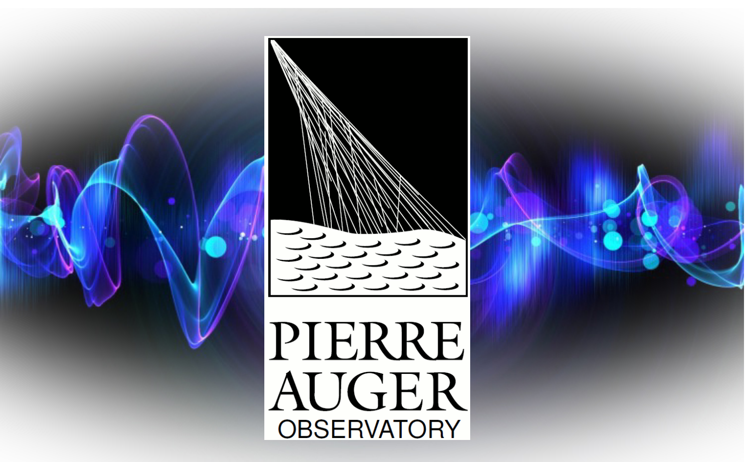
Radio detection at the Pierre Auger Observatory

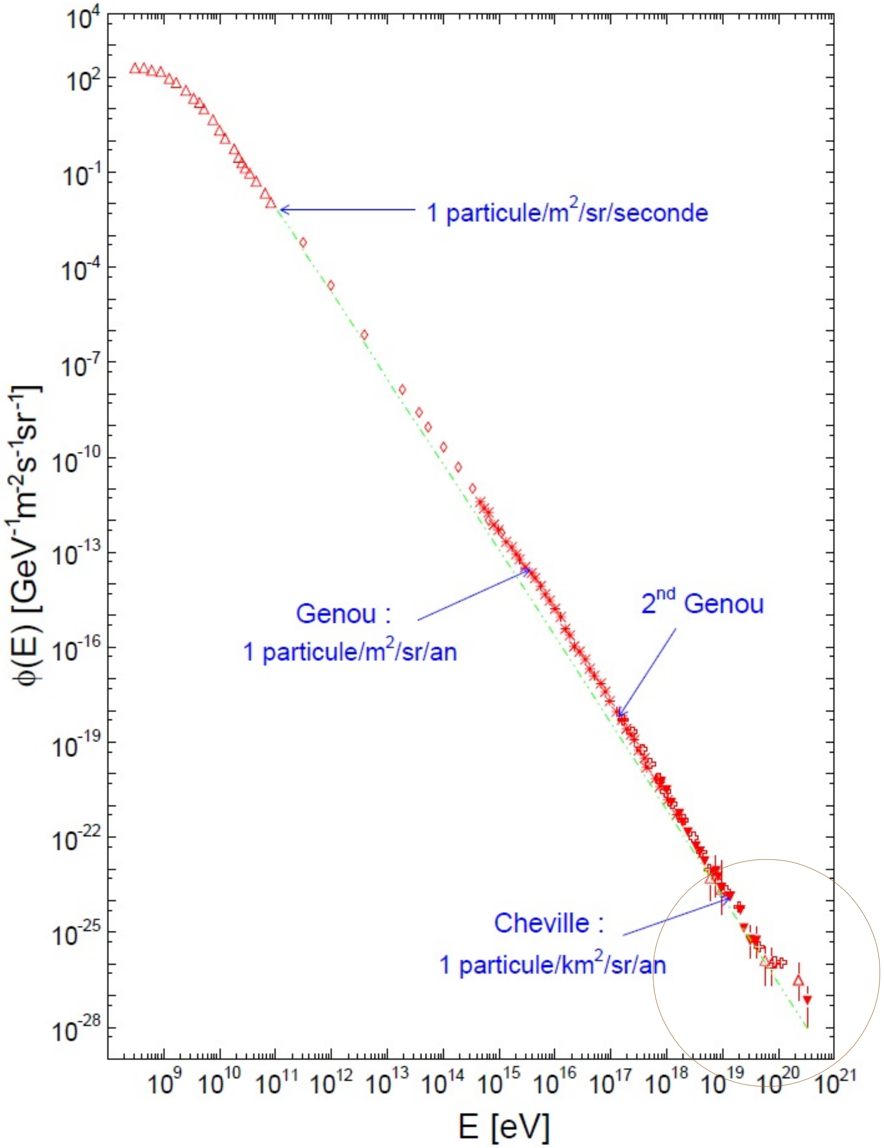


I. Air Showers and Cosmic Rays
II. Pierre Auger Observatory
III. Radio detection
IV. EASIER GHz
V. Interpretation

Le Coz Sandra, LPSC, 28.05.2013

Ultra High Energy Cosmic Rays

Cosmic Rays differential flux ∝ $E^{-\alpha}$



Ultra High Energy Cosmic Rays (UHECR) $>10^{18}$eV

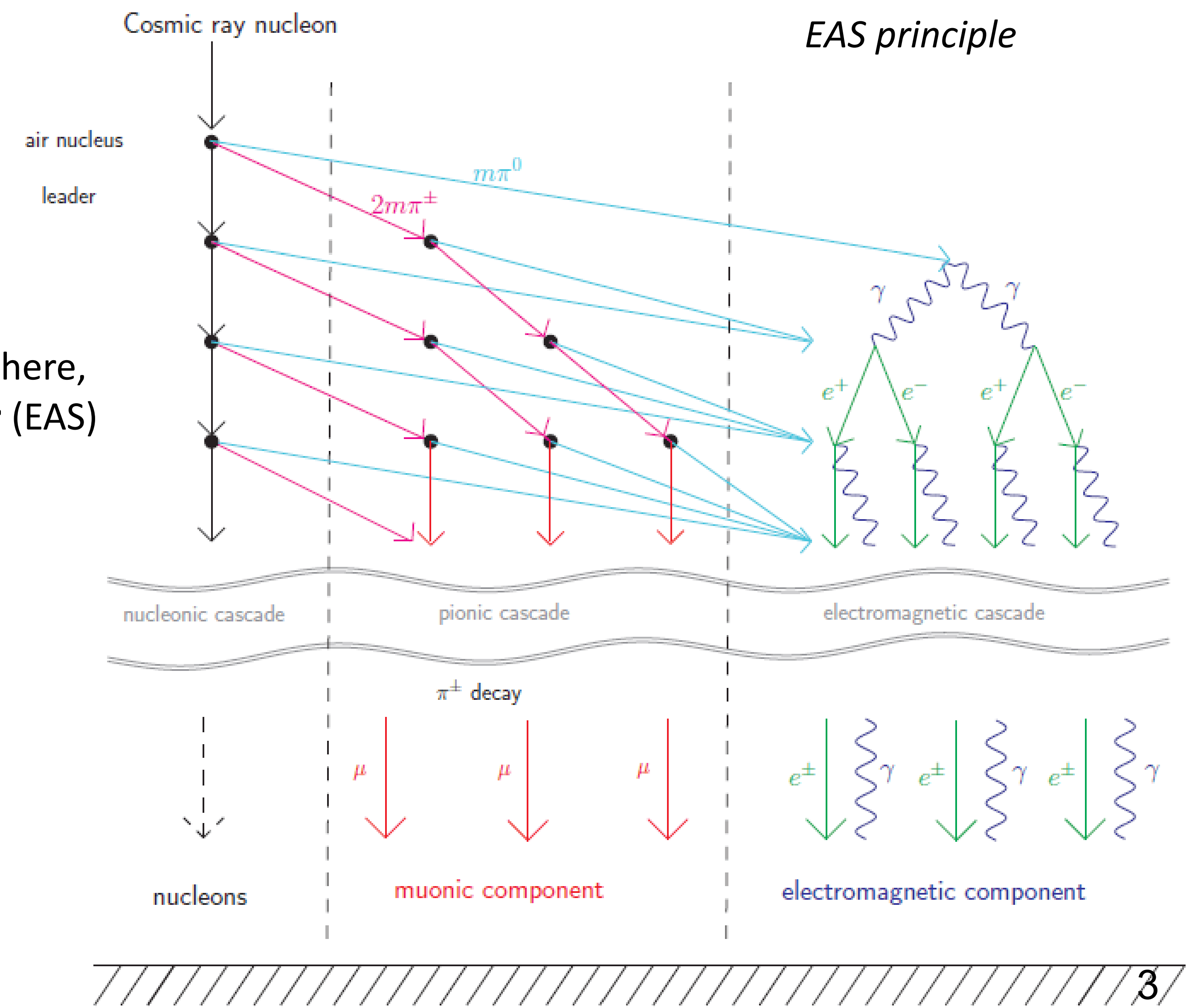
•On Earth, UHECR flux is ~1/km²/year above 10^{19} eV
•How cosmic rays may be accelarated to these extreme energies unreachable on Earth ?

→ A giant ground-observatory is needed

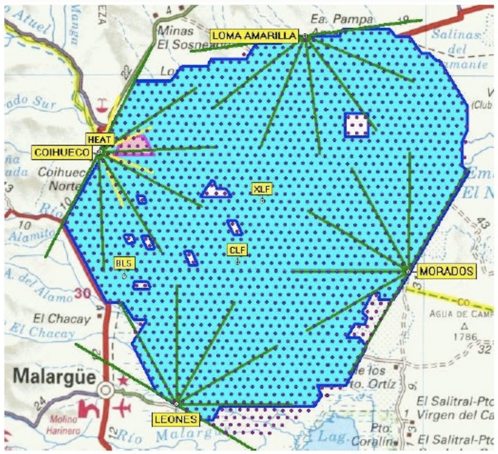
Extensive Air Shower

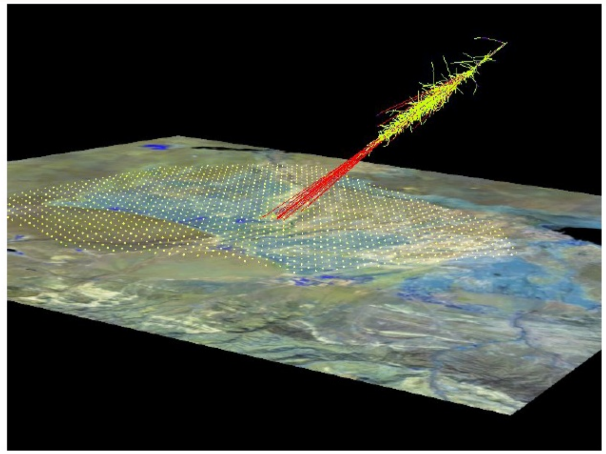
UHECR interact with the atmosphere, producing **Extensive Air Shower** (EAS)

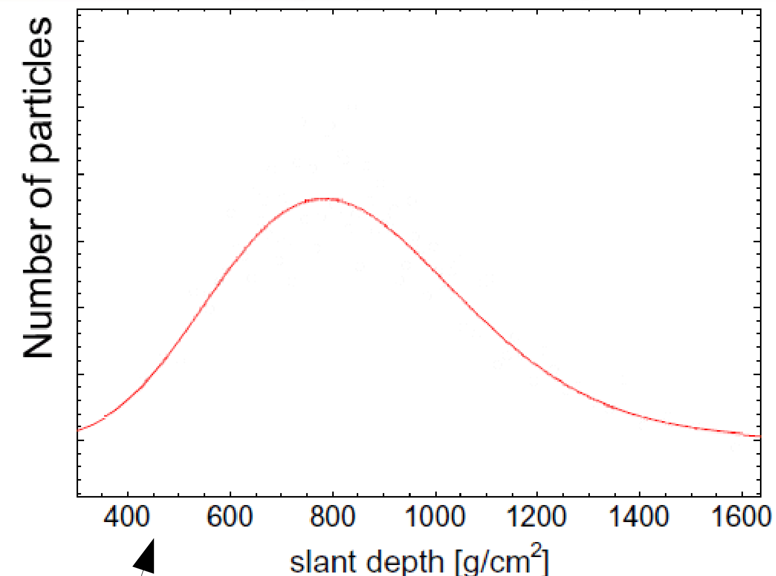
→ This observatory indirectly detects UHECR via EAS



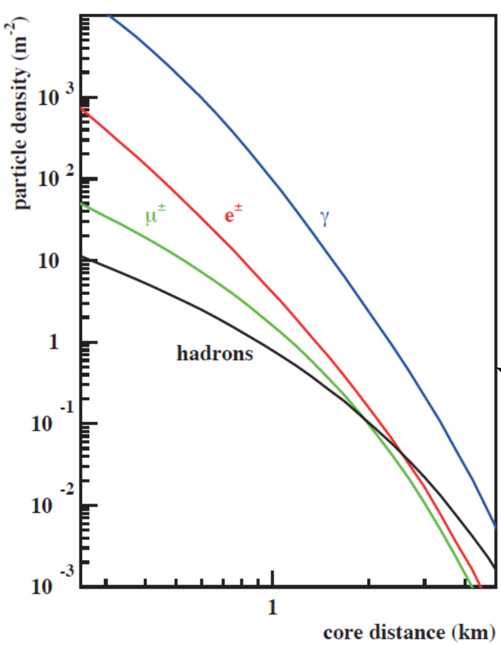
Pierre Auger Observatory

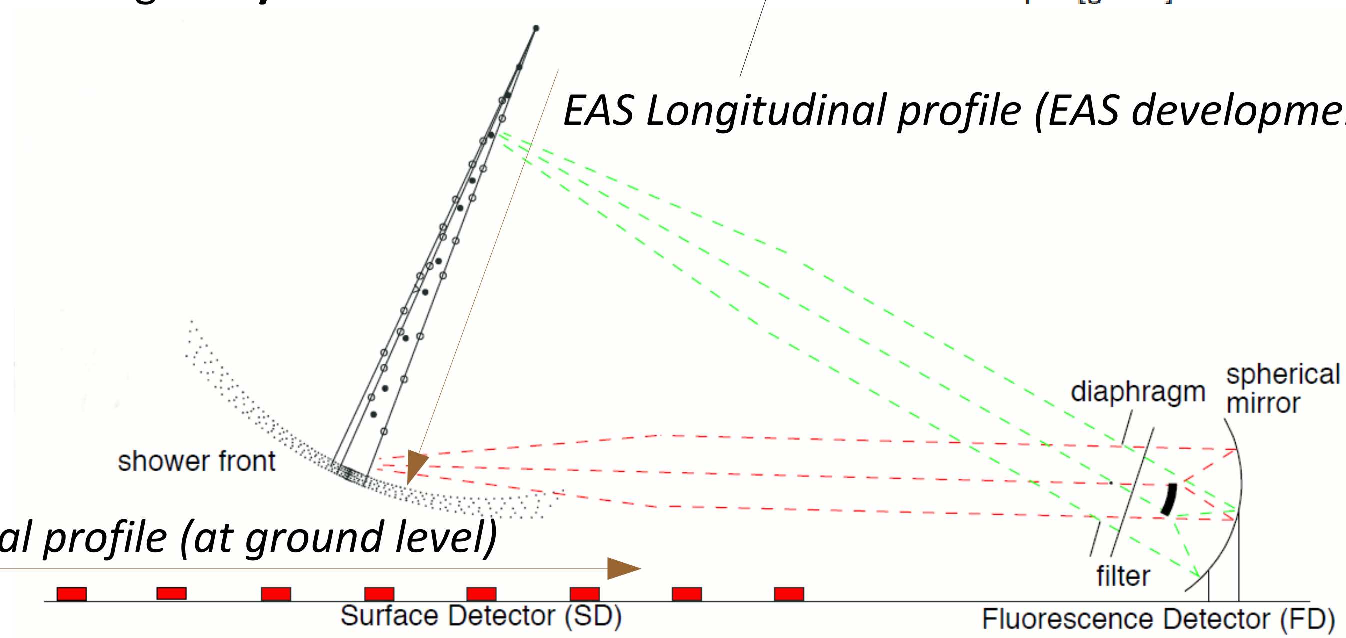






3000km² in Argentina. Installation started in 2004, completed in 2008. Study of EAS using an **hybrid** detector.





EAS Longitudinal profile (EAS development)

EAS
Lateral profile (at ground level)

Pierre Auger Observatory

Detectors

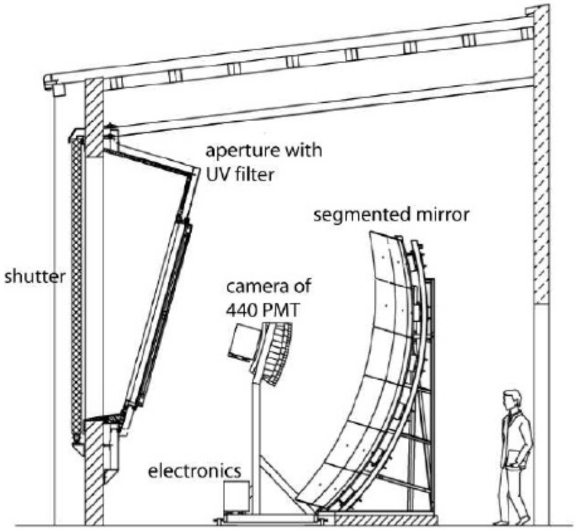
Fluorescence Detector (FD)

•Detects the fluorescence light (in UV range) coming from the desexcitation of the air-N_2, which is excited by EAS e^-

•27 fluorescence telescopes surrounding

•~13% duty cycle (clear moonless nights)

→ Provides the **longitudinal profile** of the EAS used to infer **energy** and **mass composition** of the UHECR



Surface Detector (SD)

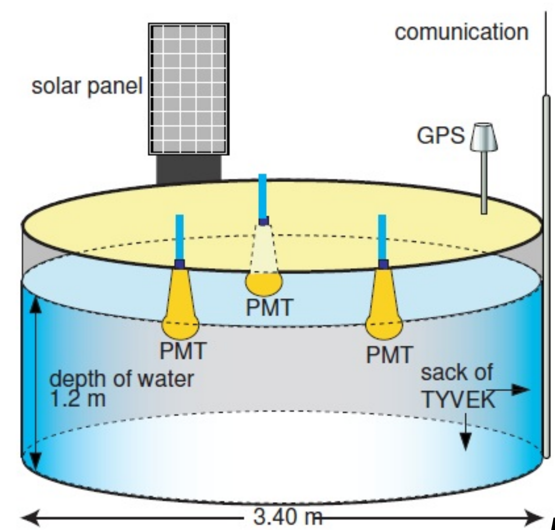
•1660 stand-alone water-Cerenkov tanks, 1,5 km spacing

•Samples the μ,e and γ of the EAS reaching the ground

•~100% duty cycle

→ Reconstruction of the EAS **direction** using the particles arrival time

→ Estimation of the UHECR **energy** using the **lateral profile** and an absolute calibration provided by the hybrid events (SD+FD)



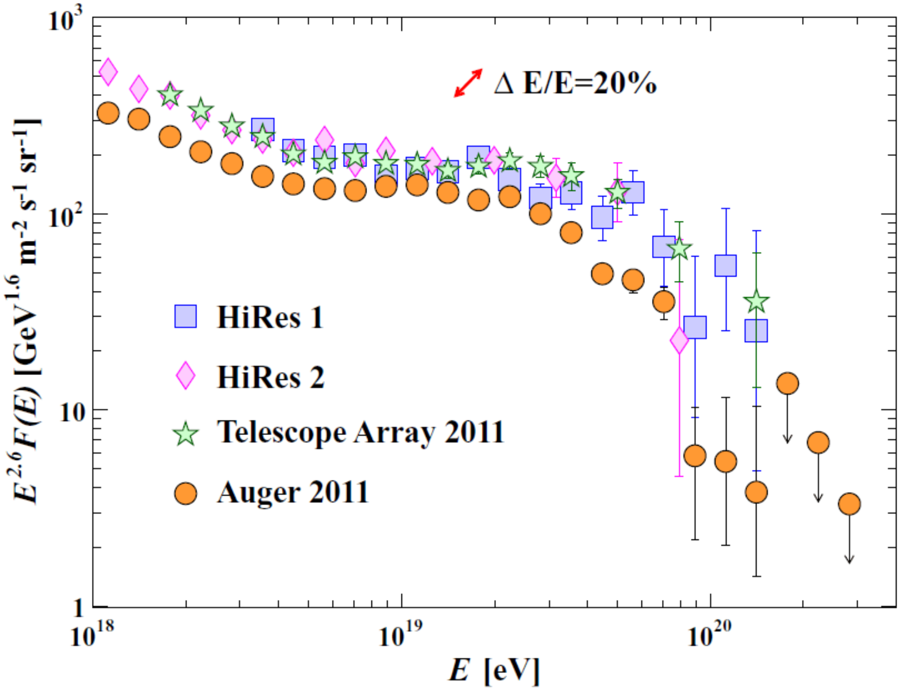
Pierre Auger Observatory

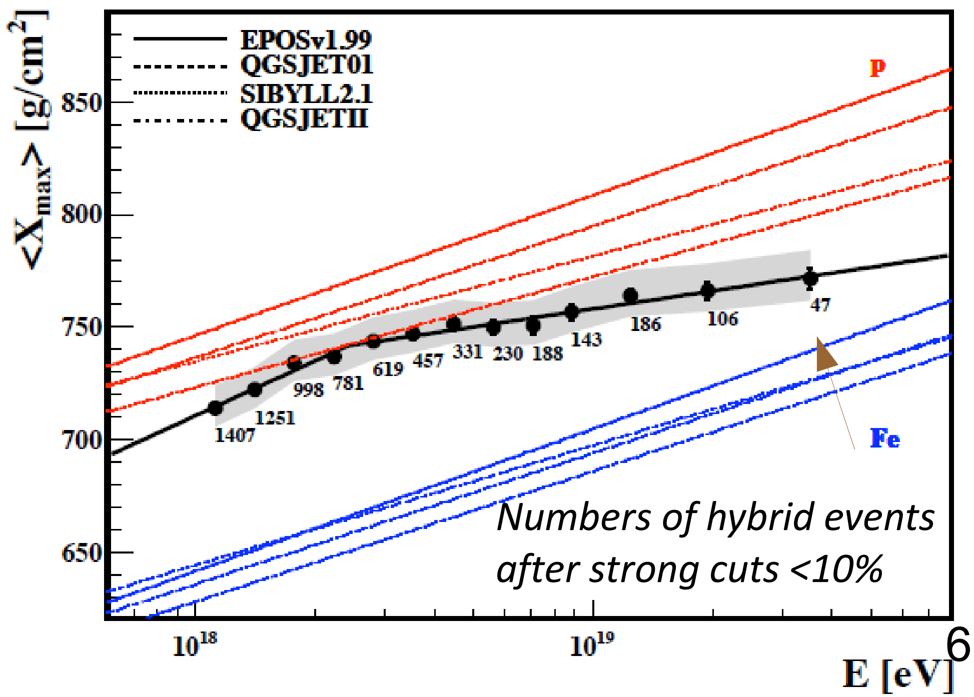
Some results

UHECR energy spectrum → confirmation of a cutoff at 5 10^{19} eV, explained by the GZK effect (UHECR interacts with CMB, and lose a part of its energy) or by the limit of acceleration mecanisms

UHECR mass composition

- X_{max} = amount of atmosphere which is needed to reach the EAS maximum of development
- X_{max} is related to the mass, **using hadronic models and simulations**
- The FD provides the longitudinal profile → X_{max}
- Mass determination is **not possible event by event** because of EAS-development fluctuations.



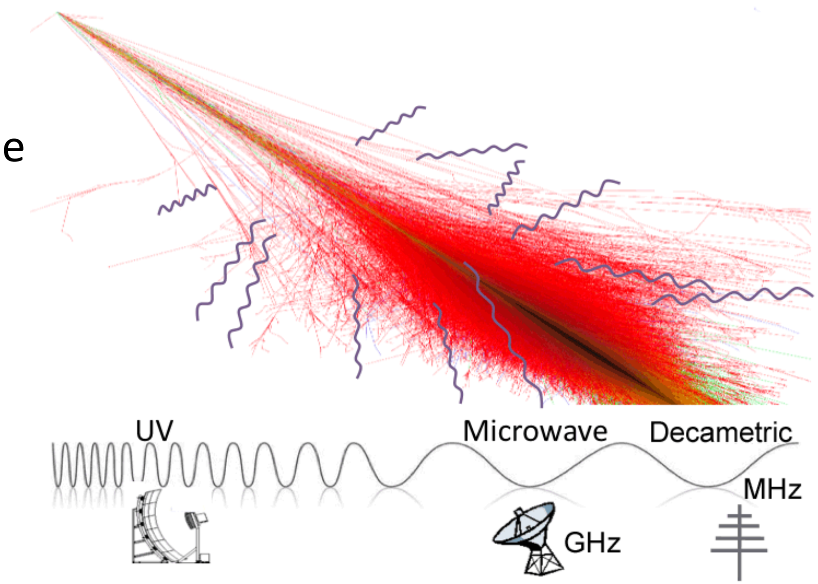


Numbers of hybrid events after strong cuts <10%

Radio detection ?

Looking for new observables related to mass composition

- To increase the amount of usefull data at higher energies
- To determine mass composition event by event



Fluorescence light is not the only EM emission related to the EM component of EAS → also radio emission (MHz & GHz)

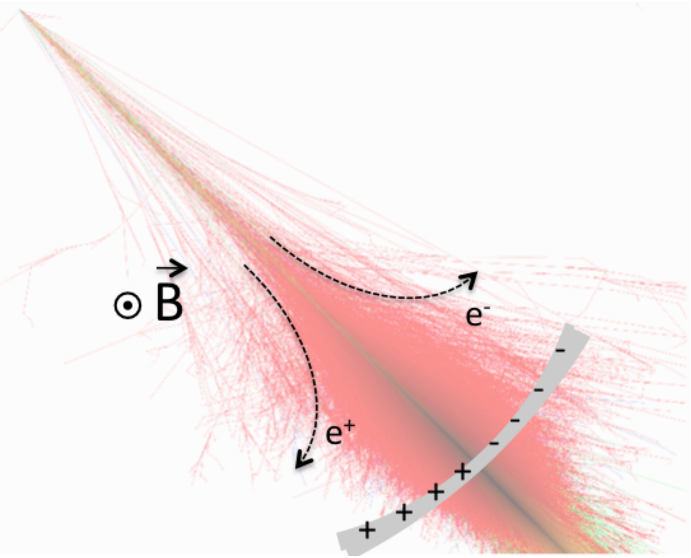
Advantages of radio detection

- 100% duty cycle
- ~no attenuation in atmosphere
- May provide the longitudinal profile as FD does
- May be associated with SD data to determine mass composition event by event
- Potentially low cost (commercial equipment)

Physical processes in radio
Geo-synchrotron

Geo-synchrotron Radiations related to EAS were detected in the **MHz** range by a few experiments (CODALEMA, LOPES...).

Geo-synchrotron process
EAS e^-/e^+ are deflected by the Earth magnetic field (e^+ and e^- in opposite ways)
→ Geo-synchrotron production (toward the ground, according to the EAS-axis)

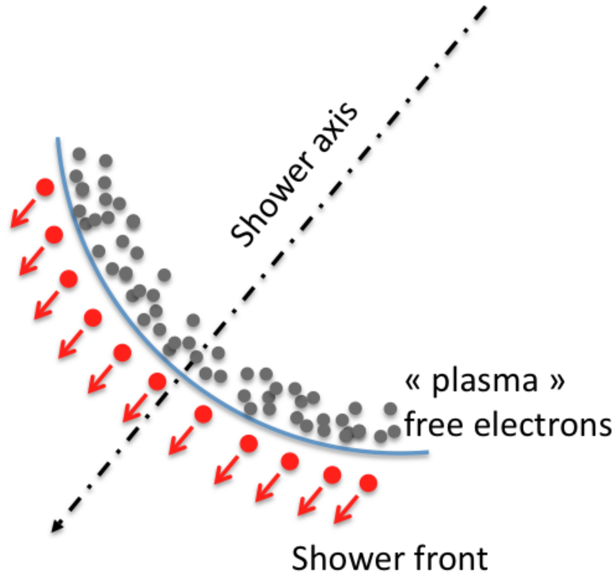


Geo-synchrotron is fonction of
•EAS-energy
•The norm of **EAS-direction** X **B-direction**

Physical processes in radio
Molecular Bremsstrahlung (MBR)

GHz emission were detected at **SLAC**, in a GeV electron beam experiment simulating a part of EAS. This emission was interpreted as Molecular Bremsstrahlung Radiations (MBR).

MBR process
EAS e^- ionize the air-molecules, making ions and low-energy electrons
→ the resulting low energy-electrons are scattered by the neutral air-molecules
→ MBR production (isotropic and unpolarized)



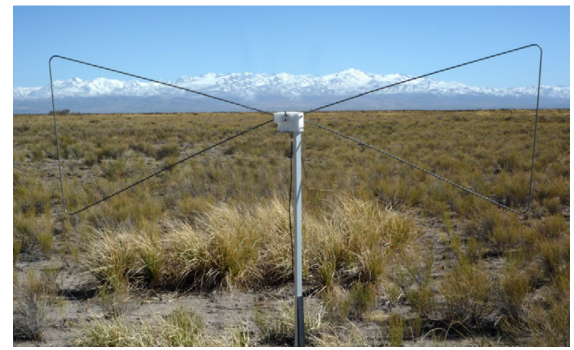
MBR is fonction of
•EAS-energy
•Air-molecules density

EASIER

Set up

R&D

Power supply, trigger & data acquisition from SD, replacing 1PMT→ slave mode

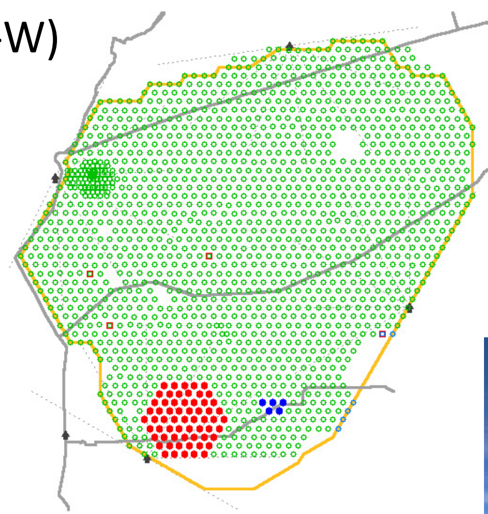


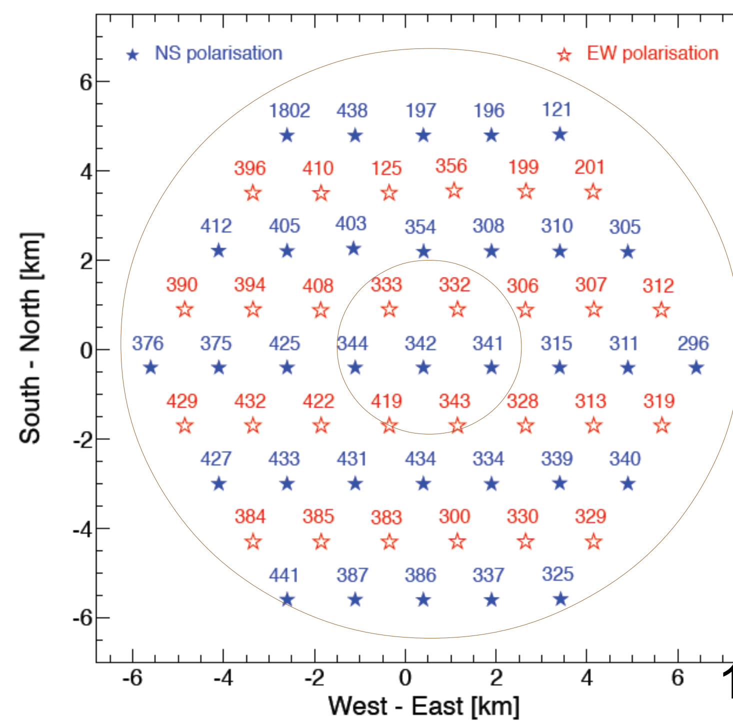
MHz (30-60 MHz)

March 2011 & Nov 2011, dipolar antennas

Feb 2103, butterfly antennas

Single-polarized (E-W)





GHz C-band (3.4-4.2 GHz)

April 2011, 7 feed horn antennas

April 2012, 61 feed horn antennas

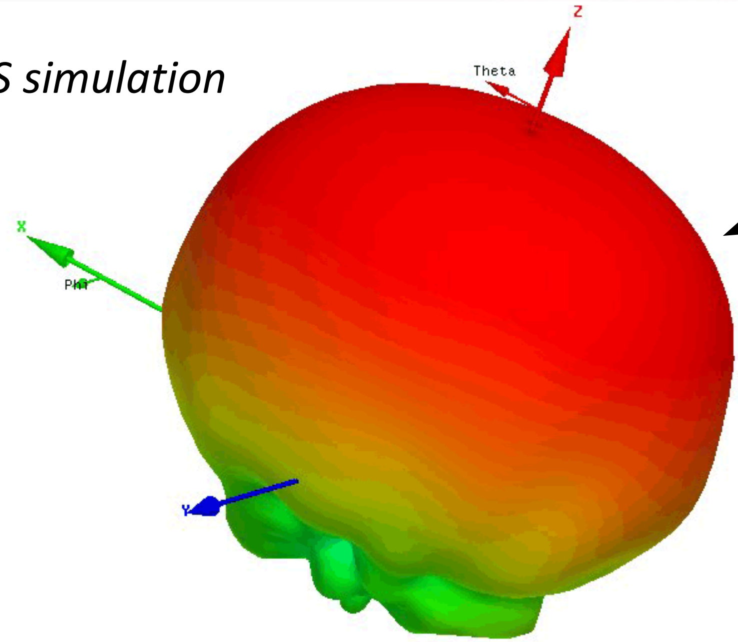
Single-polarized (28 E-W and 33 N-S)

<u>→ Next parts will be focused on EASIER GHz</u>

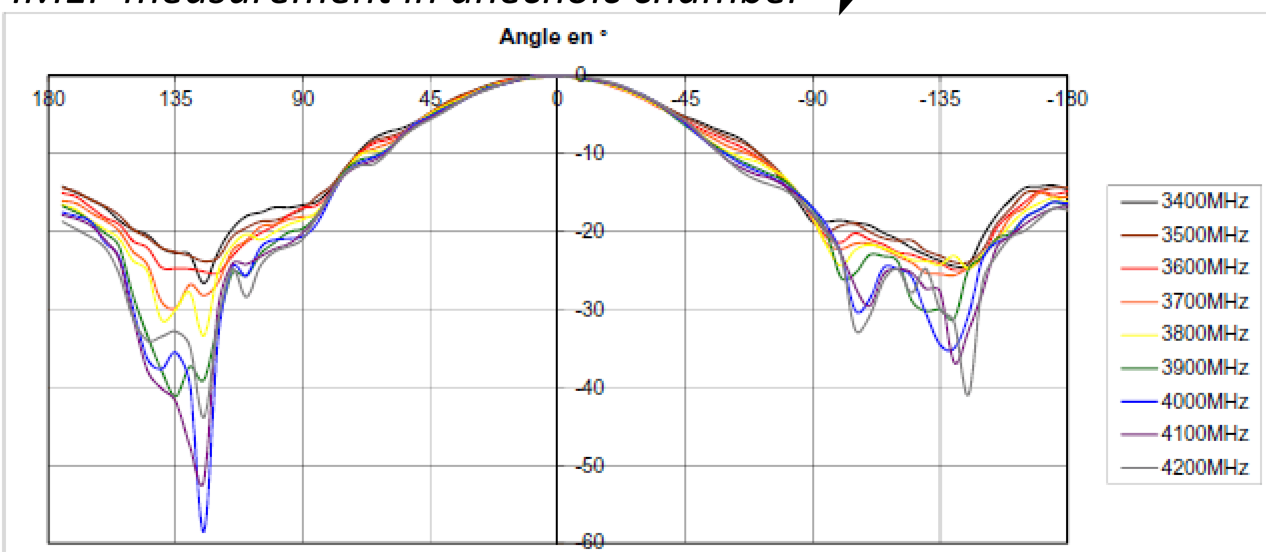
EASIER GHz

Radiation pattern and effective area

HFSS simulation



IMEP measurement in anechoic chamber



Antenna radiation pattern

$D(\theta,\varphi,\nu)$ (normalized to 0 dB)

60°x60° FoV, (sky-faced)

Antenna effective area

$A_{eff}(\theta,\varphi,\nu)$ $= \lambda^2/4\pi * D(\theta,\varphi,\nu) \sim= 10^{-3} m^2$

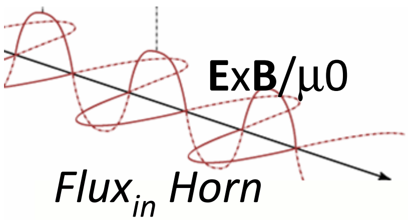
Antenna received power

P_{out}Horn $= A_{eff}(\theta,\varphi,\nu) * Flux_{in}$Horn

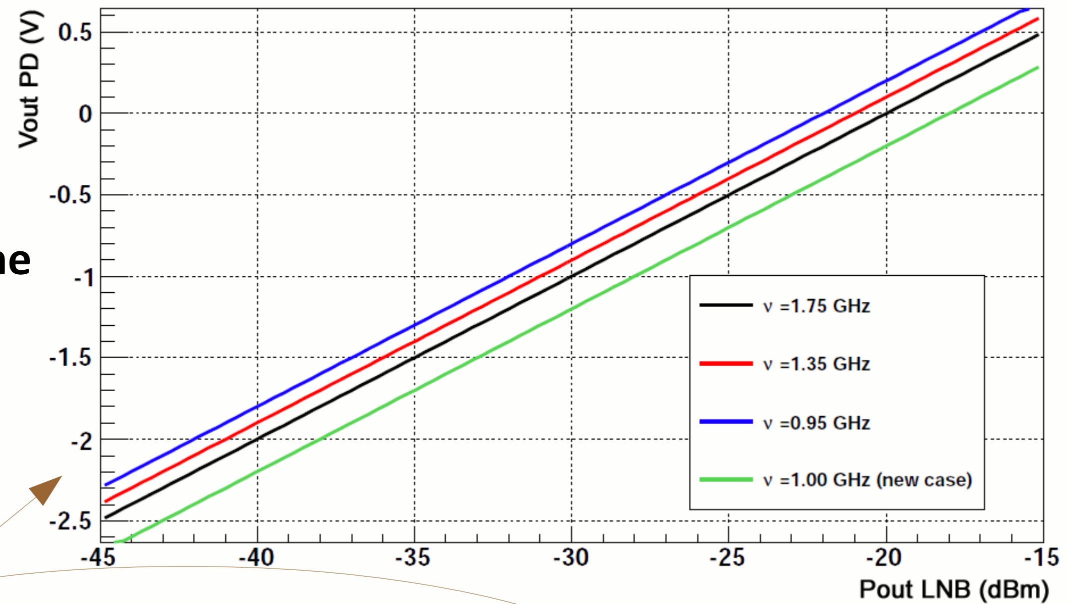
EASIER GHz

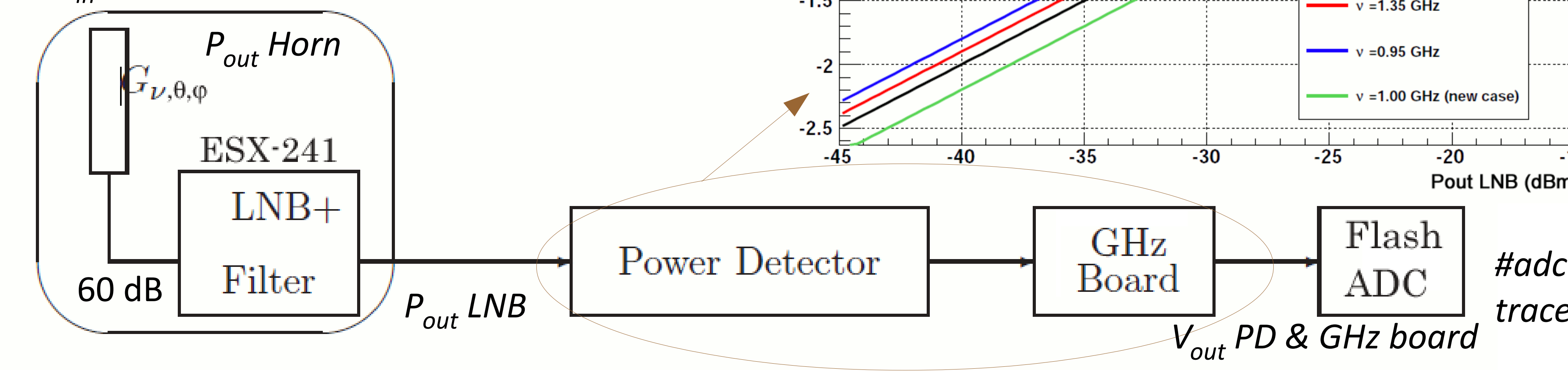
Active antenna - Calibration

SLAC beam experiment → wait for ~1 pW signal
→ detection range 10^{-10} to 10^{-8} mW

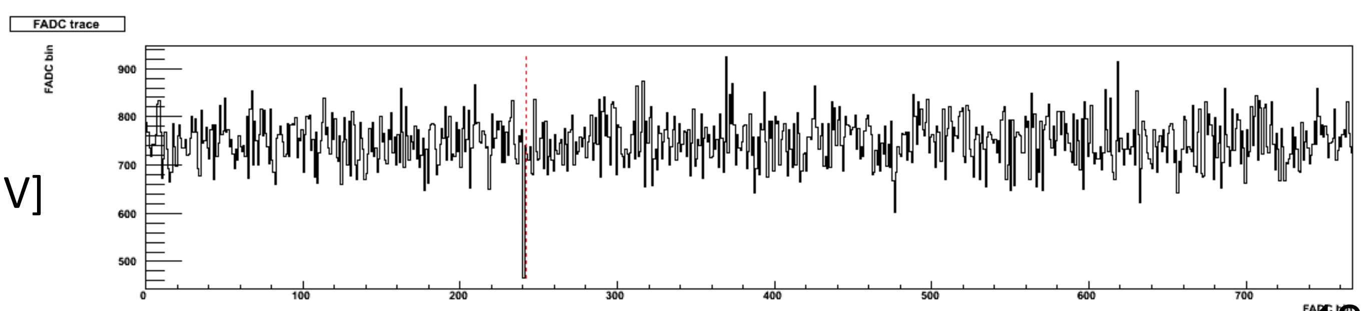


Electronic chain to adapt the antenna to the tank FADC



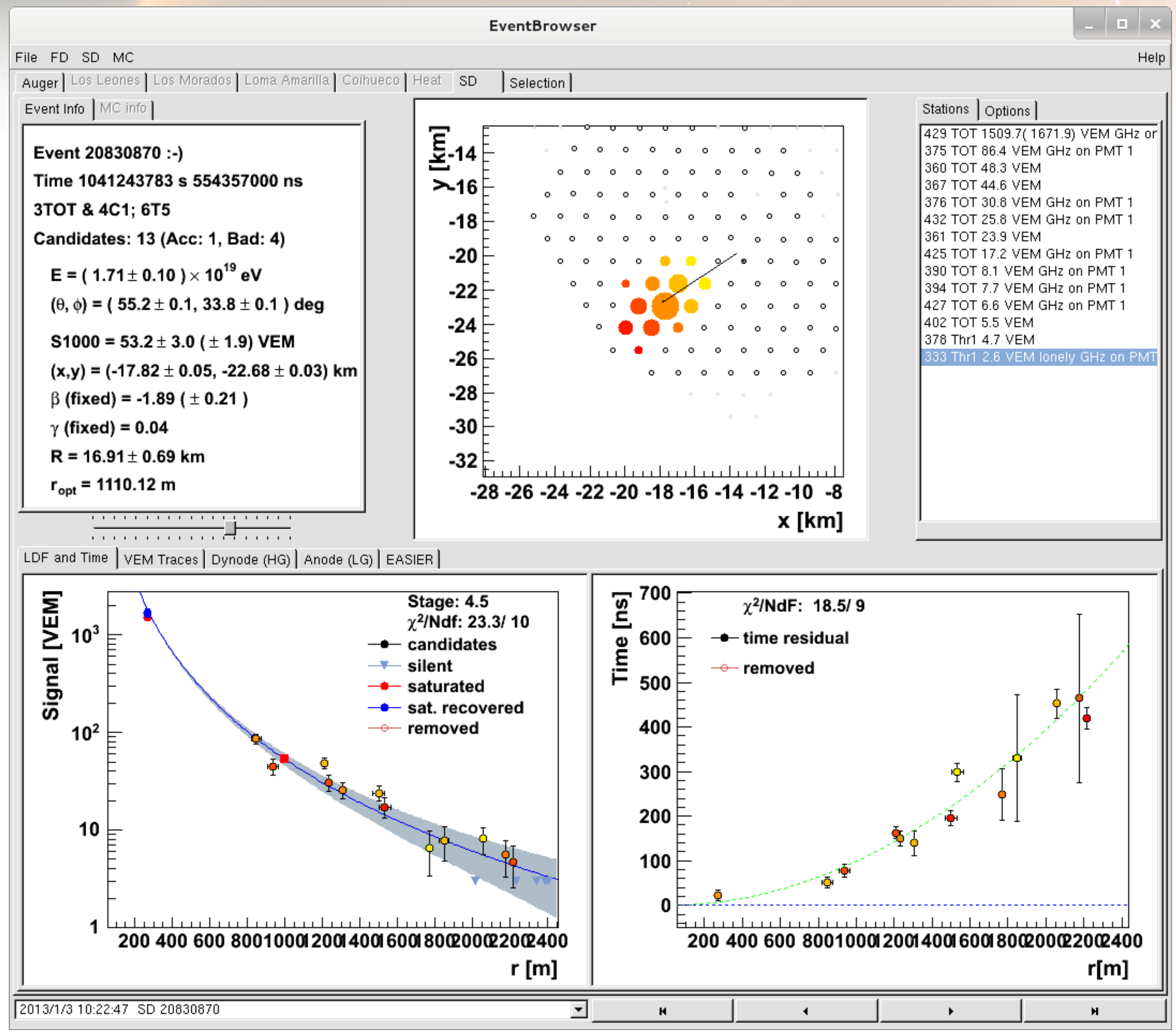


- P_{out} Horn [-100;-80 dBm]
- P_{out} LNB [-40;-20 dBm]
- V_{out} PD & GHz board [-1,93;0,1 V]
- Flash ADC [1023;0 bins]



EASIER GHz

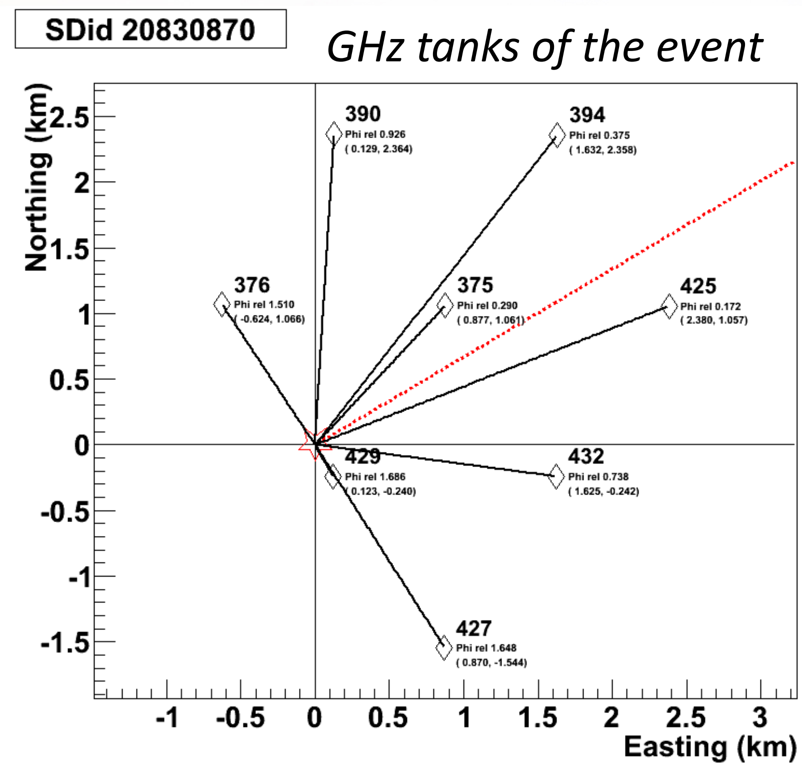
Data



Event Browser

ROOT

GHz tanks of the event

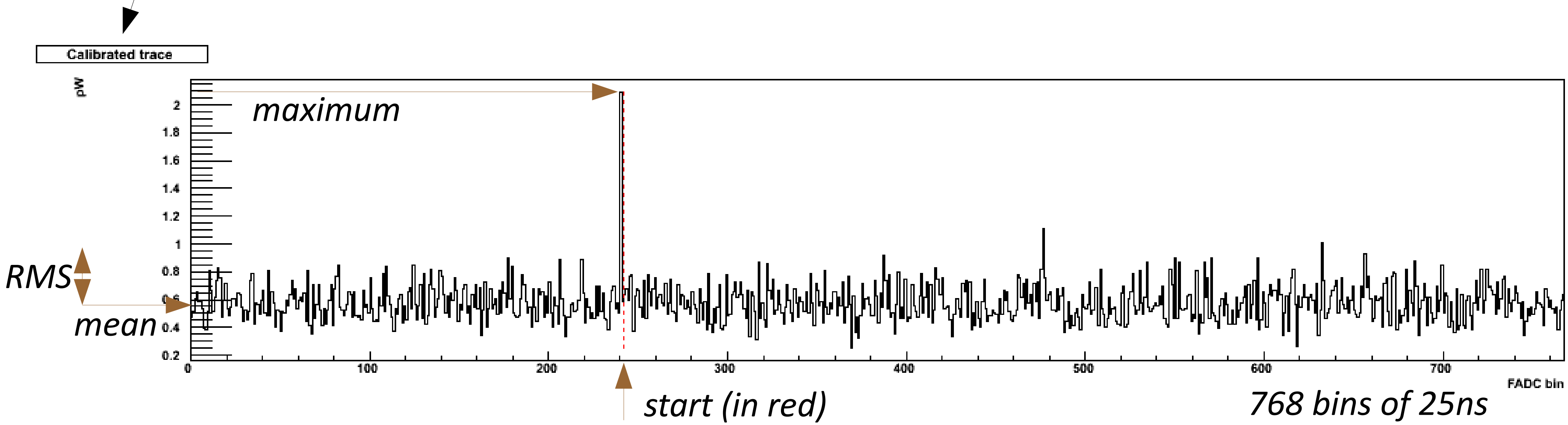


Each time a tank with a GHz antenna is reached by EAS-particles, the antenna signal is recorded.

For each EAS event, reconstruction of

- EAS (UHECR) **energy** and **direction** : zenith (angle from vertical), azimuth (angle from East)
- **Distances** between EAS and antennas

- Calibration of traces (#adc to pW)



For each calibrated trace, calculation of

- The **mean** power (baseline)
- The **RMS** (standard deviation)
- The **maximum** power above the baseline
- The **time to start** position of the maximum (start is when the EAS-particles reach the tank)

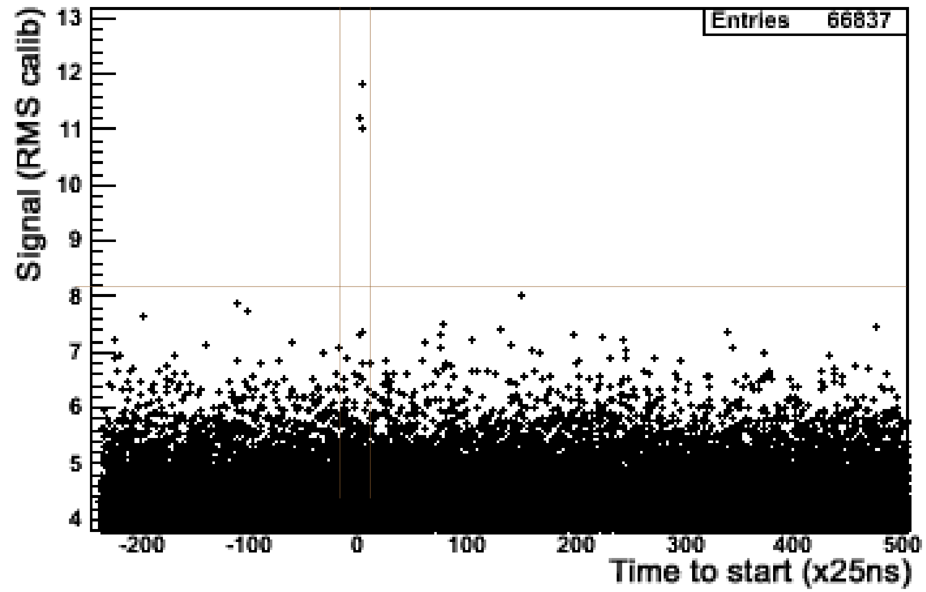
Maxima in RMS unit VS Time to start

Strong cuts (to be sure that the signal is not noise)

•Time to start [-4;1]

•Maximum in RMS unit > 8

→ Three 11-RMS events

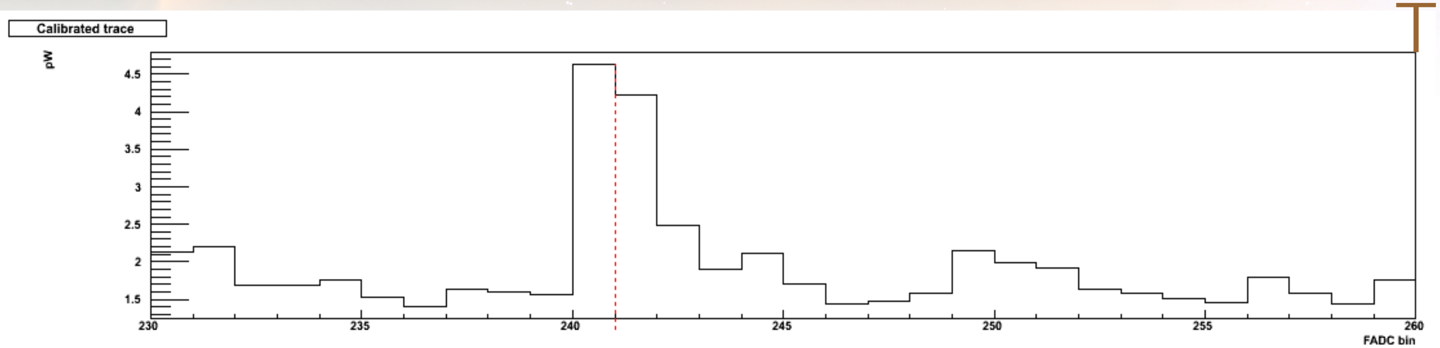


Caracteristics of the 3 events

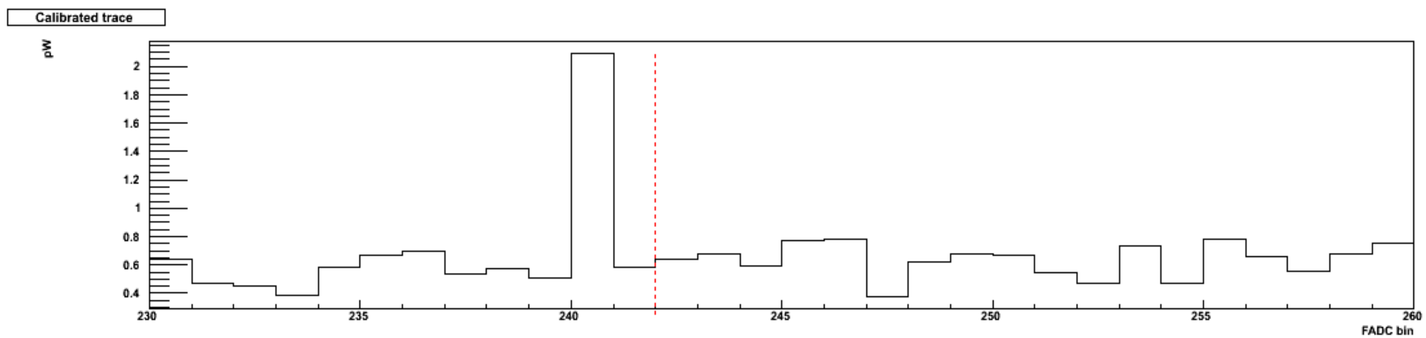
N°SD	Max (RMS)	Time to start (bins)	Energy (eV)	Zenith°	Azimuth°	Distance to EAS	Polar
342	11,7	-1	$1,3\ 10^{19}$	30	343	136m	EW
429	11,2	-2	$1,7\ 10^{19}$	55	33	269m	EW
306	11,1	-2	$2,6\ 10^{18}$	47	290	193m	EW

EASIER GHz

The 3 events signals

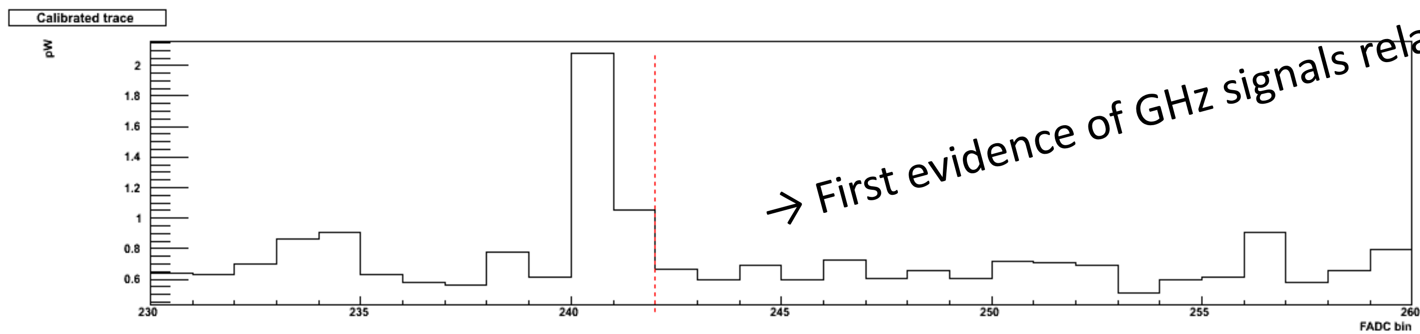


30.06.2011
Max = 2,9 pW
Σ(3bins)= 6,3 pW



03.01.2013
Max = 1,5 pW

→ First evidence of GHz signals related to a EAS → Is it MBR ?



07.02.2013
Max = 1,4 pW
Σ(2bins) = 1,8 pW

- Time-compression of signals (~50ns large) is due to the short distances to EAS (all the energy reach the antenna at ~the same time)
- More is the time-compression, better is the SNR, but worse is the EAS profile time-resolution
- Signal must be seen by several antennas the find the X_{max}, as the different PMT of FD do

Interpretation

MBR SLAC beam experiment

SLAC experiment parameters

- Energy of the beam — E_0 = 28 GeV . 1,2 10^7 e^- = 3,36 10^{17} eV
- Bandwidth of the antenna — $\Delta\nu_0$ = 2,5 GHz
- Lenght of beam (equivalent EAS) observed — L_0 = 0,65m
- Distance between the beam and the antenna — R_0 = 0,5m
- Density of the air (ground level) — ρ_0 = 1,2 10^{-3} g/cm^3

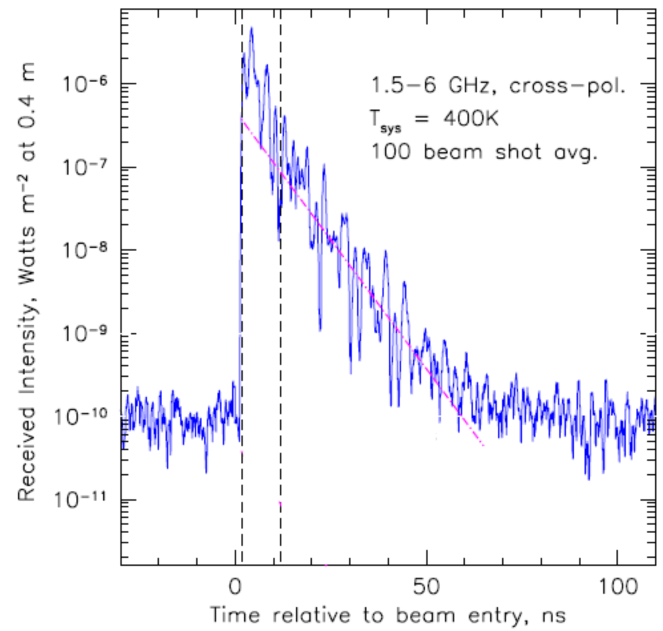
Results of the experiment

- Received power (W/m²)

$$P_r(t) = P_{r0} e^{-t/\tau}$$

with $P_{r0} = 10^{-6}$ W/m² and τ = 10 ns

Isotropic and interpreted as MBR



- Received energy $E_{SLAC} = \int P_r\, dt = \int P_{r0} e^{-t/\tau} dt = P_{r0}\tau$ = 10^{-5} J/m²

Interpretation

MBR SLAC extrapolation to real EAS

Numerical extrapolation to real EAS reaching EASIER antennas

•Received enery at **each simulation step** of any EAS

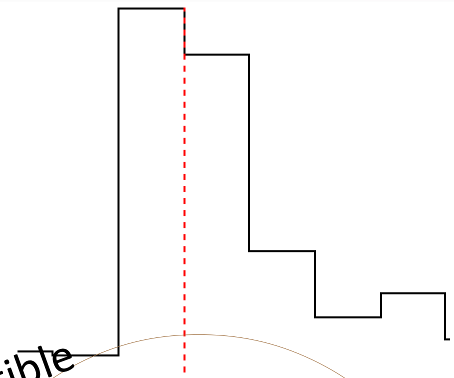
$$E_r(step) = E_{SLAC} \frac{E}{E_0} \frac{L}{L_0} \frac{\Delta\nu}{\Delta\nu_0} \frac{\rho^2(step)}{\rho^2_0} \frac{R^2_0}{R^2(step)} \times N_{norm}(step) \times A_{eff}(step)$$

•Each Er is propagated toward the antenna at the speed of light, according to **air refractive index** *n(h)*
•The final energy in each 25ns bin is the sum of Er that reach the antenna in the same 25ns interval

$$P(bin) = \frac{\Sigma_{bin} E_r(step)}{25\,ns}$$

Interpretation

MBR - Preliminary results

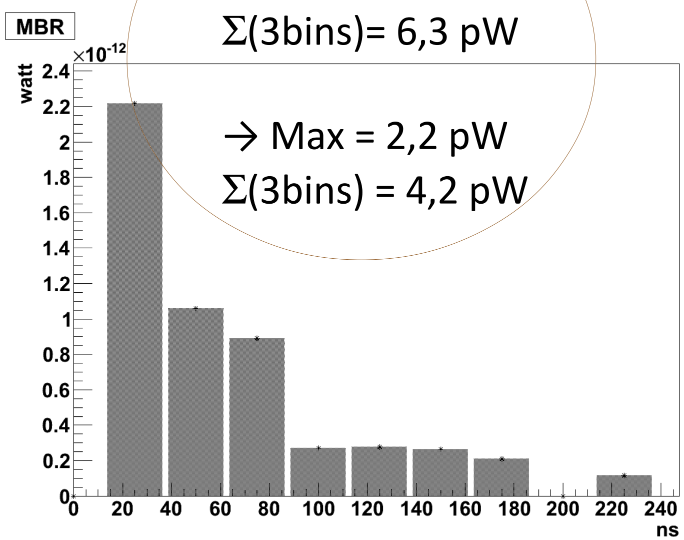


Compatible

30.06.2011

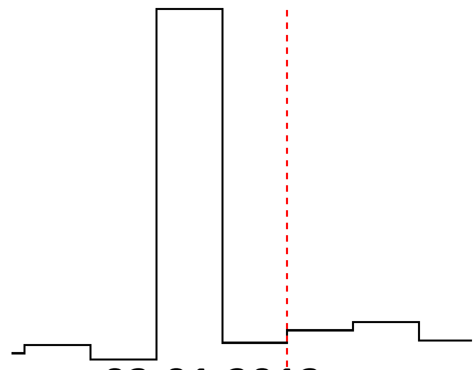
Max = 2,9 pW

Σ(3bins)= 6,3 pW



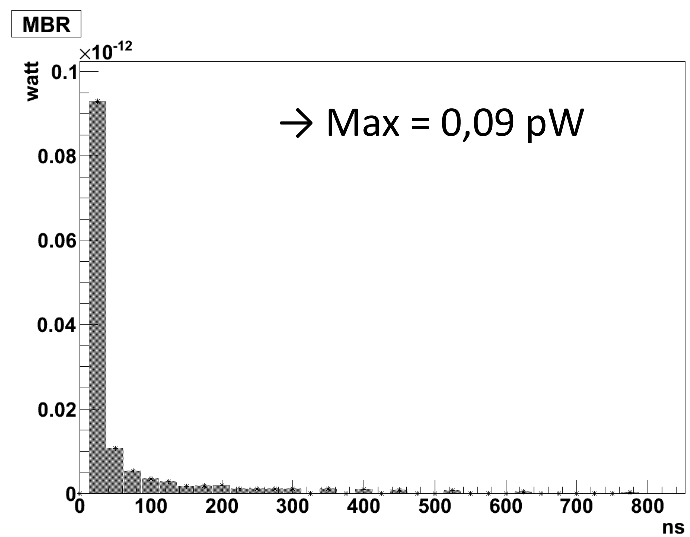
→ Max = 2,2 pW

Σ(3bins) = 4,2 pW

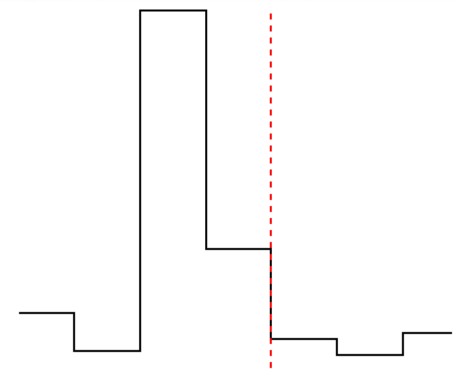


03.01.2013

Max = 1,5 pW



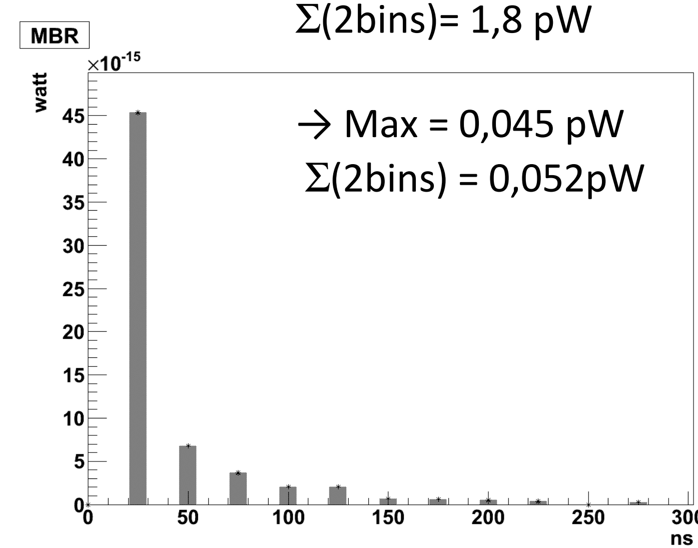
→ Max = 0,09 pW



07.02.2013

Max = 1,4 pW

Σ(2bins)= 1,8 pW



→ Max = 0,045 pW

Σ(2bins) = 0,052pW

- Applying the MBR simulation to the all GHz data → a lot of events are more awaited than the 2 lasts !

Differential enery radiated by an electron of energy $m_e c^2/\sqrt{1-\beta^2}$
for a dx travel, for a dω frequency range (here 3.4-4.2 GHz)

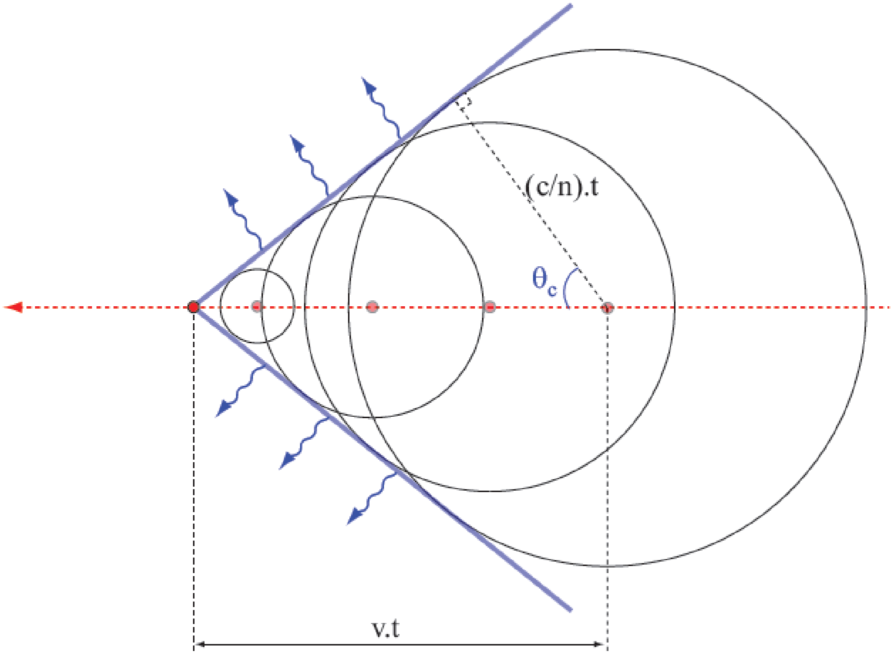
$$d^2E = \frac{e^2 \mu_0}{4\pi} \omega \left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) d\omega \, dx$$

At **each EAS-step**

The total Cerenkov emission using
•the number of EAS-e^-
•**EAS-e^- energy distribution**
•air refractive index

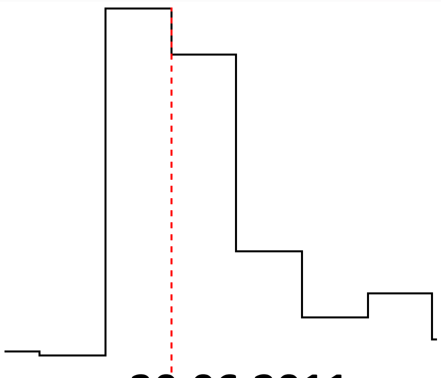
The received amount of Cerenkov using
•the angle between EAS and antenna
•Cerenkov angle + **EAS-e^- lateral distribution**

The 25ns bins trace is generated as the MBR one is.



Interpretation

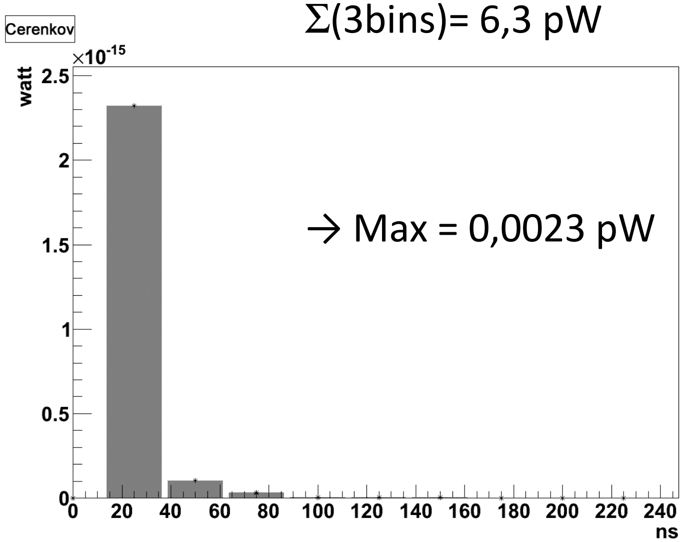
Cerenkov - Preliminary results

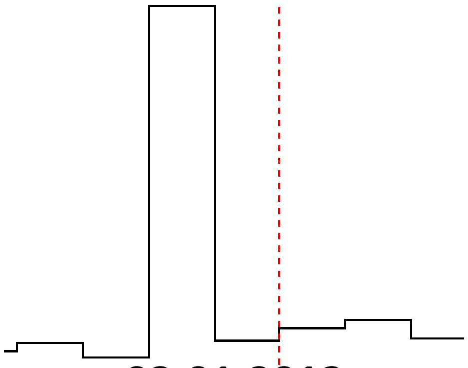


30.06.2011

Max = 2,9 pW

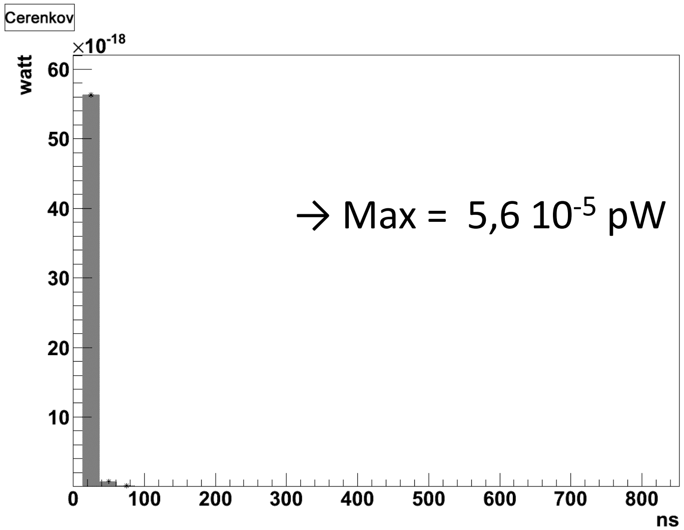
Σ(3bins)= 6,3 pW

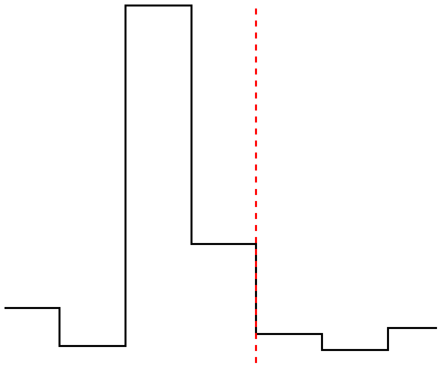




03.01.2013

Max = 1,5 pW

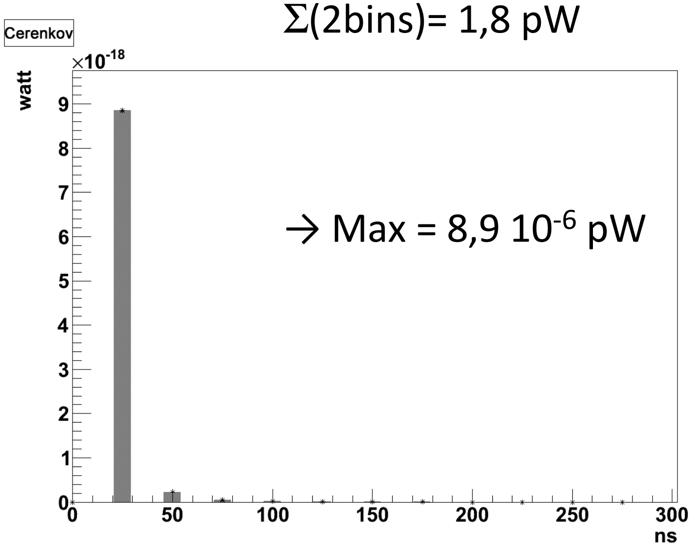




07.02.2013

Max = 1,4 pW

Σ(2bins)= 1,8 pW



- Cerenkov is always weak and prompt compared to MBR

Finally

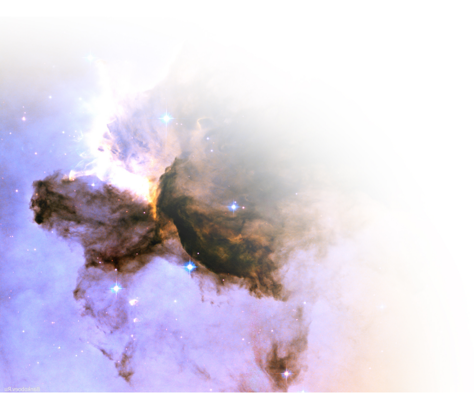
Conclusions

- First evidence of GHz signals related to a EAS
- The physical process at the origin of the 3 signals is not etablished well
- More data, more simulations (geo-synchrotron & physical MBR) and a better SNR are necessary

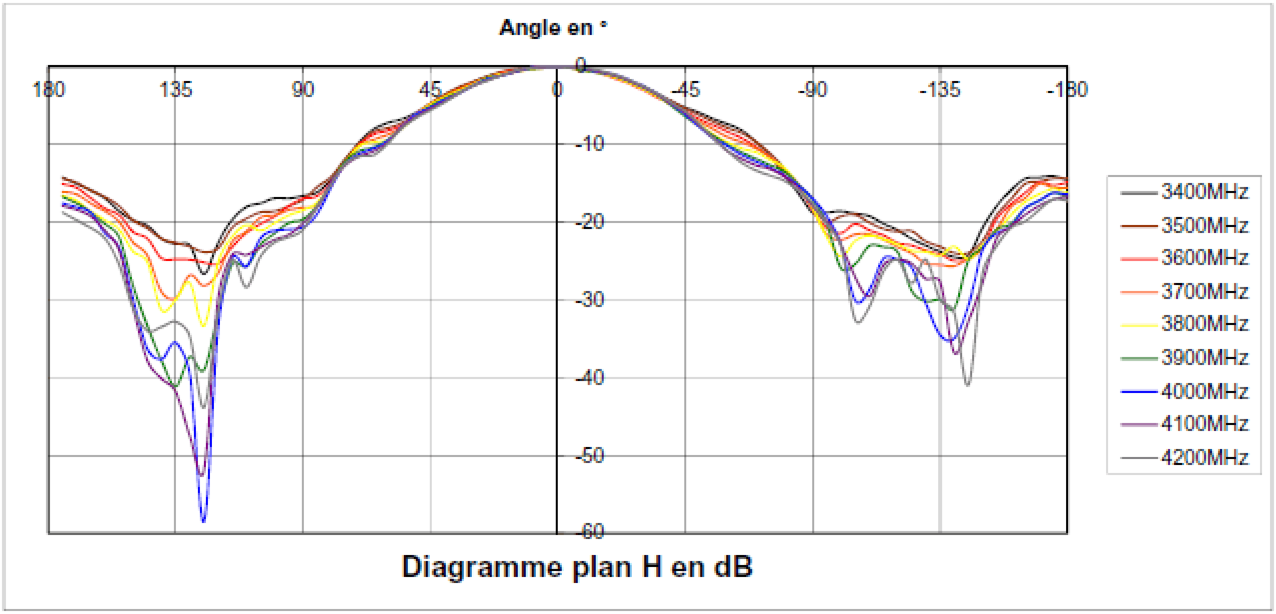
In progress or to do

- Same work is done for MHz
- Noise measurements of different antennas, to use the lower-noise one
- HFSS simulations to calculate impedance matching, and gain of antennas with SD geometry
- Apply FT to loose the cuts on events selection in MHz
- Numerical simulations of physical processes at the origin of MHz and GHz emissions
- Prospect in other frequency radio bands (A_{eff} increases when ν decreases)

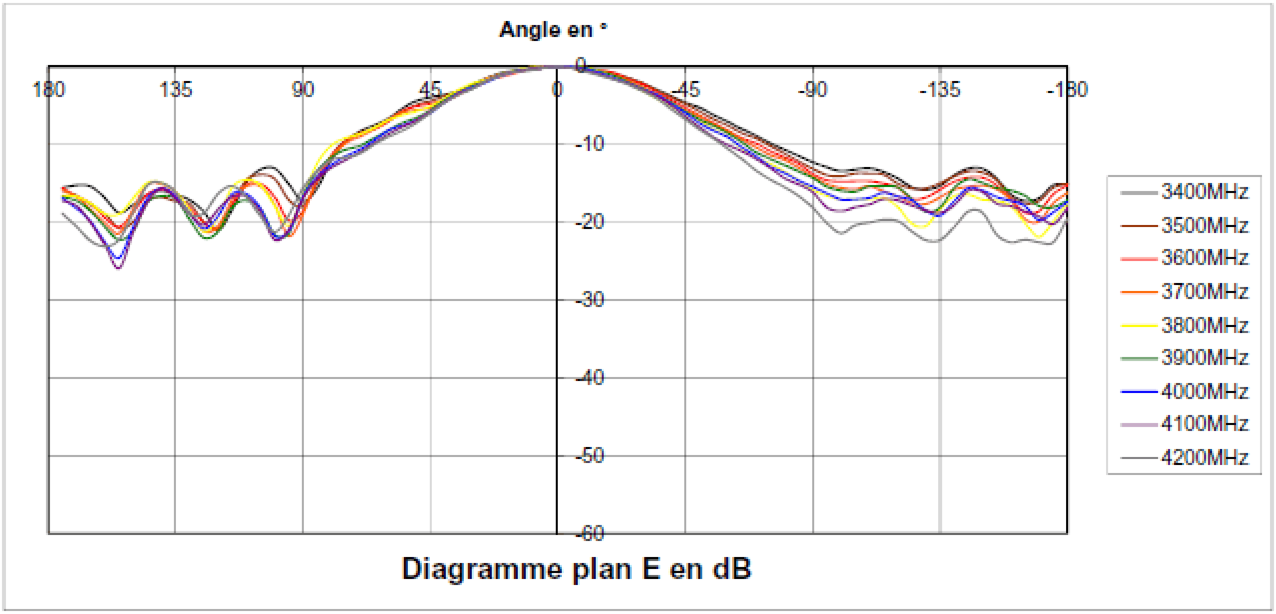
Thank you !



Back up



Angle en °
180
135
90
45
0
-45
-90
-135
-180
0
-10
-20
-30
-40
-50
-60
3400MHz
3500MHz
3600MHz
3700MHz
3800MHz
3900MHz
4000MHz
4100MHz
4200MHz
Diagramme plan H en dB



Angle en °
180
135
90
45
0
-45
-90
-135
-180
0
-10
-20
-30
-40
-50
-60
3400MHz
3500MHz
3600MHz
3700MHz
3800MHz
3900MHz
4000MHz
4100MHz
4200MHz
Diagramme plan E en dB