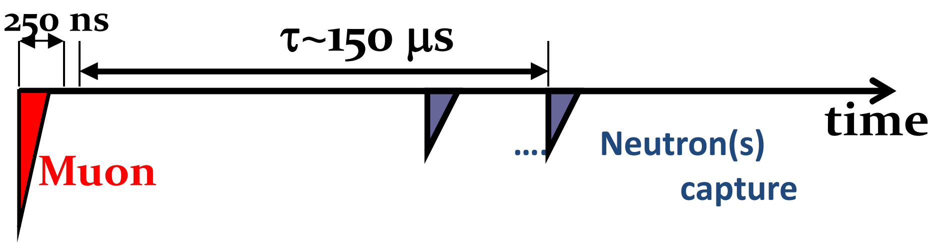


Length ×Width ×Height	22.7×13.2×10 m
Iron mass	1020 т
Scintillator mass	1008 т
Amount of scintillation counters	840
Number of PMTs	2520
Average depth minimal	3620 m w.e. 3000 m w.e.
Mean muon energy	280 GeV
E_μ on see level (min.)	**1.3 TeV**
Muon rate (on 1 tower)	~ 120 h^{-1}
Threshold ε_{th}	5MeV

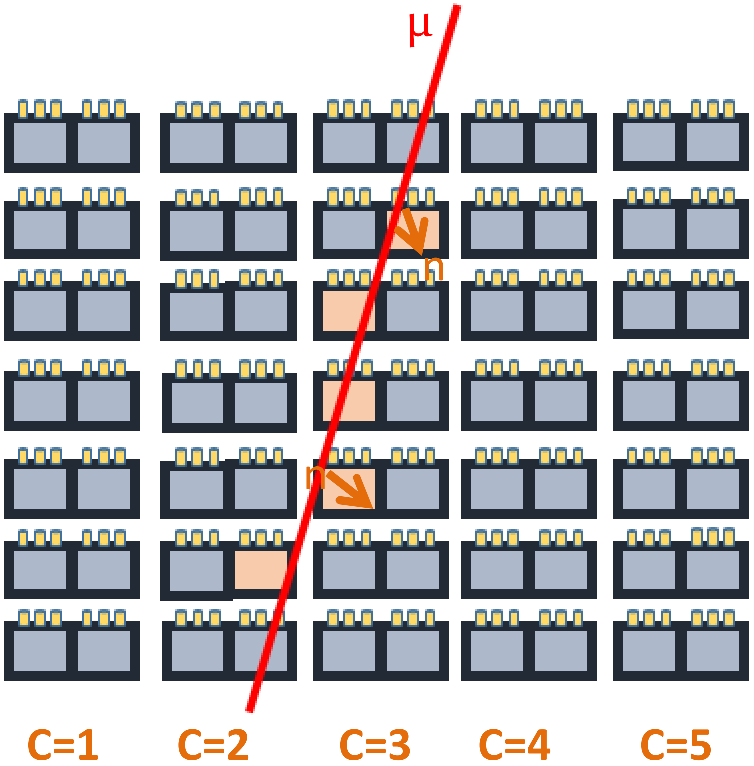
The main goal: detection of neutrinos from the collapse of stellar cores

Muon selection and neutron detection:

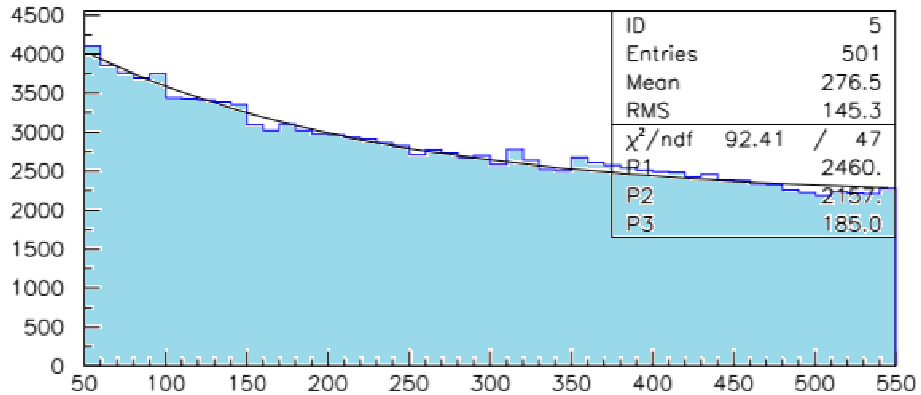
$n + p \rightarrow D + \gamma, \quad E\gamma = 2.2\ MeV$
$n + Fe^{56} \rightarrow Fe^{57} + \gamma, \quad \Sigma E\gamma = 10.16 MeV$



An event is selected as 'muon event' if there are at least 2 distinct counters with $E_{tr} > 10$ MeV and time difference $\Delta t < 250$ ns.
We have selected from muon events the inner counter triggers having energy $E_{tr} > 50$ MeV.



- Neutron searching for in the same counter where muon trigger is produced (Etr > 50 MeV);
- Energy of gamma pulses: 1 – 12 MeV;
- Time window: 50 – 550 microseconds



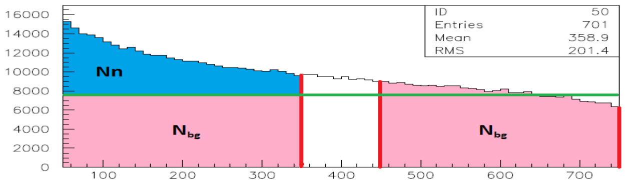
$N(t) = Bg + N_0 \times \exp(-t/\tau)$

Methods of the N_n/N_{tr} determination :

Specific number of muon-induced neutron is the determined number of neutrons divided by number of triggers in the same counter.

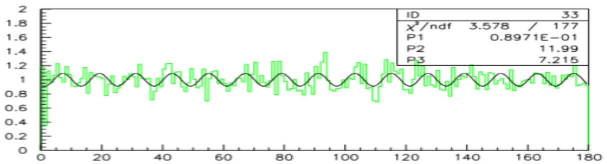
Epoch folding method

Background determination



Nn=Ntot-Nbg

Nn/Ntr (during 180 months)



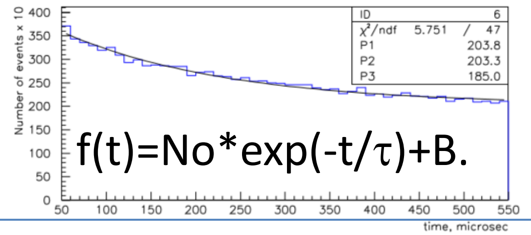
$F(t)=1+\delta\cdot\cos(2\pi(t-\varphi)/T)$

Residual method

«summer» - «winter»

Winter: 3 mon. x 15 year = 45 months

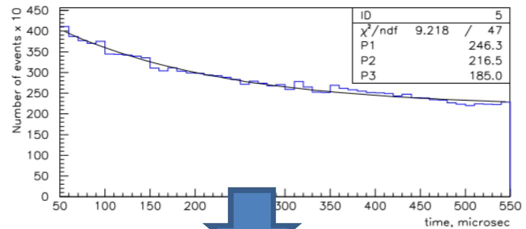
n_w



$f(t)=No*\exp(-t/\tau)+B.$

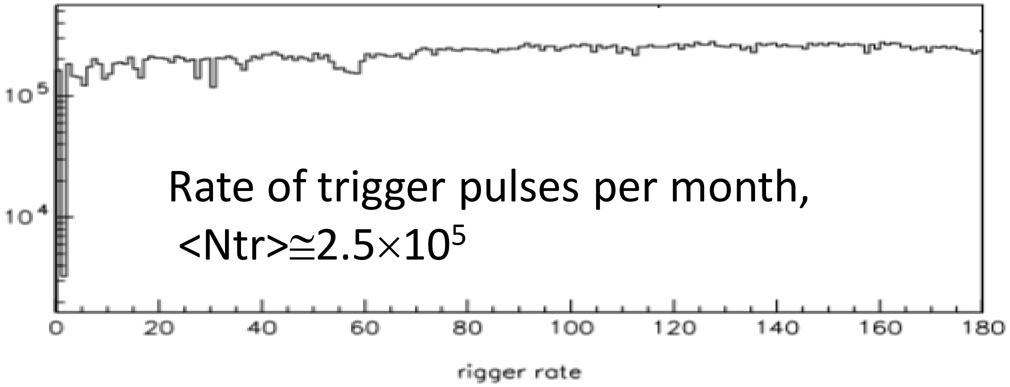
Summer: 3 mon. x 15 year = 45 months

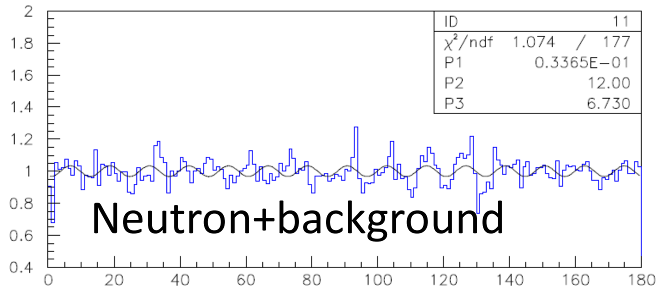
n_s

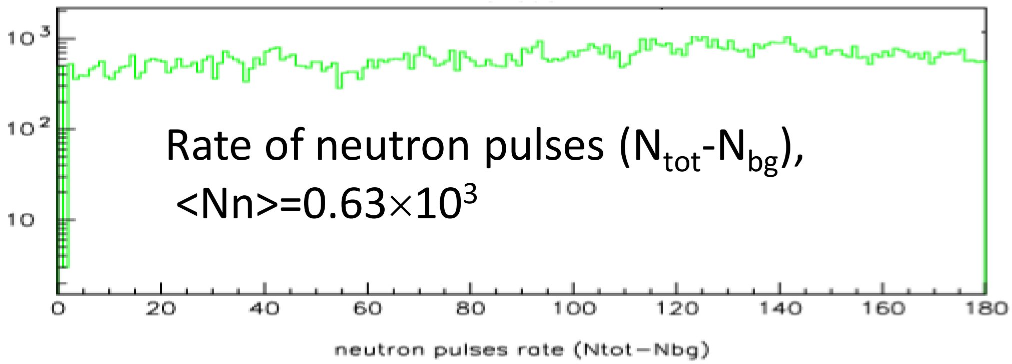


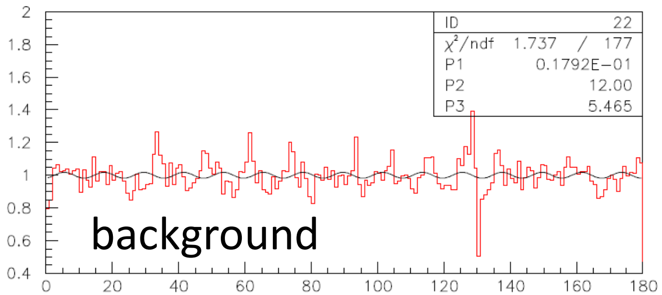
$\delta=(n_w - n_s)/(n_w + n_s)$

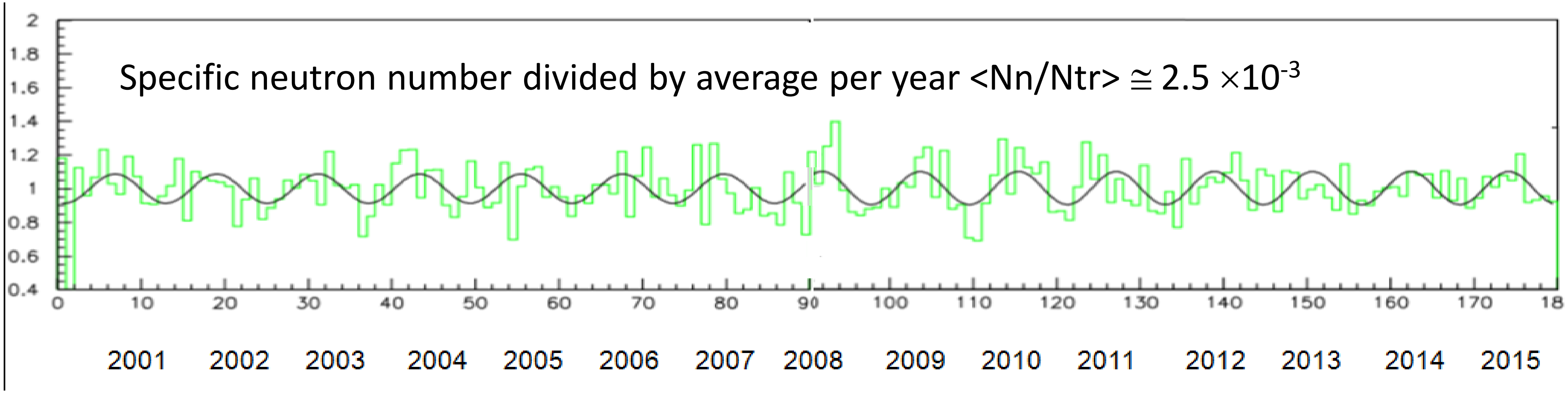
Specific neutron number N_n/N_{tr}



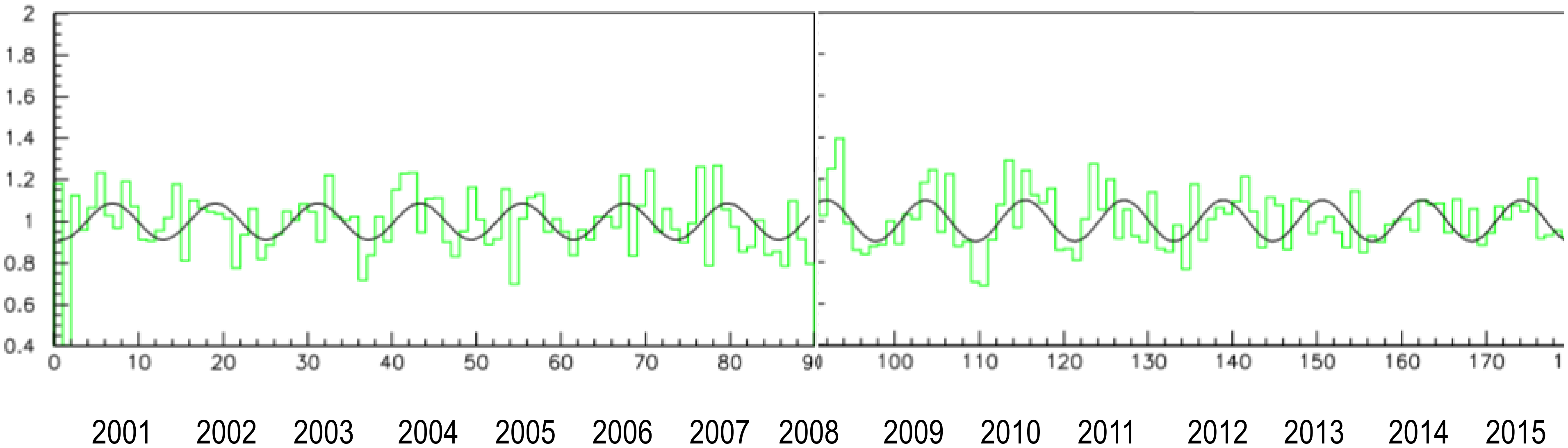








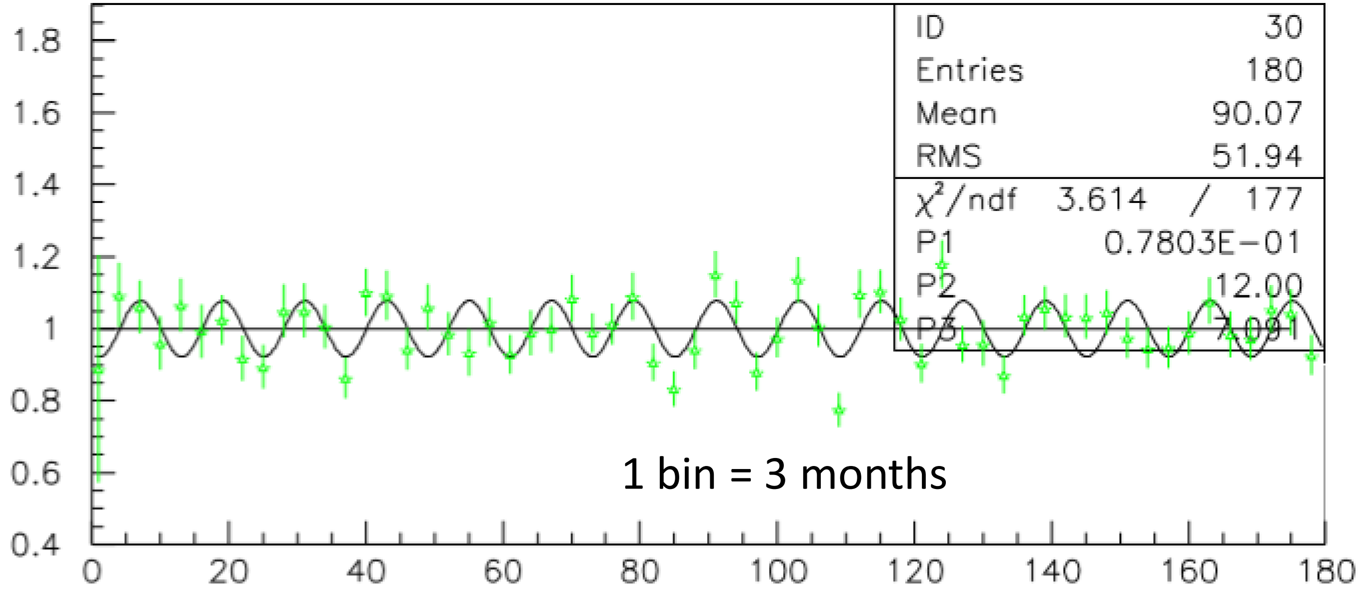
Epoch folding method



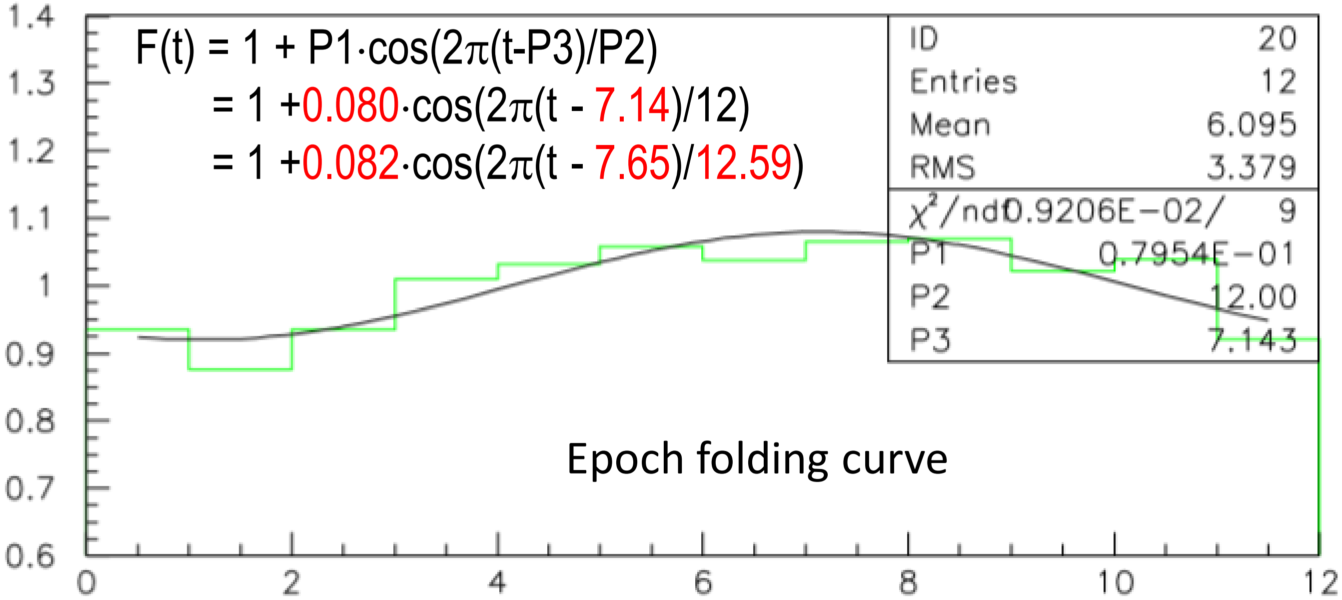
We analyzed the whole available data set with the detector in its final configuration (T1+T2+T3), starting in 1 January 2001 and ending in 31 December 2015.

$$\delta \equiv \delta\left(\frac{N_n}{N_{tr}}\right) \propto \delta\; N_n\left(\overline{E}_\mu\right)$$

Epoch folding method



Here the T value is fixed: T=12 month.
If all three parameters are fitted:
T=11.99,
f=7.153,
δ=0.078



Here the T value is fixed: T=12 month.
If all three parameters are fitted:
T=12.59,
f=7.165,
δ=0.082

$\delta N_n = 0.08 \pm 0.02$

Residual method

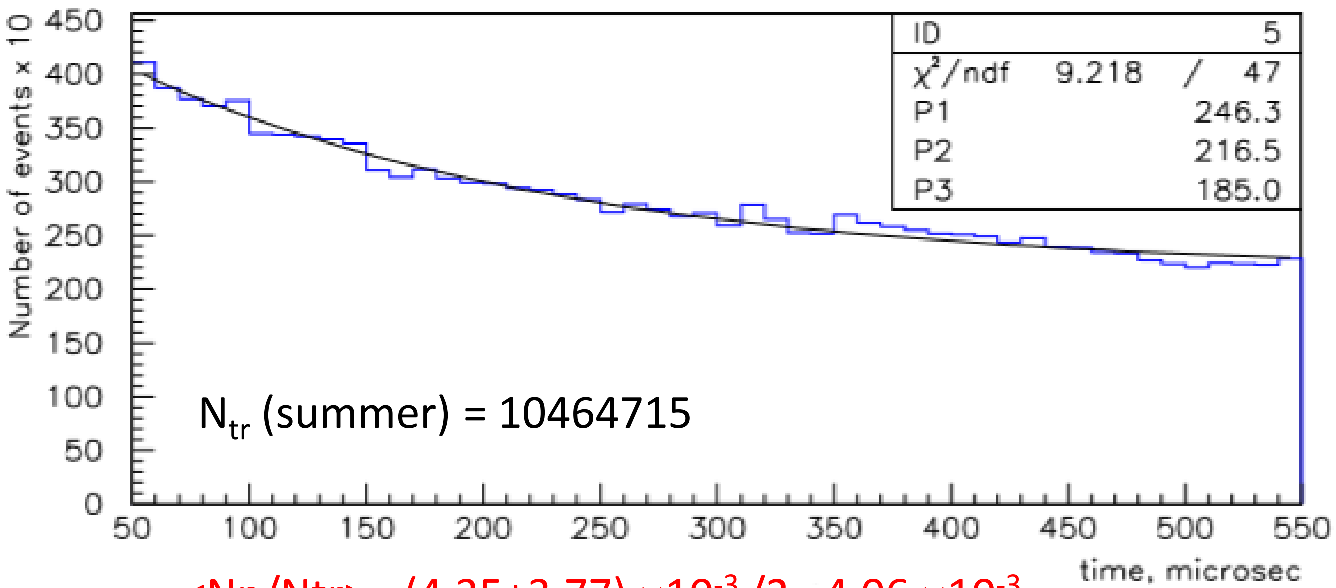
N_n/N_{tr} (s)=
246.3×185/10464715
= 4.35 ×10^{-3};

N_n/N_{tr} (w)=
203.8×185/10006669
= 3.77 ×10^{-3};

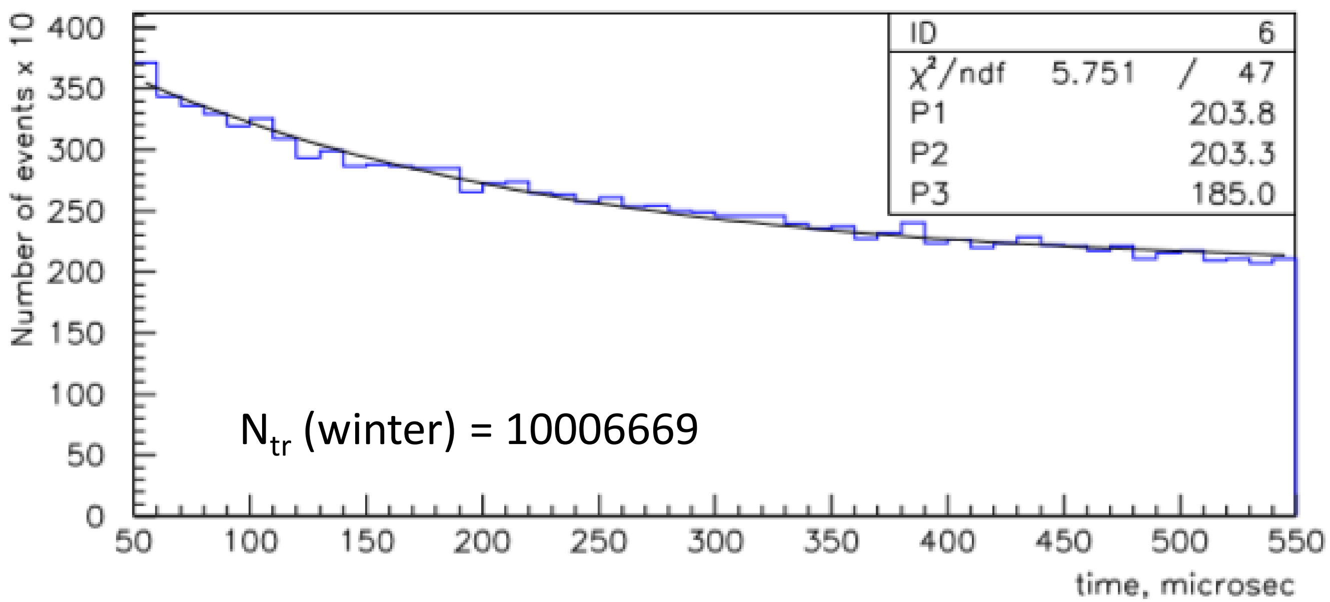
δN_n=(s-w)/(s+w) =
(N_n/N_{tr} (s)- N_n/N_{tr} (w))/
(N_n/N_{tr} (s)+ N_n/N_{tr} (w))

δN_n =0.072±0.002±0.008

E_{th}, MeV	δ
0.7	0.073
1.0	0.072
1.5	0.072
2.0	0.083
3.0	0.068



<Nn/Ntr>= (4.35+3.77) ×10^{-3} /2 =4.06 ×10^{-3}



Determination of modulation amplitude δ of the average muon energy underground:

$$\frac{N_n + \delta N}{N_n} = \left(\frac{E_\mu + \delta E}{E_\mu} \right)^{0.78}$$

$N_n \sim E_\mu^{0.75}$ for hadronic showers;

$N_n \sim E_\mu^{0.78}$ for hadronic and electromagnetic showers

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

$$\frac{\delta E}{E_\mu} = (1 + 0.076)^{1/0.78} - 1 \approx 0.10$$

Changing energy muons 10% leads to a change 8% in the specific number of neutrons.

Conclusions:

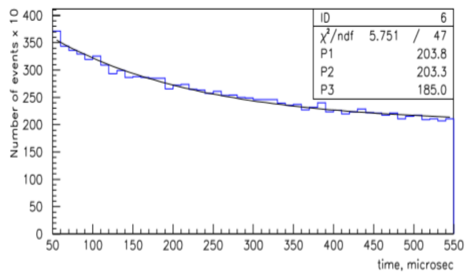
- ❑ The seasonal variations of the average energy of muon flux underground has been found using number of muon induced neutrons:
- ❑ The characteristics of the muon induced neutron variations are defined using different methods
  - residual method (summer - winter): variation magnitude is $\delta N_n = 0.072 \pm 0.002$ (stat) ± 0.016 (sys) ;
  - epoch folding method: $f(t) = 1 + \delta \cdot \cos(2\pi(t - \varphi)/T)$, $\delta N_n = 0.08 \pm 0.02$, $\varphi = 7.15 \pm 0.5$
- ❑ The measured characteristics of the neutron variations indicate seasonal variations in the average energy of muons at the LVD depth of 280 GeV with an amplitude of 10%: $\bar{E}_\mu = 280 \pm 28$ GeV .
- ❑ The neutron flux produced by muons underground undergoes seasonal variations with the amplitude $1+\delta\Phi_n = (1+\delta I_\mu)(1+\delta N_n) = 1.076 \times 1.015$
  $$\delta\Phi_n(I_\mu, N_n) = 9.2\%$$
- ❑ It was assumed that the neutron flux is proportional to the intensity of muons with an amplitude variation of 1.5%. We have shown that the neutron flux has an amplitude of seasonal variations in 6 times more, because the energy muons also varies with the amplitude of ~ 10%.

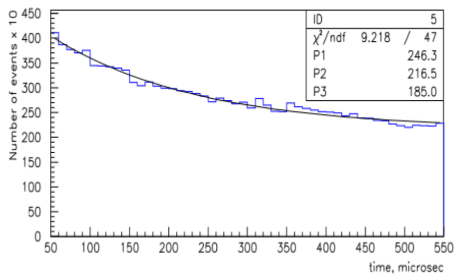
Thank you!

The definition uncertainties of the modulation amplitude value

❑ For residual method:

Statistic uncertainty – 2.6 %
number of triggers: Ntr= 1.0×10^7,
number of neutrons: Nγ = 1.5×10^3,





Systematic uncertainty – 22 %

$$\delta\, \boldsymbol{\delta} = \delta\left(\frac{n_s - n_w}{n_s + n_w}\right)$$

$$\delta\, \boldsymbol{\delta} = \sqrt{\delta^2(n_s - n_w) + \delta^2(n_s + n_w)}$$

$$\delta^2(n_s + n_w) = \delta^2(n_s - n_w) = \sqrt{\delta^2 n_s + \delta^2 n_w}$$

$$n_s \approx n_w \Rightarrow \delta\, \boldsymbol{\delta} = \sqrt{4\delta^2 n_s} \qquad \delta n_s = \delta(N_0 \times \tau / N_{tr})$$

δ = 0.072 ± 0.002 (stat) ± 0.016 (sys)

δ δ =0.22

$$\sqrt{\left(\frac{35}{1263}\right)^2 + \left(\frac{20}{185}\right)^2} = 0.11$$

❑ For epoch folding method:

From fitting procedure – 20.0 %

δ = 0.08 ± 0.02 (sys)

Muon-induced neutron yield Y_{SC} and Y_{Fe} using value of the specific neutron number:

$$Y_n \sim \frac{N_n}{N_\mu}\frac{1}{\rho l_i}\frac{q_i(\eta_{sc},\eta_{Fe})}{\varepsilon_1\varepsilon_2}$$

4.06×10^{-3}

ρl_{sc}=65 g/cm^2,

ρl_{Fe}=59 g/cm^2,

q_{sc} (E_{th}>1.5 MeV) =1.084

q_{Fe} (E_{th}>1.5 MeV) = 4.940

ε_1=0.24 (geom.factor),

ε_2=0.87 (tay-Bruno effect)

η_{sc}=0.33

η_{Fe}=0.13

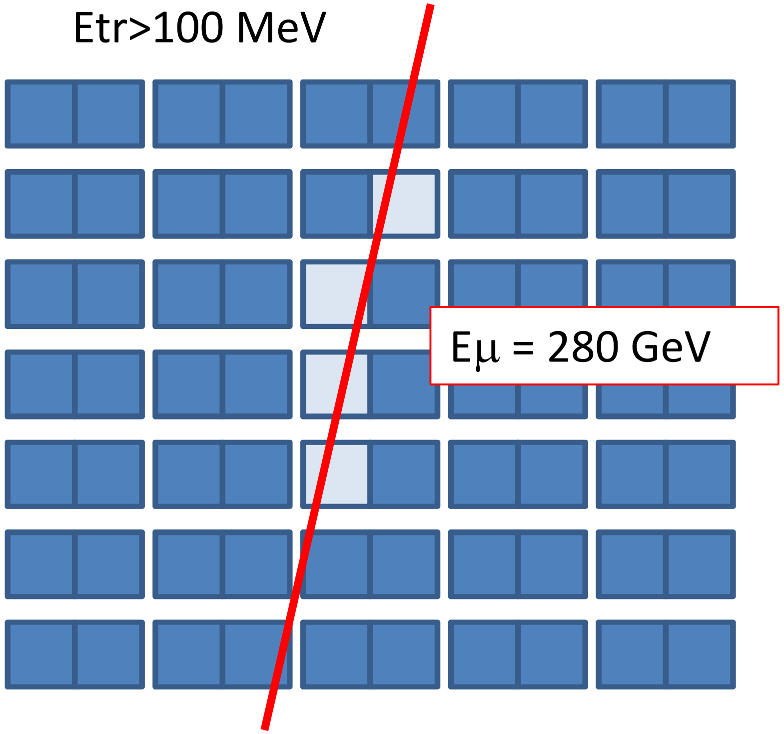
Y_{sc}, n/μ/(g/cm²)	**Y_{Fe}, n/μ/(g/cm²)**
3.24×10^{-4}	16.3×10^{-4}

$$q_{sc} = \frac{Q}{Q\eta_{sc} + (1-Q)\eta_{Fe}},$$

$$q_{Fe} = \frac{(1-Q)}{Q\eta_{sc} + (1-Q)\eta_{Fe}}$$

Q=0.18

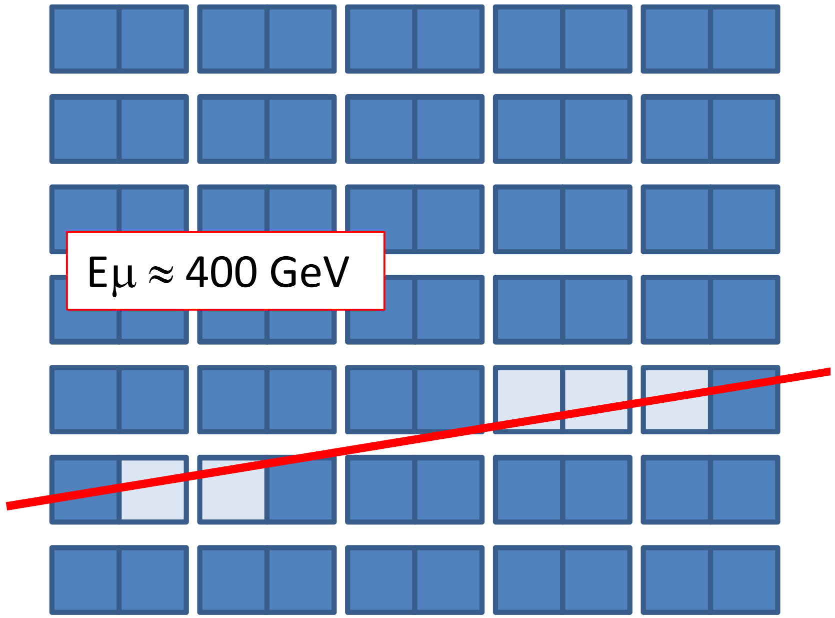
Quasi-Vertical Muons
Etr>100 MeV



muons	2428151
neutrons	9858
length	65 g/sm²
Y_sc, n/μ/(g/sm²)	3,2×10⁻⁴

$$\frac{N_n + \delta N}{N_n} = \frac{4.3\cdot 10^{-3} - 3.24\cdot 10^{-3}}{3.24\cdot 10^{-3}} = 0.33$$

Quasi-horizontal muons
Etr>100 MeV, level L=±1

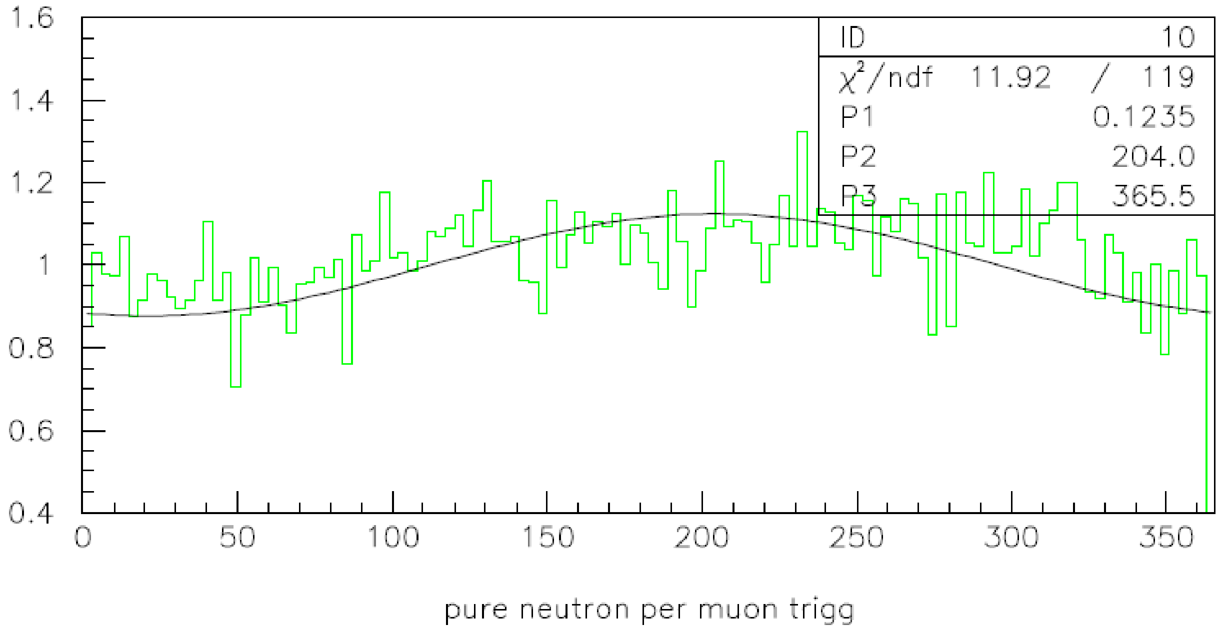


muons	11510
neutrons	71
length	75,6 g/sm²
Y_sc, n/μ/(s/sm²)	4,3×10⁻⁴

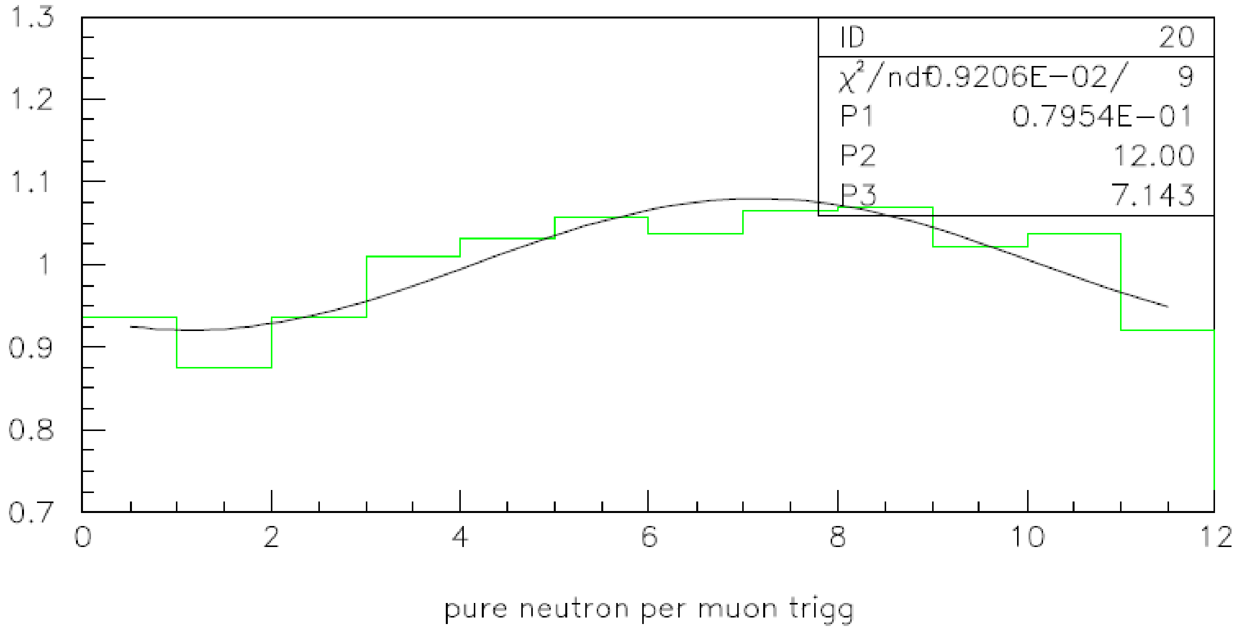
$$\frac{N_n + \delta N}{N_n} \sim \left(\frac{E_\mu + \delta E}{E_\mu}\right)^{0.78} \Rightarrow \frac{\delta E}{E} = (1+0.33)^{1/0.78} - 1 = 0.44$$

$$280 GeV + 280 \times 0.44 \approx 400\ GeV$$

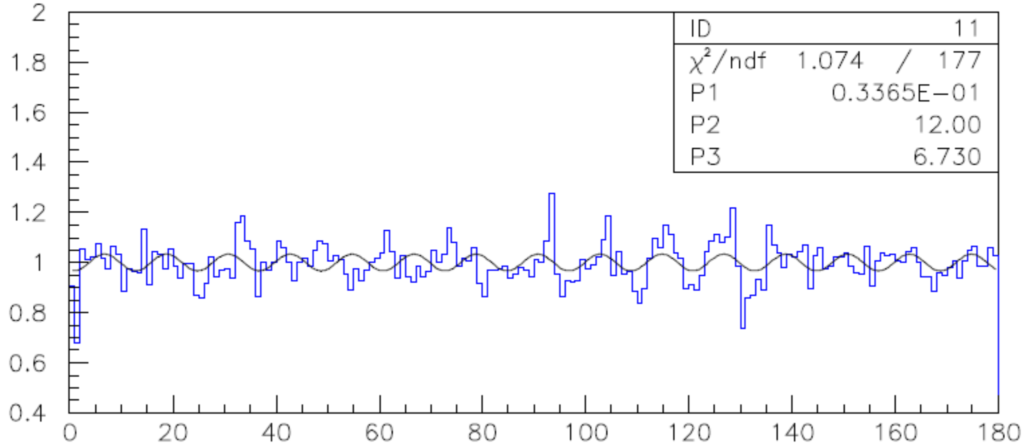
Backup slides

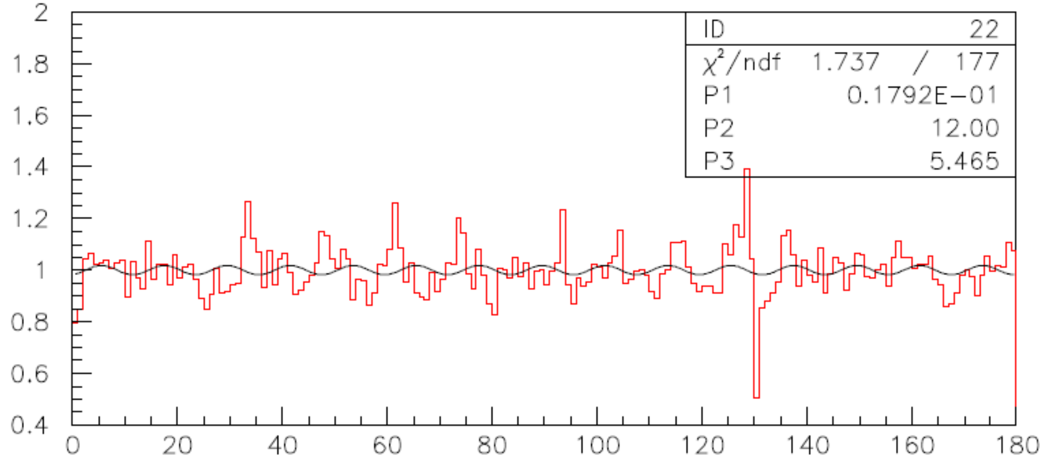


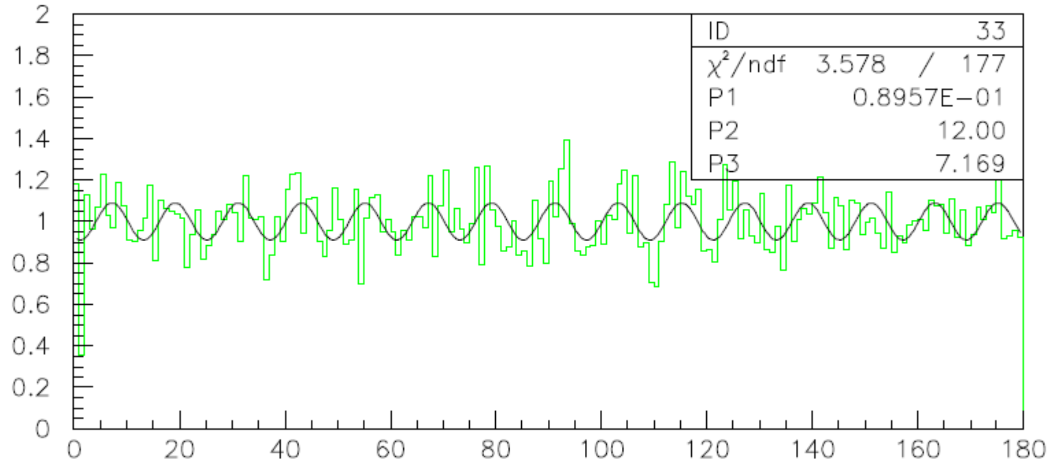
ID 10
χ^2/ndf 11.92 / 119
P1 0.1235
P2 204.0
P3 365.5
pure neutron per muon trigg



ID 20
χ^2/ndf 0.9206E−02/ 9
P1 0.7954E−01
P2 12.00
P3 7.143
pure neutron per muon trigg

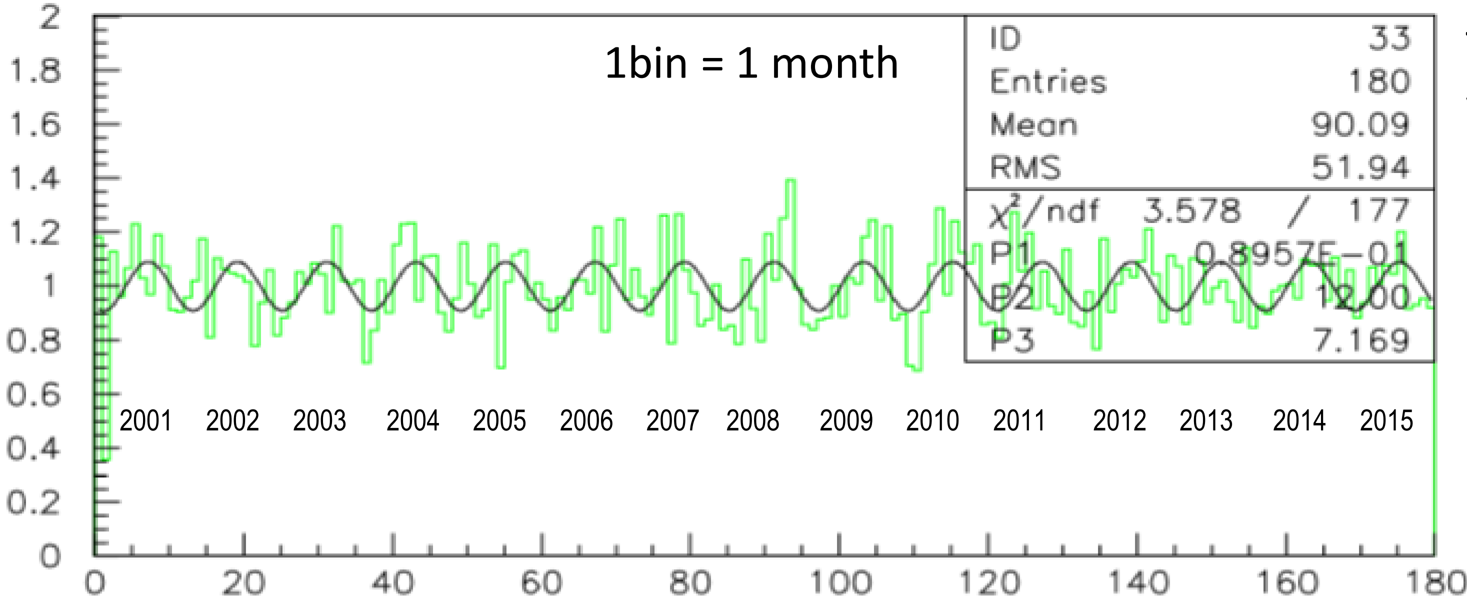


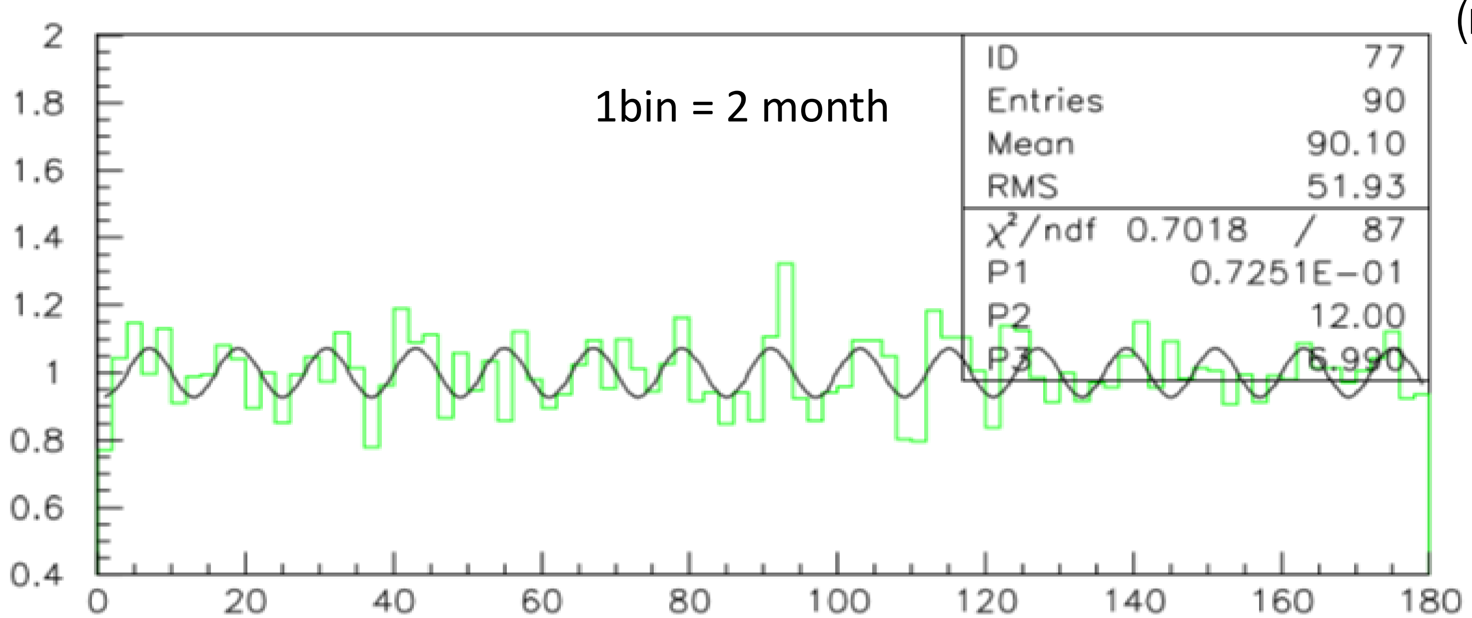




$$F(t)=1+P1\cdot\cos(2\pi(t-P3)/12.0)$$

Epoch folding method





To determine the variation phase we use the fitt:

F(t)= $1+P1\cdot\cos(2\pi(t-P3)/P2)$

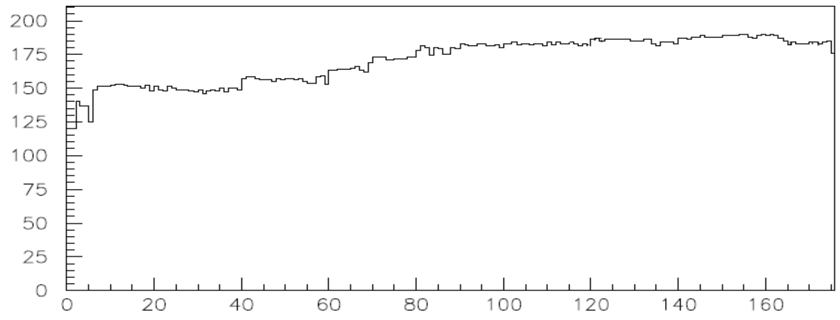
$P1=0.09\pm0.02$ – modulation value,

$P2=12.0\pm0.5$ – period,

$P3=7.2\pm0.5$ – phase (month),

Muon events selection:

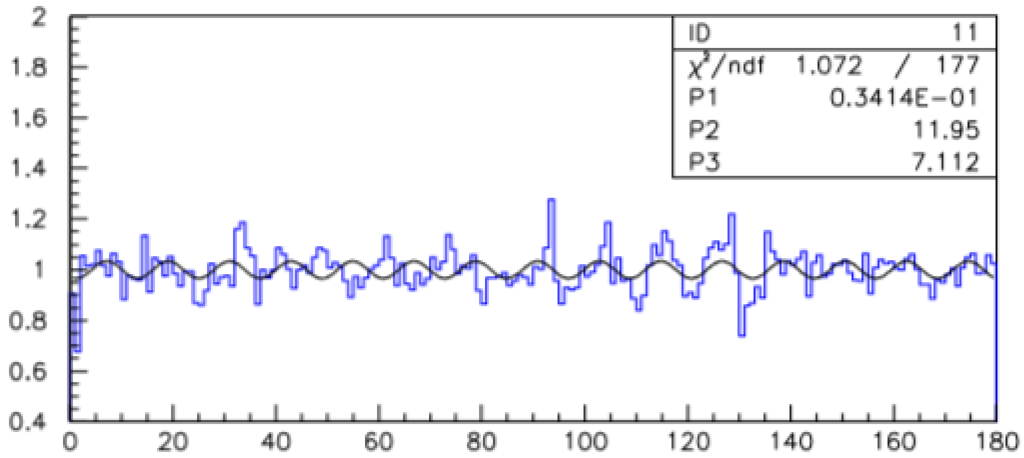
An event is selected as 'muon event' if there are at least 2 distinct counters with $E_{tr} > 10$ MeV and time difference $\Delta t < 250$ ns.
We have selected from muon events the inner counter triggers having energy $E_{tr} > 50$ MeV.



Amount of counters using in analysis (T1+T2+T3)

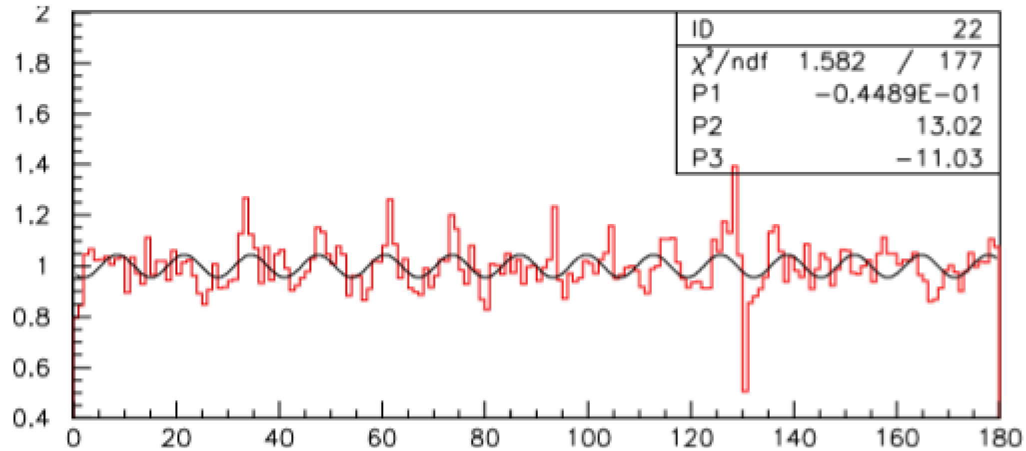
We analyzed the whole available data set with the detector in its final configuration (T1+T2+T3), starting in 1 January 2001 and ending in 31 December 2015.

$$F(t)=1+P1\cdot\cos(2\pi(t-P3)/P2)$$



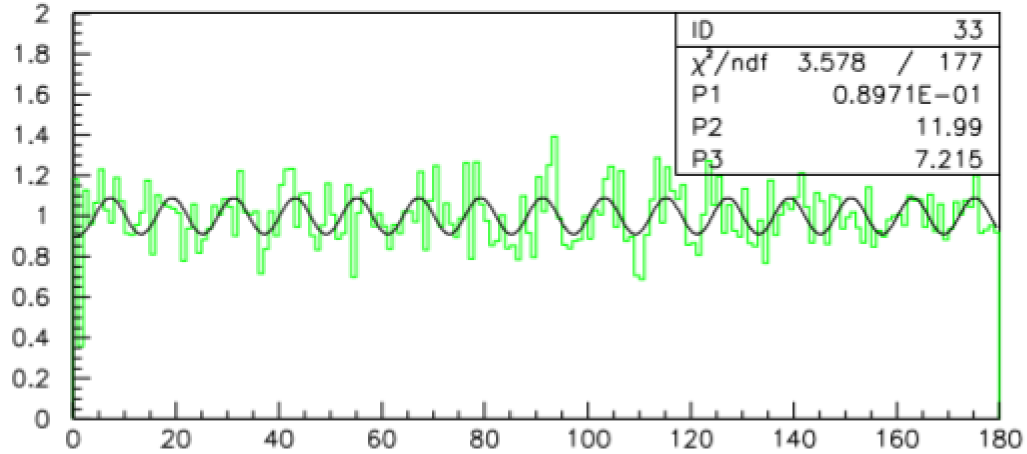
N_{tot}/N_{tr} per month

$< N_{tot}/N_{tr} > \cong 8.5 \times 10^{-3}$



N_{bg}/N_{tr} per month

$< N_{bg}/N_{tr} > \cong 6 \times 10^{-3}$



N_{n}/N_{tr} per month

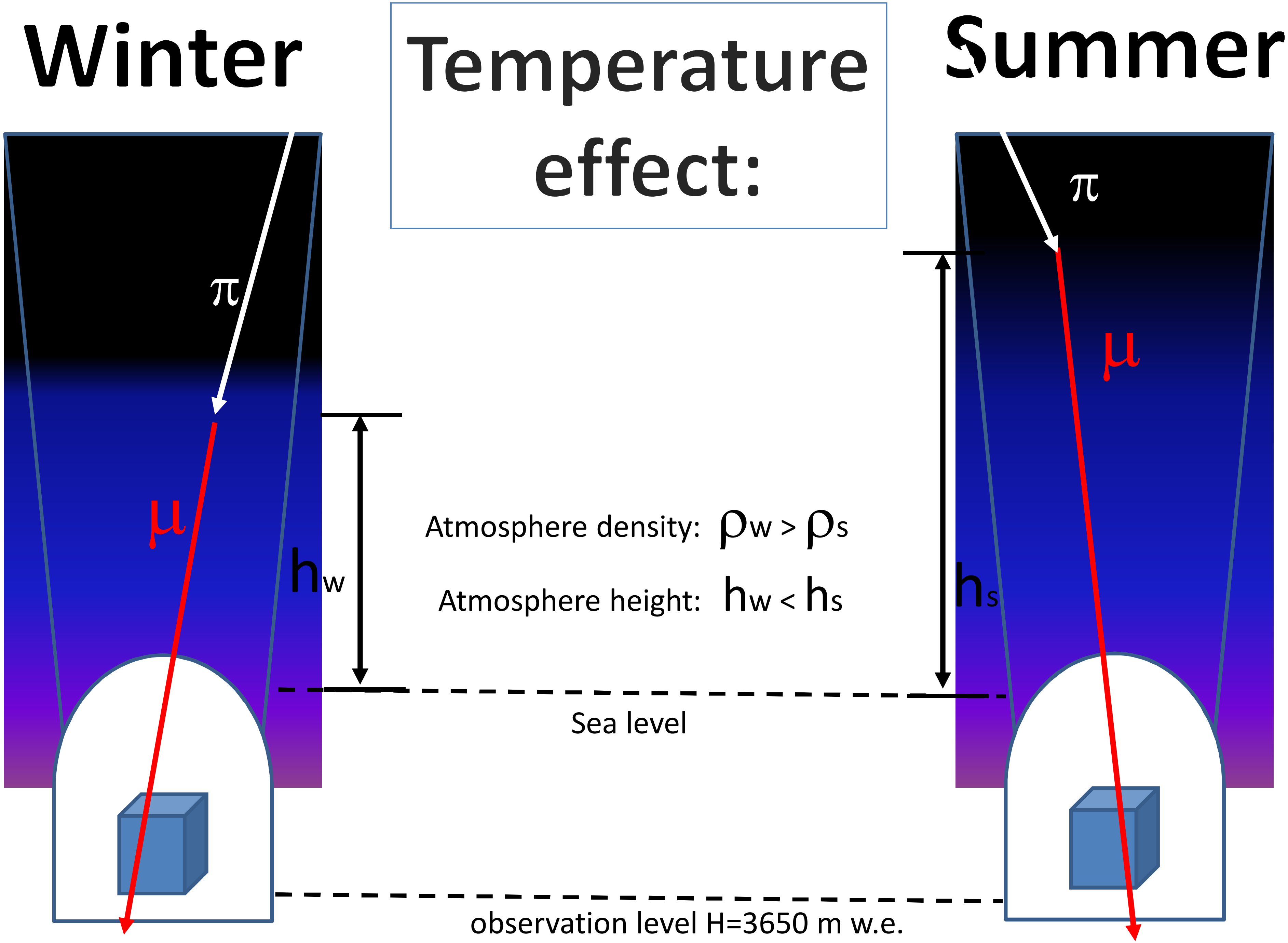
$< N_{n}/N_{tr} > \cong 2.5 \times 10^{-3}$

Specific number of muon-induced neutrons is the determined number of neutrons divided by number of triggers in the same counter.

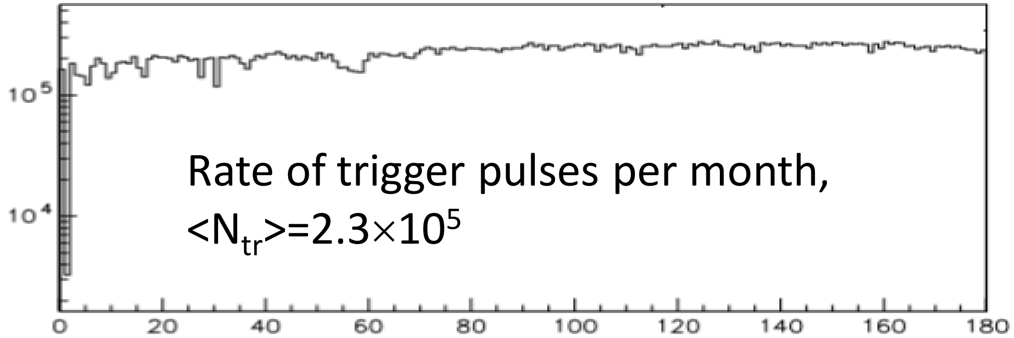
The specific number is the averaged magnitude over a muon flux. Then the specific number is proportional to a number of neutrons produced by muon at mean Eμ energy of muon flux underground:

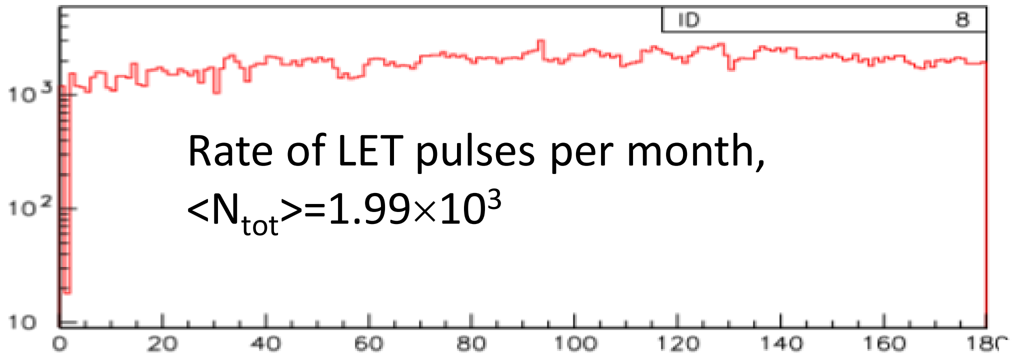
$$\frac{N_n}{N_{tr}} \propto N_n\left(\overline{E}_\mu\right)$$

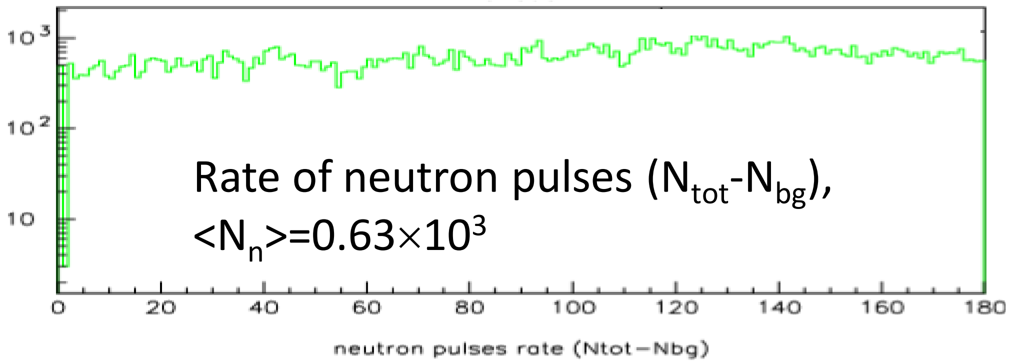
$$\delta \equiv \delta\left(\frac{N_n}{N_{tr}}\right) \propto \delta\ N_n\left(\overline{E}_\mu\right)$$


Winter
Temperature effect:
Summer
π
π
μ
μ
h_w
h_s
Atmosphere density: $\rho_w > \rho_s$
Atmosphere height: $h_w < h_s$
Sea level
observation level H=3650 m w.e.

Specific neutron number N_n/N_{tr}







(N_{tot}-N_{bg}) / N_{tr} per month