Karlsruhe Institute of Technology

PIERRE AUGER OBSERVATORY

Atmospheric monitoring at the Pierre Auger Observatory and effects of aerosol attenuation on UHECR detection

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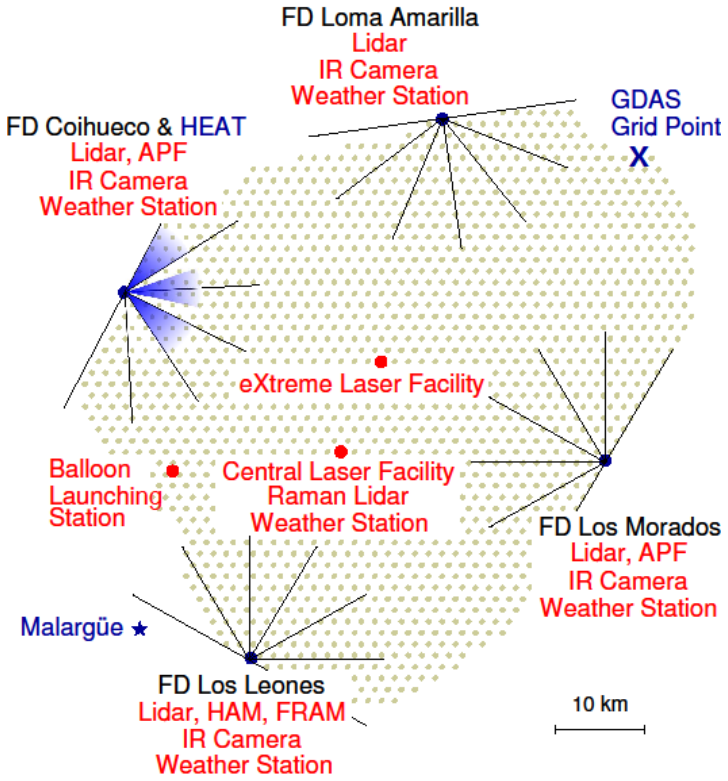
Atmospheric monitoring at the Auger Observatory

Main instruments for recording

- Aerosols
  - CLF / XLF
  - Elastic lidars
  - Raman lidar
- Clouds
  - IR Cameras
  - Elastic lidars
  - CLF / XLF



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Elastic lidars ☞ Roberto Mussa, Thursday afternoon

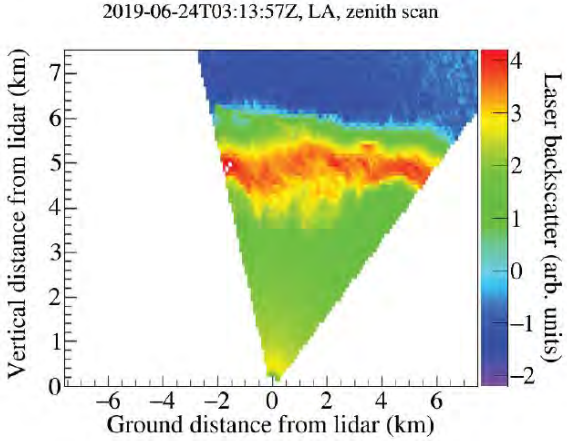
Raman lidar ☞ Vincenzo Rizi, Thursday afternoon

Cloud monitoring

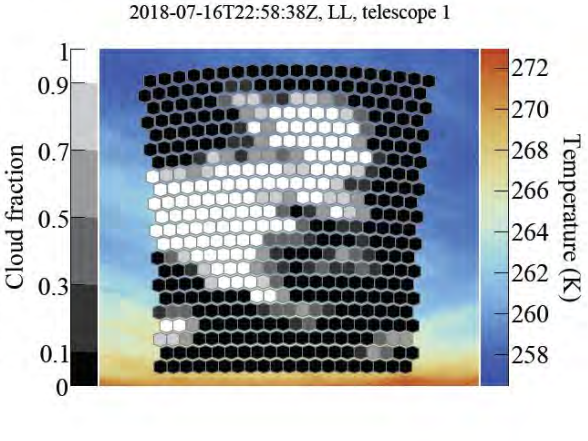
Instruments on side

- IR Cameras – every 5 - 15 min.
- Elastic lidars – every 15 min.
- CLF / XLF – every hour

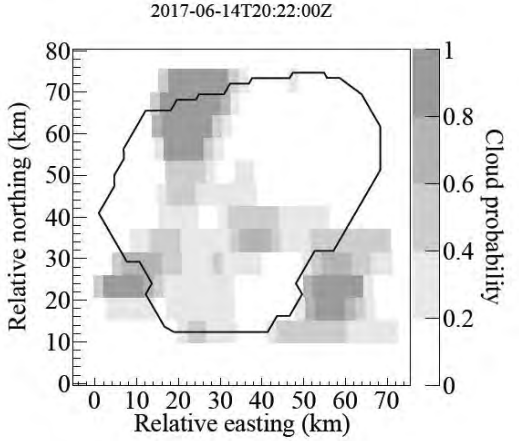
plus GOES satellite data – every 30 min.



(a) FD lidar scan.

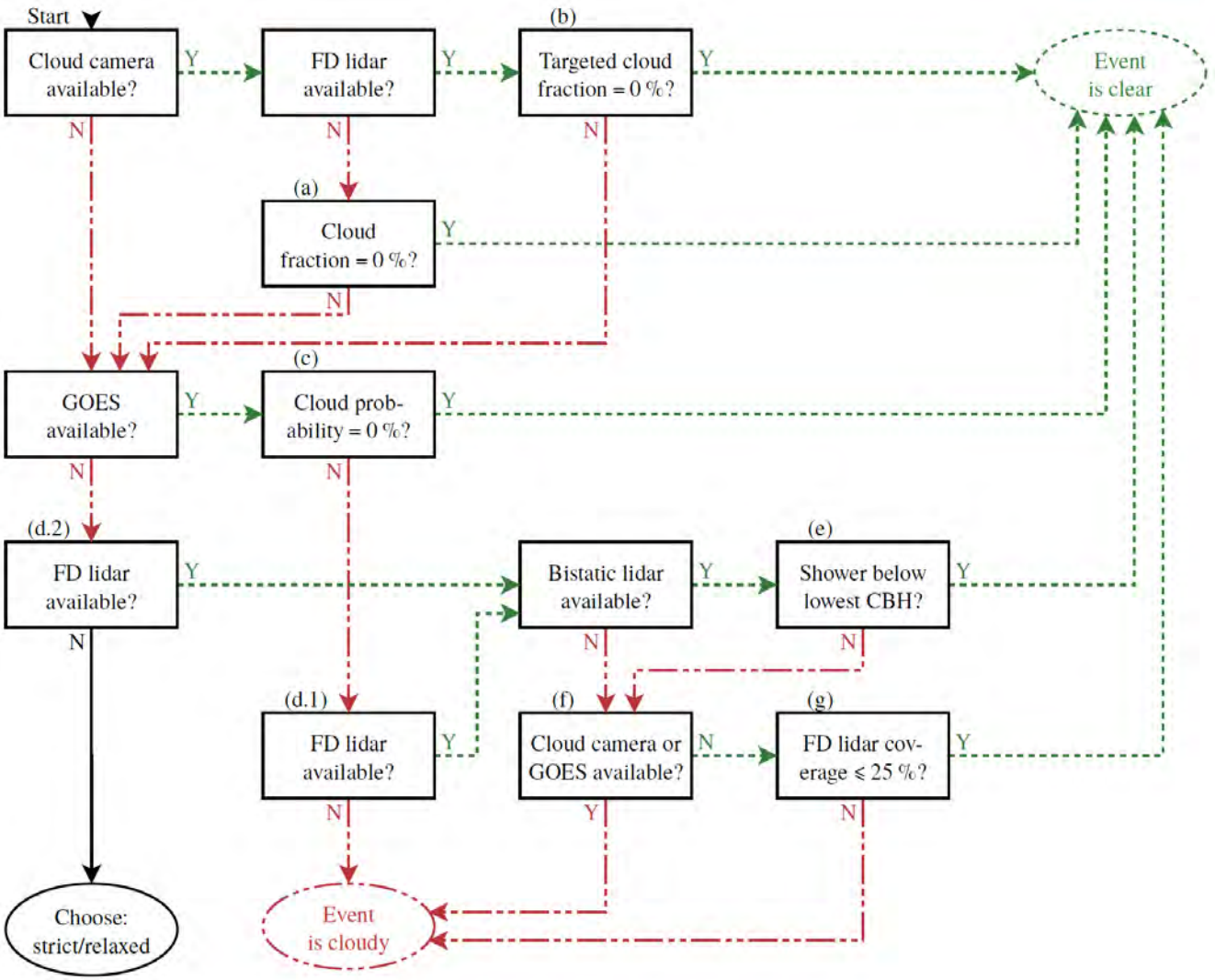


(b) Cloud camera image.



(c) Satellite cloud probability map.

Cloud data in air shower reconstruction



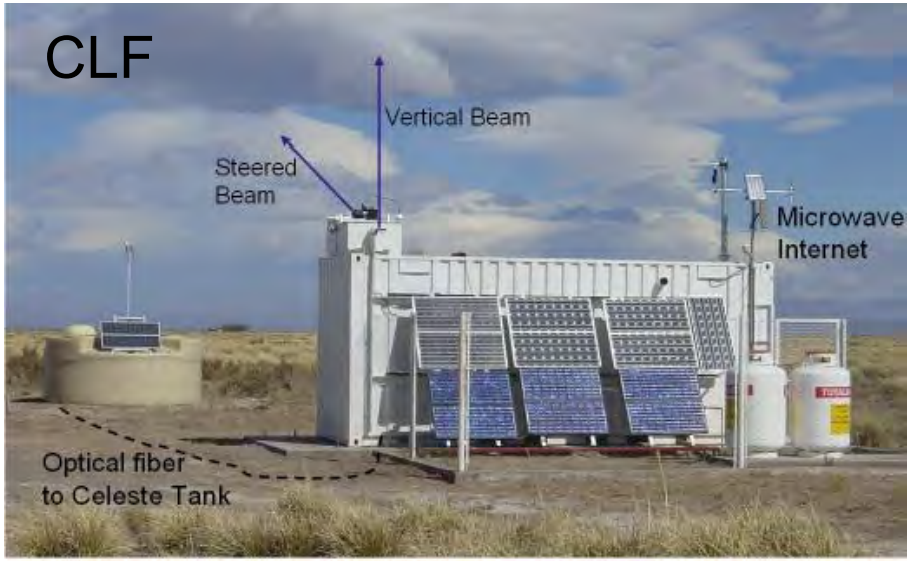
CLF / XLF aerosol measurements

Operating scheme

- During FD data taking
- 50 vertical laser shots every 15 min.
- Fully automated operation

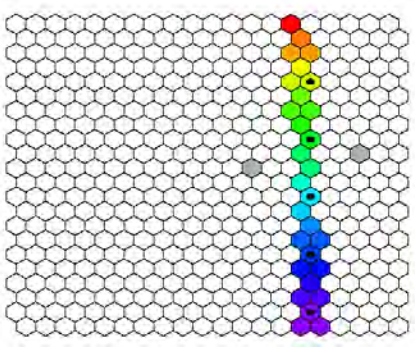
Data output

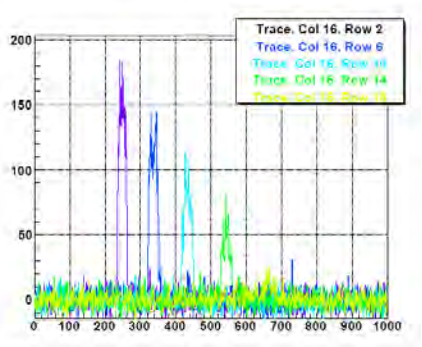
- Hourly averages of VAOD profiles
- CLF data since 2004
- XLF data since 2009
- Standard aerosol information for cosmic ray event reconstruction

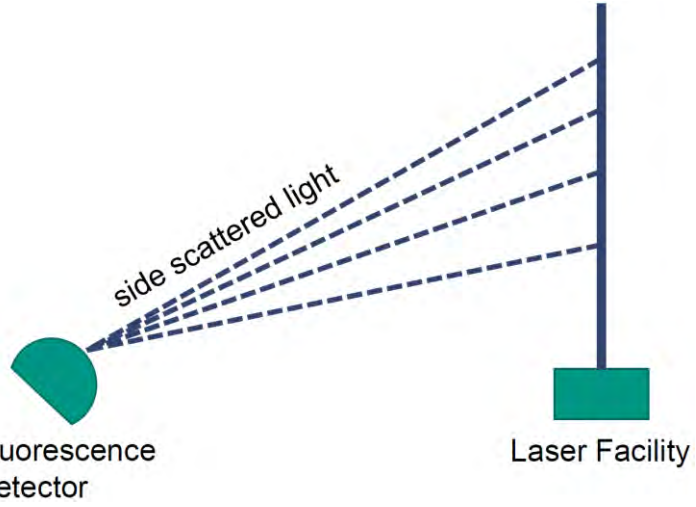


CLF / XLF - Operating scheme

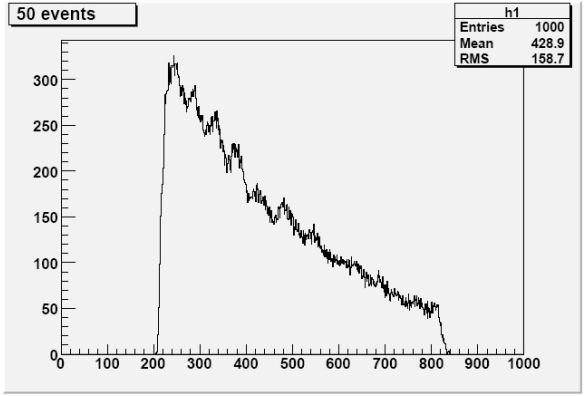
Fluorescence Detector view

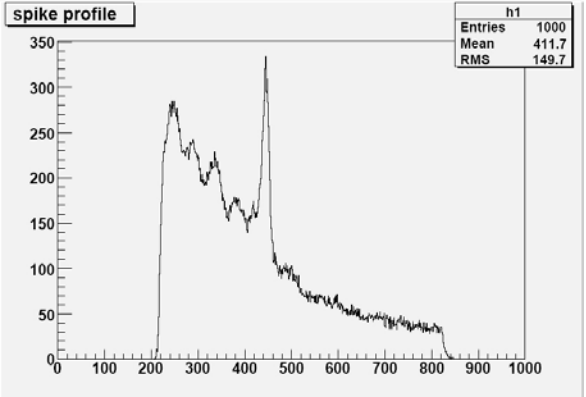






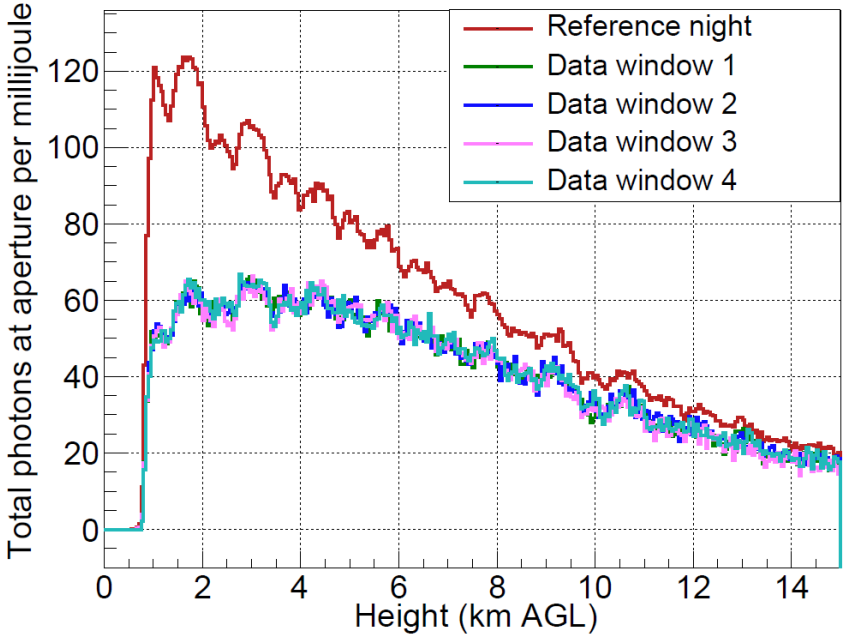
Photons@FD vs time





CLF / XLF – Data Normalized (DN) Analysis

- Measure flux of photons scattered from the laser beam arriving at an FD as a function of height, $N_{data}[h]$
- Compare it to the same observation under “aerosol-free” conditions, when less attenuation will occur, $N_{ref}[h]$
- All other attenuation effects (e.g., Rayleigh scattering from air molecules) cancel out between two light profiles and leave only the form of $\tau_{aer}[h]$, the vertical aerosol optical depth (VAOD)

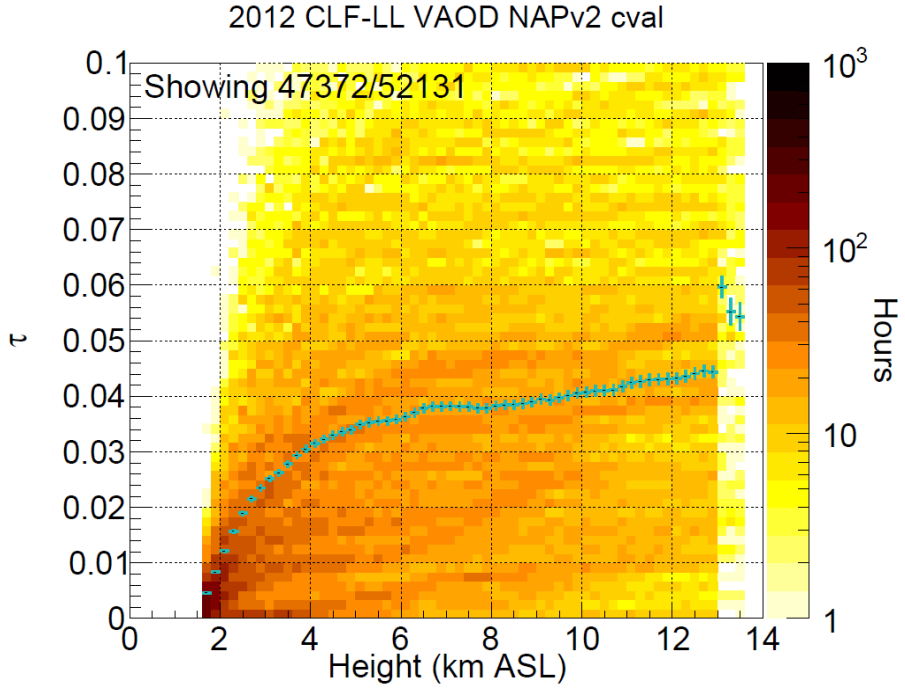


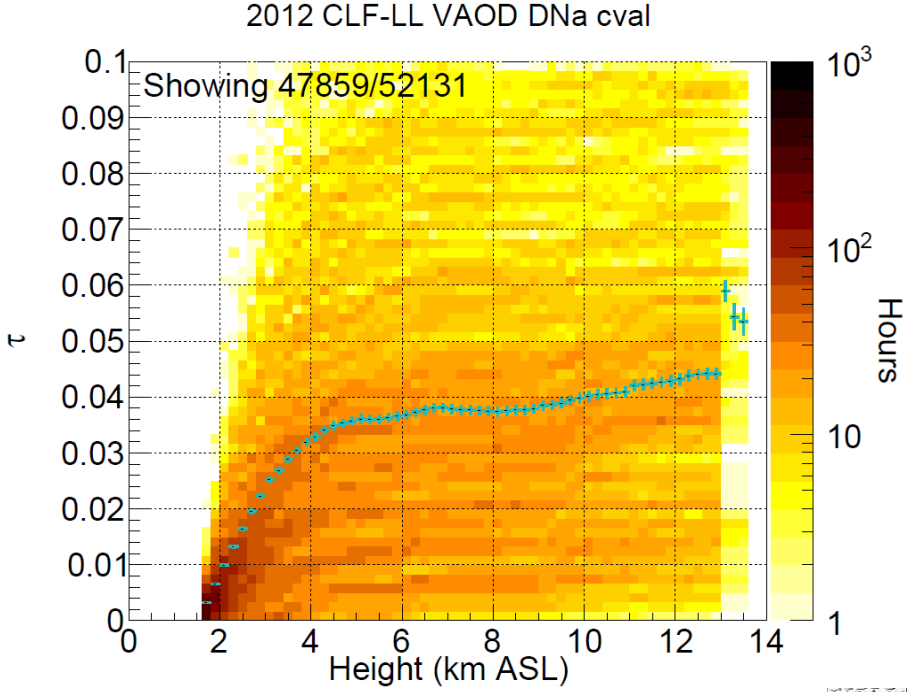
Improvements on DN method for ICRC2019

- Uses full suite of Auger Offline utilities
- Significantly more efficient data flow
- Algorithm improvements:
  - Cloud detection distinguishes hit/block (exact/limit)
  - Smoothing reduces systematic rise in VAOD at high altitude
  - Uncertainty propagation fully reviewed and reimplemented, which corrects issues with artificial structure and overestimated values

Comparison of former and new DN analysis

Central value of VAOD vs height, for LL in 2012





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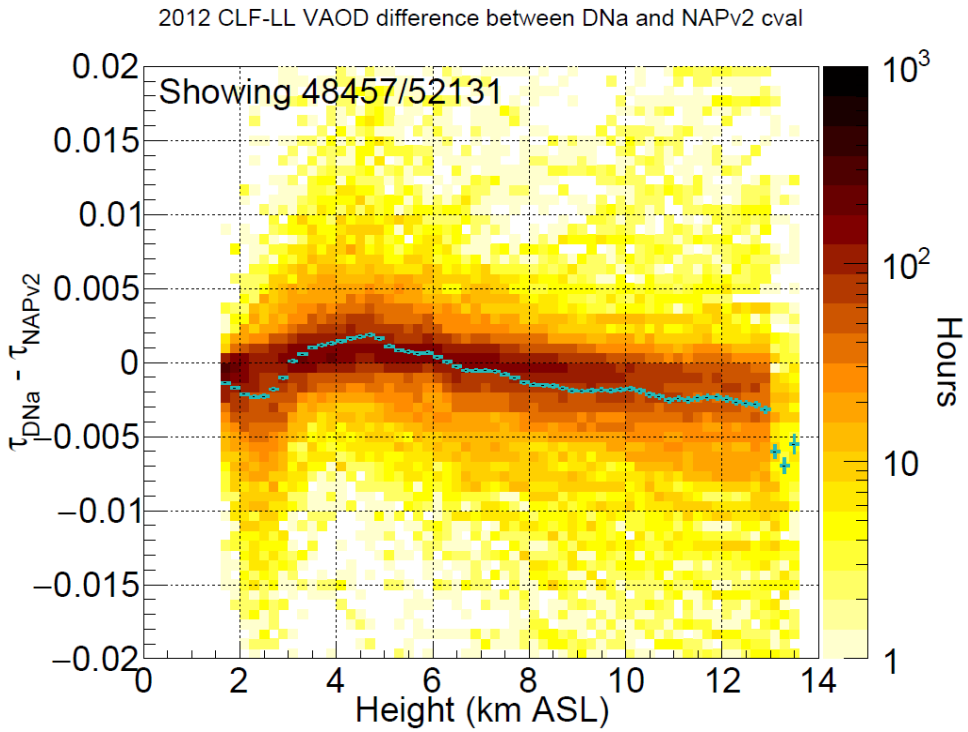


Low:

Change in interpolation; formerly overestimated.

Mid:

Change in light collection; formerly underestimated.

High:

Improved smoothing; formerly overestimated.

Updated uncertainties of DN method for ICRC2019

Uncertainty propagation for the DN method places uncertainties of two types on the two contributing light profiles (ref and data).

Time-correlated uncertainties

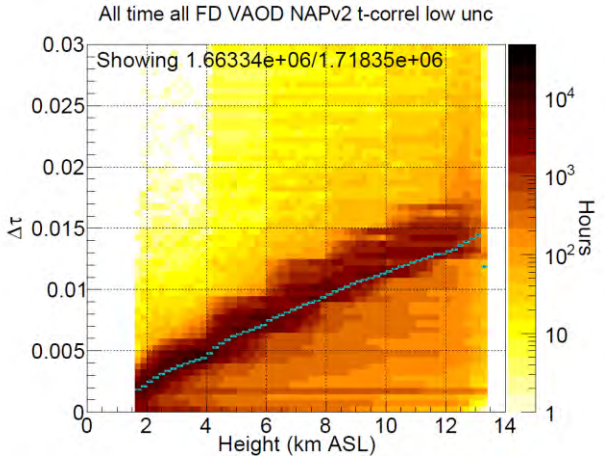
- Correlated with time, i.e. systematic between events.
- Set the coherent shift of the energy scale (accuracy).
- Height-correlated sources:
  - Laser energy (1 % to 2.5 %),
  - FD calibration (2 %),
  - Choice of reference night (3 %; applied only to ref light profile).

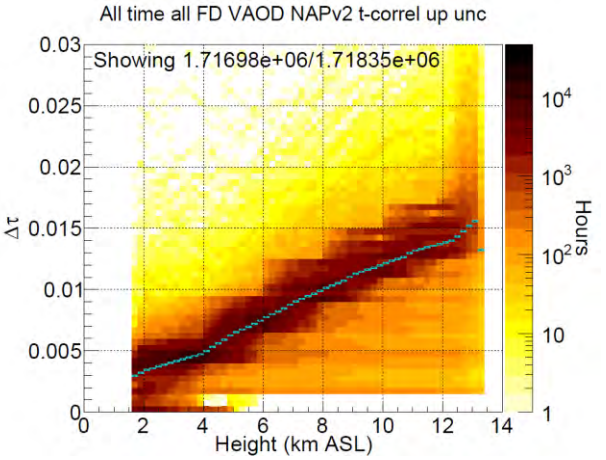
Time-uncorrelated uncertainties

- Independent of time, i.e. random between events.
- Set the spread of the energy scale (precision).
- Height-correlated sources:
  - Laser energy (2 %),
  - FD calibration (4 %),
- Height-uncorrelated source:
  - Standard deviation of quarter-hourly light profiles in each hourly light profile (∼3 %)

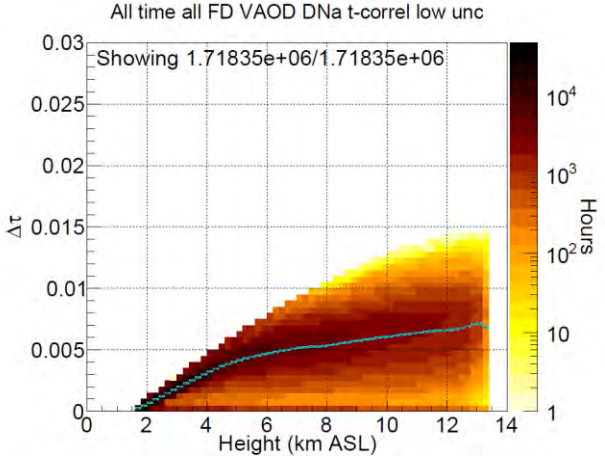
Comparison of systematic uncertainties

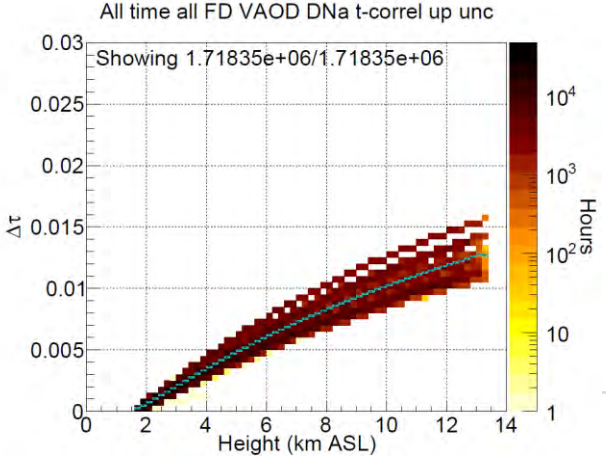
former DN





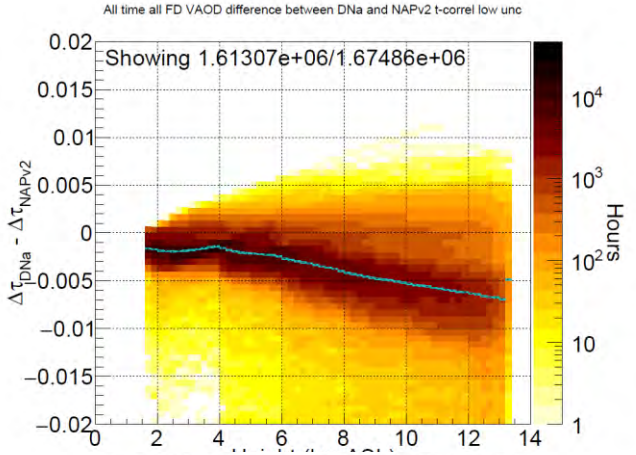
new DN

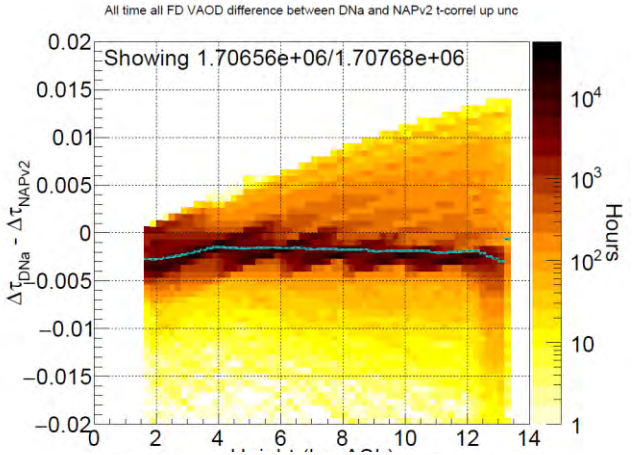




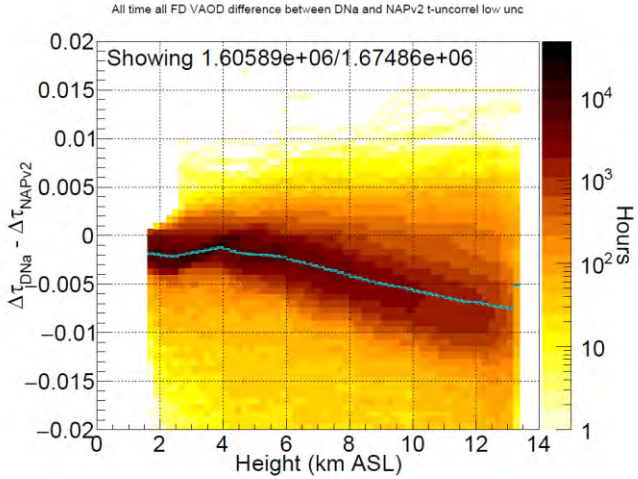
Comparison of syst. and stat. uncertainties

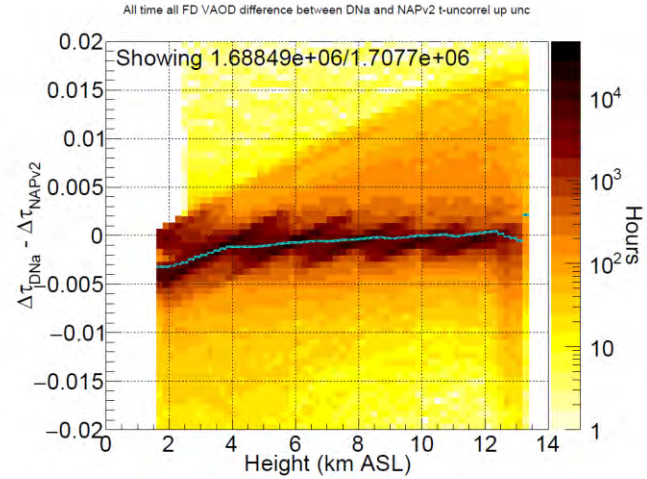
Systematic uncertainties





Statistical uncertainties



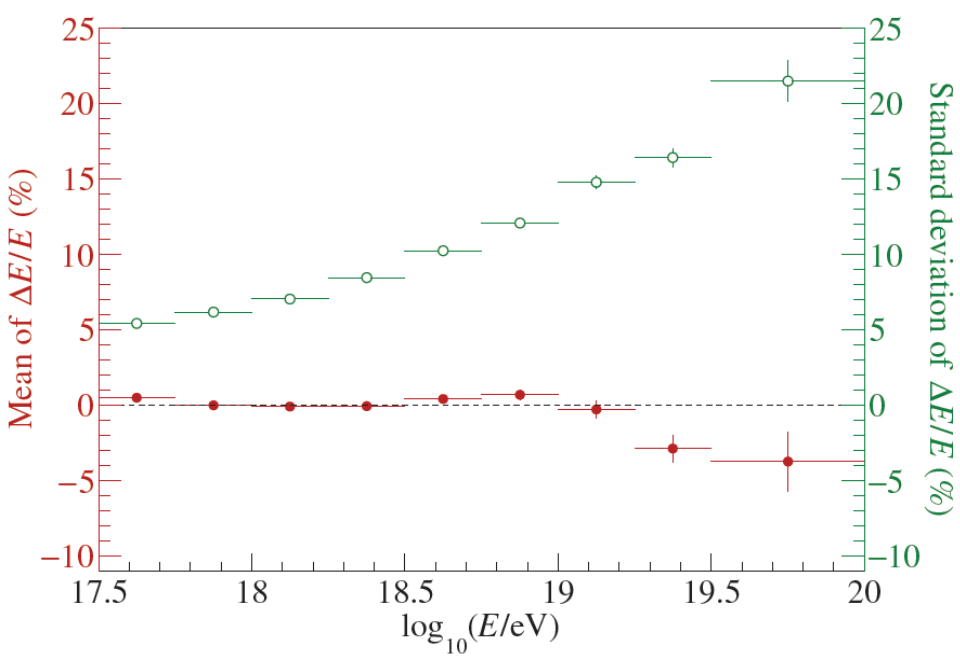


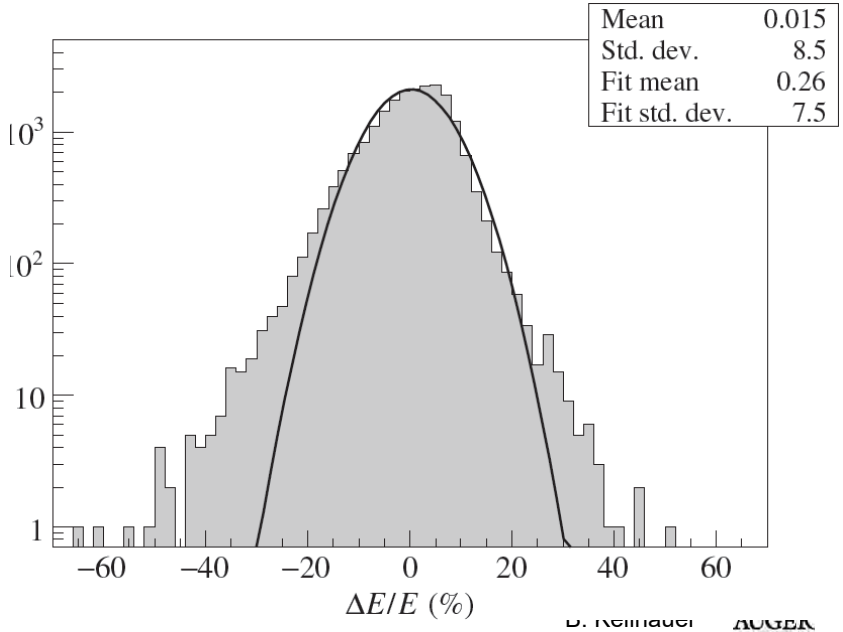
Importance of hourly aerosol profiles – energy reconstruction

Apply full air shower reconstruction once with new DN analysis hourly profiles and another time with a fixed average vertical distribution of aerosols

Change in energy

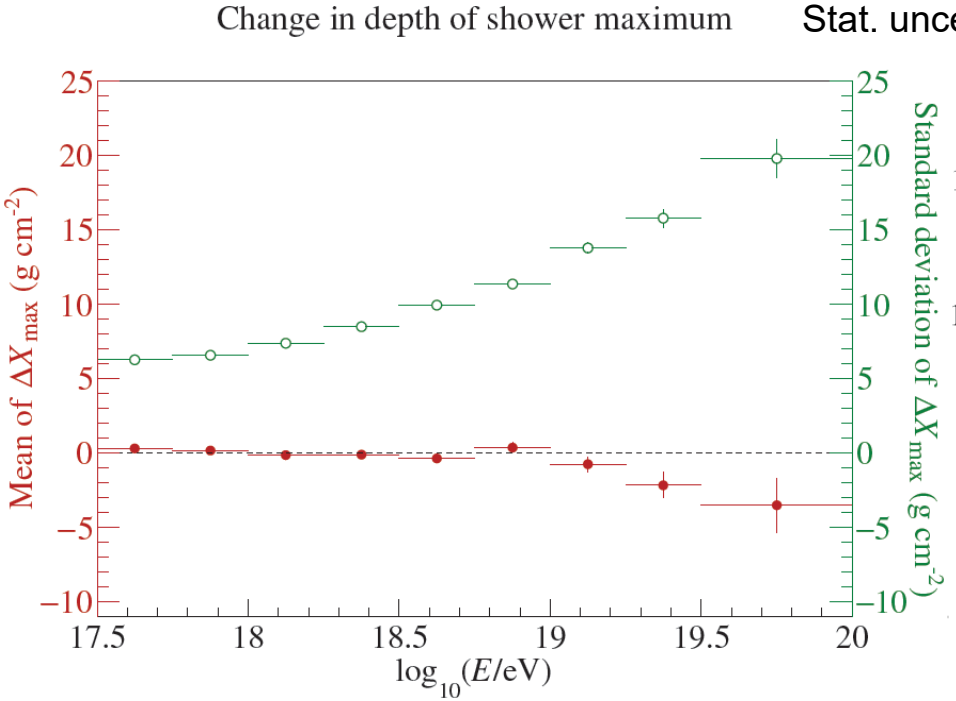
Stat. uncertainty of E about 8%



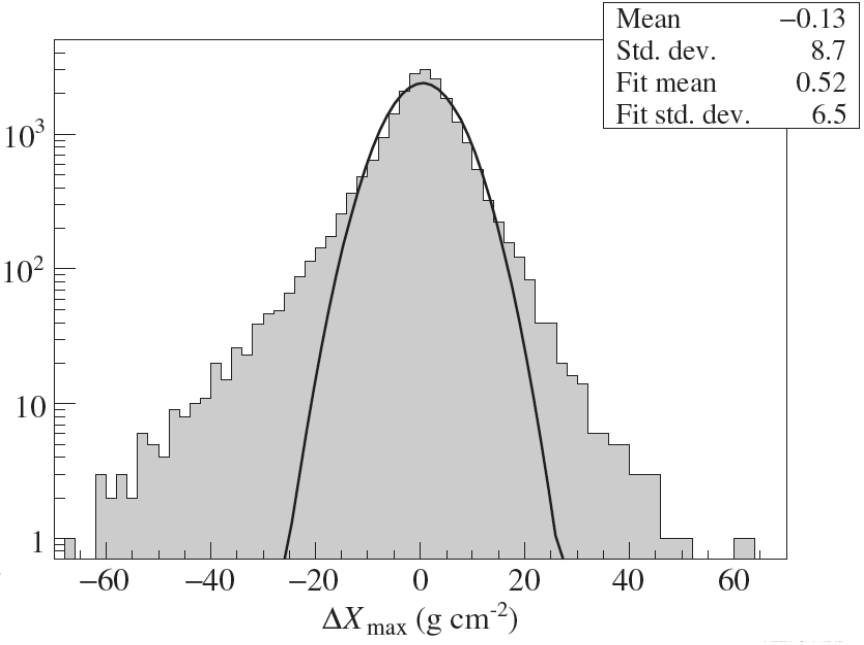


Importance of hourly aerosol profiles – shower maximum reconstruction

Apply full air shower reconstruction once with new DN analysis hourly profiles and another time with a fixed average vertical distribution of aerosols

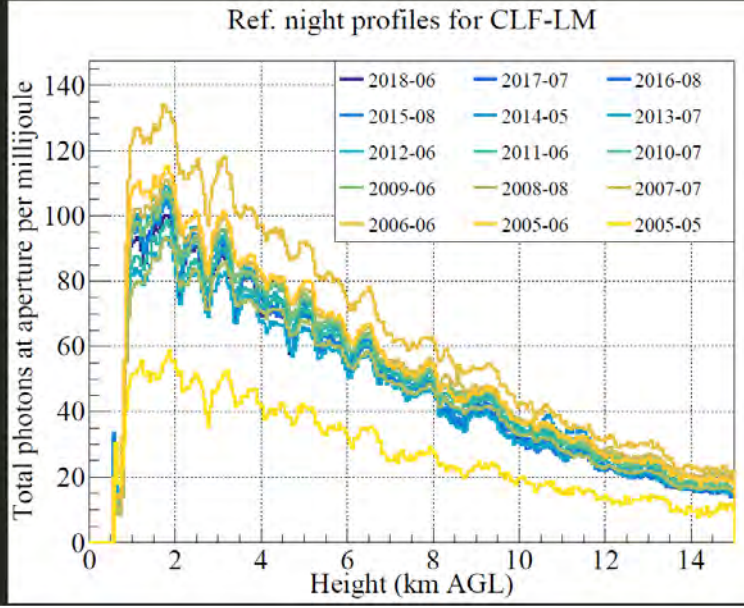


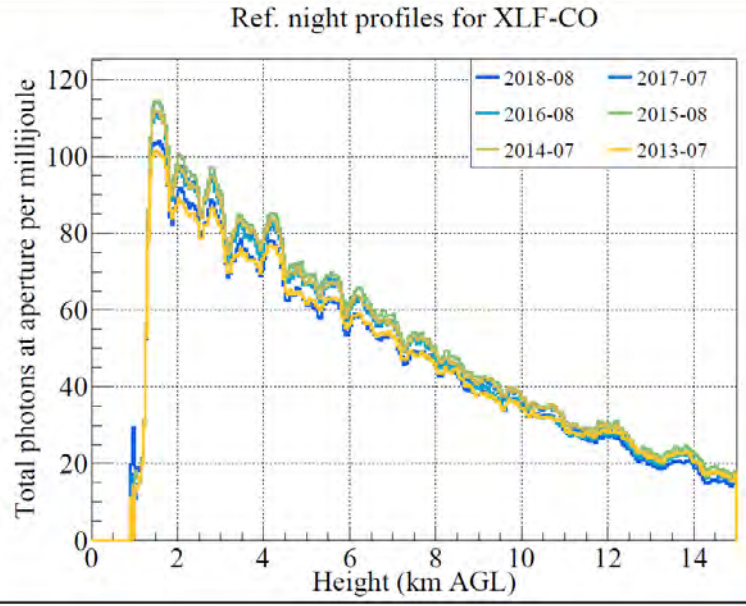
Stat. uncertainty of X_{max} from 15 g/cm² to 25 g/cm²



Ongoing studies: How much aerosol content is in our reference nights?

Sounds easy, right? The problem: normalisation of light profiles evolves from year to year, independent of laser energy, due to detector and laser calibration.





Ongoing studies: How much aerosol content is in our reference nights?

Testing several techniques:

- Compare real reference night data to laser simulation
- Stereo energy balance
- E_{SD}/E_{FD} vs aerosol transmission to X_{max}

Ongoing studies: How much aerosol content is in our reference nights?

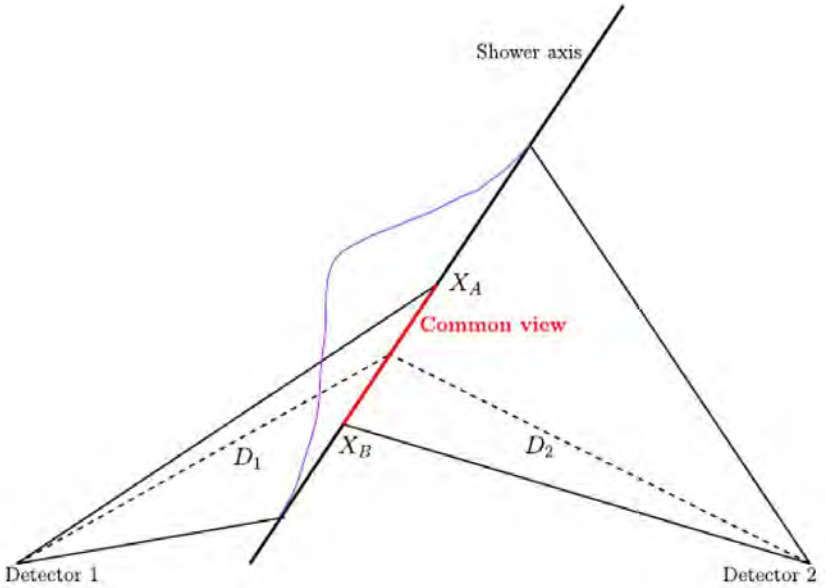
Testing several techniques:

- Compare real reference night data to laser simulation
- Stereo energy balance
- E_{SD}/E_{FD} vs aerosol transmission to X_{max}

☑ Stereo energy balance method is most promissing

Idea of the stereo energy balance method

For a hybrid event seen by at least two FD sites, calculate the average dE/dX along the common segment of shower track.

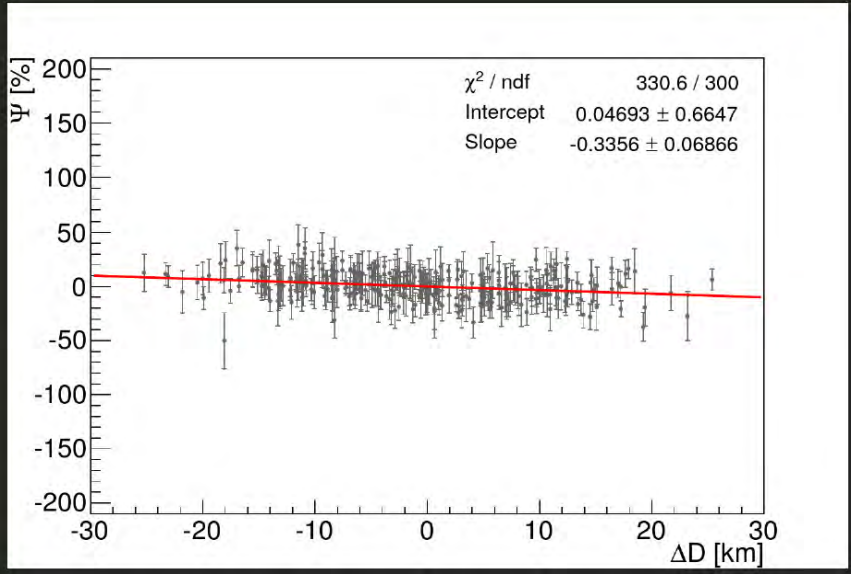


Idea of the stereo energy balance method

The metric $\Psi = 2(\phi_1 - \phi_2)/(\phi_1 + \phi_2)$ gives the relative difference in the calculation of energy deposited per unit depth.

For each site, calculate the average distance D_k to the common segment of track. Therefore calculate $\Delta D = D_1 - D_2$, the difference in distance to the track.

A nonzero slope indicates that the atmosphere model (probably aerosols) is not correct.



Summary

- The Pierre Auger Observatory operates a multitude of atmospheric monitoring devices
- Most recently, the aerosol analysis has been improved
- Tracking of acutal aerosol content is important for EAS reconstruction accuracy