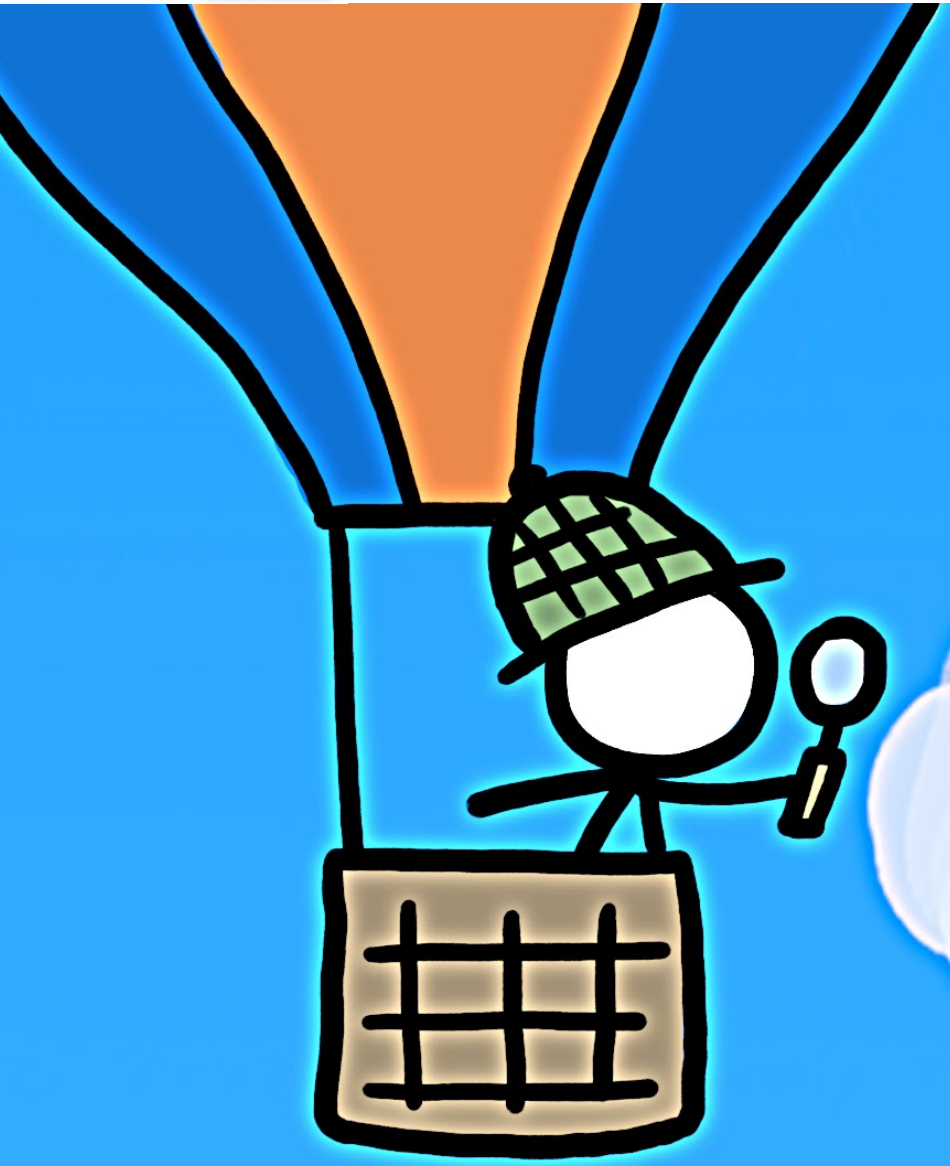
Dr. Laura Valore
University of Naples “Federico II”
INFN Sec. of Naples

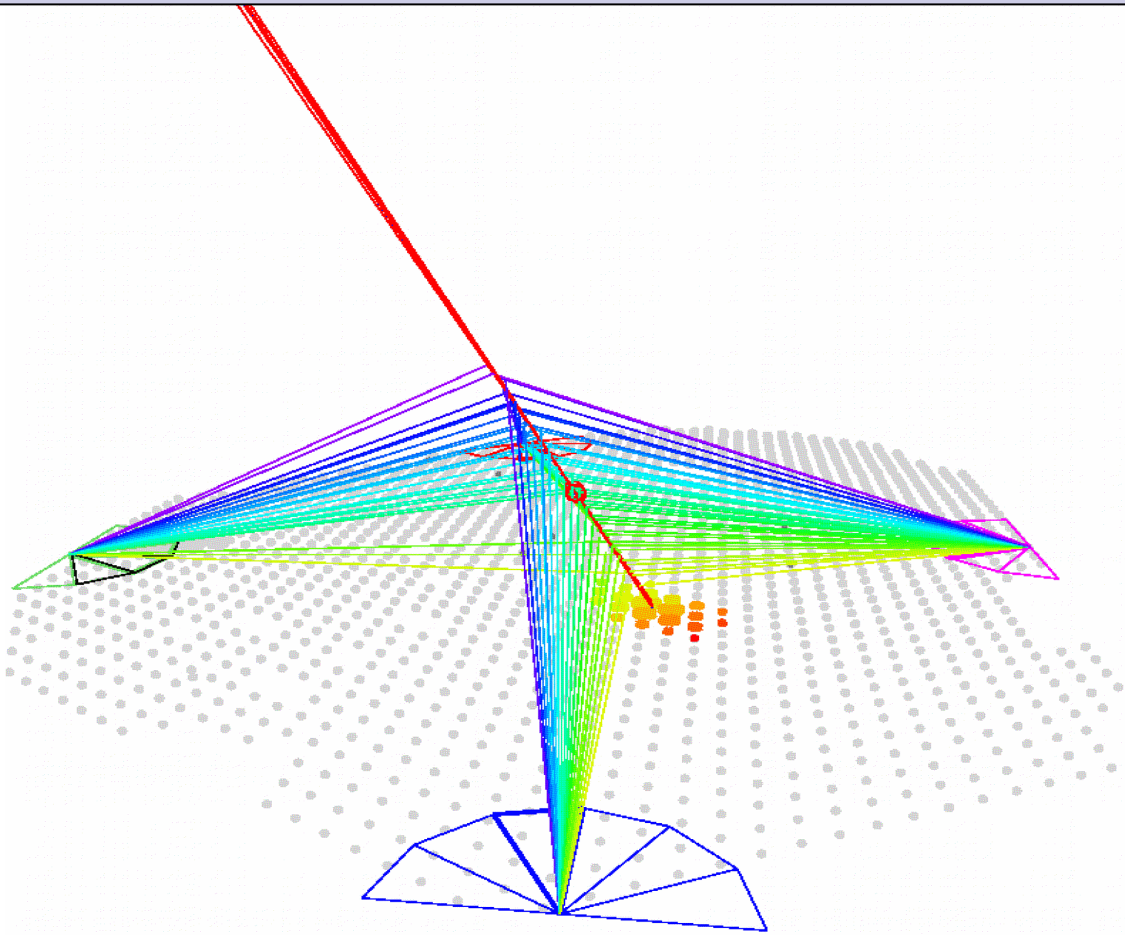


12 years of aerosol profile measurements at the Pierre Auger Observatory with CLF and XLF

AtmoHEAD2018 – Anacapri, September 25th 2018

AUGER STRATEGY

- use of hybrids to achieve a model independent energy calibration of SD
- use of SD only events for physics items where large statistics is needed

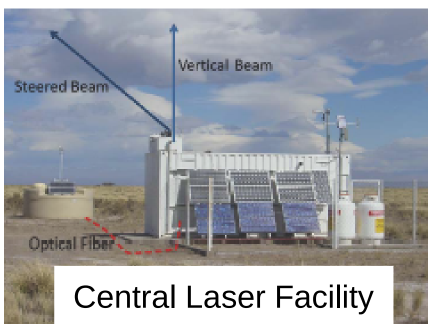


Very high quality hybrid events are used to calibrate the SD energy estimator using FD measurements which are model independent

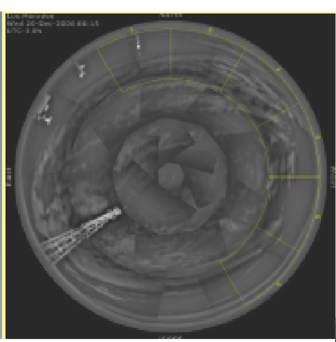
THE ATMOSPHERE NEEDS TO BE WELL KNOWN!

The Pierre Auger Observatory Atmospheric Monitoring System

The Pierre Auger Observatory operates an array of monitoring devices to record the atmospheric conditions. Most of these instruments are used to estimate the hourly aerosol transmission between the point of production of the fluorescence light and the FD

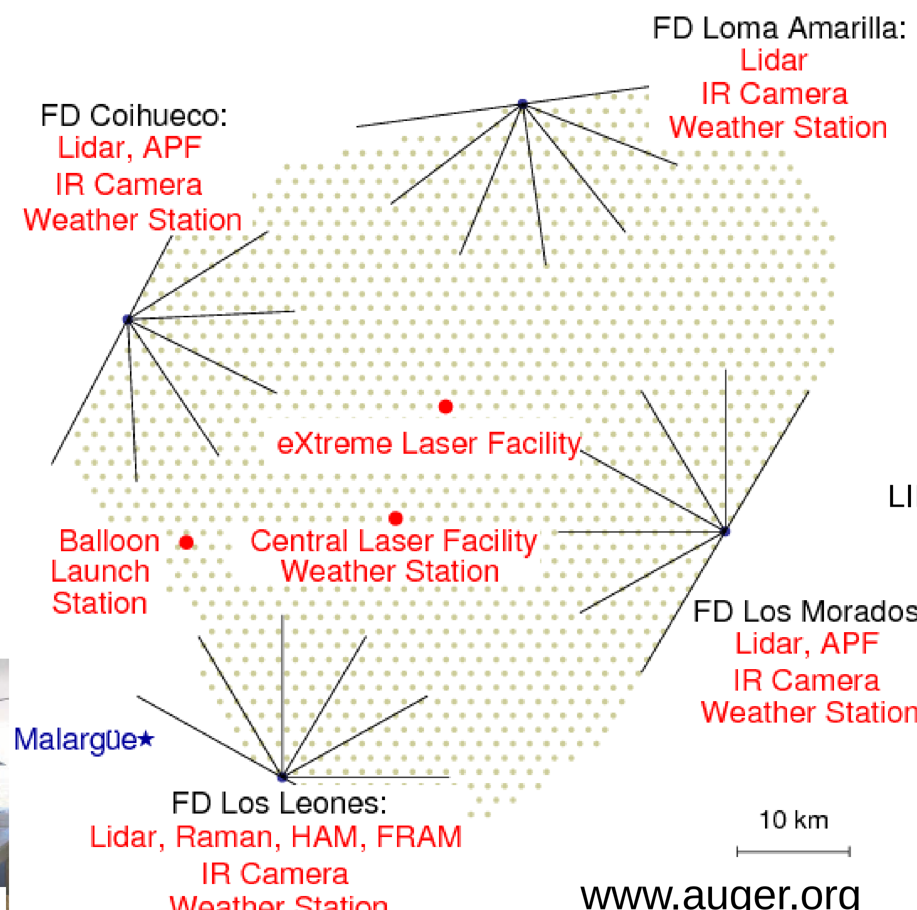


Central Laser Facility



IR cloud camera

Phase Function Monitor



www.auger.org

LIDAR

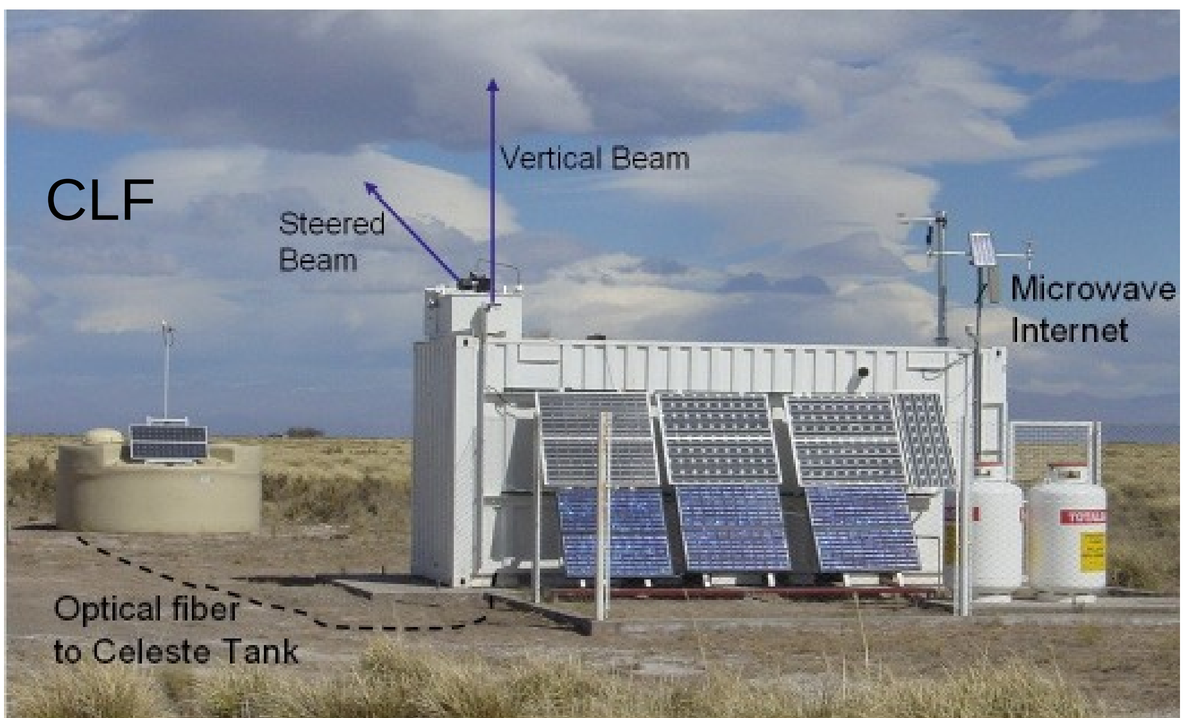
FRAM

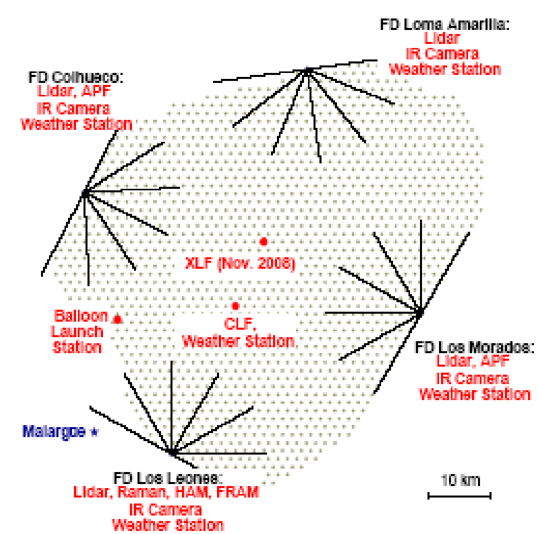
The Pierre Auger Observatory Central Laser Facility (CLF) and the eXtreme Laser Facility (XLF)

- Nd::YAG laser source @ 355nm
- Distance from FD buildings between 26km and 40km
- Position, direction and energy known

since 2010

since 2004

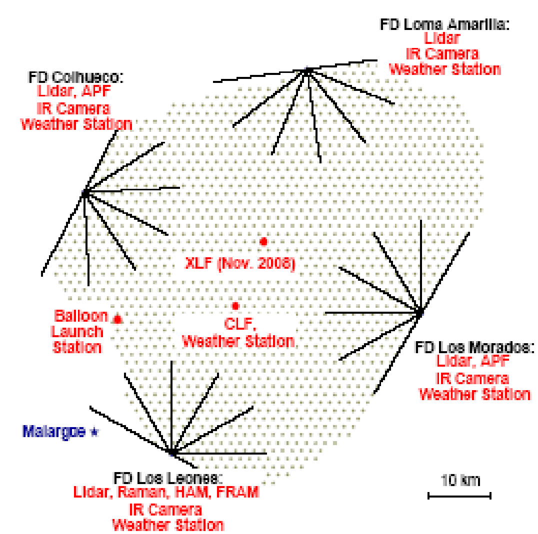




The Pierre Auger Observatory Central Laser Facility (CLF) and the eXtreme Laser Facility (XLF)

- Nd::YAG laser source @ 355nm
- Distance from FD buildings between 26km and 40km
- Position, direction and energy known

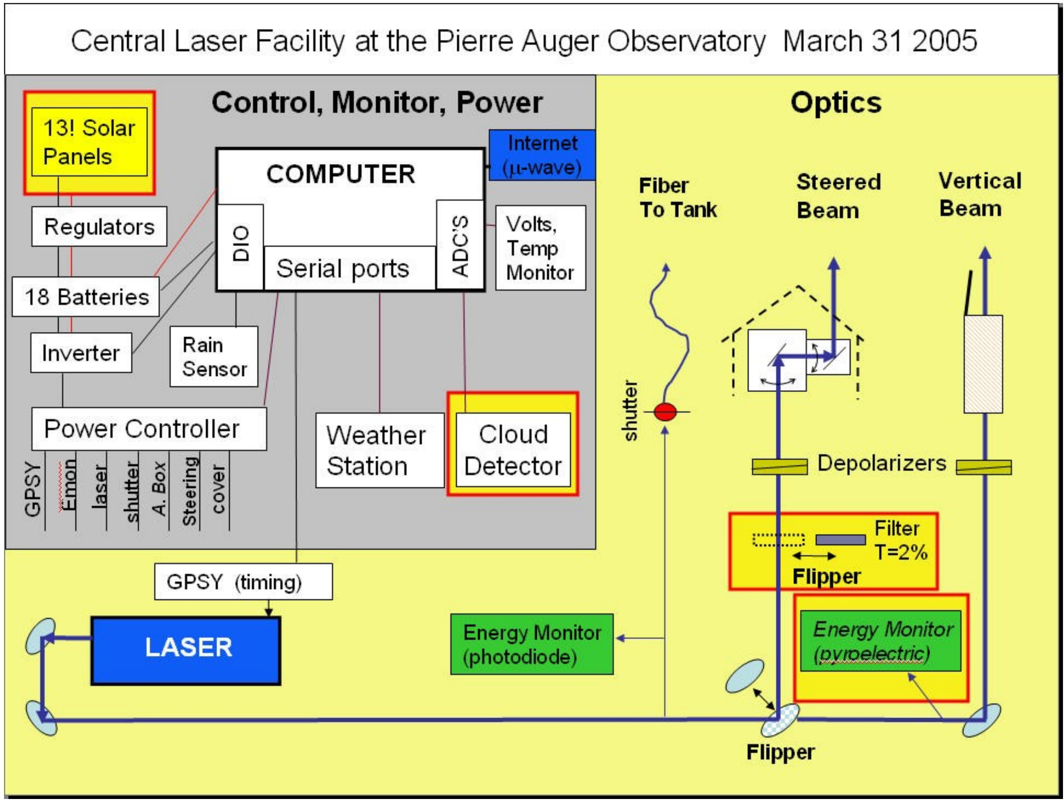
UPGRADE TO CLRF (2013)

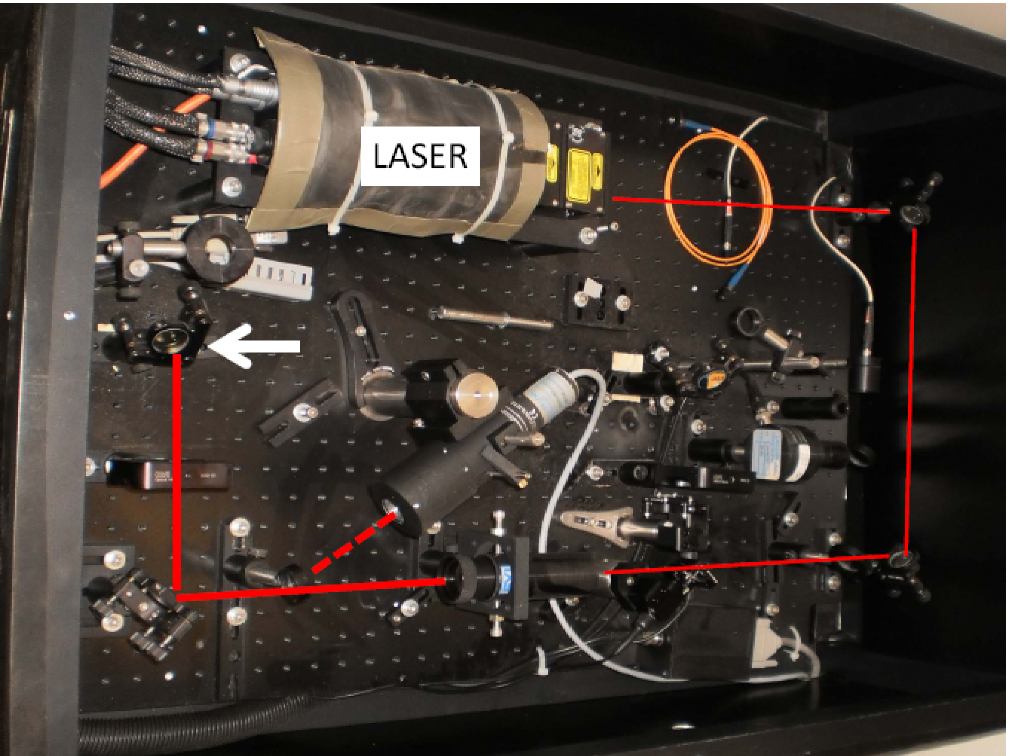


CLF hardware
(version 1.0)

The CLF system is described in :

JINST 1 P11003 (2006) *"The Central Laser Facility at the Pierre Auger Observatory"*





The trajectory of the vertical beam is shown.

A fraction of the laser beam goes into the pyroelectric probe for the relative shot by shot calibration.

CLF calibration system (v 1.0)

Relative and absolute energy calibration of the laser are mandatory! The sky energy of each shot must be known with the highest precision for aerosol profiles measurements.

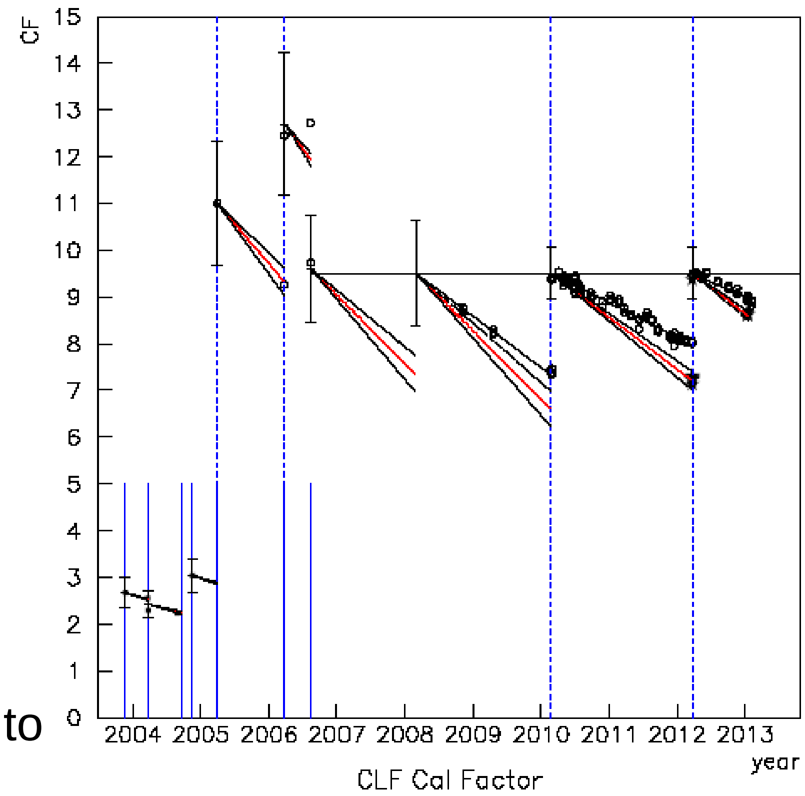
The laser energy of the CLF is monitored by two pick-off probes inside the optical table : a photodiode ad a pyroelectric probe. The second one is used for the relative calibration since 2005. In addition, absolute calibrations were periodically performed.

BUT !

dust accumulating on the last mirror of the optical table, downstream the probe, caused a reduction of the effective energy sent to the sky that was revealed by absolute calibration measurements.

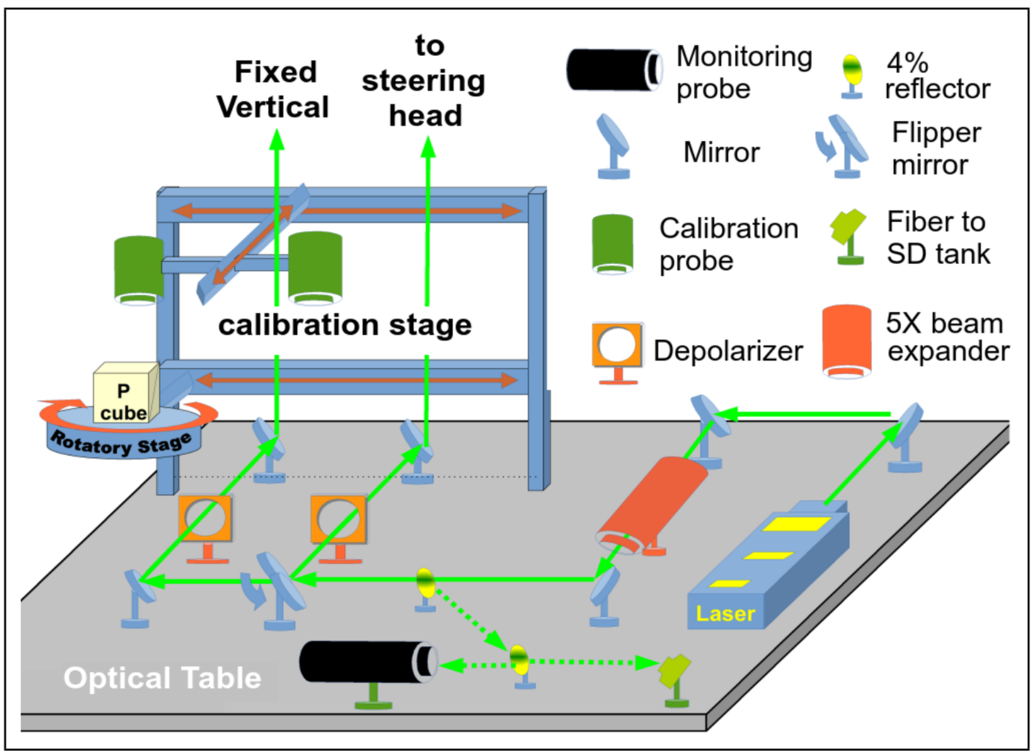
Since 2010, monthly absolute calibrations are performed at the CLF to trace this trend accurately

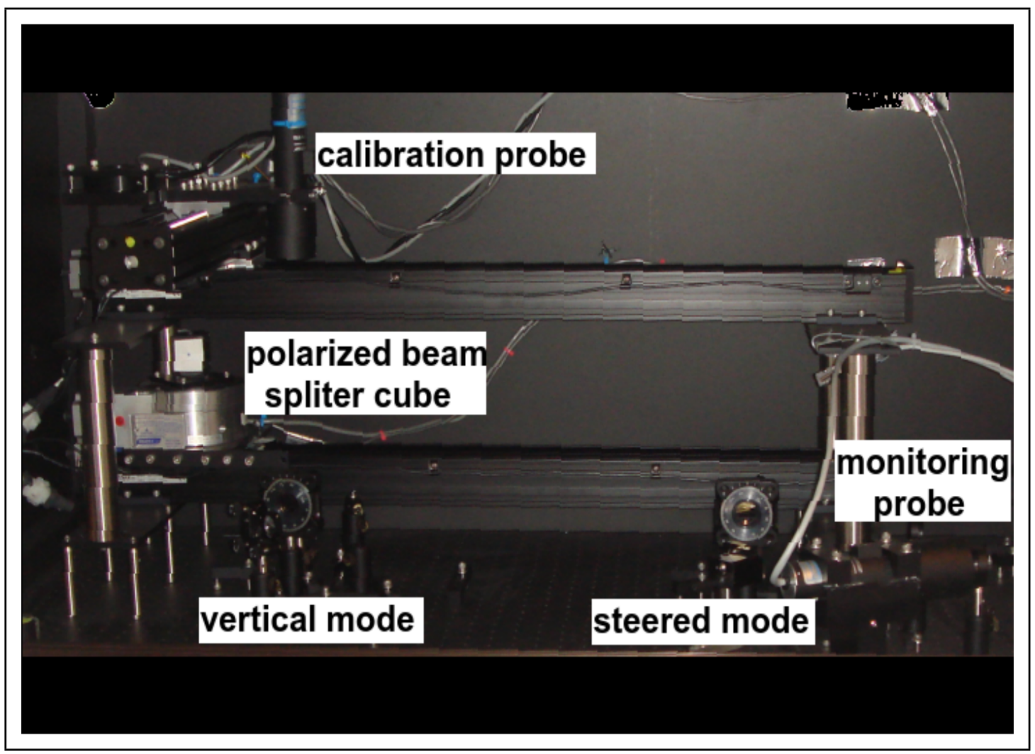
Since 2013, the calibration system was improved to perform authomatic measurements of the energy sent to the sky.



CLRF calibration system (v2.0, since 2013)

Authomatic absolute calibration of the effective energy sent to the sky : a robotic arm moves a calibration probe in the beam path of the laser every night.

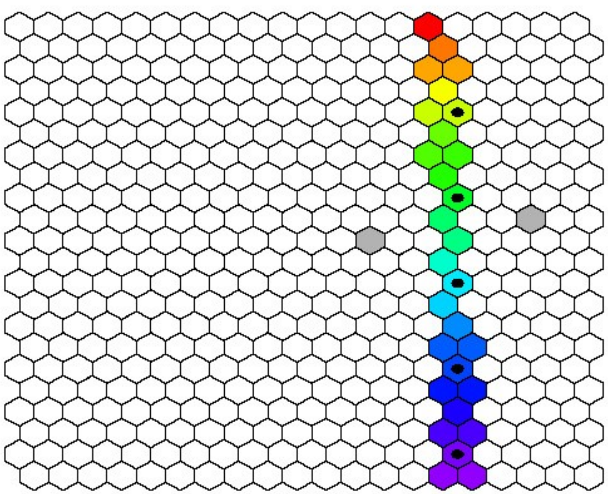


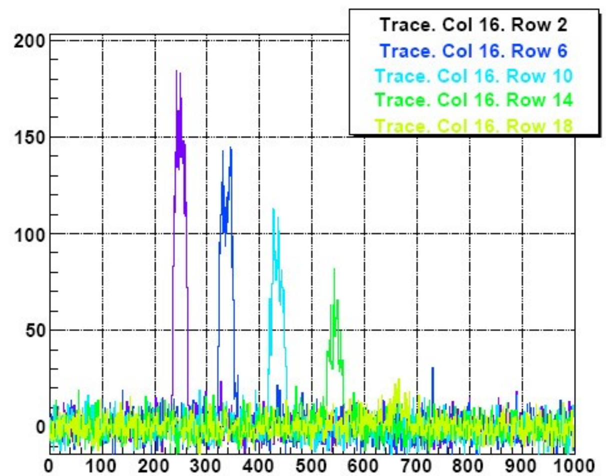


The XLF (from 2010) was already equipped with a similar system

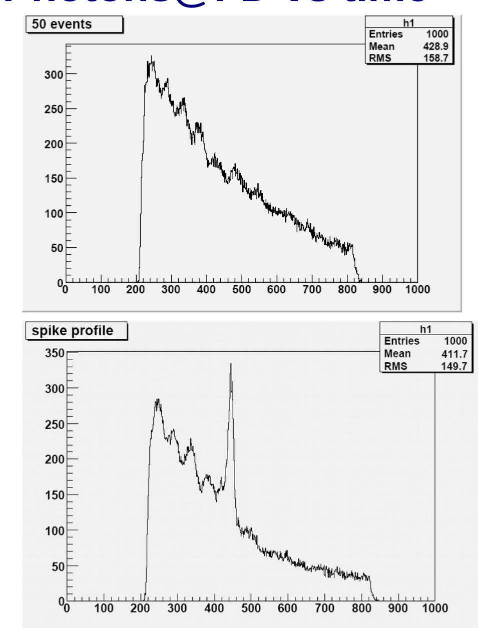
How is the light from the Laser Facilities seen from the FD?

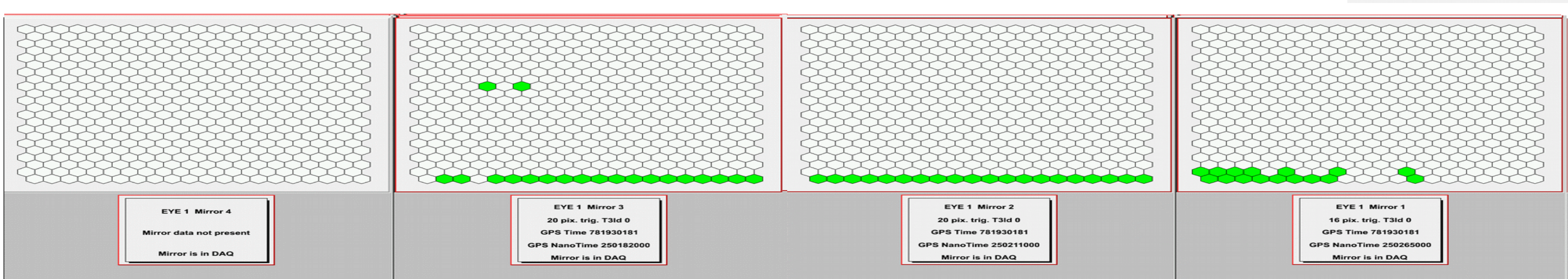
- CLF/XLF operation (during FD shifts):
- Completely automathic operation
- 50 vertical shots every 15 minutes, a shot every second, average energy 6.5 mJ
- on request, 2 sets of inclined shots





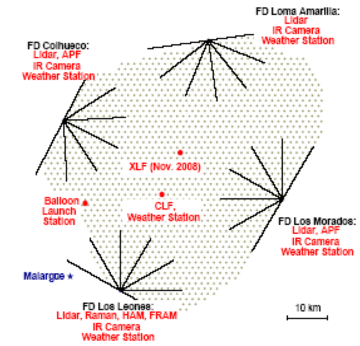
Photons@FD vs time





7 mJ laser track seen at different distances

ranging from 26 km to 42 km



Simulated aerosol attenuation

VAOD @ 3km a.s.l. = 0.03 (T = 0.77)

Average aerosol attenuation conditions

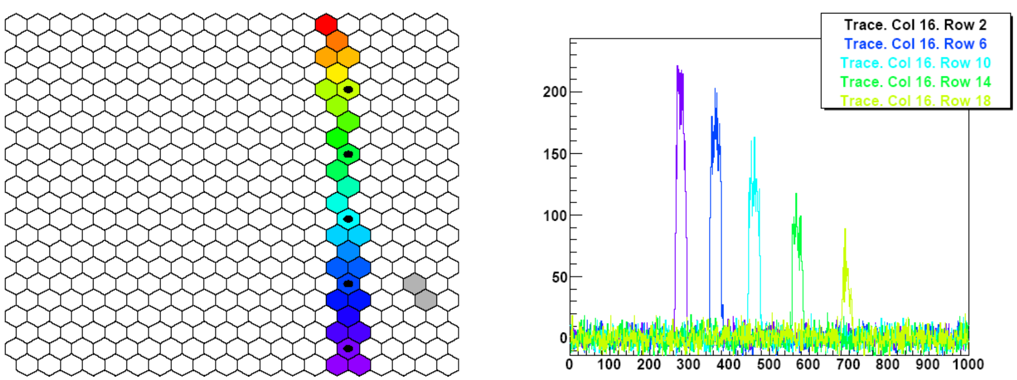


Figura 1: Eye1 : Distance CLF - Eye1 26km

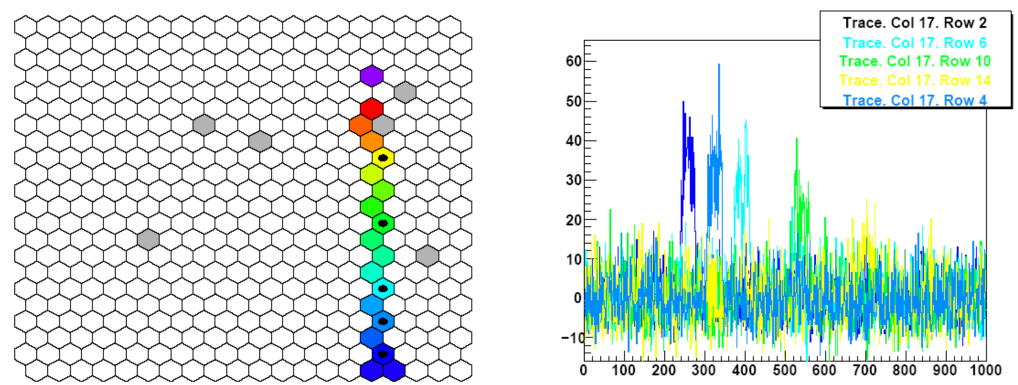


Figura 3: Eye3 : Distance CLF - Eye3 42km

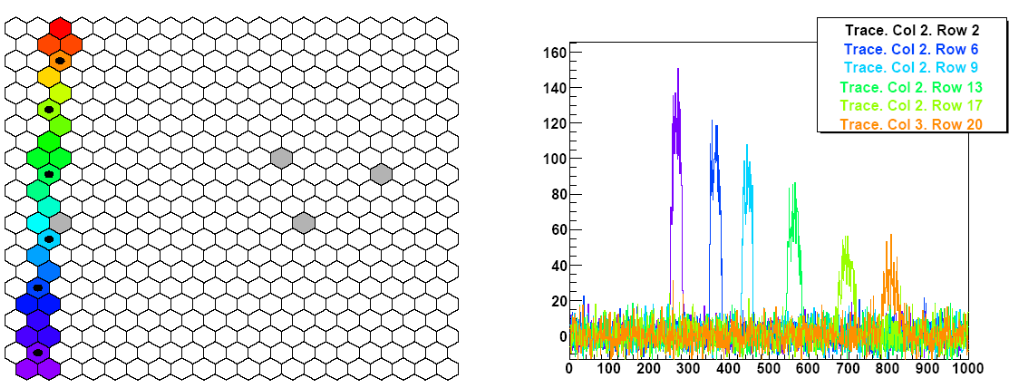


Figura 2: Eye2 : Distance CLF - Eye2 30km

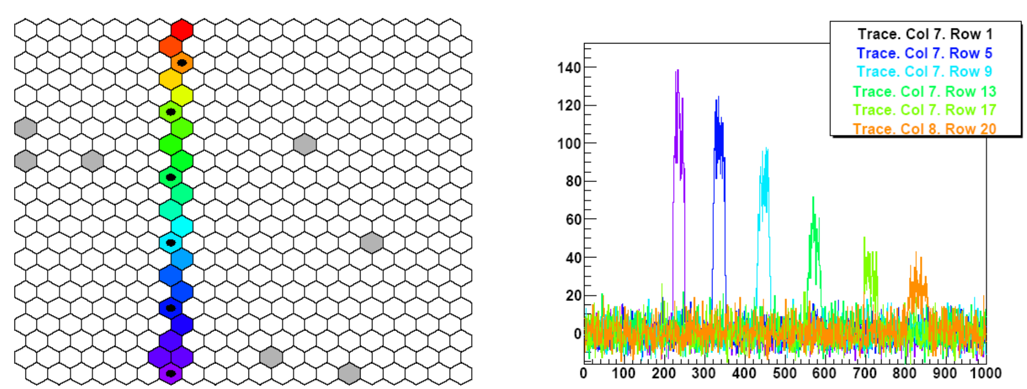
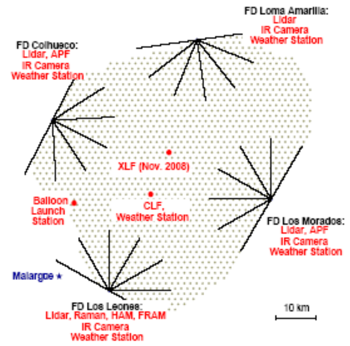


Figura 4: Eye4 : Distance CLF - Eye4 30km

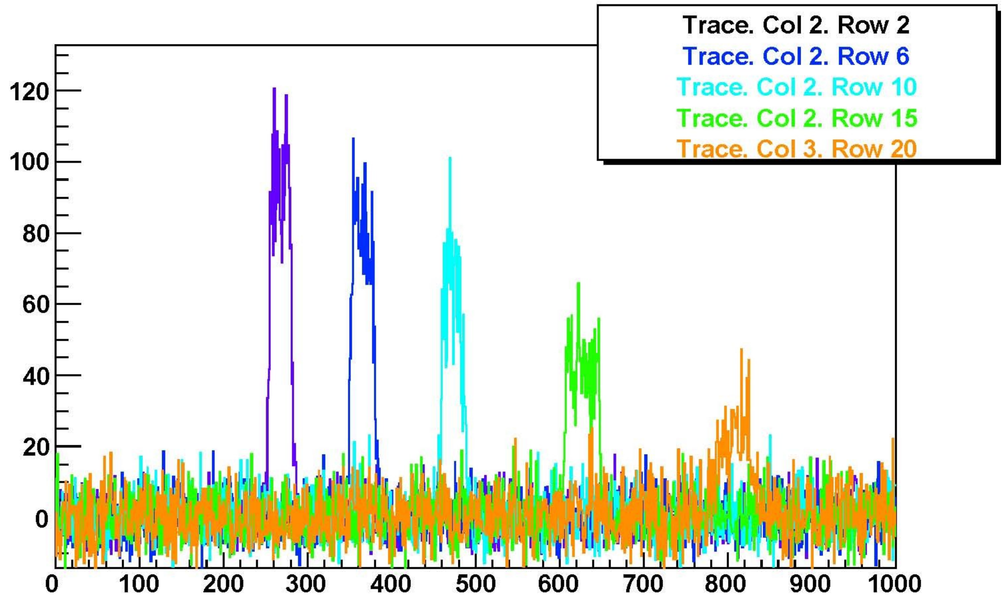
7 mJ laser track seen at different distances

ranging from 26 km to 42 km

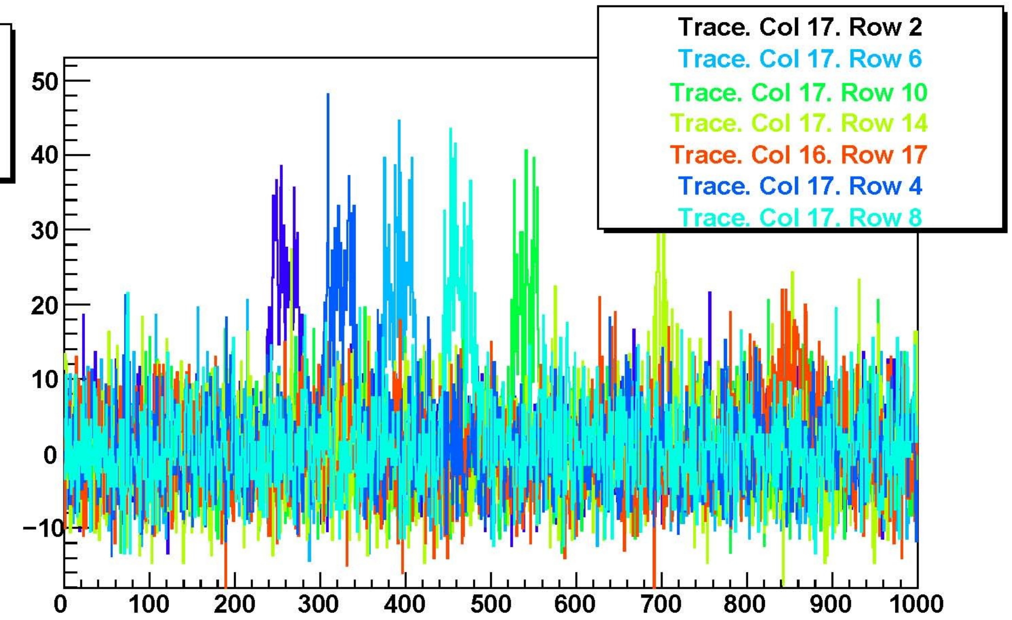
Hazier conditions : VAOD @ 3km a.s.l. = 0.05 → T = 0.63



Los Morados, 30 km



Loma Amarilla, 42 km



Methods for the determination of the atmospheric aerosol attenuation of UV light

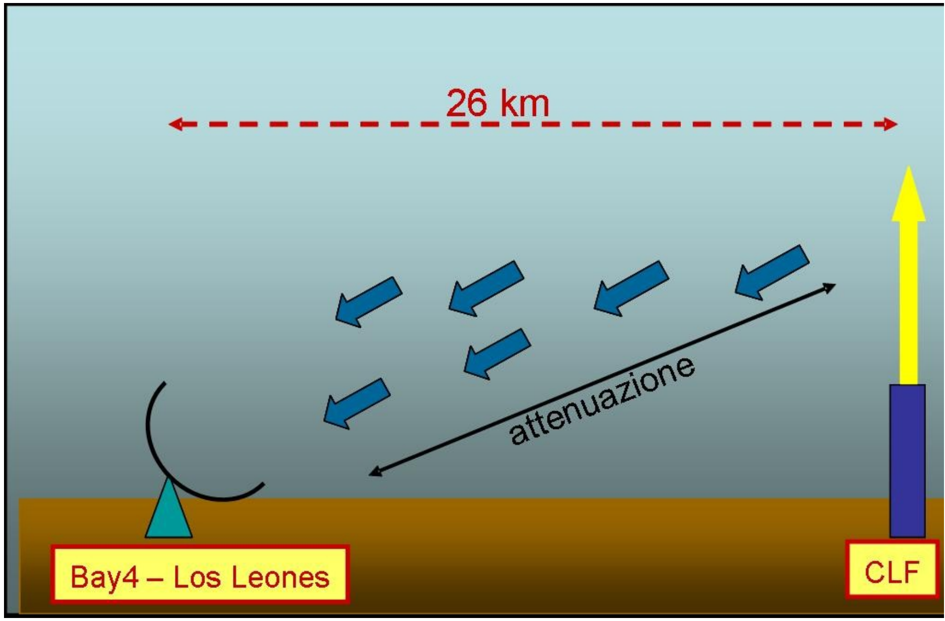
Techniques for Measuring Aerosol Attenuation using the Central Laser Facility at the Pierre Auger Observatory
JINST 8 P04009 (2013)

The Pierre Auger Collaboration*

Laser light is attenuated in the same way as fluorescence light as it propagates towards the FD. Measuring the amount of photons reaching the FD allows us to evaluate the attenuation in atmosphere due to aerosols

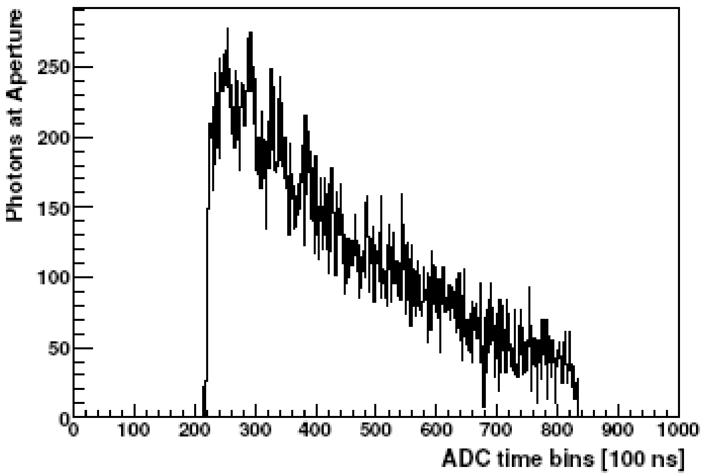
Data Normalized Analysis → 90% of AerosolDB
the aerosol attenuation is measured by comparing laser events with those of a reference purely molecular night in which the aerosol attenuation is negligible (Rayleigh Night)

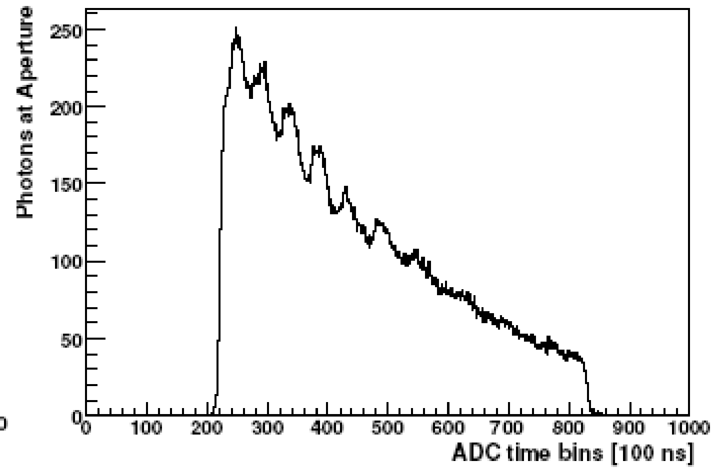
Laser Simulation Analysis → 10% (filling gaps)
the aerosol attenuation is measured by comparing measured and simulated laser events in different atmospheric conditions, described by a two parameters model.



Laser Simulation & Data Normalized Analyses
what they have in common

To minimize fluctuations, both analyses make use of average profiles of light measured at the aperture of the FD buildings, normalized to a reference energy





Measured profiles are affected by unavoidable systematics related to FD and laser calibrations; simulated profiles are affected by systematics related to the simulation procedure; using measurements recorded on extremely clear nights where molecular Rayleigh scattering dominates, laser observations can be normalized without the need for absolute photometric calibrations of the FD or laser.

Reference Profile

These “reference clear nights” are identified using a procedure looking for profiles with :

maximum photon transmission

maximum compatibility with the shape of a profile simulated in conditions with negligible aerosol attenuation (Kolmogorov-Smirnov test)

The procedure is repeated for each FD telescope, for both laser facilities. One reference clear night per year is identified.

Cross-checks with data from other instruments are performed to confirm the validity of the chosen reference profile.

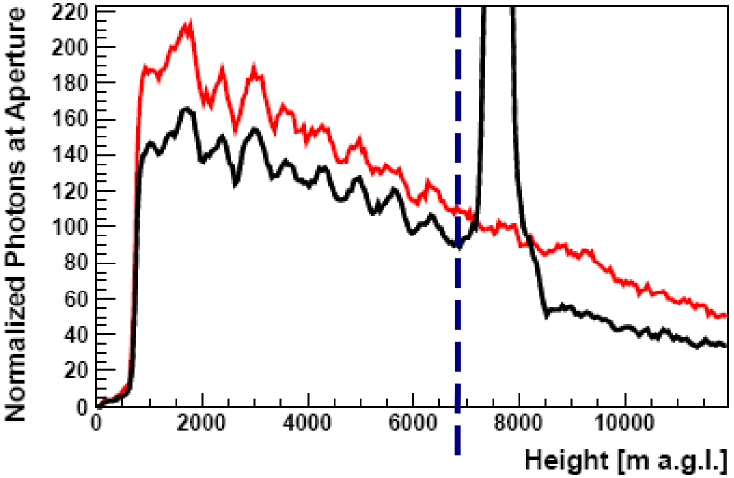
Data Normalized Analysis

building hourly profiles and marking clouds

The procedure starts building quater-hour profiles of light collected at the aperture of the FD building corresponding to the 50 laser shots. Profiles are normalized to 1mJ.

Clouds are then marked by comparing the photon transmission of the quarter-hour profiles to that of the clear profile. The ratio Tquarter/Tclean is used to identify clouds and set the minimum cloud layer altitude. Hours are marked as cloudy only if clouds are found in at least two quarter-hour sets.

After cloud identification, the full hour profile is built averaging all quarter-hour profiles available.



Data Normalized Analysis

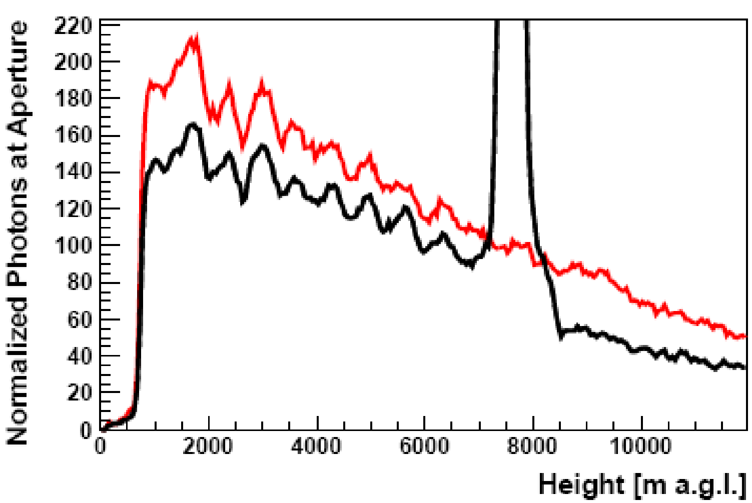
measuring the aerosol attenuation profiles $\tau_{aer}(h)$

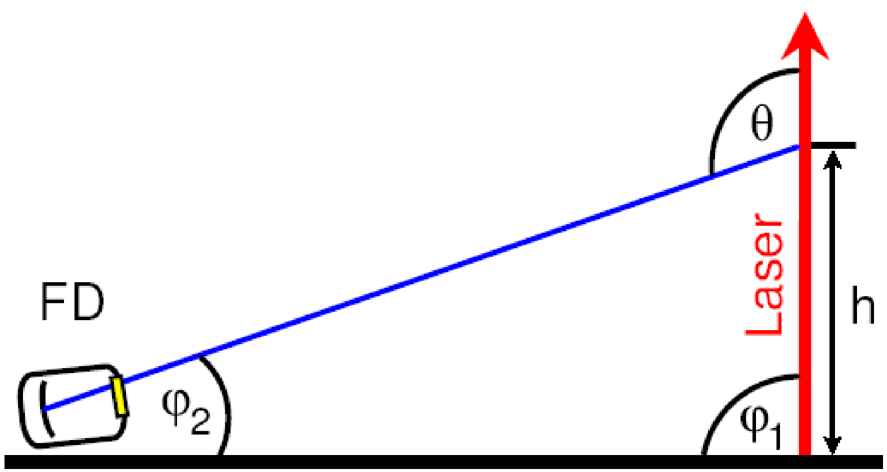
Using vertical laser shots, and taking into account the laser – FD geometry, the vertical aerosol optical depth is :

$$\tau_{\text{aer}}(h) = \frac{\ln N_{\text{mol}}(h) - \ln N_{\text{obs}}(h)}{1 + \operatorname{cosec}\varphi_2}$$

Where $N_{mol}(h)$ is the number of photons of the reference clear night, $N_{obs}(h)$ is the number of photons of the measured hourly profile in analysis and φ_2 is the elevation angle

A first guess of $\tau_{aer}(h)$, named $\tau^{meas}_{aer}(h)$, is measured for each bin



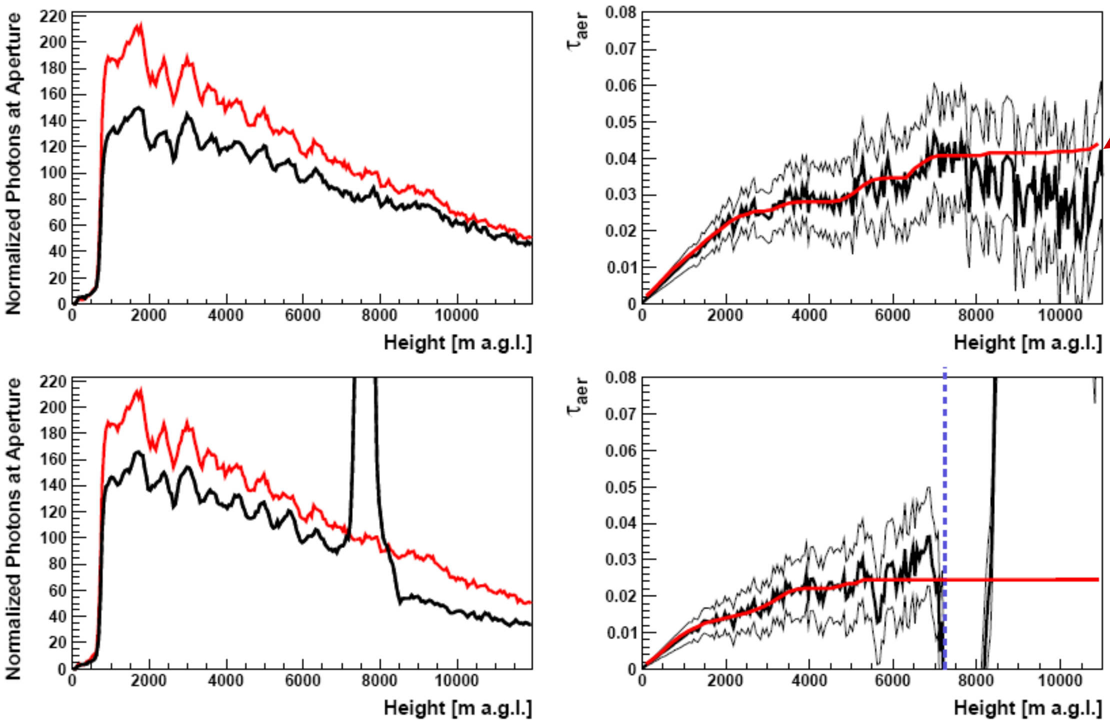


Data Normalized Analysis

measuring the aerosol attenuation profiles $\tau_{aer}(h)$

An iterative procedure is applied to differentiate $\tau^{meas}_{aer}(h)$ to obtain the aerosol extinction α(h) for each bin, in which it can be assumed as constant (this was used to overcome the missing aerosol scattering evaluation in the beam → now it is accounted for).

After a number of iterations, the final α(h) is integrated to obtain the $\tau^{fit}_{aer}(h)$

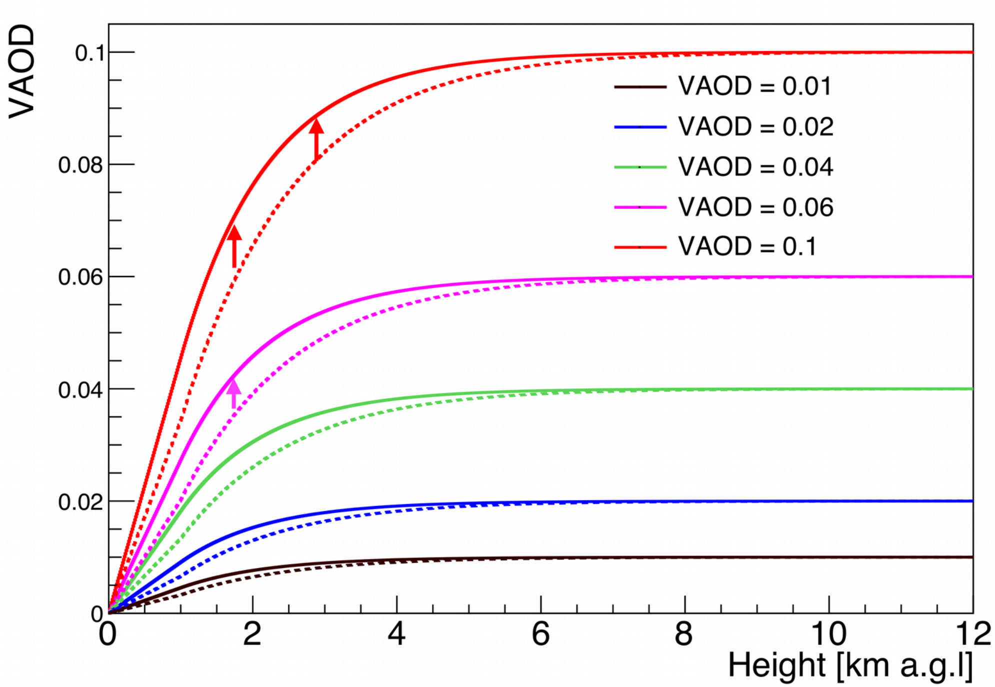


Black traces show $\tau^{meas}_{aer}(h)$ (with upper and lower bounds)

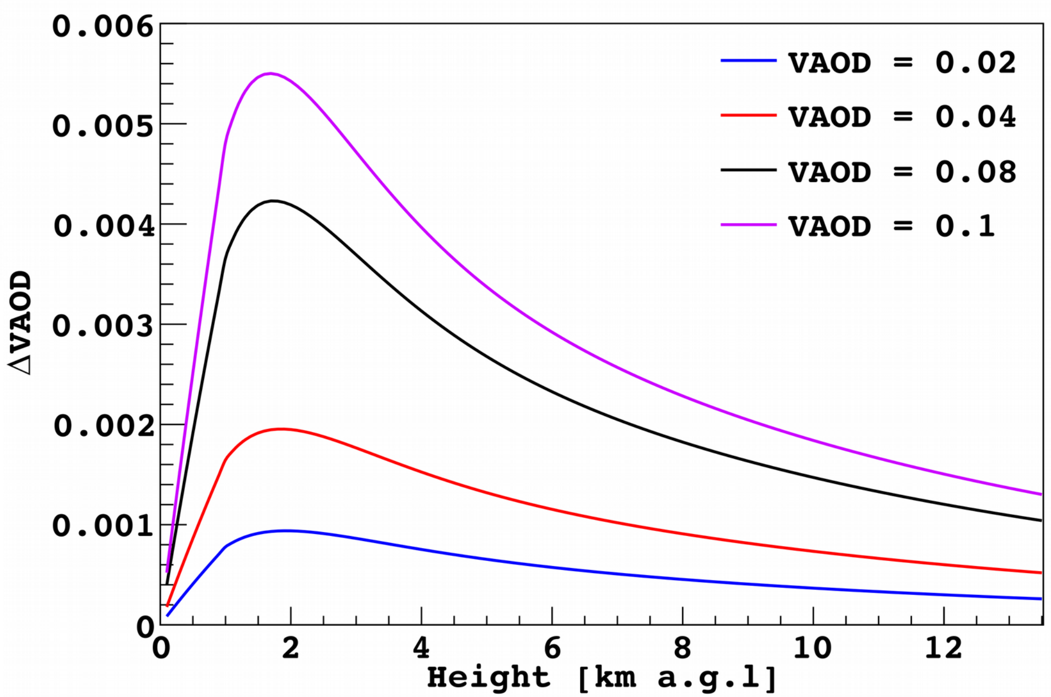
Red traces represent $\tau^{fit}_{aer}(h)$

Recent upgrades → aerosol and multiple scattering corrections

Aerosol scattering correction in the laser beam



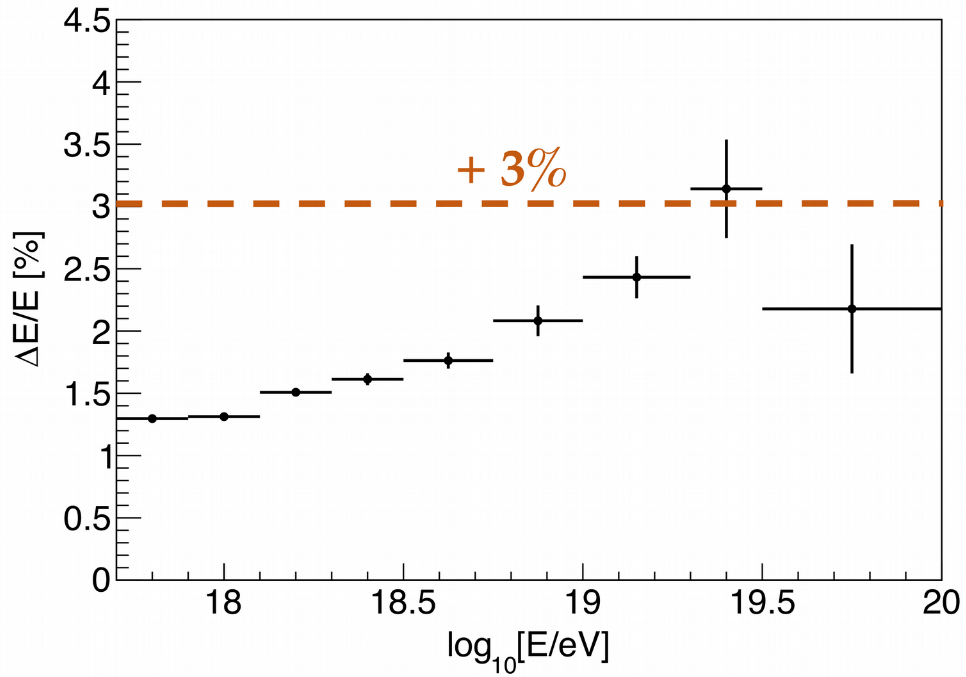
Multiple scattering correction towards the detector

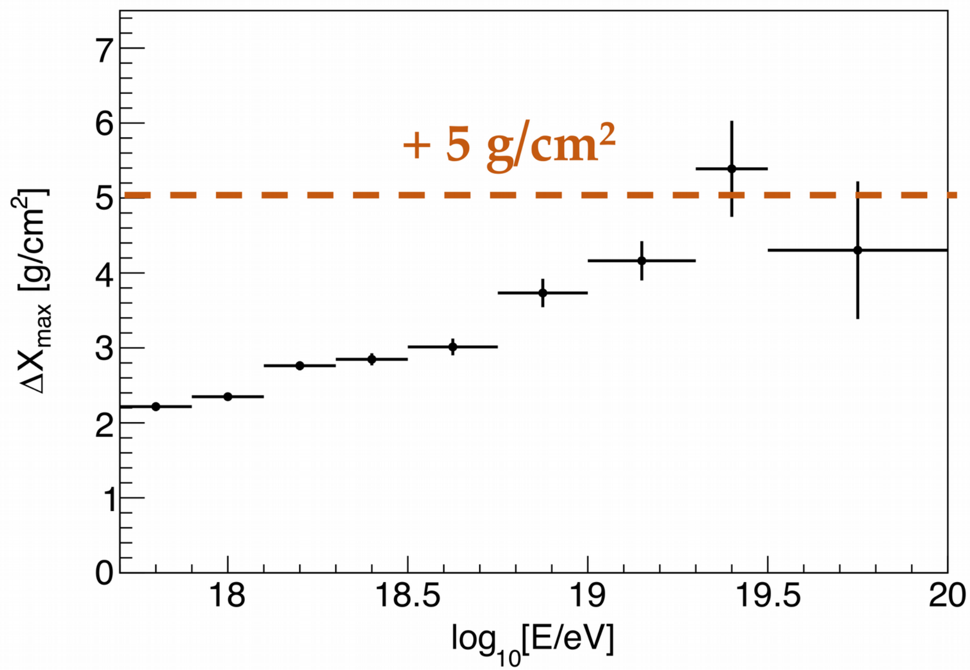


FD reconstruction

Small energy and X_{max} increase relative to reconstruction using old aerosol database.

~25,000 high-quality events measured between 2004 and 2015.





Increasing shower distance

Aerosol systematic uncertainties ($3\times10^{18} \div 10^{20}$ eV)

Energy scale: 3% - 6% [ICRC 2013]

X_{max}: $\pm 5\ g/cm^2$ - $^{+8}_{-5}\ g/cm^2$ [Phys. Rev. **D** 90 (2014) 122005]

Laser Simulation Analysis

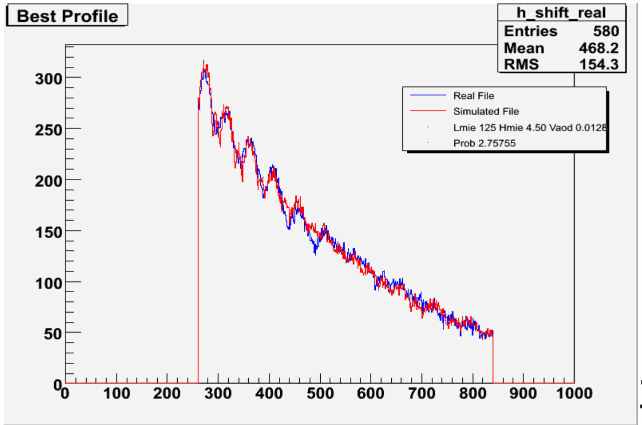
parametric model of the aerosol attenuation

The method is based on the comparison between measured and simulated events. Simulated laser events are generated at a fixed energy using a parametric description of the aerosol attenuation.

The vertical aerosol optical depth is described with a function of two parameters:
L_{aer}, the aerosol horizontal attenuation length
H_{aer}, the aerosol scale height

$$\tau_{\rm aer}(h_2 - h_1) = \int_{h_1}^{h_2} \alpha_{\rm aer}(h)\,{\rm d}h = -\frac{H_{\rm aer}}{L_{\rm aer}}\left[\exp\left(-\frac{h_2}{H_{\rm aer}}\right) - \exp\left(-\frac{h_1}{H_{\rm aer}}\right)\right]$$

A third parameter, the aerosol mixing layer height, taking into account the Planetary Boundary Layer, has been added to this model but is not used so far.



Laser Simulation Analysis

building quarter hour profiles and simulations

the relative energy scale between measured and simulated events is set using the normalization to the reference clear night.

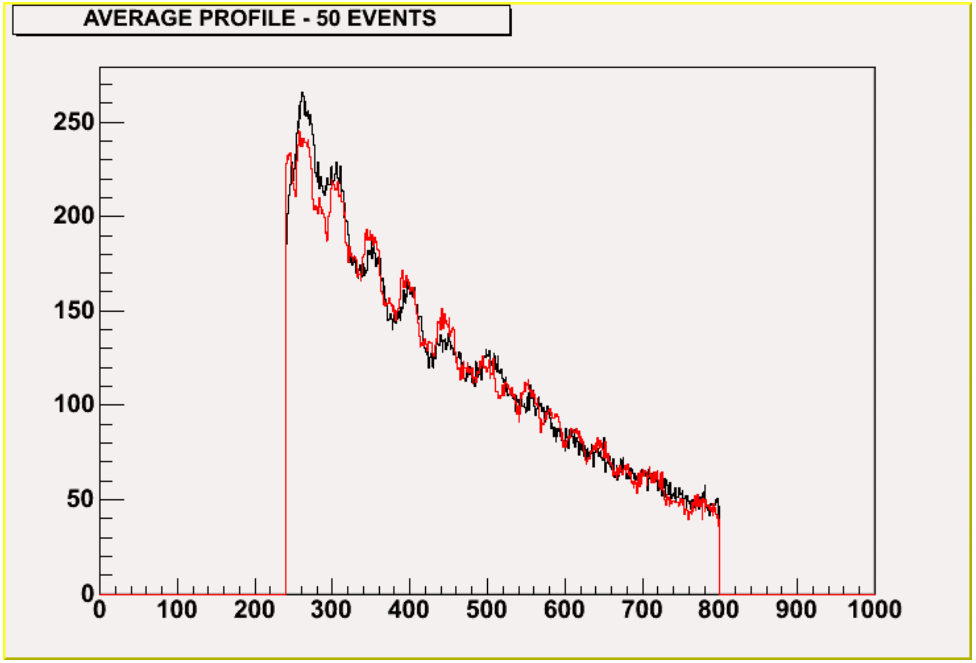
Quarter-hour profiles are built averaging over 50 shot groups, normalizing each profile to 6.5 mJ. Simulations are generated in groups of fifty events at 6.5 mJ.

GRID FEATURES :

Lmie : 5km – 50km , step 1.25km
Lmie : 50km – 150km, step 2.5km

Hmie : 500m - 5km , step 250m

A grid is produced for each laser facility, for each FD site and for each month using molecular monthly density profiles.



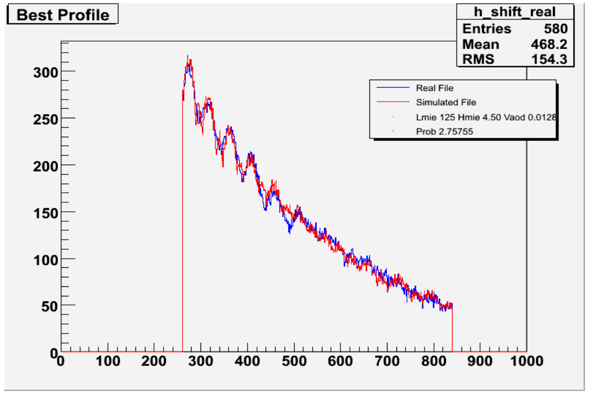
Laser Simulation Method

measuring the aerosol attenuation profiles $\tau_{aer}(h)$

Each measured profile is compared to the whole grid of simulations. The simulated profile that best matches the measured one is chosen minimizing the square difference of the number of photons per each bin.

The L_{aer} and H_{aer} parameters of the chosen best simulated profile are used to measure the aerosol attenuation profile

$$\tau_{aer}(h_2 - h_1) = \int_{h_1}^{h_2} \alpha_{aer}(h)\mathrm{d}h = -\frac{H_{aer}}{L_{aer}}\left[\exp\left(-\frac{h_2}{H_{aer}}\right) - \exp\left(-\frac{h_1}{H_{aer}}\right)\right]$$



The 4 quarter-hour VAOD profiles are averaged to build the hourly aerosol profile.

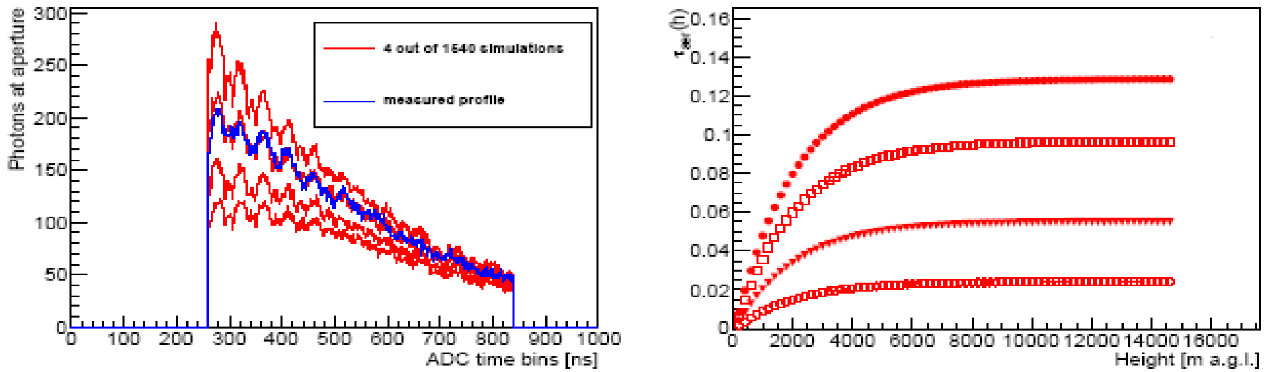
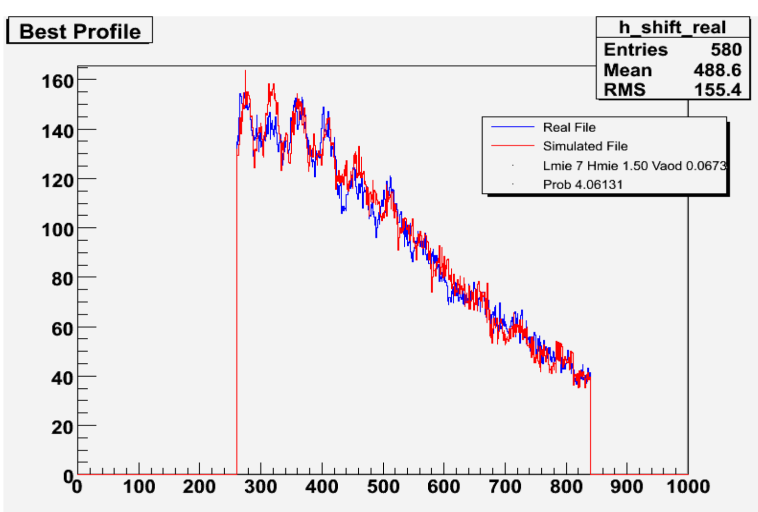
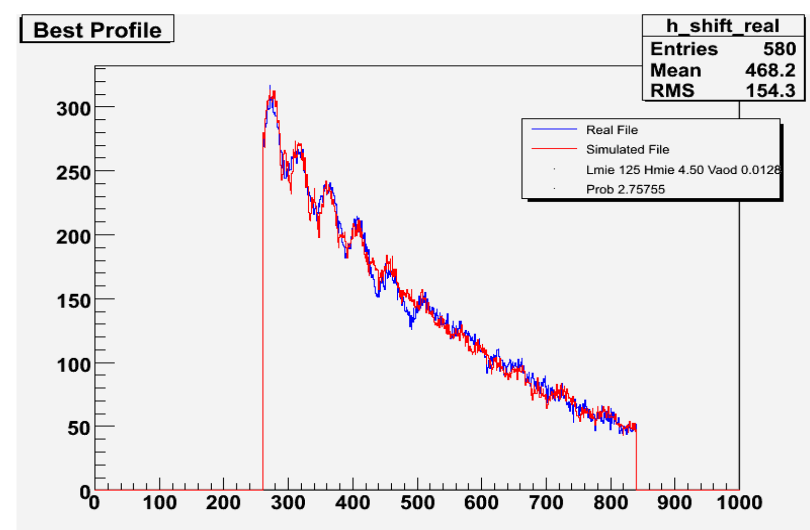


Figure 4: Left : four out of the 1540 simulated profiles of a monthly grid (red), superimposed on a measured profile (blue). Right : the four $\tau_{\rm aer}^{\rm LS}(\rm h)$ profiles corresponding to the simulated CLF profiles.

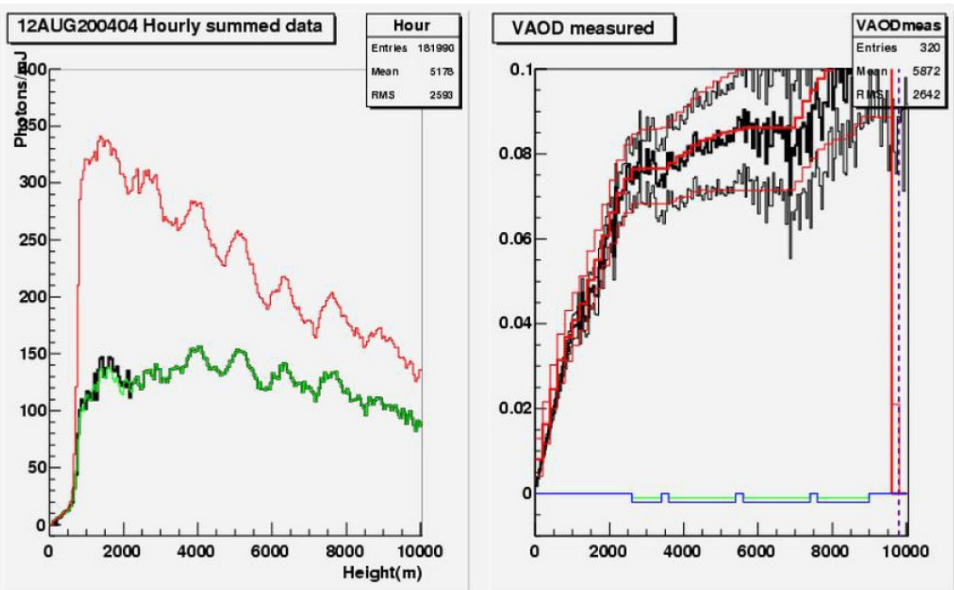
hazy

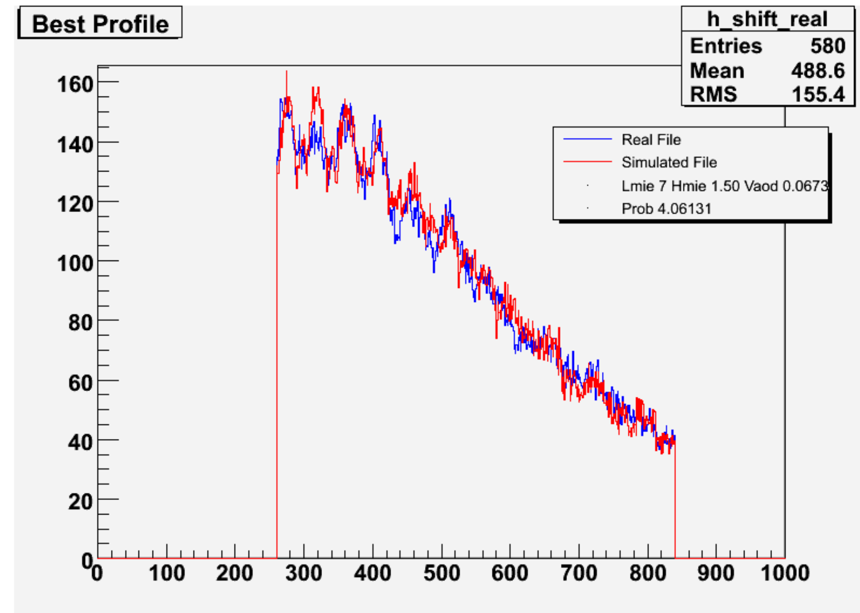


clean

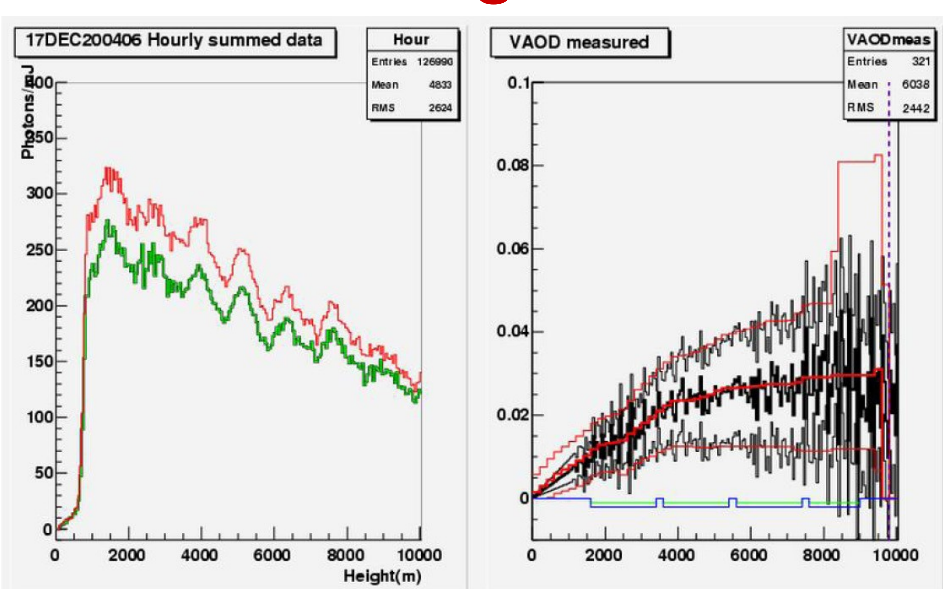


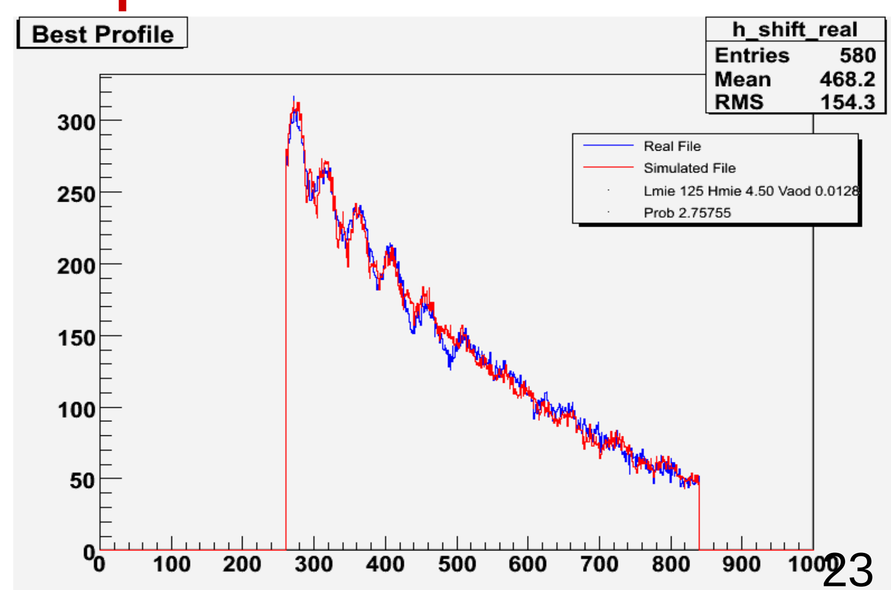
Hazy atmo laser profiles





Average clean atmo laser profiles

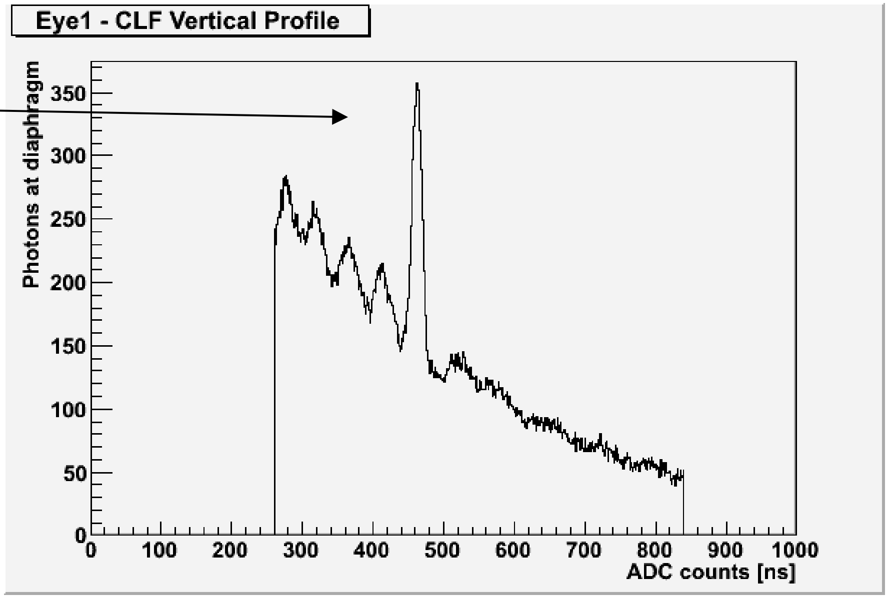


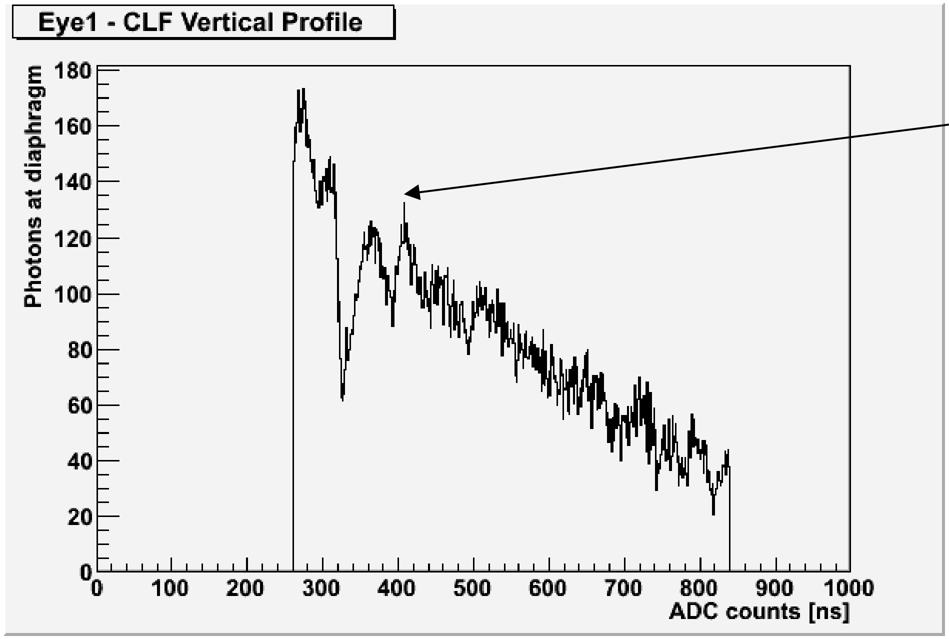


How clouds appear in light profiles ...

PEAK
in case of a cloud directly above the laser beam.

It scatters more light in the telescopes field of view, appearing as a spike in the light profile.





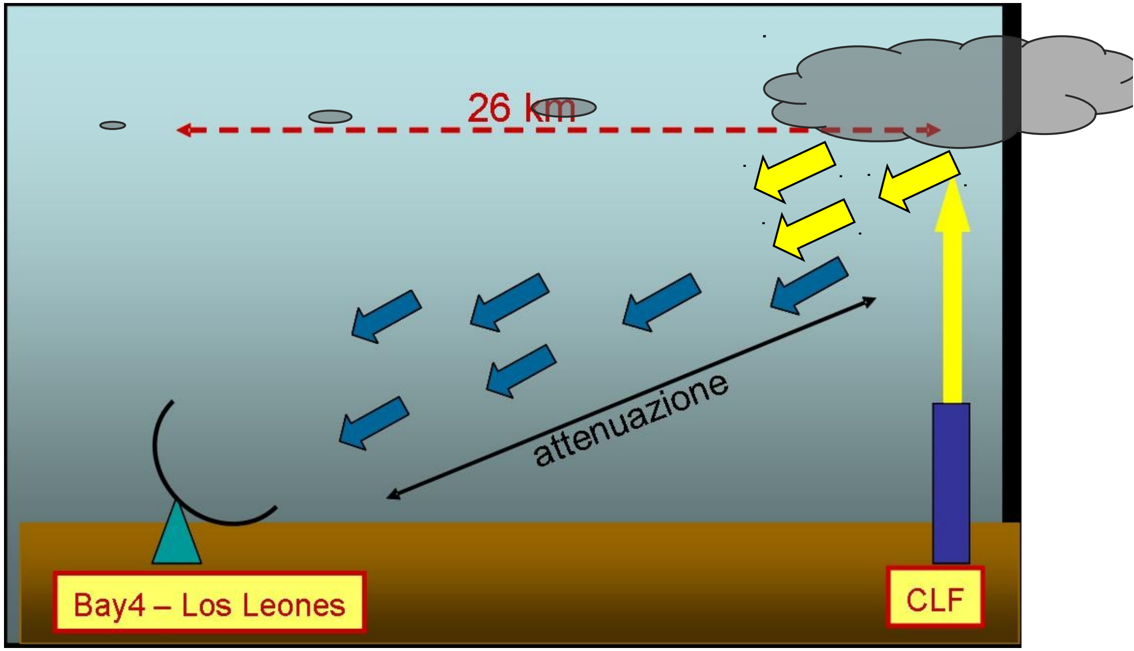
HOLE
in case of a cloud positioned between the laser beam and the telescopes.

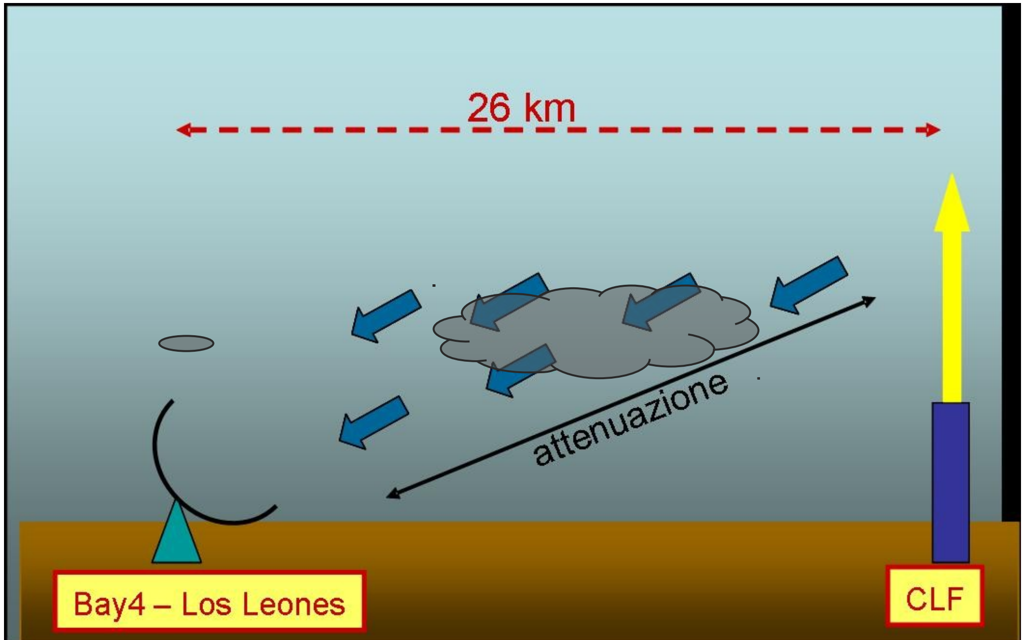
It blocks the light travelling from the laser beam to the detectors and appears as a hole in the light profile.

How clouds appear in light profiles ...

PEAK
in case of a cloud directly above the laser beam.

It scatters more light in the telescopes field of view, appearing as a spike in the light profile.



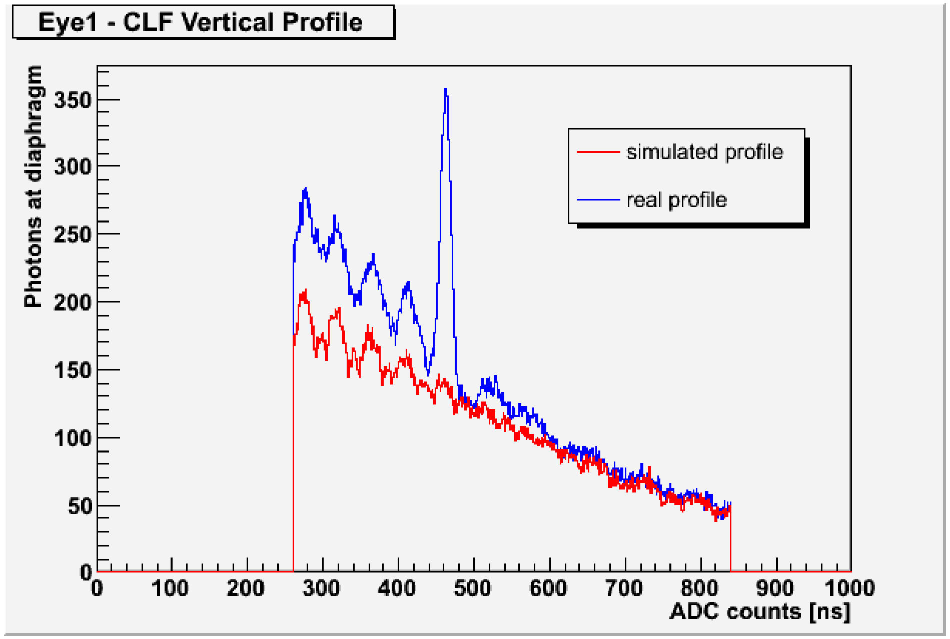


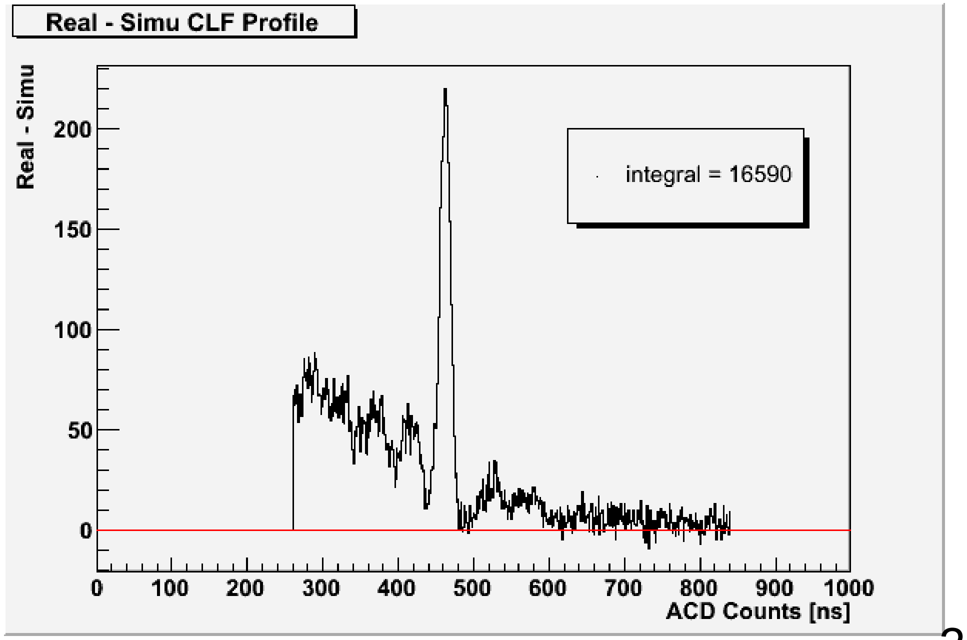
HOLE
in case of a cloud positioned between the laser beam and the telescopes.

It blocks the light travelling from the laser beam to the detectors and appears as a hole in the light profile.

The cloud identification method

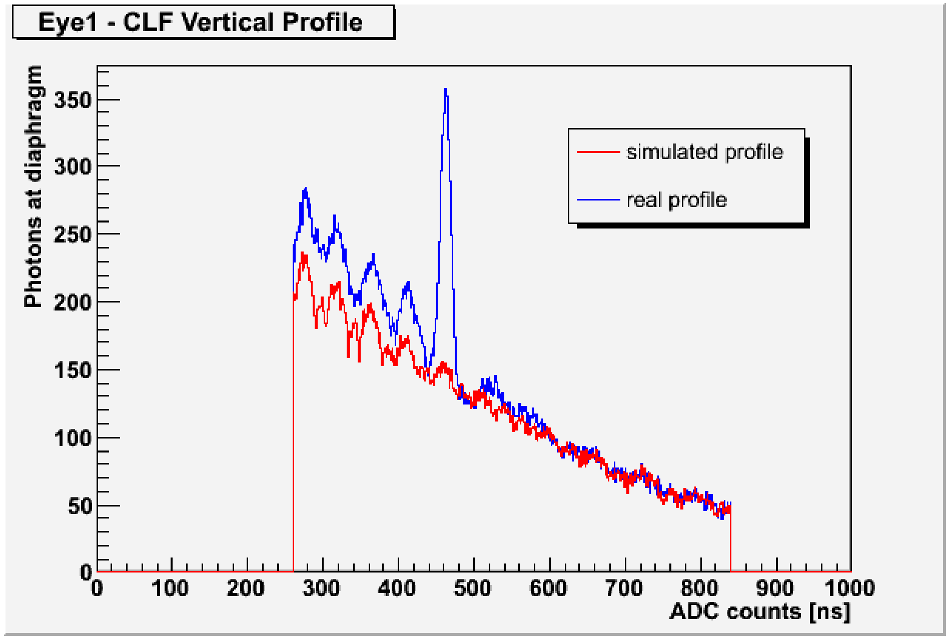
- In the Laser Simulation analysis, each quarter-hour CLF average profile is compared to the whole grid of simulated profiles
- for each simulated profile, we compute a histogram of the difference between the real and simulated profile (for each bin)
- the integral of the histogram is computed

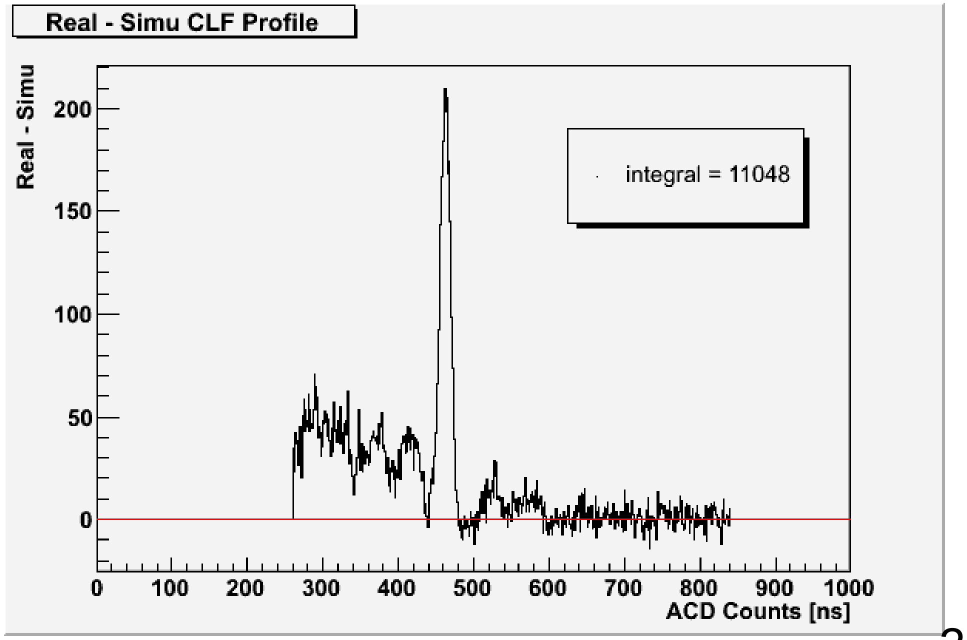




The cloud identification method

- In the Laser Simulation analysis, each quarter-hour CLF average profile is compared to the whole grid of simulated profiles
- for each simulated profile, we compute a histogram of the difference between the real and simulated profile (for each bin)
- the integral of the histogram is computed





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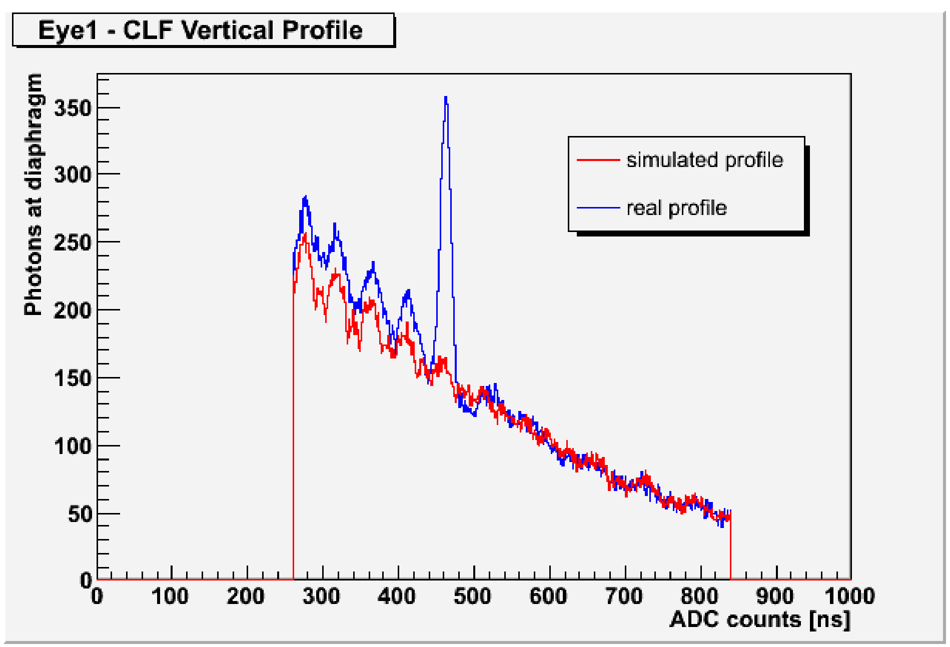

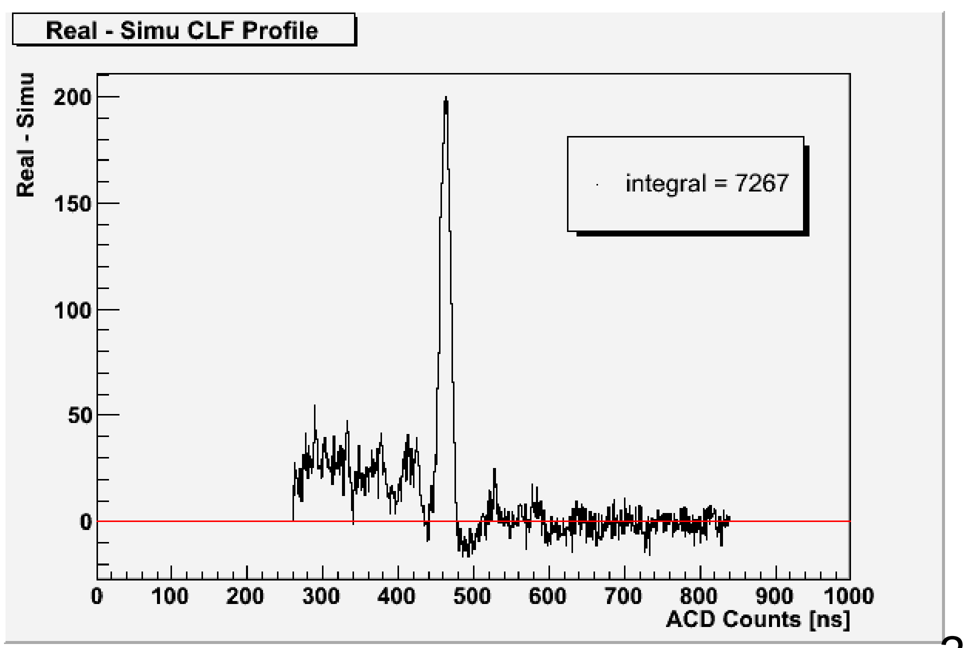

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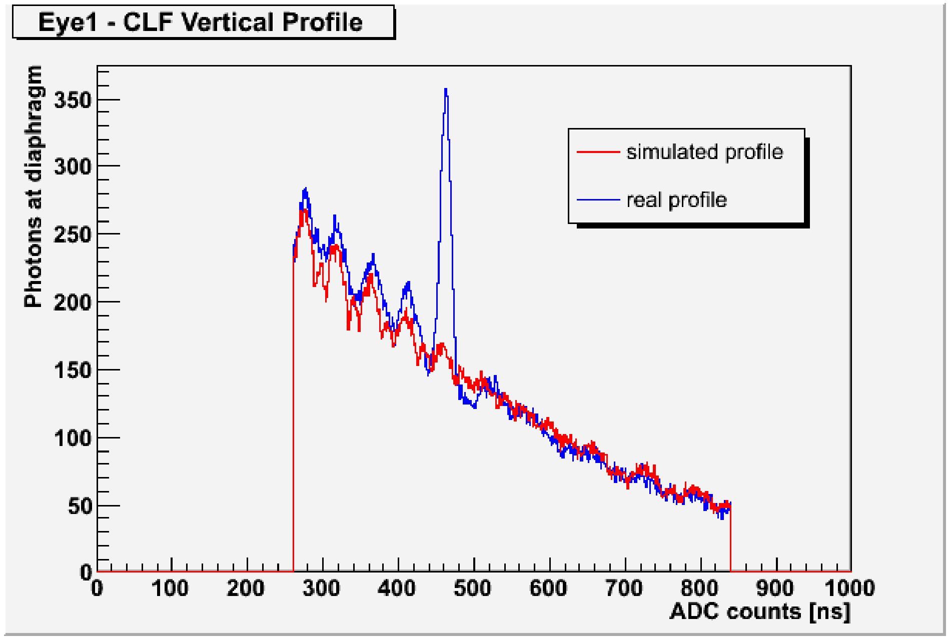

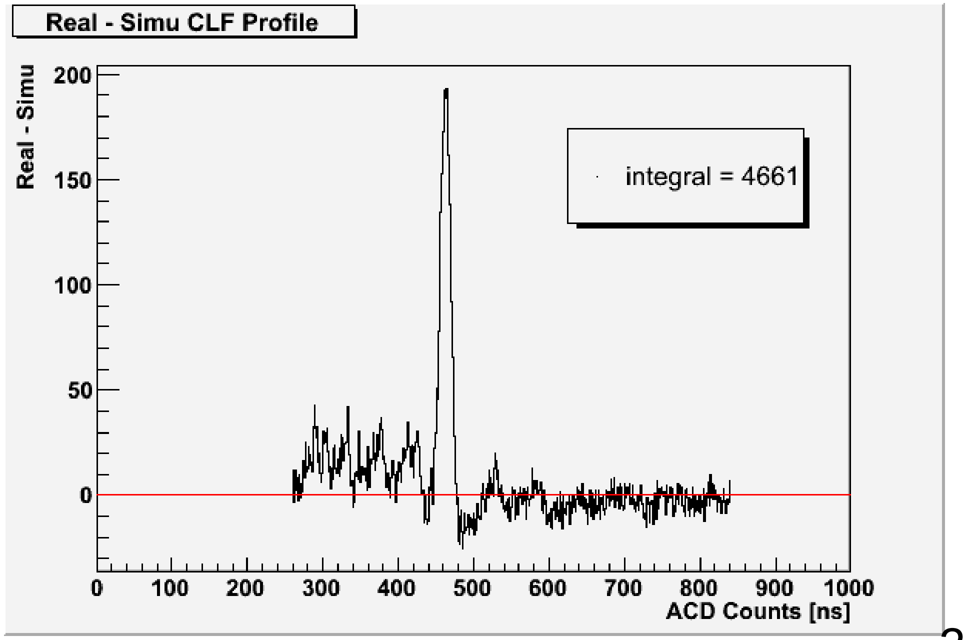

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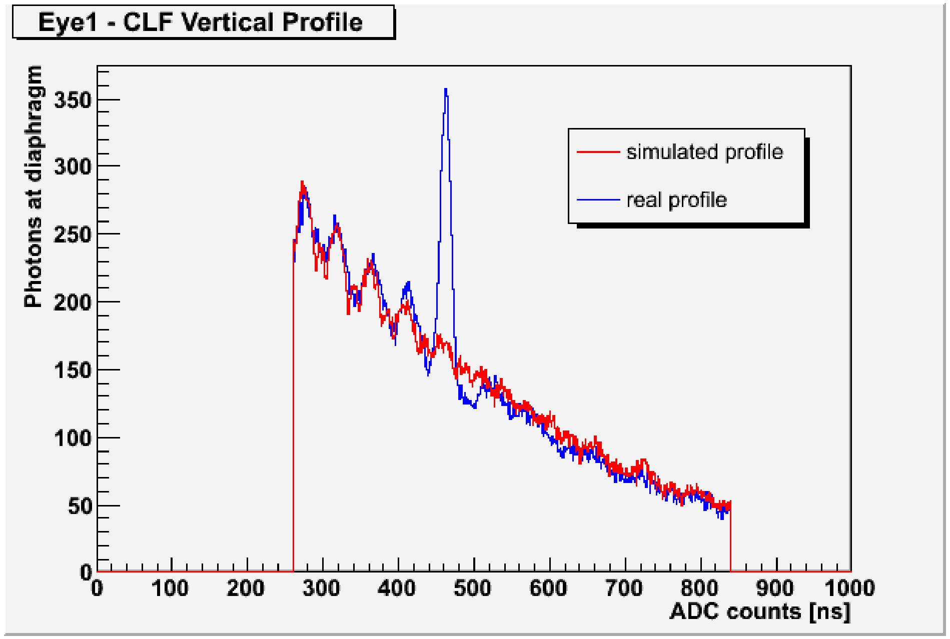

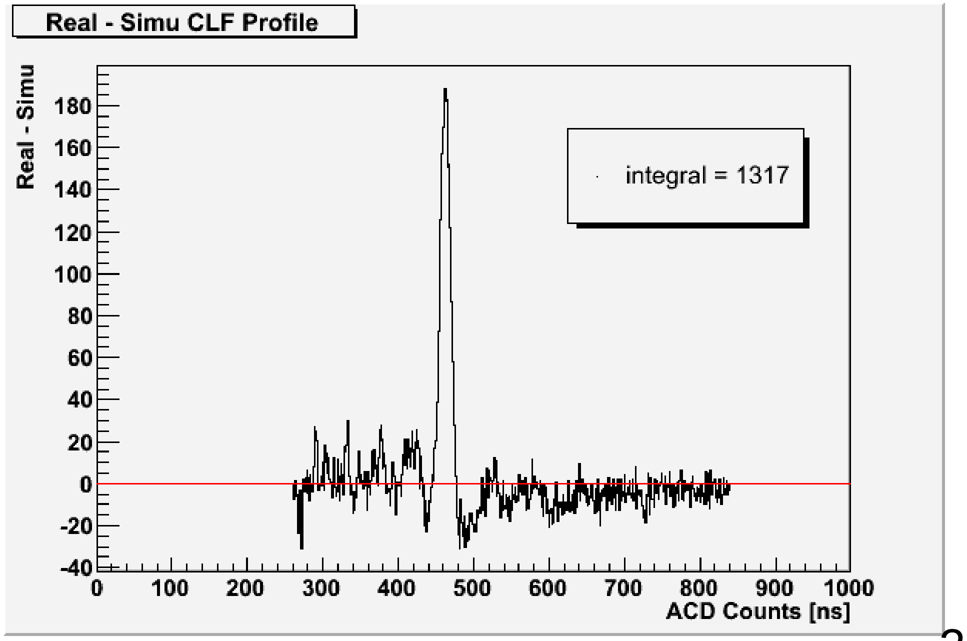

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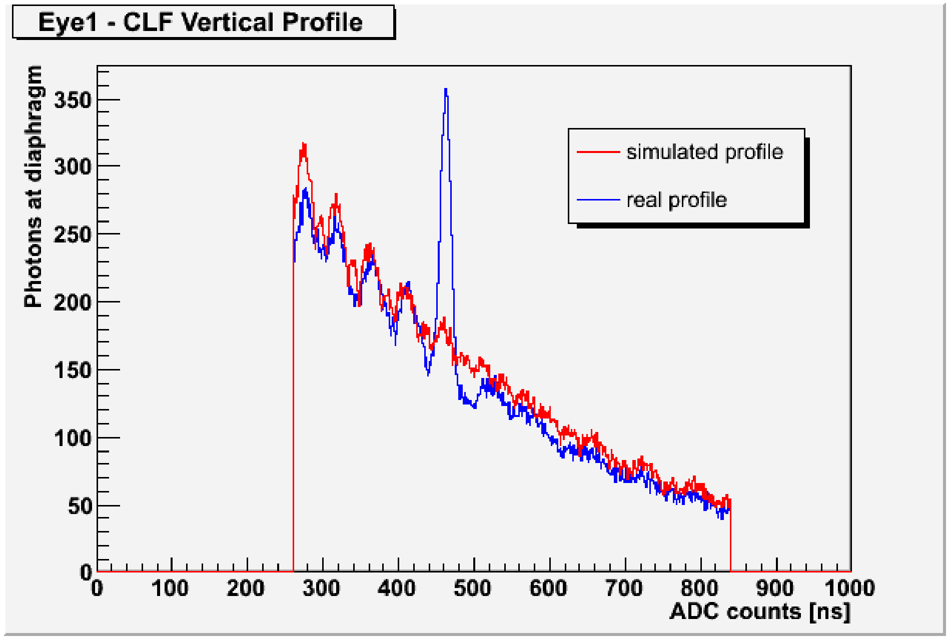

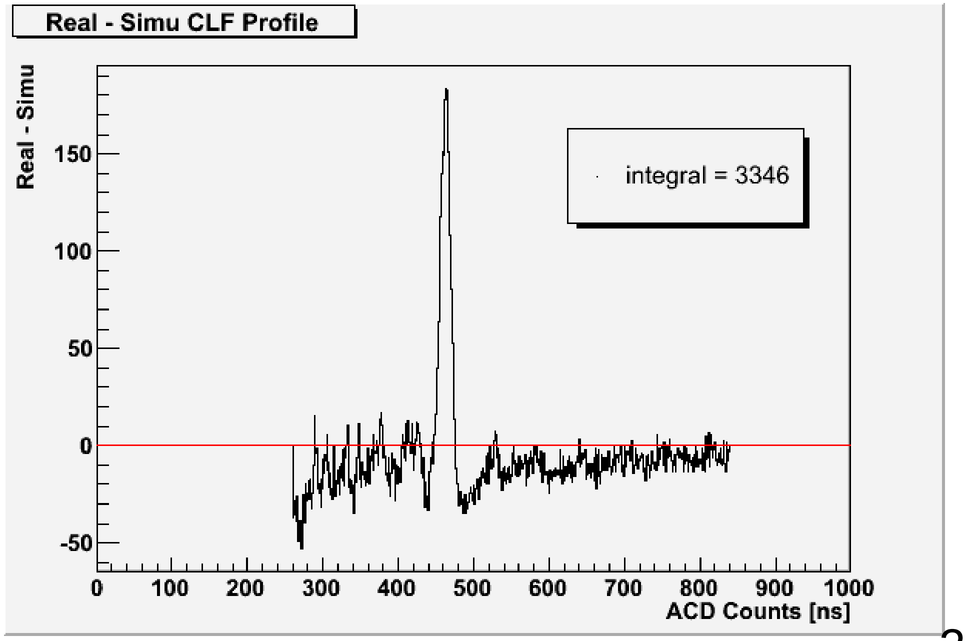

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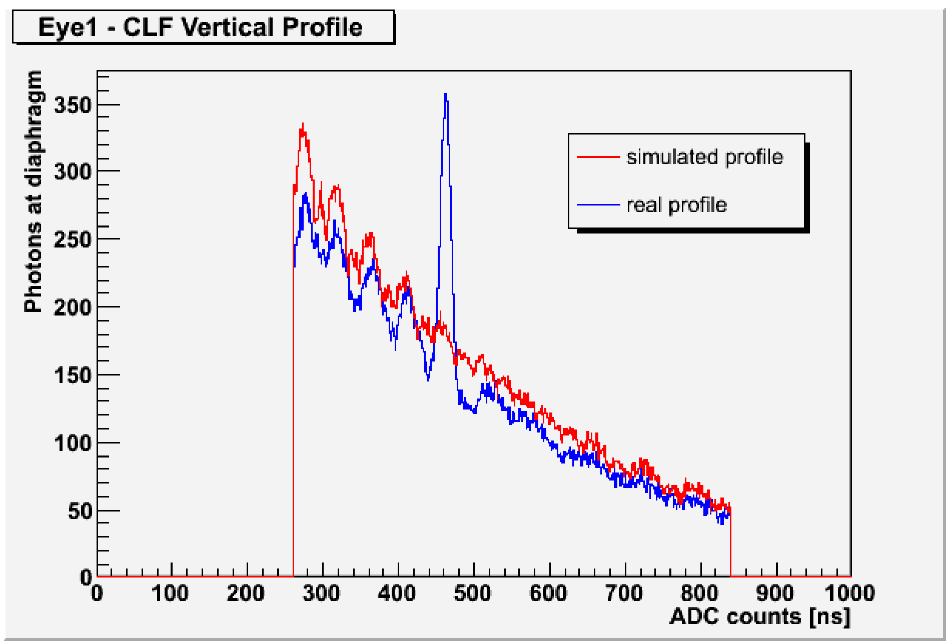
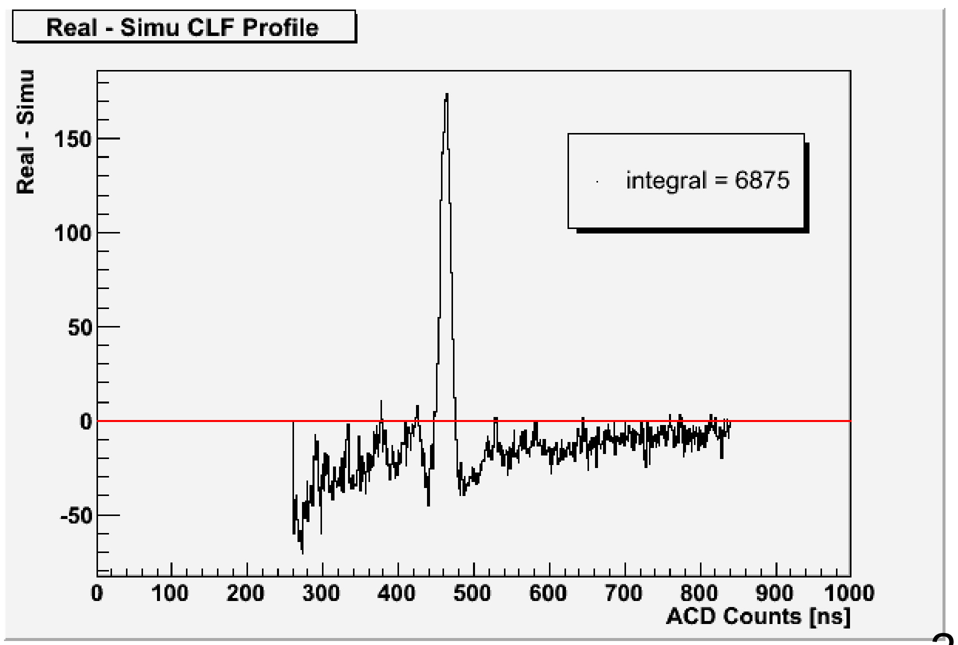
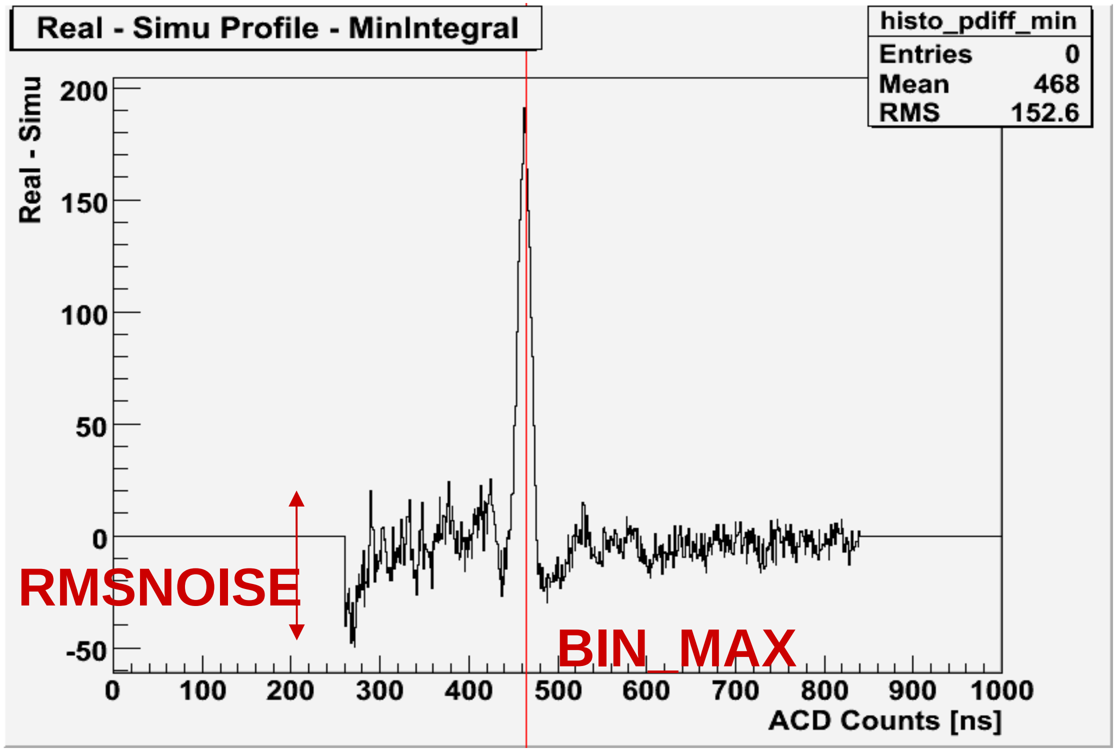




The cloud identification method

The profile providing the minimum integral is chosen. The baseline is close to zero and the peaks and holes in the signal are clearly visible. The signal to noise ratio and the highest/lowest signal are used to mark the cloud lowest layer height, and the maximum height of the aerosol profile measured.



Statistical and systematic uncertainties

Various uncertainties were identified in the methods fot the determination of the τ_{aer}(h), that are listed below.

The uncertainties are separated into statistical and systematic contributions.

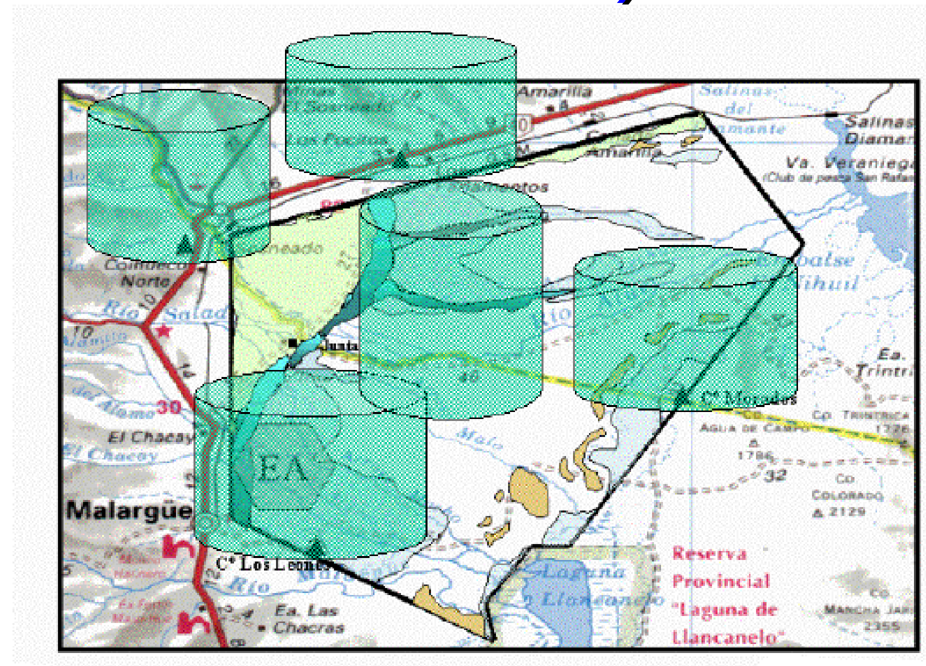
Assignments were based on whether the effect of the uncertainty would be correlated over a given shower data sample, or largely uncorrelated from one air shower event to the next.

	Correlated	Uncorrelated
Relative FD Calibration	2%	4%
Relative Laser Energy (CLF)	1 - 2.5%	2%
Relative Laser Energy (XLF)	1%	2%
Reference Clear Night	3%	-
Atmospheric Fluctuations	-	3%

Table 1: List of uncertainties in the determination of the $\tau_{aer}(h)$ profiles (see text).

The Pierre Auger Observatory Aerosol Database
(containing 12 years of data : 2004-2015)

The Pierre Auger Observatory Aerosol Database is described by 5 vertical sections, on for each FD site + one at the center of the array.

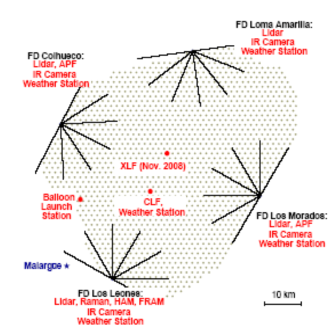


Each section is filled with α(h) and τ_{aer}(h) in steps of 200 m, once per hour.

Due to the distance, CLF data are analyzed to produce aerosol attenuation profiles for the correction of events detected at Los Leones (26 km), Los Morados (30 km) and Coihueco (30 km).

XLF data are used for Loma Amarilla (28 km), Los Morados (31 km) and Coihueco (30 km).

When no aerosol data are available from the main laser facility, data from the other are used. Full compatibility was proven.



90% of the data are from the DN technique, 10% from LS

9 years of aerosol attenuation profiles

The hourly aerosol attenuation have been measured using the two analyses described. The compatibility of the results obtained is shown

The spread of the points is within the systematic error bands.

More than 6000 hours are shown in this plot.

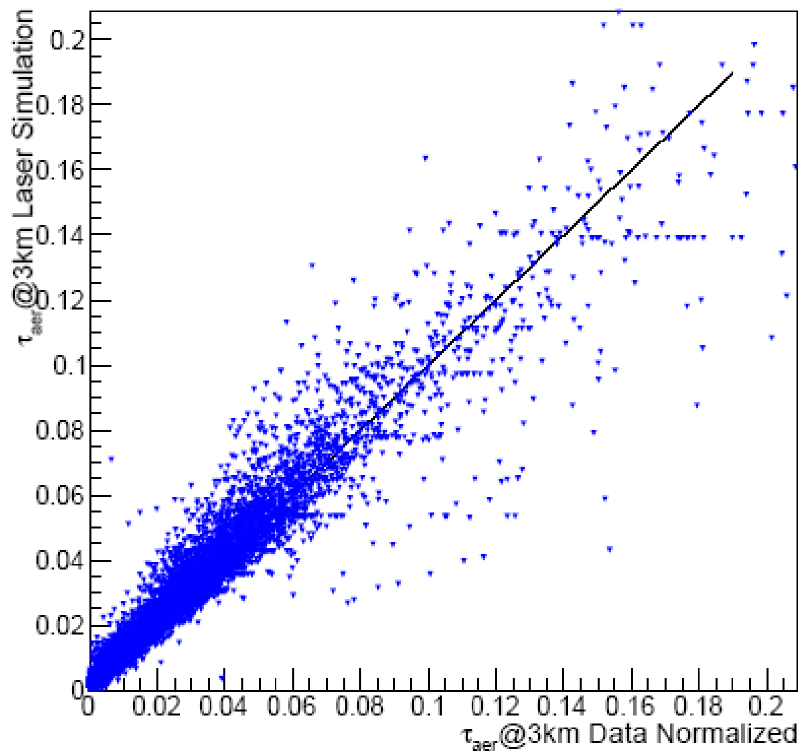


Figure 5: Comparison of Vertical Aerosol Optical Depth at 3 km above ground measured with the two analyses for the Coihueco site. 9 years of data are shown.

An example of aerosol attenuation profile in average aerosol attenuation conditions measured with the two analyses described, together with correlated (systematic) and uncorrelated (statistical) errors

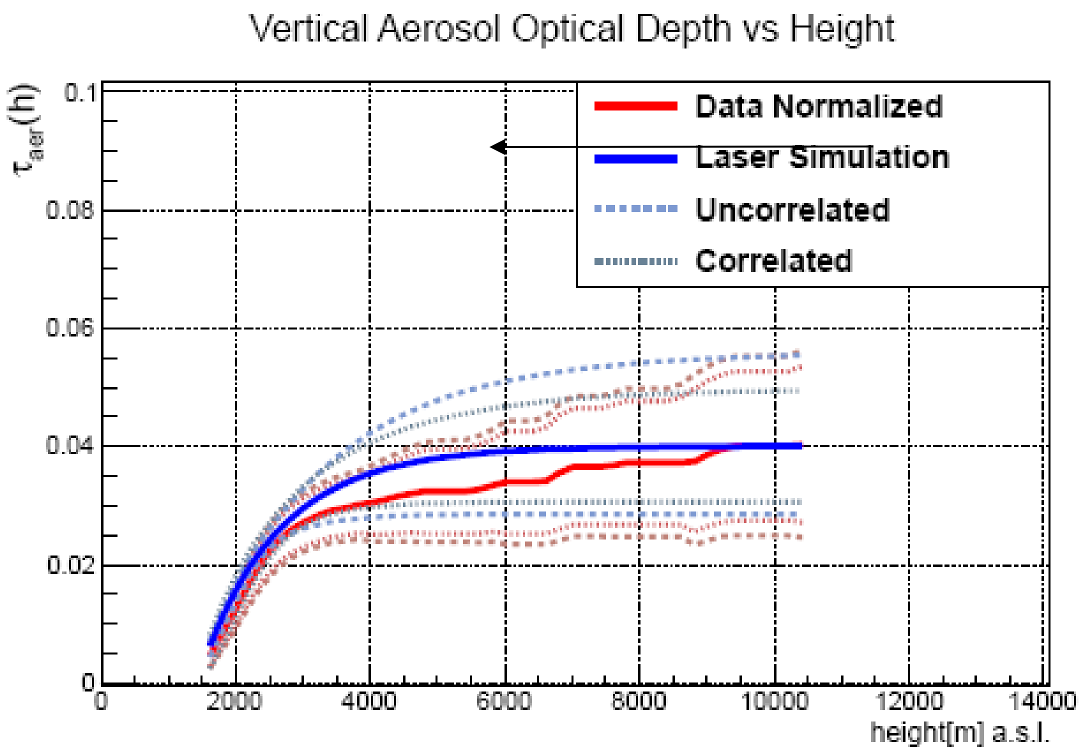


Figure 6: Hourly aerosol profiles measured with the Data Normalized (red) and Laser Simulation (blue) analyses in average conditions. Correlated and uncorrelated uncertainties are shown.

9 years of aerosol attenuation profiles measured .

Results from the two analyses (DN + LS) are used for showers analysis

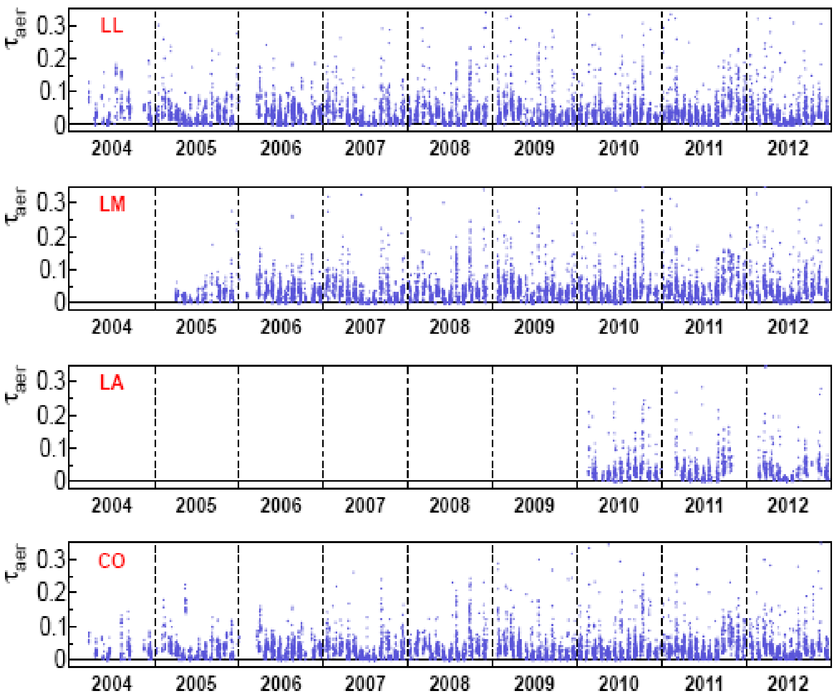


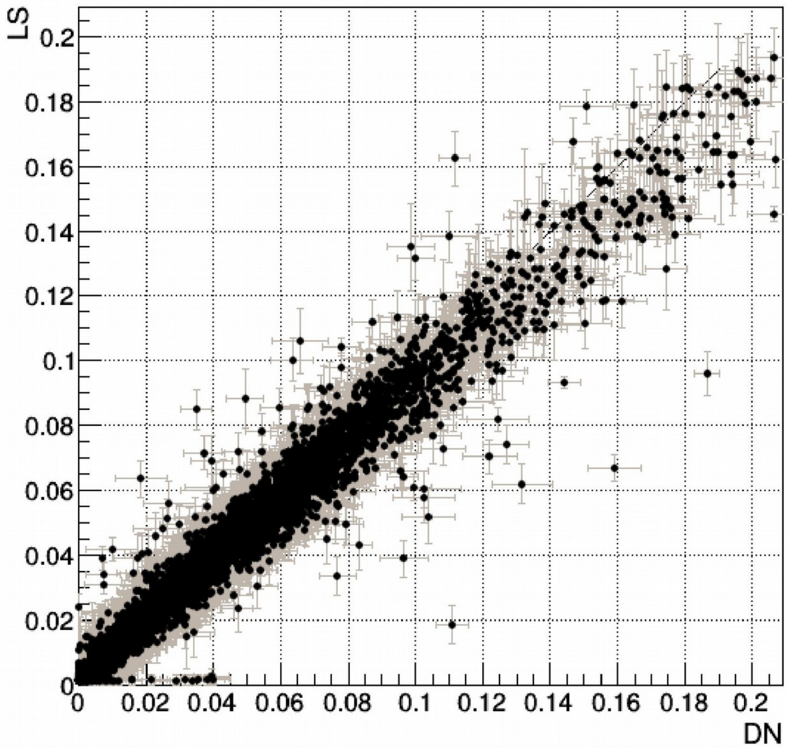
Figure 7: 9 years of τ_{aer} measured at 3km above ground.

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
→ Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

12 years of data → 2004 - 2015

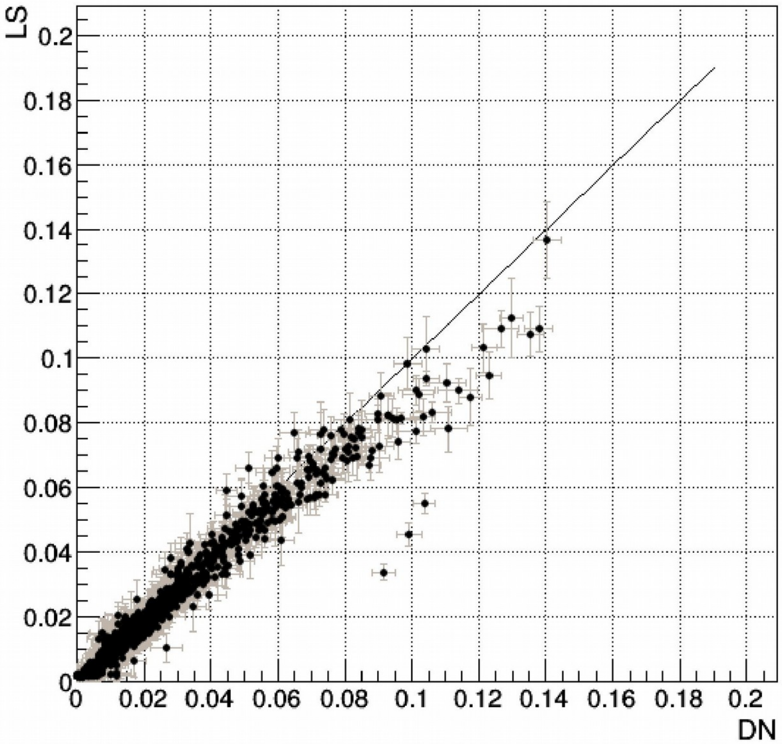
Laser Simulation and Data Normalized VAOD @ 3km comparison

2004 - 2015



CLF

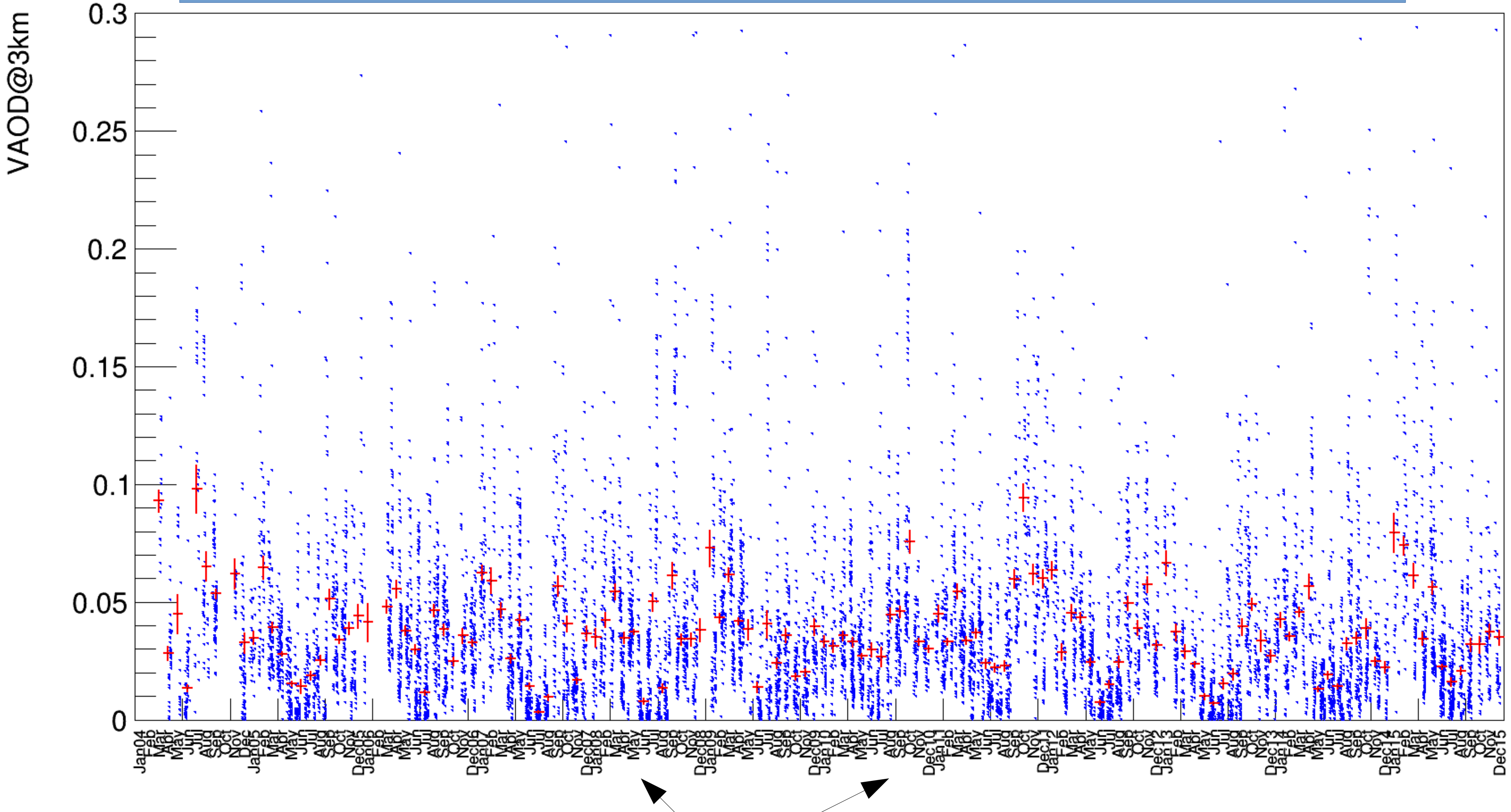
2010 - 2015



XLF

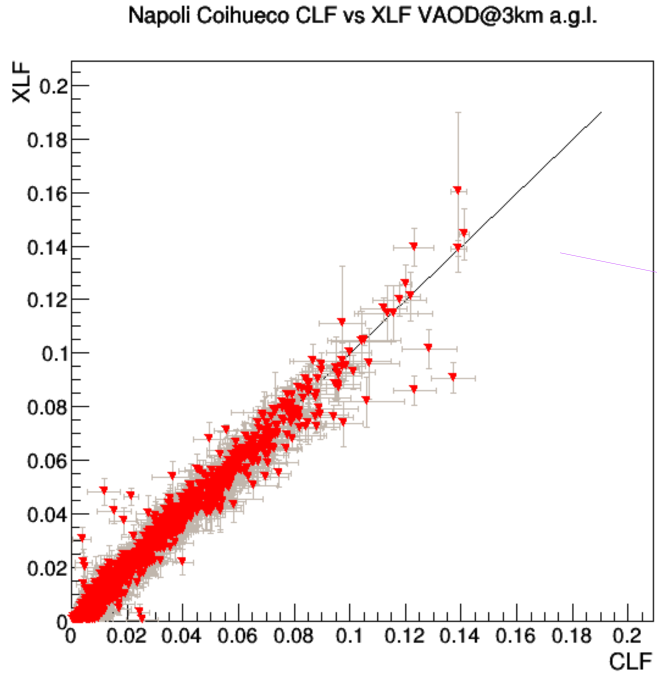
8

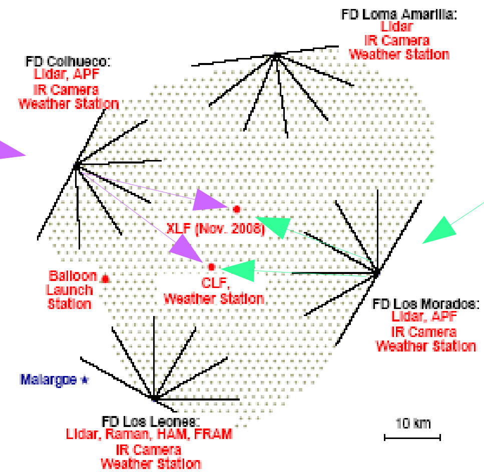
VAOD @ 3km – Los Leones – 2004 - 2015

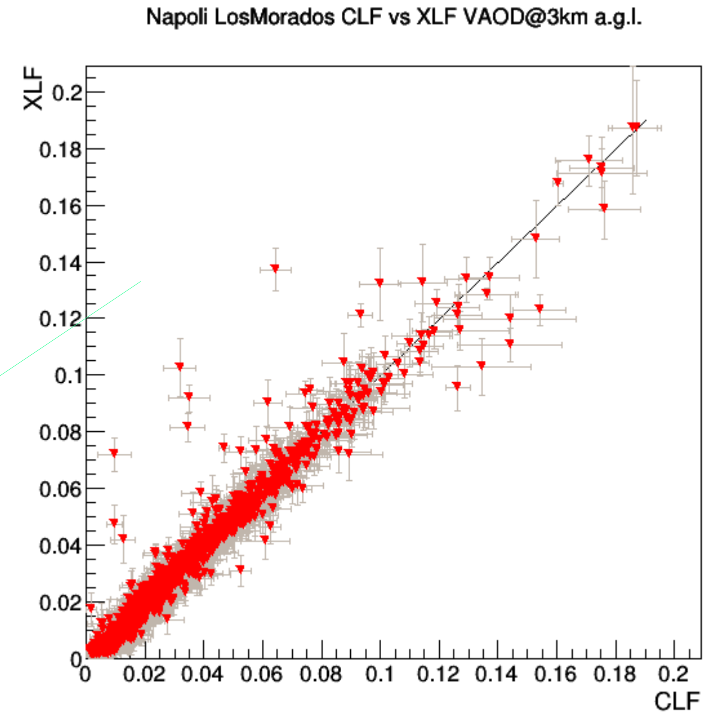


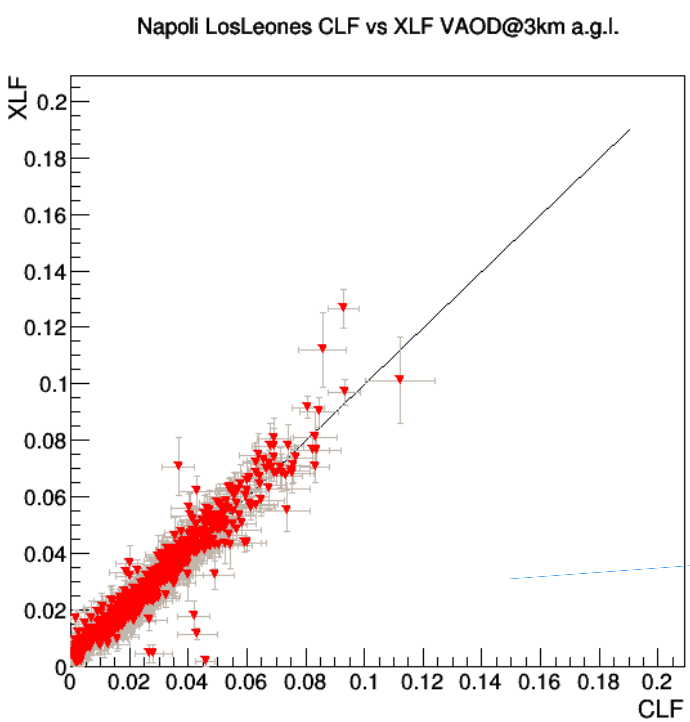
Seasonal behaviour clearly visible

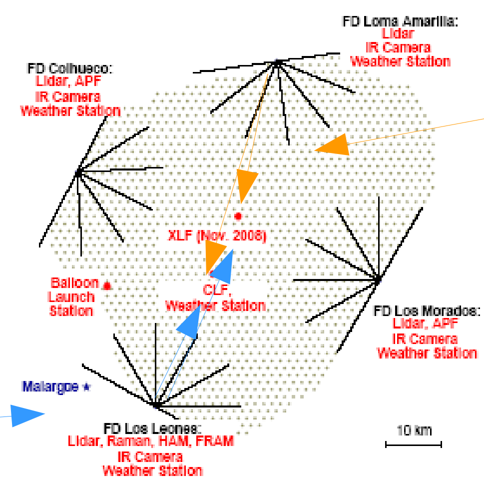
CLF vs XLF for the same hours

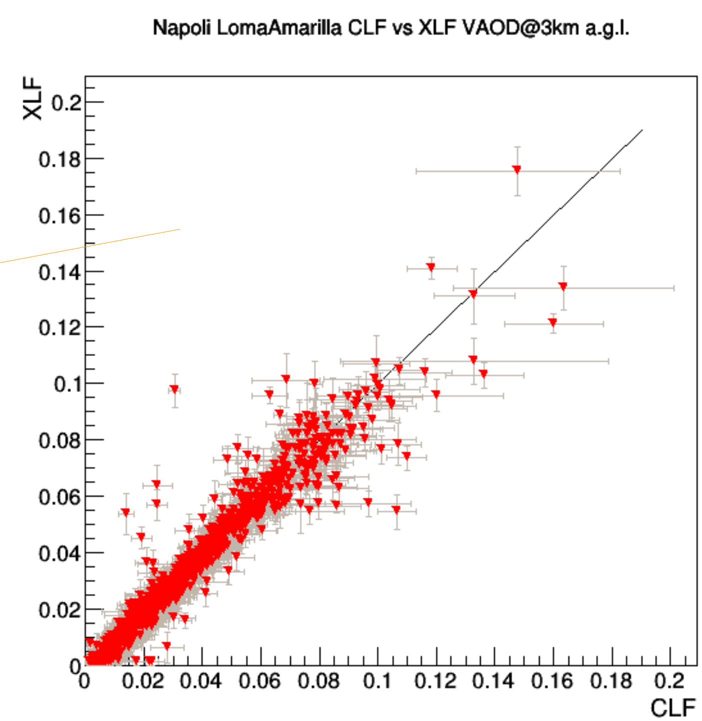






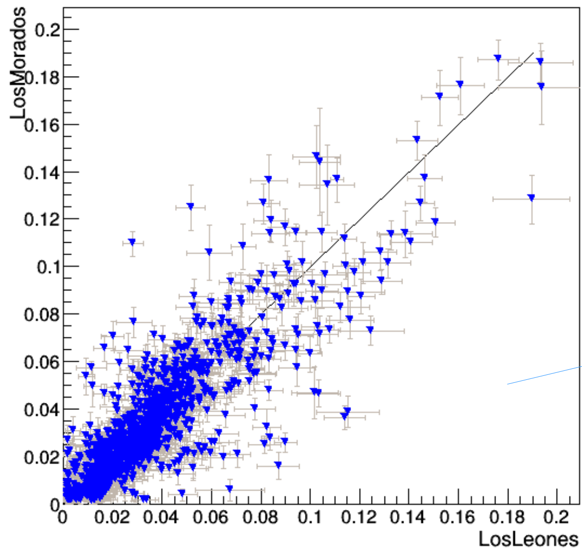


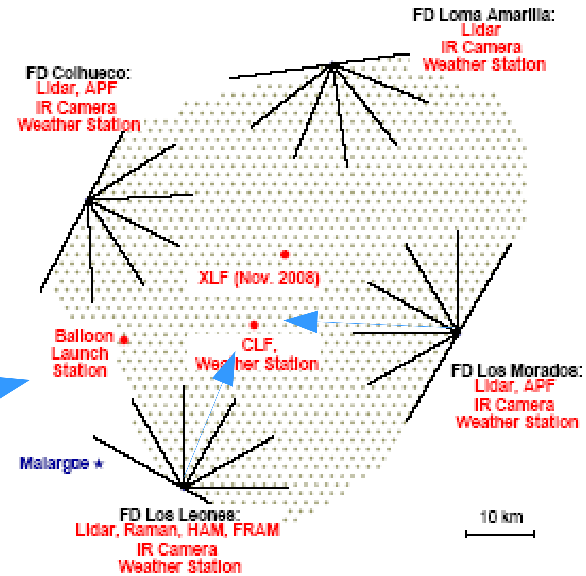


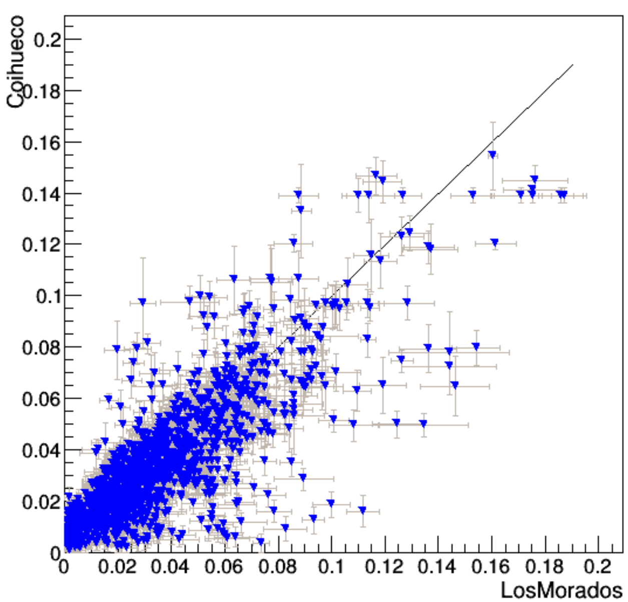


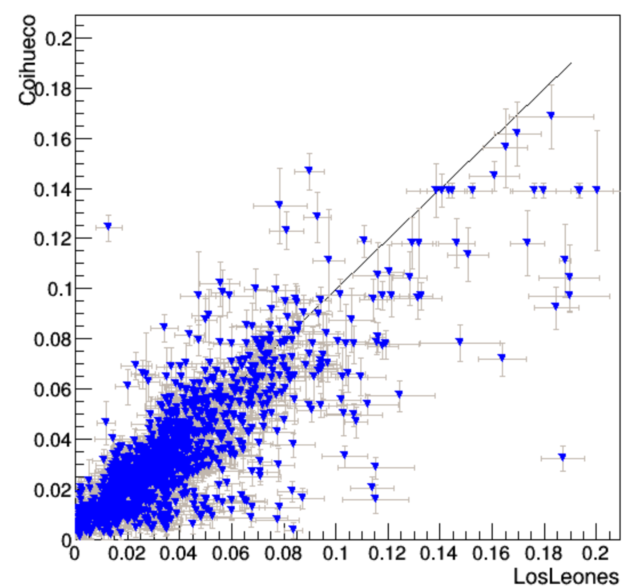
Same laser, different telescopes

correlation is not bad, looking at different regions



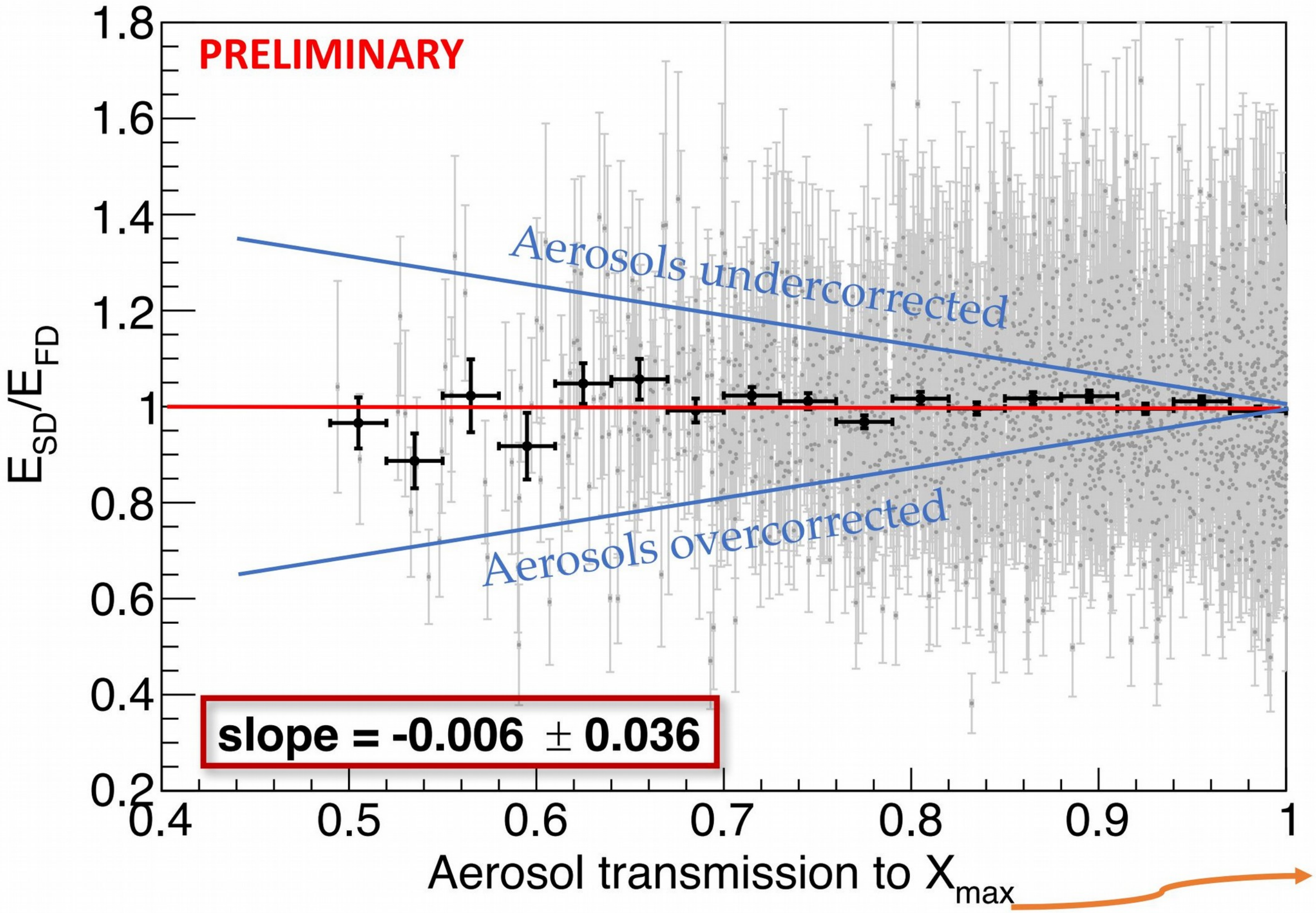






Internal consistency check

- Valid description of the aerosol atmosphere → E_{SD}/E_{FD} no dep. on $T_A(X_{max})$.



Proxy for the total aerosol loading between the FD and the brightest part of the shower

Internal consistency within reconstructed data

Conclusions

- The two techniques used to produce aerosol attenuation profiles of the fluorescence light are stable, compatible and producing results since 2004
- 90% of the data come from the DN technique, 10% from the LS which is used to fill the gaps
- Internal consistency checks have proven the validity of the results
- More cross checks with other instruments of the Auger Atmospheric Monitoring System are forthcoming