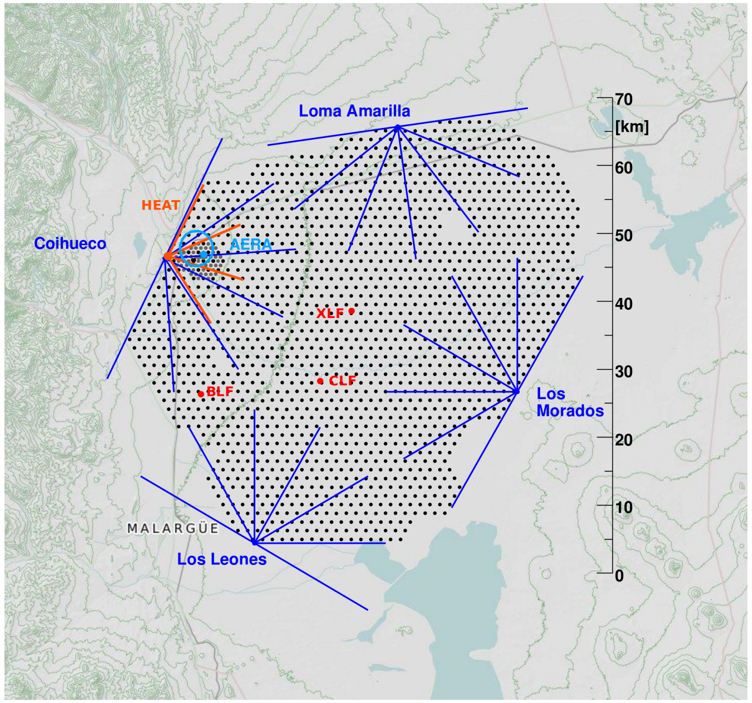
The Importance of Atmospheric Monitoring at the Pierre Auger Observatory

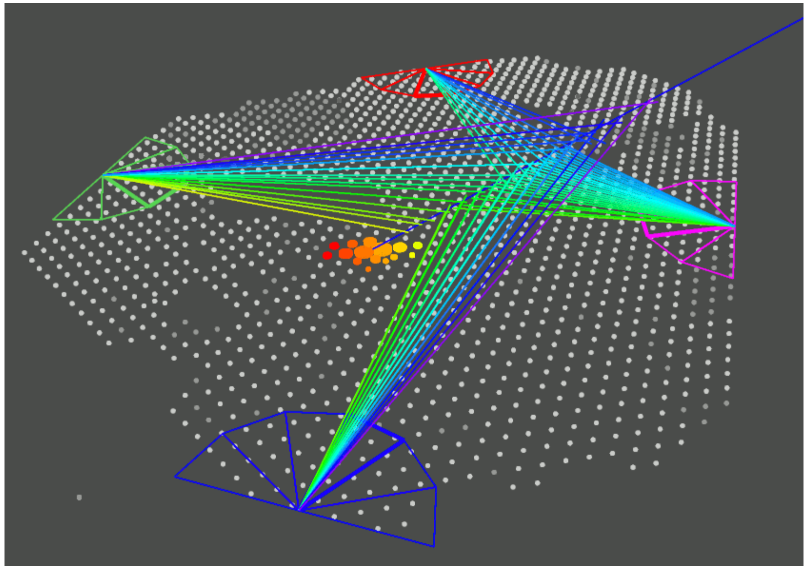
Bruce Dawson
for the Pierre Auger Collaboration

Photo: Steven Saffi, University of Adelaide

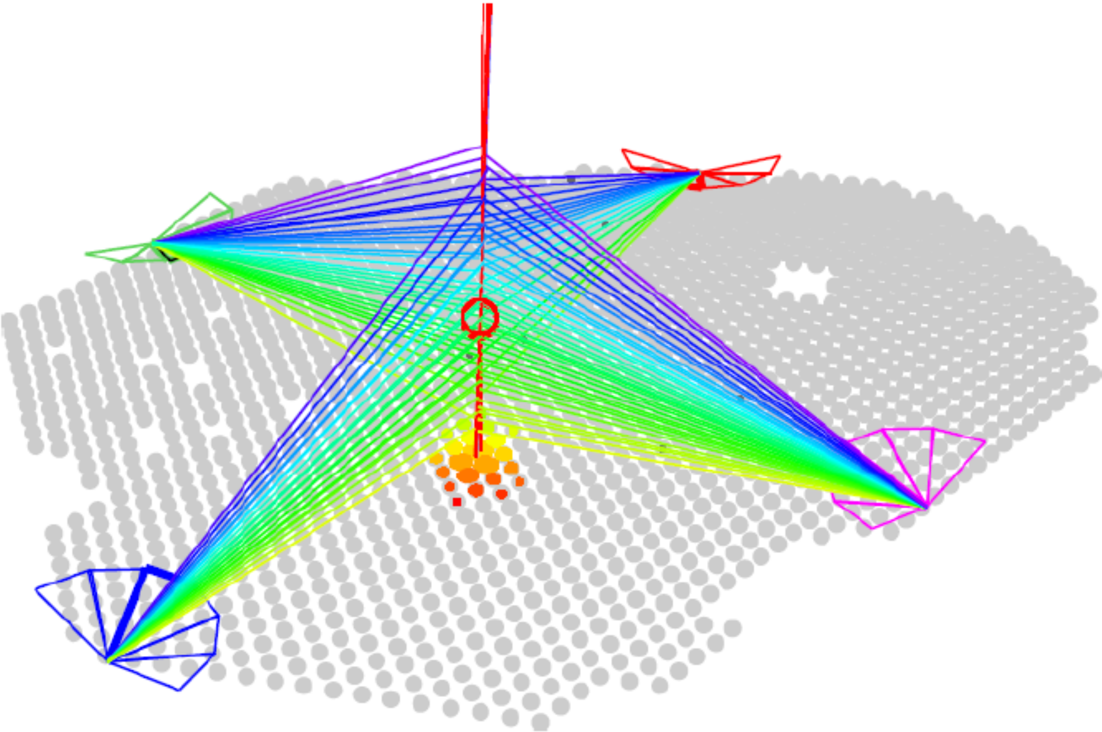
The task

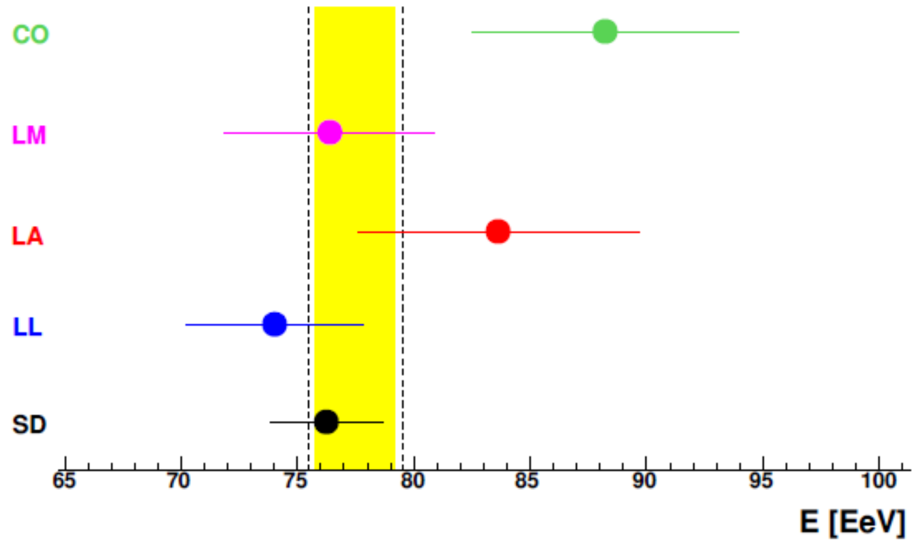
- 3000 square kilometres
- surface and fluorescence detectors (SD, FD)
- FD sets energy scale of Observatory; systematic uncertainty 14%
- Most atmospheric tasks related to FD, but SD needs some atmospheric corrections

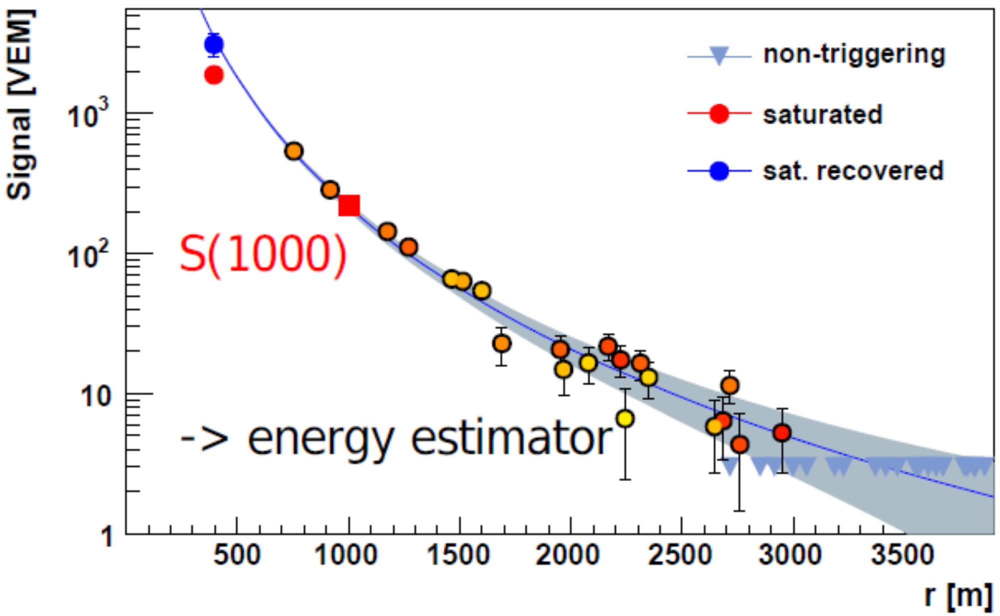


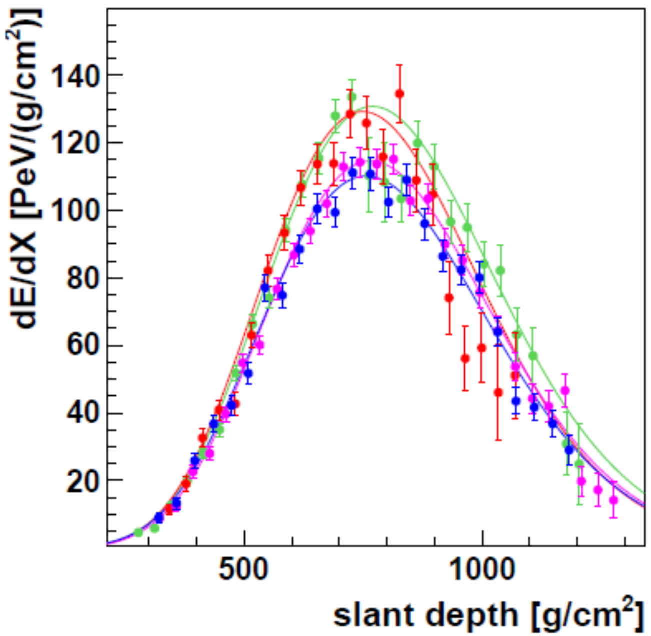


Reconstructing the air shower



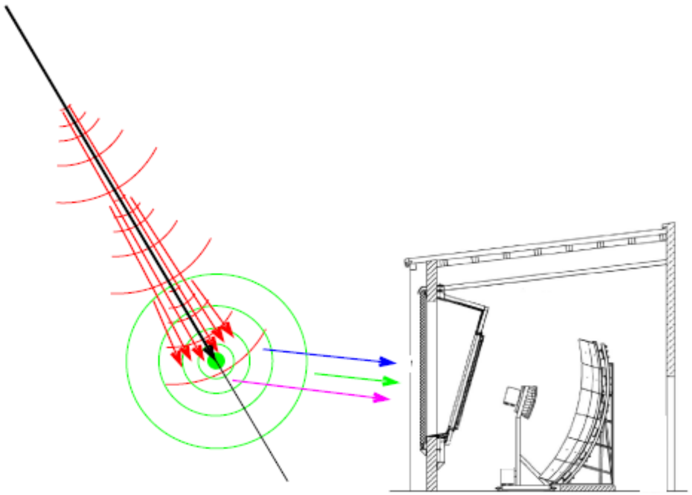


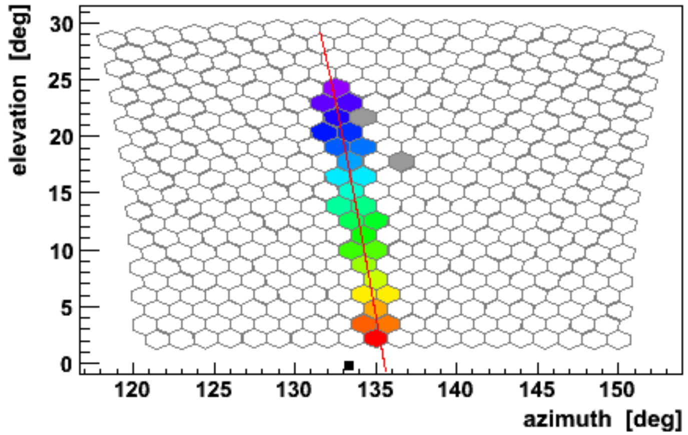


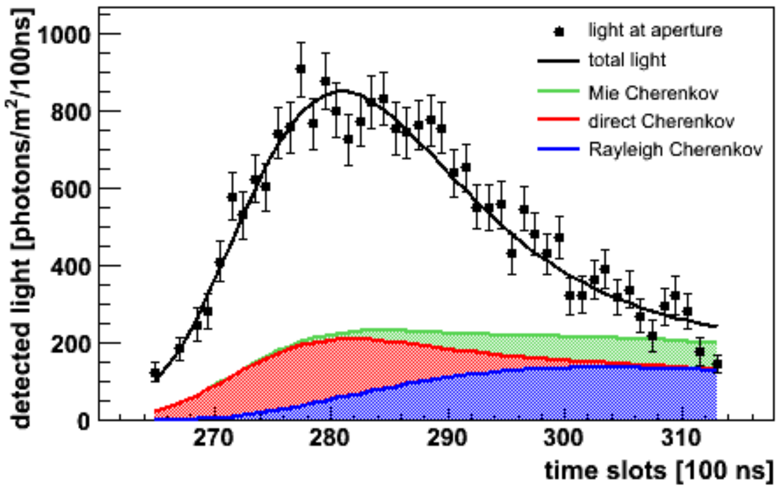


FD (hybrid) Reconstruction

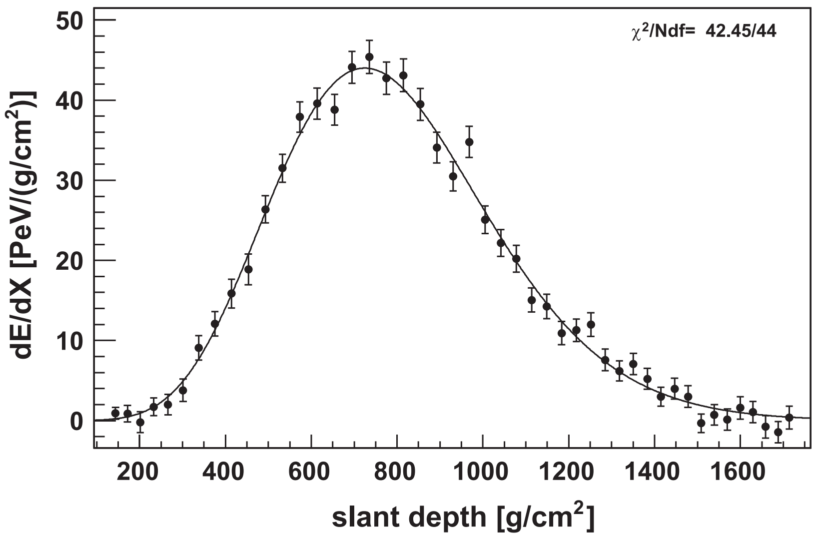
- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light







geometry,
atmospheric corrections,
fluorescence yield



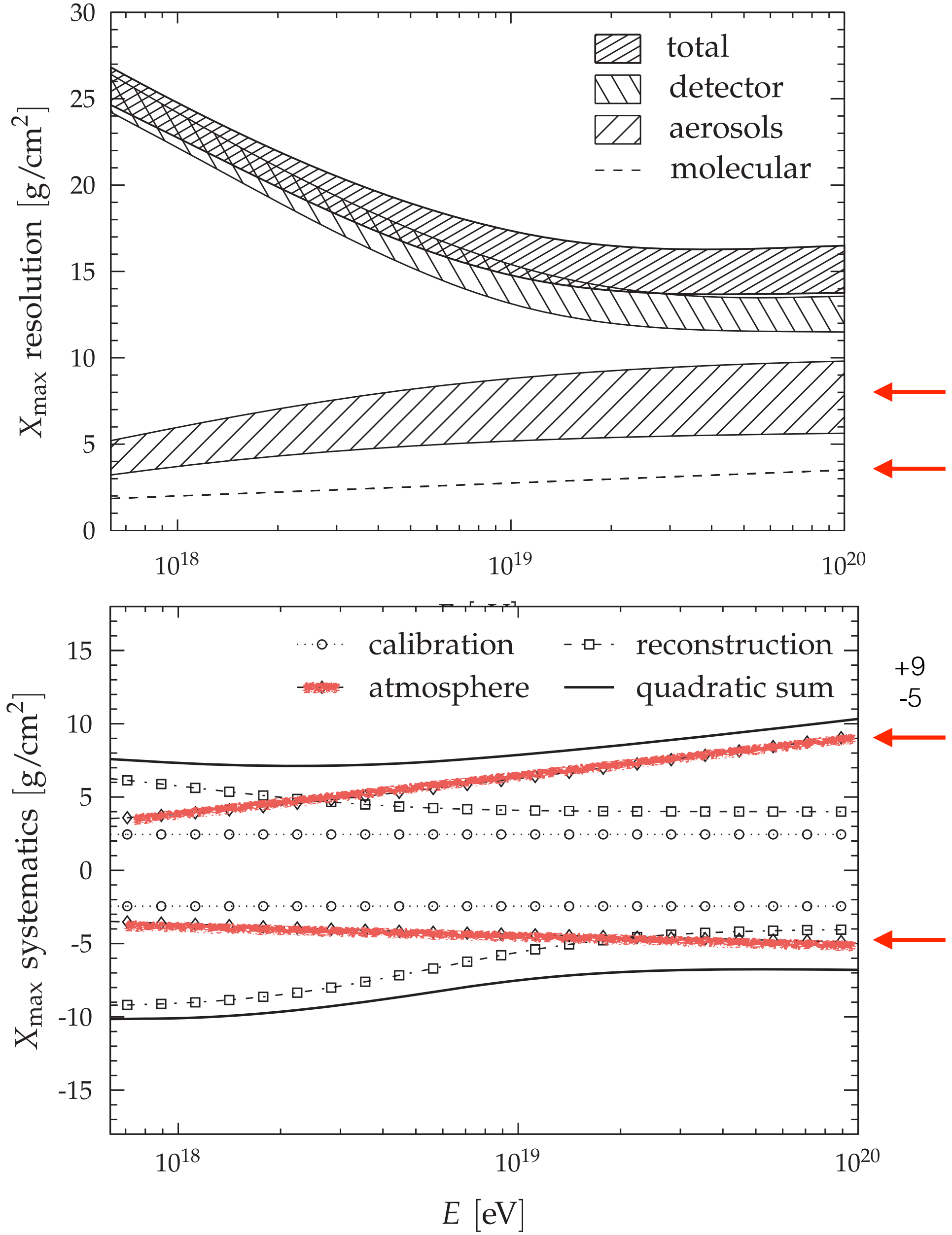
→ energy, X_{max}

Key FD Systematic Uncertainties

Energy (ICRC 2013)

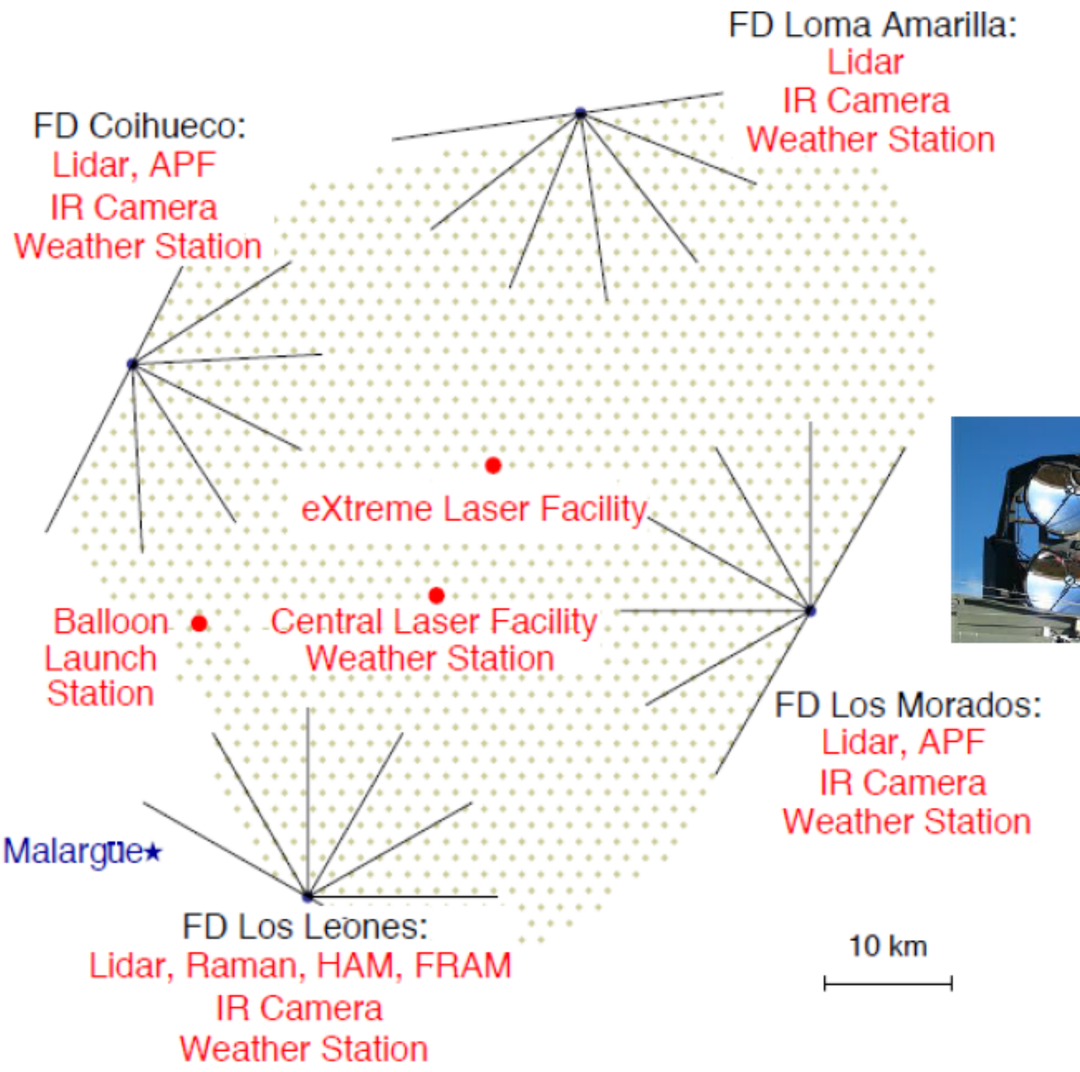
Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**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.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

Depth of Shower Maximum, X_{max}

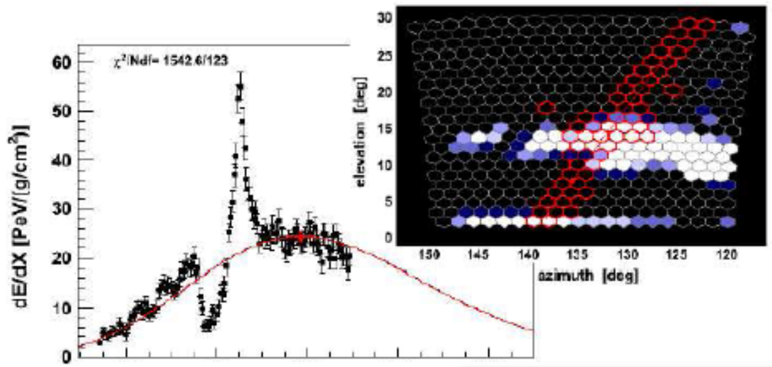


PHYSICAL REVIEW D **90,** 122005 (2014)

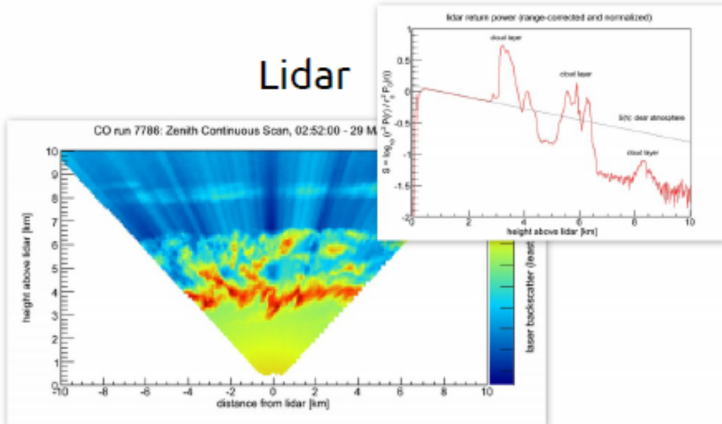
Atmospheric Monitoring Instruments



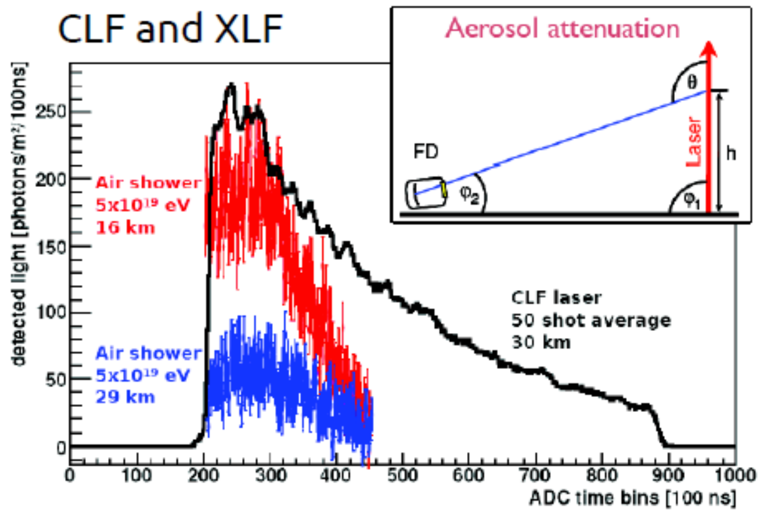
IR Cloud cameras



Lidar

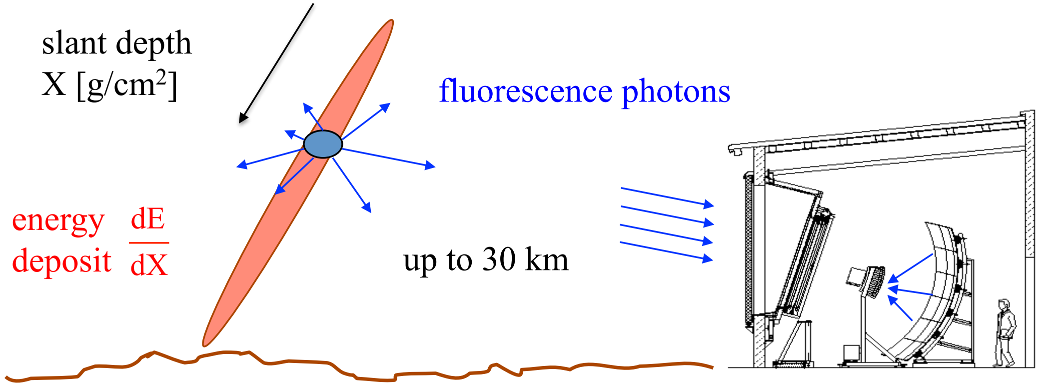


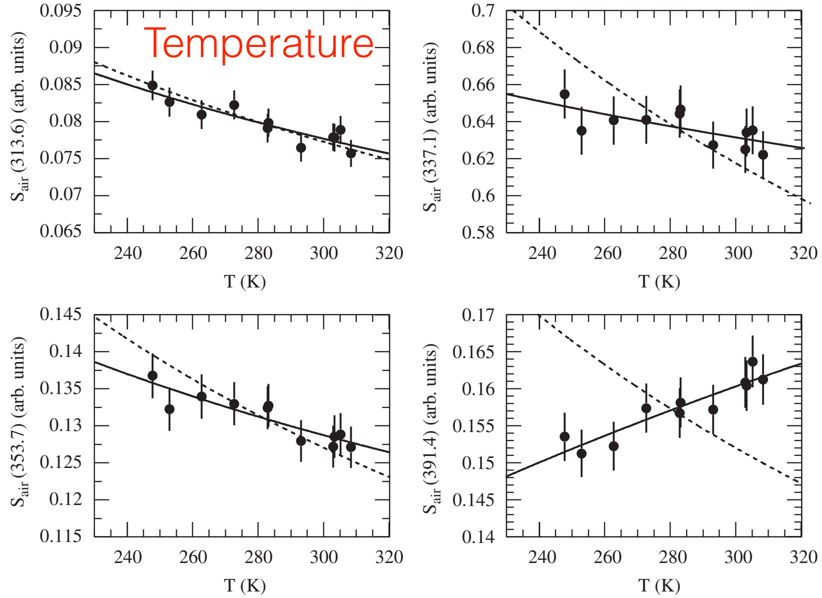
CLF and XLF



+ Global Data Assimilation System (GDAS)

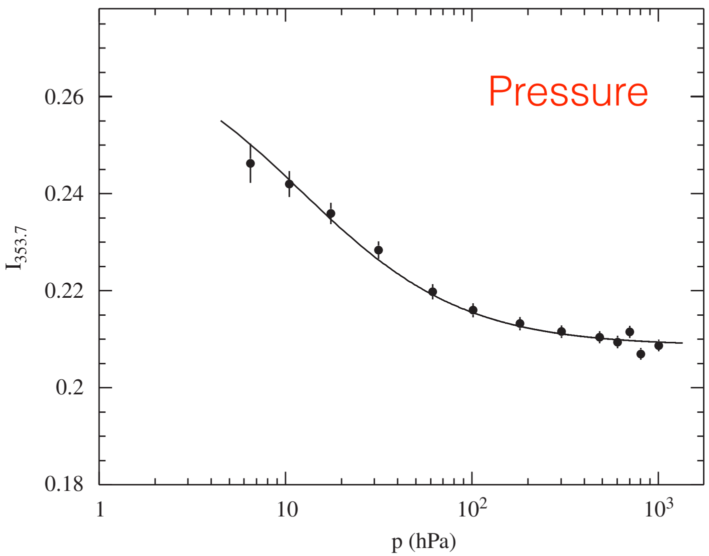
Fluorescence yield and the atmosphere

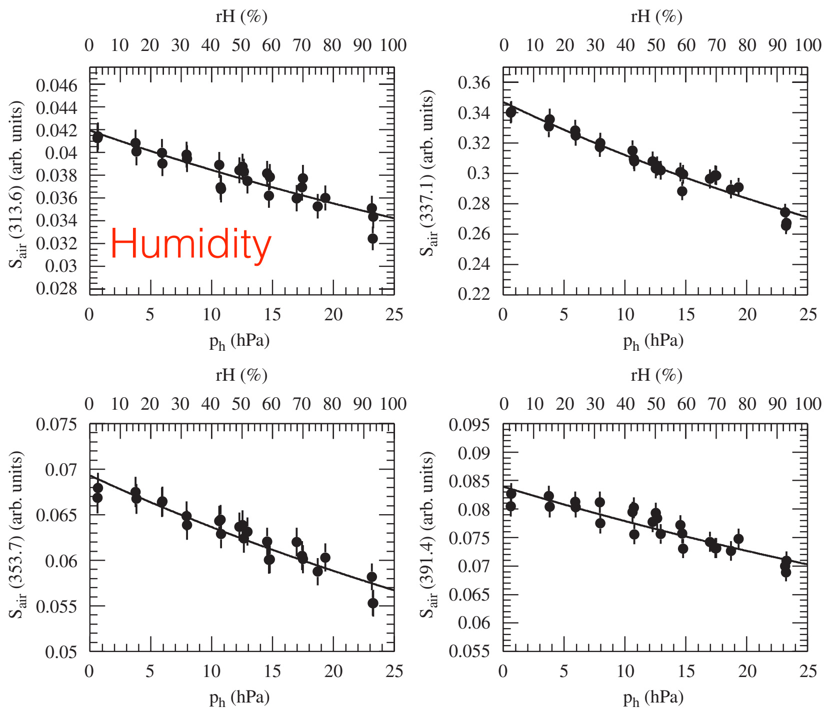




- competition between excitation and quenching
- quenching by nitrogen, oxygen and water
- temperature dependence includes collision probability & cross-sections
- AIRFLY measurements of coefficients, now much better known

Get P,T, humidity profiles from GDAS

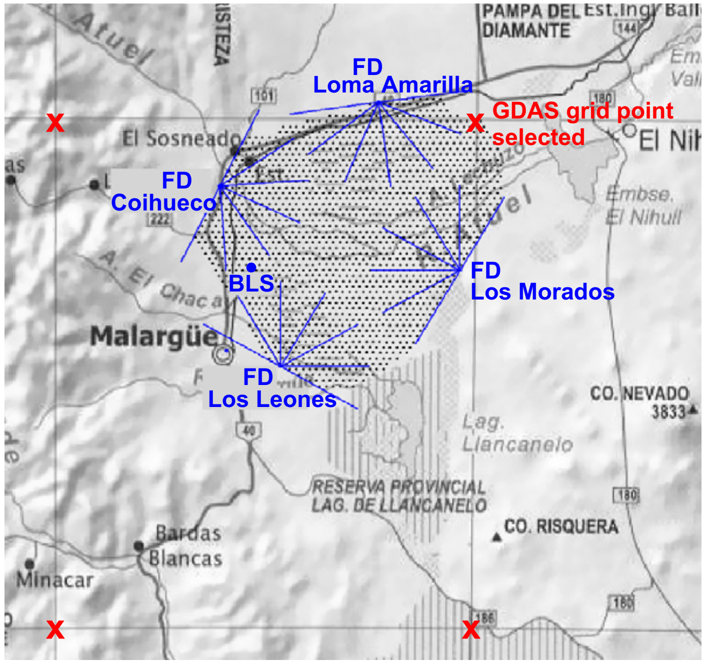




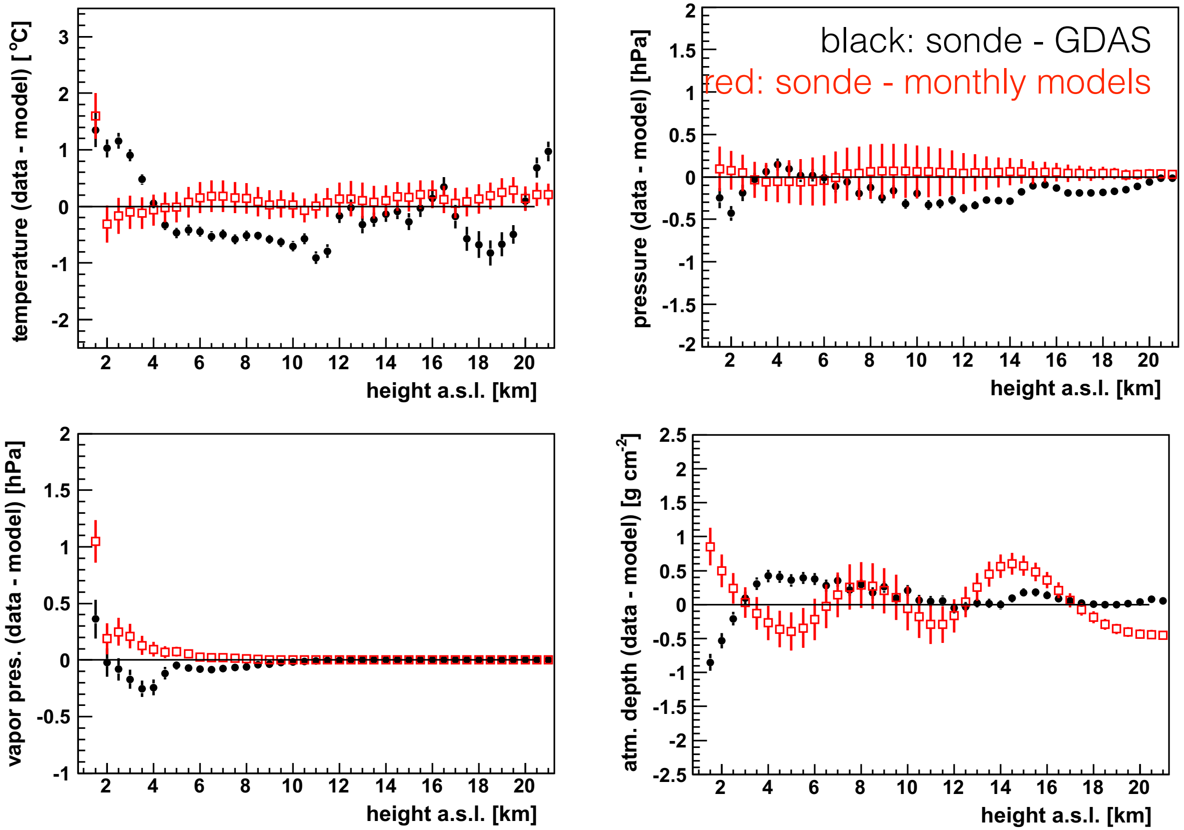
AIRFLY collaboration
NIM A597 41-54 (2008)
Astropart Phys, 42 90 (2013)

GDAS validation

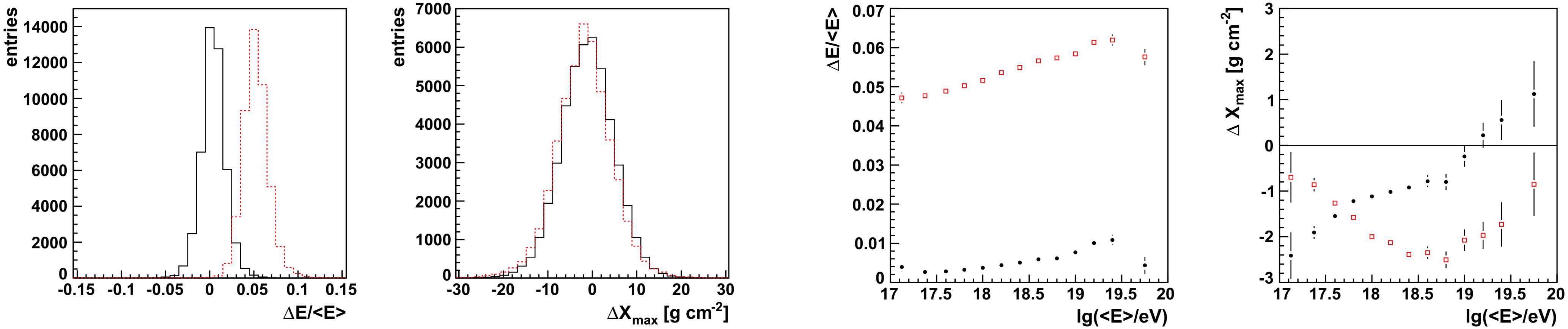
P. Abreu et al./Astroparticle Physics 35 (2012) 591–607



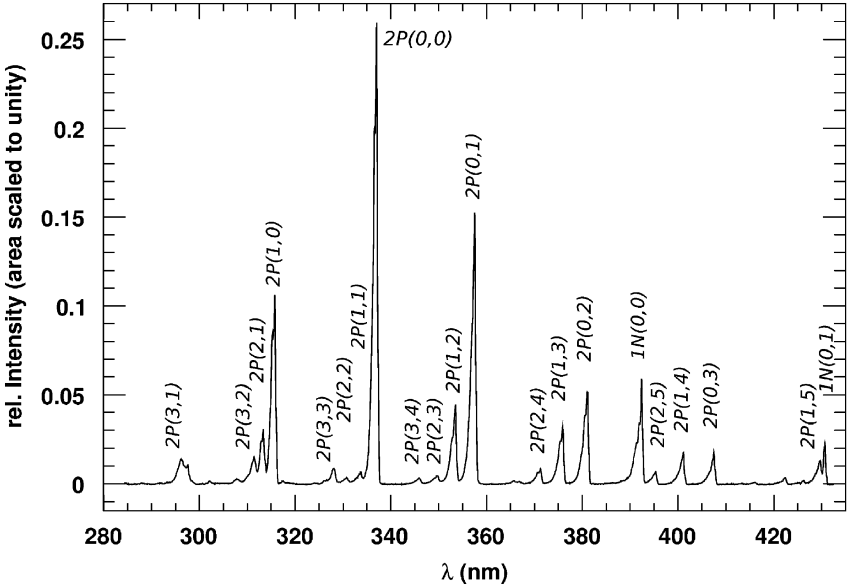
Comparing GDAS with radiosondes 2005-2008



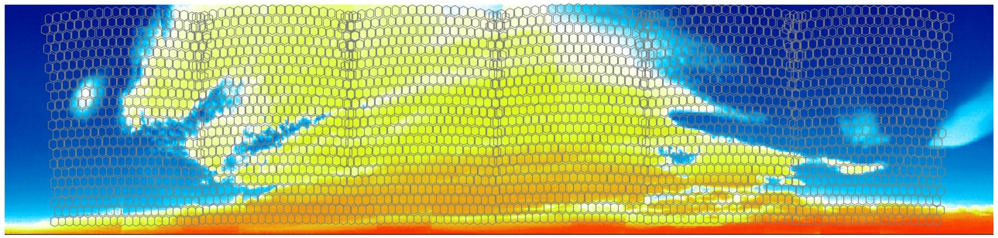
Black: effect of using GDAS rather than monthly models (ignore red)



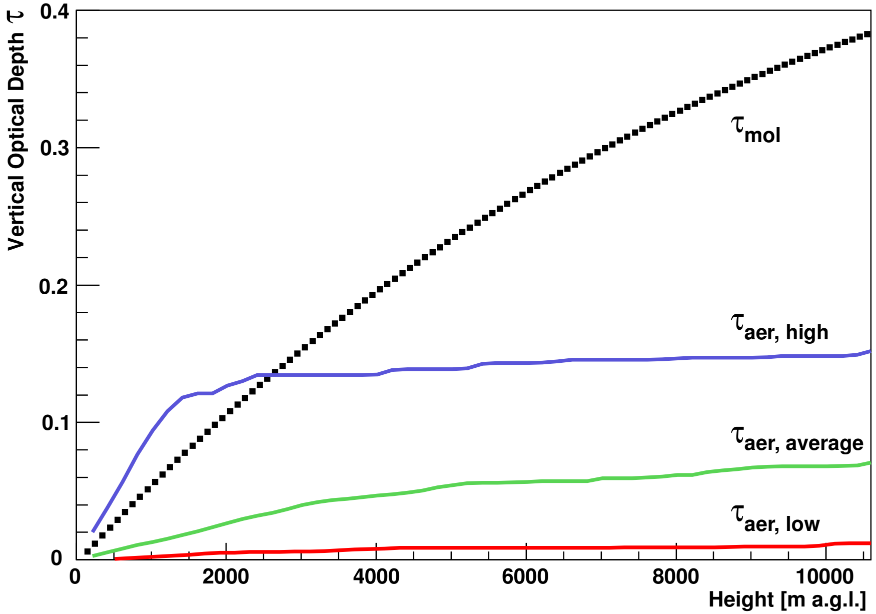
Optical attenuation



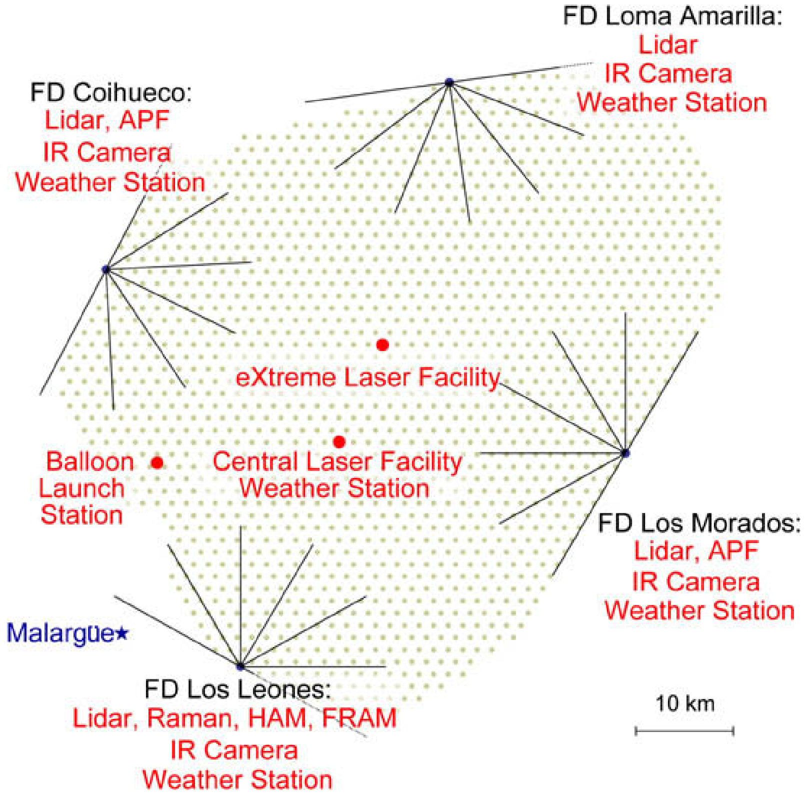
- Attenuation due to Rayleigh and aerosol scattering, and cloud
- negligible absorption (ozone)
- Molecular: GDAS
- Aerosols: Central laser facilities, Raman lidar, FRAM, (elastic lidars)
- Cloud: IR cameras, GOES satellite (10km^2), scanning elastic lidars, FRAM



Typical molecular and aerosol VODs

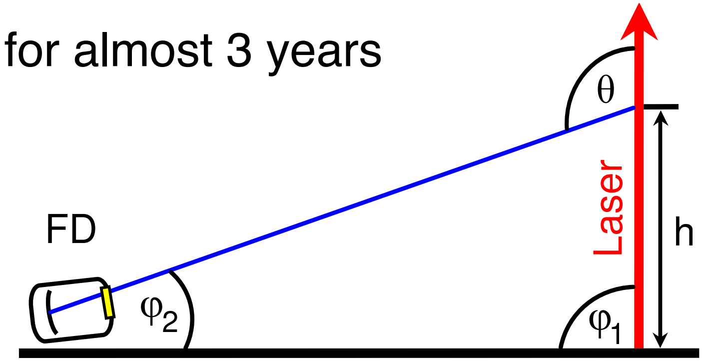


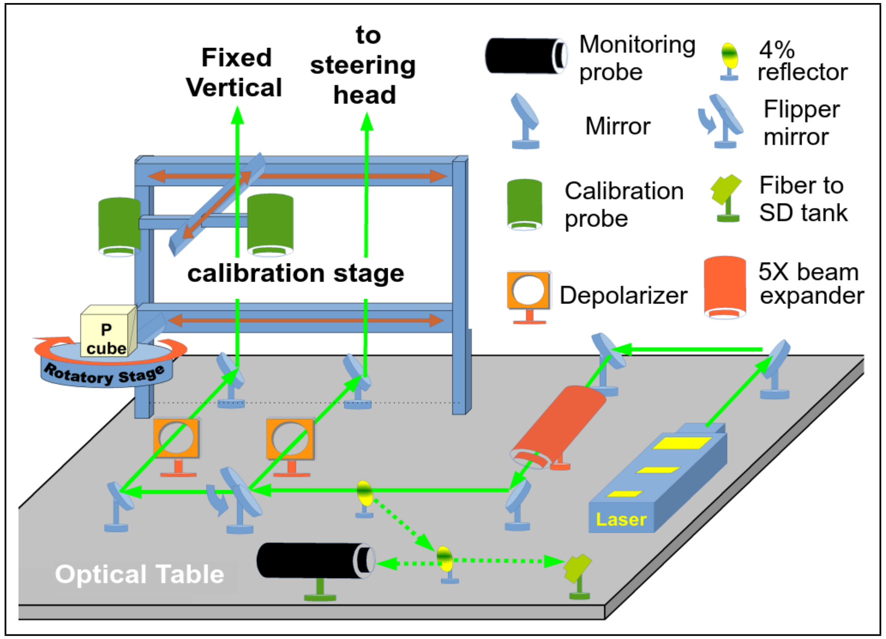
Aerosols



- CLF and XLF - *bi-static* lidar
  - two methods
  - based on reference night (assumed aerosol-free)
- (mono-static lidars used in the past)

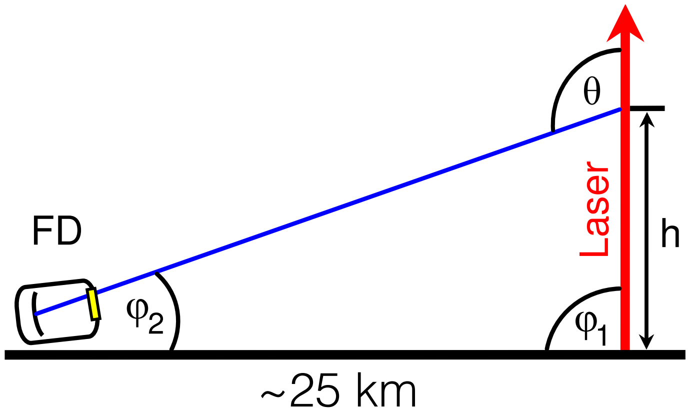
- Raman LIDAR for almost 3 years

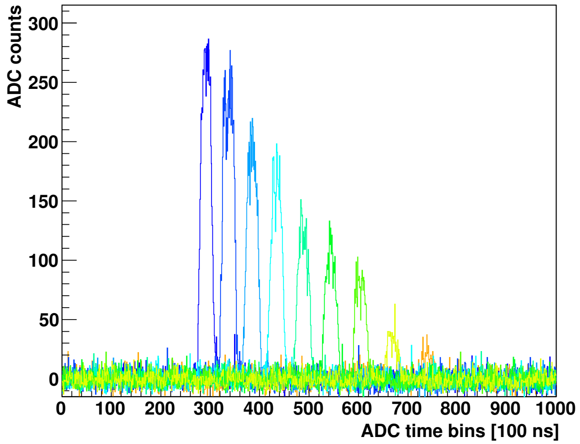


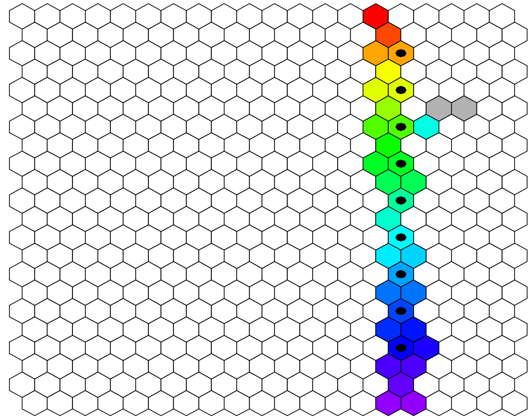


C. Medina-Hernandez et al. ICRC2015

CLF methods for Vertical Aerosol Optical Depth τ_{aer}







- 355nm frequency-tripled YAG laser
- ~ 6 μJ per pulse
- 50 shots every 15 minutes

P. Abreu et al. (Pierre Auger Collab), JINST 8 P04009 (2013)

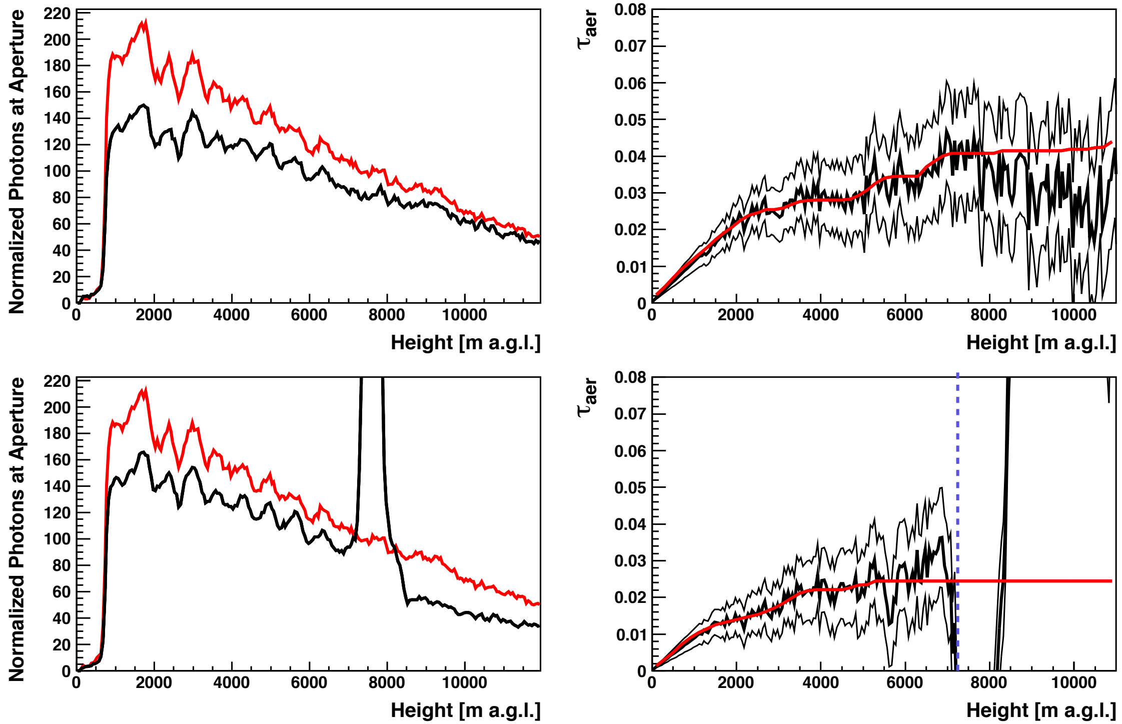
CLF methods for Vertical Aerosol Optical Depth τ_{aer}

"Data normalised" (DN) method

$$\tau_{\mathrm{aer}}(h) = -\frac{\sin\varphi_1 \sin\varphi_2}{\sin\varphi_1 + \sin\varphi_2}\left(\ln\left(\frac{N_{\mathrm{obs}}(h)}{N_{\mathrm{mol}}(h)}\right) - \ln\left(1 + \frac{S_{\mathrm{aer}}(\theta,h)}{S_{\mathrm{mol}}(\theta,h)}\right)\right)$$

normalised to
1 μJ energy

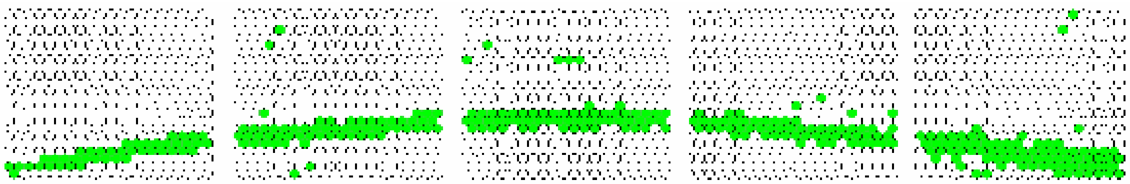
red: reference night

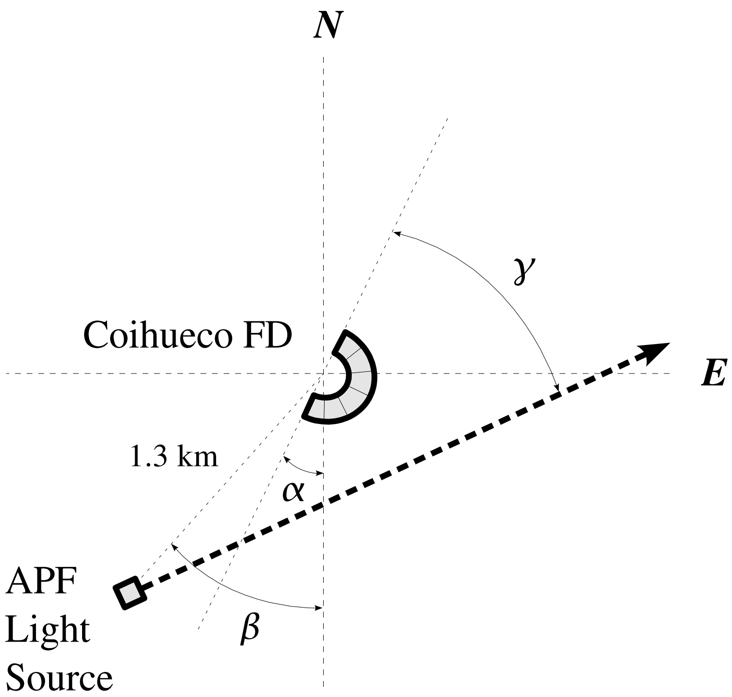


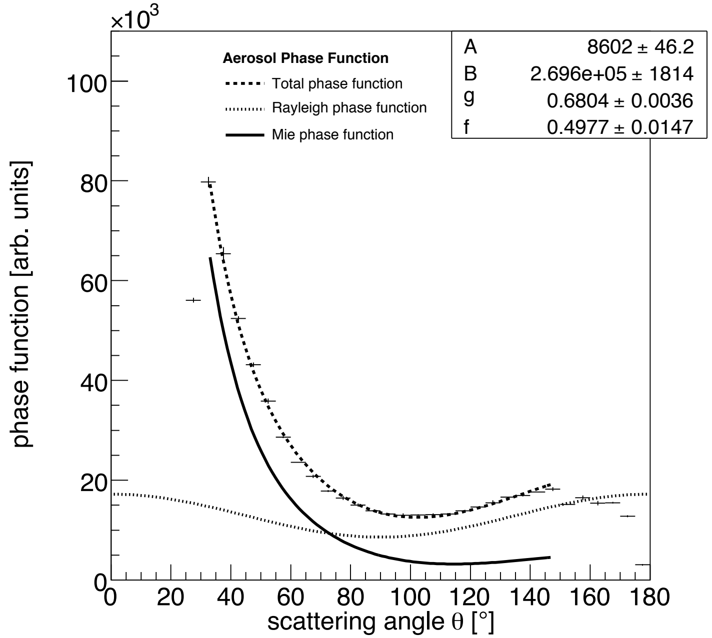
P. Abreu et al. (Pierre Auger Collab), JINST 8 P04009 (2013)

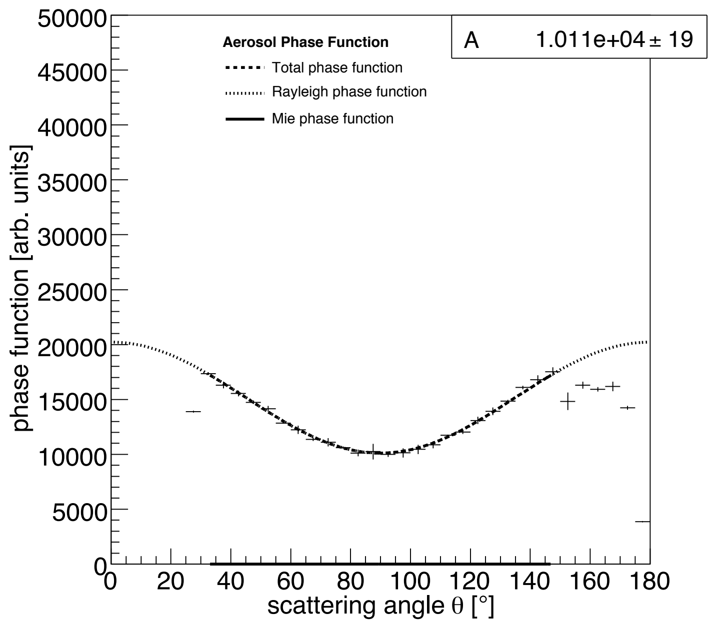
Aerosol Phase Function (APF) Monitor

(one use - checking reference nights)







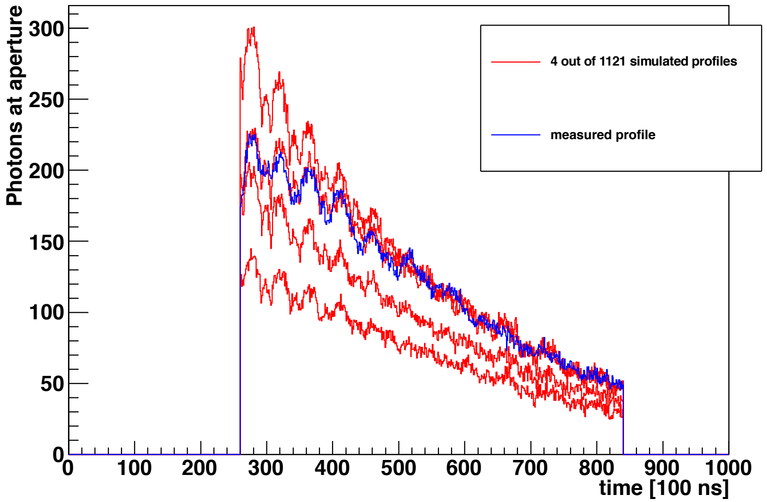


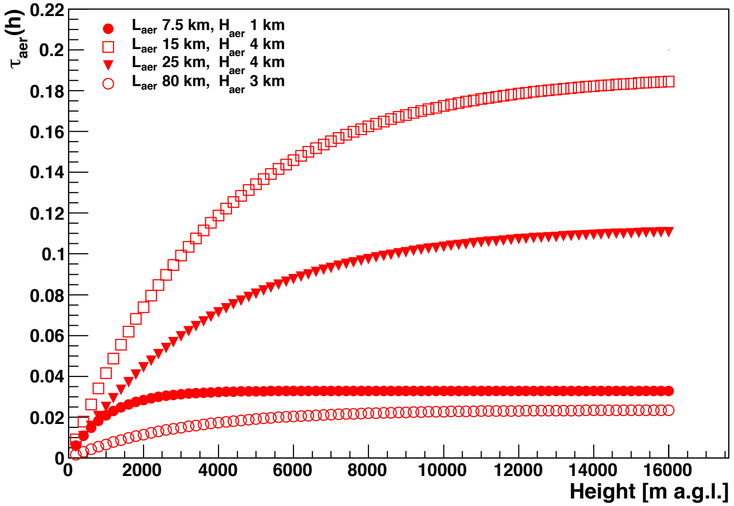
Near-horizontal collimated xenon flash lamps
at two FD sites

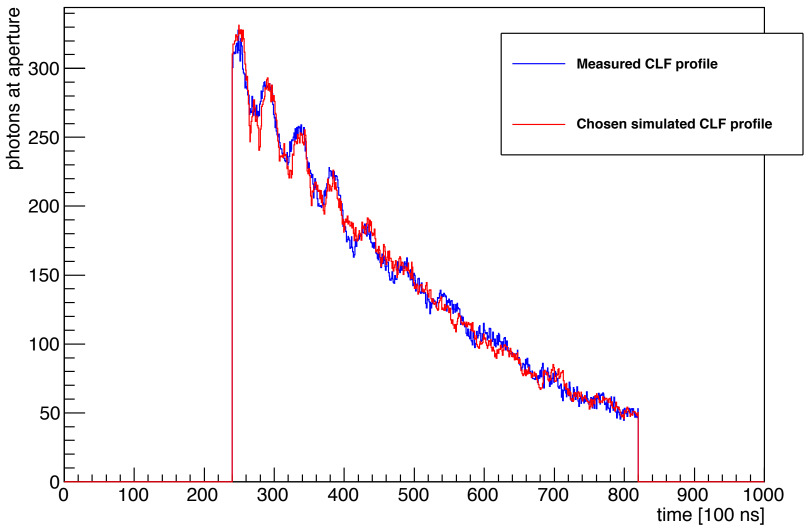
BenZvi et al., Astropart Phys. 28, 312 (2008)

CLF methods for Vertical Aerosol Optical Depth τ_{aer}

"Laser Simulation" (LS) method



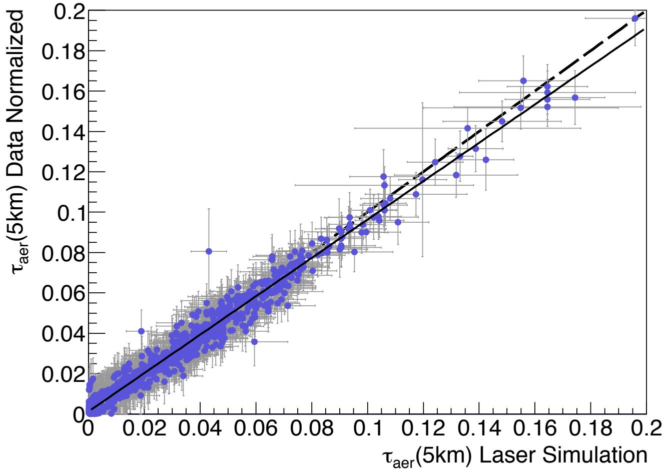




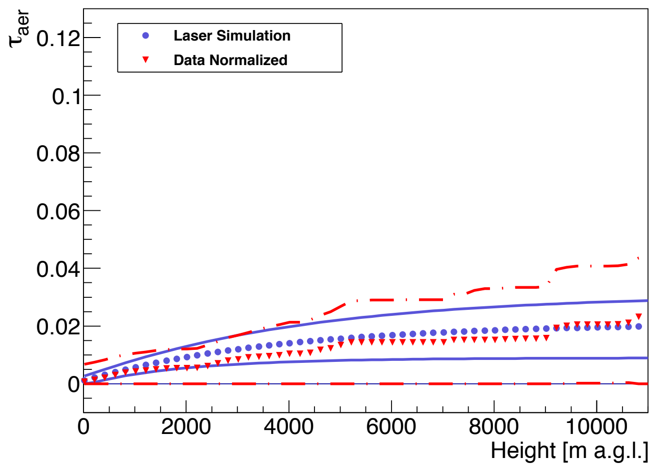
For technical reasons (normalisation of simulations), this method also requires use of a reference (clear) night.

P. Abreu et al. (Pierre Auger Collab), JINST 8 P04009 (2013)

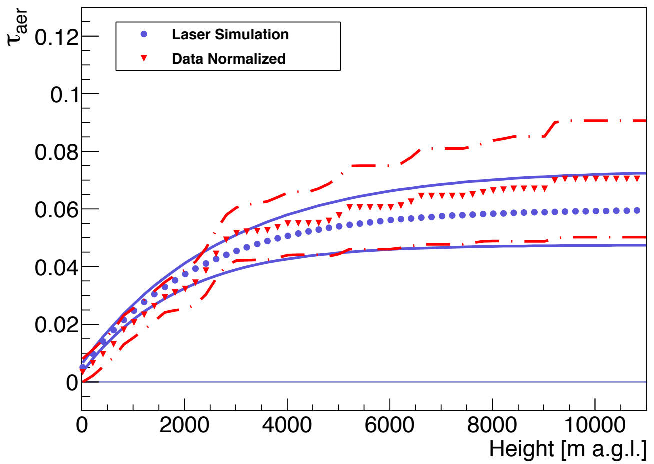
CLF methods for Vertical Aerosol Optical Depth τ_{aer}



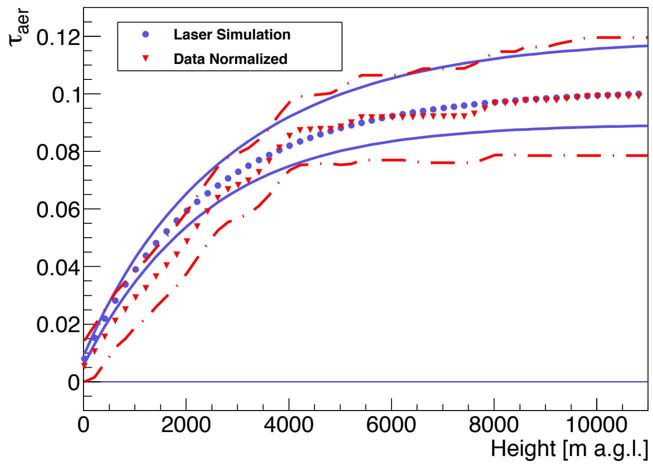
(a) Correlation between the analyses.



(b) Low aerosol attenuation.



(c) Average aerosol attenuation.



(d) High aerosol attenuation.

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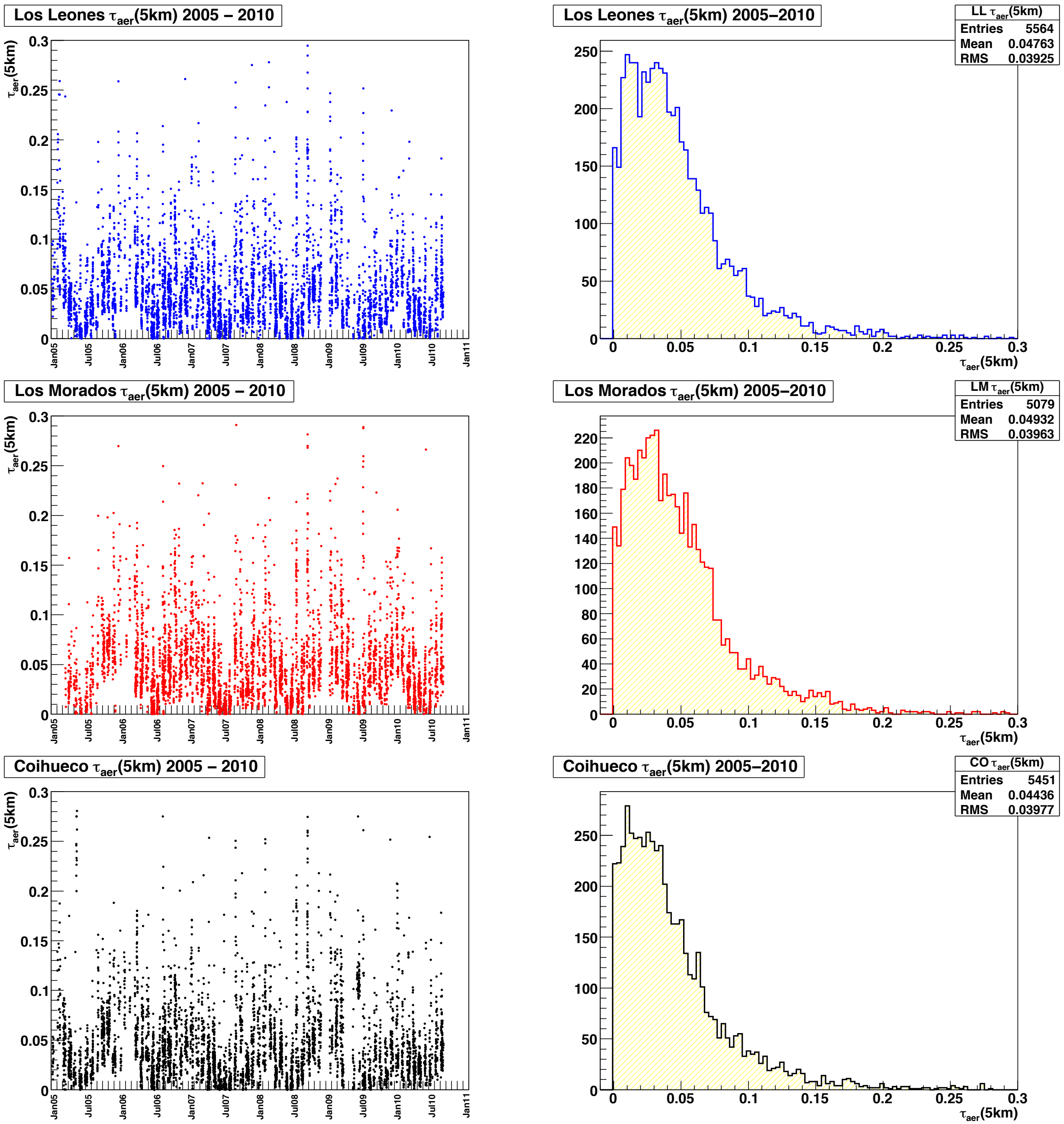
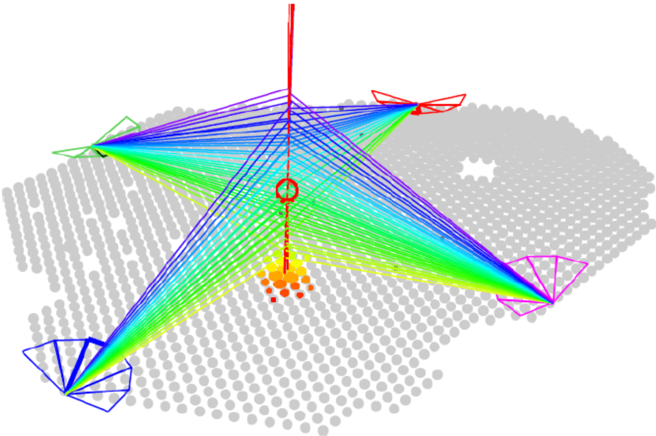
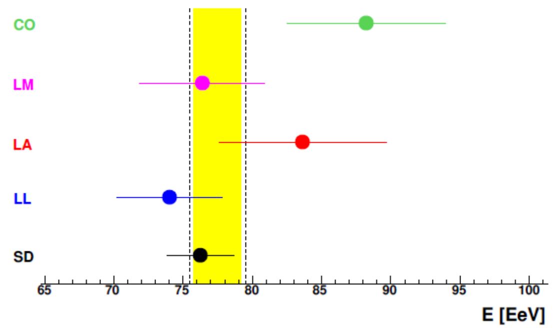
CLF methods for Vertical Aerosol Optical Depth τ_{aer}

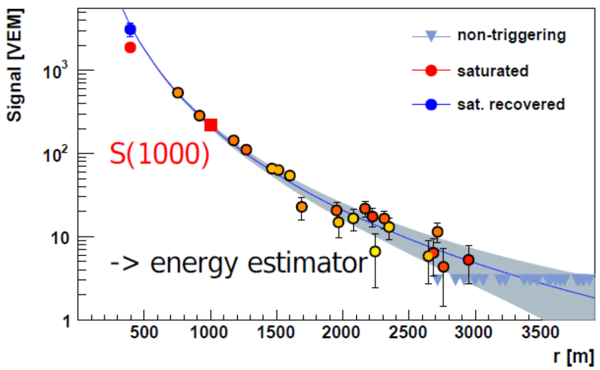


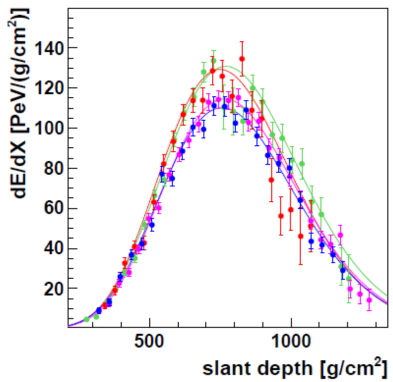
P. Abreu et al. (Pierre Auger Collab), JINST 8 P04009 (2013)

Cross-checks





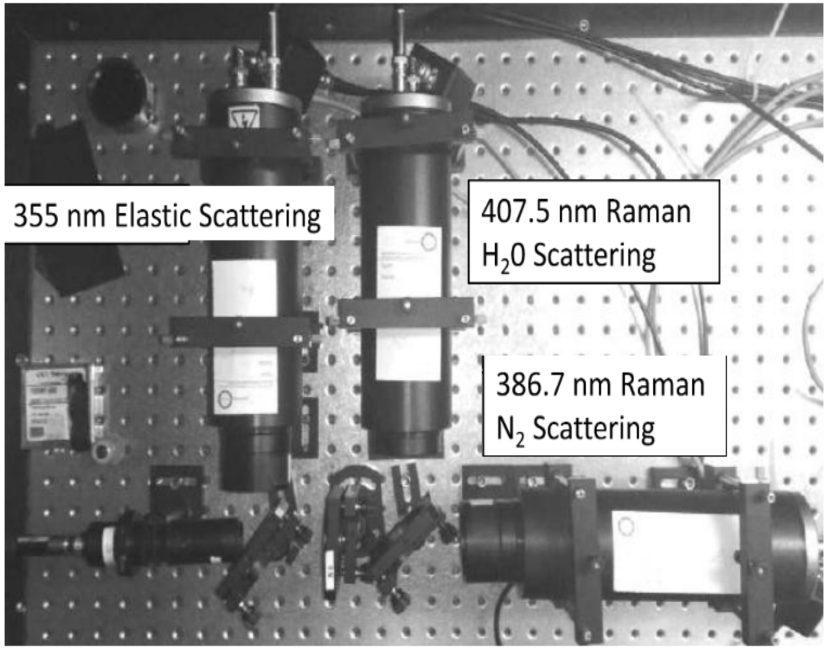


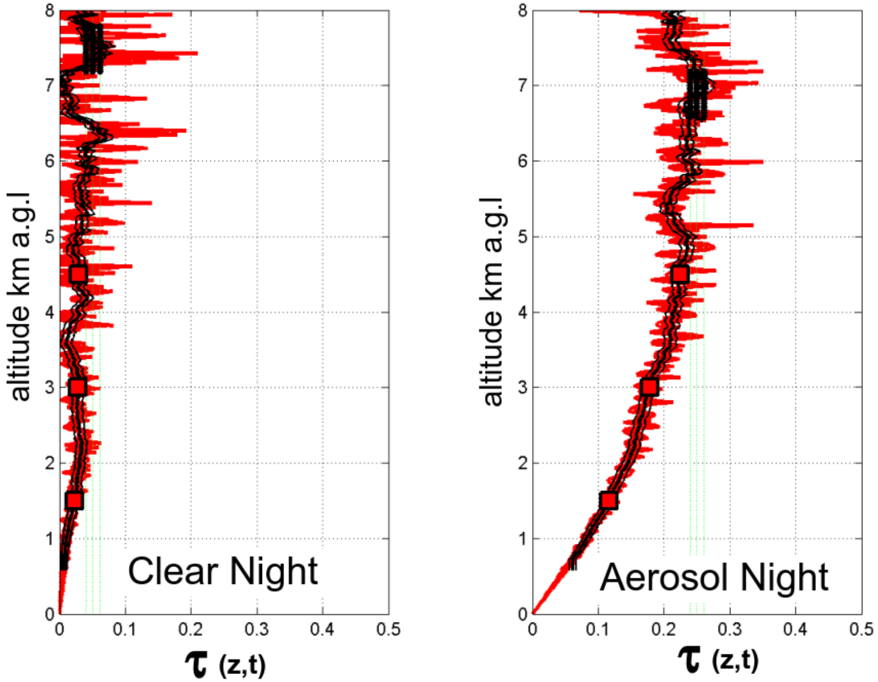


- We exploit stereo-views of showers to check assumptions of atmospheric attenuation (HiRes “stereo-balance”)
- Even hybrid events can be used to check E_{FD}/E_{SD} as a function of the distance to the FD.

Cross-checks

Raman LIDAR receiver
(since Nov. 2013 at CLF site)





- uses 355nm YAG at CLF
- runs 3 times per night (12 minute integration time)
- running reliably, comparisons in progress

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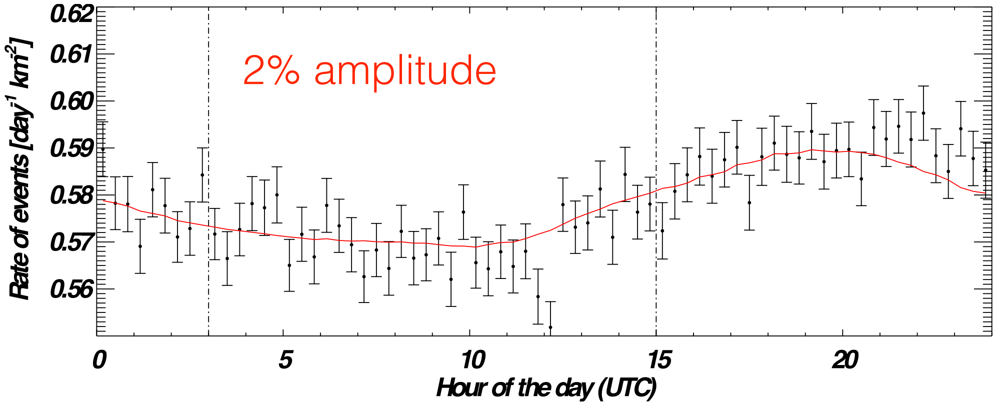
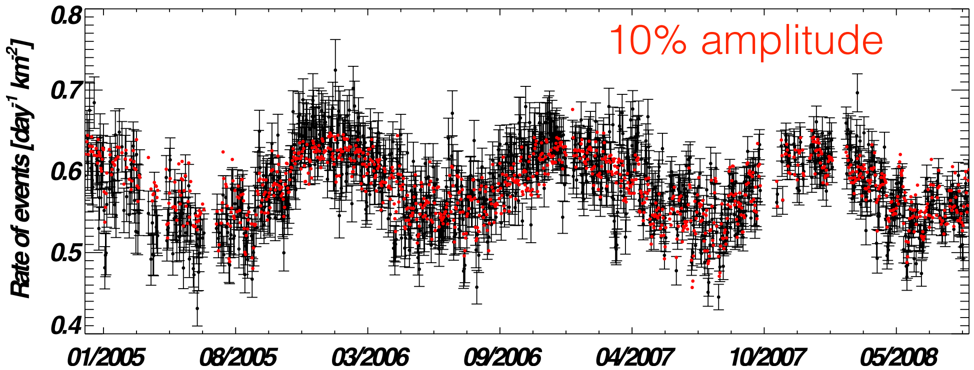
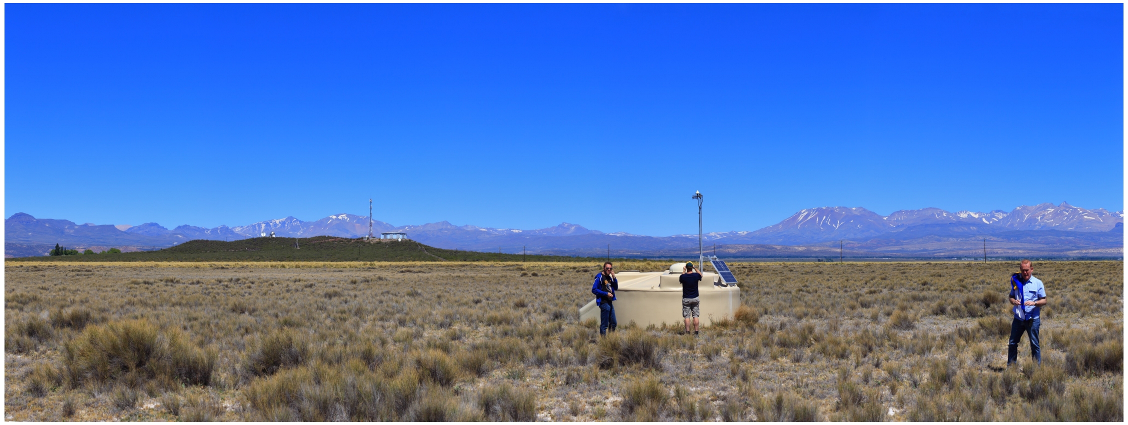
Surface detector energy - P,T dependence







- Shower rates above a given assumed energy threshold show diurnal and seasonal variations
- due to
  - density (ρ ~ P/T) related changes to the Moliere radius (most important)
  - shower attenuation with increasing P
- can be corrected empirically using weather station data (5 min latency)
- particularly important in broad scale anisotropy studies, where harmonic amplitudes are ~ 1%

Astroparticle Physics 32 (2009) 89–99
with a new analysis in preparation

Conclusions

- the challenge of monitoring the atmosphere over 3000 square kilometres is achieved with a suite of instruments
- measurement redundancy is important!
- creative use of air shower data for cross-checks is fruitful
- work continues to improve understanding, cross-check our assumptions and results

Photo: Steven Saffi, University of Adelaide