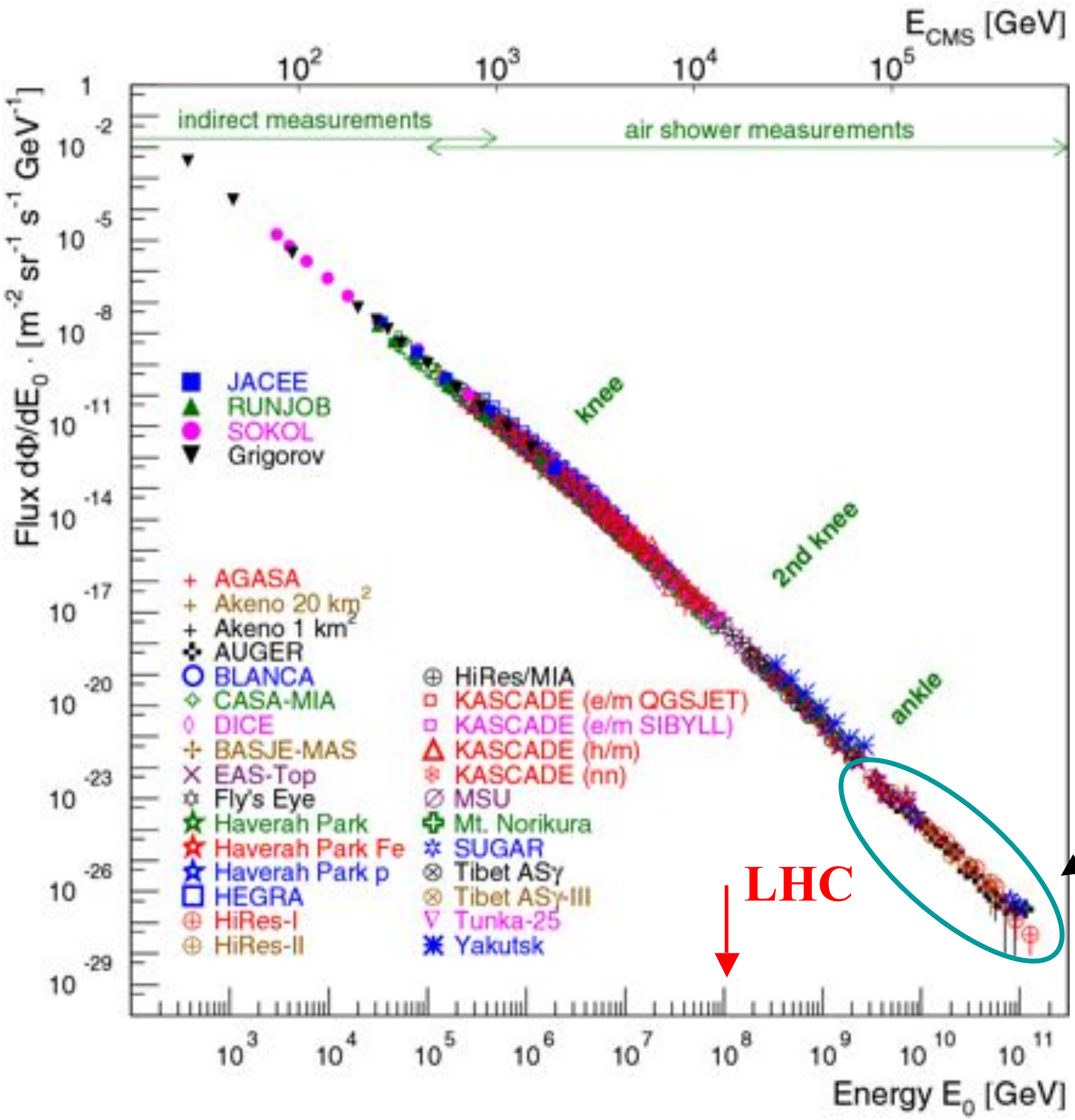
THE ENERGY SCALE OF THE PIERRE AUGER OBSERVATORY

Valerio Verzi

for the Pierre Auger Collaboration

Sezione INFN di Roma "Tor Vergata"

COSMIC RAYS FLUX



$$\approx \frac{1}{E^3}$$

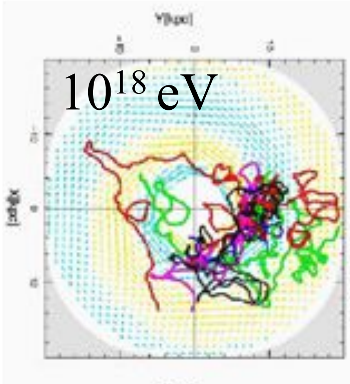
10^{20} eV

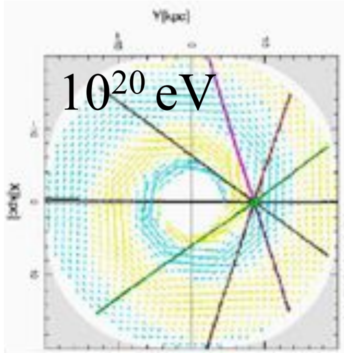
16 J

1 particle/km^2/century

WHERE DO COME FROM?

Trajectory in galactic and inter-galactic B





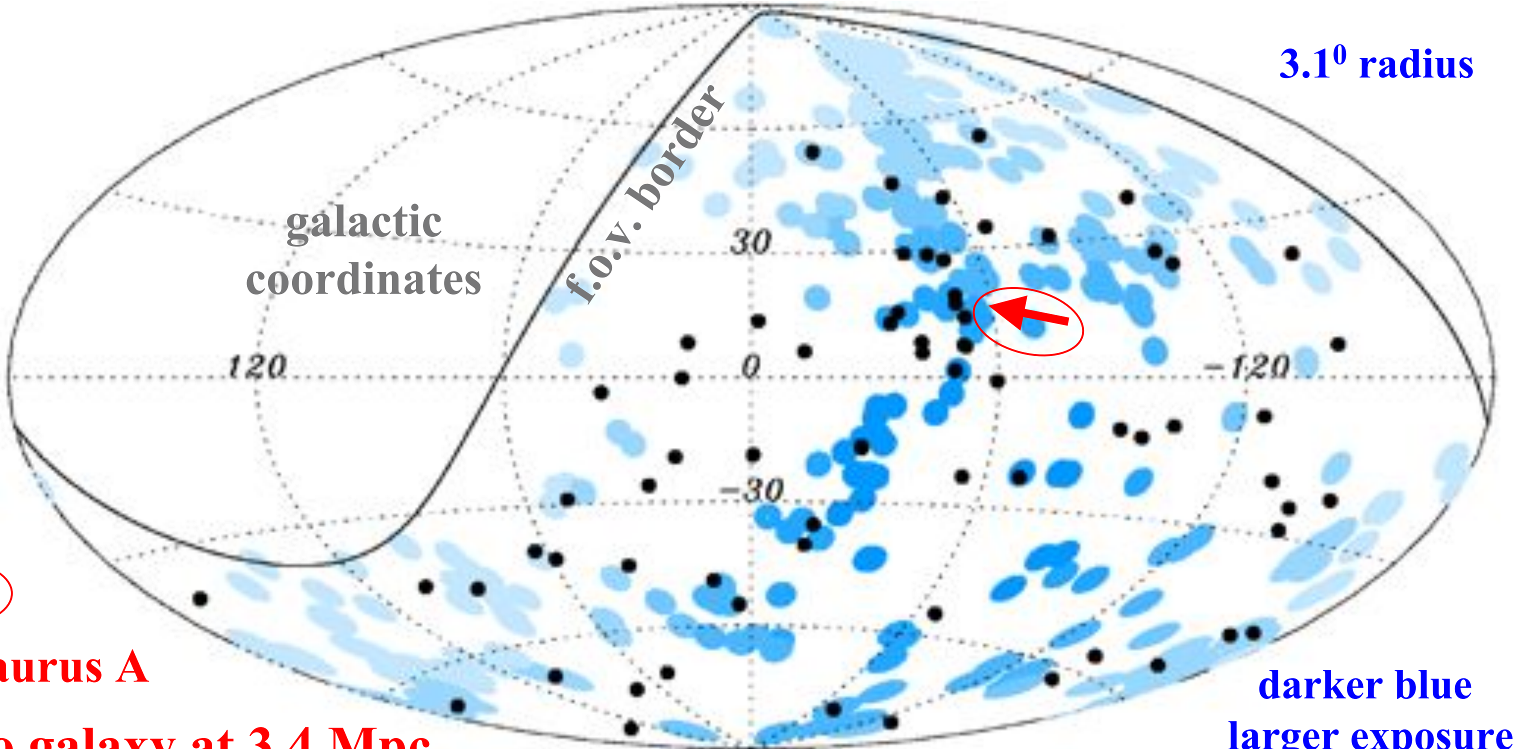
Back to origin!

AUGER SKY

318 AGNs within 75 Mpc VCV catalogue

69 events
E > 57 EeV

29 correlates
14.5 expected
(isotropic sky)



3.1^0 radius

darker blue larger exposure

Centaurus A

radio galaxy at 3.4 Mpc

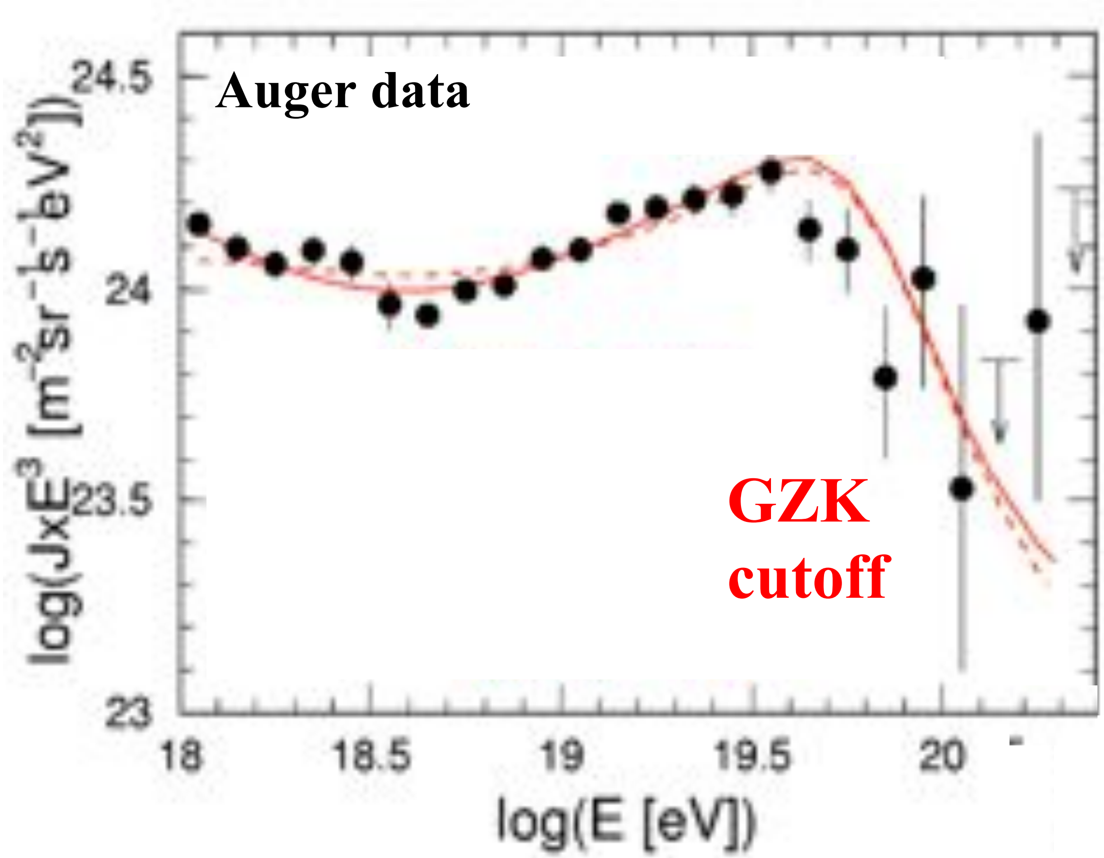
Greisen-Zatsepin-Kusmin (GZK) cutoff

at the highest energies

$p \ \gamma_{CMB} \rightarrow N \ \pi$

energy loss
≈ 15 % / interaction

λ = 5÷10 Mpc



Above $6x10^{19}$eV sources must be closer than 50-100 Mpc!

AUGER – HYBRID DETECTOR

Surface Detector (SD):

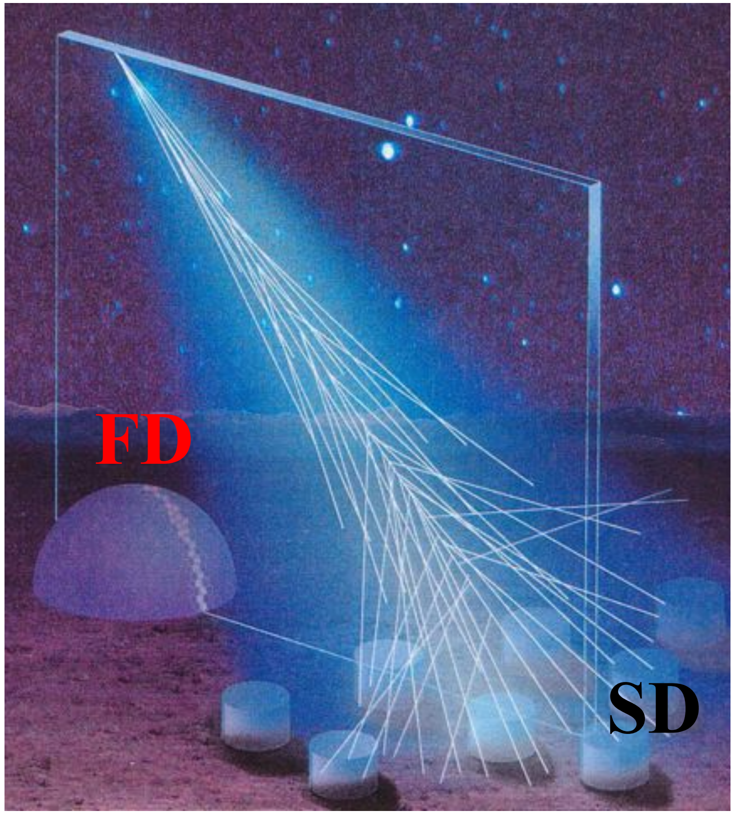
•detection of the shower front at ground

(+) Duty cicle ~ 100%

(-) Shower size at ground $\propto$ E (systematics)

simulation needs the extrapolation of hadronic interactions beyond accelerator measurements

⇒ **FD CALIBRATION**



Fluorescence Detector (FD):

•fluorescence light from the N_2 de-excitation

(+) Longitudinal shower development
calorimetric measurement of E
sensitivity to CR mass (X_{max})

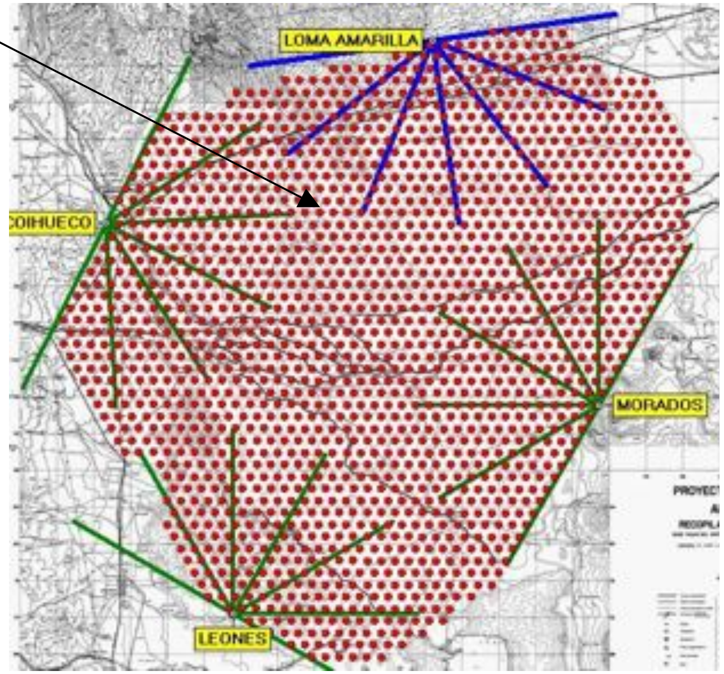
(-) Duty cicle ~ 10%

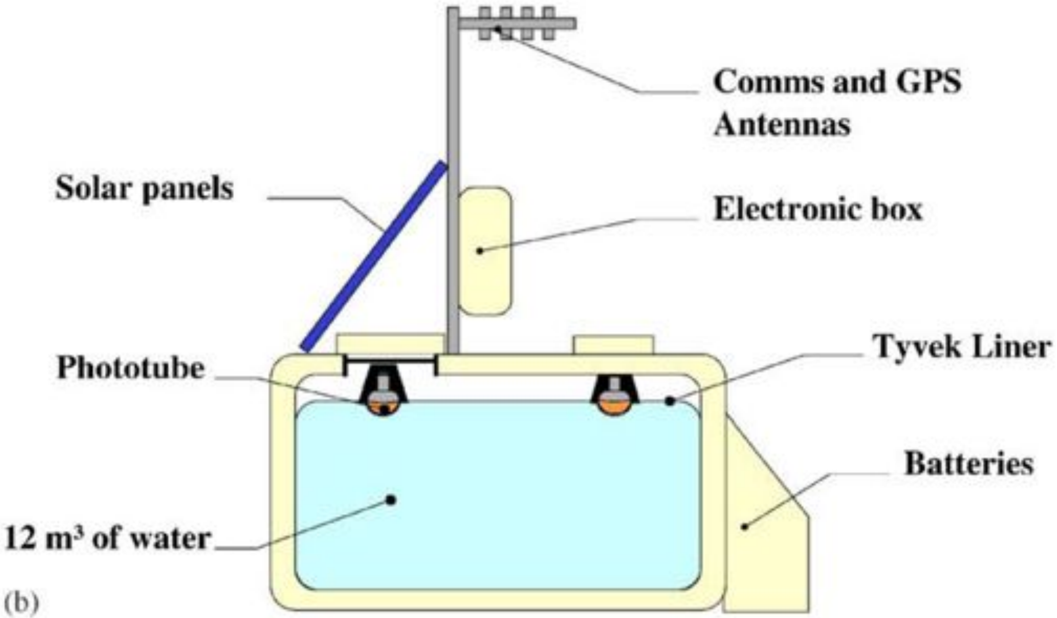
PIERRE AUGER OBSERVATORY

SD

Malargue (Argentina)
3000 km^2

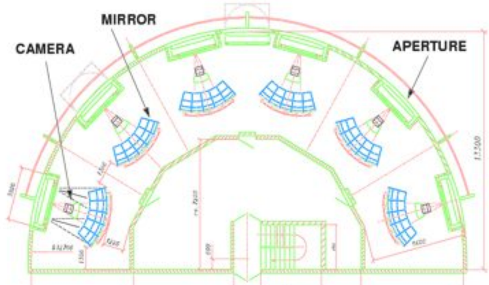
1600 water Cherenkov detectors
on a 1.5 km hexagonal grid





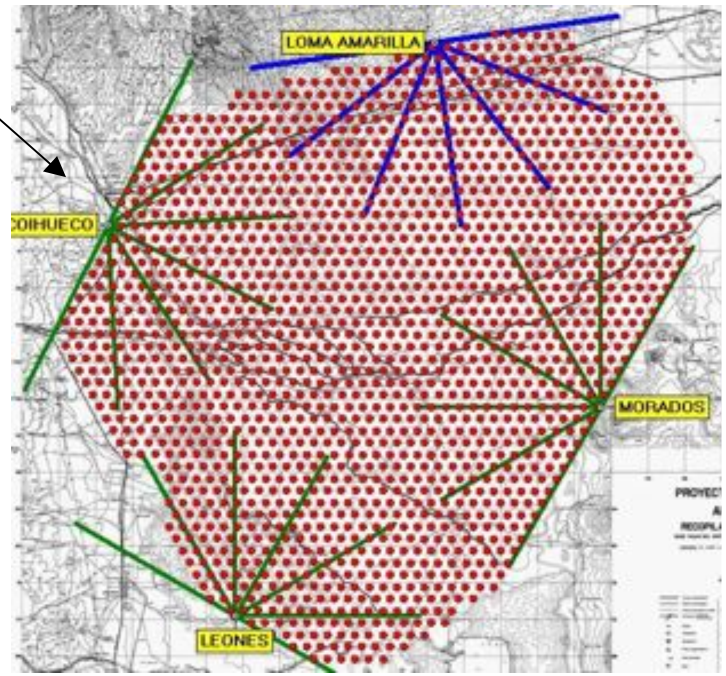
PIERRE AUGER OBSERVATORY

FD



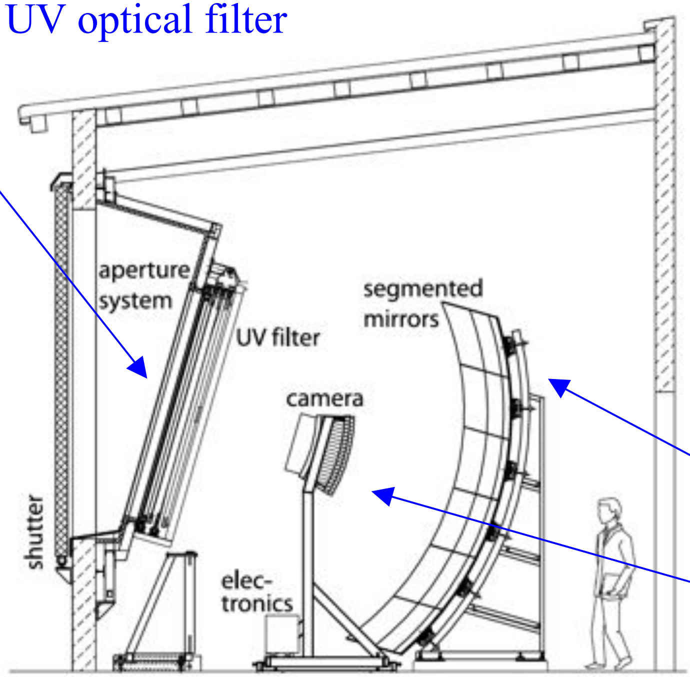
Malargue (Argentina)
3000 km^2

4 x 6 fluorescence telescopes



2.2 m diameter diaphragm
corrector ring, UV optical filter

Schmidt optics



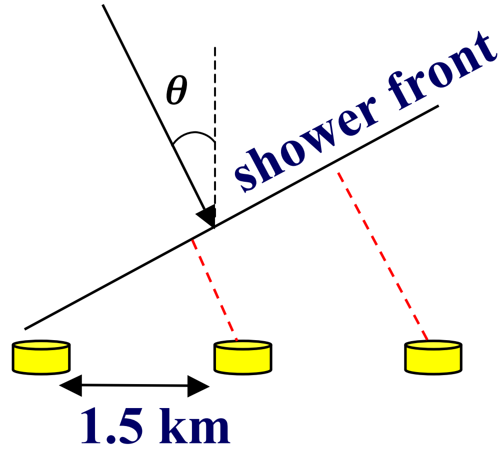
spherical mirror 3.4 m m radius of curvature

camera (focal surface) - 30^0X30^0 FOV

440 PMT's - 100 ns FADC

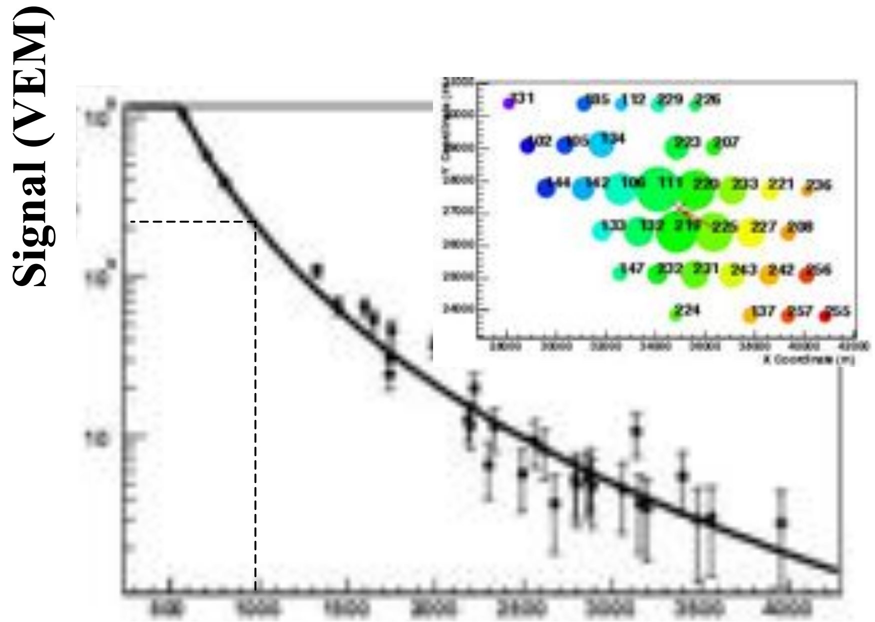
SD SHOWER RECONSTRUCTION

Shower front from particle arrival times



Core position and S(1000) from LDF (NGK) fit

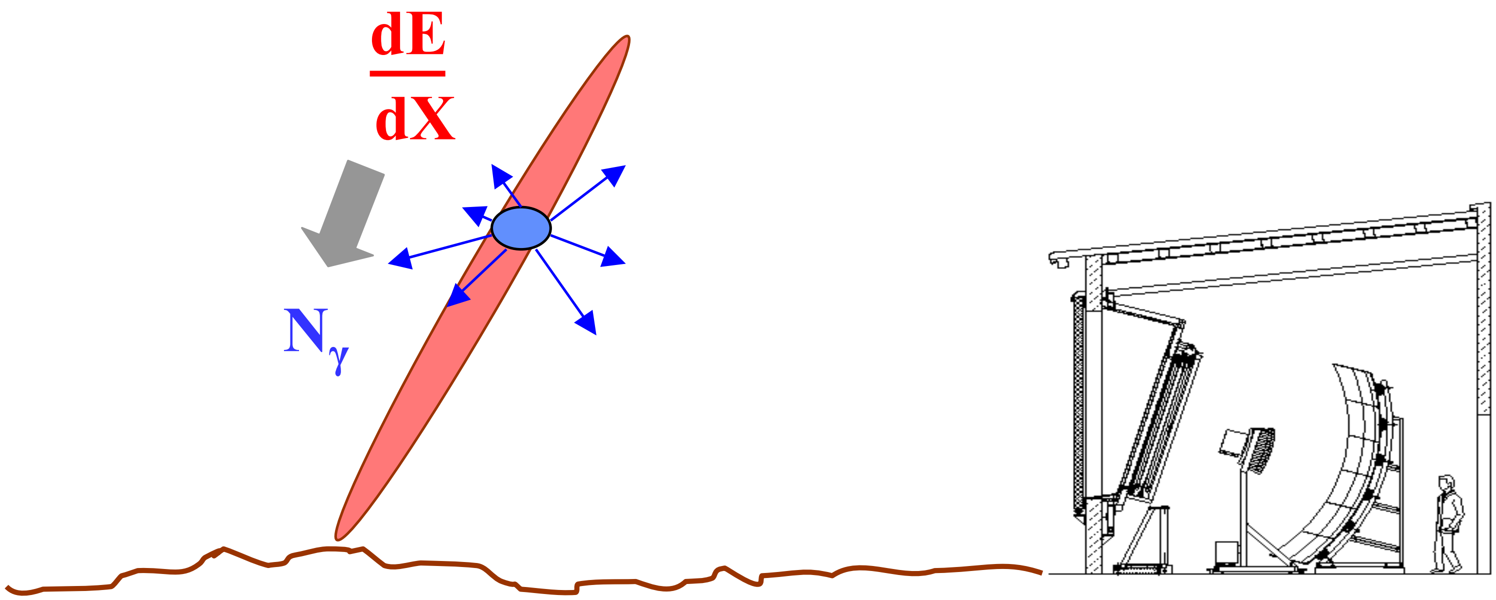
$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+700}{1700}\right)^{-\beta}$$



S(1000) is the best energy estimator

conversion factor from FD

FLUORESCENCE YIELD



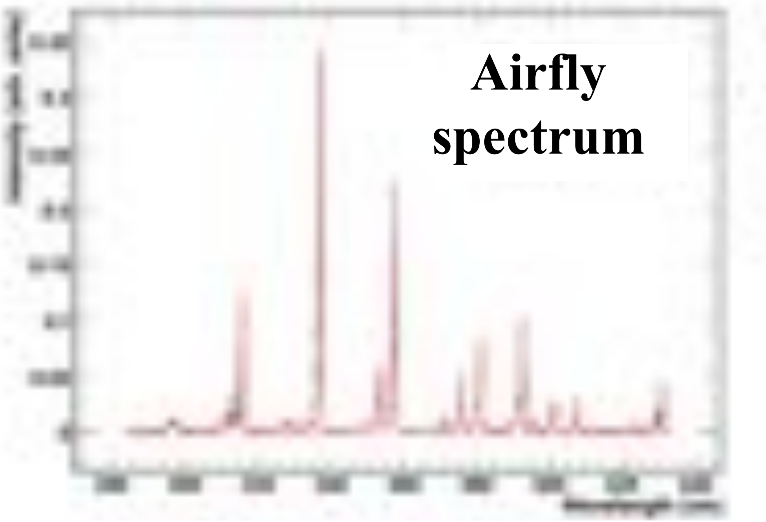
in Auger:

5.05 ± 0.71 ph/MeV at 337 nm

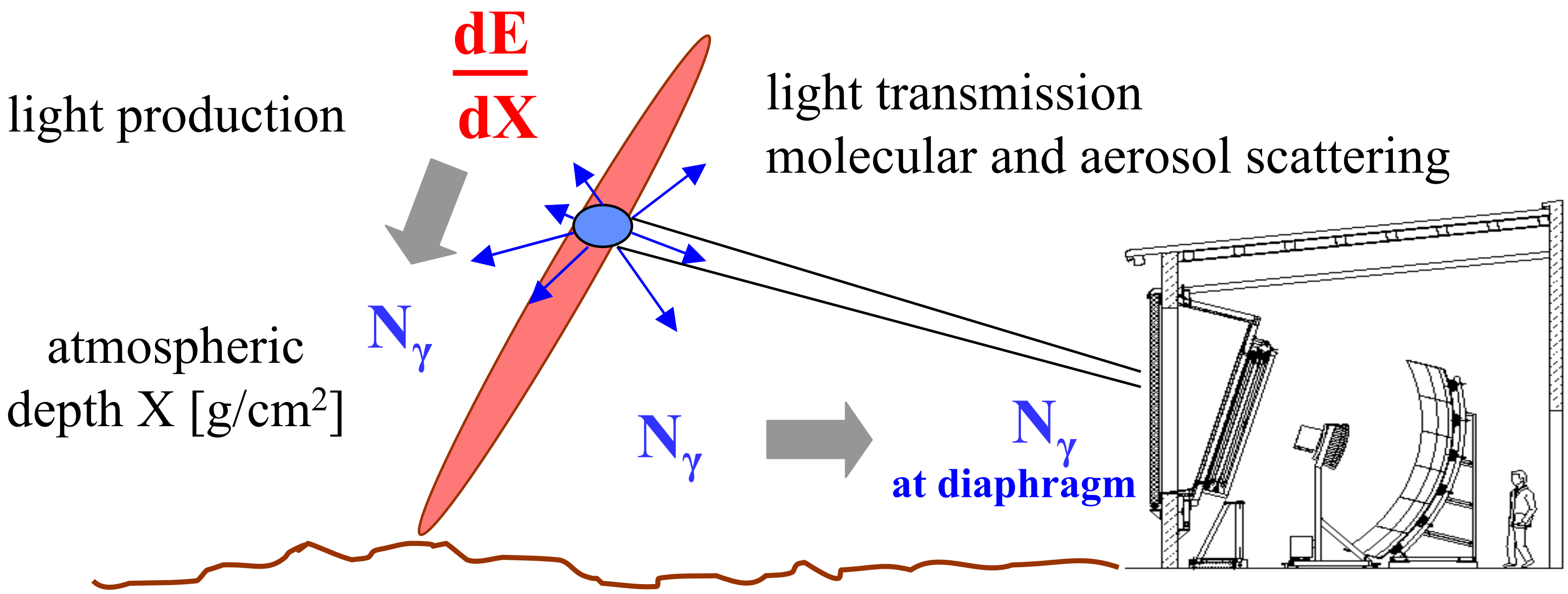
Nagano et al. Astrop. Phy. 22 (2004) 35

spectrum and pressure dependence

M.Ave et al. Astrop. Phy. 28 (2007) 41



ATMOSPHERIC MONITORING



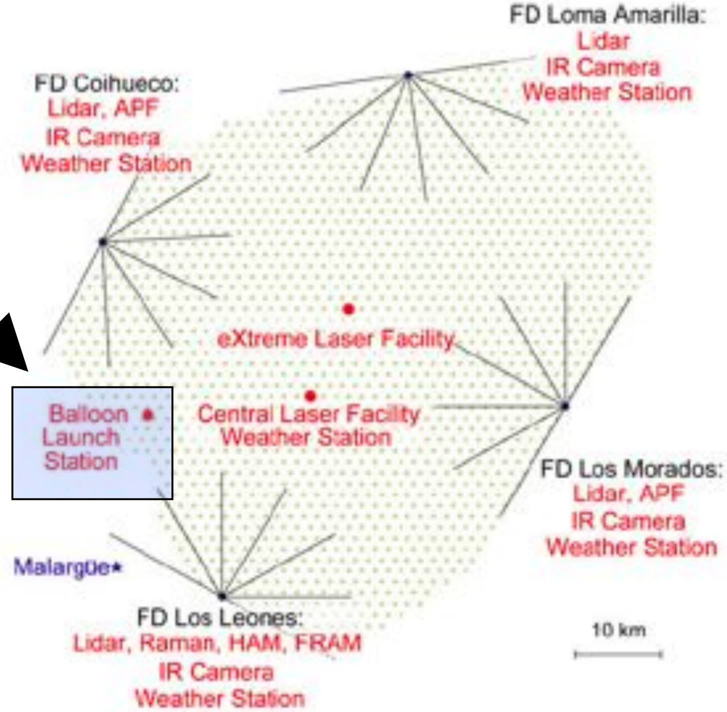
Atmospheric monitoring

pressure, temperature and umidity

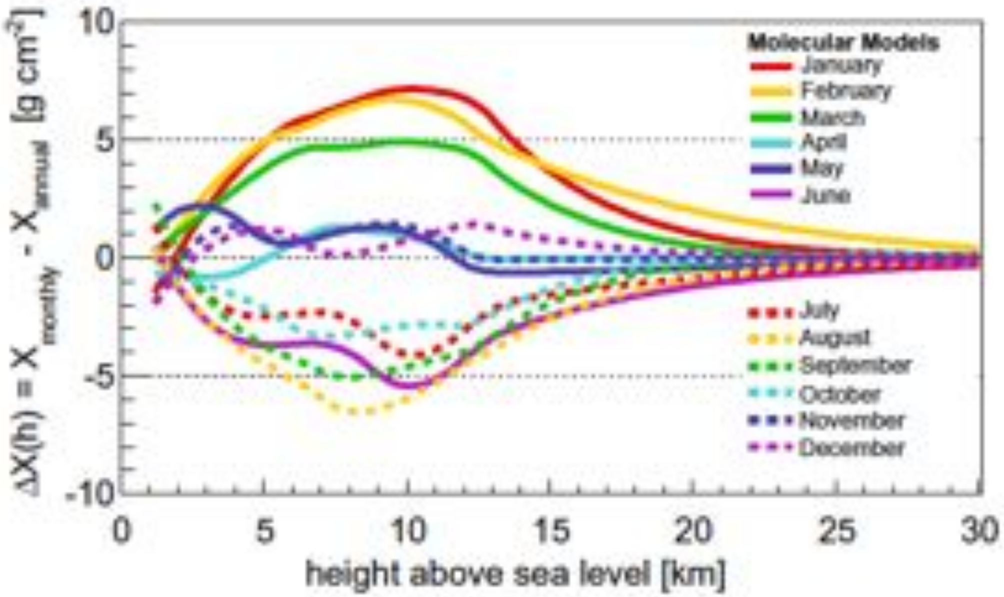
aerosols (clouds, dust, smoke, …)

ATMOSPHERIC MONITORING

Radio soundes to provide atmospheric profiles (pressure, temperature, …) vs altitude



Montly Malargue average model

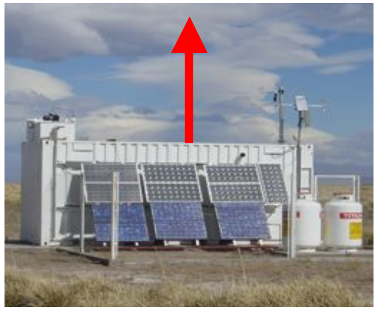


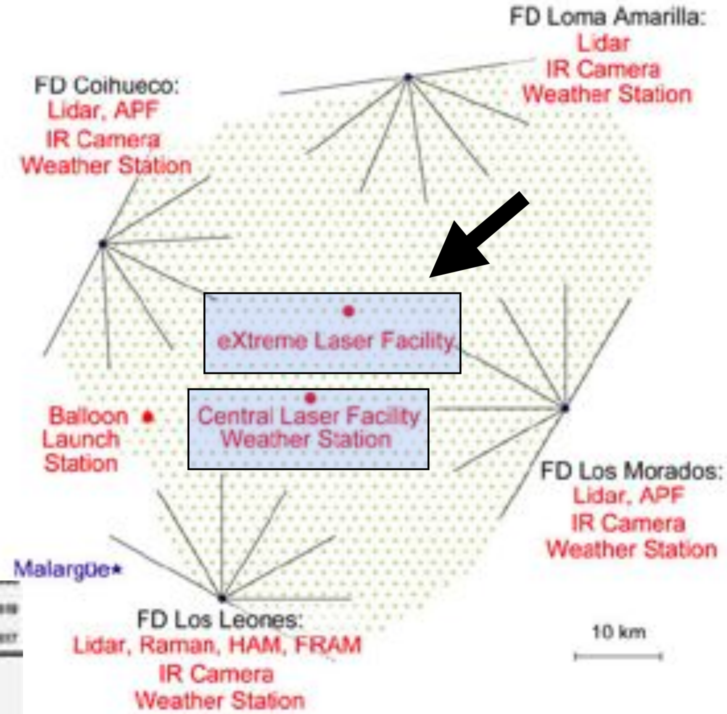
atmospheric depth X(h): deviation of montly mean values from the yearly average

ATMOSPHERIC MONITORING

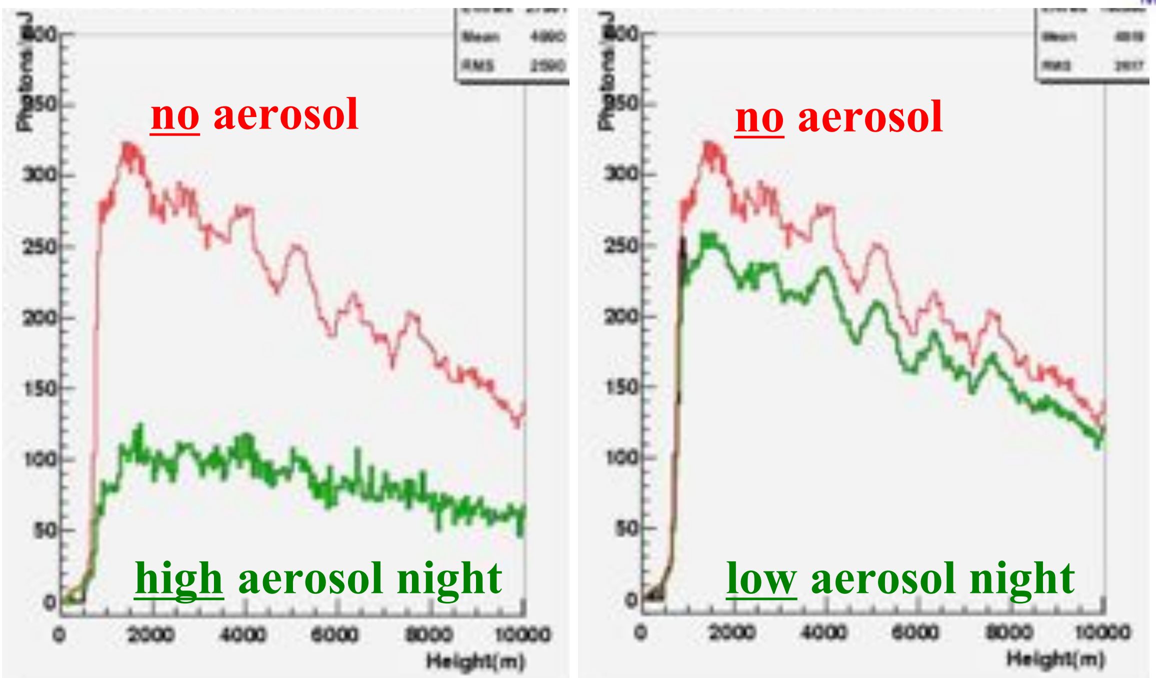
355 nm
steerable laser

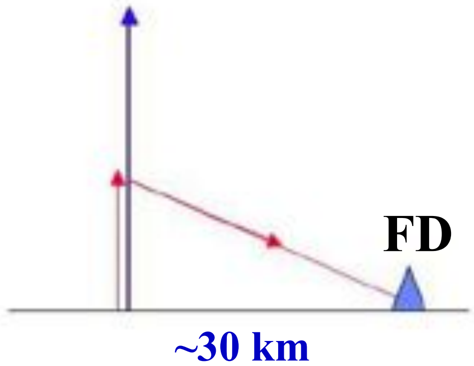
50 shots every
15 min





Laser profiles measured by FD





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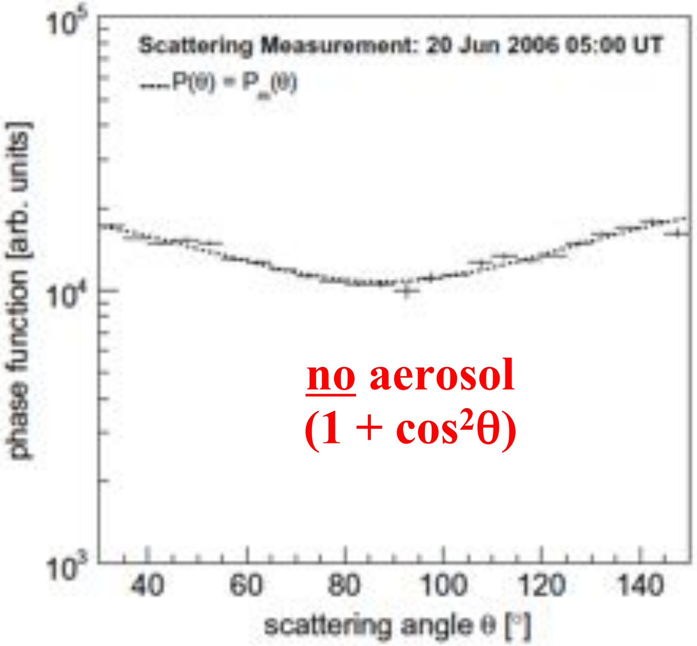
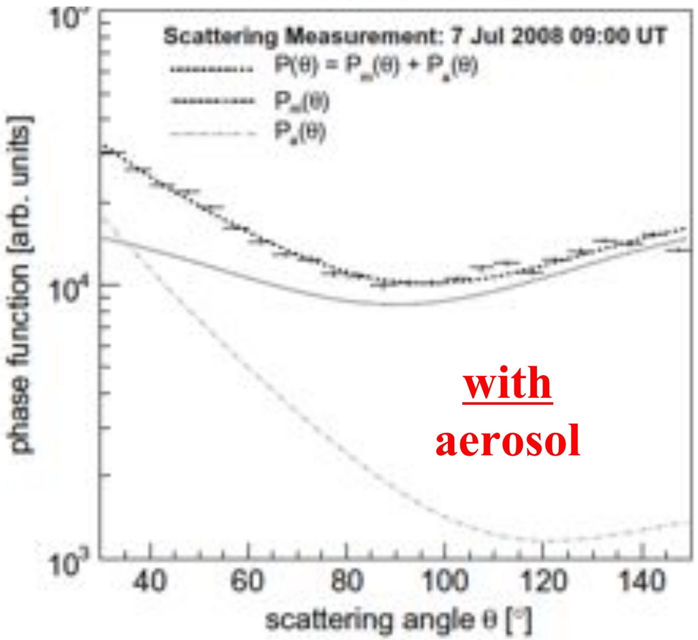
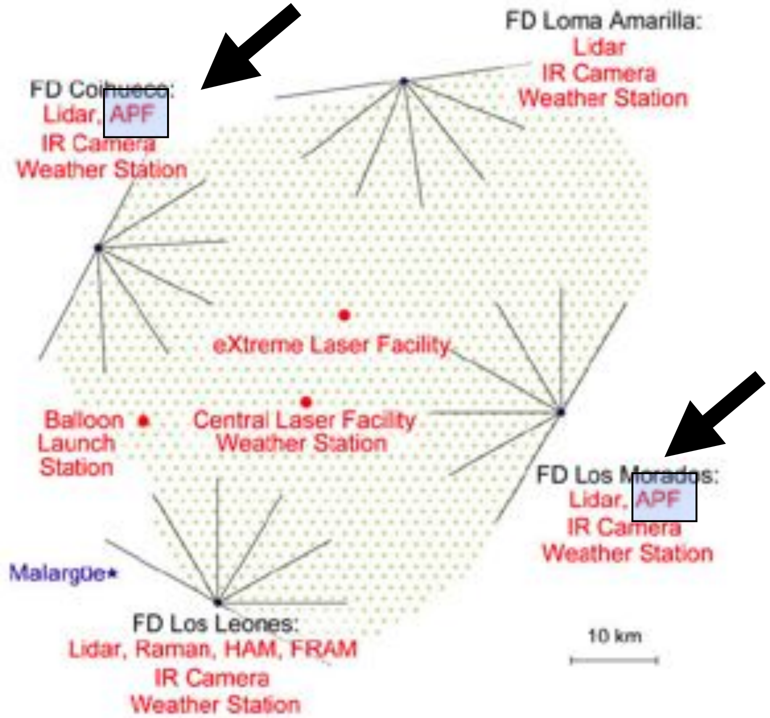
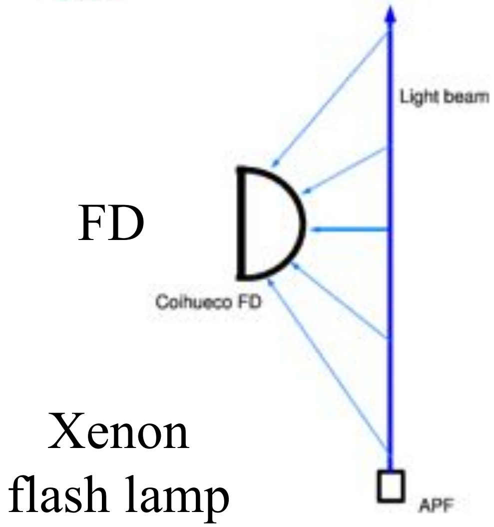






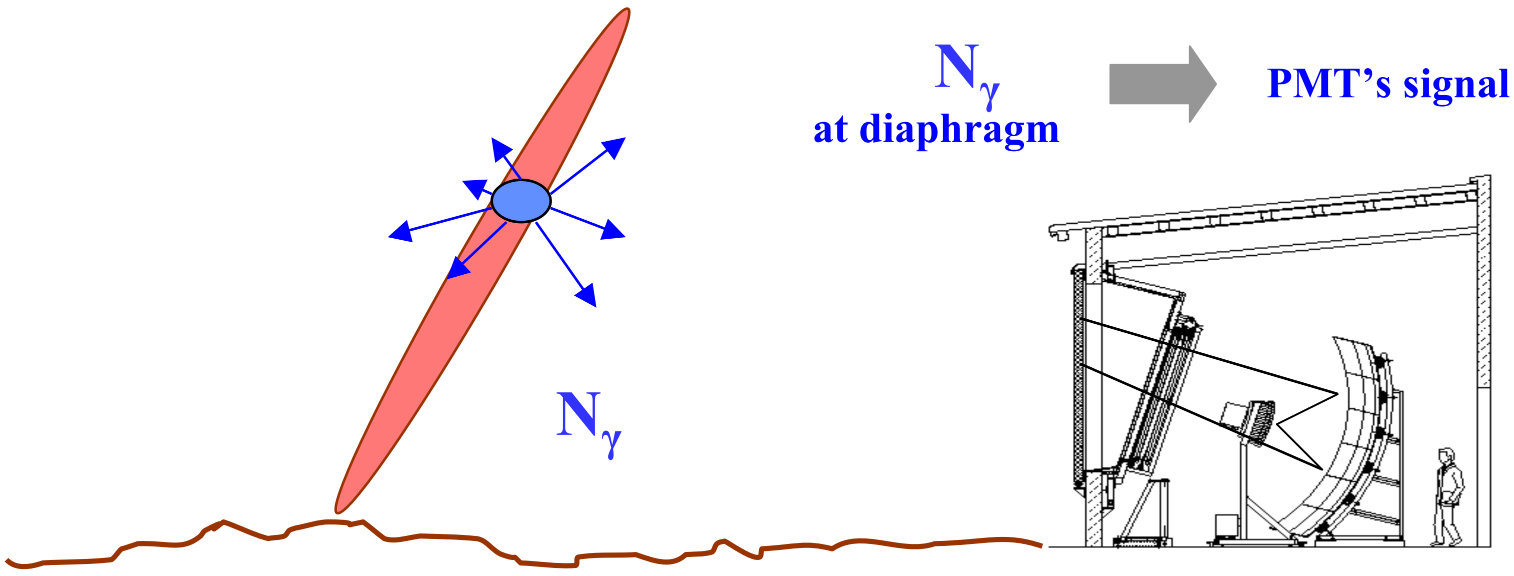
Aerosol phase function monitors



SYSTEMATICS RELATED TO ATMOSPHERE

SOURCE	ΔE/E
Quenching effects on fluorescence yield	+5.5%
Horizontal uniformity	1%
Pressure, temperature and umidity variability	0.5%
Aerosol optical depth	3.5% - 7.5%
λ dependence	0.5%
Phase function	1%
TOTAL	≈ 7% - 9%

FD CALIBRATION



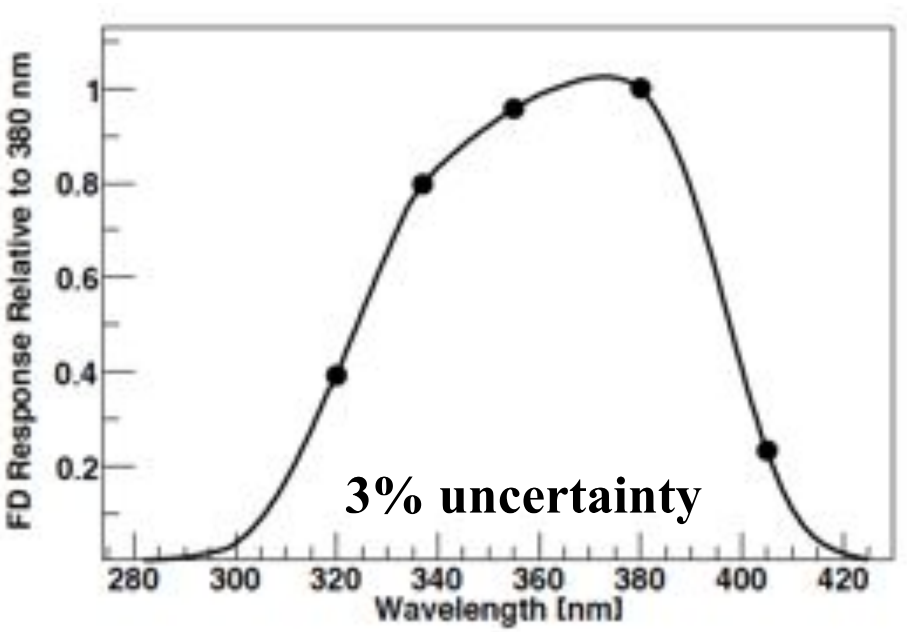
We need to know the number of photons at diaphragm per ADC count detected by each pixel

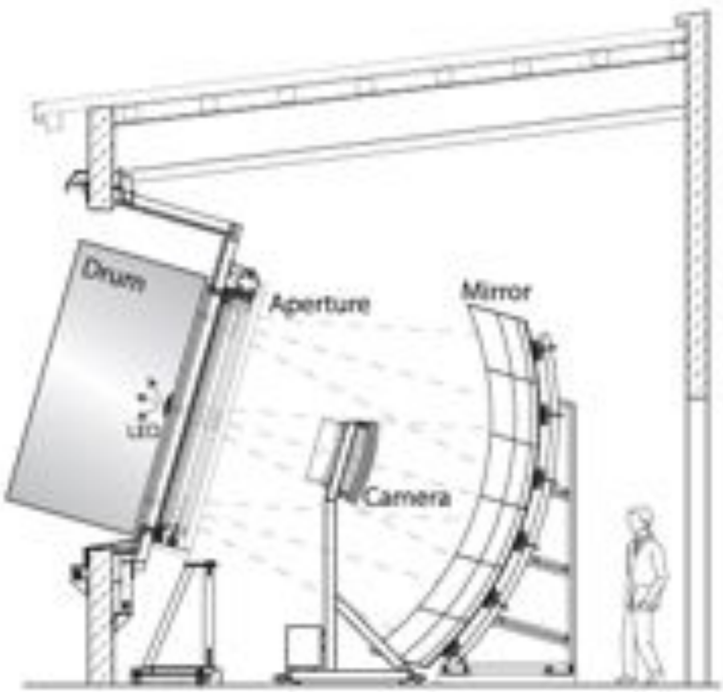
ABSOLUTE CALIBRATION

Drum absolute calibration

uniform camera illumination with a calibrated light source

~ 5 γ/ADC   9% uncertainty



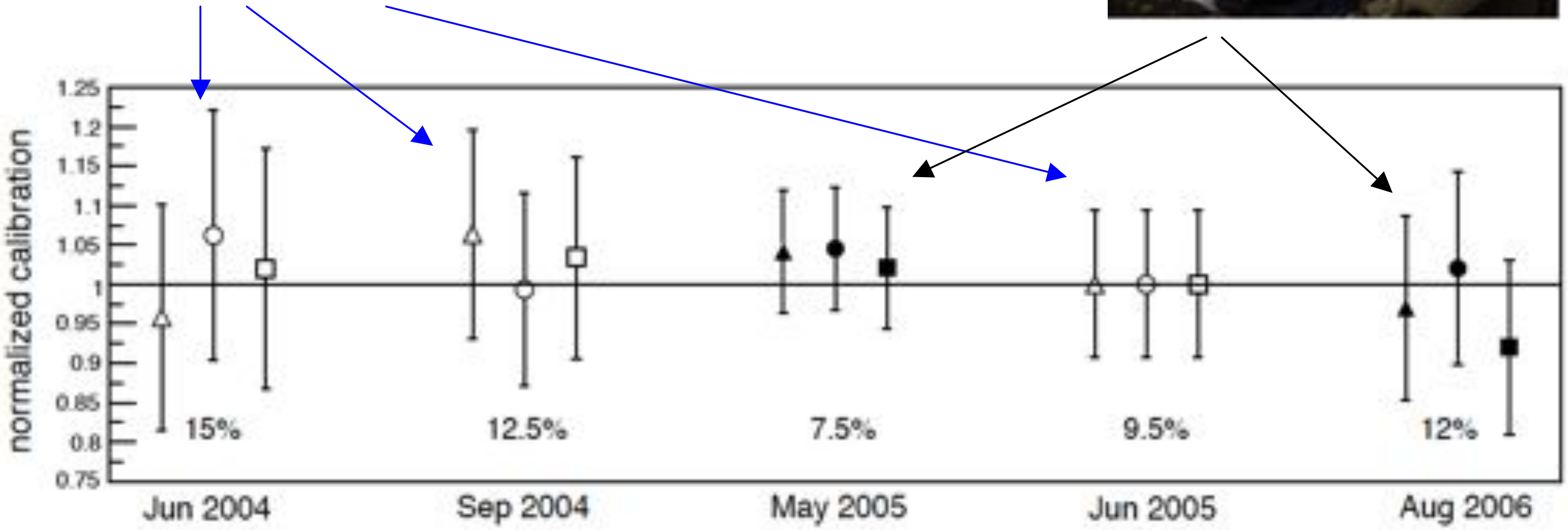


CROSS CHECK OF THE ABSOLUTE CALIBRATION

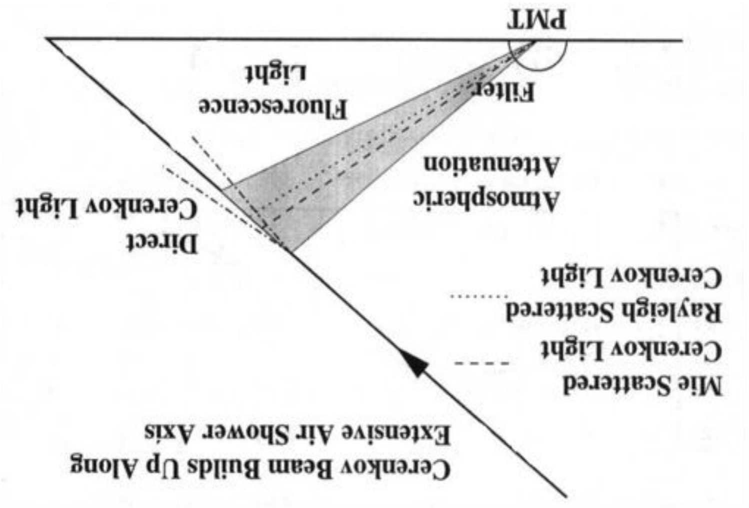
Roving lasers
λ = 337 nm
R ≈ 3 Km (atmospheric attenuation minimized)

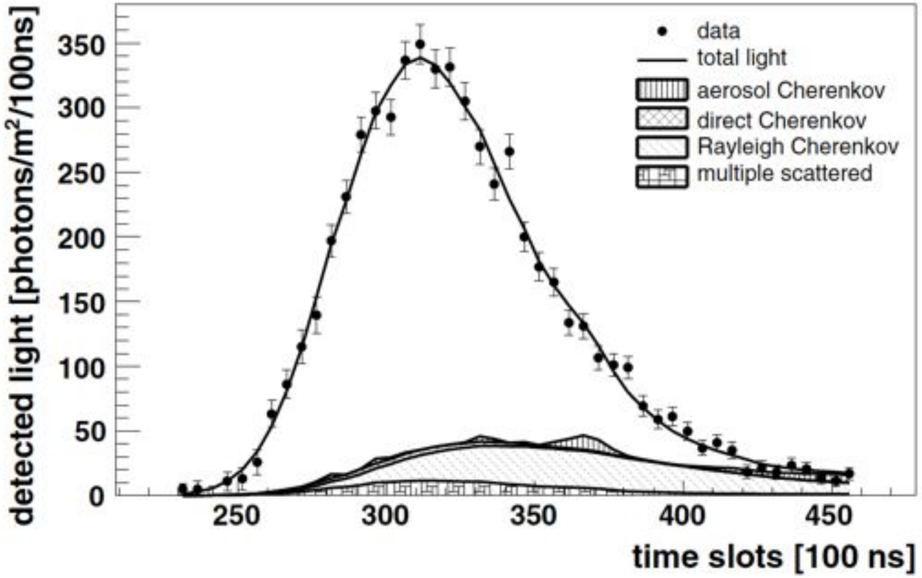
Energy probe to measure the beam intensity --> 10% uncertainty

DRUM



FD SHOWER RECONSTRUCTION

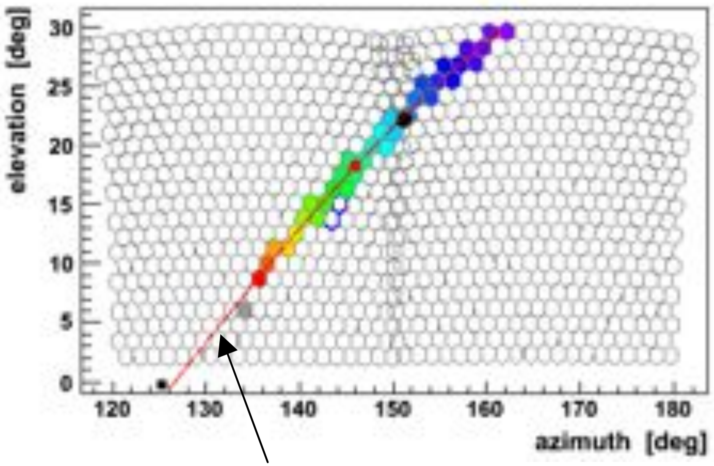




Systematic uncertainty ~ 10%

related to light collection

- select pixels close to SDP to maximize S/N
- accounts for the light detected by not selected pixels (finite shower width, optic imperfections, …) where the signal is completely masked by the noise



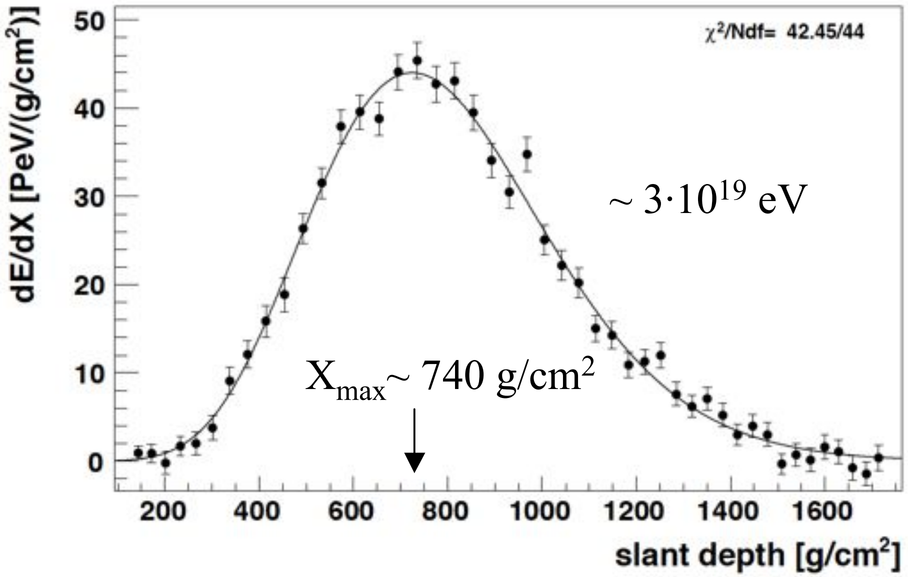
Shower Detector Plane (SDP)

FD SHOWER RECONSTRUCTION

expected dE/dX profile:

fitted Gaisser-Hillas function

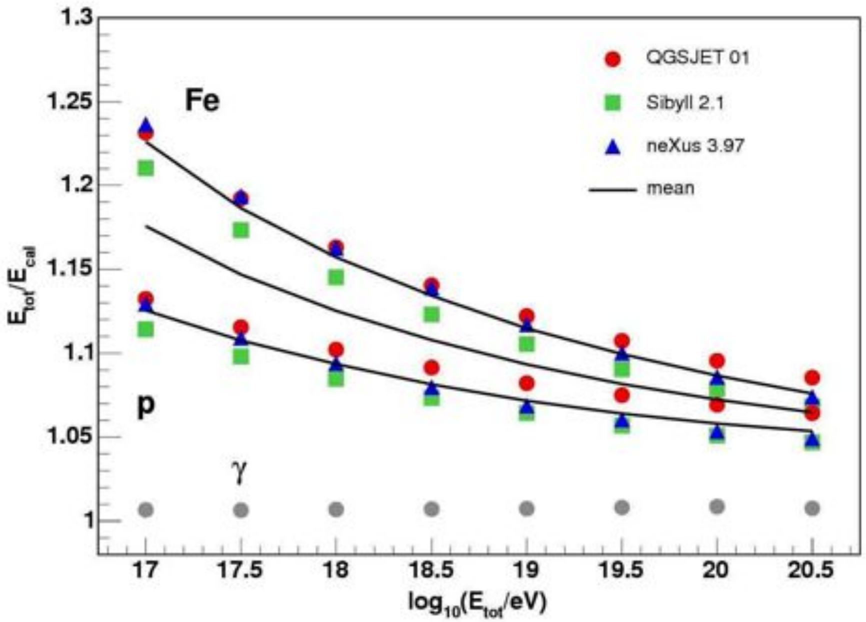
$$E_{cal} = \int dX \frac{dE}{dX}$$



From E_{cal} to shower energy

only a 10% model dependent correction

~ 4% uncertainty on shower energy



SD CALIBRATION USING FD ENERGY

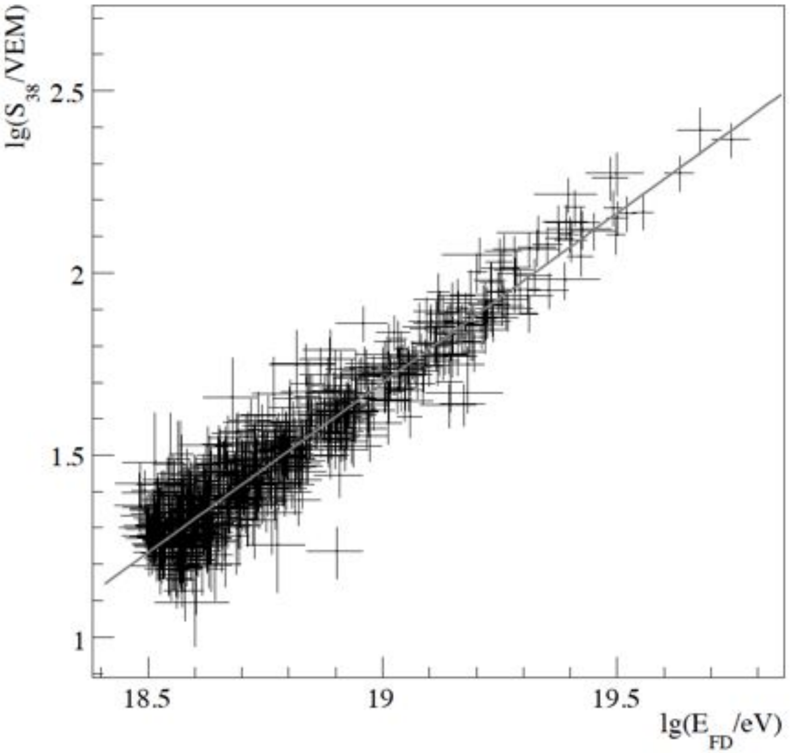
$S_{38} = S(1000, \theta = 38^0)$

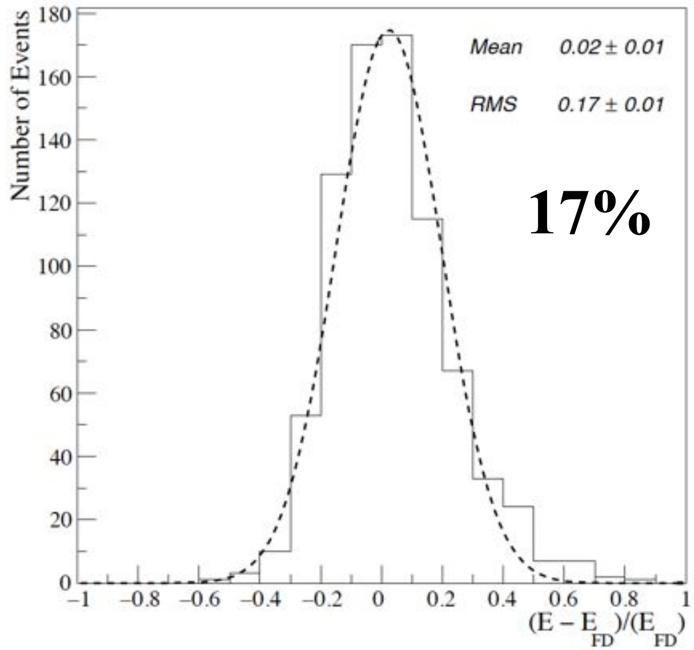
Attenuation curve derived using constant intensity cut technique

$$E_{FD} = A \cdot S_{38}^B$$

$$B \approx 1.07$$

50 VEM ~ 10^{19} eV



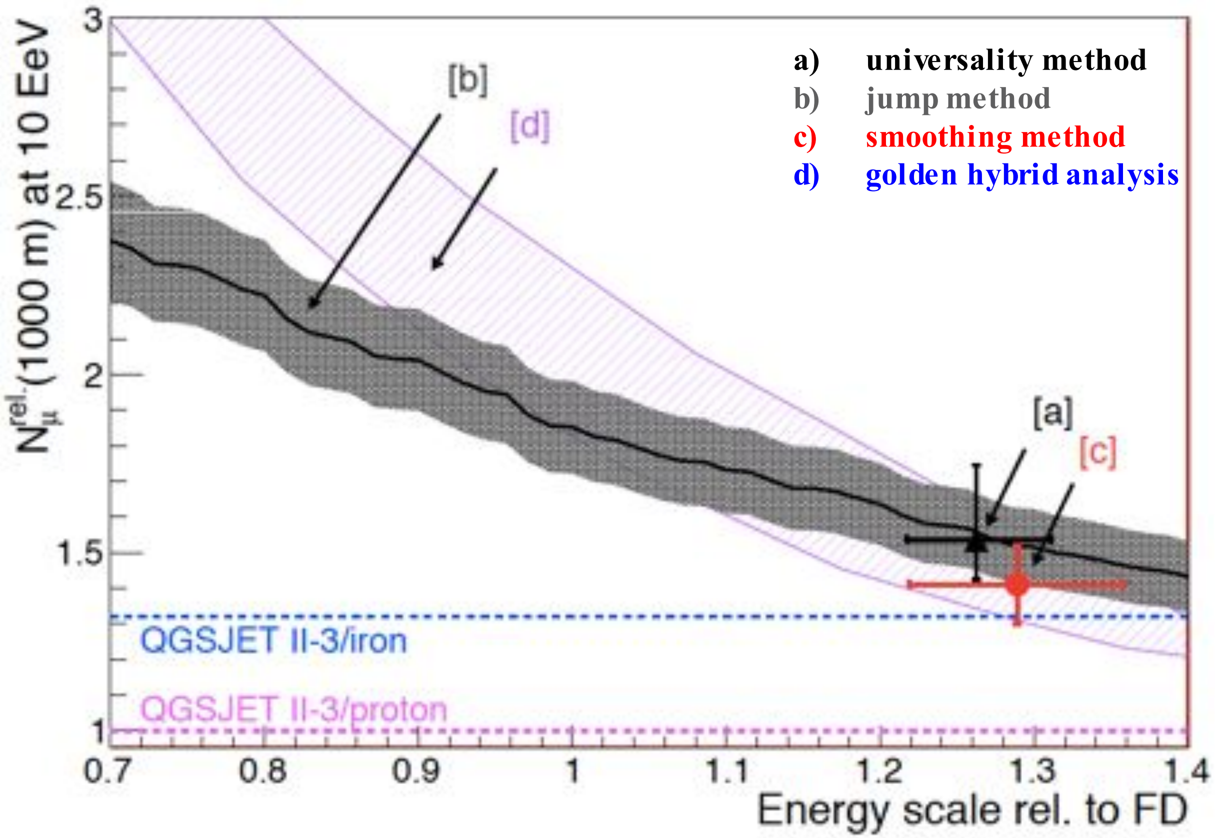


measurement of the energy resolution

14%-S_{38} 9%-E_{FD} $\sqrt{14^2 + 9^2} \approx 17\%$

FD ENERGY SCALE vs SIMULATION

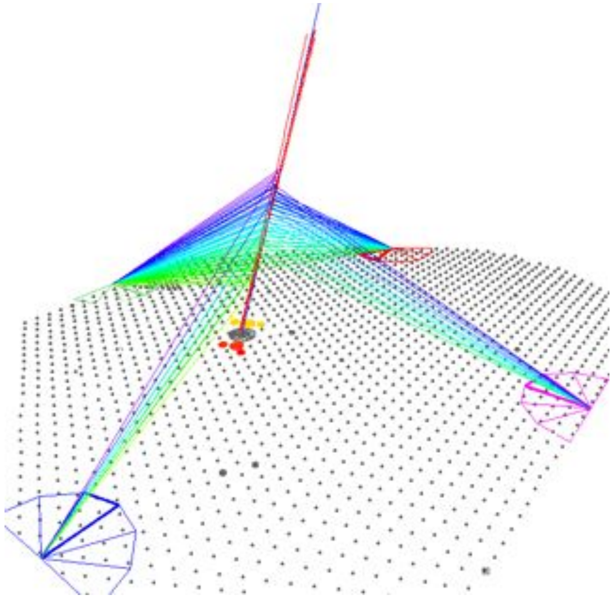
Detailed analysis of S(1000) - separation of muonic and elettromagnetic components

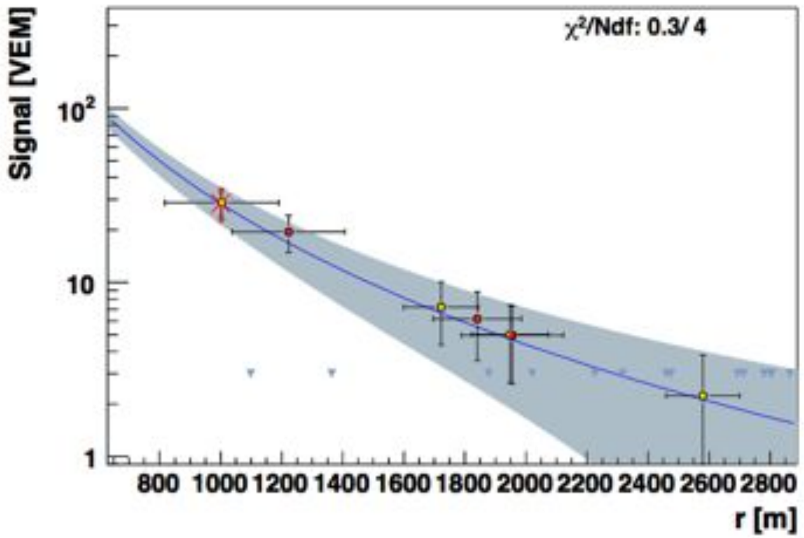


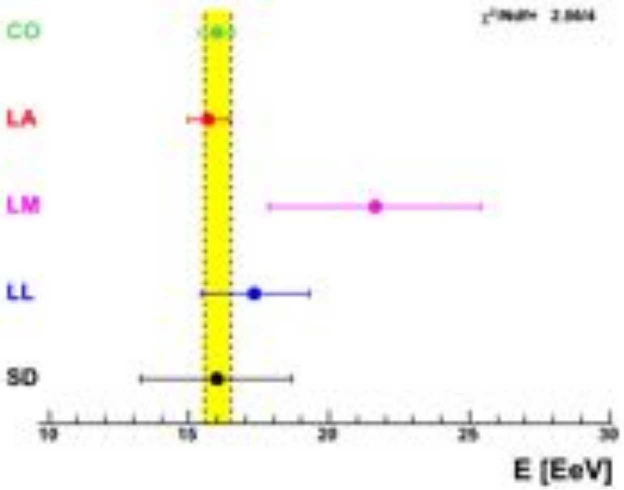
$$[a]\quad E_{MC} = 1.26^{+0.05}_{-0.04}\,(\text{syst.}) \times E_{FD}$$

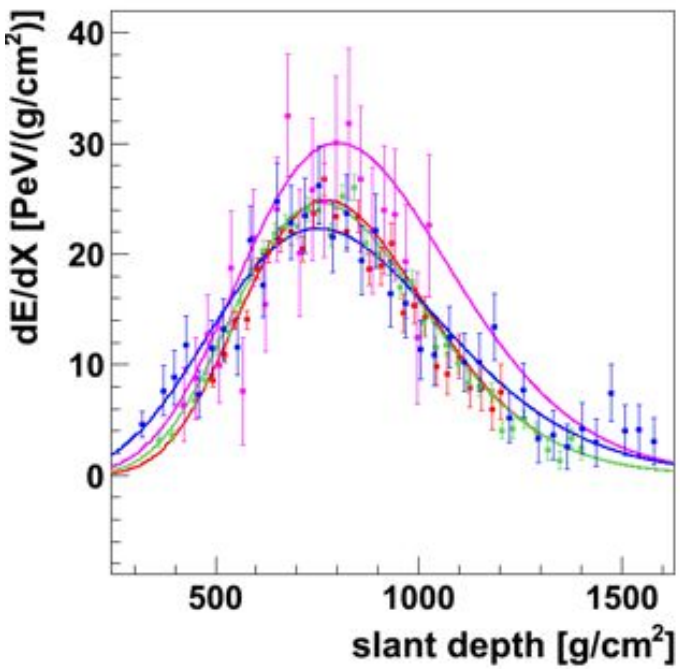
compatible within FD uncertainties (22%)

TRUSTING ON OUR DATA









SYSTEMATIC UNCERTAINTIES ON AUGER ENERGY SCALE (PUBLISHED RESULTS)

SOURCE	ΔE/E
Absolute fluorescence yield	14%
Atmosphere	8%
FD calibration	9.5%
FD reconstruction	10%
Invisible energy	4%
TOTAL	≈ 22%

SYSTEMATIC UNCERTAINTIES ON AUGER ENERGY SCALE (PUBLISHED RESULTS)

SOURCE	ΔE/E	
Absolute fluorescence yield	14%	→ 5%
Atmosphere	8%	
FD calibration	9.5%	
FD reconstruction	10%	
Invisible energy	4%	
TOTAL	≈ 22%	→ 18%

OUTLOOK

• **Systematic uncertainty on the energy scale is**

22% *(Phys. Rev. Lett. 101 (2008), 061101)*

dominated by the uncertainty on absolute fluorescence yield (14% - *Nagano et al. Astrop. Phy. 22 (2004) 35)*

• We are working to reduce the systematics and soon there will be an update of the energy scale. It will be worthwhile to use a more precise value of the absolute fluorescence yield

• An important goal of this series of workshops is to provide a recommendation on what is the best fluorescence yield (combination of different experiments ?), including spectrum, pressure dependence, ….

OUTLOOK

• **Systematic uncertainty on the energy scale** is

22% *(Phys. Rev. Lett. 101 (2008), 061101)*

dominated by the uncertainty on absolute fluorescence yield (15% - *Nagano et al. Astrop. Phy. 22 (2004) 35)*

• We are working to reduce the systematics and soon there will be an update of the energy scale. It will be worthwhile to use a more precise value of the absolute fluorescence yield

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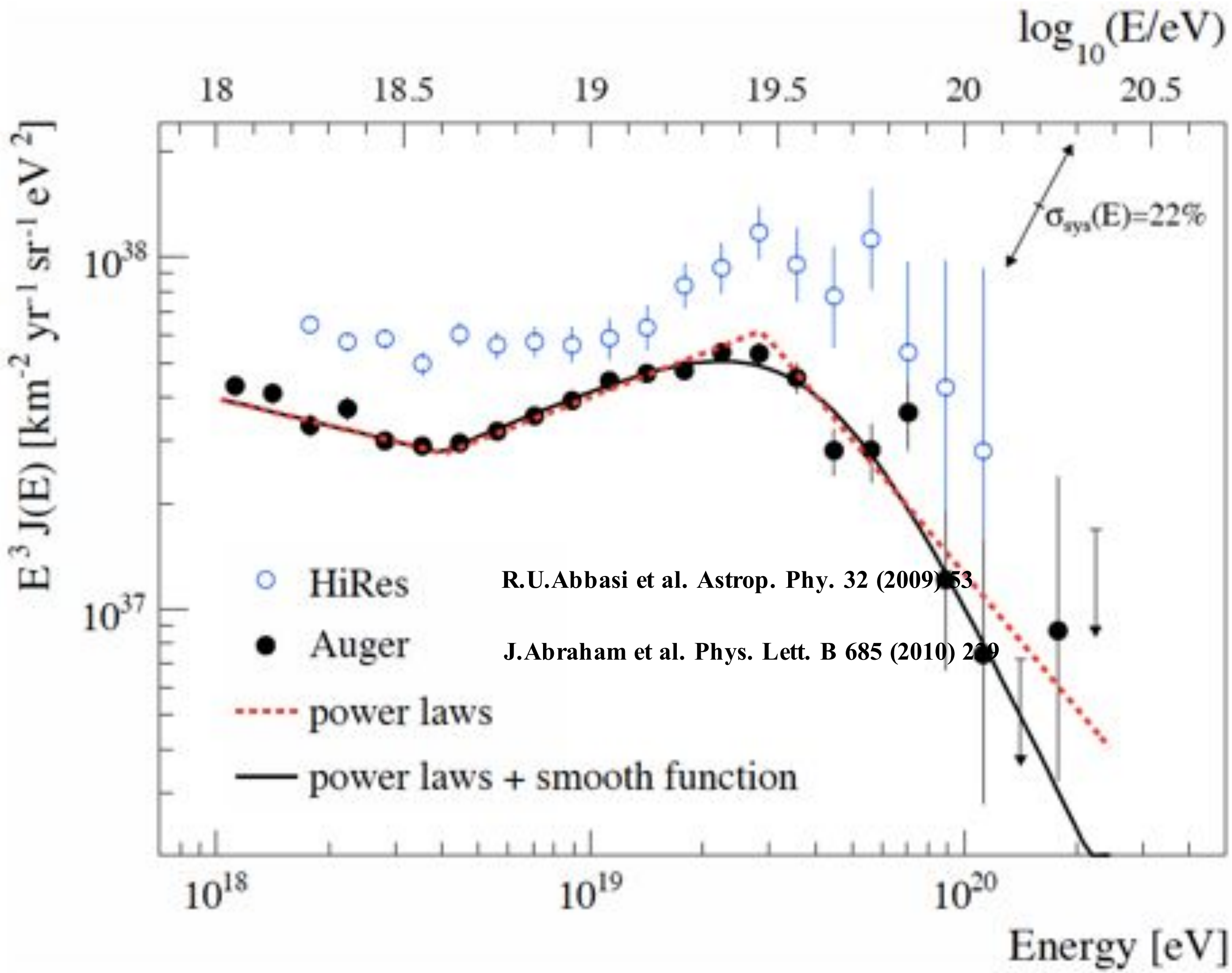
AUGER vs HIRES SPECTRUM



fairly agreement between systematics

Notice: HIRES uses a different fluorescence yield (FLASH) and spectrum (Bunner)