Candidate: Luigi Ernesto Ghezzer

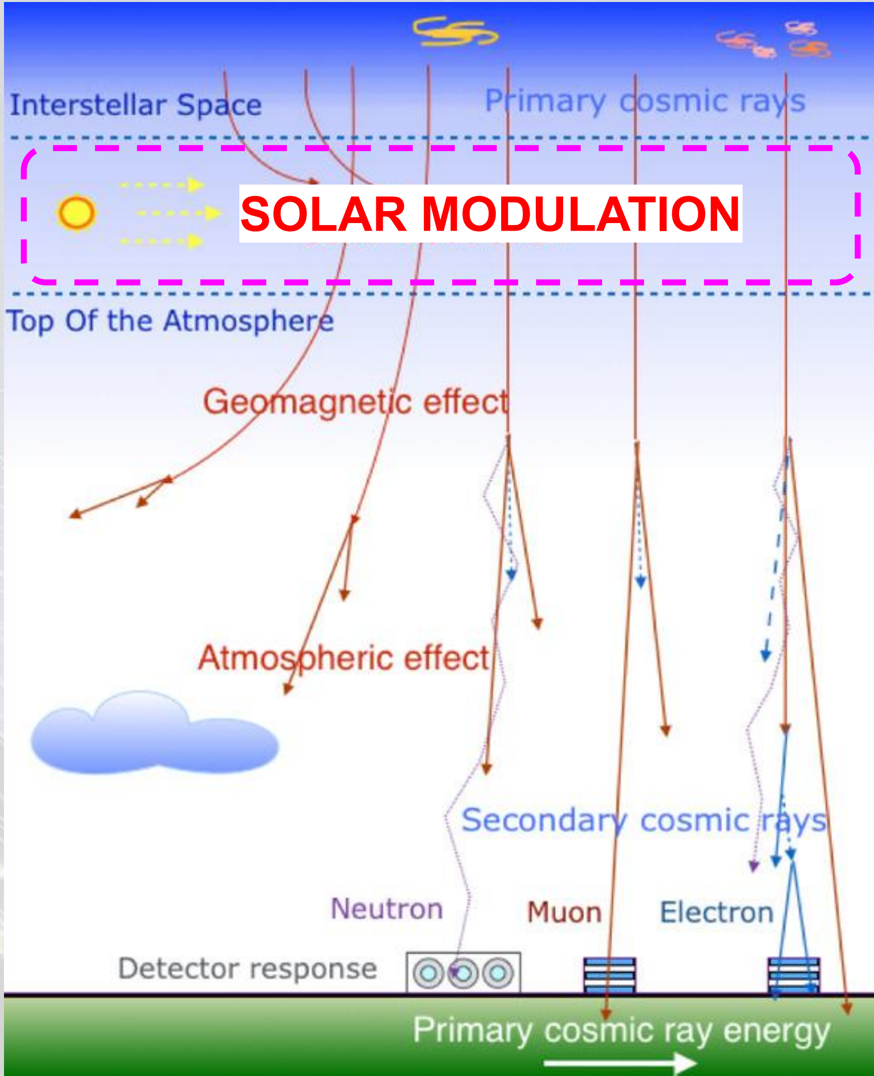
Supervisor: Francesco Nozzoli

Master thesis defense

Study of the variability of the muon cosmic ray flux

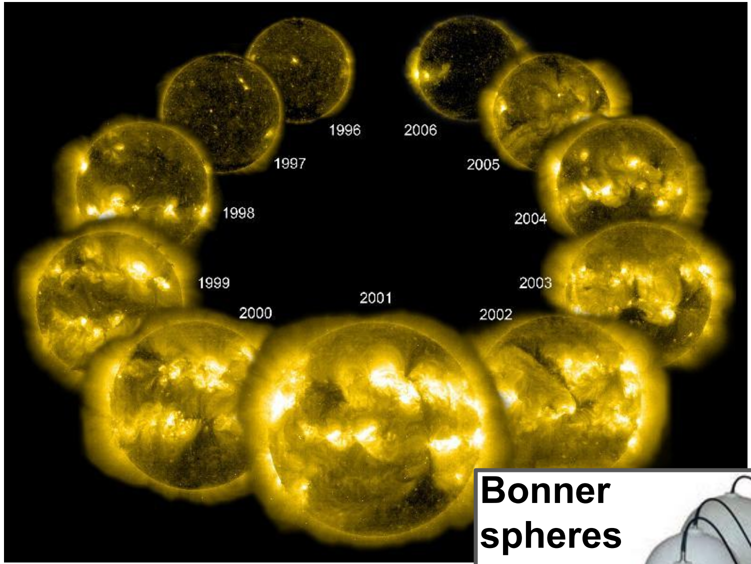
Outlook:

1) **Variabilities of CR**
2) Detector & systematics
3) Physics results
4) Perspectives @ Doss Trento
5) Conclusion

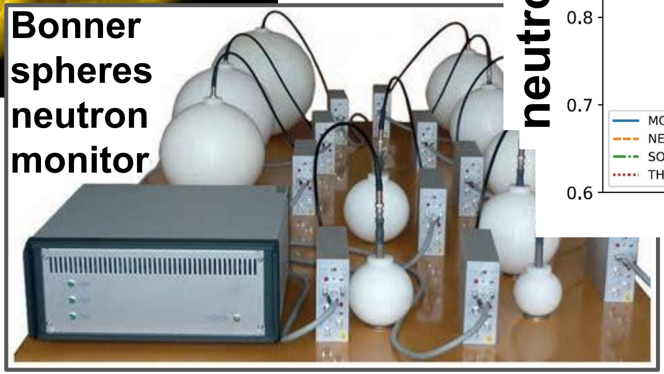


Solar modulation & cycles

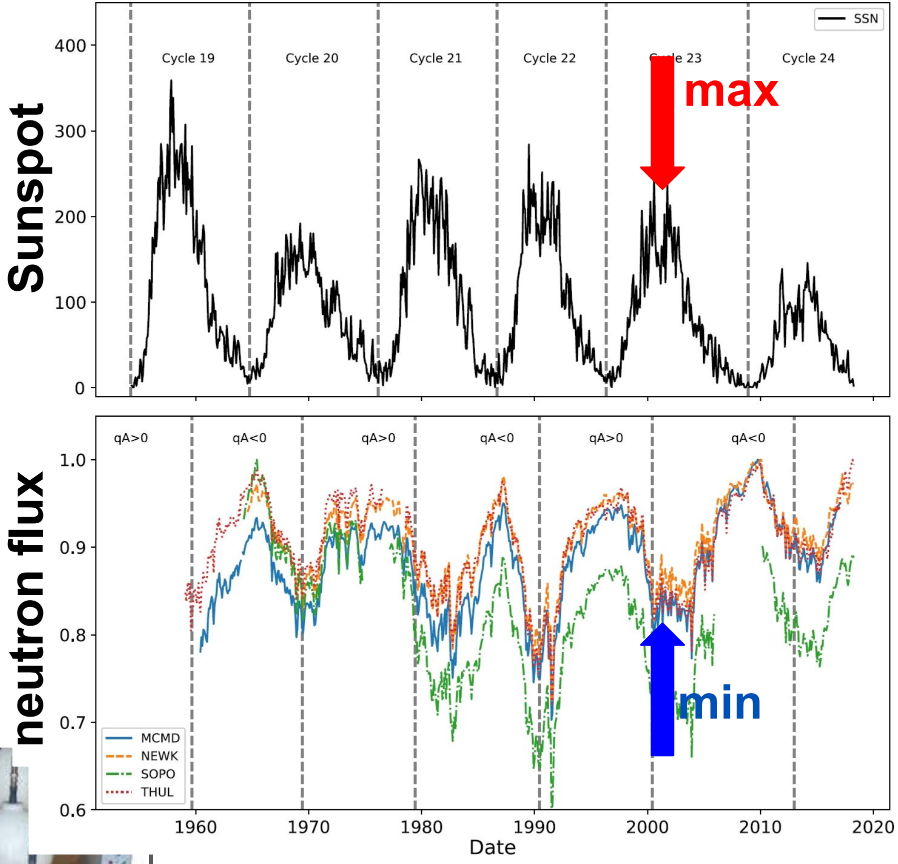
11-years quasi periodicity of Sun's activity measured as variations in the N of sunspots



UV light (286 A), SOHO



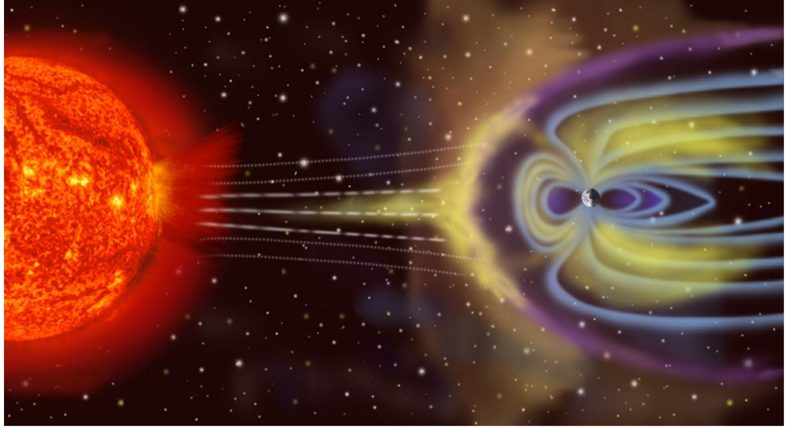
Bonner spheres neutron monitor

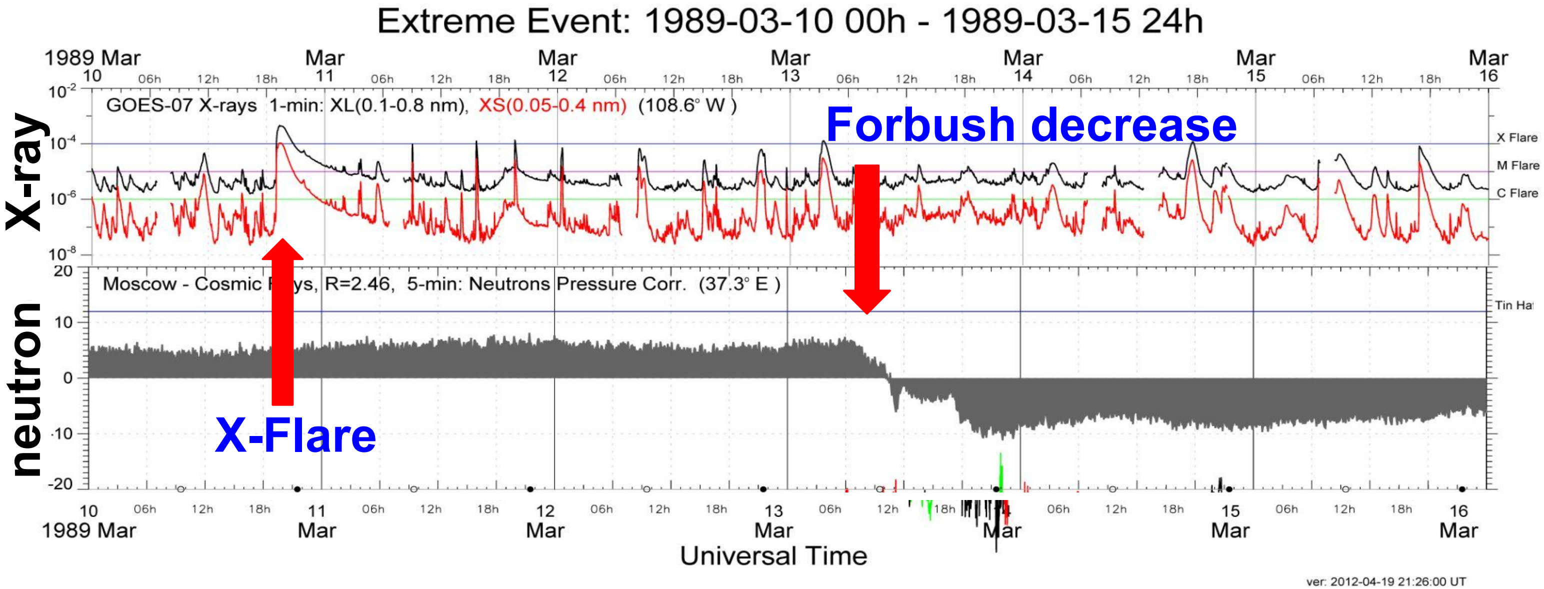


@ maximum of activity: solar wind and magnetic field are more intense turbulent: reduction of galactic CR flux

Forbush decrease

Reduction in the observed intensity of galactic cosmic rays following a solar flare with coronal mass ejection (CME).
The magnetic field within the solar wind plasma deflecting some galactic cosmic rays away from Earth.





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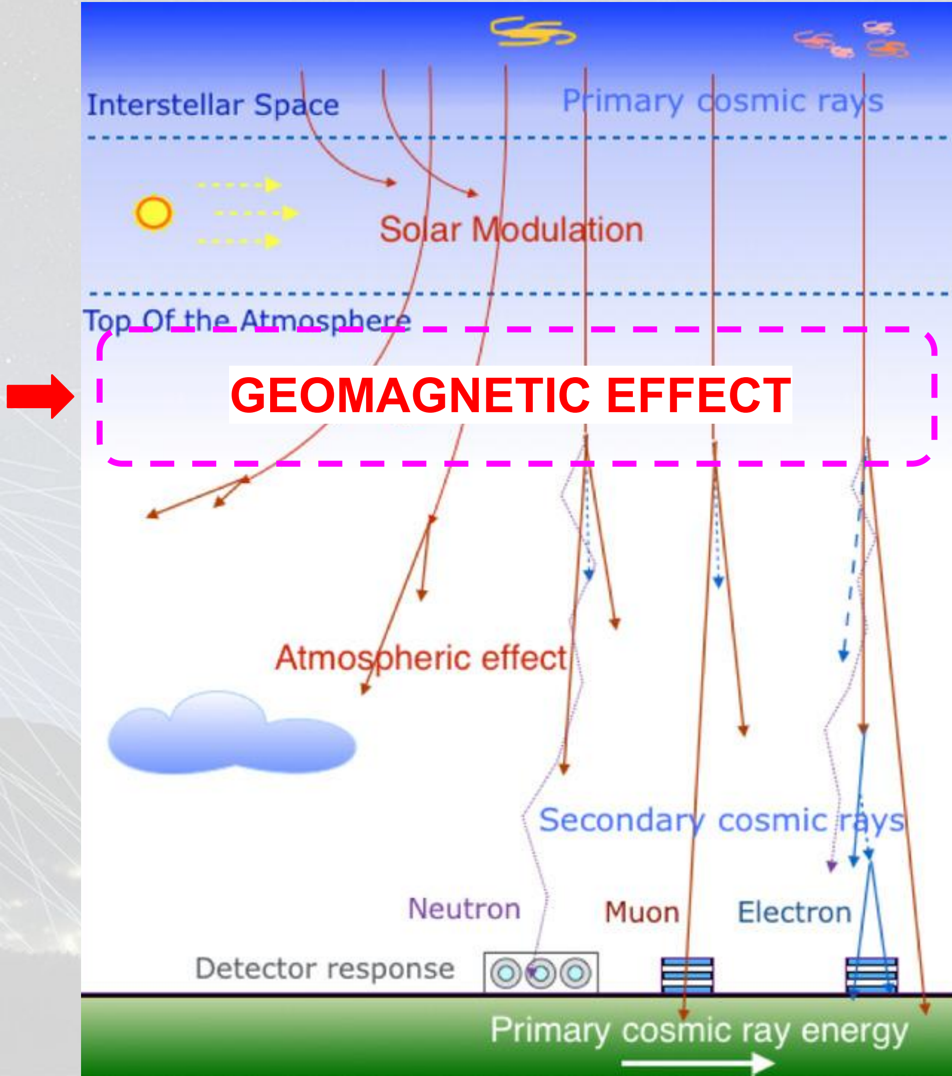
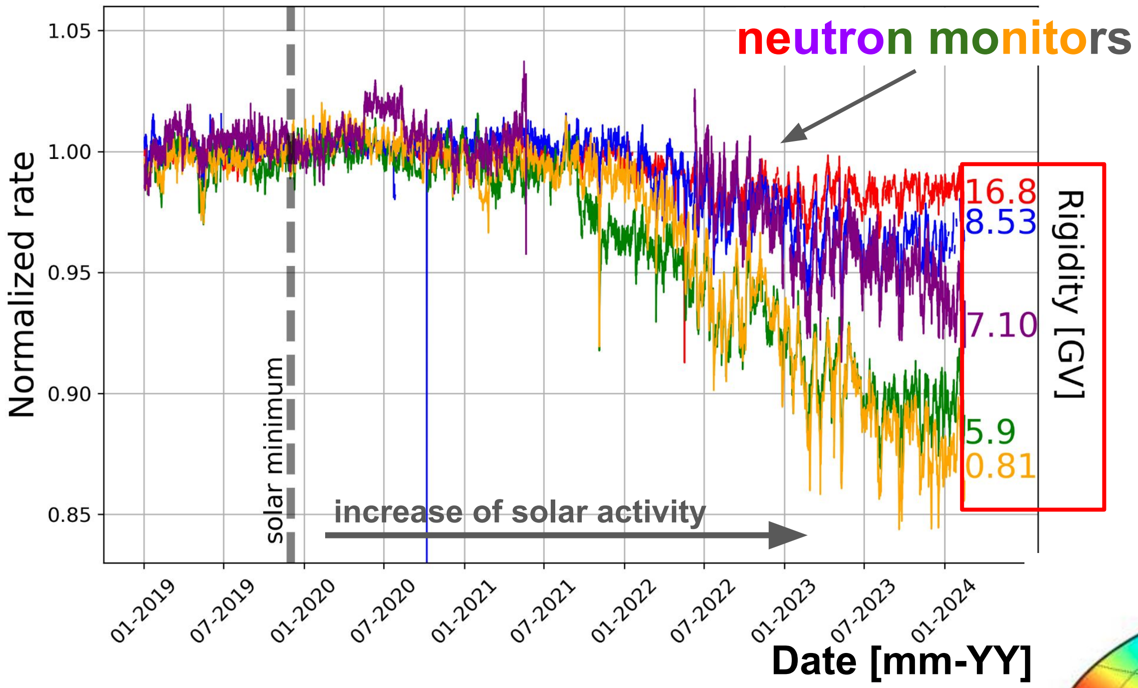
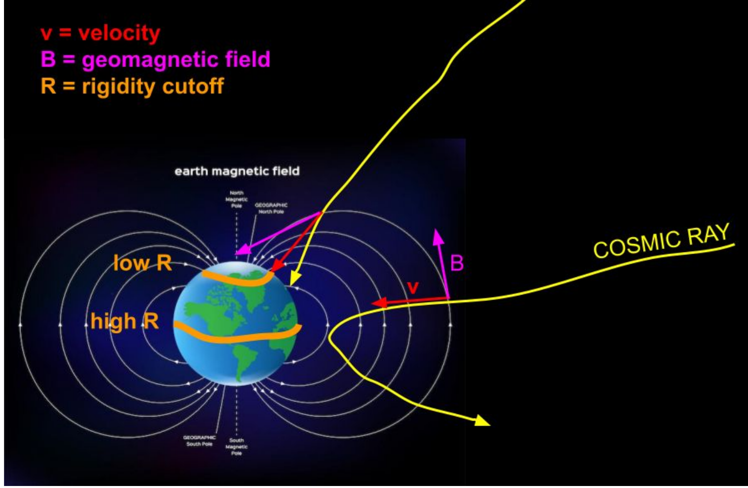
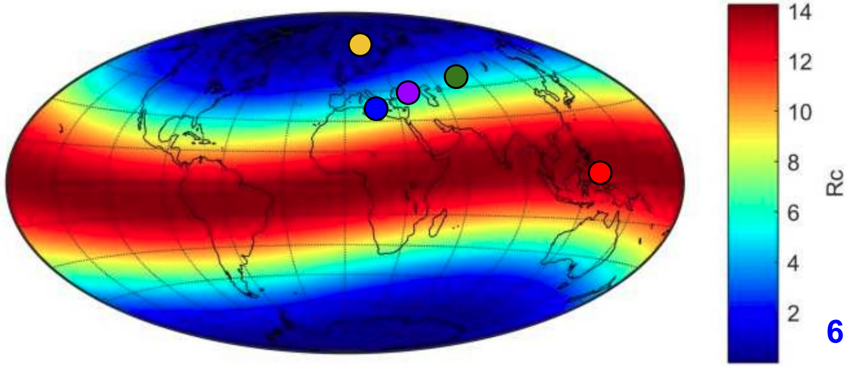


Geomagnetic rigidity cutoff





Geomagnetic rigidity cutoff R_C measures the shielding effect by Earth's magnetic field.



Rigidity

$$R = \frac{p}{q}$$

Larmor radius

$$r_g = \frac{p_\perp}{|q|B} = \frac{\gamma m v_\perp}{|q|B}$$

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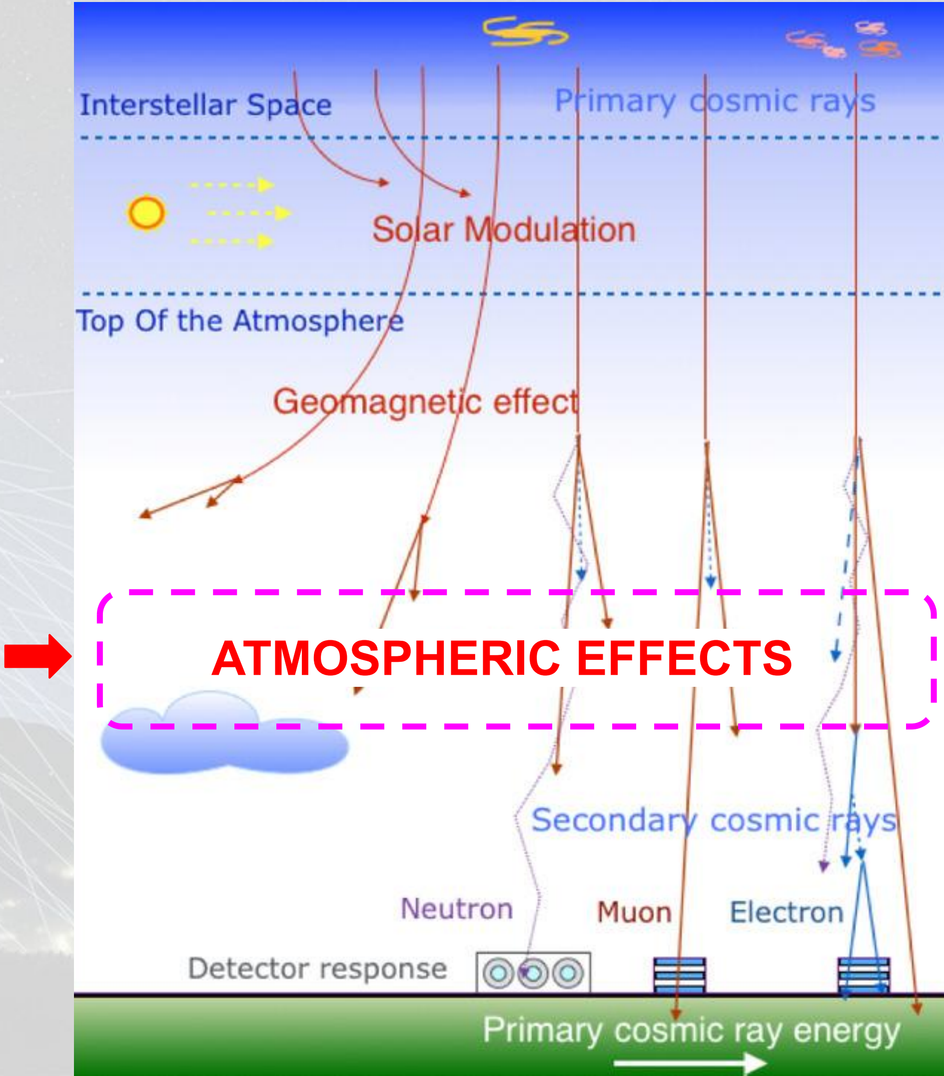
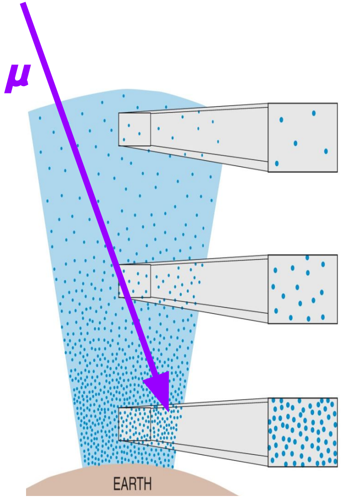
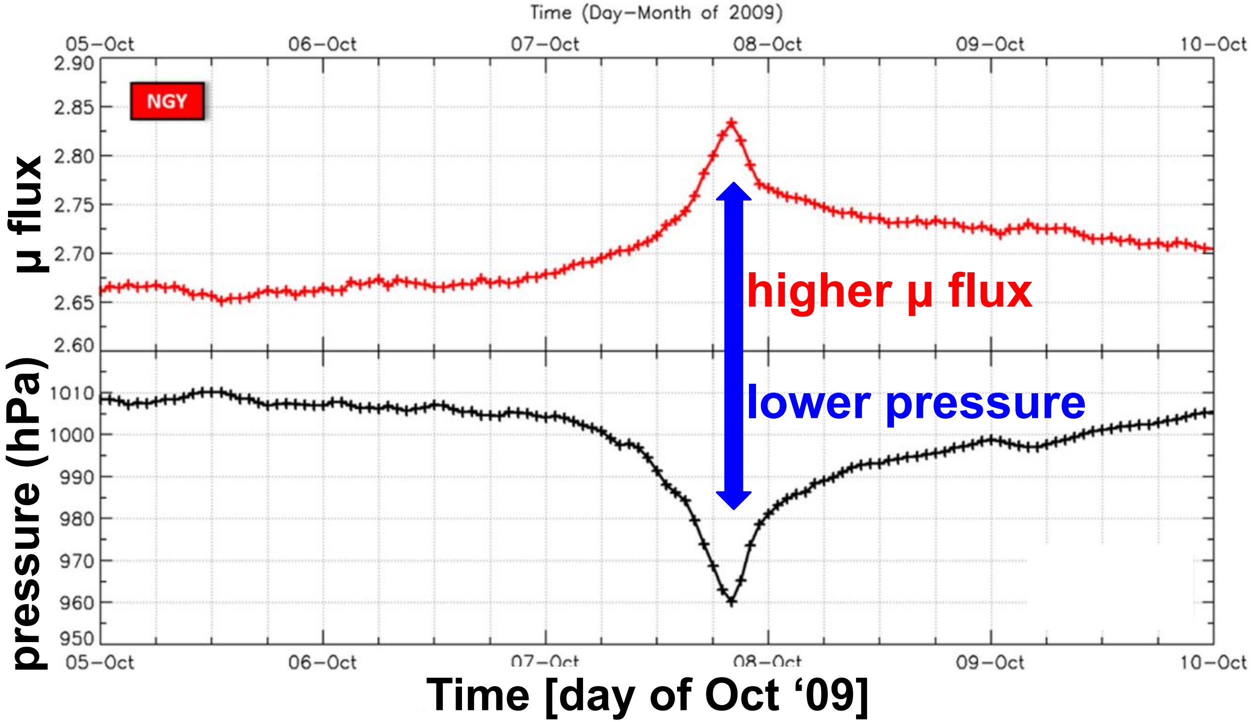


Pressure: negative correlation with low energy μ



When pressure grows more energy is lost crossing the atmosphere because of the higher air density: stopping & decay

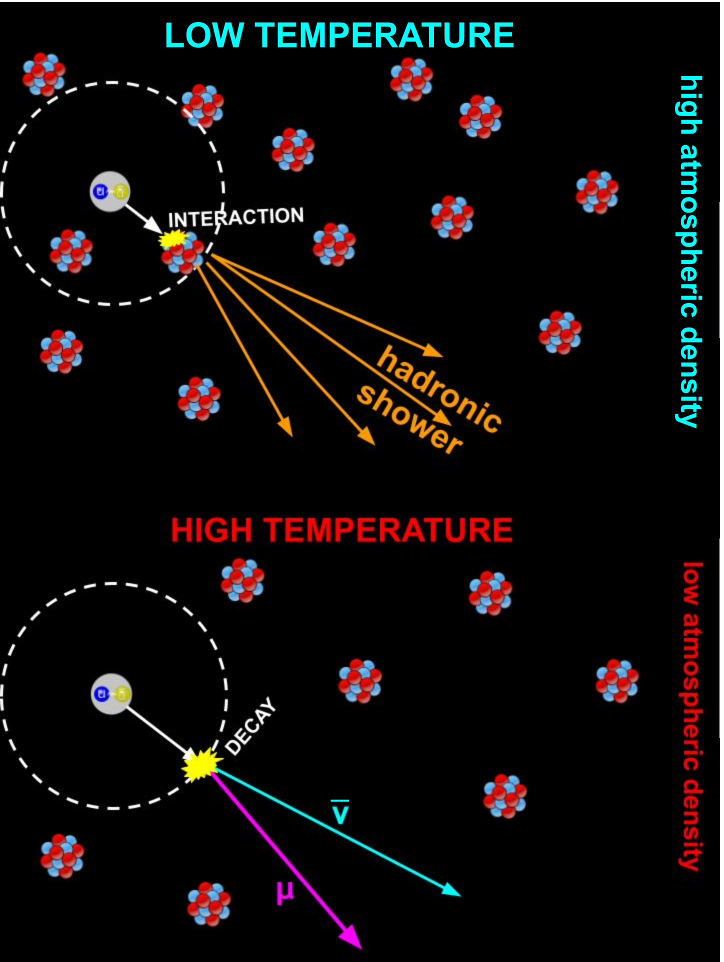
$$\Phi = \Phi_0 \ \exp[\beta(p - p_0)]$$



Passage of a typhoon above a muon detector Nogaya, Japan, October 2009

[doi:10.3847/0004-637X/830/2/88]

Temperature: positive correlation with high energy μ



high energy μ produced by high energy π decay Effect due interplay between π interaction and decay

Complex multi-particle system:

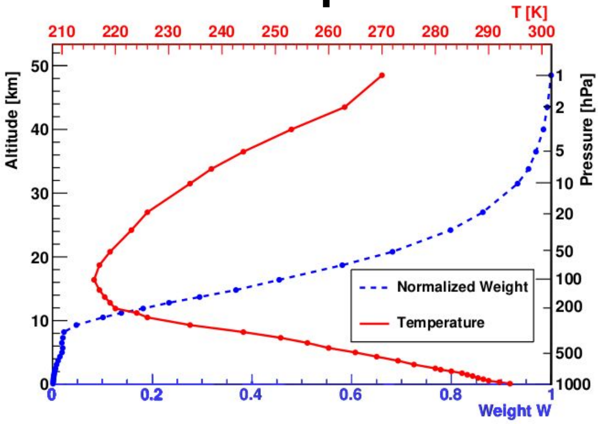
$$\frac{dN_i(E_i,X)}{dX} = -\frac{N_i(E_i,X)}{\lambda_i(E_i)} - \frac{N_i(E_i,X)}{d_i(E_i)} + \sum_j \int_E^\infty dE_j \frac{N_j(E_j,X)F_{ji}(E_j,E_i)}{\lambda_j E_i}$$

[https://doi.org/10.1016/j.astropartphys.2009.12.006]

ionization and decay con be ignored for high energy μ: this simplifies the cascade equation

$$\Delta I_\mu = \alpha_{T_{\text{eff}}}(\langle E_{\text{thr}}\cos(\theta)\rangle)\Delta T_{\text{eff}}$$

$$T_{\text{eff}} = \int_0^{X_{\text{GRD}}} dX\, w(X, \langle E_{\text{thr}}\cos(\theta)\rangle) T(X)$$

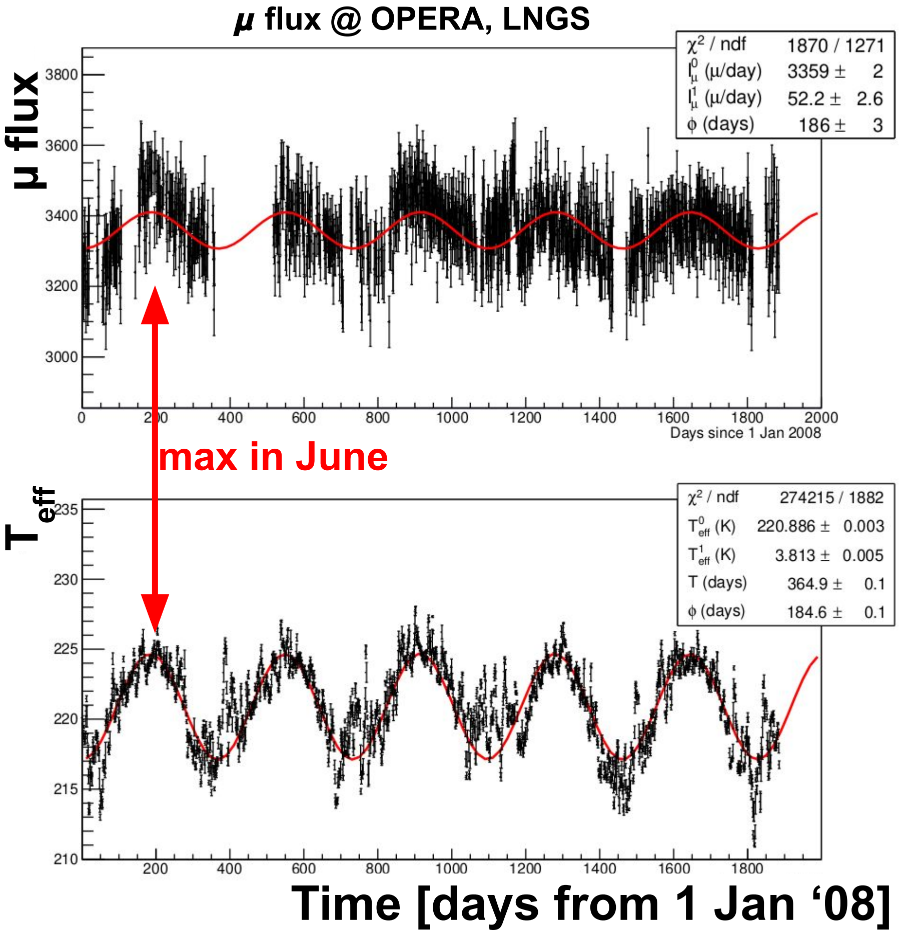


Typical scales:

$\epsilon_\pi \approx 150$ GeV
$\tau_\pi \approx 26$ ns
$m_\pi \approx 140$ MeV

→ $d_\pi \approx 8$ km

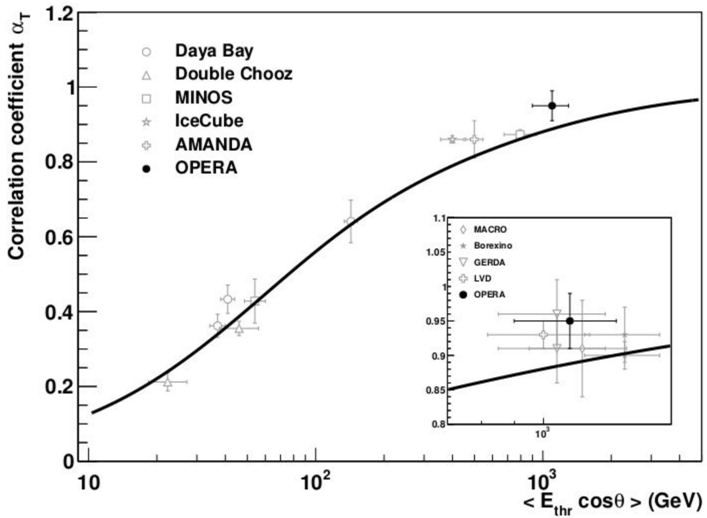
Temperature: effect @ underground laboratories



For underground detector, expected positive correlation between T_{eff} and μ flux

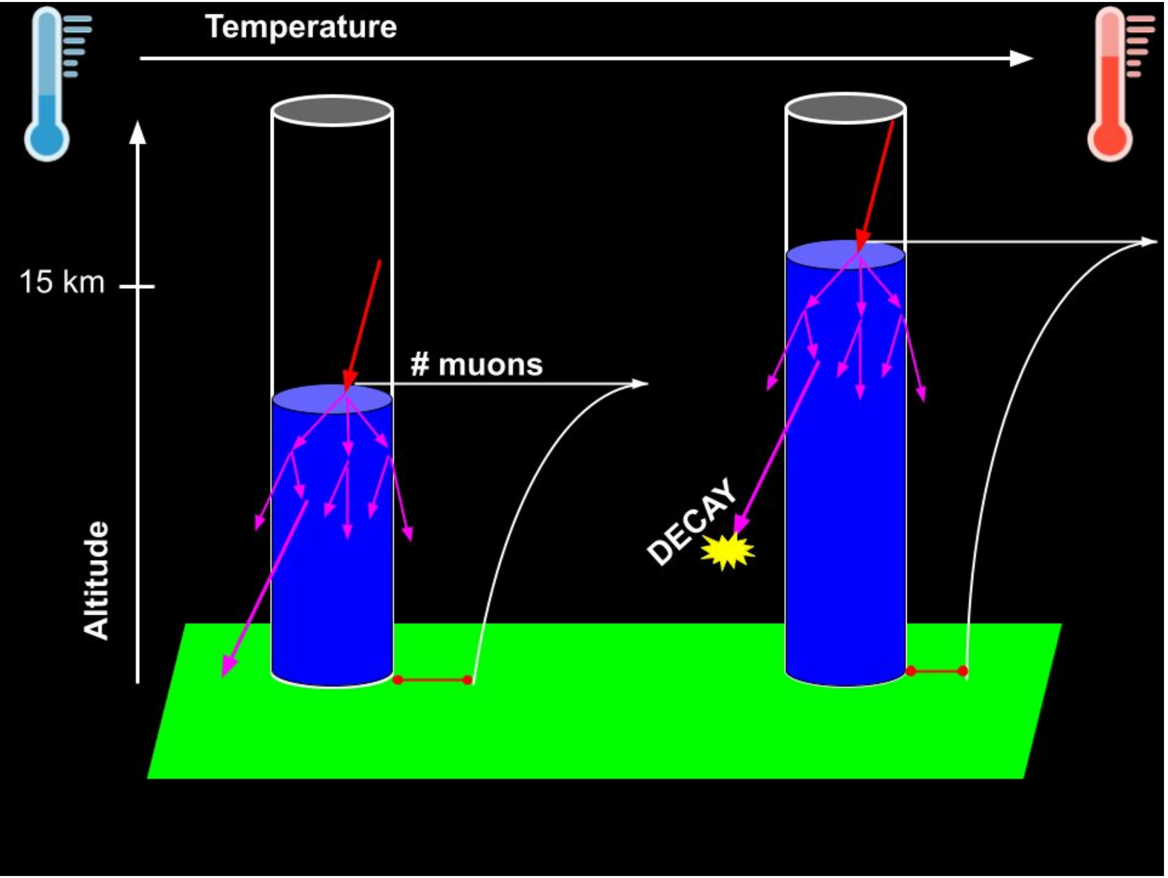
the linear coefficient α_T depend only on the energy threshold $\langle E_{thr} \cos\theta \rangle$

Information about K/π ~ 0.1 production



[DOI 10.1088/1475-7516/2019/10/003]

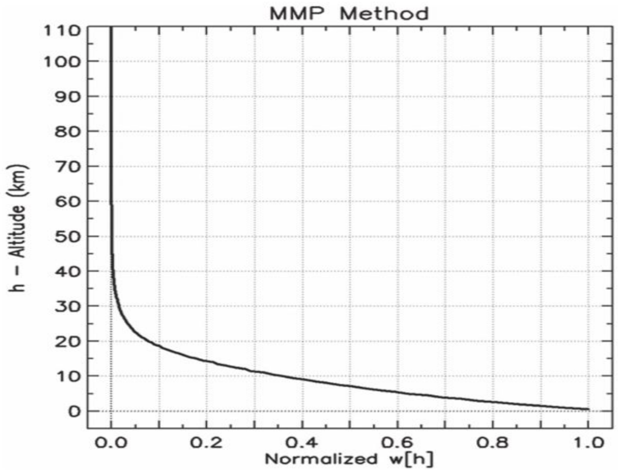
Temperature: negative correlation with low energy μ



low energy μ affected by decay and ionization processes, longer path imply a decrease of the flux, transportation is more complex, empirical method are more popular

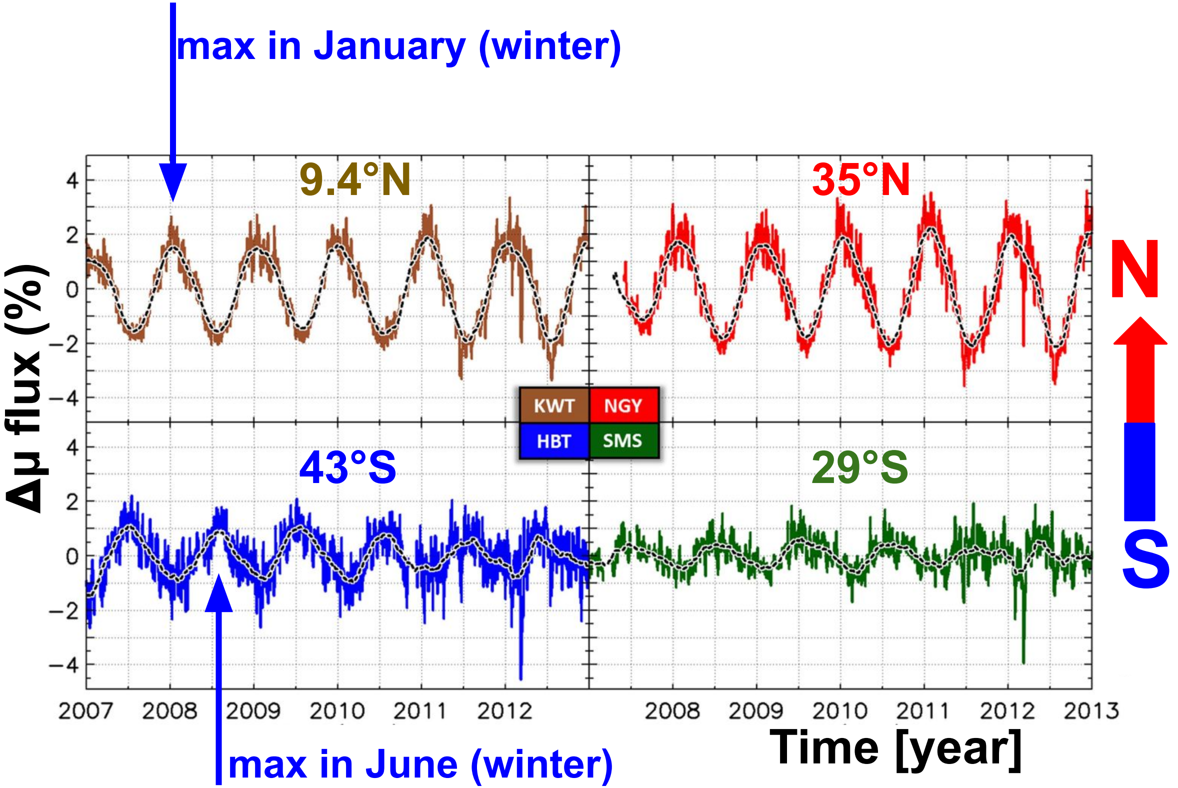
$$\Delta I_{\mu} = \alpha_{T_{\mathrm{MSS}}} \Delta T_{\mathrm{MSS}}$$

$$T_{\mathrm{MSS}} = \int_0^{X_{\mathrm{GRD}}} dX\, T(X)$$



[doi:10.3847/0004-637X/830/2/88]

Temperature: effect @ ground based μ telescopes



μ **flux measured by ground-based GMDN, top: North hemisphere, bottom: Southern hemisphere**
[doi:10.3847/0004-637X/830/2/88]

For ground based detector expected negative correlation between T_{MSS} and *μ* flux

Linear coefficient α_T have a complex dependency on:

E_{thr}, altitude, geomagnetic cutoff, latitude, …

Data is needed to better understand the effect

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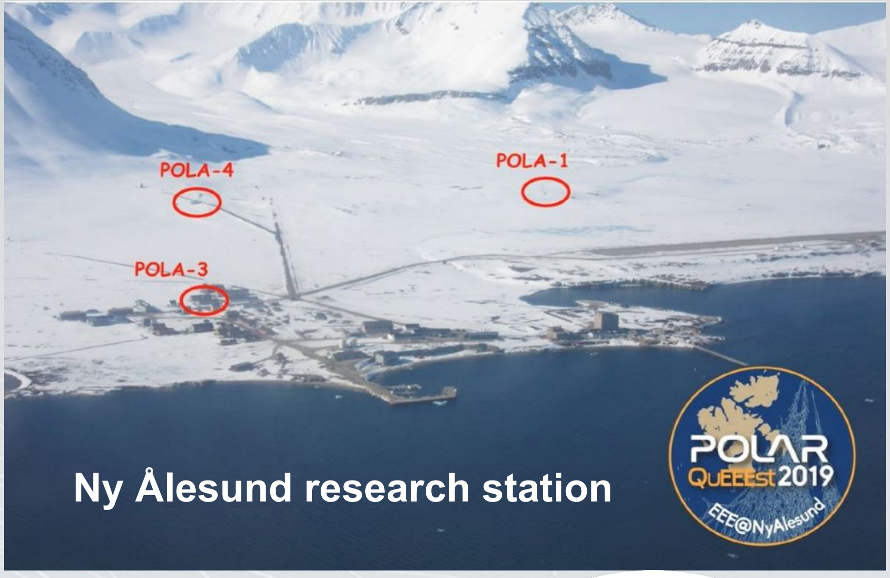
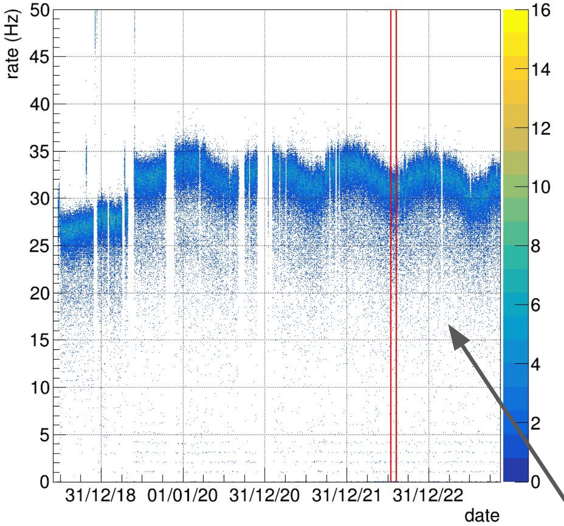


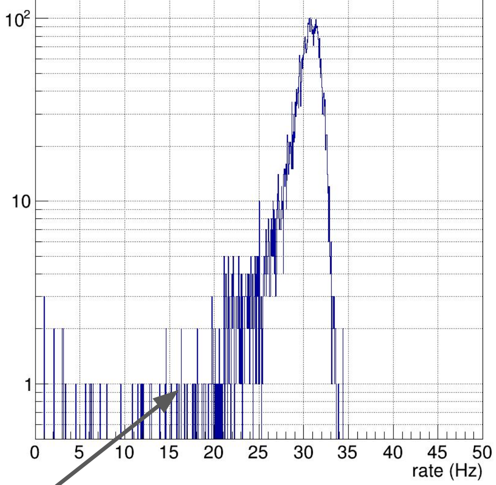
nowadays is the northernmost muon detector: 79°N, Rigidity Cutoff 0.18GV

Study/minimization of systematics: rate drops

POLA1: 1 minute rate



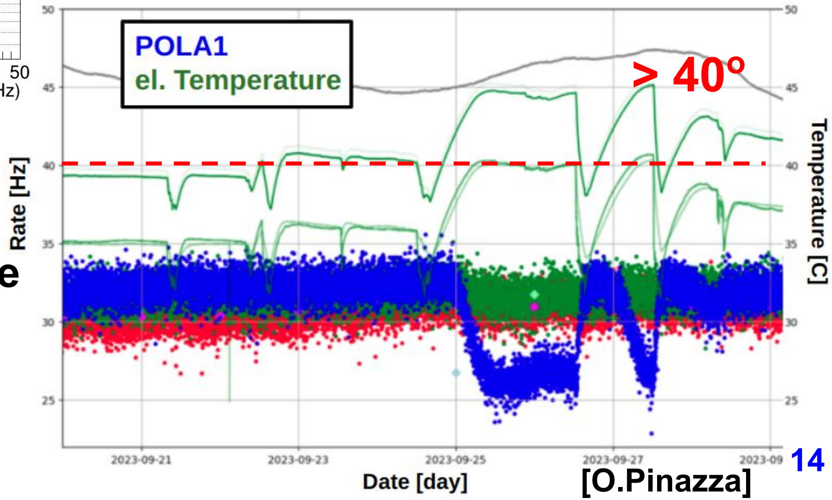
15 days proj.



rate drops

Distribution is not symmetrical and the left tail deviates from a normal distribution

Outliers: drops in the measured rate (possibly due to efficiency loss @ high detector temperature)

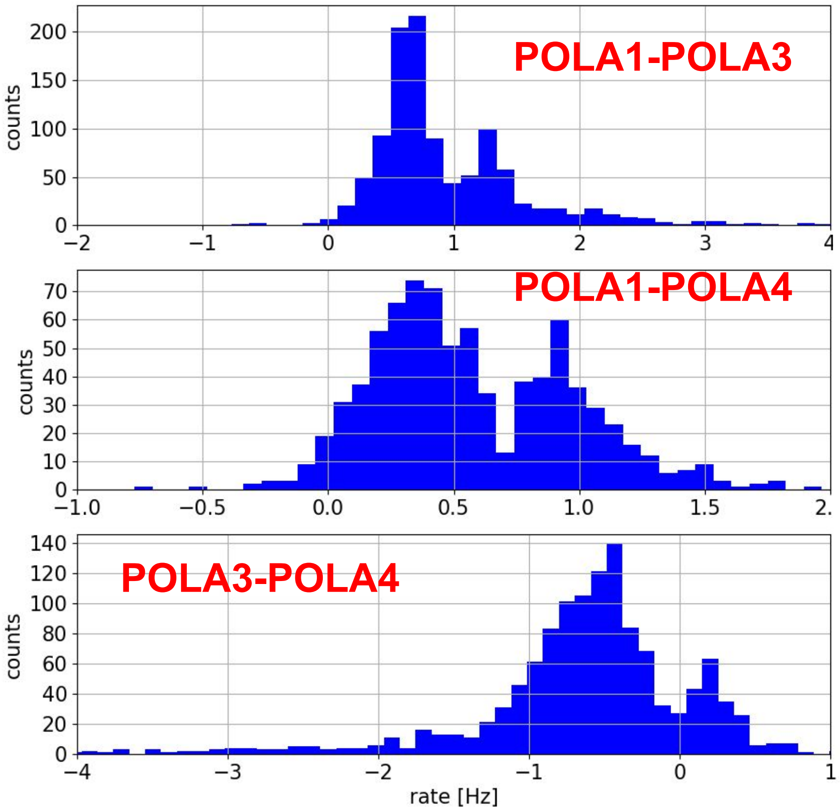


[O.Pinazza]

median is chosen as rate estimator since it is more robust to outliers wrt mean. Cautious systematic:

$$\sigma_{spk} = |\text{median}-\text{mean}|$$

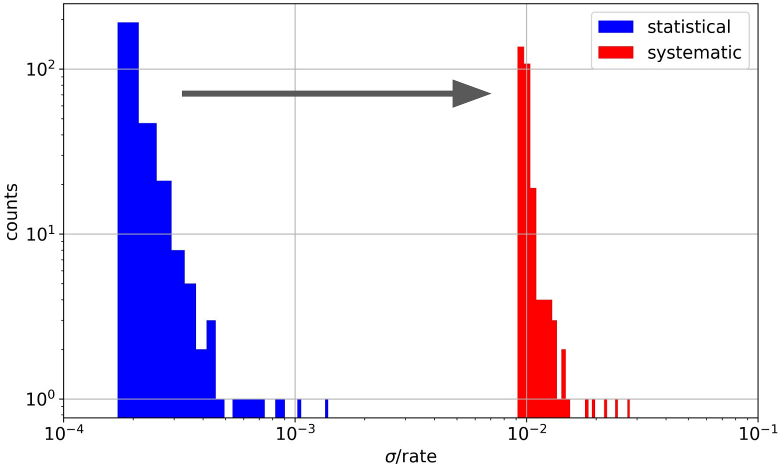
Study of systematics: comparison of different detectors



The dispersion of the difference of measured flux by POLA1 - POLA3 give information about the uncertainty of single detectors.

$$\sigma_{diff} = \sigma(r_1 - r_2) / \sqrt{2} < 0.3\text{Hz}$$

$$\sigma_{sys} = \sigma_{spk} \oplus \sigma_{diff}$$



cautious systematic uncertainties estimated still few % of measured rate

Outlook:

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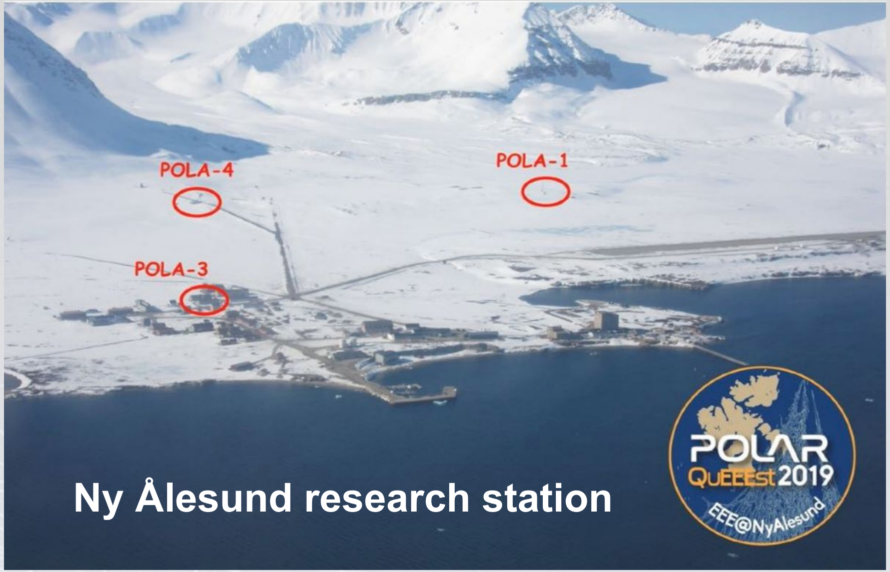
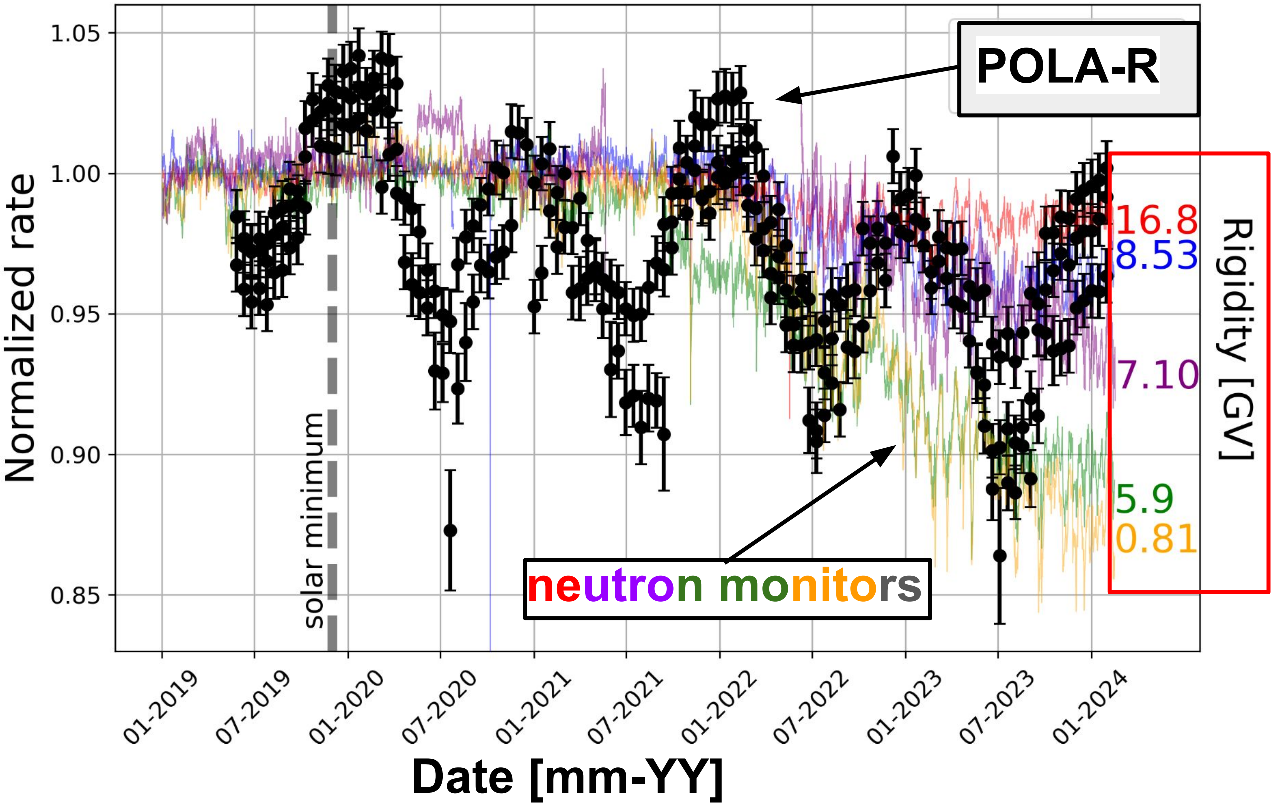


Solar modulation: comparison with NM



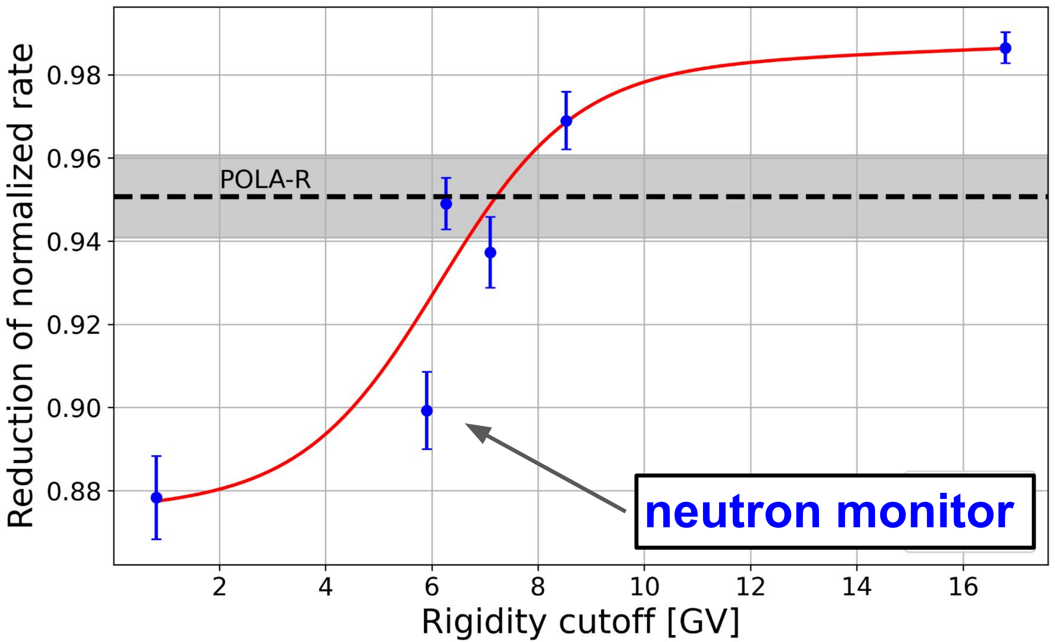
Solar modulation clearly visible in both in NM and μ flux (POLA-R).

Intensity of the solar modulation of NM depends on the R_c

A quantitative comparison:
Ny-Alesund R_c = 0.18 GV
reduction factor: 0.95

OULU R_c = 0.8 GV
reduction factor: 0.88

Solar modulation: μ production cutoff @ Ny-Alesund



Comparison with NM reduction suggests an effective cutoff for μ:

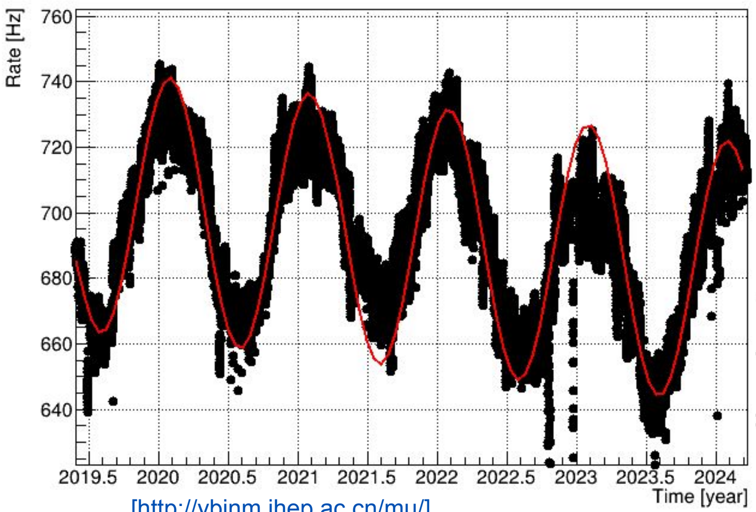
7 ± 1 GV >> R_C = 0.18 GV @ 79°N

expected a production cutoff since a primary proton need to have an higher energy to produce a μ compared to neutron

MIP μ deposit ~ 2 GeV energy crossing the atmosphere
μ can carry only a fraction (~ 0.3) of the primary proton
→ production cutoff dominates over R_C

Solar modulation: μ reduction @ high R_C (YBJ)

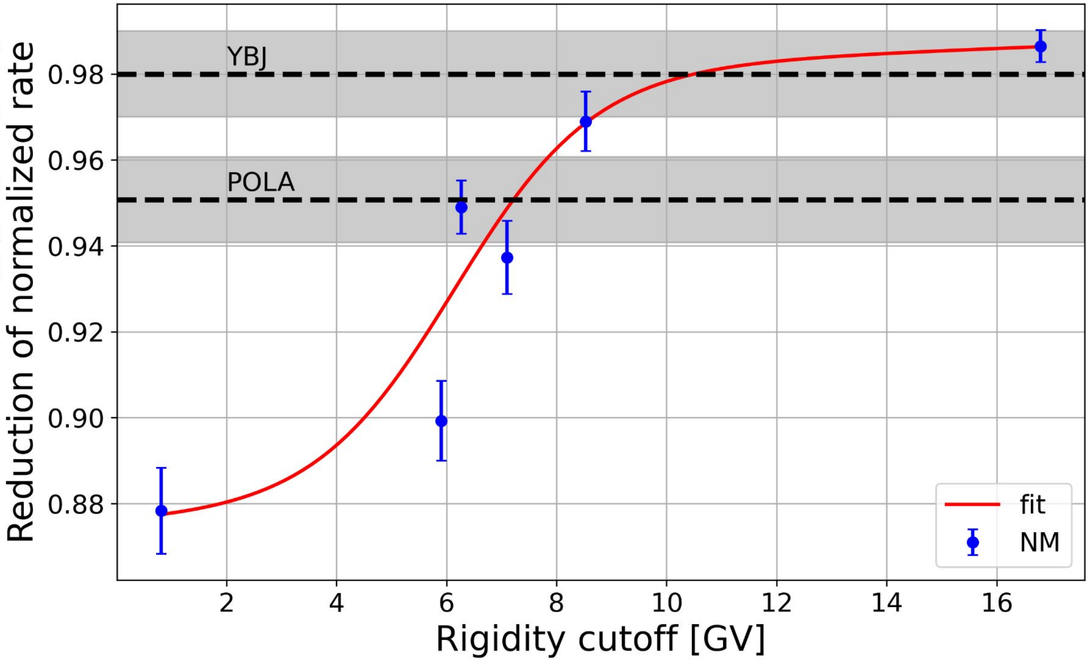
μ flux at Yang Ba Jing (Tibet)



[http://ybjnm.ihep.ac.cn/mu/]

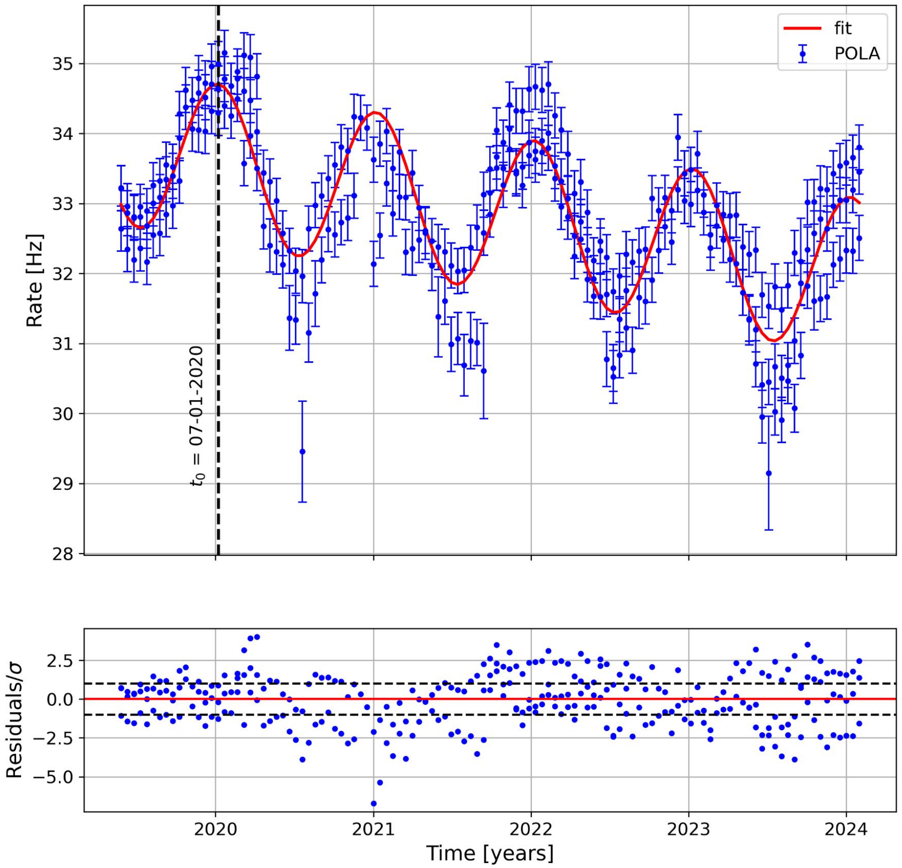
Yan Ba Jing μ detector is located in Tibet (near equator)

R_C = 13 GV >> 7 GV (prod. cut.)



➡ **R_C dominates over production cutoff, reduction of μ flux comparable with NM**

Seasonal variation

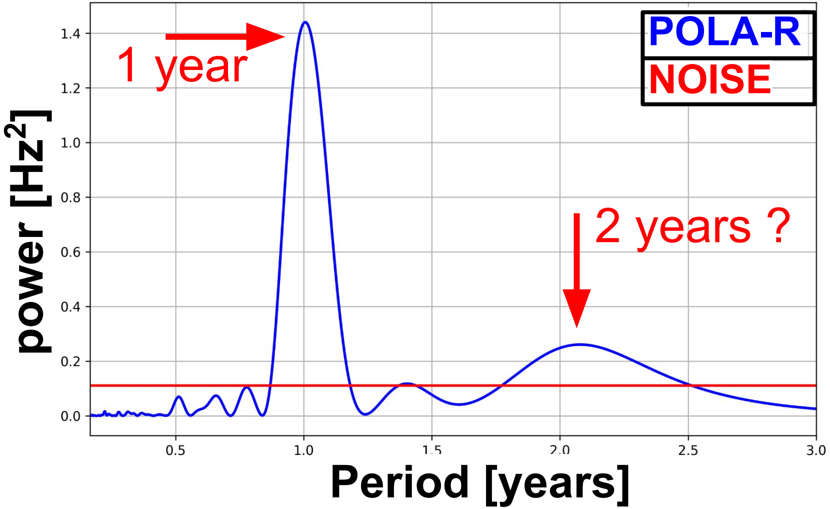


Clear presence of annual periodicity, expected from the effect of atmospheric temperature variation, confirmed the negative correlation for ground based detector

$$\Phi(t) = A\cos\left(2\pi\frac{t-t_0}{T}\right) + Bt + C$$

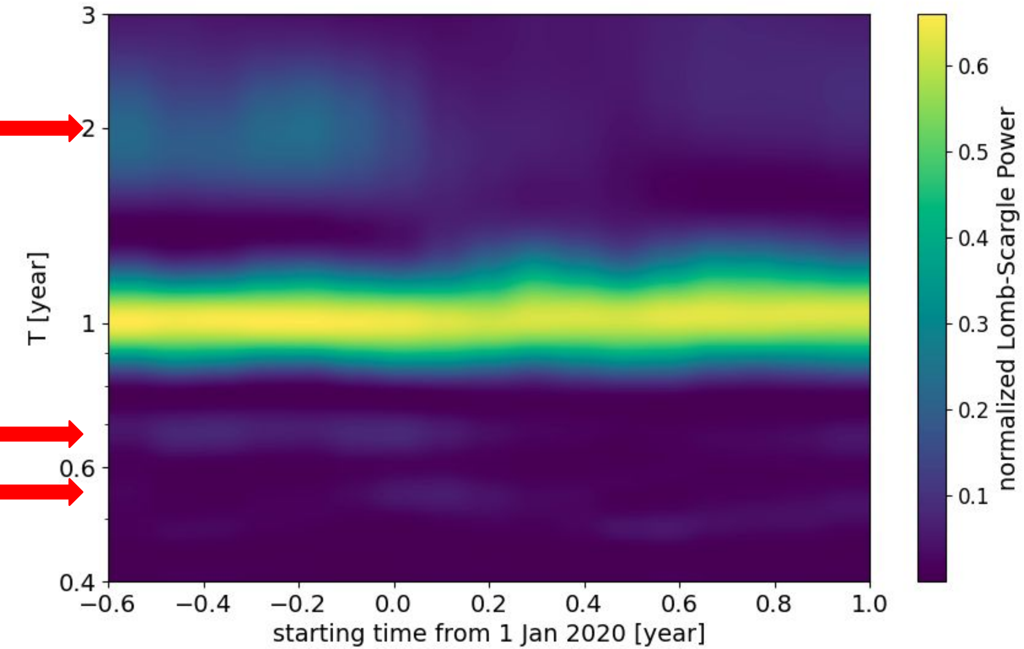
Amplitude[%]	Period [years]	t_0 offset [days]	chi^2/dof
3.4 ± 0.1	1.003 ± 0.003	7 January ± 2	846/283

Lomb-Scargle periodogram



[doi: 10.1051/0004-6361:20081296]

Hints for sub and bi-annual periodicities



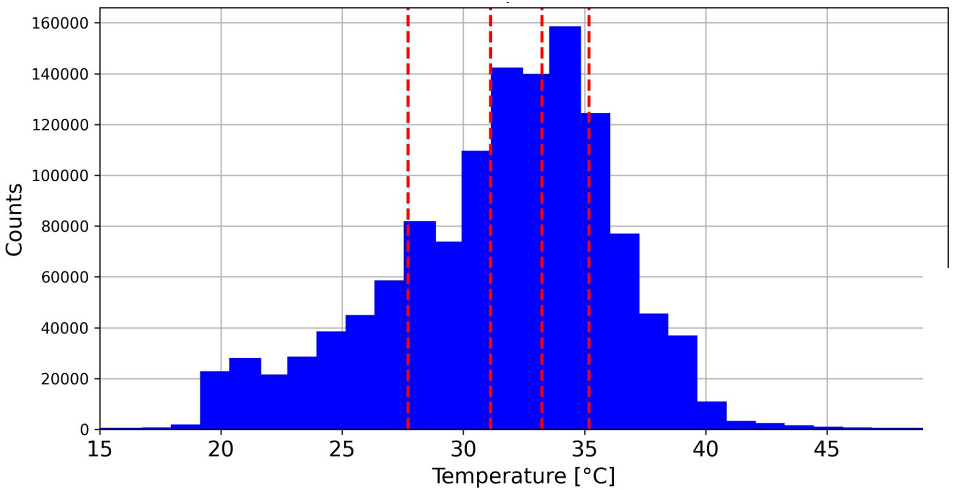
3yr moving window Lomb-Scargle periodogram suggests the possible presence of:

- **bi-annual modulation, possibly connected to the atmospheric QBO** [https://doi.org/10.1016/B978-0-12-382225-3.00232-2]
- **quasi-periodic ~250 days and ~150 days modulation, similar to ones suggested by other studies** [https://doi.org/10.3390/universe9090387]

The exact nature could be both of solar or atmospheric origin. A deeper investigation of these effects deserve additional experimental/analysis efforts to reduce systematic uncertainties in the μ flux measured by POLA-R detectors.

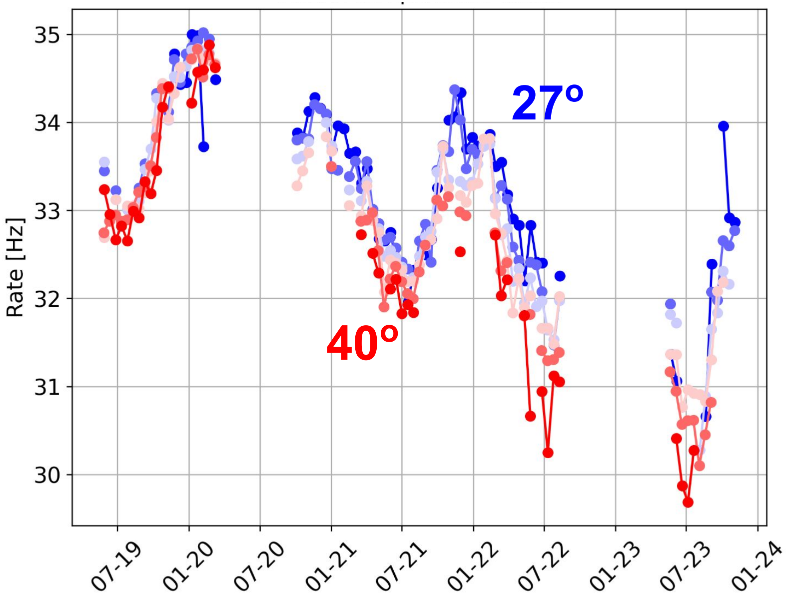
Excluding detector temperature effects

POLA4: DETECTOR TEMPERATURE



Temperature of the electronics influences the efficiency of the detectors.
Detectors are maintained in a stable environment, however a small seasonal variation of detector temperature is expected.

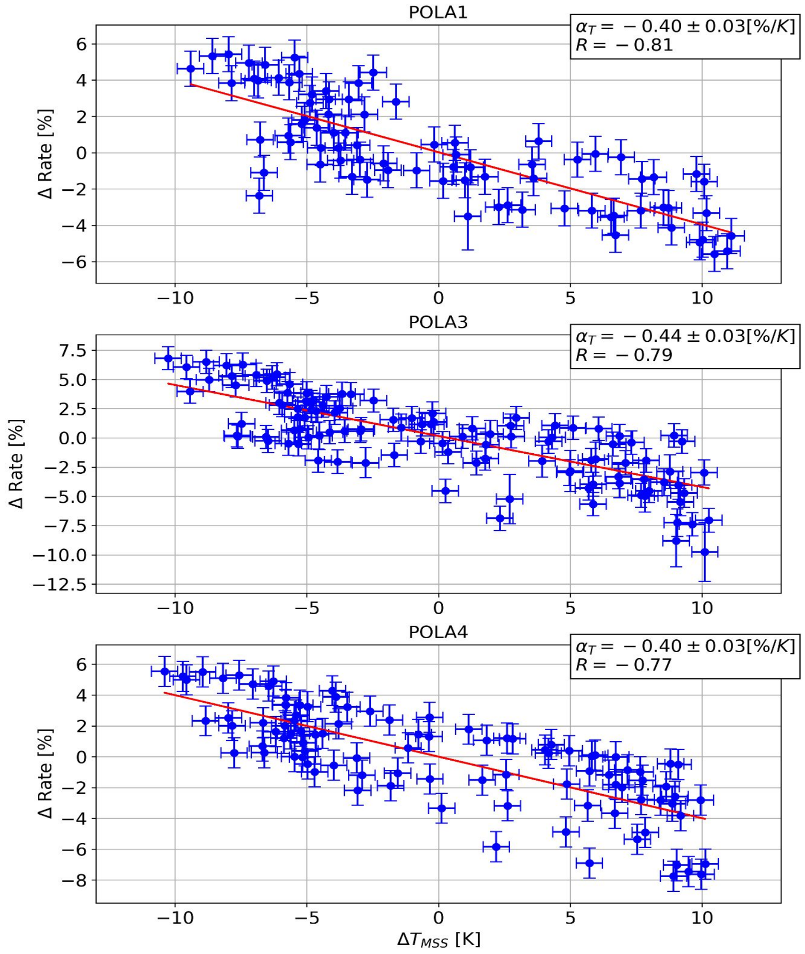
POLA4 rate for different detector T



seasonal variation parameters with systematic std

Amplitude [%]	Period [years]	t_0 offset [days]
3.4 ± 0.7	1.00 ± 0.01	12 January ± 8

Correlation between T_{MSS} and μ rate: α_T



Temperature influence on μ ground based flux is described by α_T the correlation with the T_{MSS}, the mass weighted temperature

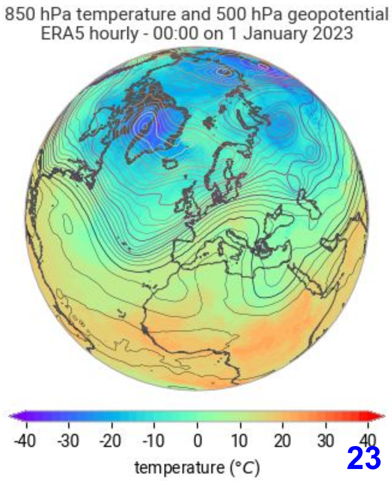
$$\Delta I_\mu = \alpha_{T_{\mathrm{MSS}}} \Delta T_{\mathrm{MSS}}$$

$$T_{\mathrm{MSS}} = \int_0^{X_{\mathrm{GRD}}} dX\, T(X)$$

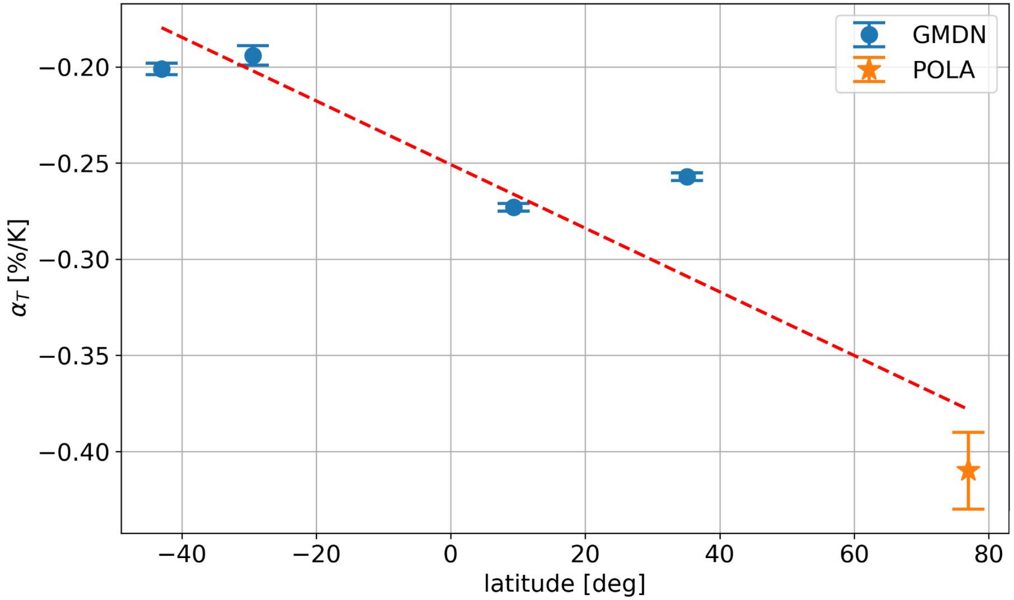
X: slant depth, the amount of materials crossed by the air shower

T(X): atmospheric temperature profile (data from ERA5)

[https://doi.org/10.1002/qj.3803]



Comparison of α_T @ Ny-Alesund and GMDN



Global Muon Detector Network is a collaboration of ground based *μ* detector.

Previous studies have suggested that $|\alpha_T|$ grows with the latitude

[doi:10.3847/0004-637X/830/2/88]

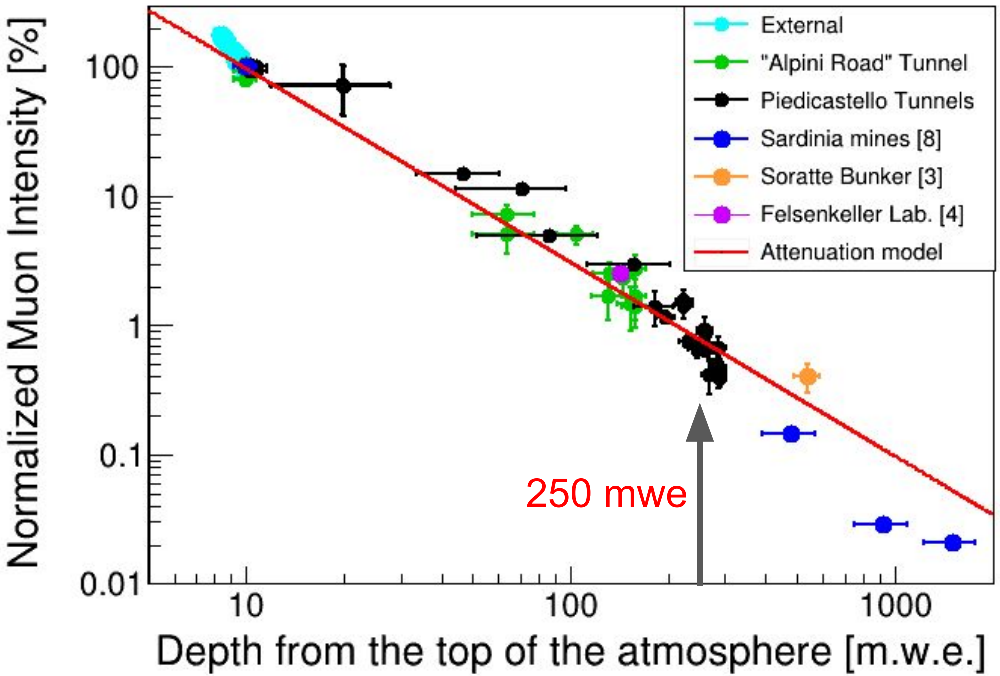
EFFECT CONFIRMED!

Measurements at Ny-Alesund add information on α_T northernmost μ detector.

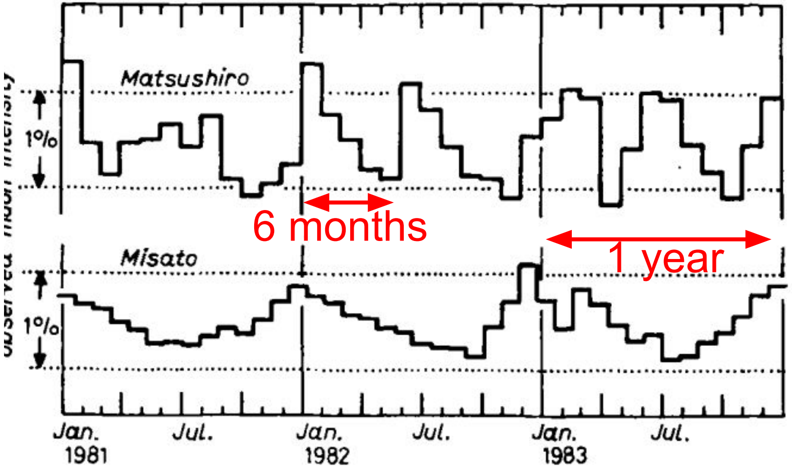
$|\alpha_T|$ @ Ny-Alesund is twice as large as that observed at middle latitude locations in the southern hemisphere.

Location	Coord.	Alt. [m]	R_c [GV]	α_T [%/K]	R_{lin}
Nagoya (NGY-Japan)	35.15°N 136.97°E	77	11.5	-0.257 ± 0.002	-0.96
Kingston (HBT-Australia)	43.0°S 147.29°E	65	1.8	-0.201 ± 0.003	-0.83
Sao Martinho da Serra (SMS-Brazil)	29.44°S 53.81°W	488	9.3	-0.194 ± 0.005	-0.69
Kuwait City (KWT-Kuwait)	9.37°N 47.98°E	19	13.8	-0.273 ± 0.002	-0.96
Ny-Alesund (POLA-R Svalbard)	78.92°N 11.92°E	30	0.18	-0.410 ± 0.020	-0.78

Prospect: investigation of the semi-annual seasonal variation @ Piedicastello tunnels



Attenuation @ Piedicastello tunnels comparable to Mitsushiro ~ 250 mwe which suggested semi-annual modulation (old data from 1986)



[https://doi.org/10.1007/BF02558081]

A simple scientific measurement could be planned with a long run using TIFPA μ detector to investigate this effect.

Summary

Time dependence of the μ flux measured @ Ny-Alesund with POLA-R detectors:

- **Highest latitude (lowest R_C) measurement of the μ flux @ the ground**
- **Observation of enhanced solar modulation and Forbush due to the low R_C**
- **Observation of the μ flux seasonal dependence anti-correlated with atmospheric T & P**
- **Strong support to the suggested latitude dependence of the temperature effect coefficient**
- **Hints for bi-annual and sub-annual periodicities possibly related to solar/atmospheric effects**
- **New measurement proposal @ Doss Trento looking for a semi-annual periodicity of μ flux**

Talks and publications:

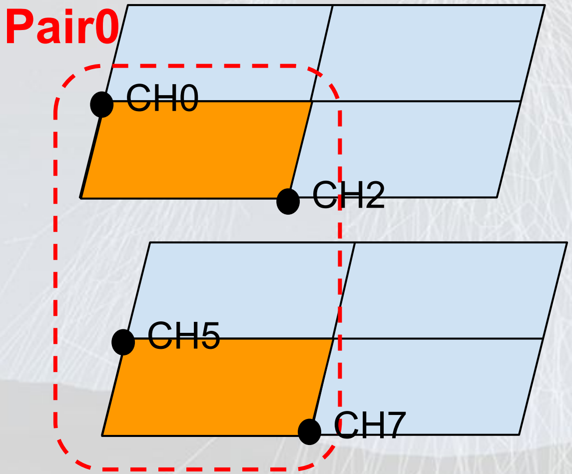
"Studio delle variazioni stagionali e pluriennali del flusso dei muoni atmosferici" 110° Congr. Naz. SIF, Bologna

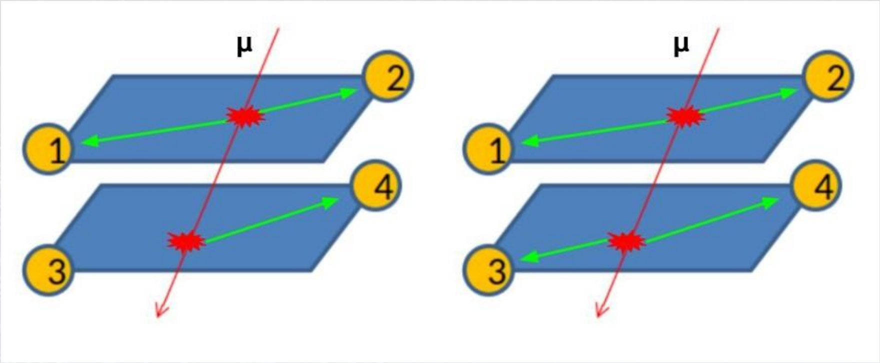
"Measurement of the muon flux in the tunnels of Doss Trento hill" submitted to Nuclear Instruments and Method A

"Annual quasi-periodicity in muon rate observed by PolarquEEEst detectors at 79°N" submitted to Eur. Phys. J

Thank you

Ongoing: Pseudoefficiency and systematic mitigation

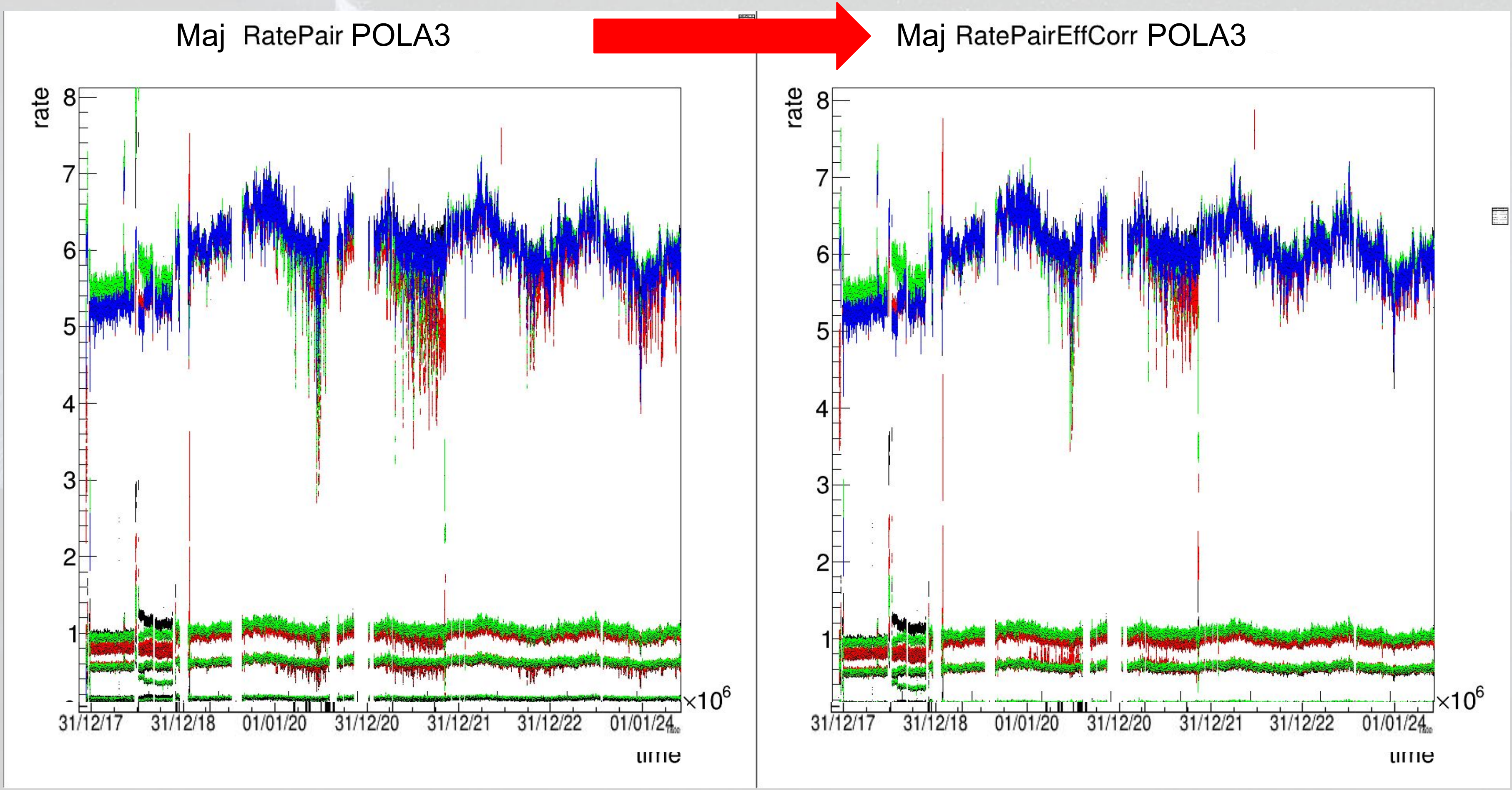




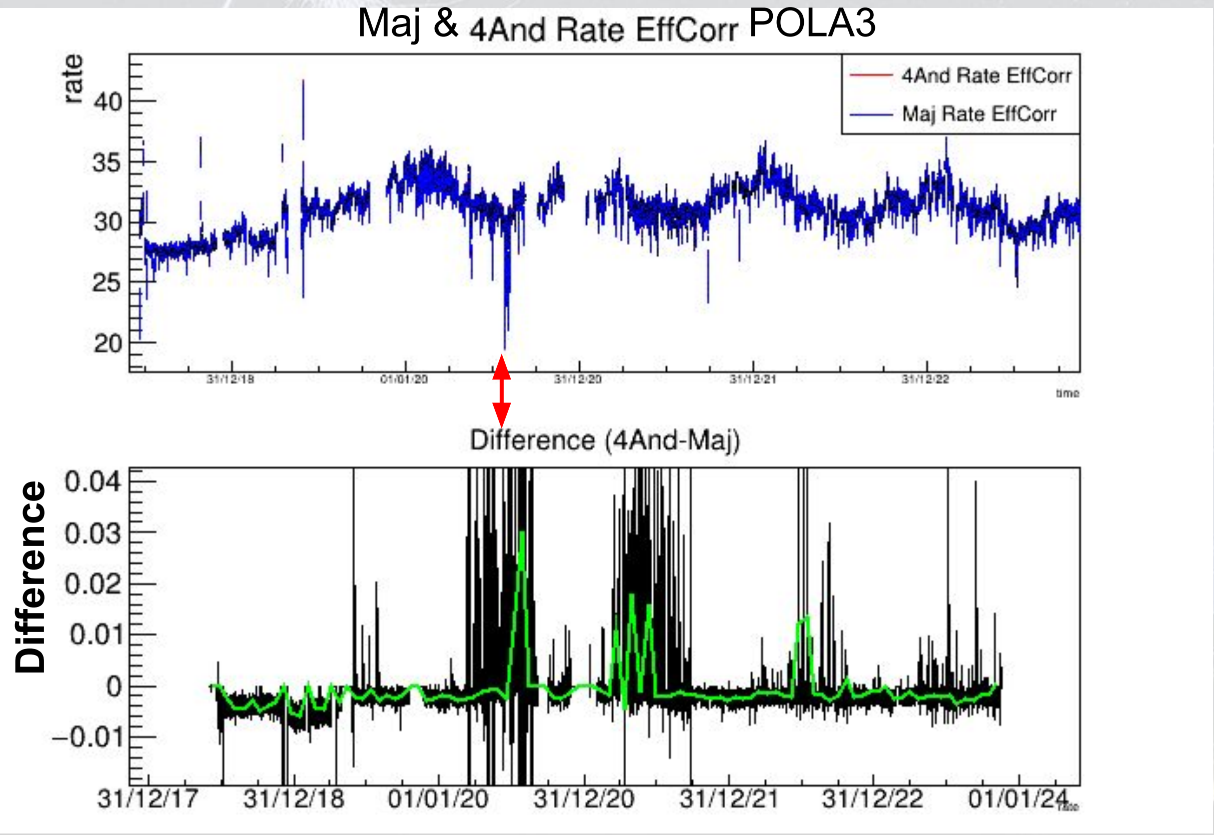
Majority:
at least ¾ SiPM fires

4And:
all SiPM fires

Effect of pEfficiency correction



Majority vs 4And rate



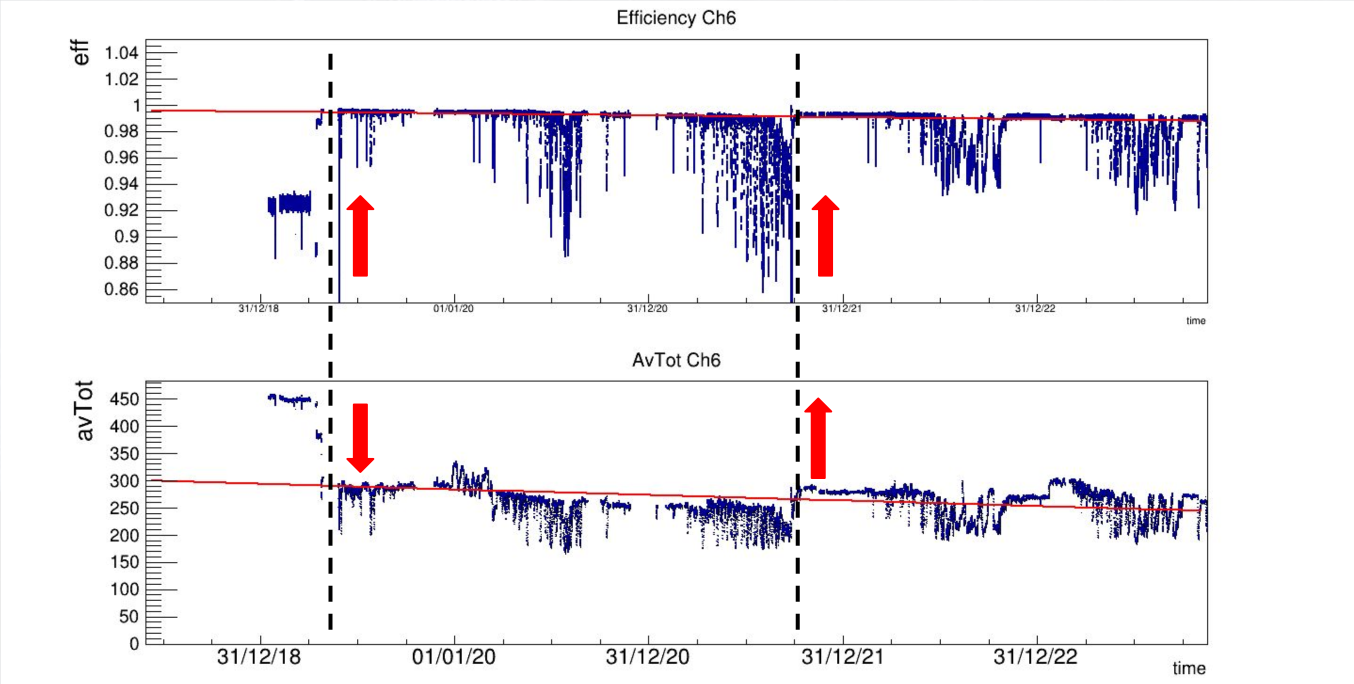
Difference could give information about systematics induced by pEfficiency

High difference correlated to "negative spikes"

POLA3 (more "noisy")

Time stability: changes in threshold?

threshold raised ? **threshold lowered?**

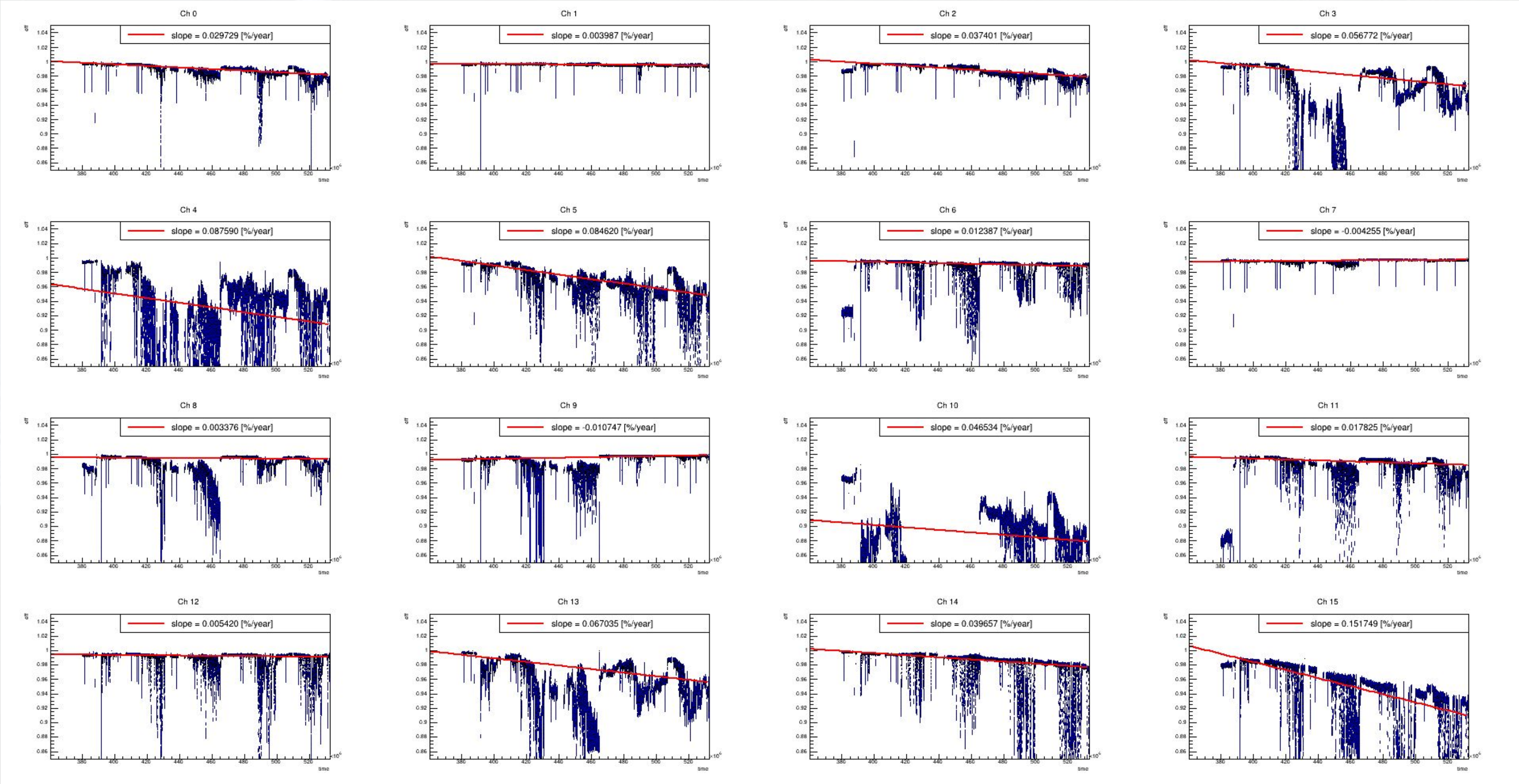


It seems that the threshold was changed, both time the efficiency rises

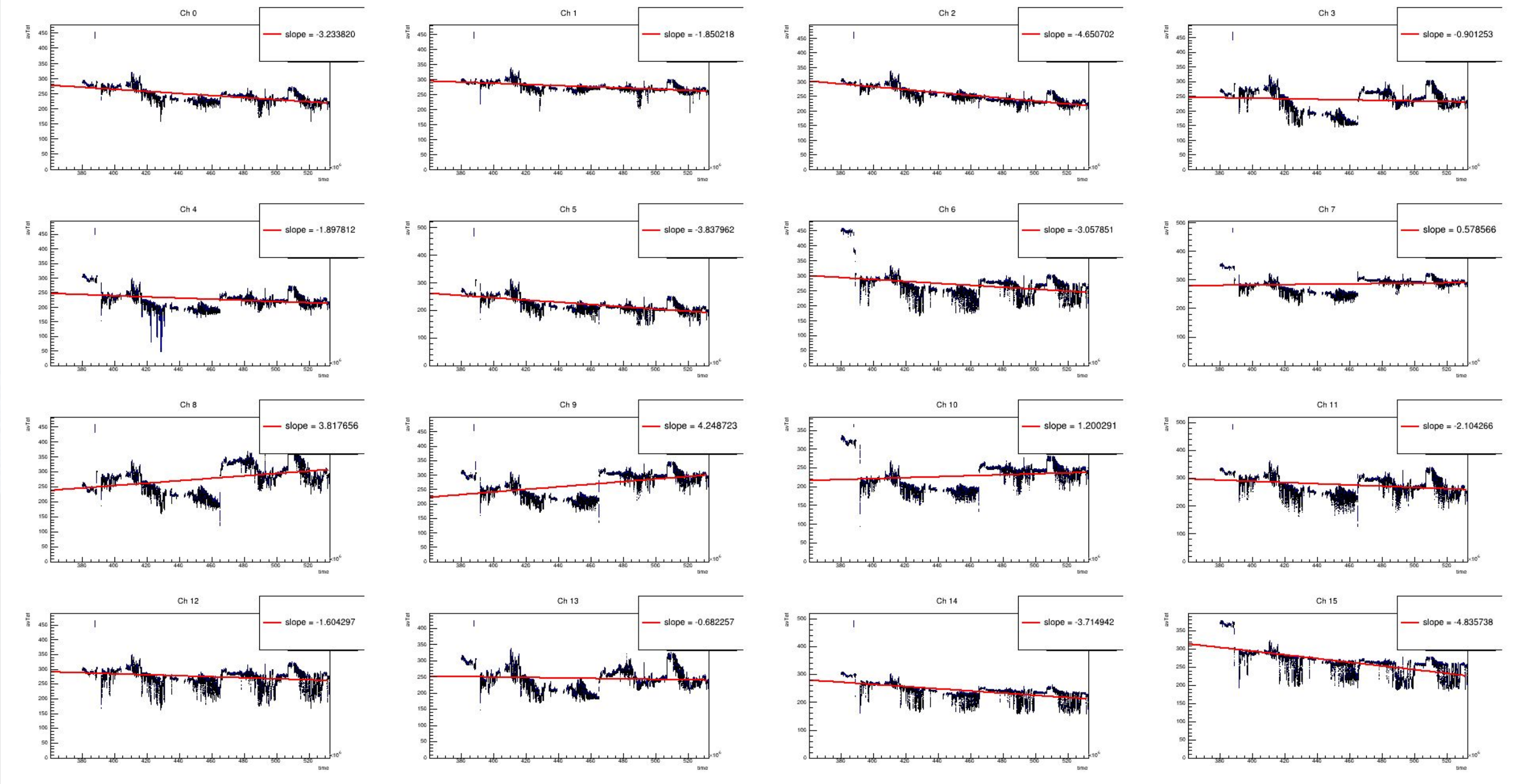
less noise coincidences?

higher sensibility?

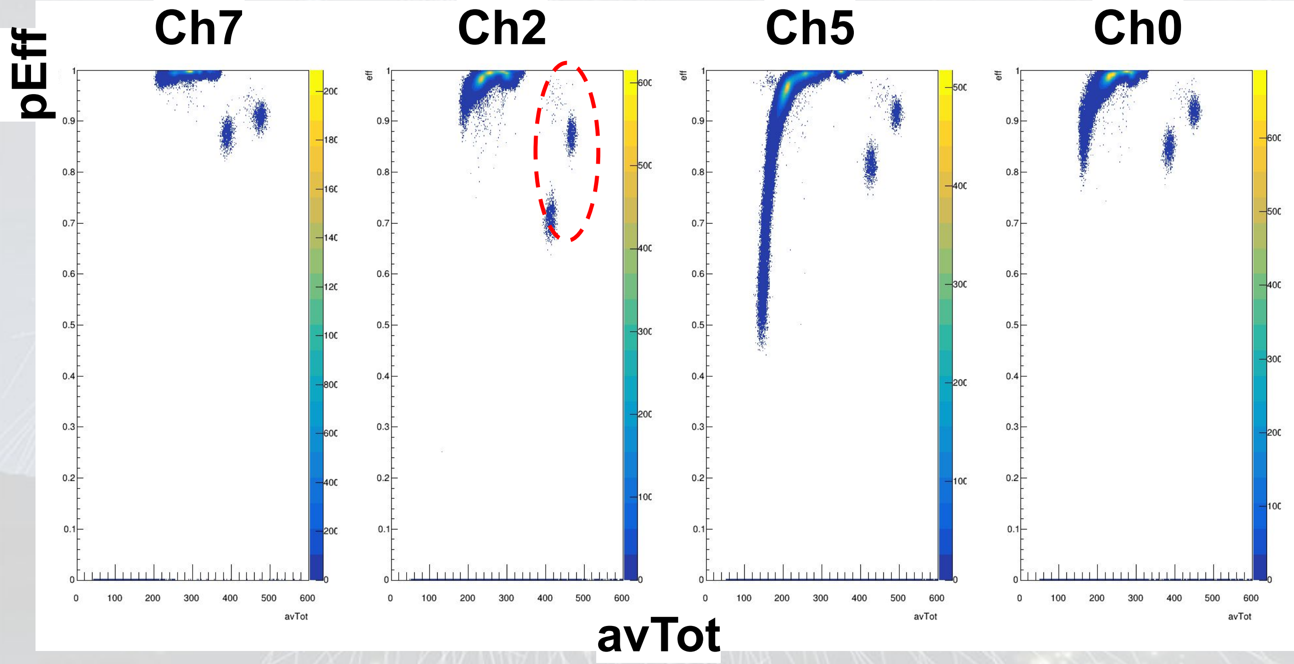
Time stability: long term reduction of pEfficiency

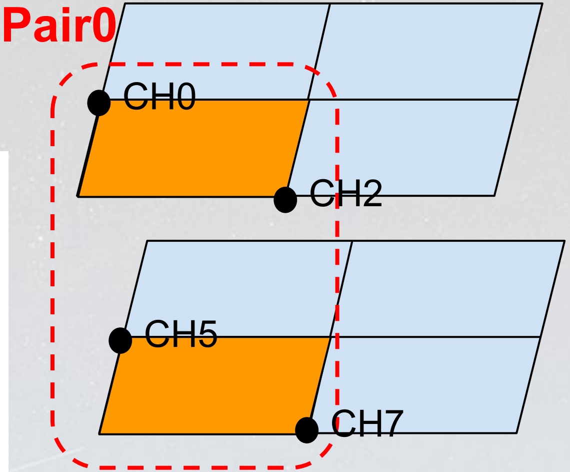


Time stability: long term reduction of TimeOverTrashold



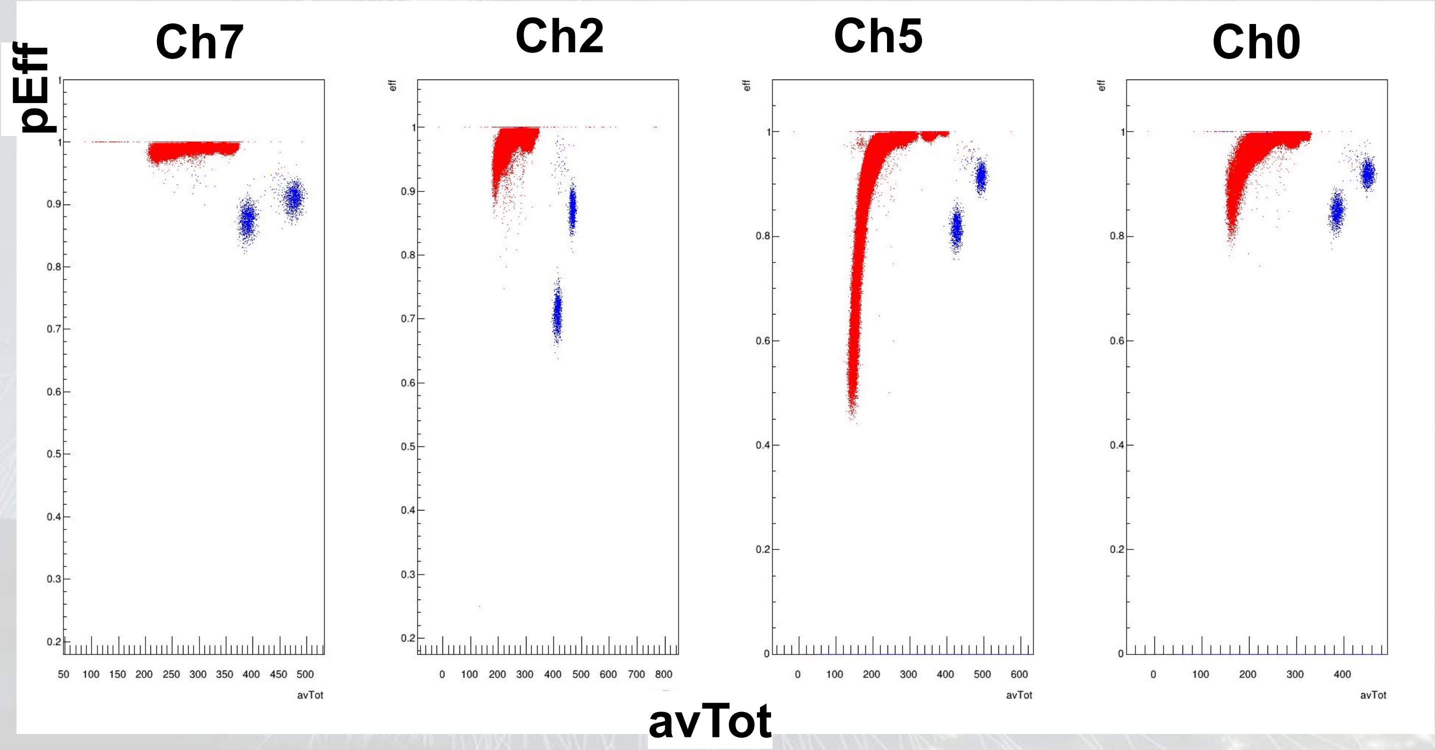
pEfficiency vs TimeOverTrashold





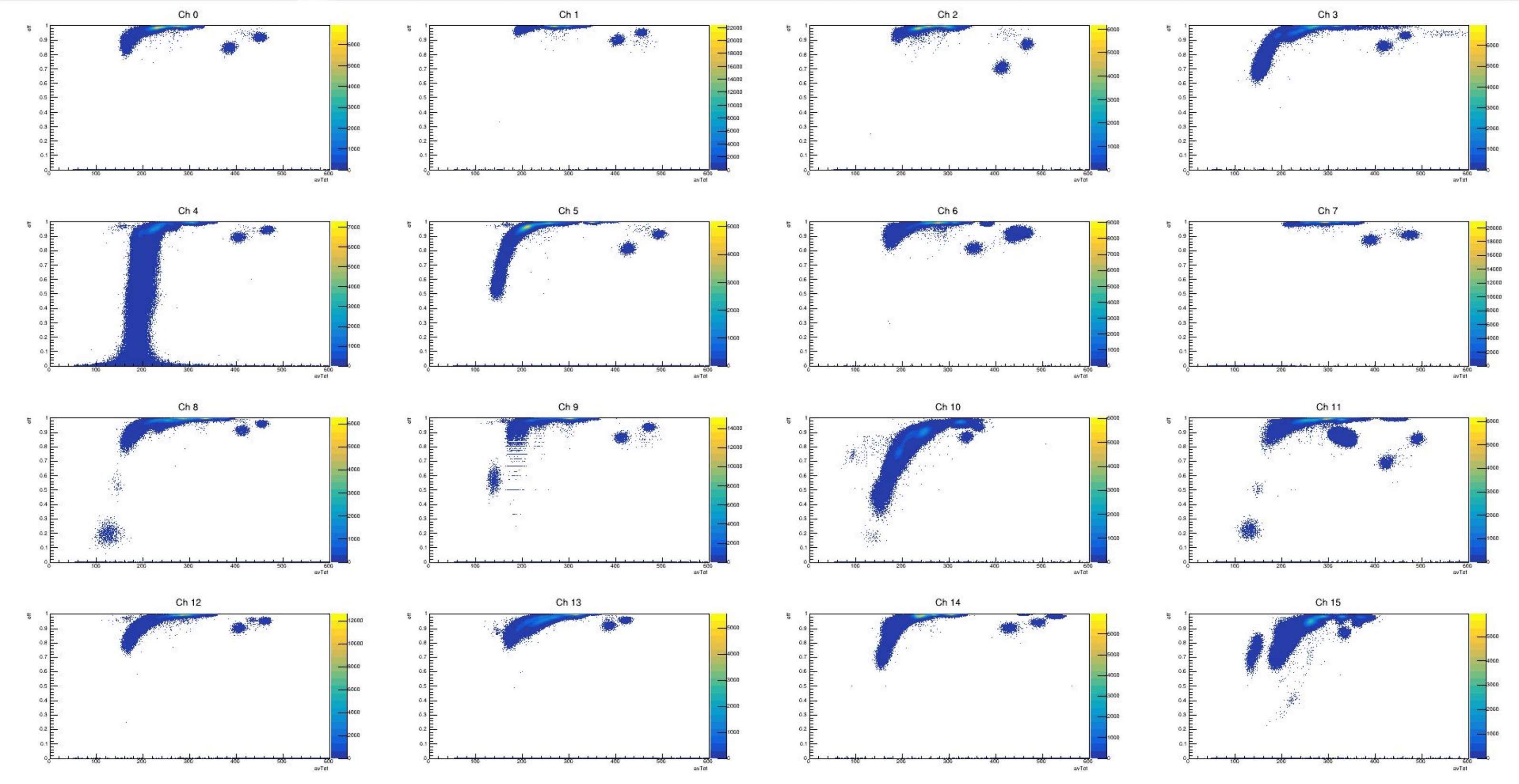
Populations of possible high noise periods correlated to high avTimeOT

pEfficiency vs TimeOverTrashold



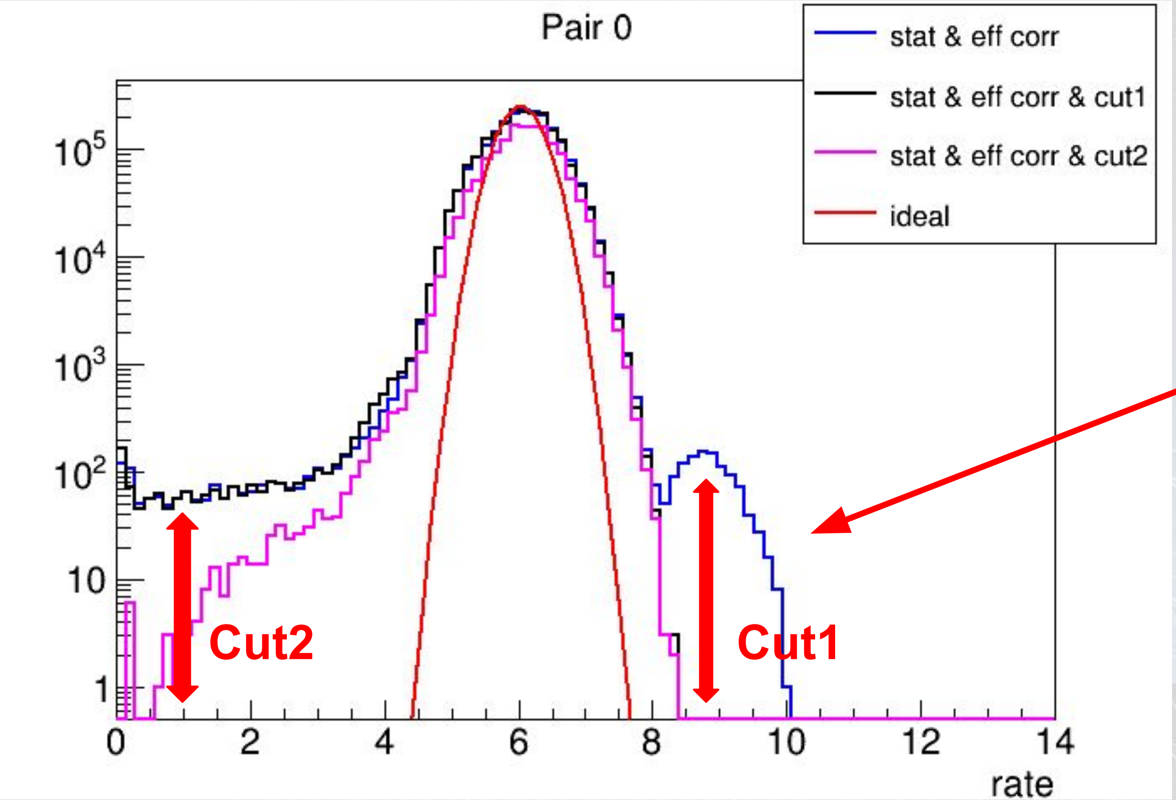
Highly correlated between the SiPM of the same Pair

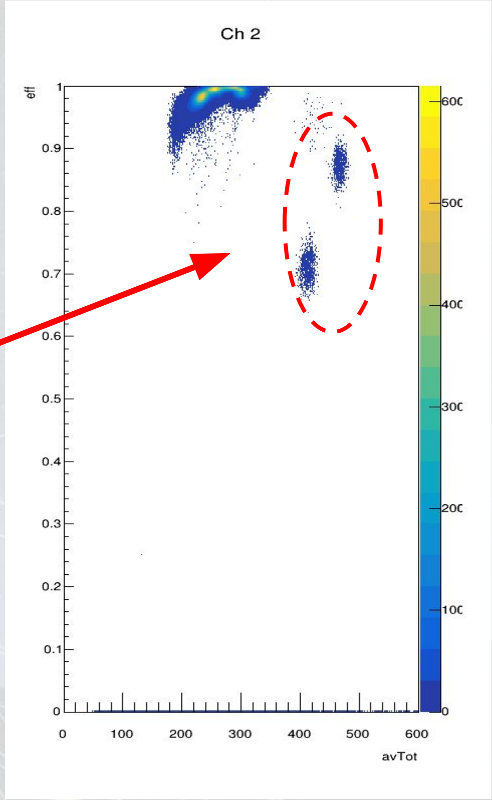
pEfficiency vs TimeOverTrashold



Possible noisy populations present in all channels

Pair0 rate contaminations



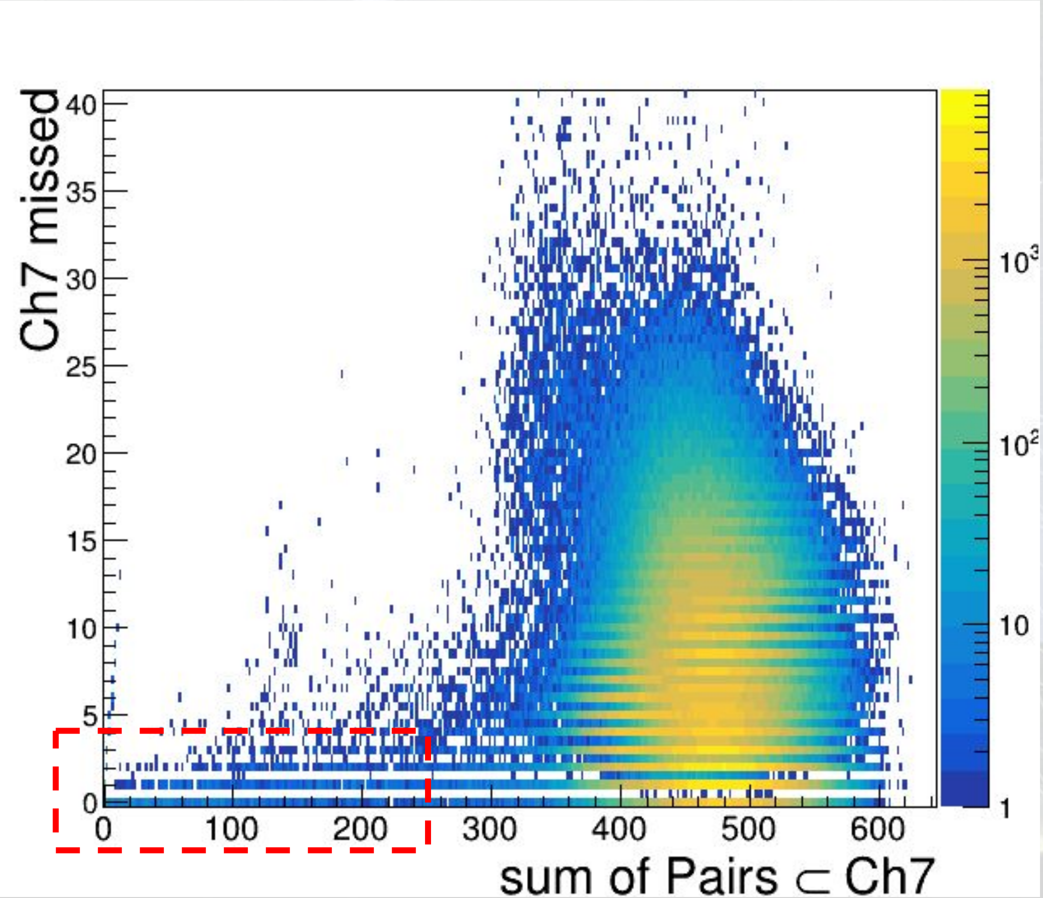


Cut1: possible noisy population seen before

Cut2: all pEfficiency != 1

both invisible to status == 0 !!!

Search for a pEff reliability parameter



In low counts and low number of missing, is pEff reliable?

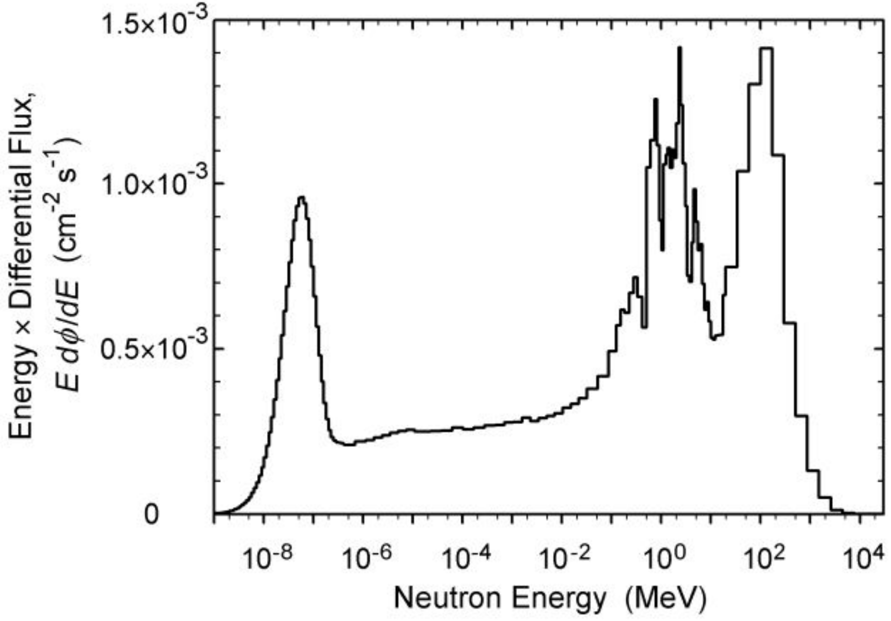
maybe regions where a SiPM is frequently over threshold and produces false coincidences?

BACKUP SLIDES

Secondary neutron

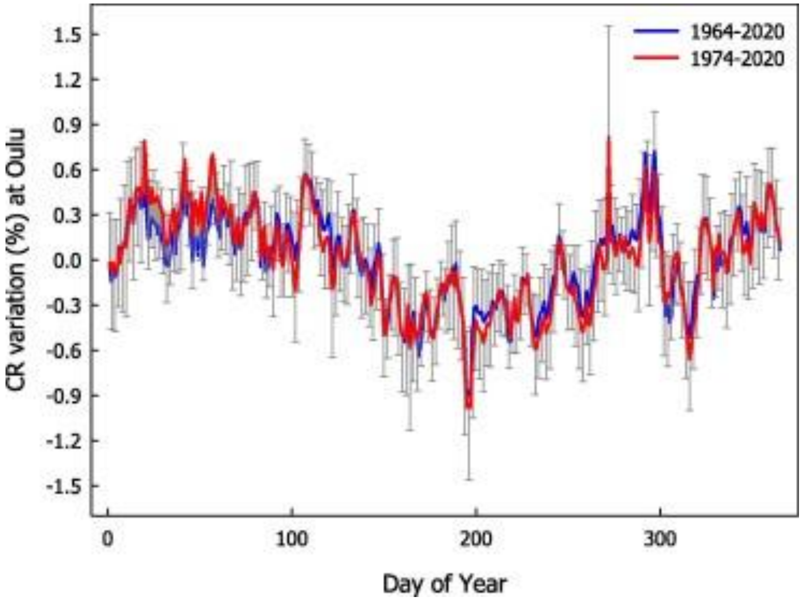
high energy: know-out, low energy: evaporation

GB neutron spectrum



Outdoor: Fremont Pass, CO; Mount Washington, NH; Yorktown Heights, NY; and Houston, TX. Indoor sites included Leadville, CO, and computer labs at IBM sites in Yorktown Heights, NY, and Burlington, VT.

Neutron modulation



OULU NM pressure corrected

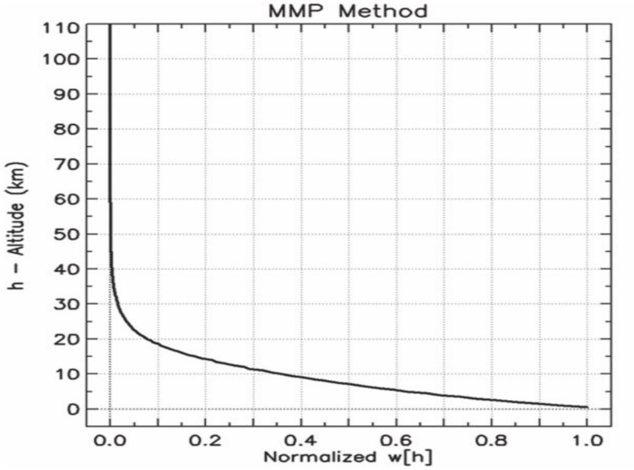
T_{MSS} from atmospheric temperature profile

$$P = \frac{\rho}{M} R^* T$$

Ideal gas equation

$$P = P_b \left[1 - \frac{L_{M,b}}{T_{M,b}} (h - h_b) \right]^{\frac{g_0' M_0}{R^* L_{M,b}}}$$

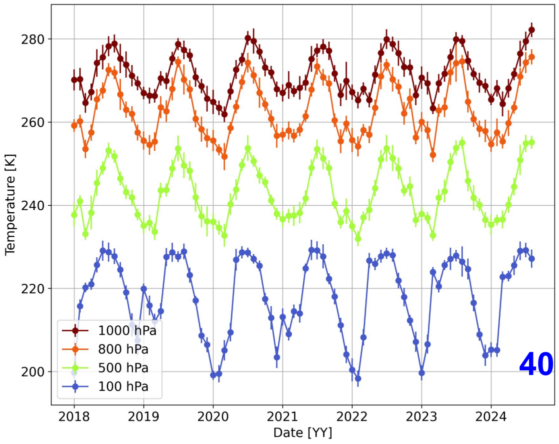
Barometric formula,
const Lapse rate ~ 10 C/km



$$x[h] = \int_h^{\infty} \rho[h] dh, \;\; \rho[h] = \frac{P[h]}{T[h]} * \frac{M_{\mathrm{Mol}}}{R}$$

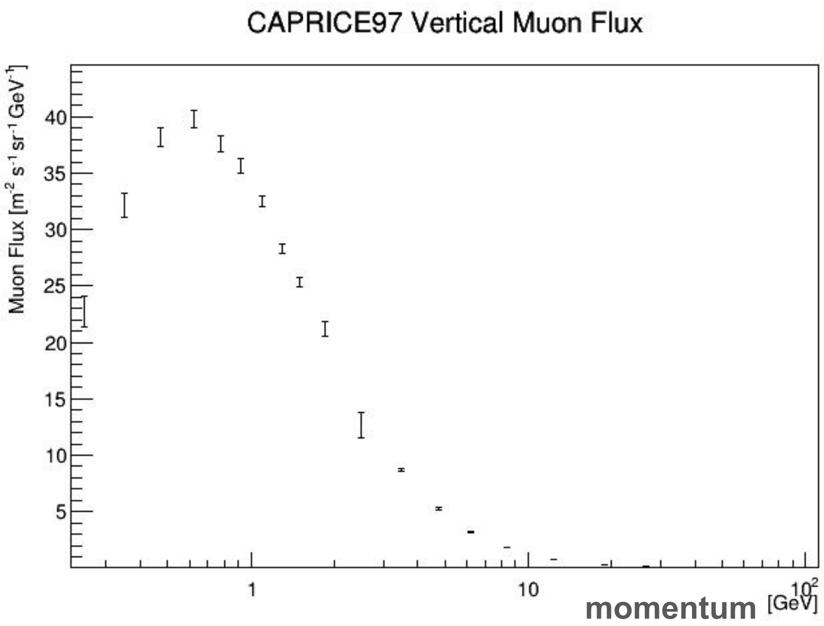
Slant depth

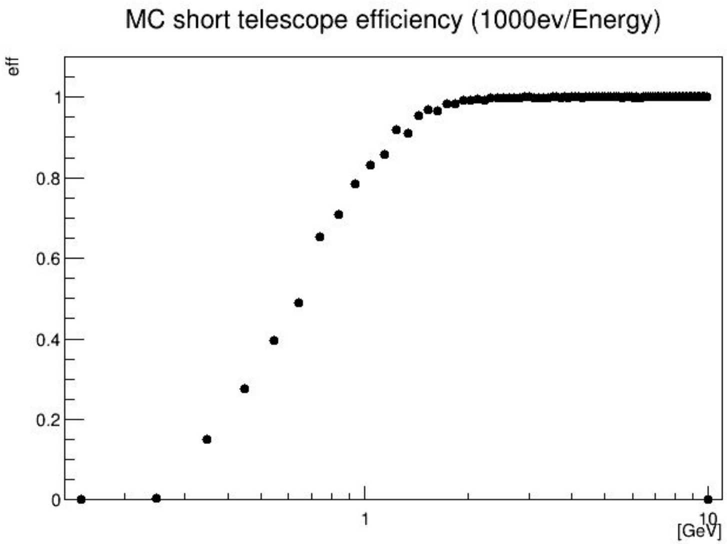
Calculation: 14 isobaric levels, ranging from 1000 to 1 hPa, with a spatial resolution of 0.25x0.25 degrees^2.

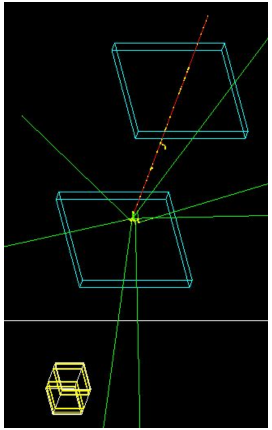


data: ERA5, European Centre for Medium-Range Weather Forecasts

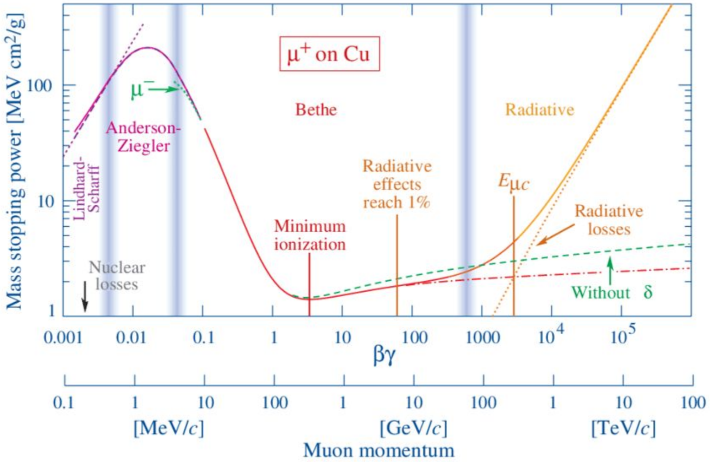
μ flux at the ground



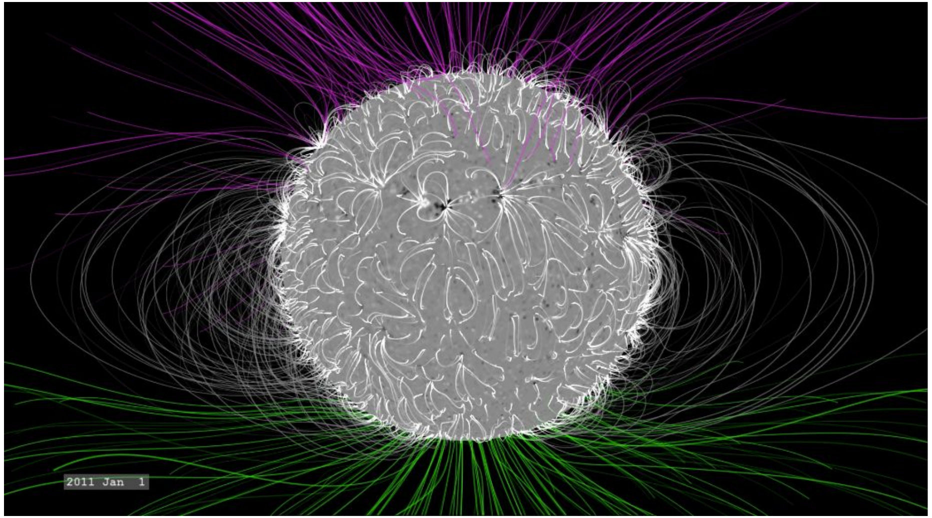


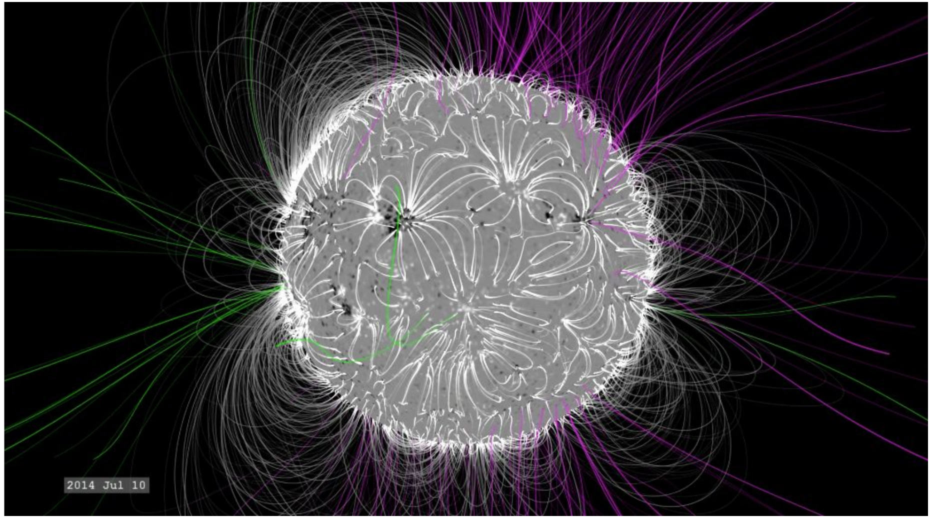


ground MIP μ E~4GeV have lost ~2GeV in the atmosphere



Sun B field

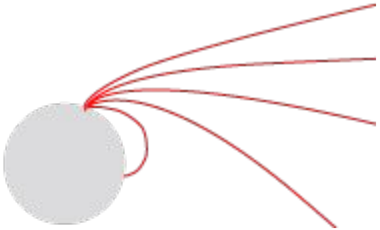


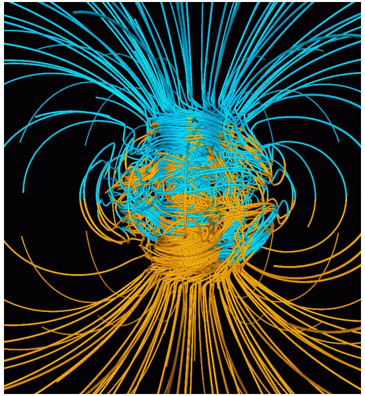


Earth B field

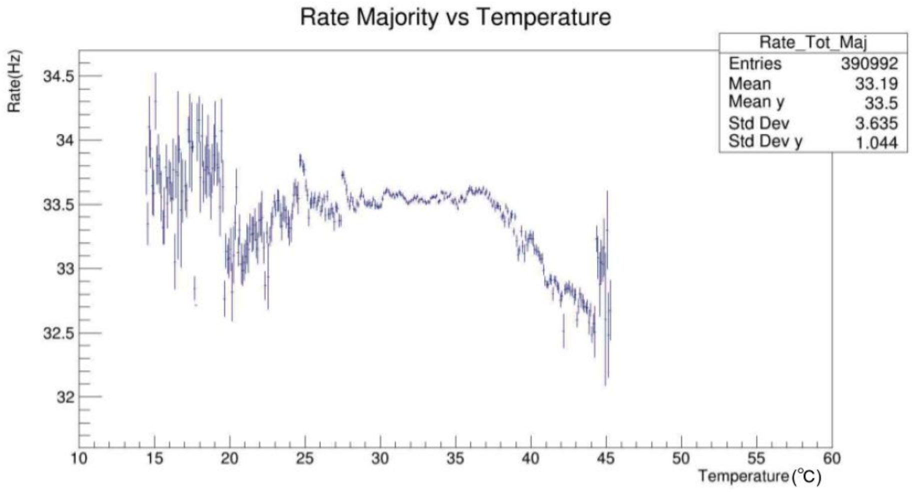
$$r_g = 3.3\,\mathrm{m} \times \frac{(\gamma mc^2/\mathrm{GeV}) \cdot (v_\perp/c)}{(|q|/e) \cdot (B/\mathrm{T})}$$

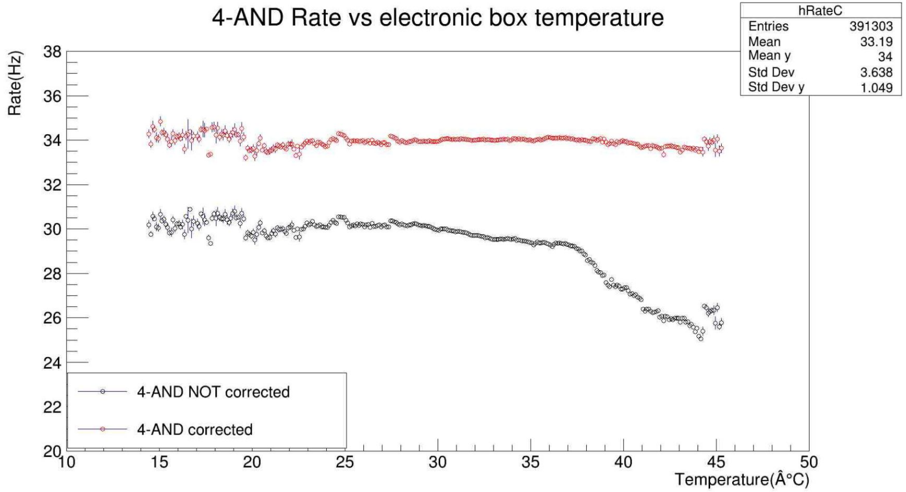
example: B ~ 50 μT
E = 1 GeV
r_g = 10 km

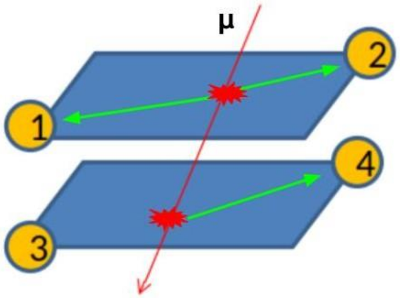


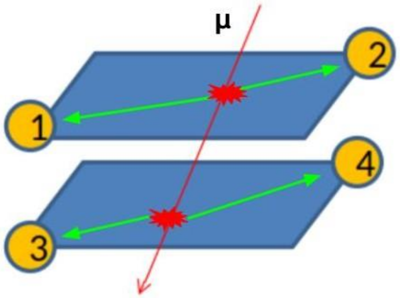


Trigger, pseudoefficiency, detector temperature



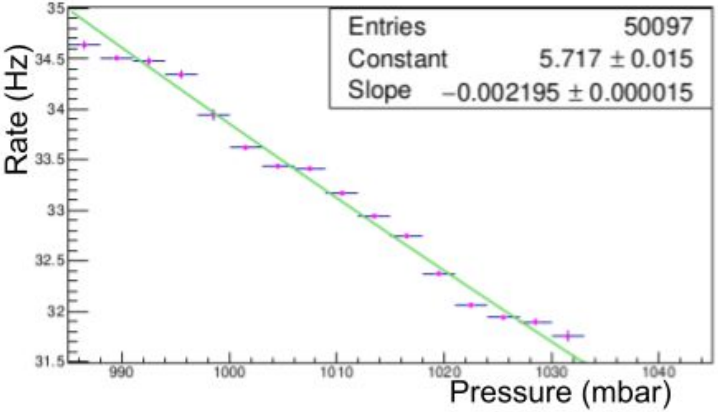


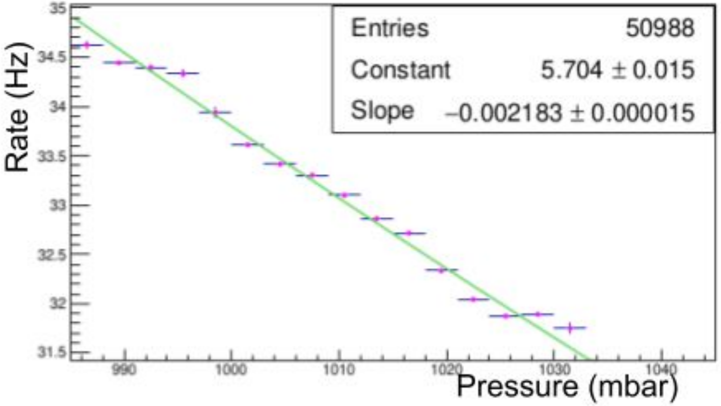


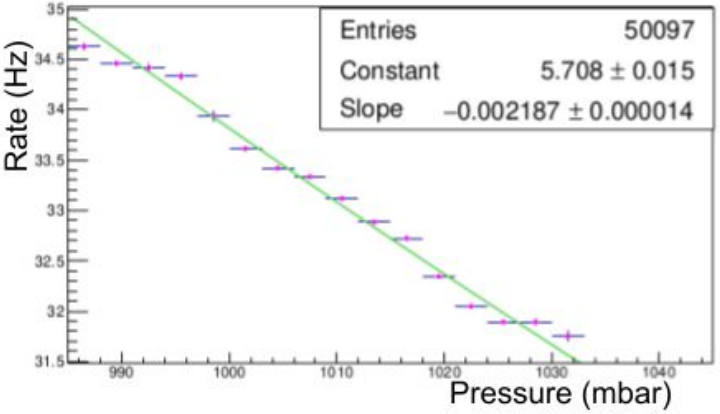


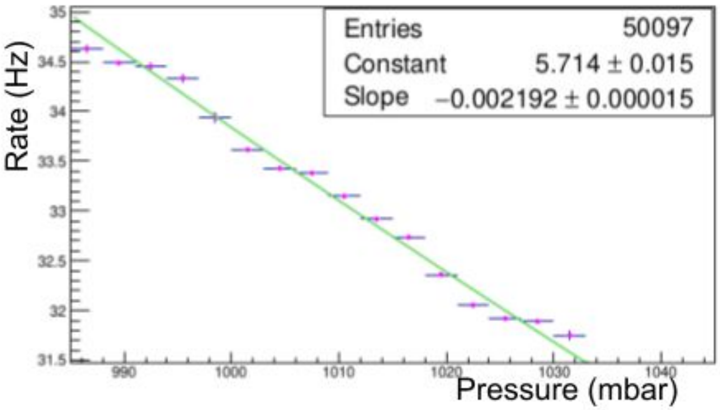
Barometric coefficient

$$\Phi = \Phi_0 \ \exp[\beta(p - p_0)]$$

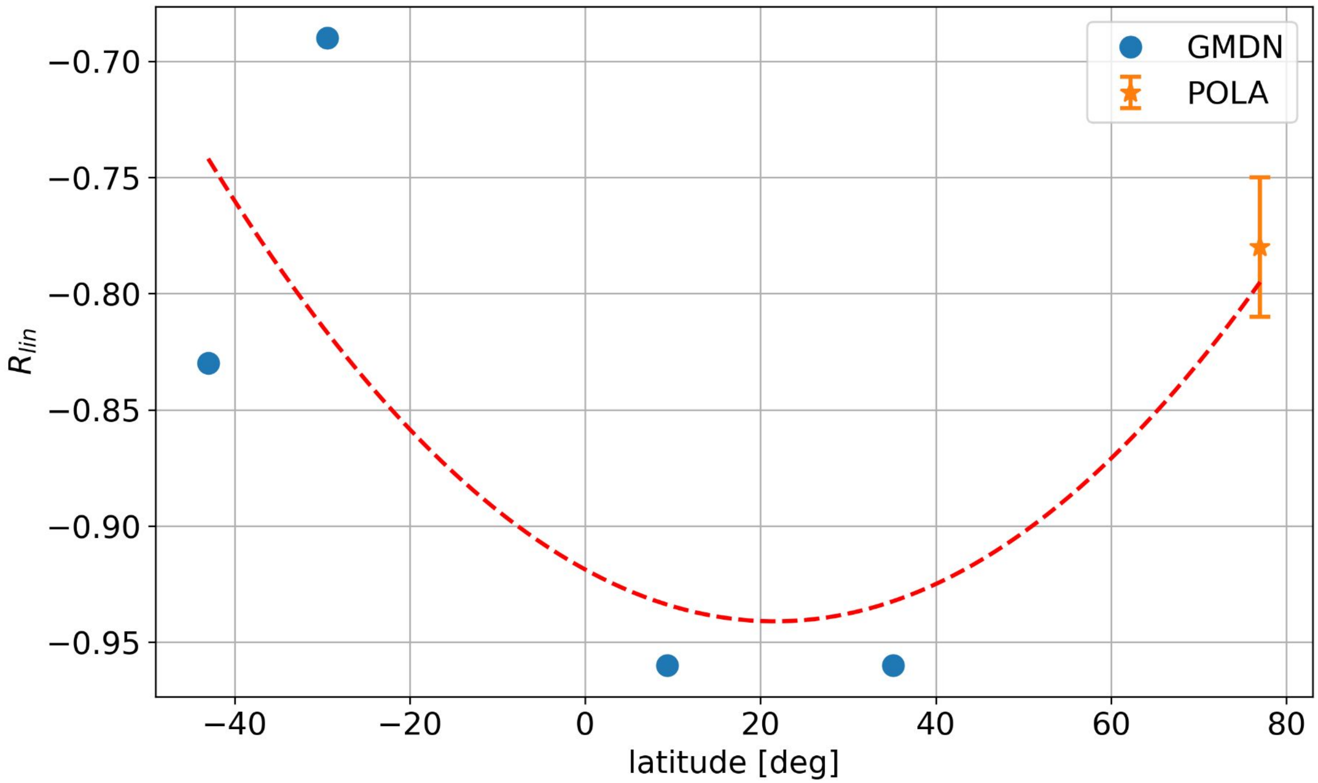


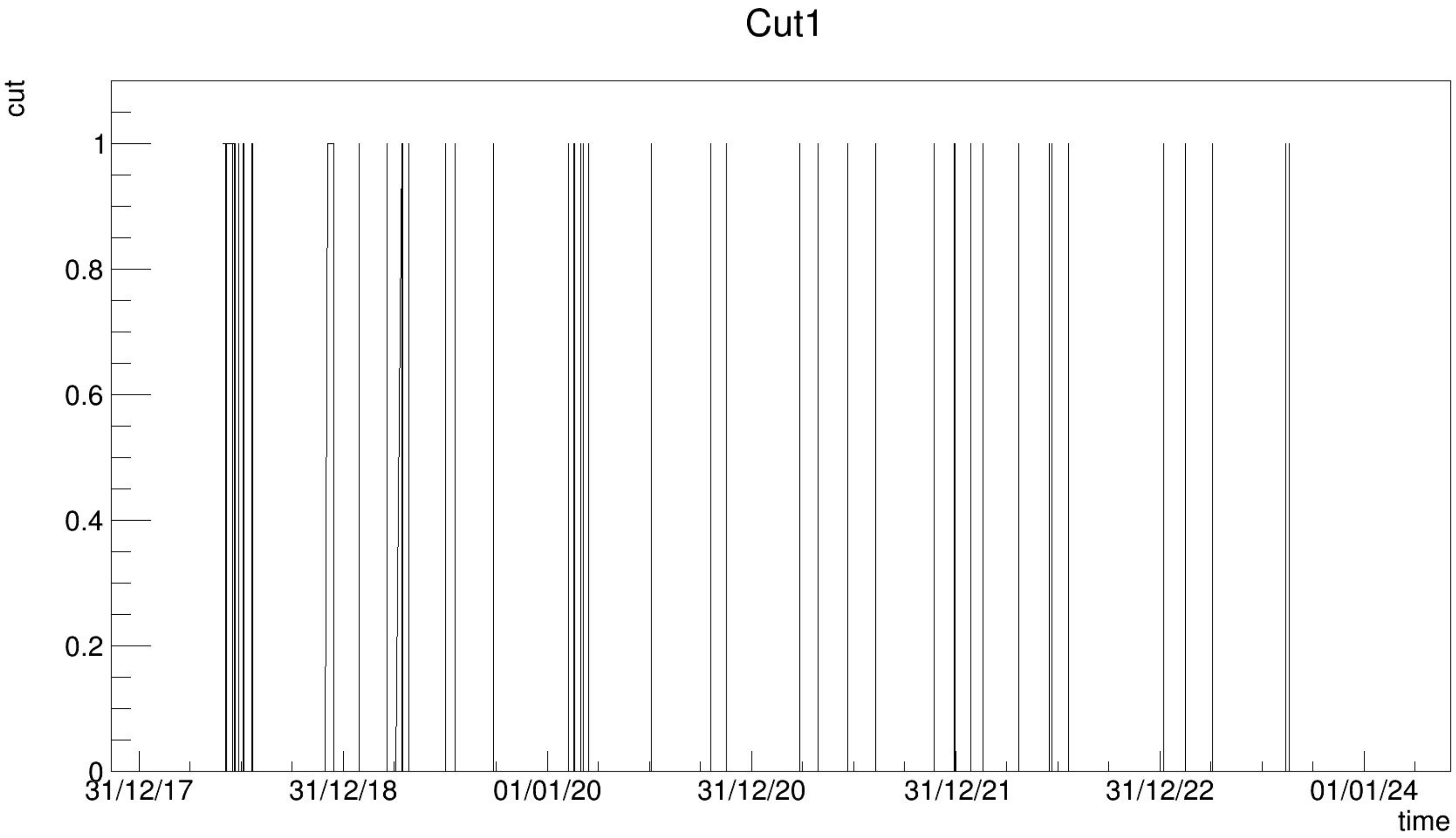






R and latitude





Cut1
cut
1
0.8
0.6
0.4
0.2
0
31/12/17
31/12/18
01/01/20
31/12/20
31/12/21
31/12/22
01/01/24
time