MAPSES Lecce 23-25 Novembre

Pierre Auger Observatory
studying the universe's highest energy particles

Tecniche di misura con l'Osservatorio Pierre Auger

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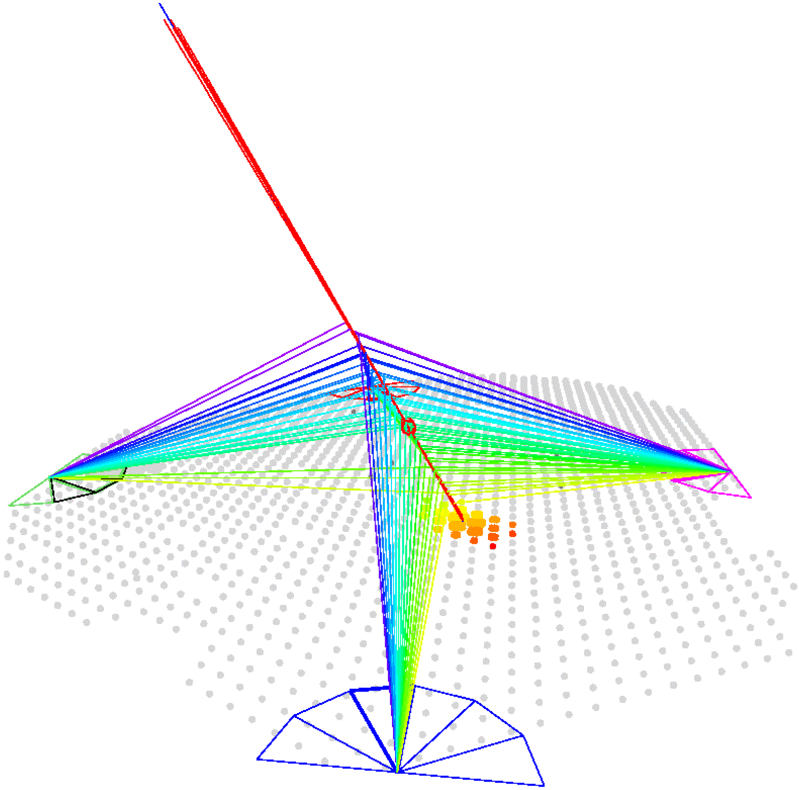
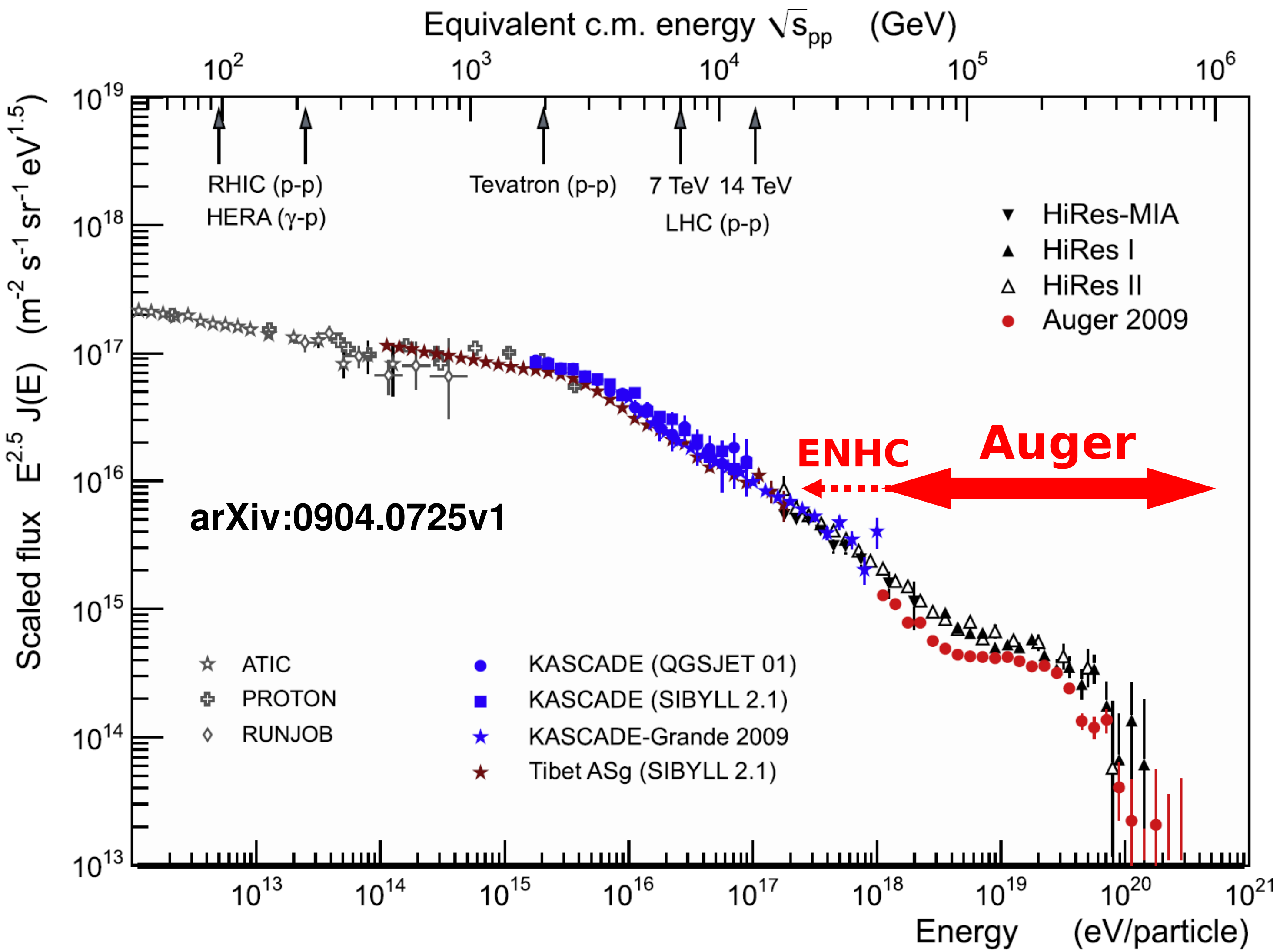
Outline

- Physics goals and operation range
- Detector description
- Performance and observables
- Results
- Enhancements



The Pierre Auger Observatory: range of operation



ENHC: Auger low energy extensions

Study of the transition between galactic and extra-galactic cosmic rays

The physics case

- Ankle region

- 2^{nd} Knee region (with lower energies extensions)

End of the spectrum (GZK region)

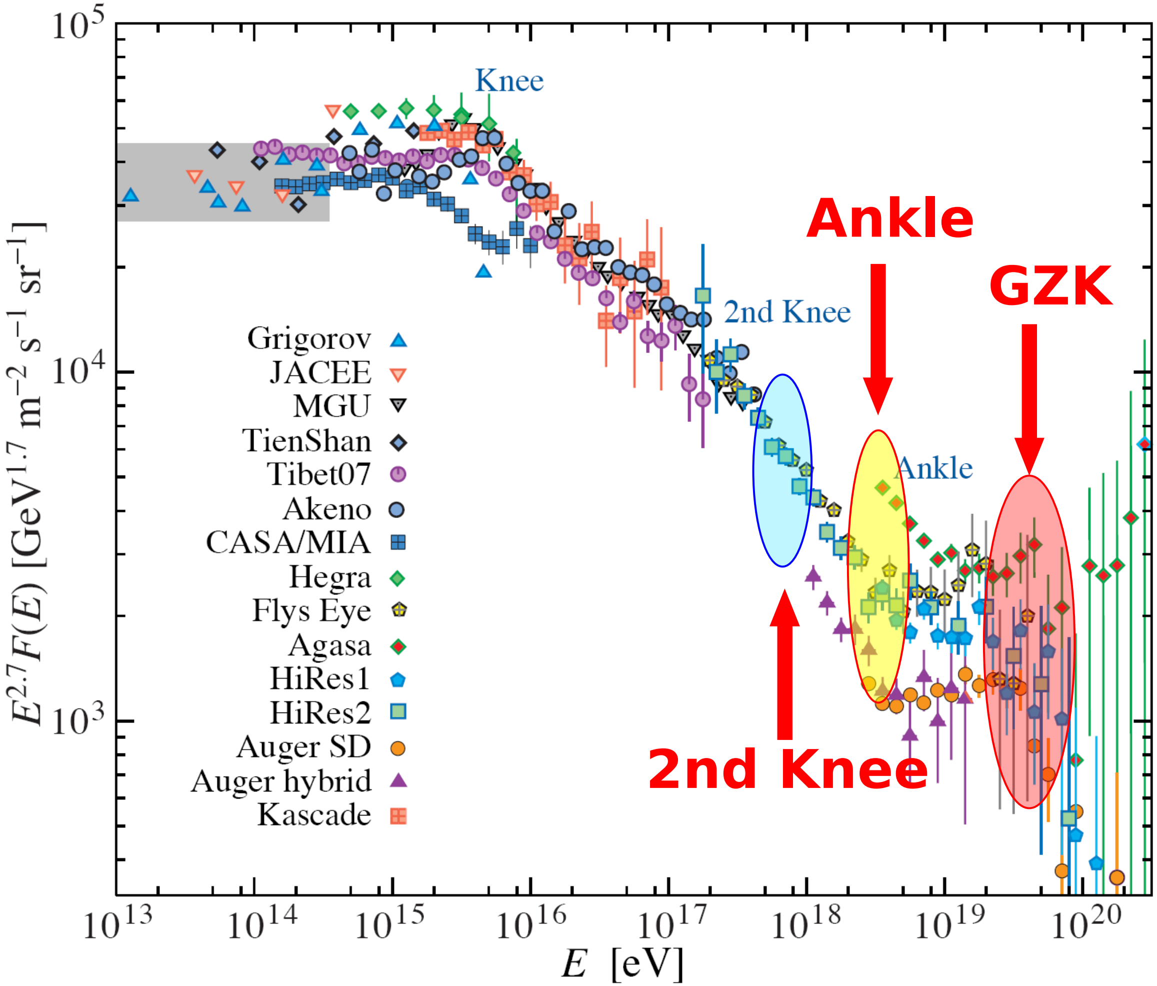
Energy spectrum

Arrival directions

Composition

Search for photon and neutrinos as primary cosmic rays

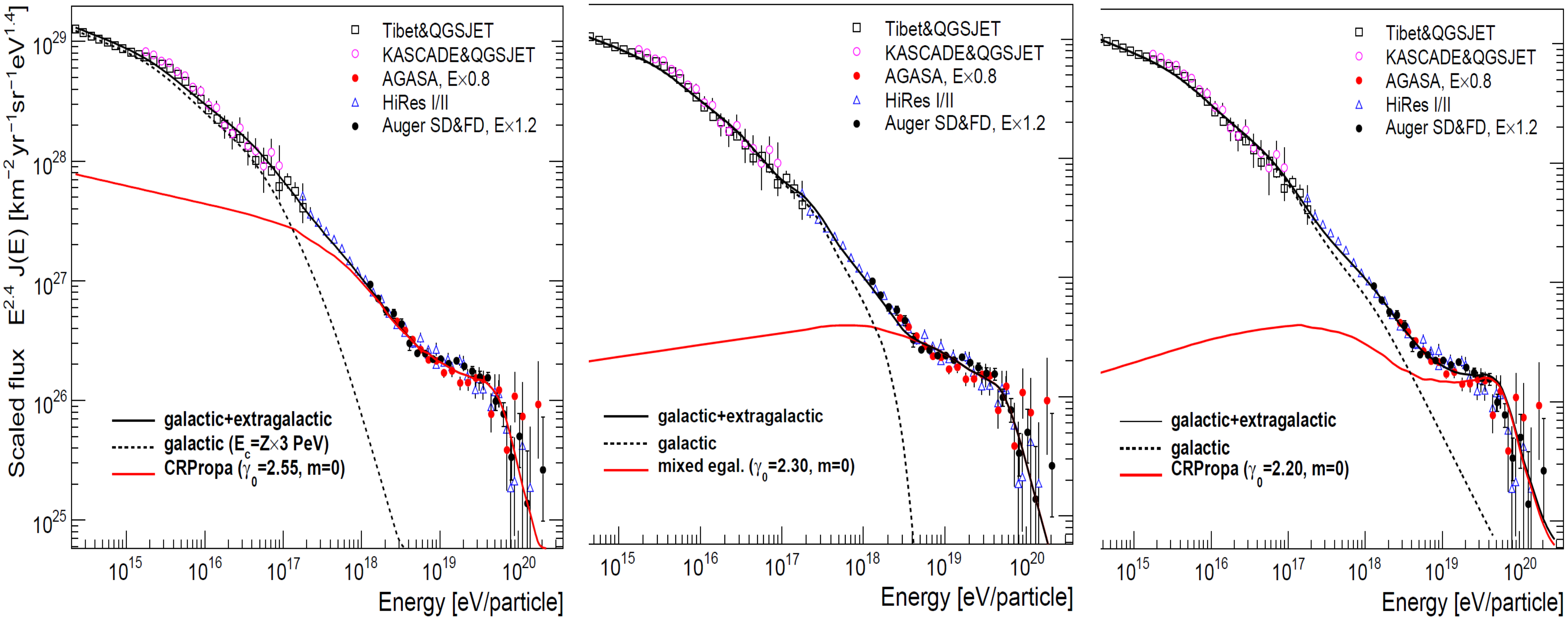
Hadronic physics



Particle Data Group

“the ankle”: models and hyphoteses

M.Unger, arXiv:0812.2763 [astro-ph]



$E_{Gal\text{-}ExtraGal} \sim 10^{17.5}$ eV

Dip Model
Extragal. protons
(Berezinsky et al.)

$E_{Gal\text{-}ExtraGal} \sim 3\ 10^{18}$ eV

Mixed comp. of
extragal. component
(Allard et al.)

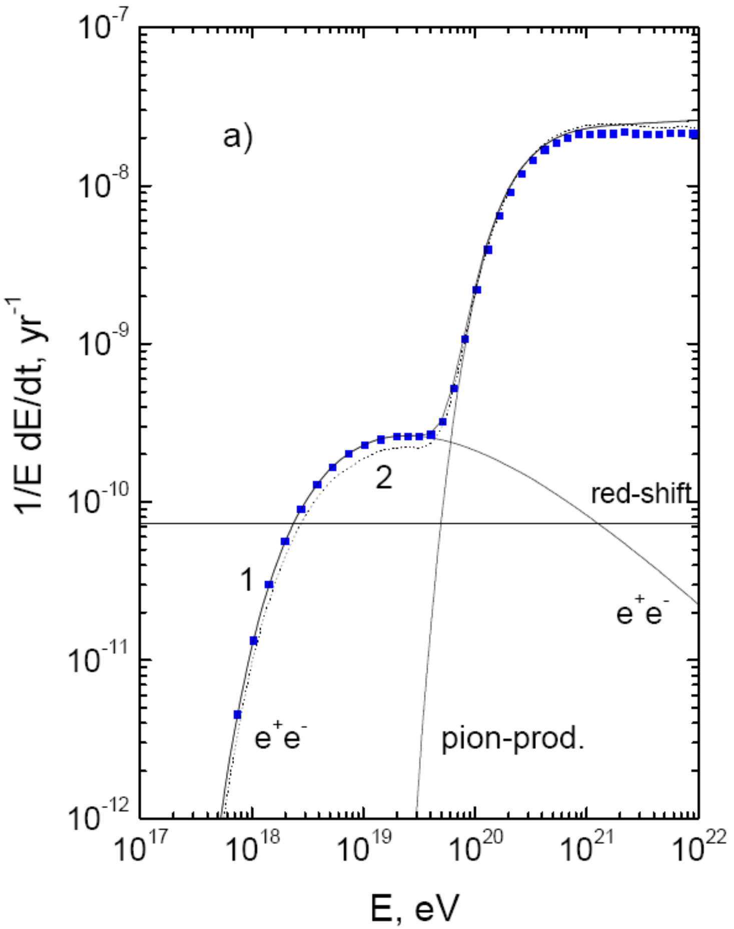
$E_{Gal\text{-}ExtraGal} \sim 10^{19}$ eV

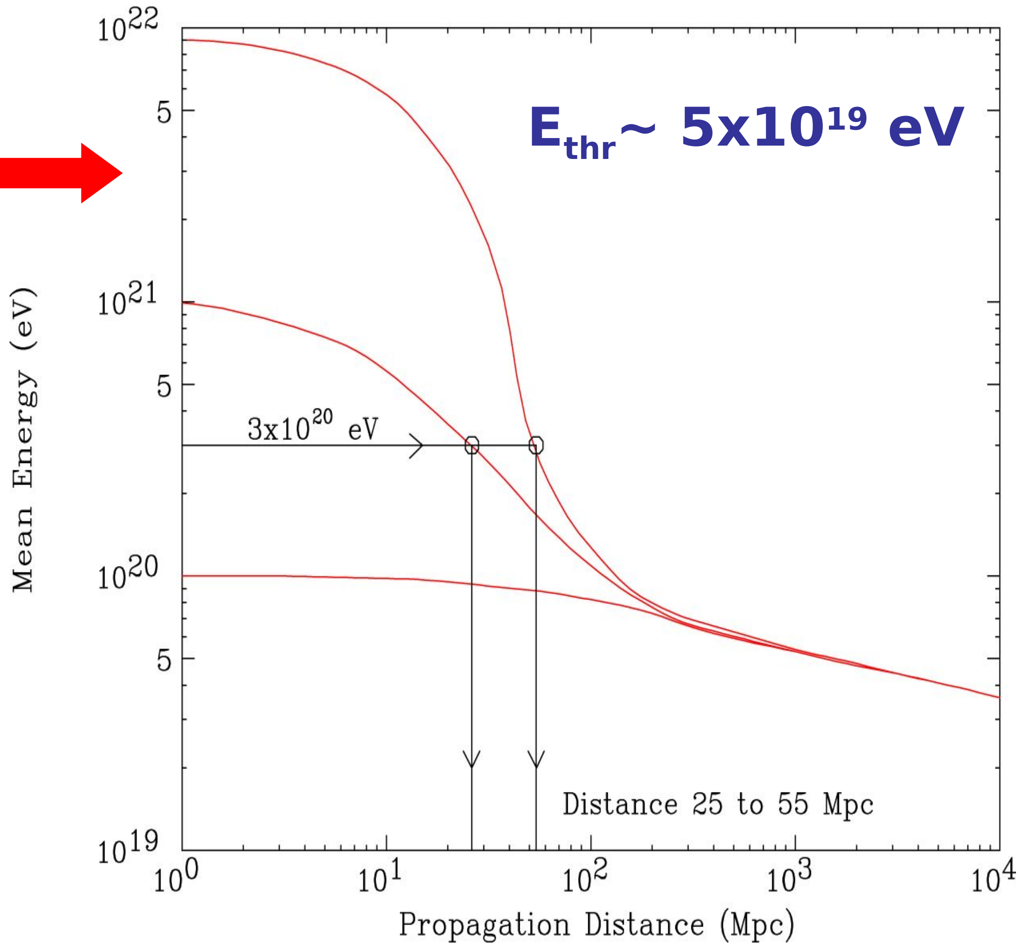
Extragal. protons
(ankle model)

Propagation of CR: implications

$$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$





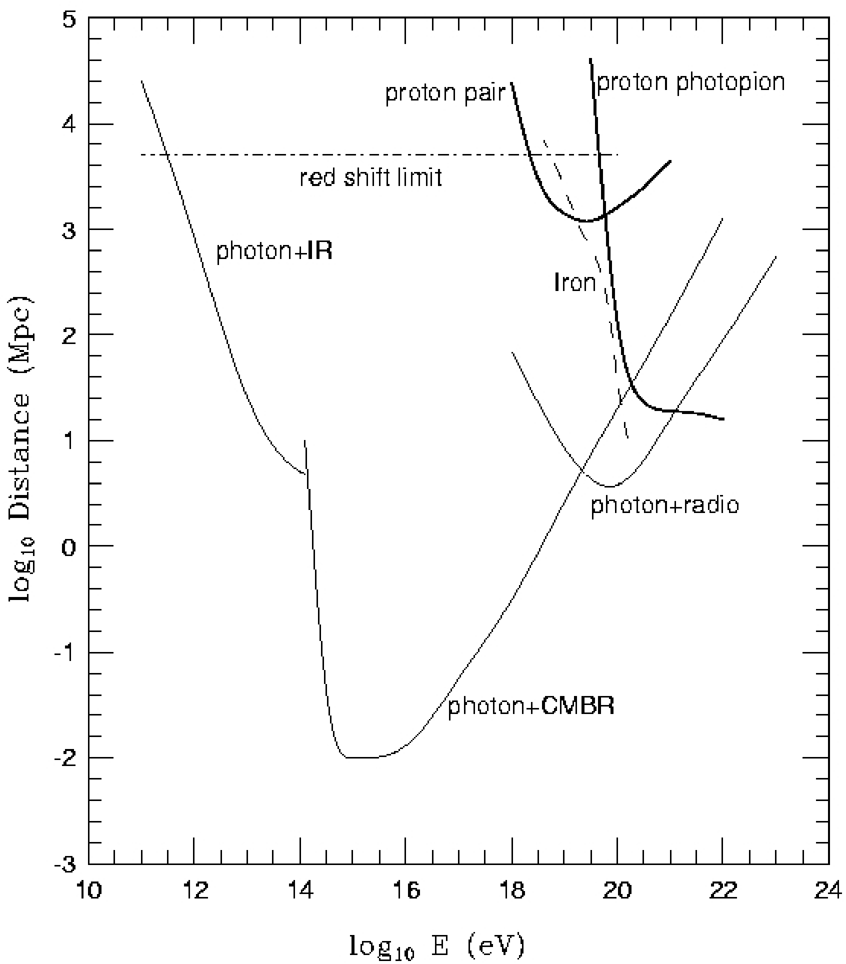
E_{thr}~ $5x10^{19}$ eV

Flux Suppression (GZK cut-off)

Protons at E >10^{20} eV within 100 Mpc

End to the cosmic ray spectrum?

Greisen Zatsepin Kuz'min effect (1966):
Interaction with the cosmic microwave background (CMB)



protons:

$$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$$

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

nuclei: photo-disintegration and pair production on CMB (RB IR)

"horizon" (p and nuclei) ~ 100 Mpc (~10^{20} eV)

photons:

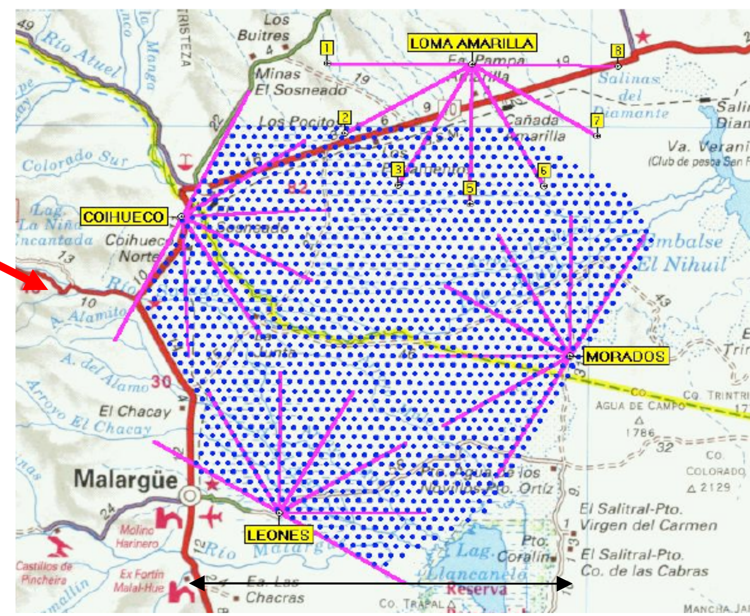
$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

$$E_{thr}(eV) \sim \frac{3 \cdot 10^{14}}{\epsilon_\gamma(eV)}$$

The Pierre Auger Observatory

17 Countries, 63 Institutions ~ 350 members

Southern hemisphere (3000 km²)
Malargüe (Mendoza) Argentina



~ 50 km

- *large and flat region*
- *low density of population (low background due to artificial light)*
- *clean and dry atmospheric conditions (small cloud coverage)*

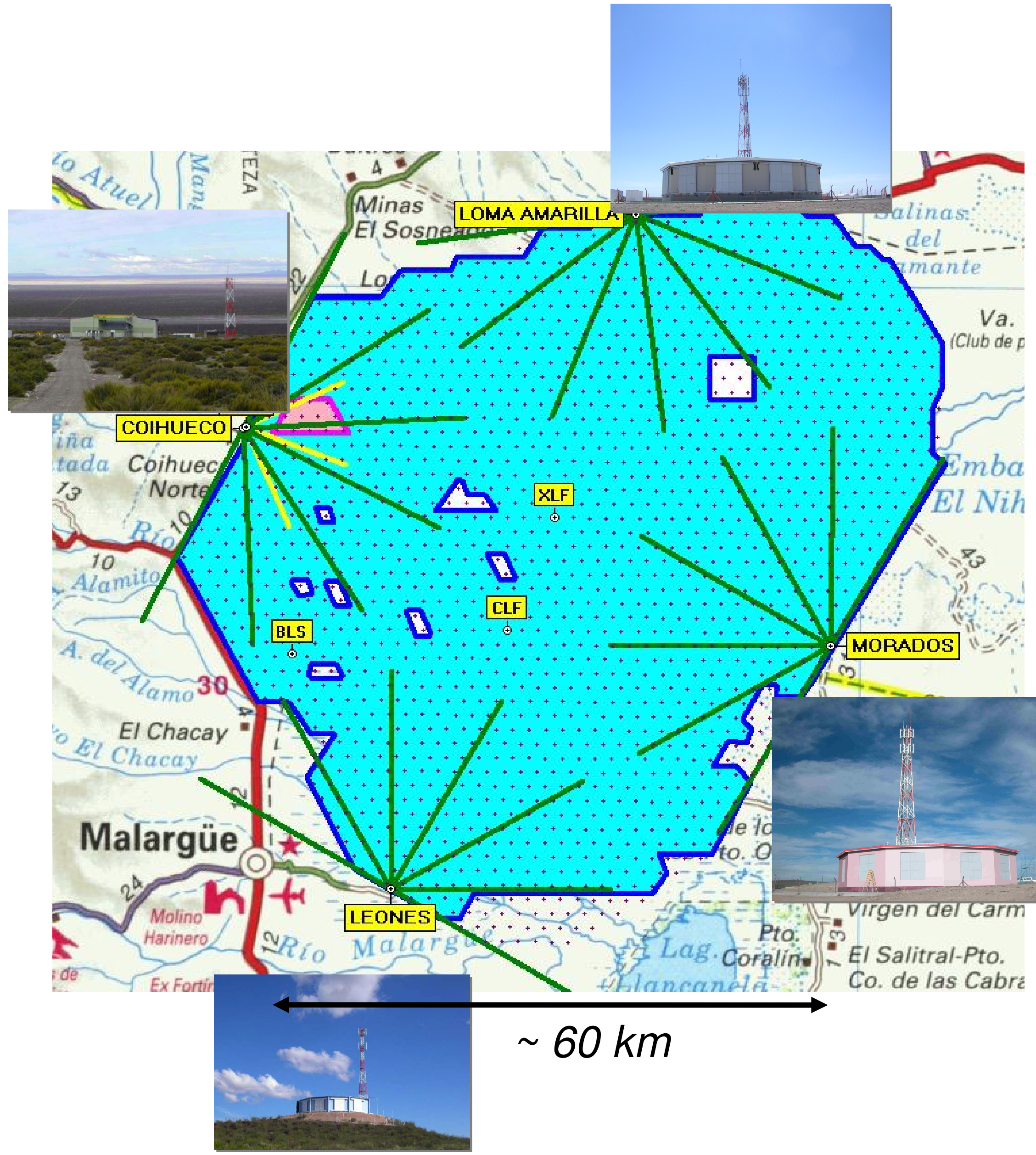
The Pierre Auger Observatory

- ***Surface detector***

an array of 1600 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km²)

- ***Fluorescence detector***

4 buildings overlooking the array



Low energy extensions

AMIGA: dense array plus muon detectors
HEAT: three further high elevation FD telescopes

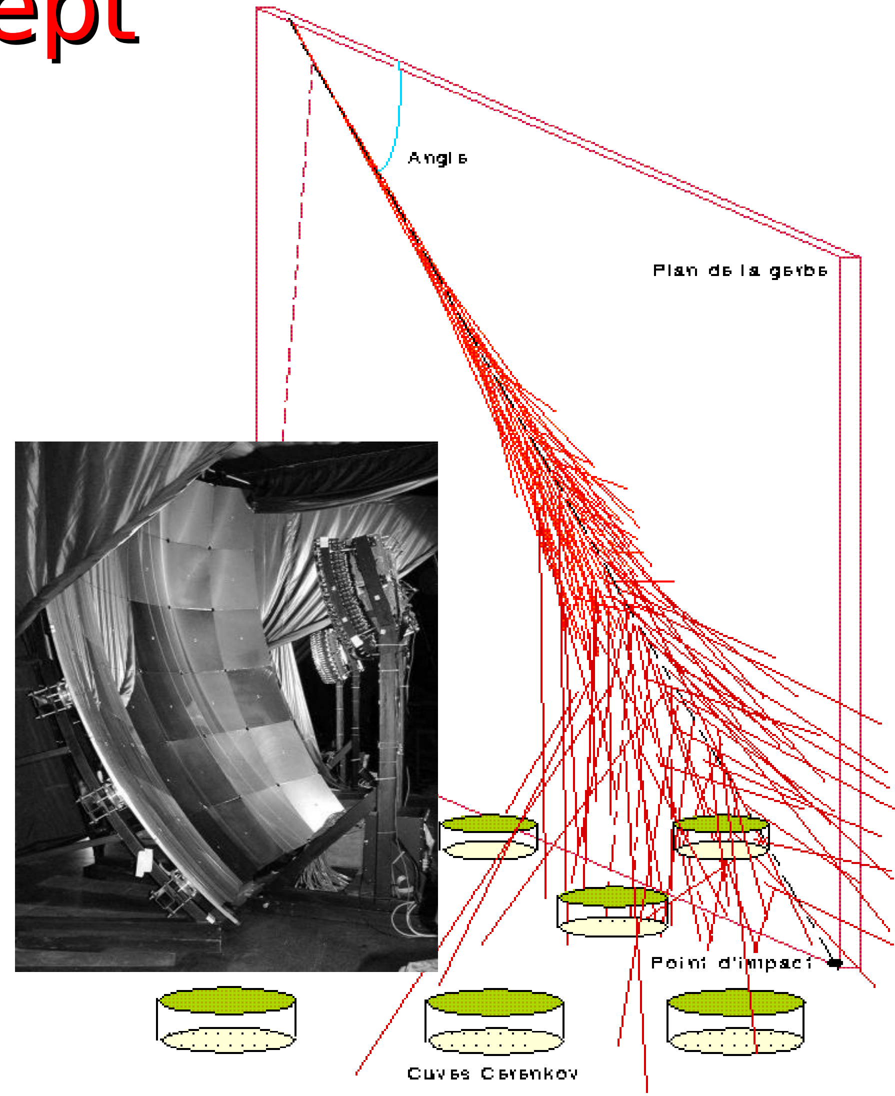
The Hybrid Concept

Surface Detector Array

lateral distribution, 100% duty cycle

Air Fluorescence Detectors

Longitudinal profile, calorimetric energy measurement, ~15% duty cycle



accurate energy and direction measurement

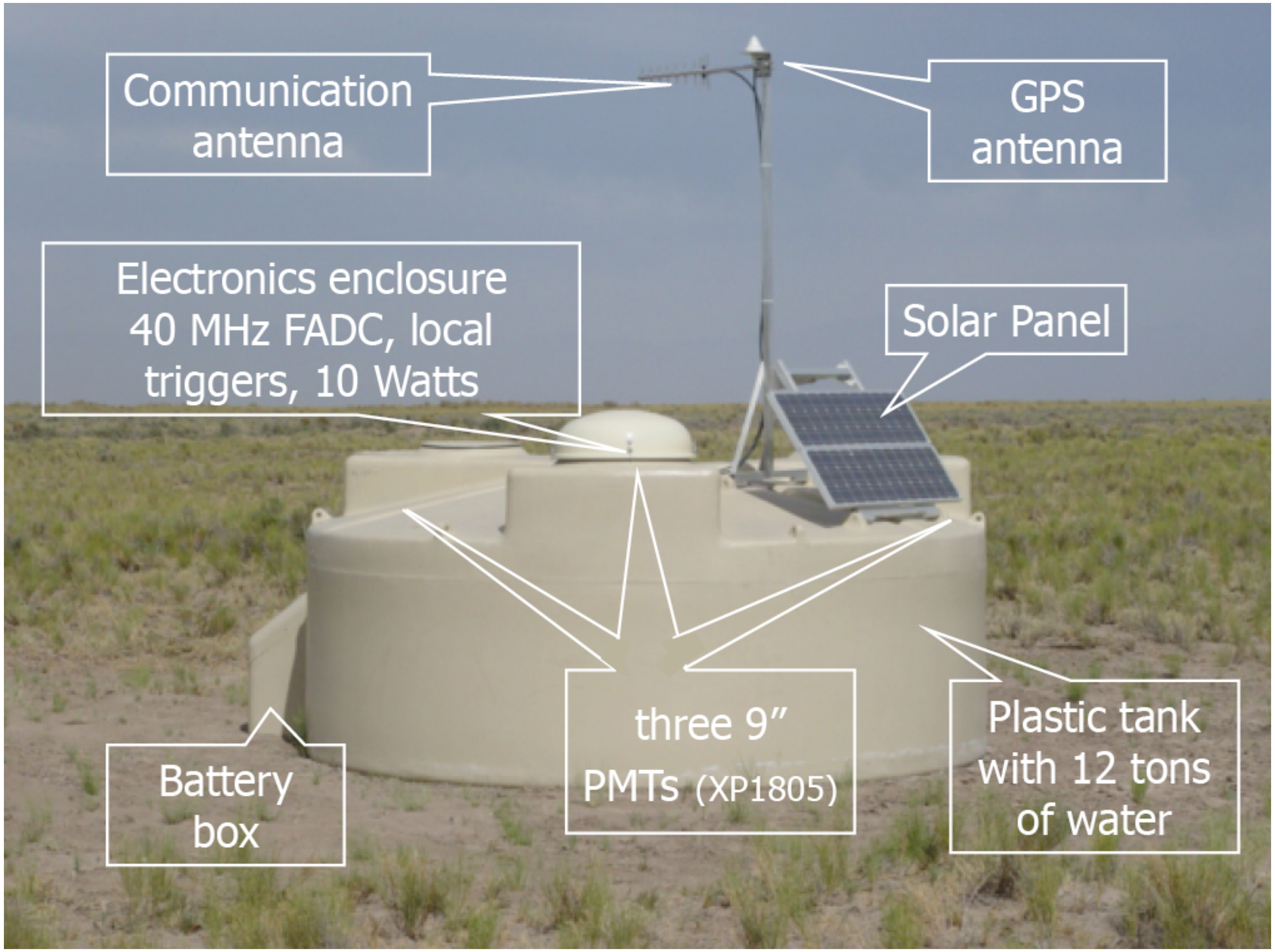
mass composition studies in a complementary way

“In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side.”

V.H.Hess, Nobel Lecture, December 1936

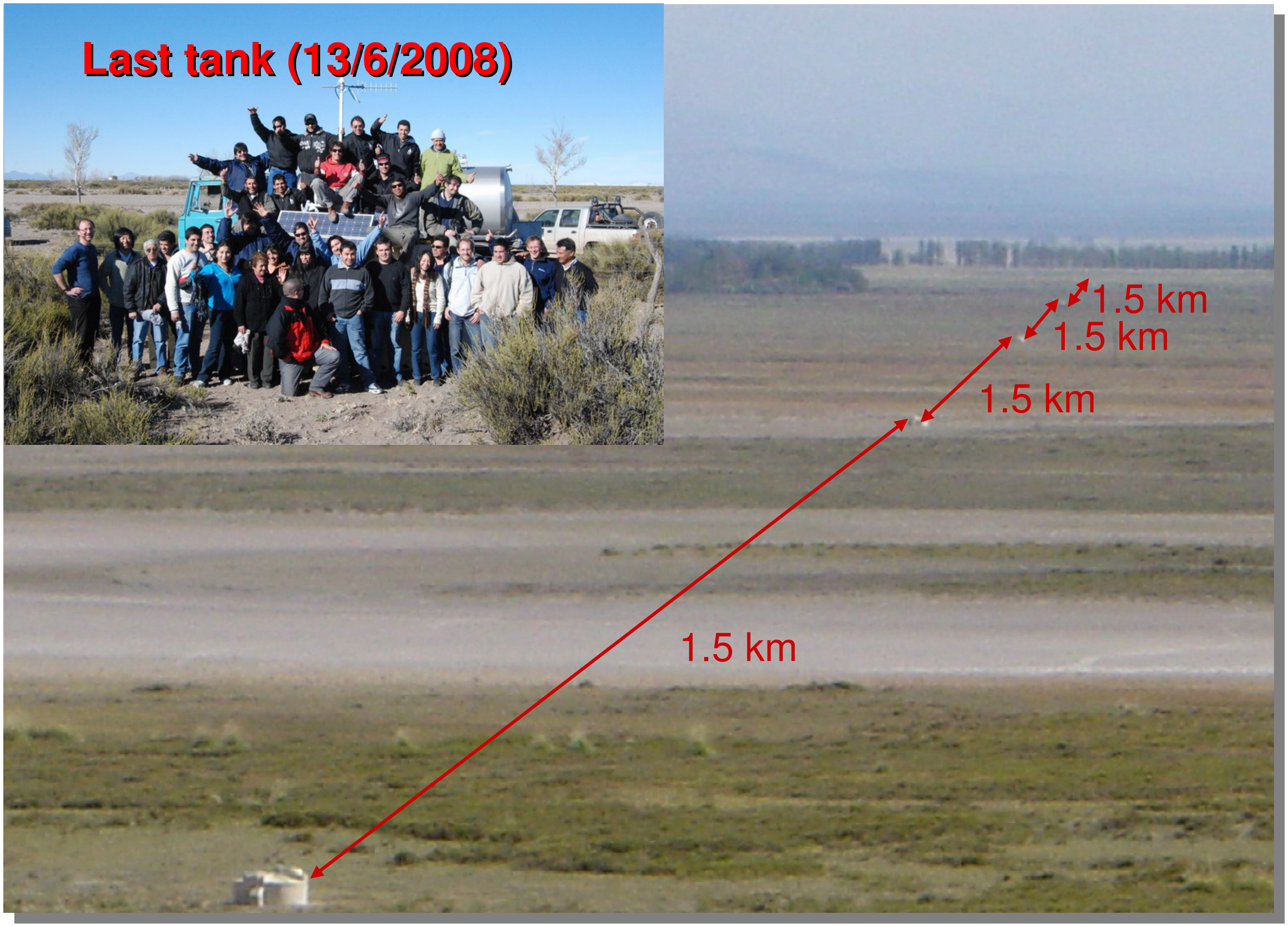
A station of the Surface Detector

- Plastic Tank
- Ultra-reflective tyvek liner
- 12 m^3 purified water
- 3 PMTs (9 inches)
- Independent power supply (solar panels)
- GPS antenna
- Communication antenna



DAQ : 40 MHz FADC sampling (10 bit resolution)

The surface detector (SD)

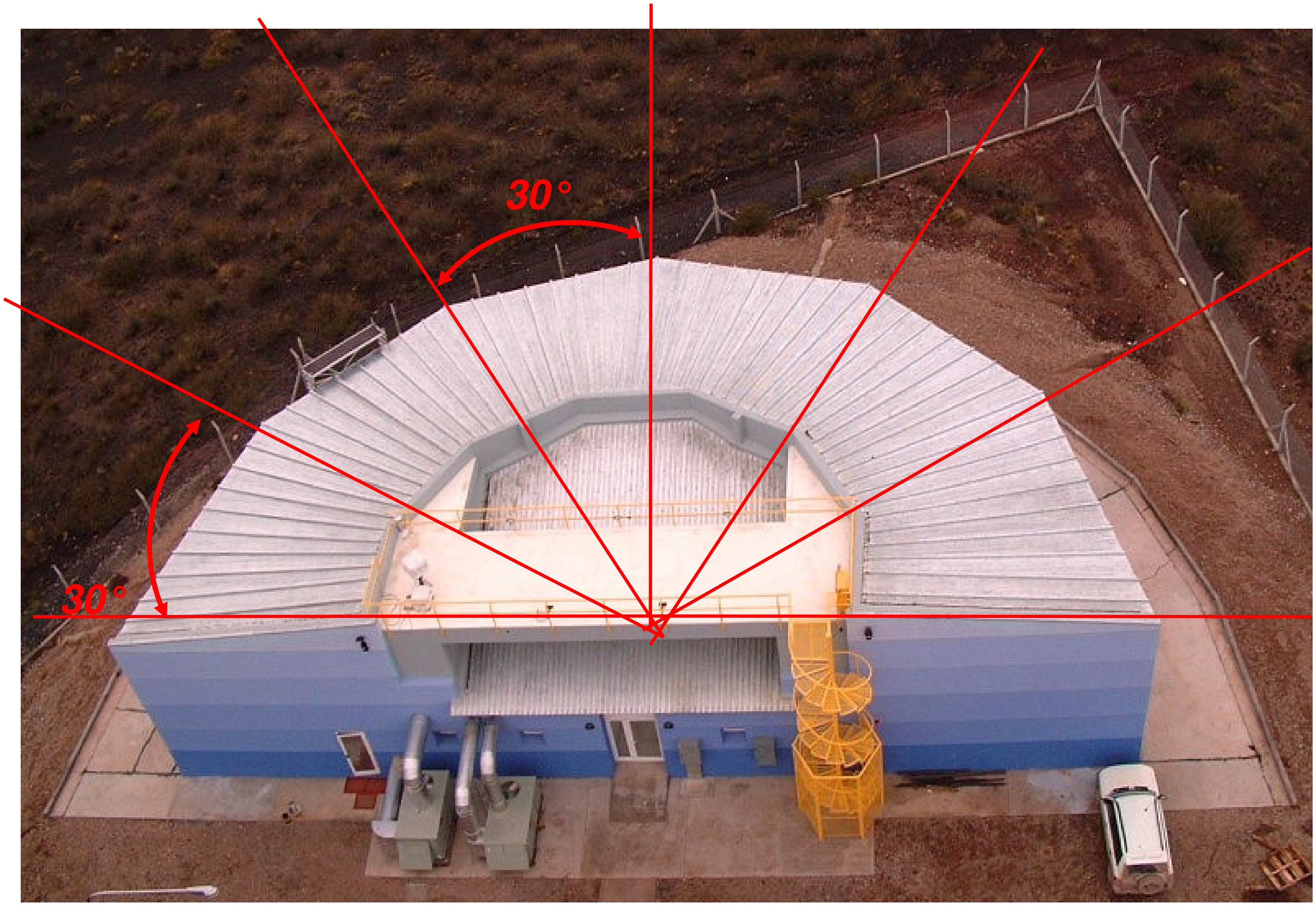


Not only muons hit the tank!!!!

Bird droppings together with dry weather degrade solar panels.

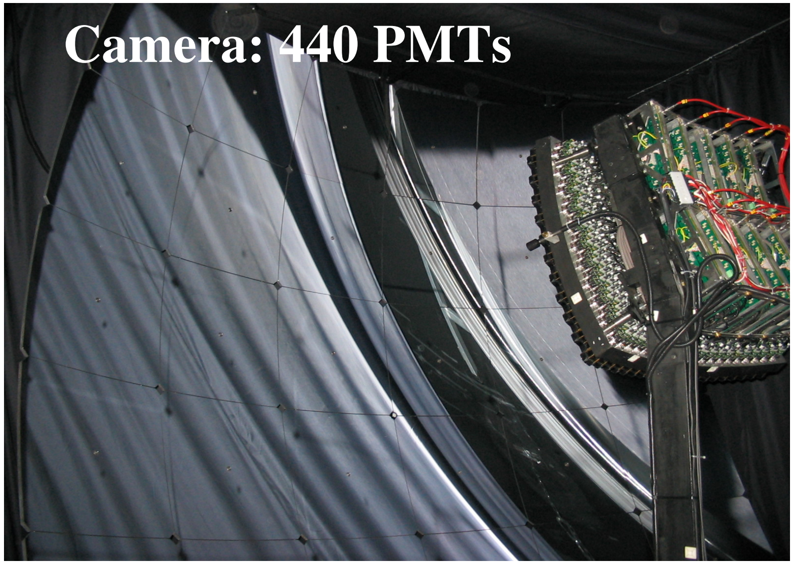
Bird nests behind solar panels sometimes catch fire.

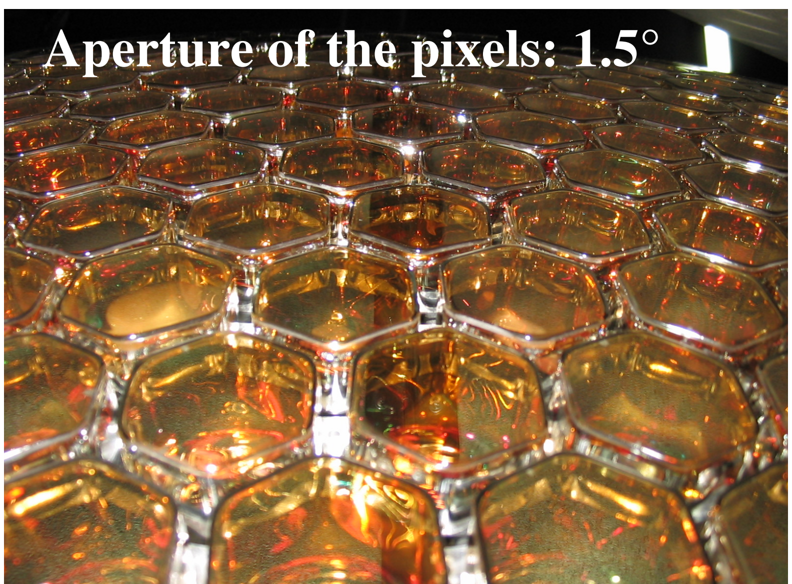
The fluorescence detector (FD)

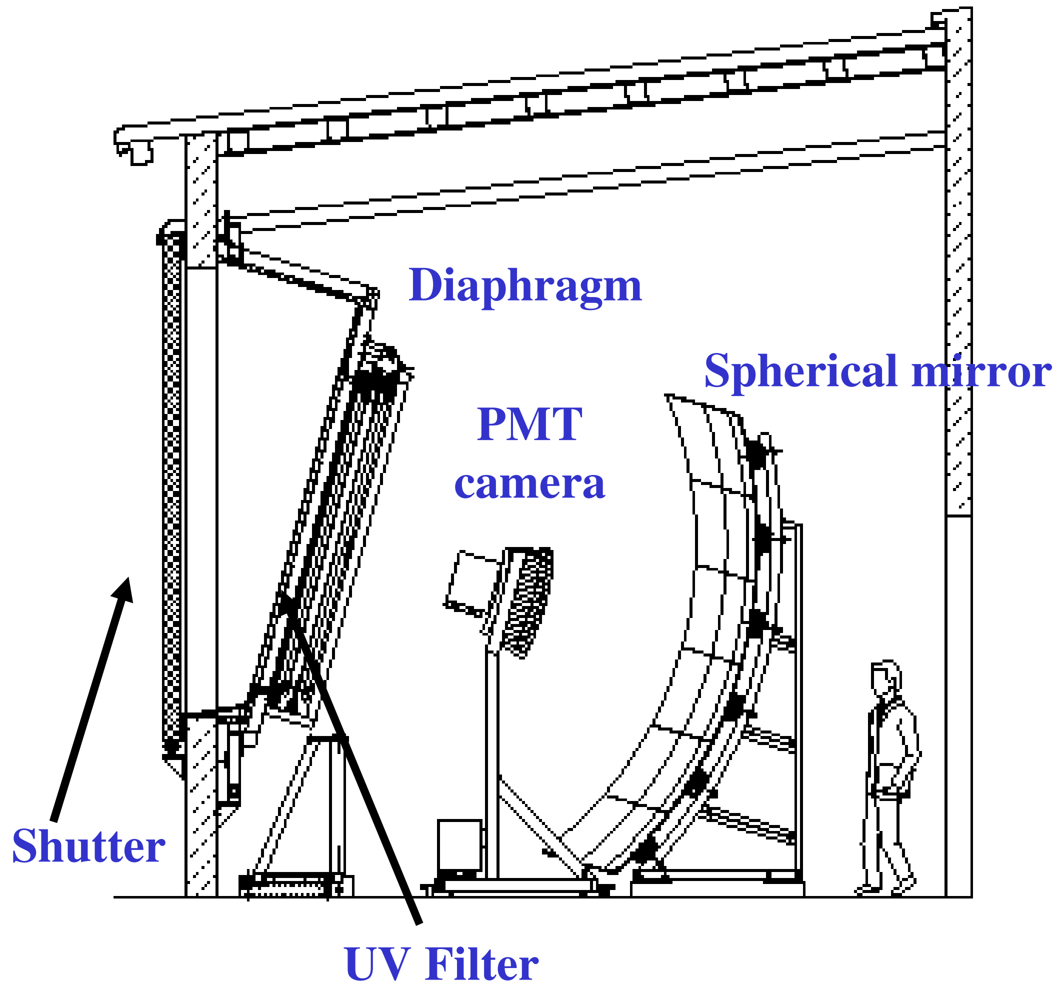


6 telescopes, each with 30° x 30° FOV

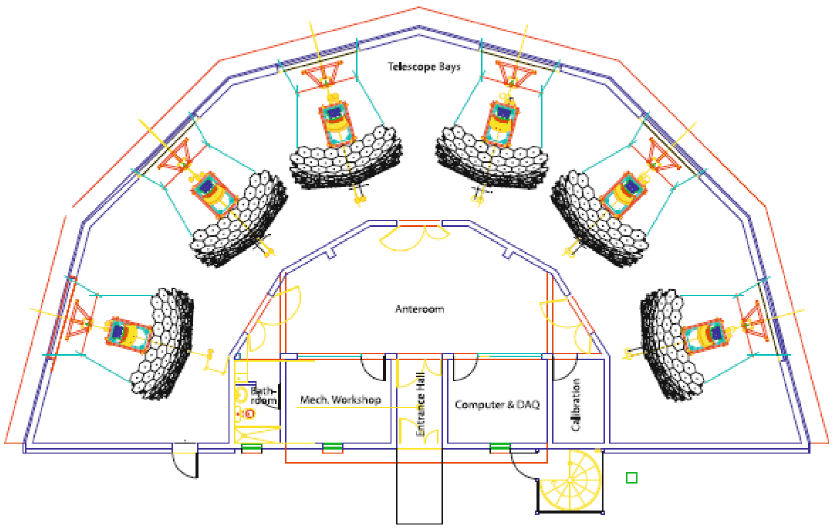
The fluorescence detector (FD)

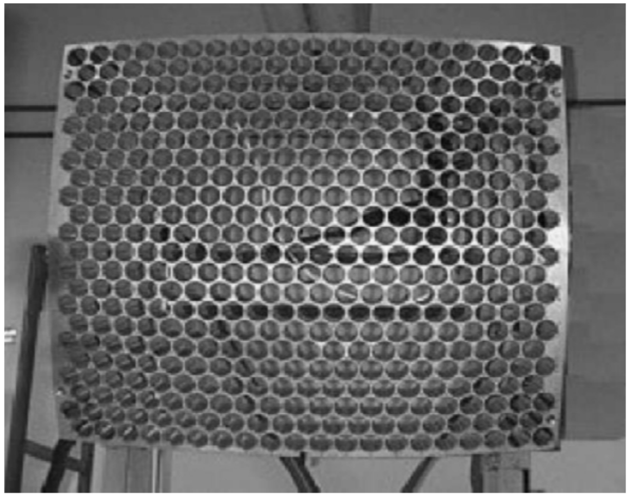


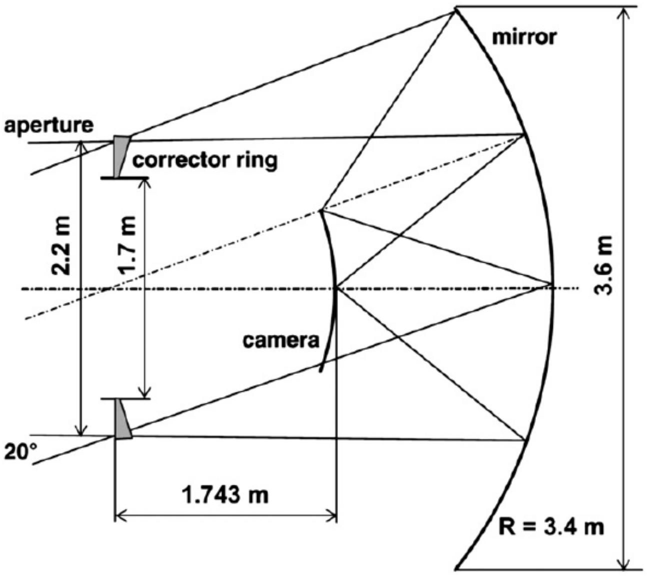


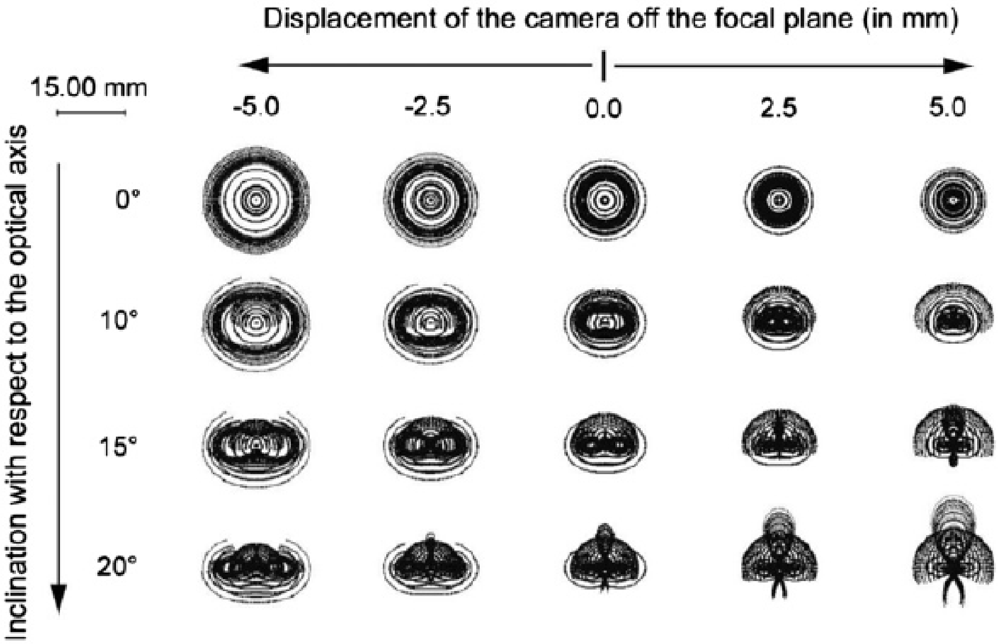


The fluorescence detector (FD)



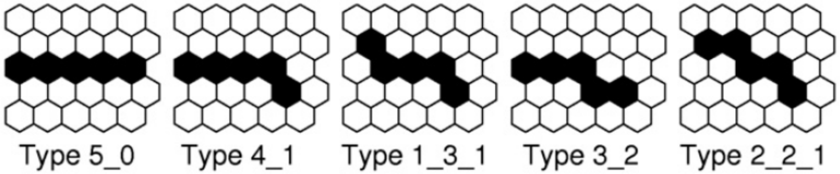




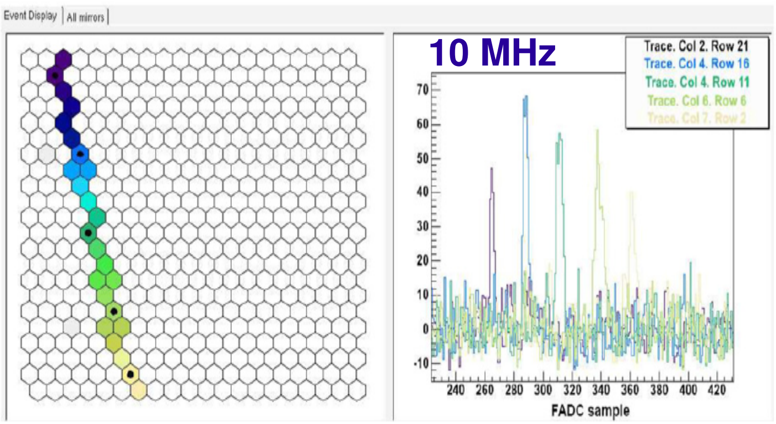


Trigger strategy for FD

T1 individual pixel above threshold - 100 Hz/pixel
T2 on specific patterns (~40000) - 0.1 Hz/telescope
T3 software trigger (event builder) 0.02 Hz/FD-site

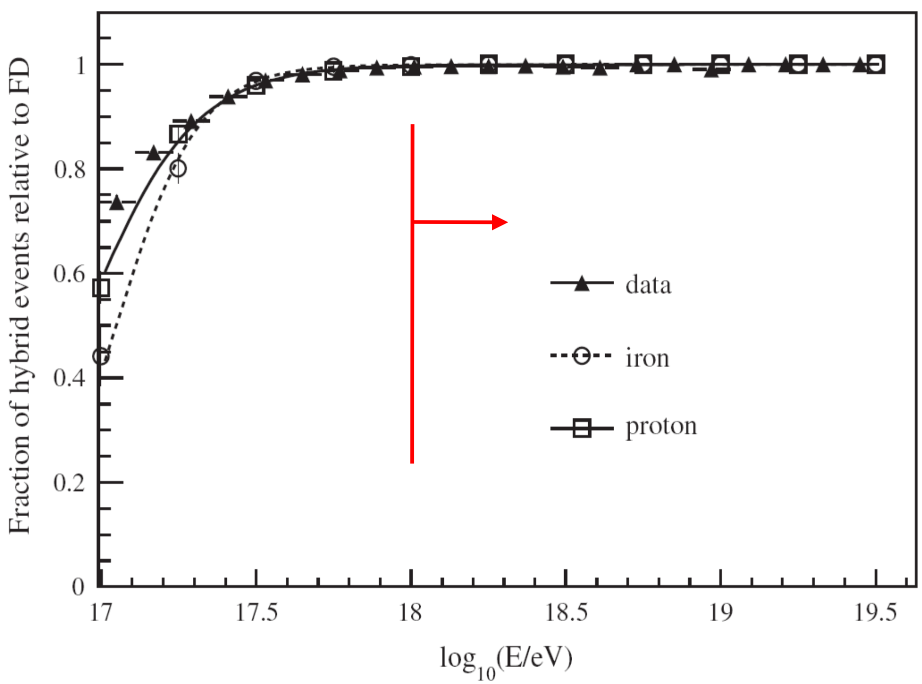


Event Display

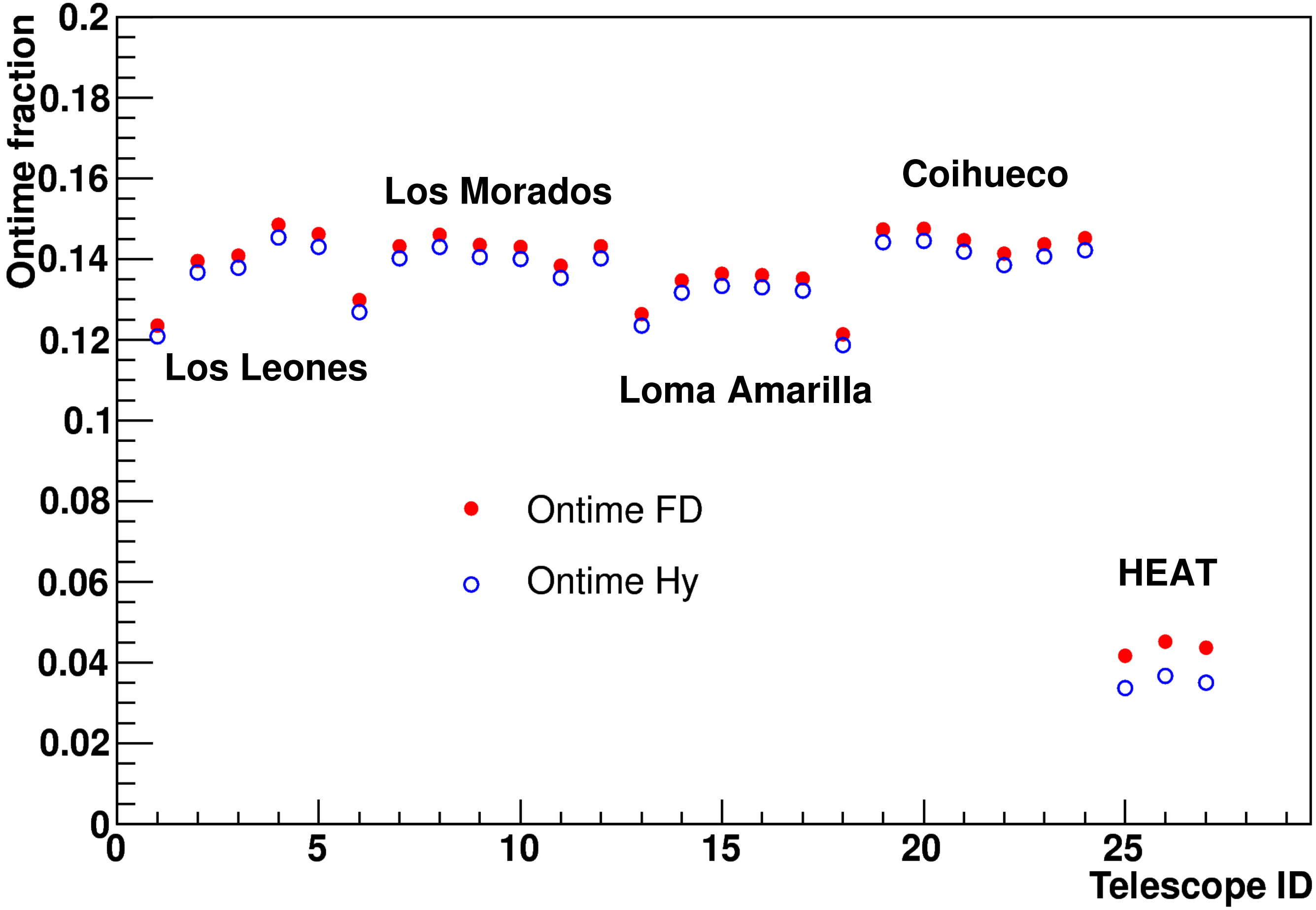


Time and geometrical info of each T3 sent to SD -> **Hybrid trigger!**

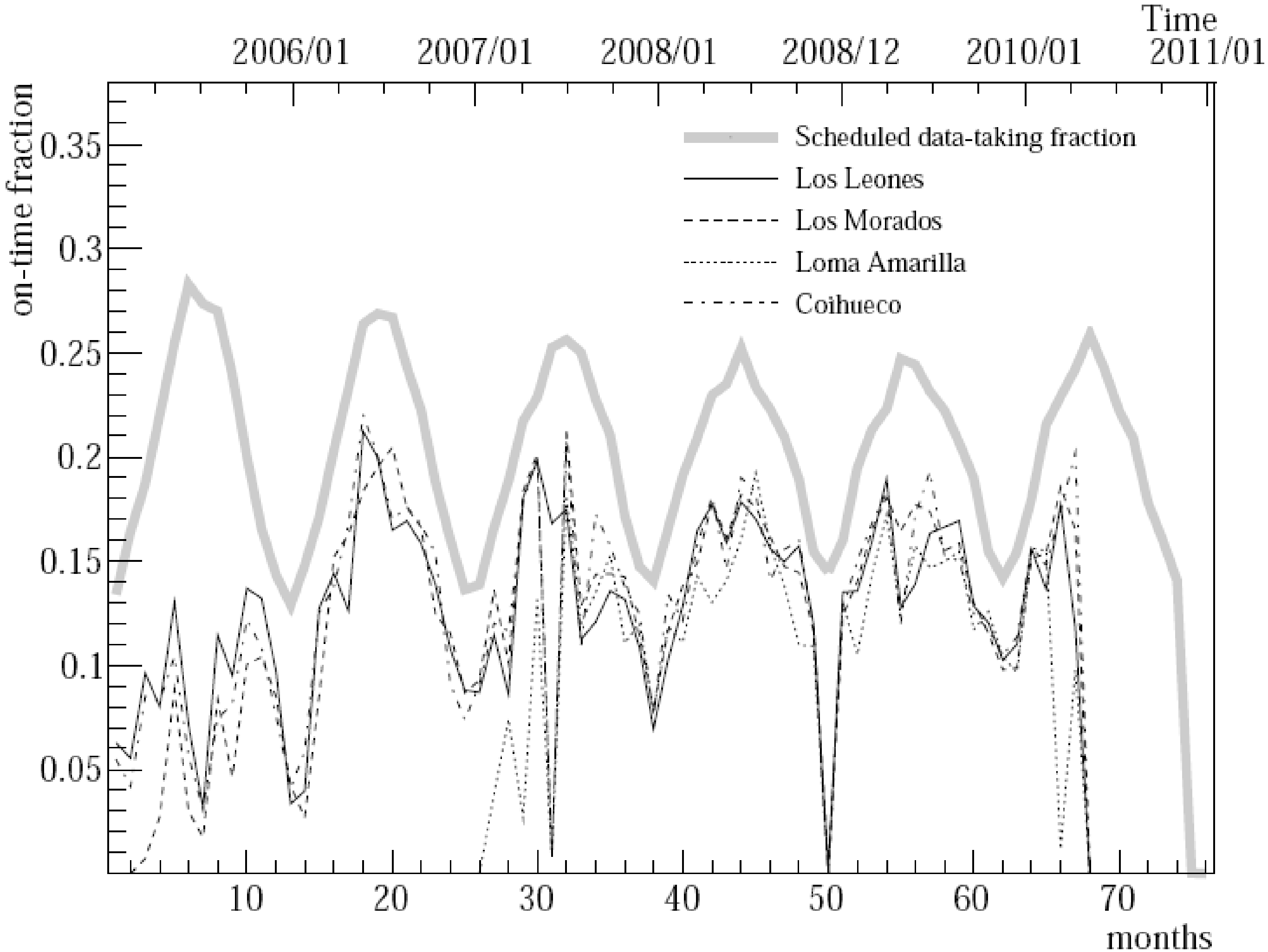
At energy above 10^{18} eV each FD event has at least one station, regardless of its primary mass if hadron



FD On-time fraction



FD On-time fraction

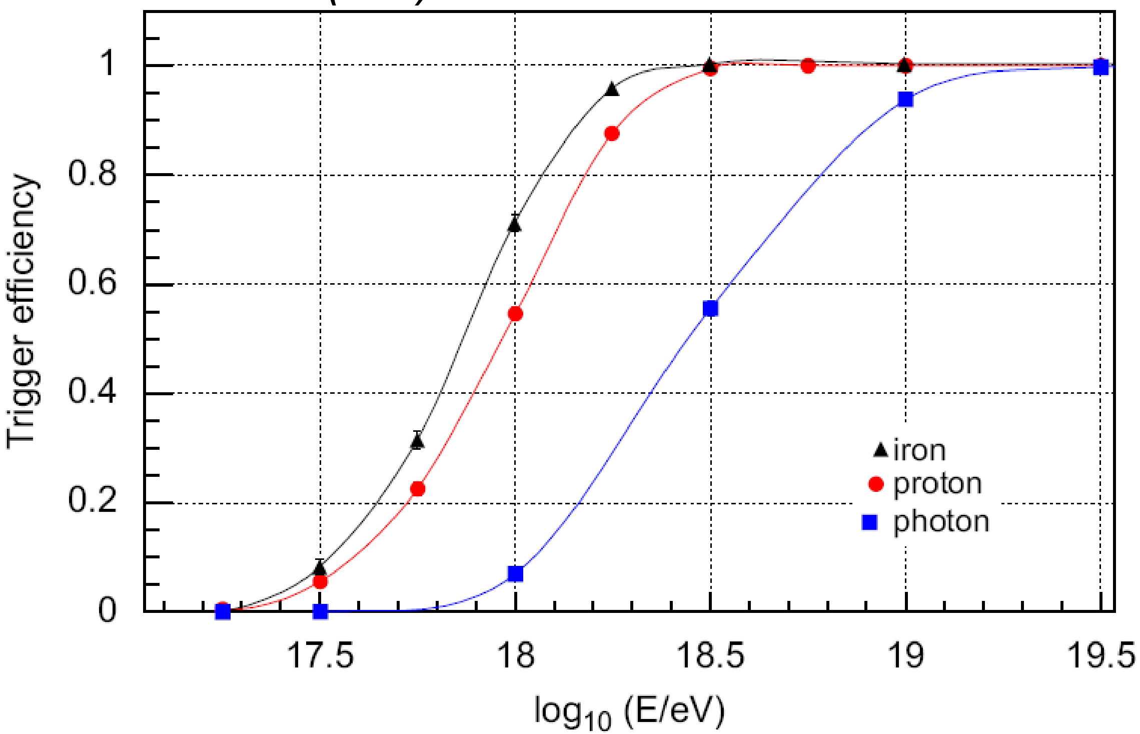


Trigger strategy for SD

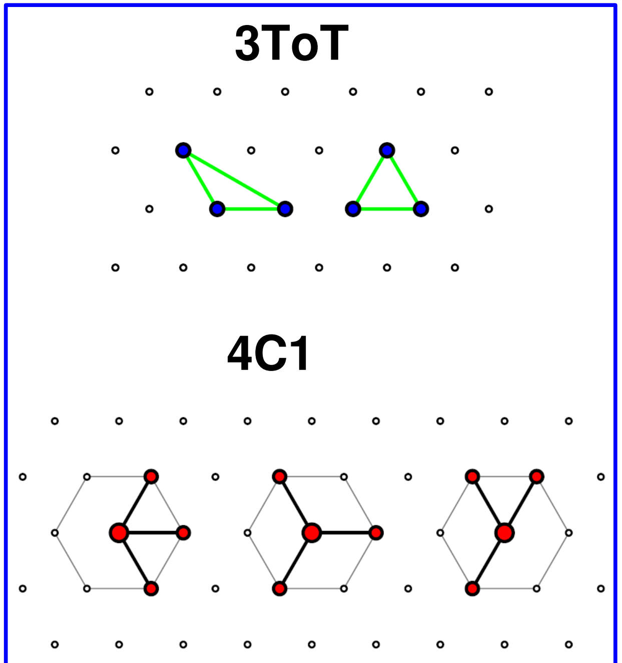
Station trigger

T1 3 PMTs above threshold 1.75 VEM – 100 Hz
ToT 13 time bins above a threshold of 0.2 VEM in 2 PMTs – 20 Hz
T2 ToT || threshold above 3.2 VEM in 3 PMTS

NIM A 613 (2010) 29–39



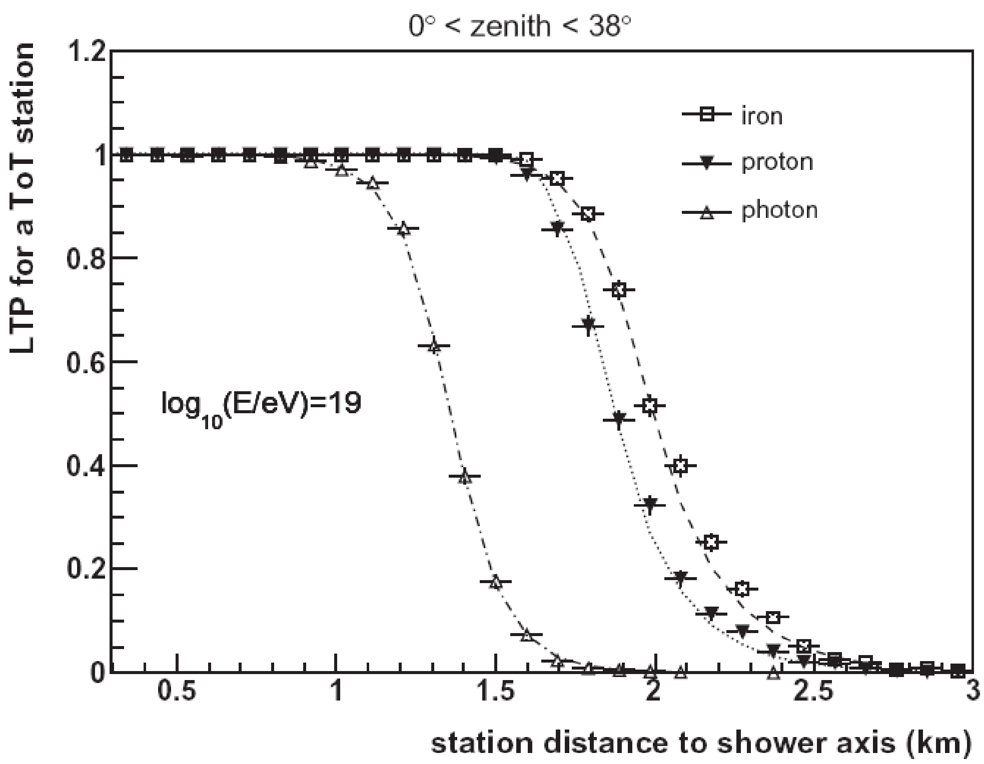
Event



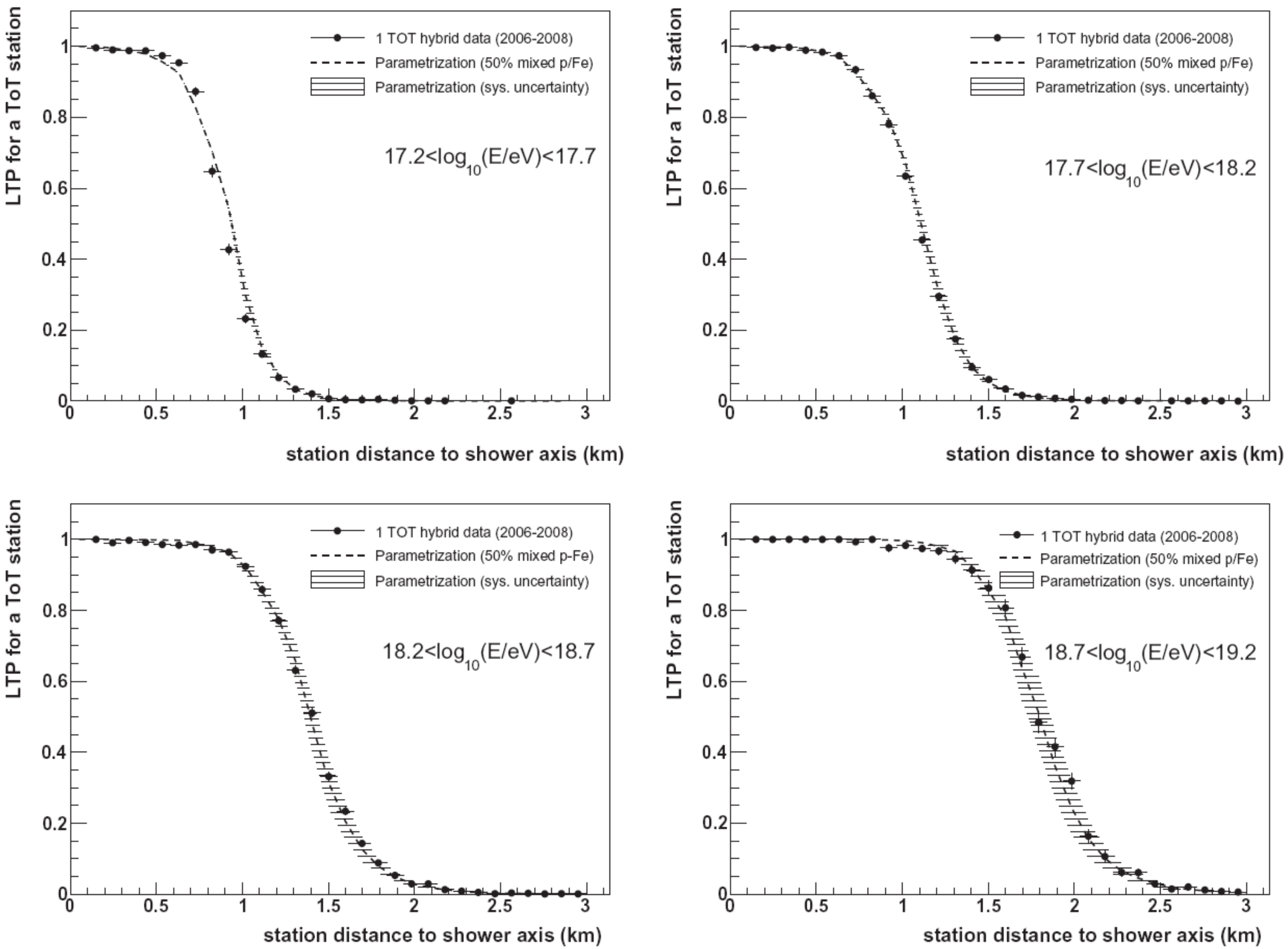
Full efficiency at energy above $10^{18.5}$ eV, regardless of its primary mass if hadron

Lateral Trigger Probability Function

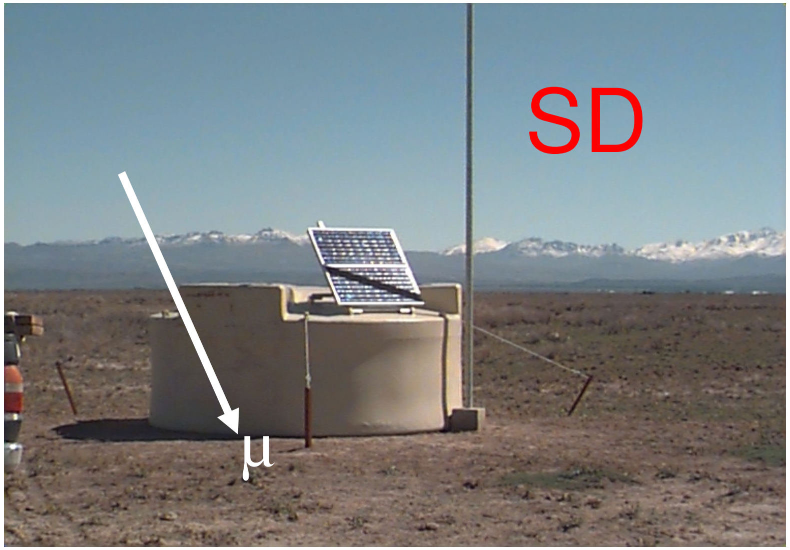
The probability for an Extensive Air Shower to trigger an individual detector of a ground based array as a function of distance to the shower axis, taking into account energy, mass and direction of the primary cosmic ray

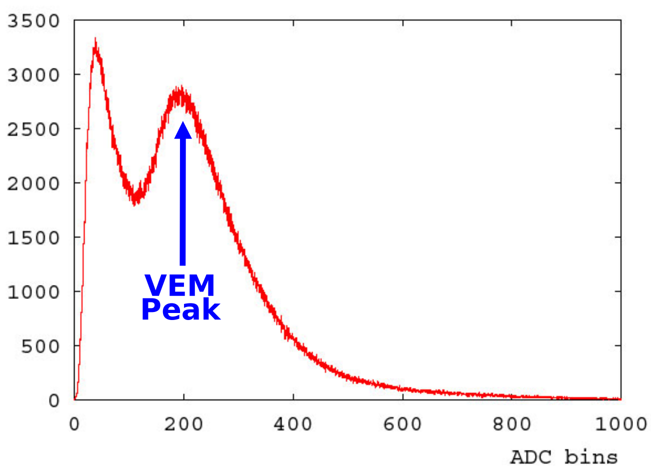


Lateral Trigger Probability Function



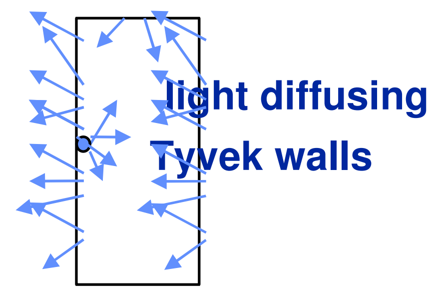
SD e FD Calibration





Through-going cosmic muons

light flux measured by absolutely calibrated PMT

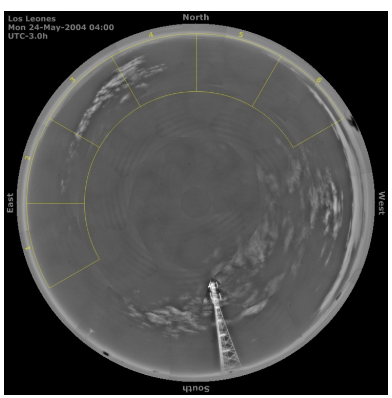


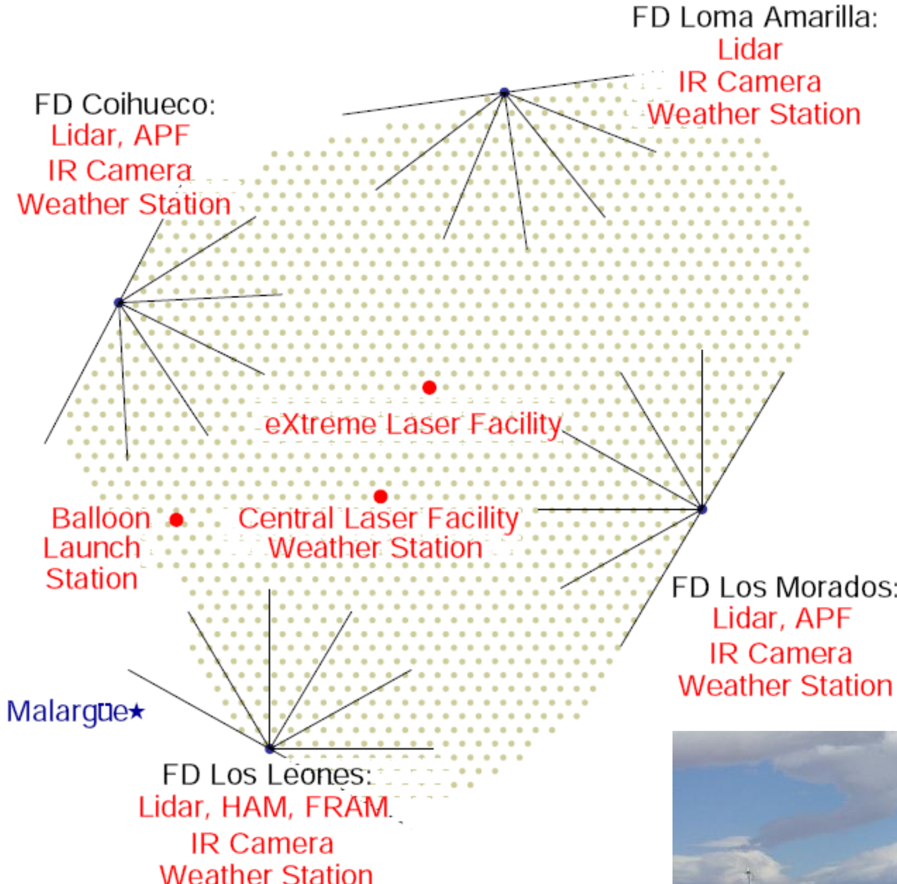
Drum: uniform camera illumination

Atmospheric monitoring

balloons

IR cloud camera





K. Louedec @ **ICRC 2011**

backscatter Lidar

Central Laser Facility

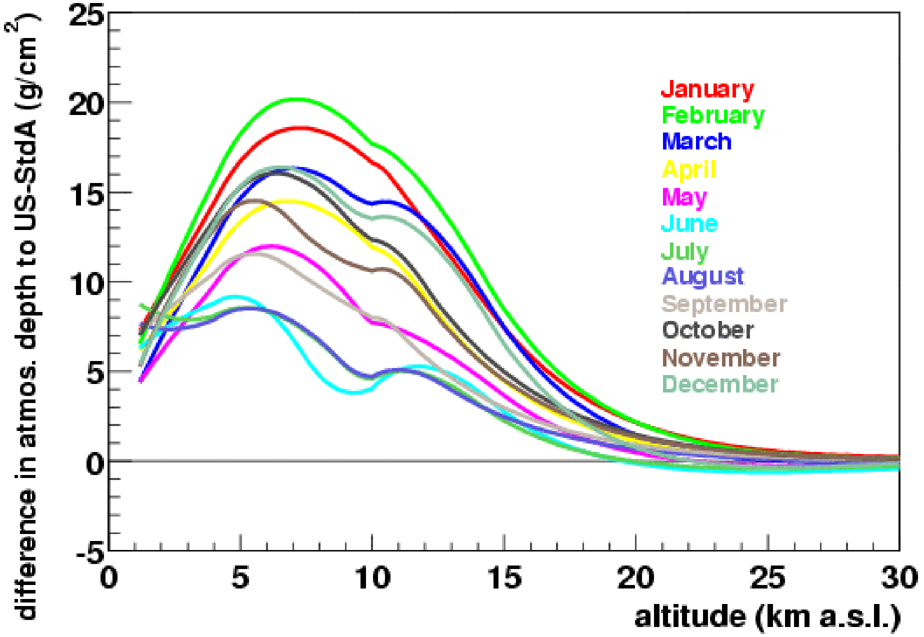
Atmospheric profiles

Local measurements with:

•radio soundes

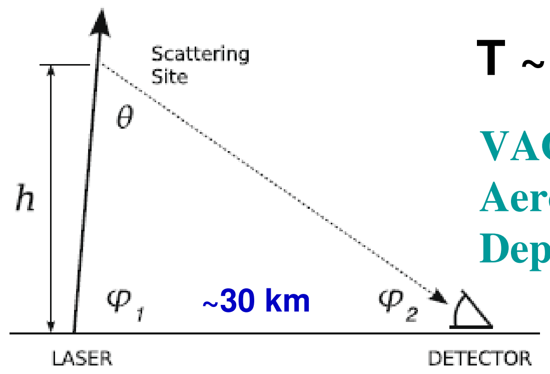
•ground based weather stations

Malargue monthly models



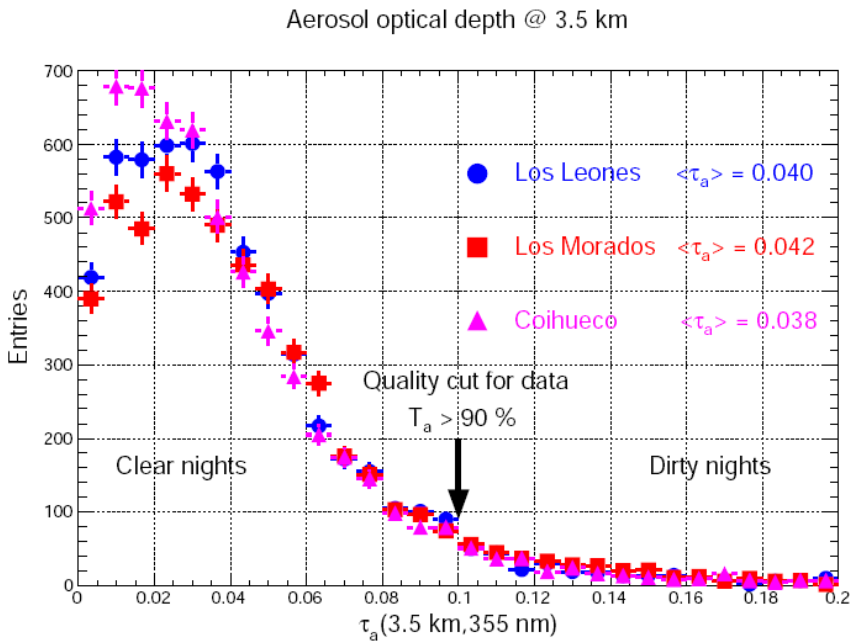
Global Data Assimilation System (GDAS) developed by the National Oceanic and Atmospheric Administration

Central Laser Facility



T ~ e^-VAOD^ ($T \sim e^{-VAOD}$)

VAOD = Vertical Aerosol Optical Depth



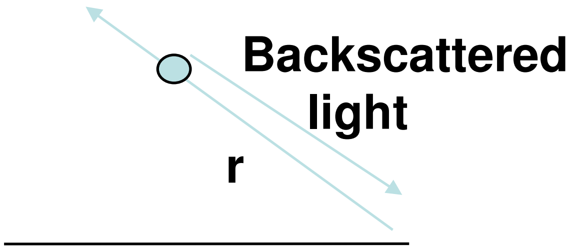
Vertical aerosol optical depth at 3.5 km above the fluorescence Telescopes measured between January 2004 and December 2010. The transmission coefficient is defined as $T = \exp(-\tau_a)$.

K. Louedec @ **ICRC 2011**

Aereosol monitoring

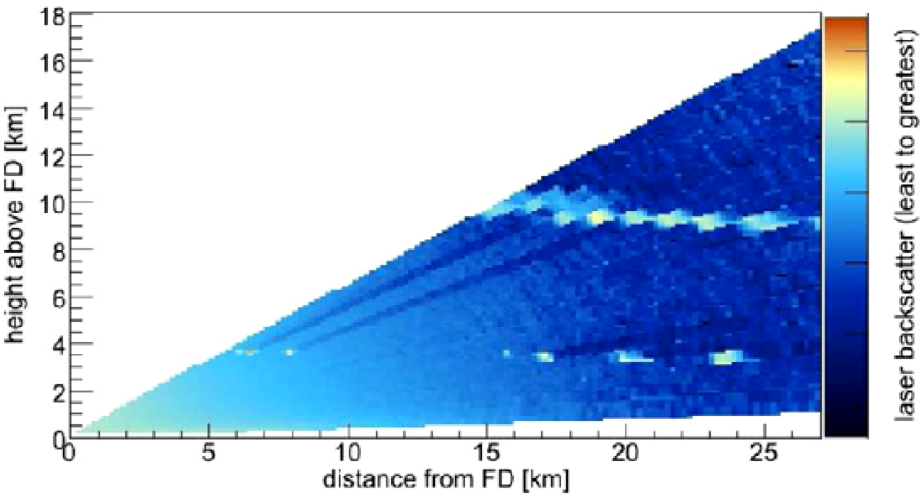
- Aerosols: clouds, dust, smoke and other pollutants

Backscatter Lidars

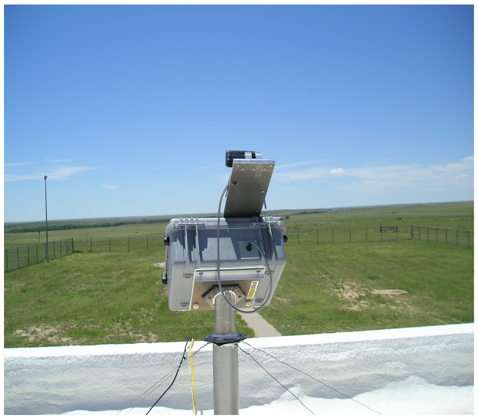


- 1 steerable laser per eye
- hourly scan of aerosols and "shoot the shower"

Cloud image

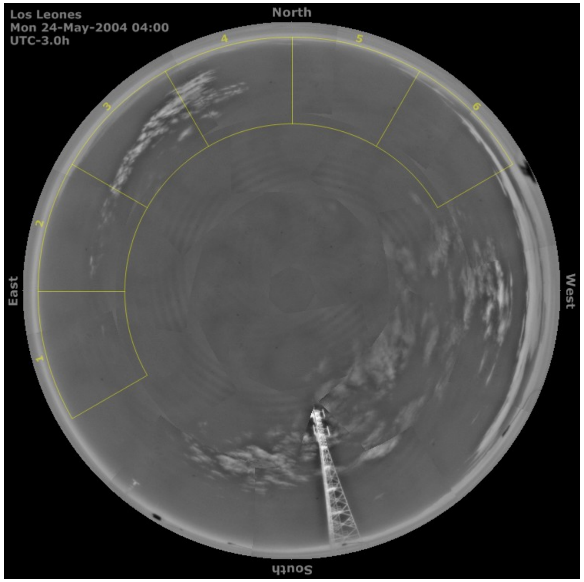


Infrared cloud monitoring

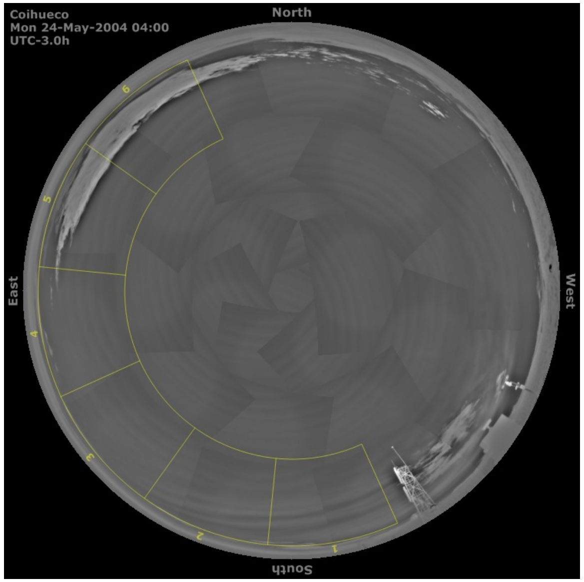


Finely pixelated infrared Raytheon 2000B camera

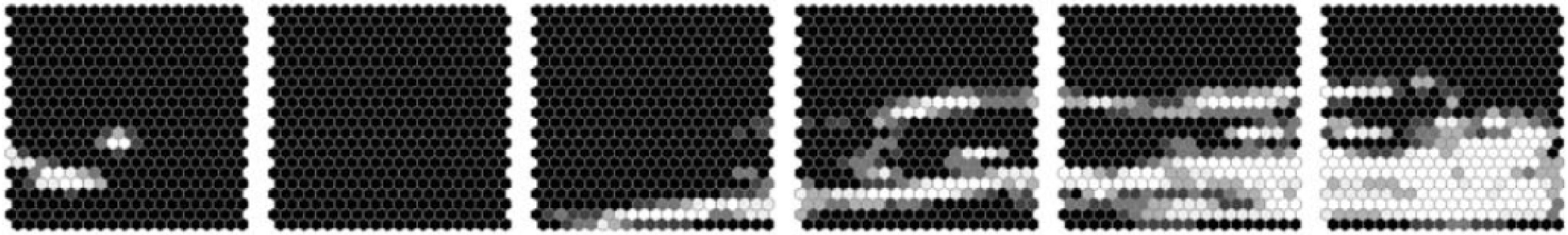
Los Leones



Coihueco



Full sky cloud scan

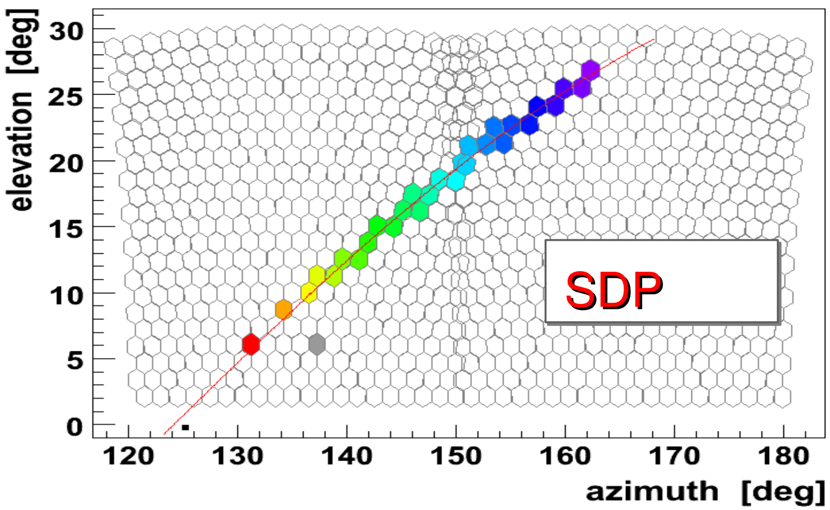


Pixel-wise mask for shower reconstruction

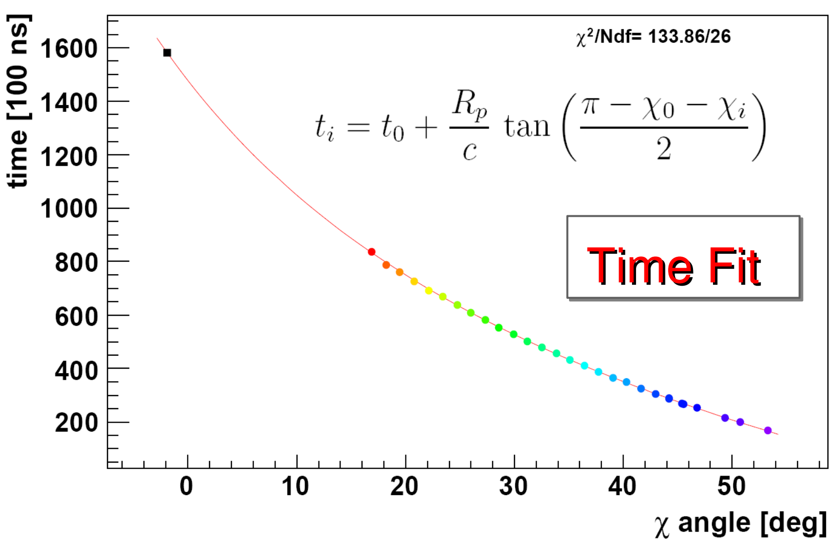
Observables and Detector Performance

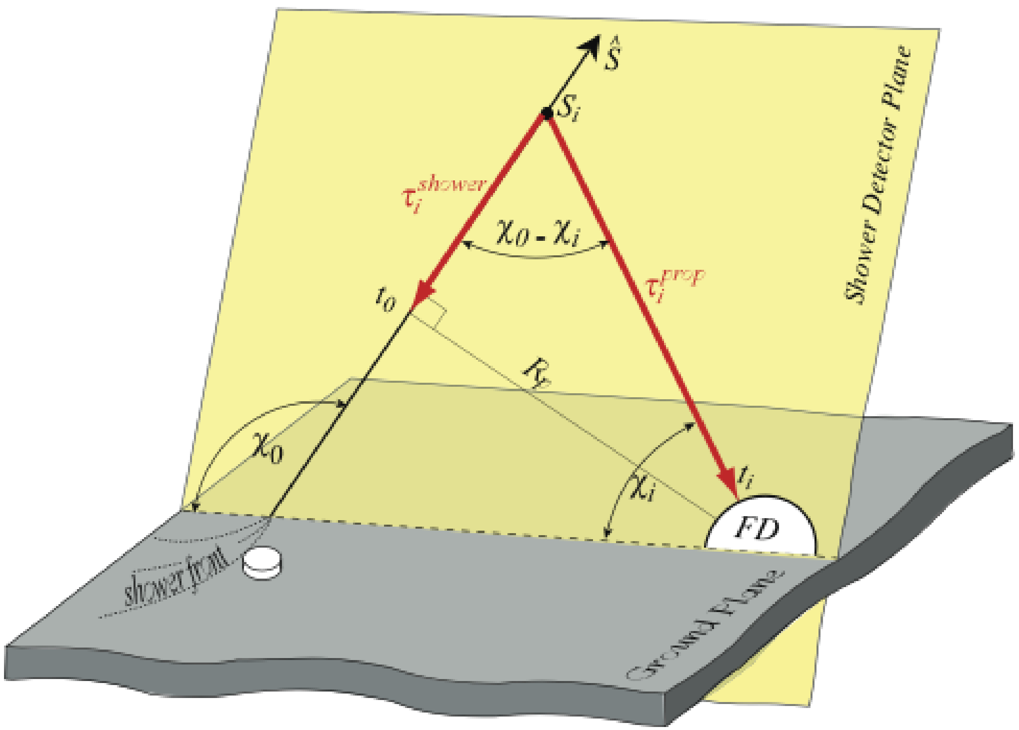
- Reconstruction of arrival directions with FD/SD/Hybrid
- Reconstruction of longitudinal profile
- Energy determination

FD-Hybrid geometry reconstruction



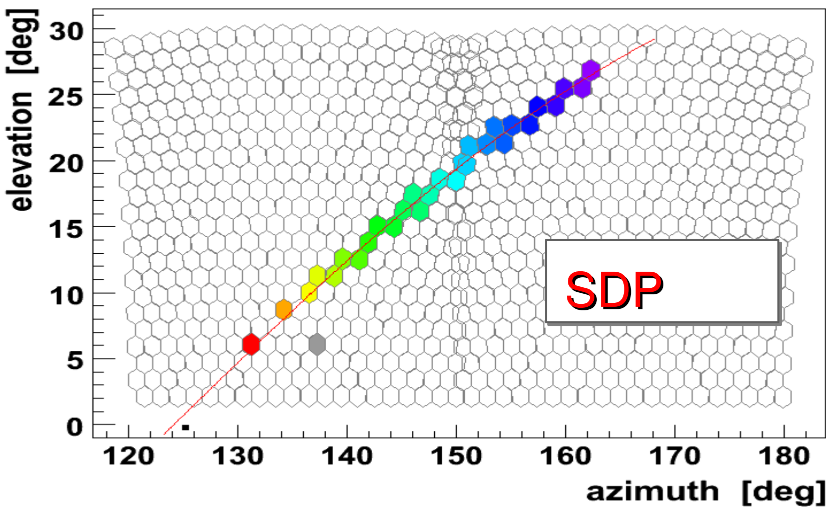
Shower-Detector Plane (SDP) using the directions of the triggered pixels



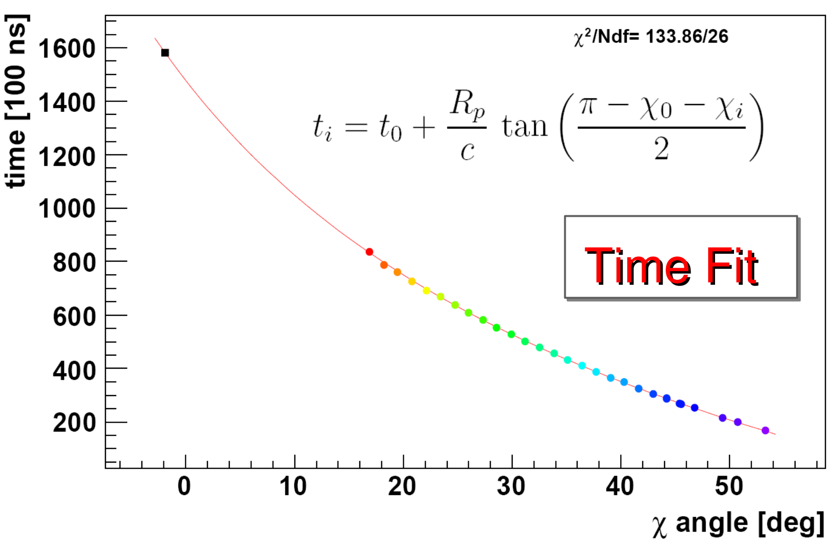


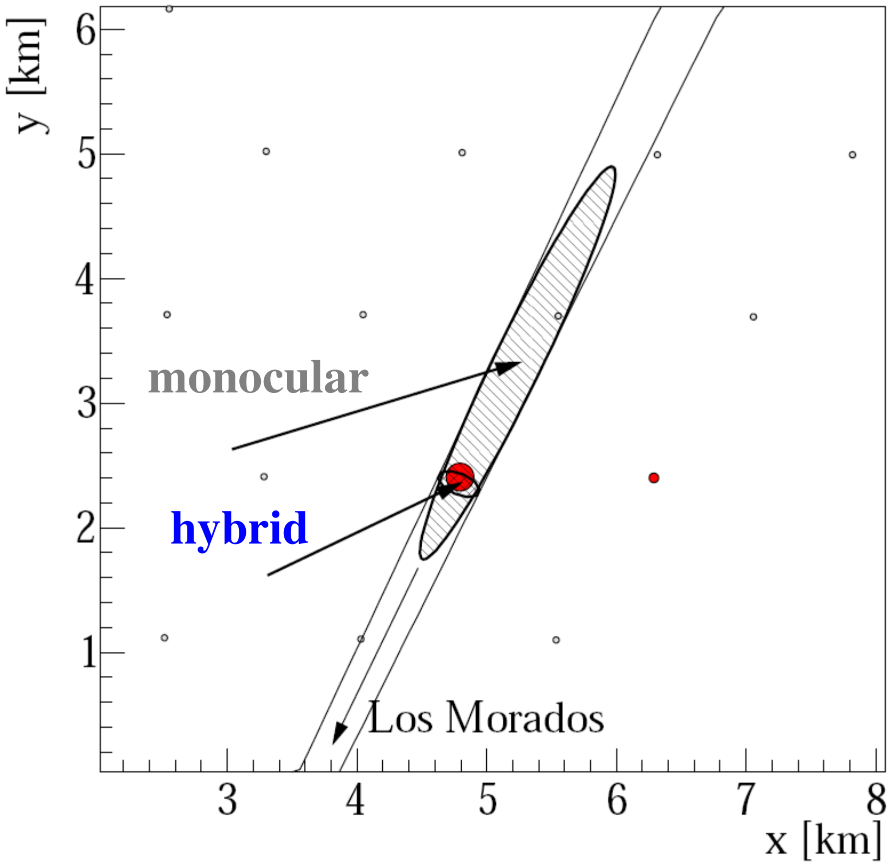
- Shower axis from the time-sequence of triggered FD pixels plus the information from the “hottest” SD station

FD-Hybrid geometry reconstruction



Shower-Detector Plane (SDP) using the directions of the triggered pixels

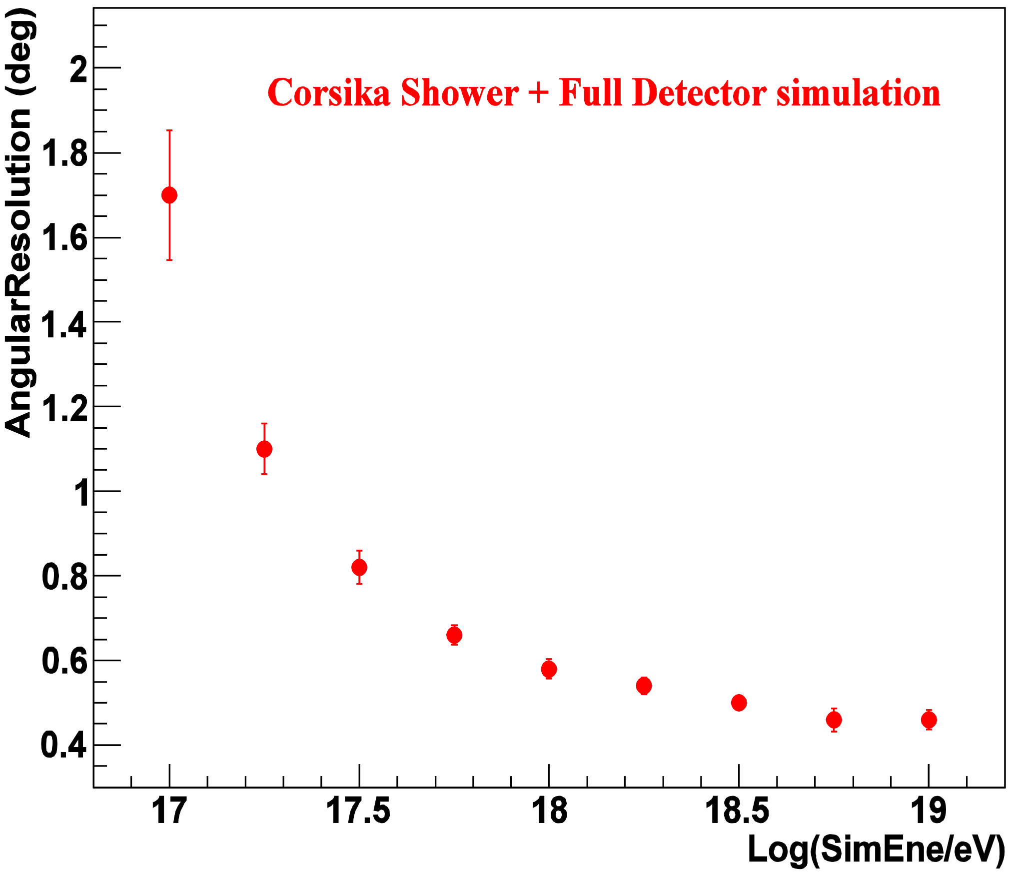




Hybrid angular resolution ~ 0.6°

Core resolution about 50 meters

Hybrid Angular resolution



Angular Resolution:

the angular radius that contains 68% of the showers coming from a given point source

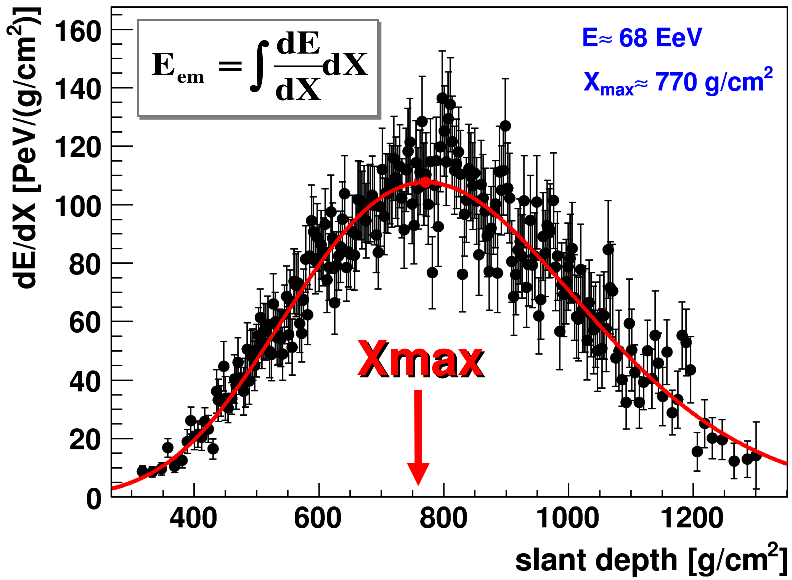
Hybrid angular resolution from simulation

E~ 10^{18} eV AR ~ 0.8º (θ<60º)

E>10^{19} eV AR ~ 0.5º (θ<60º)

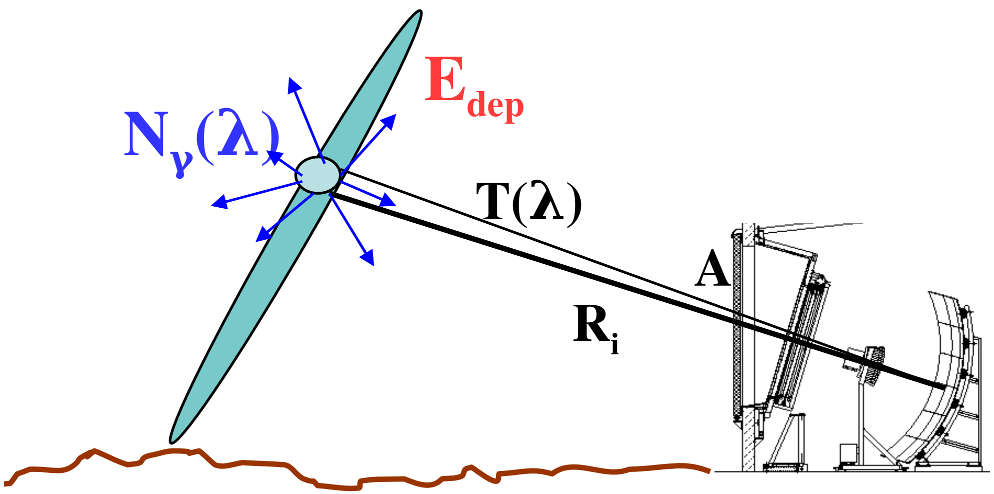
FD: energy determination

Longitudinal Profile



Energy "Calorimetric measurement"

Almost model independent



E_{dep} ⇒ $N_\gamma(\lambda)$ ⇒ **Photons in FD FOV** ⇒ **Photons at diaphragm** ⇒ **ADC counts**

Fluorescence yield (from laboratory measurements)

Geometry

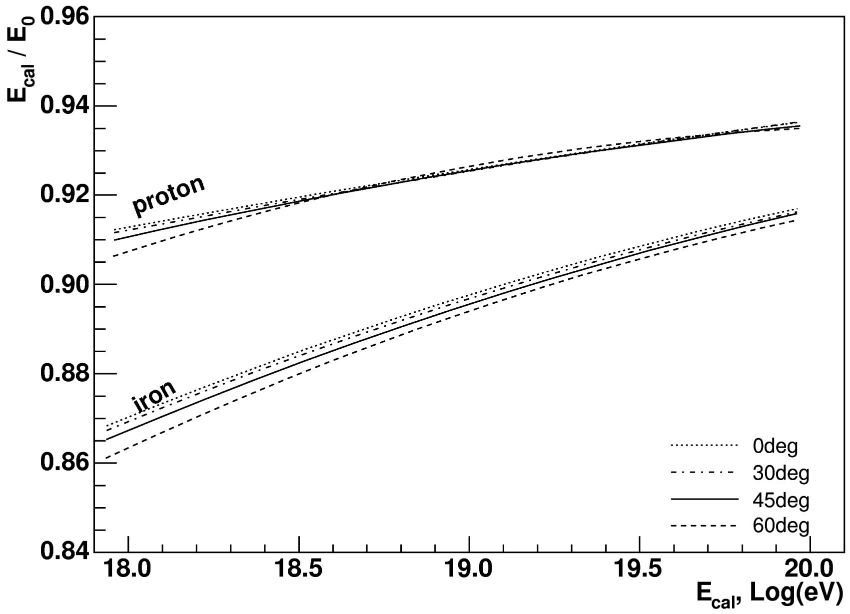
$$\frac{A}{R_i^2}$$

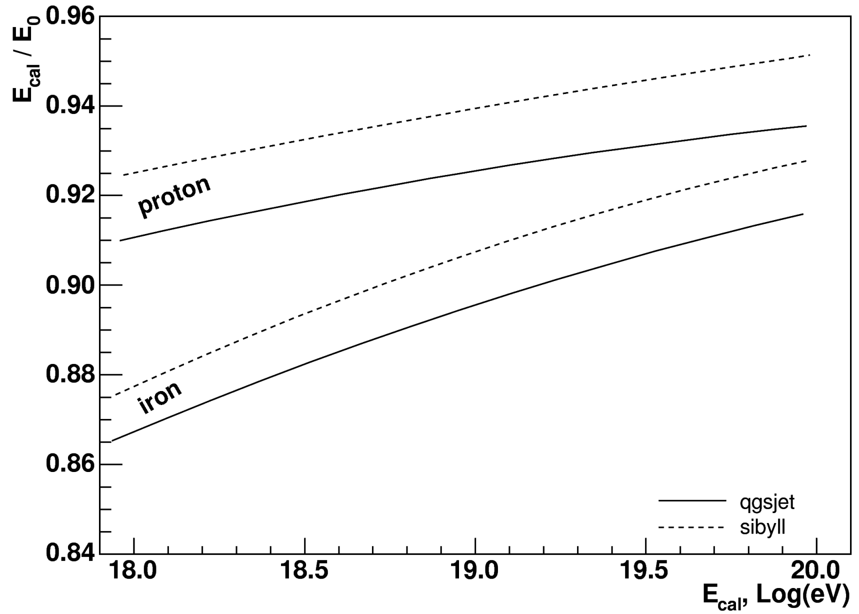
Atmosphere

$$T(\lambda)$$

Detector calibration

FD: the invisible energy





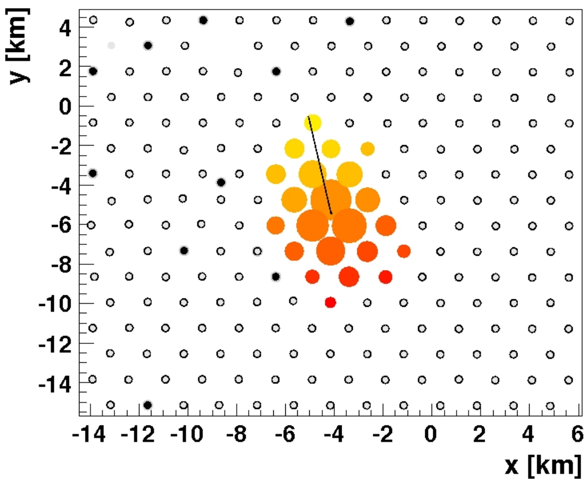
The “invisible” energy carried away mainly by muons and neutrinos has to be taken into account to reconstruct the primary energy

$$E_{\mathrm{FD}} = (1 + f_{\mathrm{inv}})\, E_{\mathrm{cal}}$$

This correction is mass and model dependent

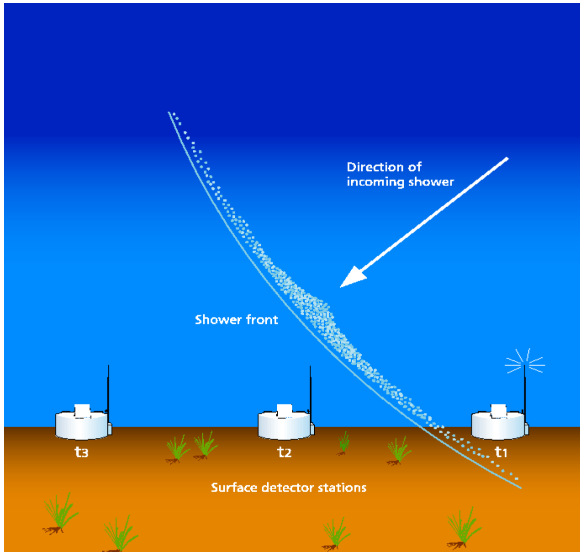
SD reconstruction

Direction:
fit to arrival times sequence of particles in shower front



Angular resolution

E > 10^{18} eV, ~ 3 stations, < 2°
E > 10^{19} eV, ~ 6 stations, < 1°



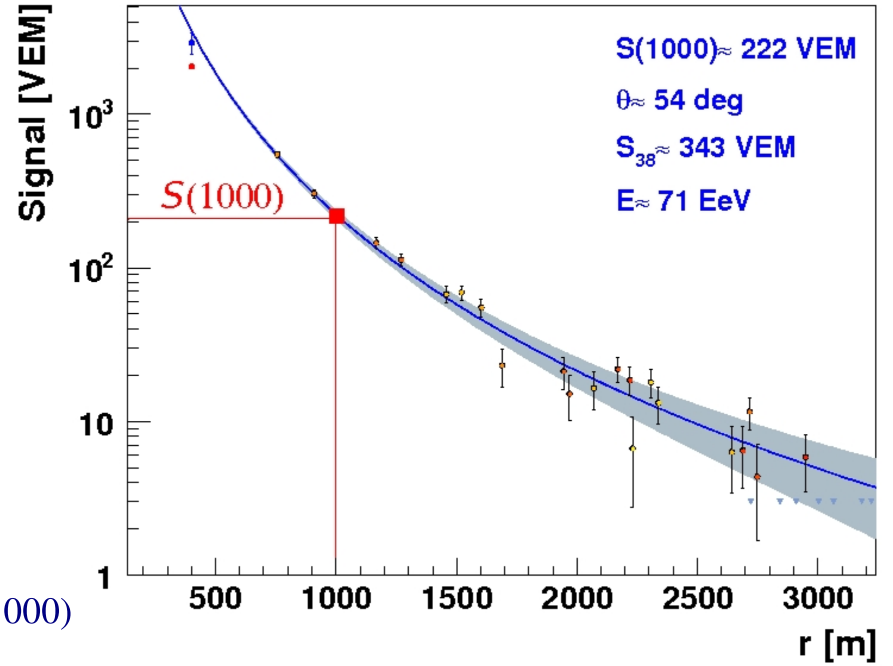
Determination of the arrival direction with χ^2-method

Determination of the lateral particle density function and LDF with a Likelihood method to fit a NKG-type function

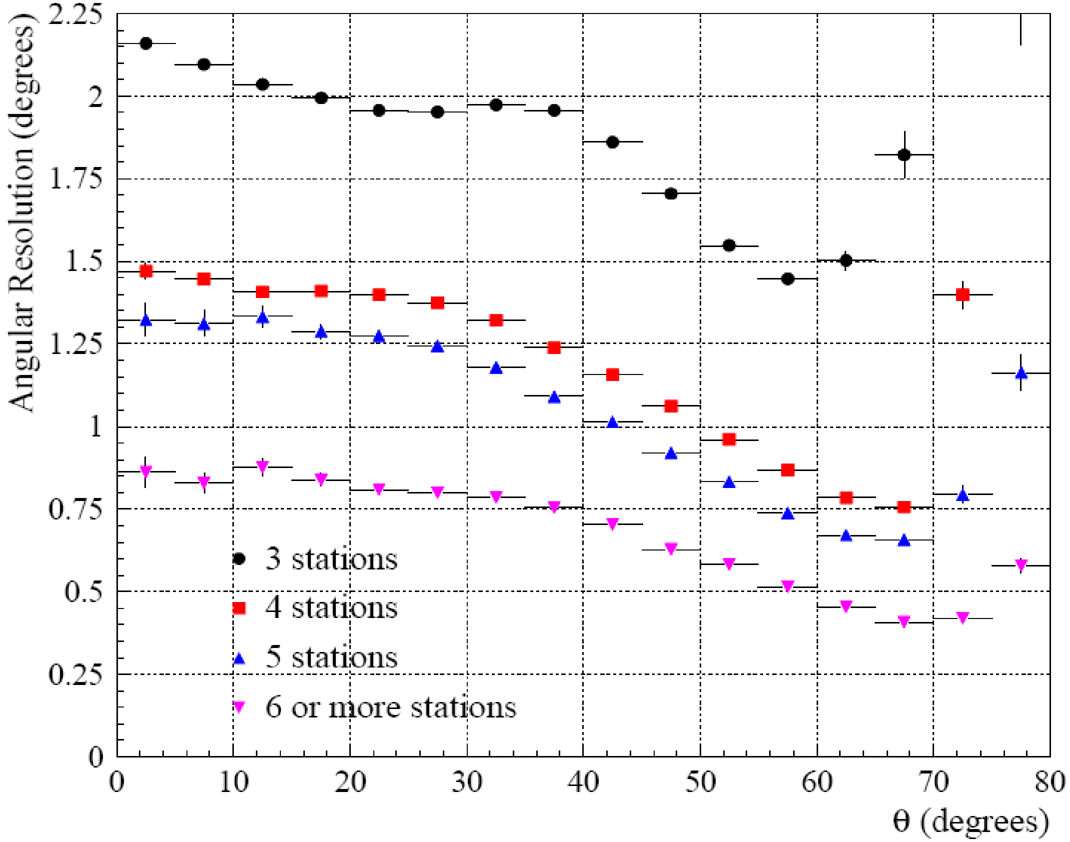
$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+700}{1700}\right)^{-\beta}$$

Free parameters: core position and signal at 1000 m, S(1000)

β is parameterized as a function of shower zenith angle and S(1000)



Angular resolution with SD



Using the time variance model
Astropart. Phys. 28 (2008) 523

$$F(\eta) = 1/2\ (V[\theta] + \sin^2(\theta)\ V[\phi])$$

$V[\theta\phi]$ = variances

η = space angle between true and reconstructed angle

$$AR = \sqrt{-2\ \ln(0.32)\ F(\eta)}$$

SD angular resolution from data

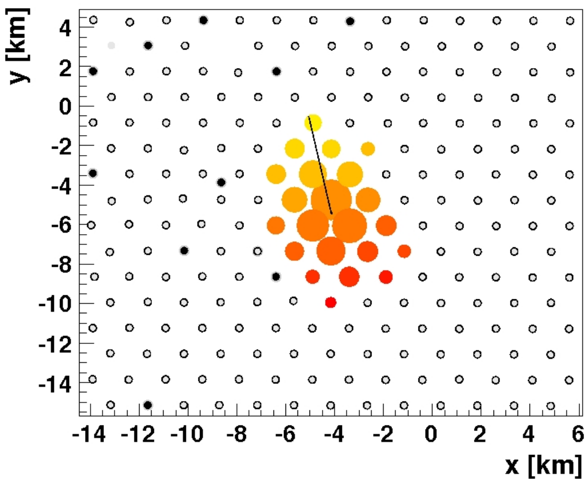
3-fold E<4 10^{18} eV AR < 2.2º (θ<60º)

4/5-fold 3 10^{18} <E<10^{19} eV AR < 1.5º (θ<60º)

More fold E>10^{19} eV AR < 1º (θ<60º)

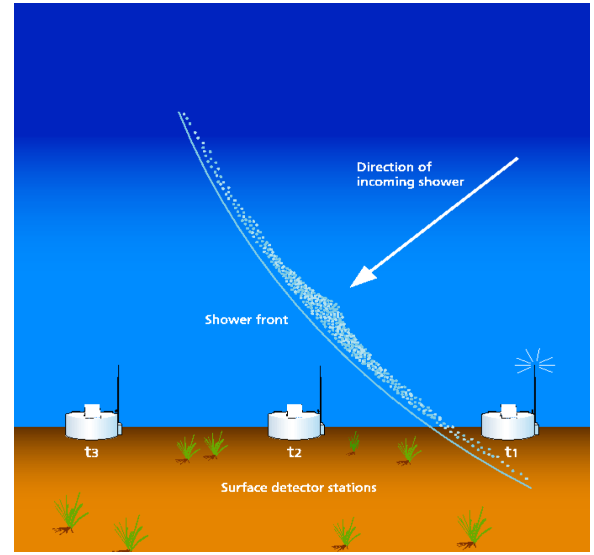
SD reconstruction

Direction:
fit to arrival times sequence of particles in shower front

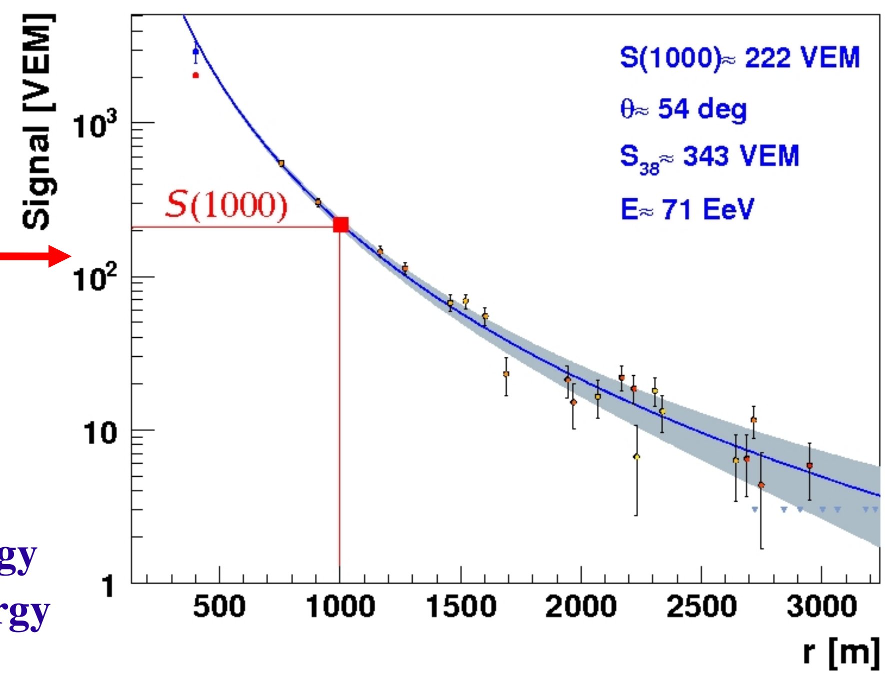


Angular resolution

E > 10^{18} eV, ~ 3 stations, < 2°
E > 10^{19} eV, ~ 6 stations, < 1°



Energy estimator: **S(1000)**
particle density at 1000 m from shower axis

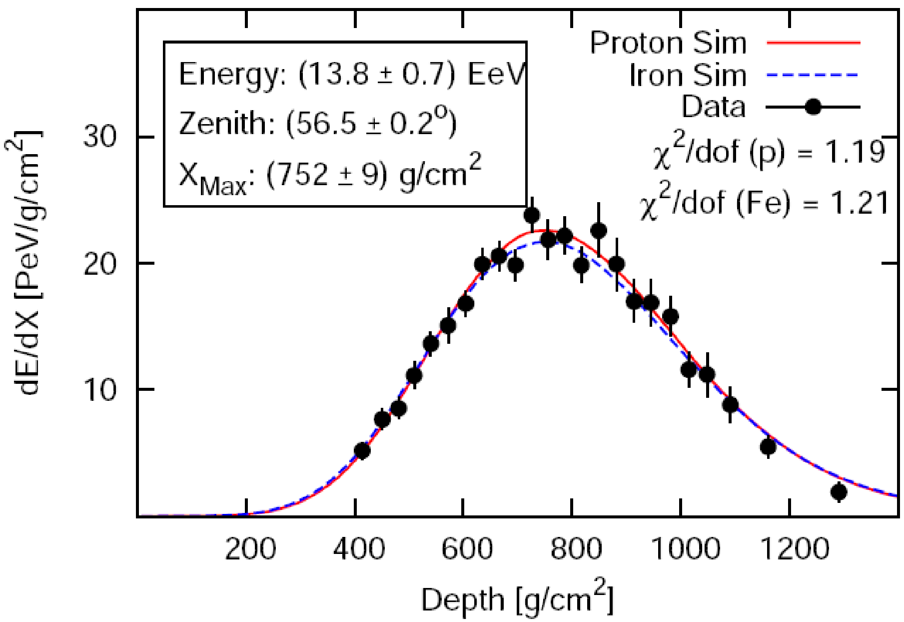


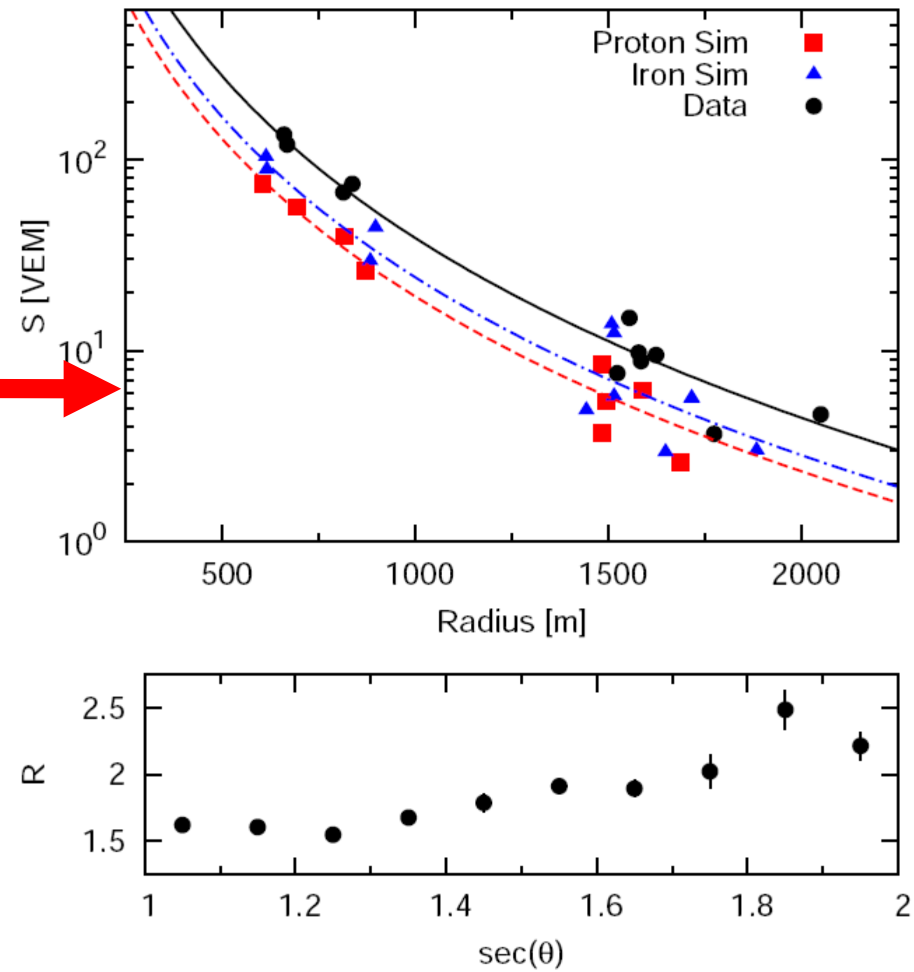
Systematic uncertainties on energy determination

- 30% from hadronic interaction models at high energy
- 10-20% from hadronic interaction model at low energy

Muon puzzle....

J.Allen @ **ICRC 2011**





More muons in data than in simulation!

Not easy to reproduce with models these measurements

SD energy based on LDF systematically overestimated w.r.t. FD

MAPSES Lecce 23-25 Novembre

Pierre Auger Observatory

studying the universe's highest energy particles

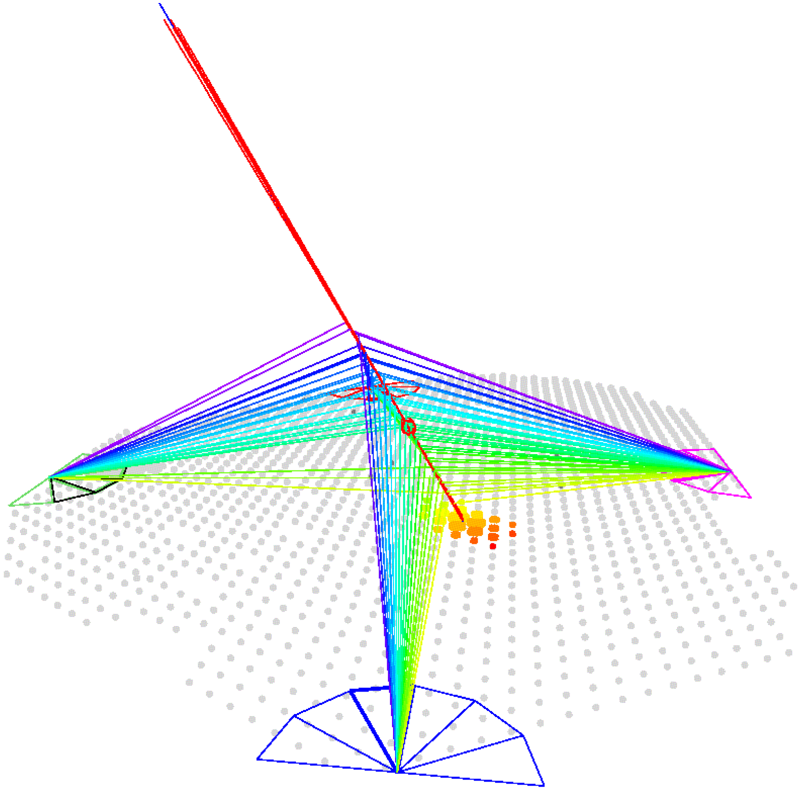
Tecniche di misura con l'Osservatorio Pierre Auger

Lorenzo Perrone

Università del Salento e INFN Lecce (Italy)

Outline

- Physics goals and operation range
- Detector description
- Performance and observables
- Results
- Enhancements



Study of the transition between galactic and extra-galactic cosmic rays

- Ankle region

- 2^{nd} Knee region (with lower energies extensions)

The physics case

End of the spectrum (GZK region)

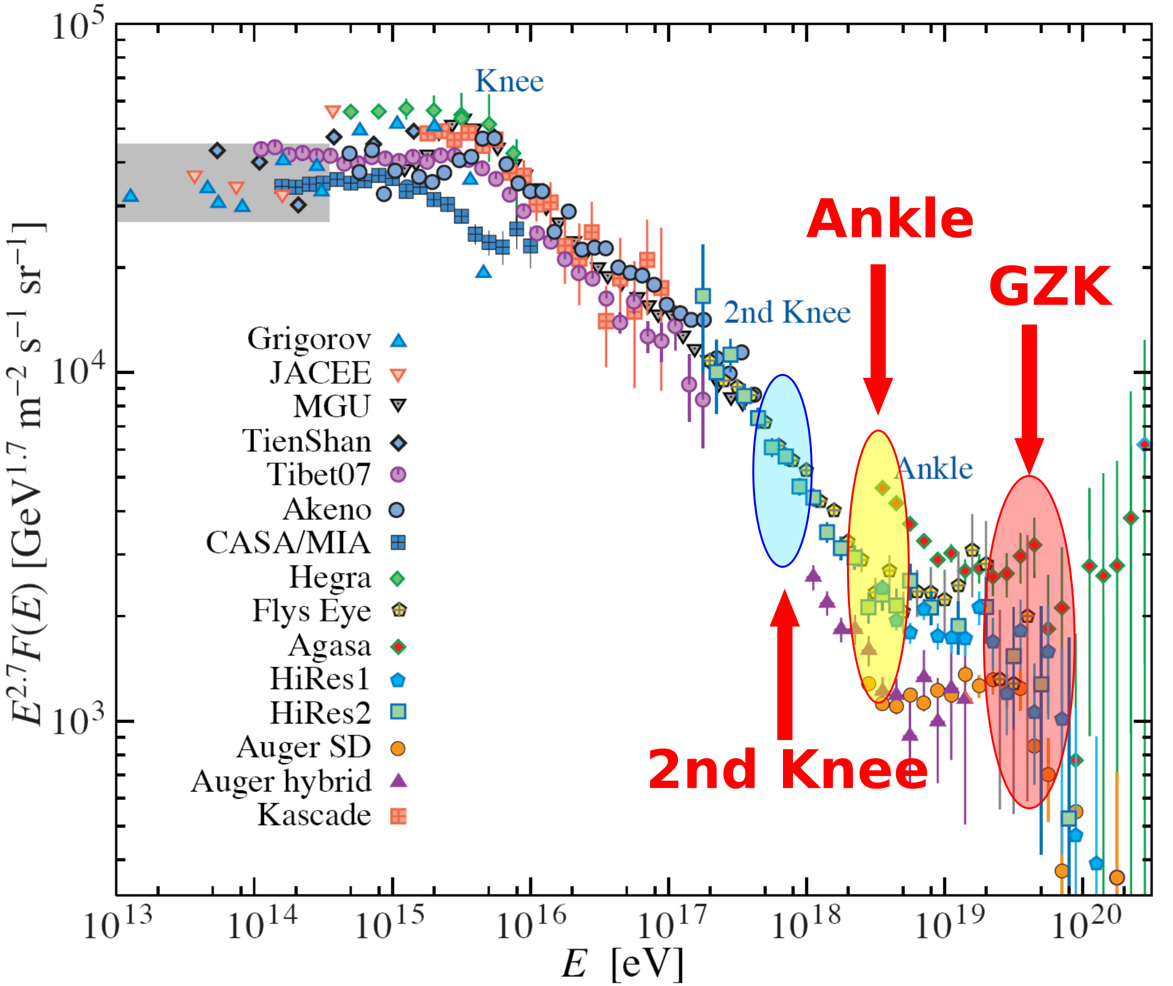
Energy spectrum

Arrival directions

Composition

Search for photon and neutrinos as primary cosmic rays

Hadronic physics



Particle Data Group

The Pierre Auger Observatory

- ***Surface detector***

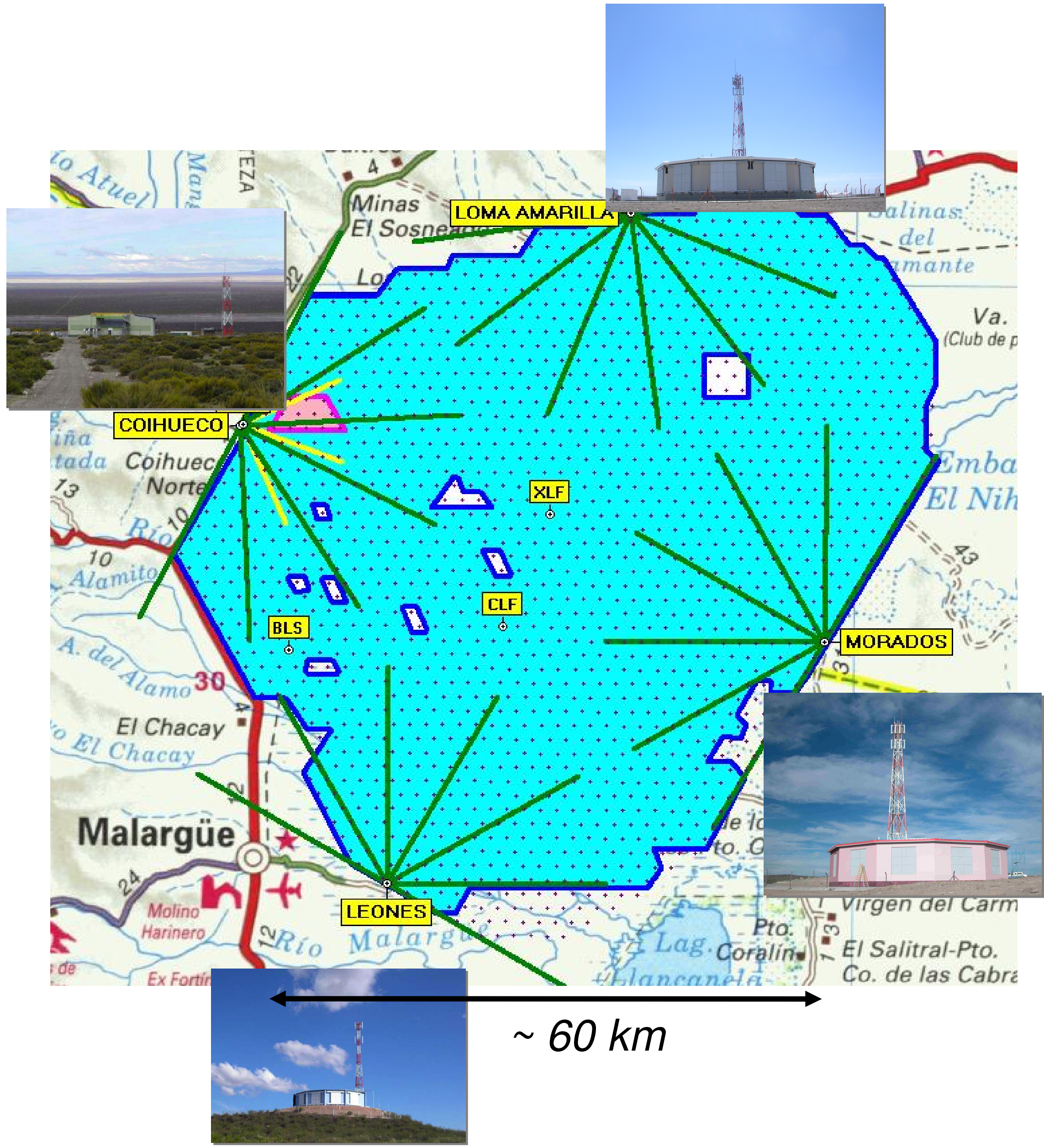
an array of 1600 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km^2)

- ***Fluorescence detector***

4 buildings overlooking the array

Low energy extensions

AMIGA: dense array plus muon detectors
HEAT: three further high elevation FD telescopes



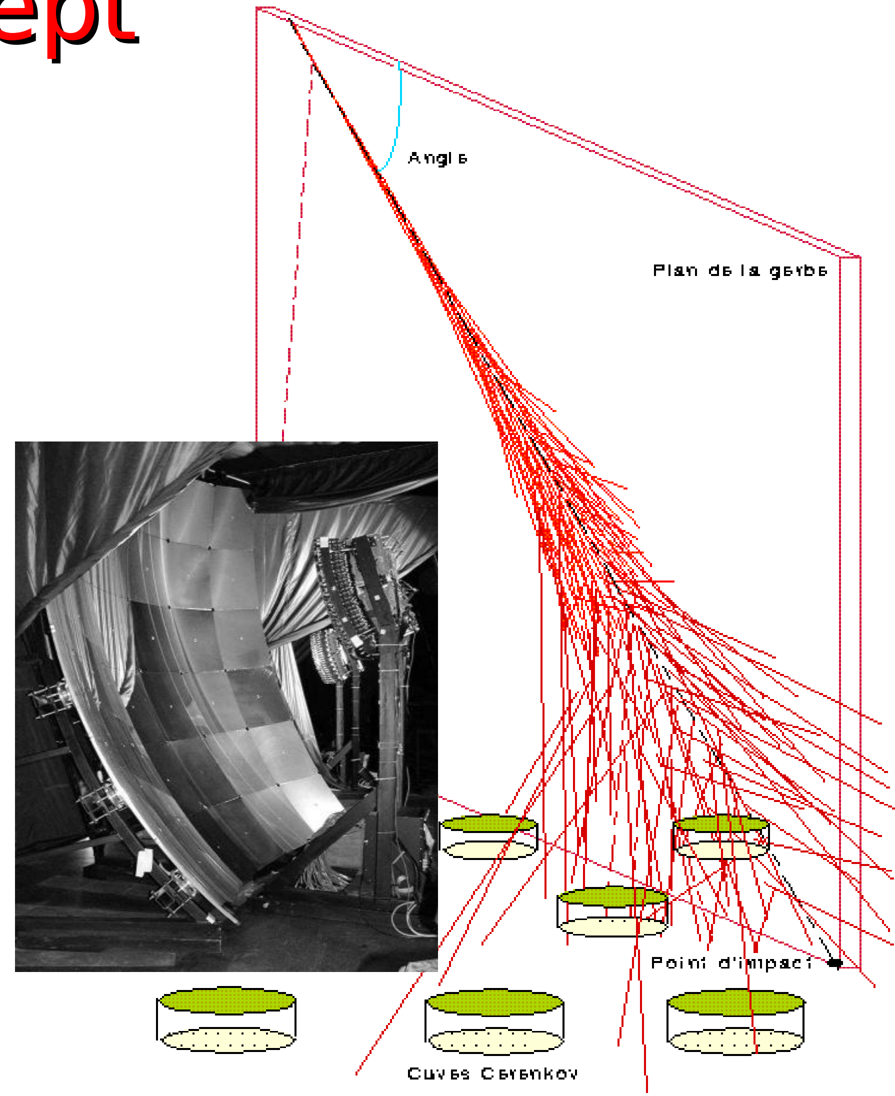
The Hybrid Concept

Surface Detector Array
lateral distribution, 100% duty cycle

Air Fluorescence Detectors
Longitudinal profile, calorimetric energy measurement, ~15% duty cycle

accurate energy and direction measurement

mass composition studies in a complementary way



"In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side."

V.H.Hess, Nobel Lecture, December 1936

FD-SD-Hybrid

	SD-only	FD-only	Hybrid
Duty-cycle	~100% (high stat)	~10-15%	~10-15%
Anguar Res.	1-2 deg	~3 deg	~ 0.5 deg (>1 EeV)
Energy	relies on MC and composition	missing energy geometry bias	missing energy
Energy Range	~>$10^{18.5}$ eV	~>$10^{17,5}$ eV	~>10^{18} eV

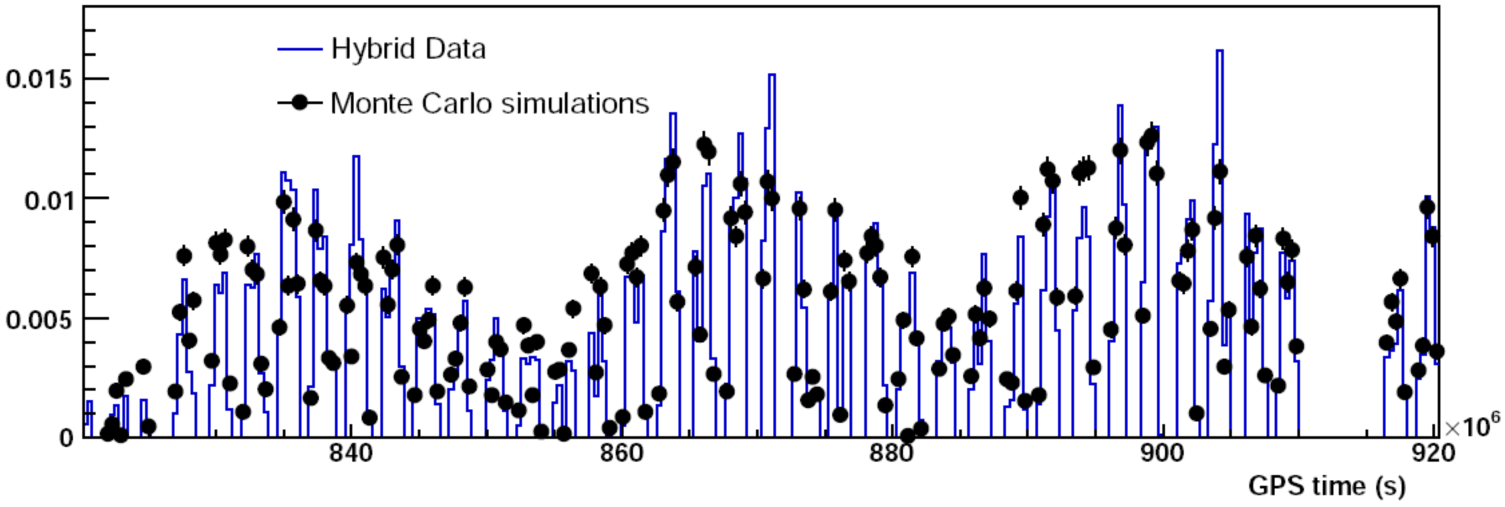
Results

- **Energy spectrum (Hybrid, SD, Combined)**
- Mass composition
- Hadronic interactions
- Search for photons and neutrinos
- Astrophysics

Hybrid Exposure

$$\mathcal{E}(E) = \int_T \int_\Omega \int_{A_{gen}} \varepsilon(E,t,\theta,\phi,x,y)\ \cos\theta\ \mathrm{d}S\ \mathrm{d}\Omega\ \mathrm{d}t$$

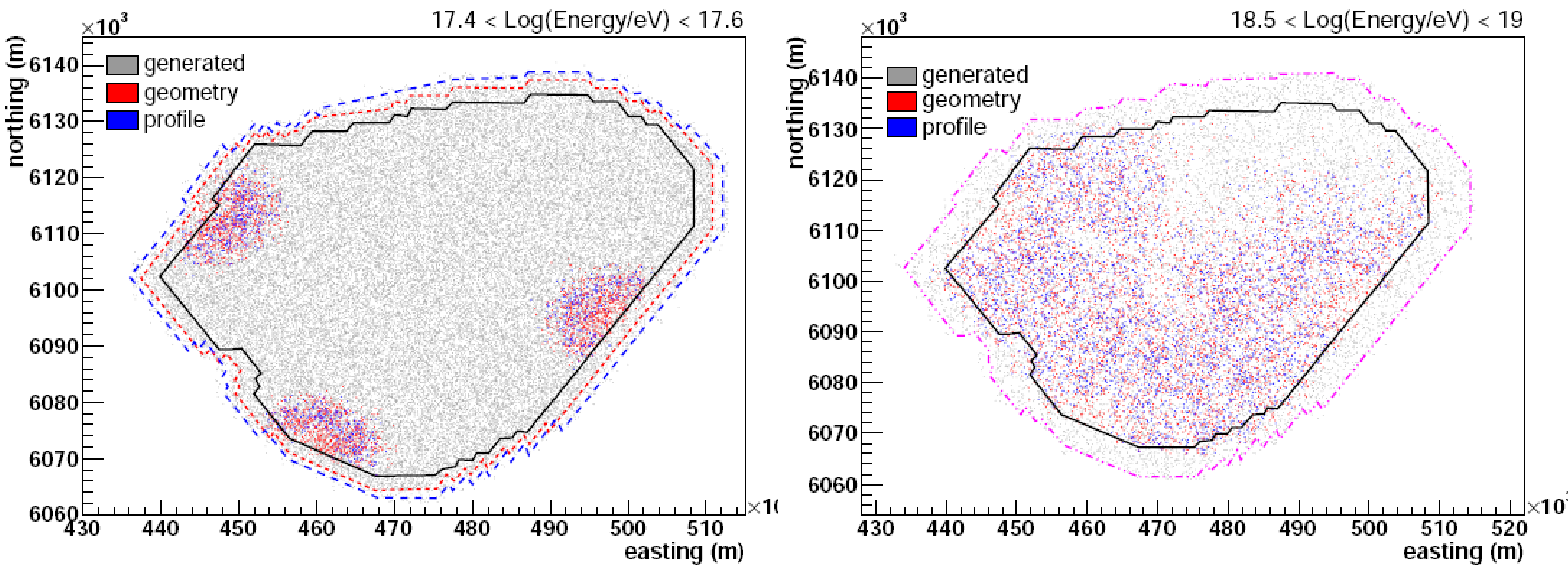
Time dependent simulations



FD on-time and SD stations status reproduced according to the actual data taking conditions along the considered time window

Efficiency

Simulations taking into account the FD and SD detector status plus the atmospheric conditions



Example: time period with only 3 FD sites, two different energy ranges

Hybrid Exposure

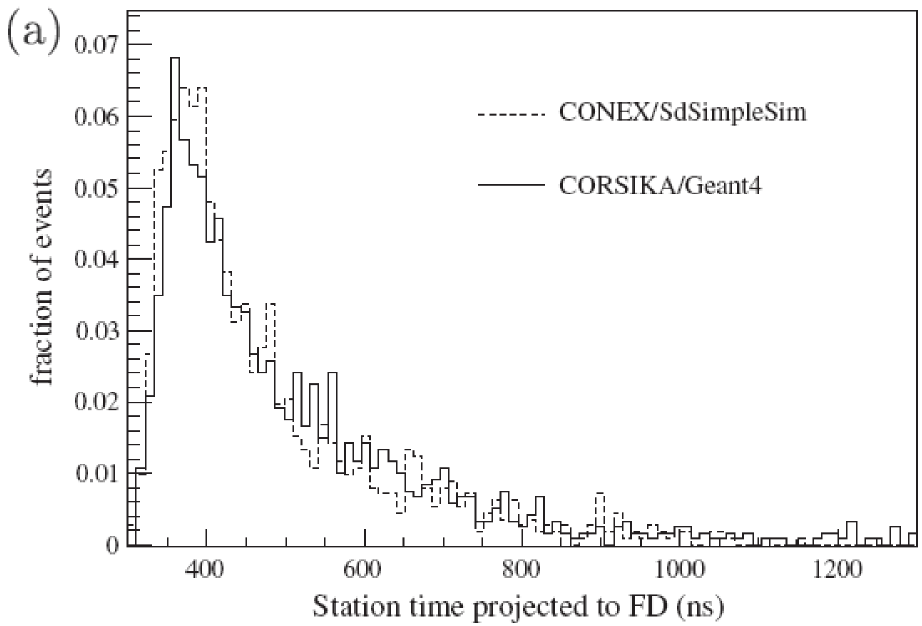
First Method : Conex profiles + LTPs (large statistics, no signal in the stations)

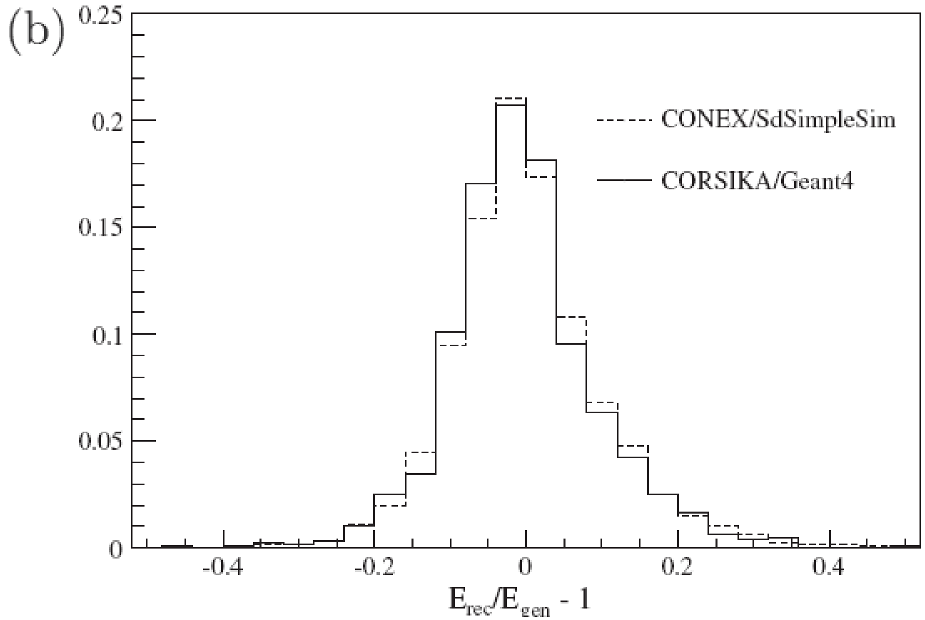
Longitudinal profile plus a parametrized station trigger response

Second Method : Corsika+Geant4 (less statistics, signal in the stations)

First method validated with the second

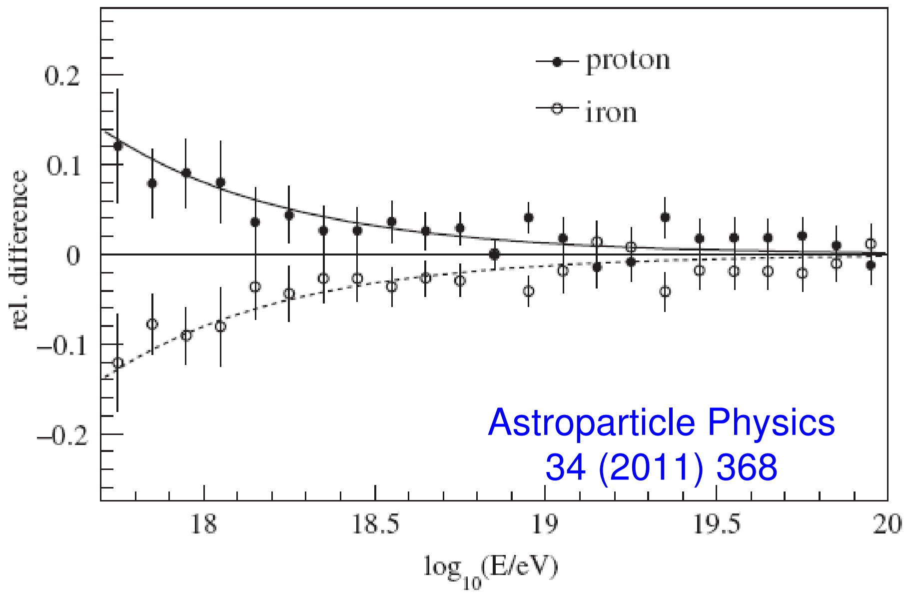
Astroparticle Physics 34 (2011) 368



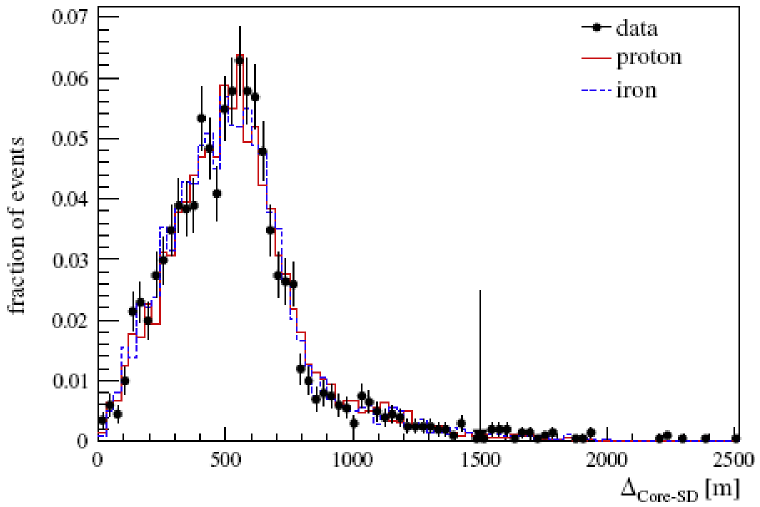


Hybrid Exposure

Weak dependence on primary mass above 1 EeV



Full agreement Data-MC

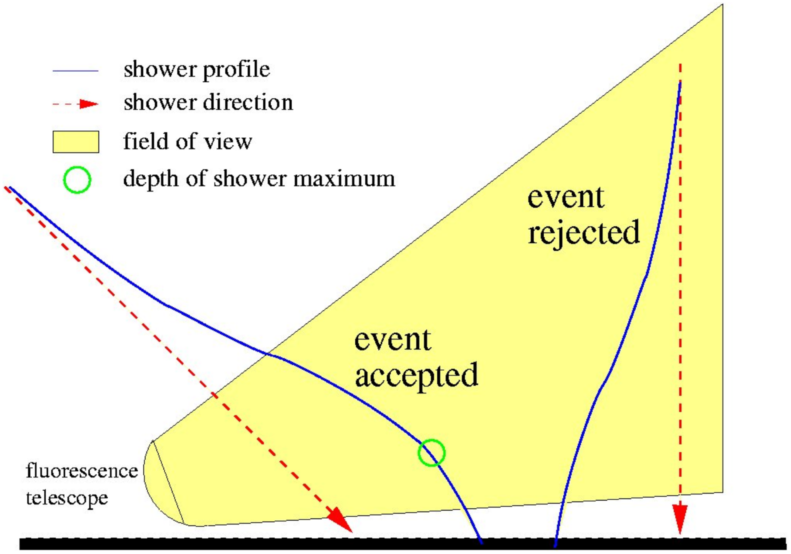


Quality cut

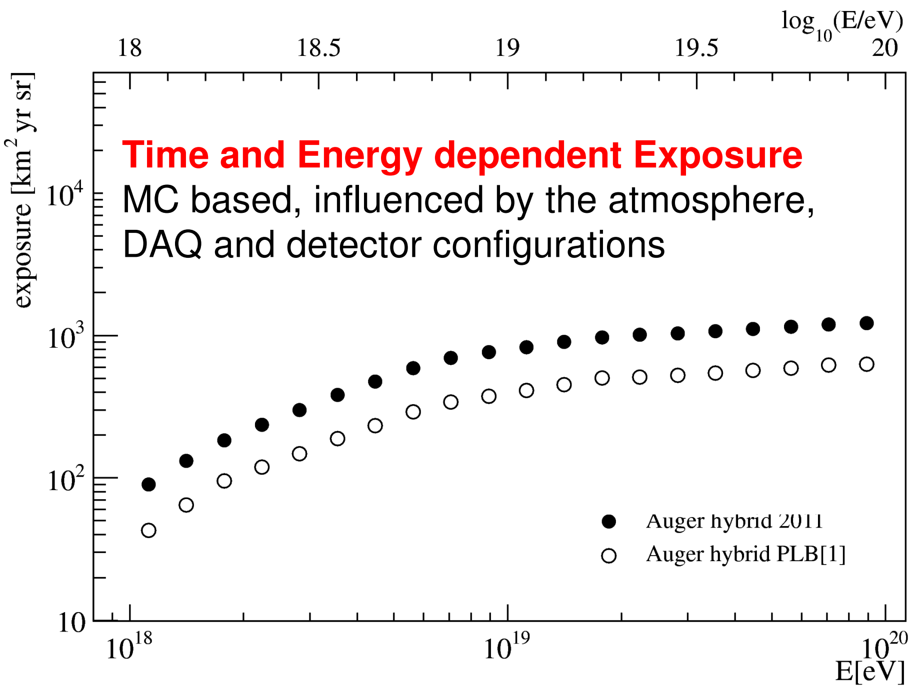
Fiducial cut

equal detection probability for all primaries

limited FD-site to shower axis distance to make the analysis robust against an energy shift within systematics



Hybrid Spectrum



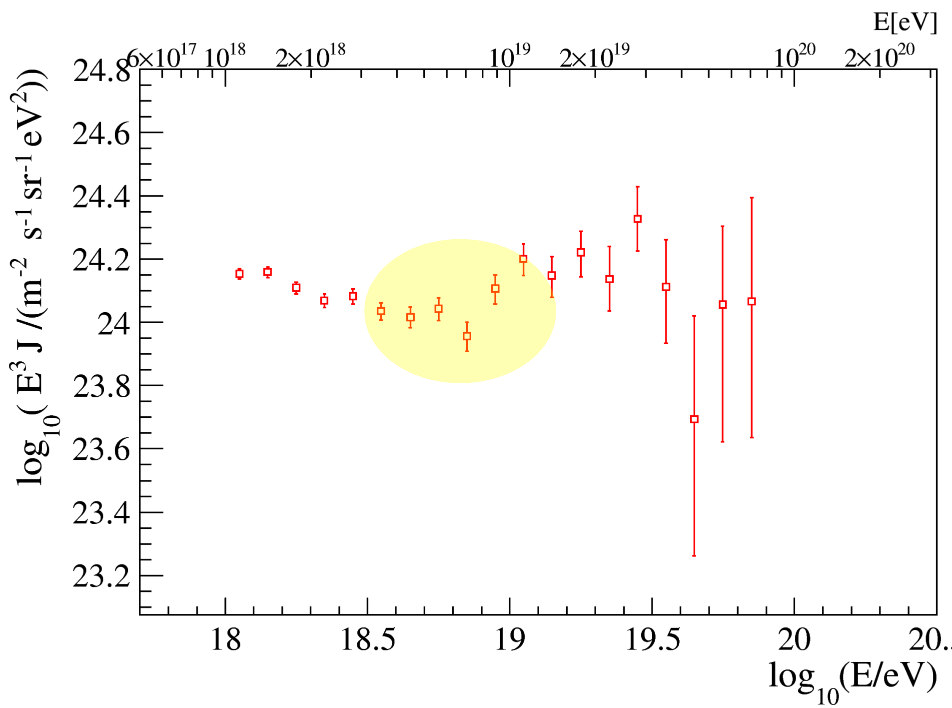
Data: Nov. 2005 – Sept. 2010

Systematic uncertainty on exposure
10% (6%) **E ~ 10^{18} eV** (>10^{19} eV)

+ Full efficiency at 10^{18} eV (ankle region)
+ Calorimetric measurement
+ Energy Resolution of 8%

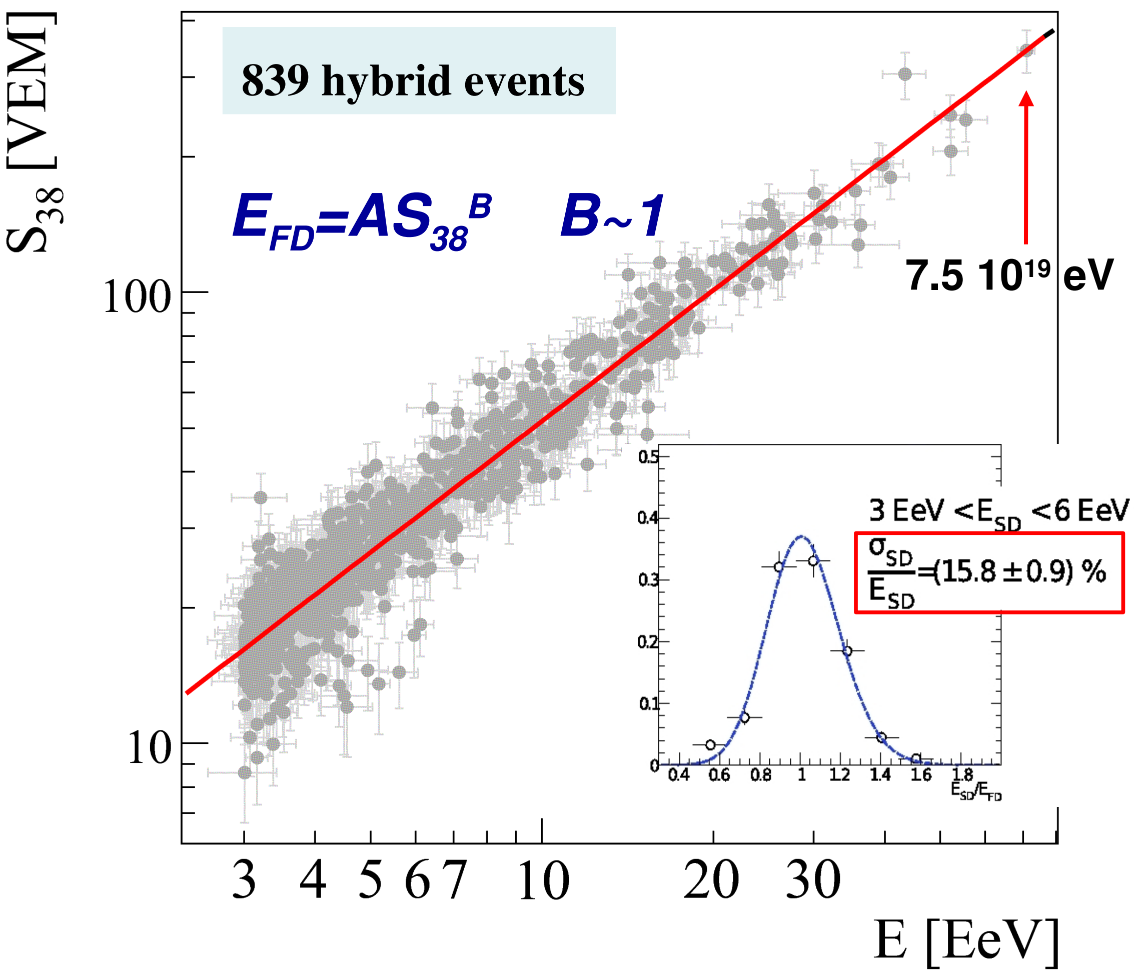
- Limited duty cycle (~13%)

Clear indication of the *ankle*



Energy calibration

R.Pesce @ ICRC 2011



Jan 2004 – Sept 2010
E > 3 EeV - zenith < 60°

Using hybrid events, the SD energy estimator is calibrated without relying on Monte Carlo

Method Systematic Uncertainties

7% a 10^{19} eV

15% a 10^{20} eV

FD Energy Systematics

- fluorescence yield 14%
- FD absolute calibration 9.5%
- invisible energy 4%
- reconstruction 10%
- atmospheric effects 8%

TOTAL: 22%

S_{38} *-> S1000 that a shower would have produced had it arrived with a zenith angle of 38°*

The attenuation curve

R.Pesce @ **ICRC 2011**

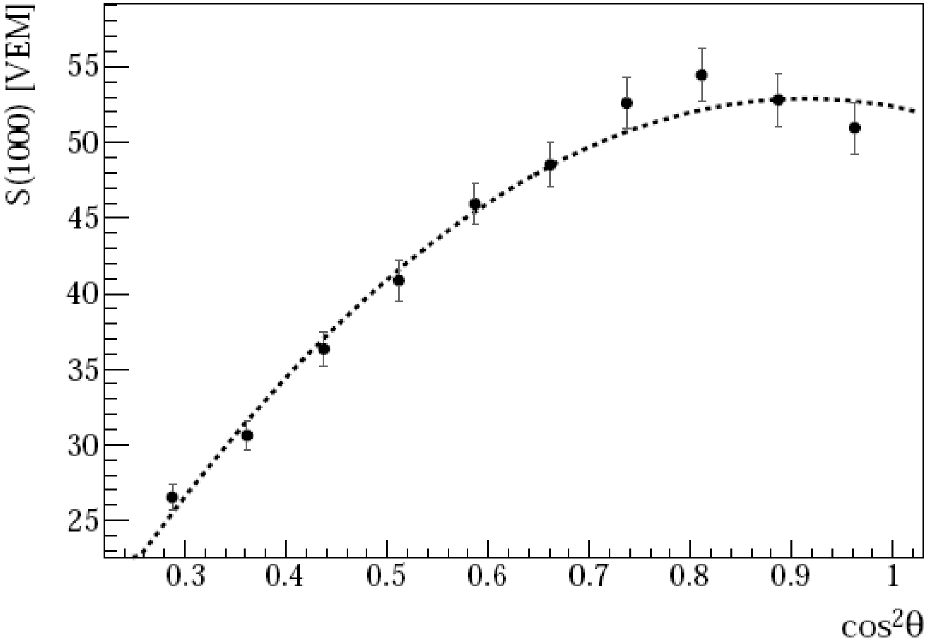
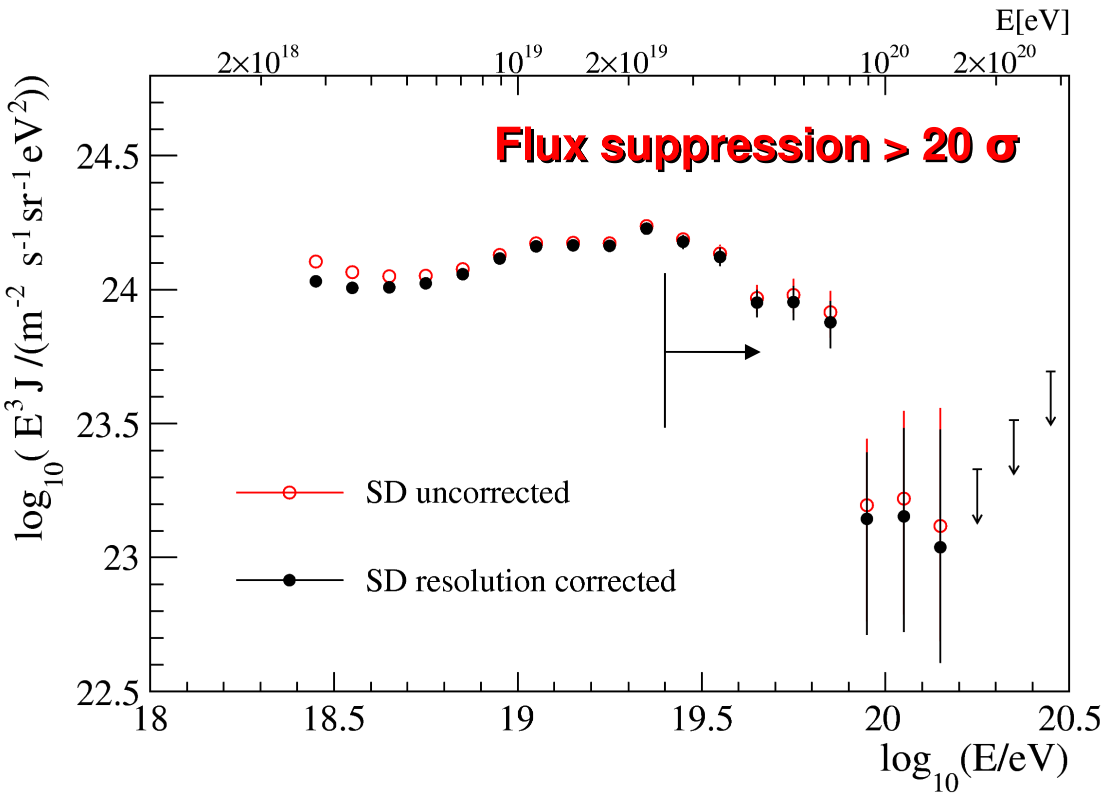


Figure 1: Attenuation curve, CIC(θ) fitted with a second degree polynomial in $x = \cos^2\theta - \cos^2\bar{\theta}$.

$$S_{38} \equiv S(1000)/\mathrm{CIC}(\theta)$$

SD Energy spectrum



64000 (5000) events **E > 3 10^{18} eV** (> 10^{19} eV)

Energy resolution ~ 15%
forward folding method to correct
for the bin-to-bin migration

SD Exposure

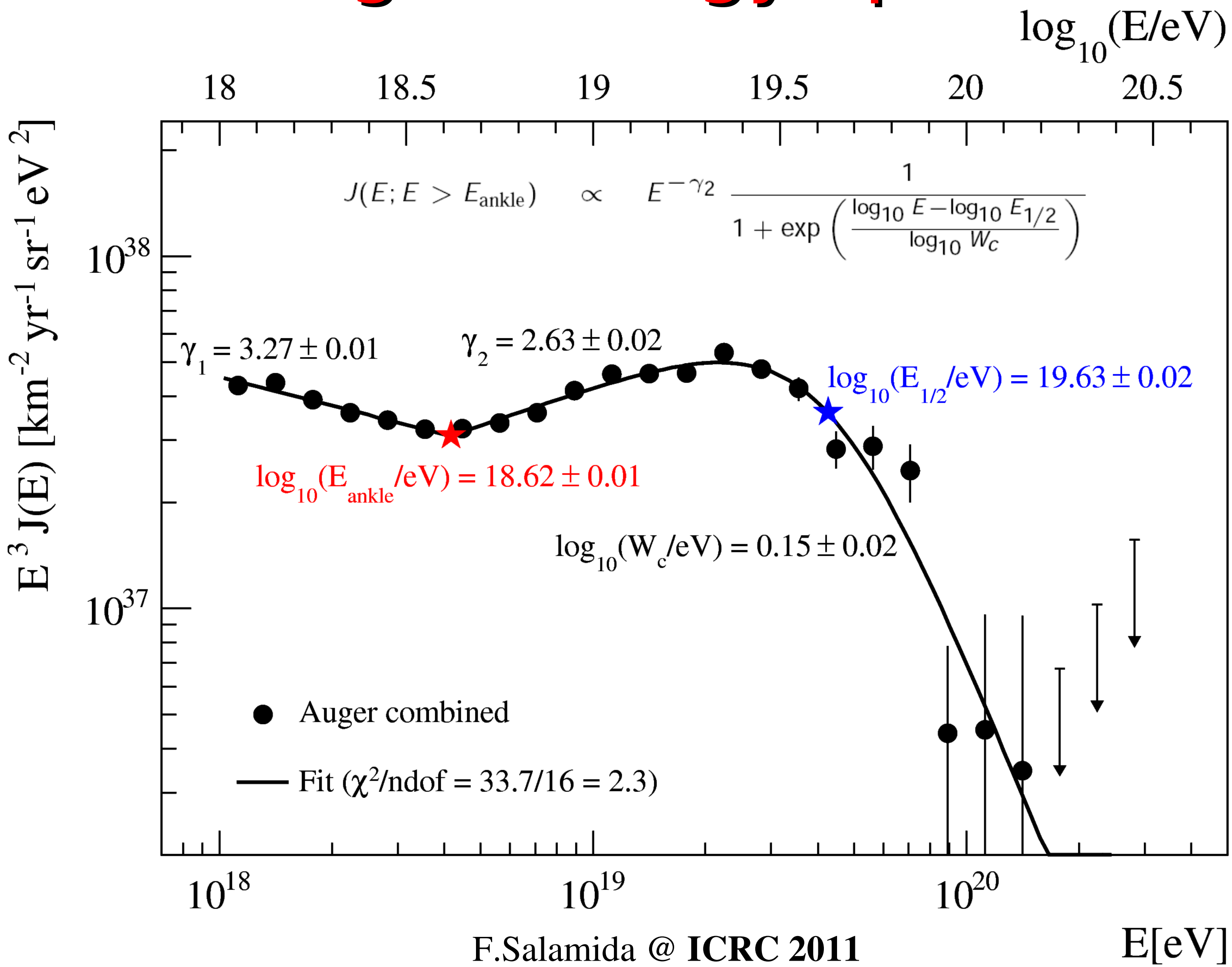
E> 3 EeV and zenith < 60°

- **20905 km² sr yr (Jan 04 - Dec 10)**
- **geometrical, counting active hexagons. Not relying on simulations, full efficiency**
- **independent of primary mass**
- **3% systematic uncertainty**

Energy scale from FD

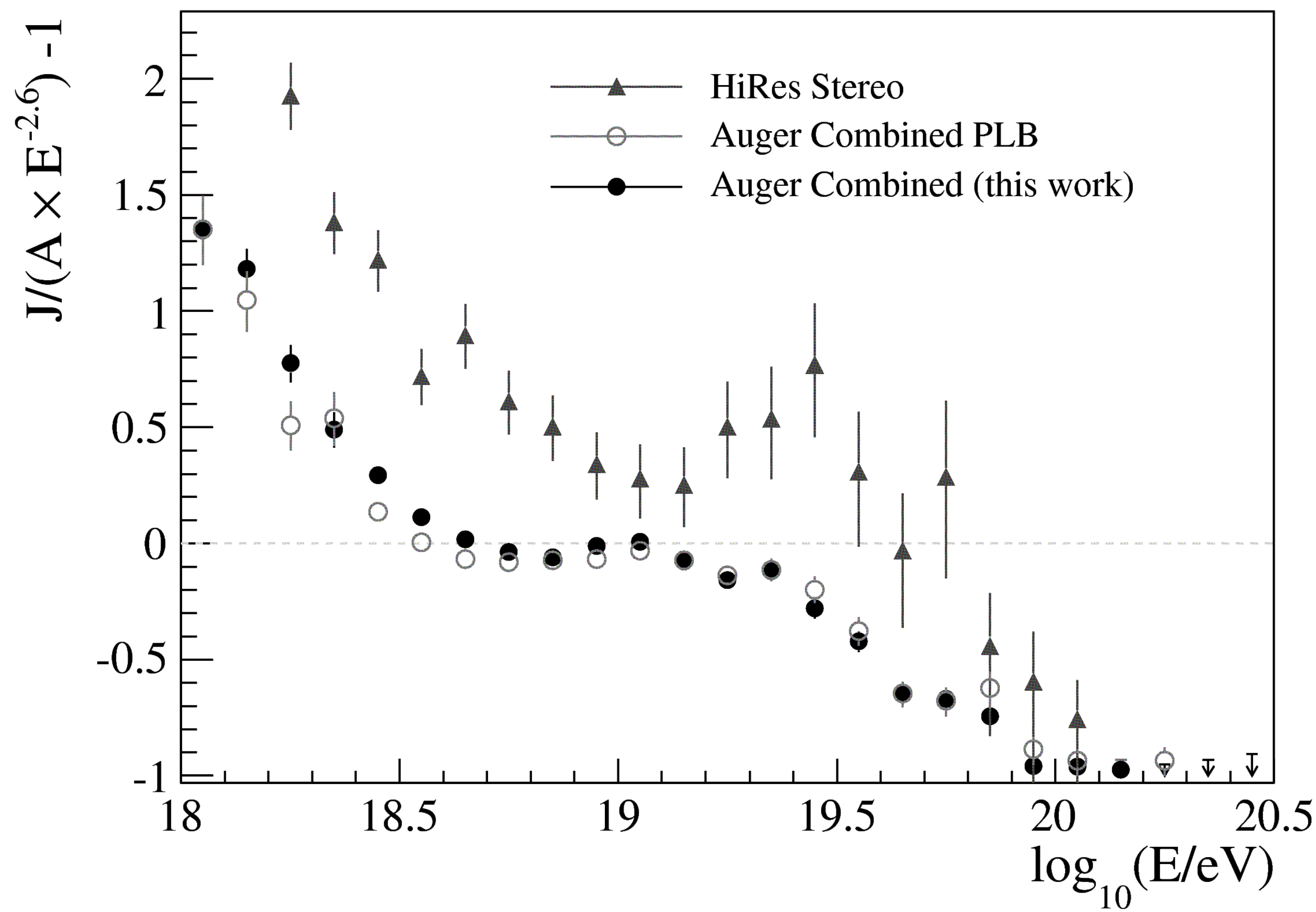
Total systematic uncertainty on flux ~ **6%**
22% on the energy scale

The Auger Energy spectrum



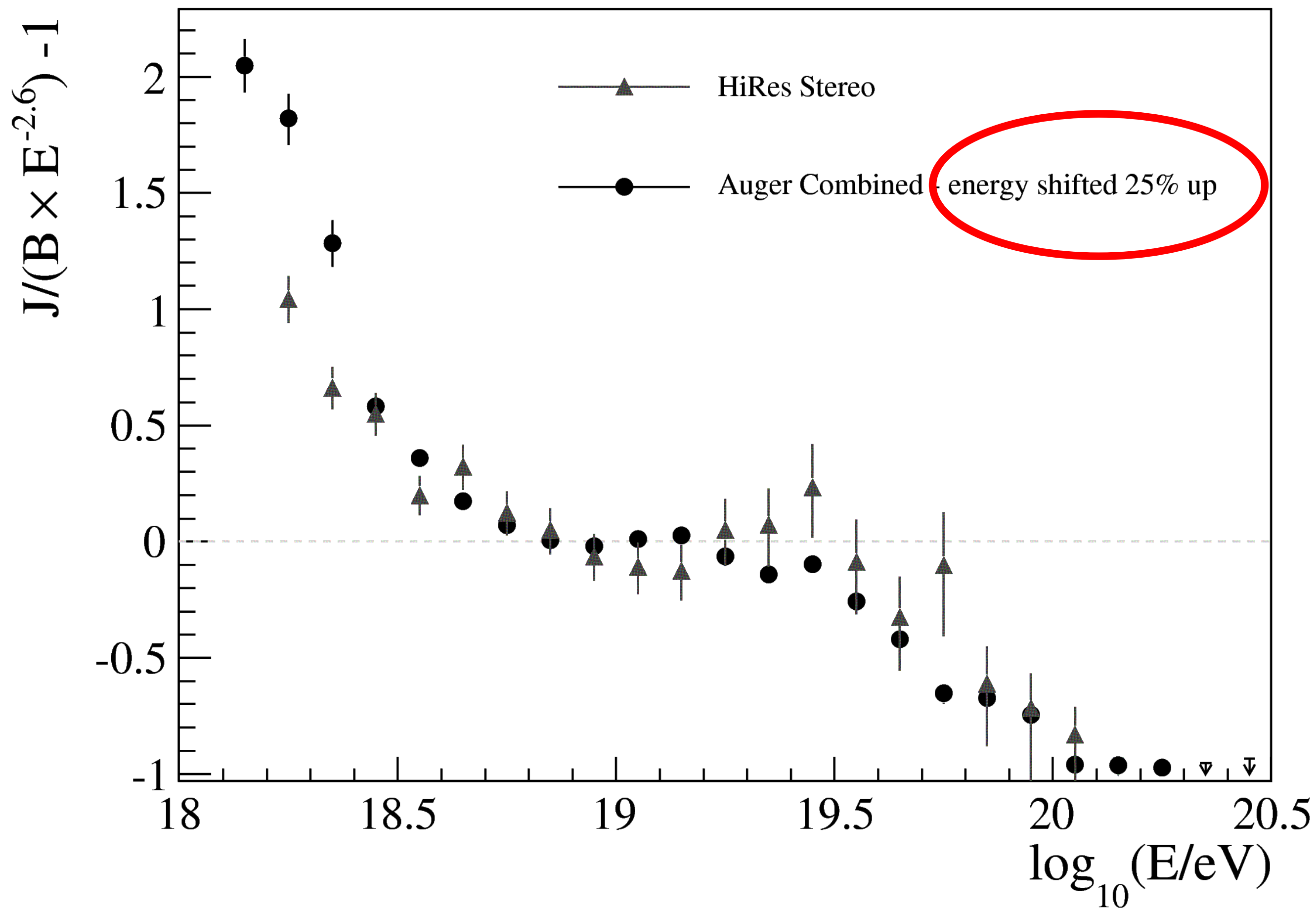
F.Salamida @ **ICRC 2011**

Energy spectrum: Auger vs HiRes



- Difference with respect to PLB 2010 due to changes of calibration curve
- Spectral features very well defined
- Compatible with HiRes within the energy scale systematic uncertainty

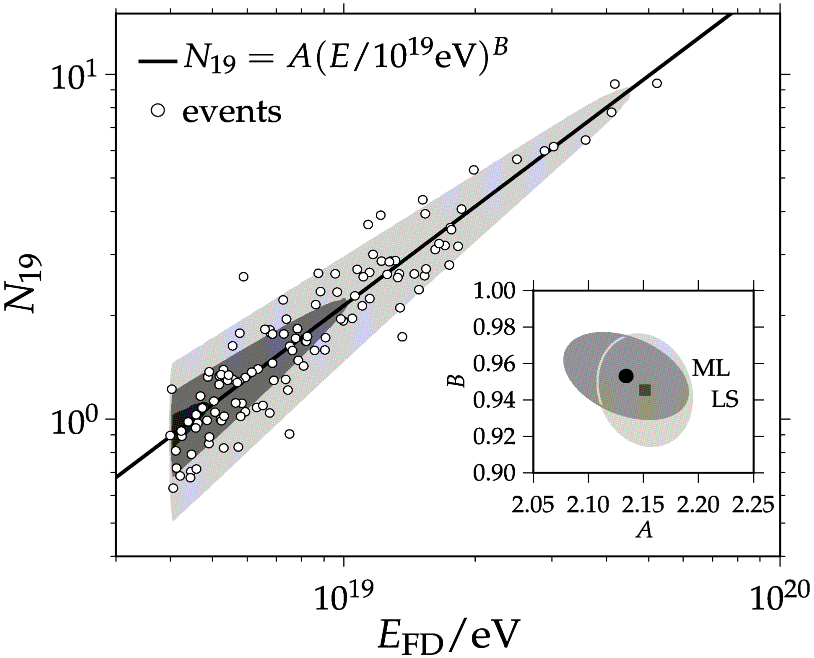
Energy spectrum: Auger vs HiRes



- Auger Energy Scale shifted of 25%
- Main spectrum features observed by both experiments

Spectrum with inclined events

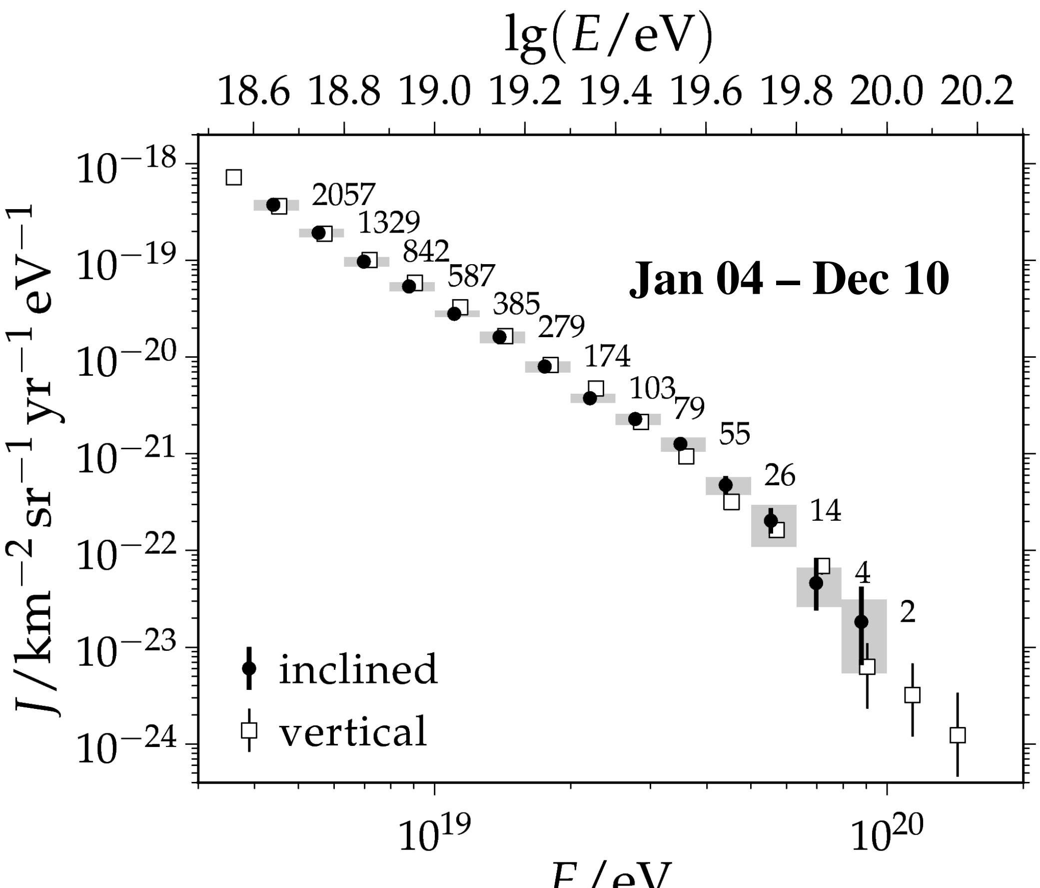
Energy Calibration with FD energy



Energy estimator:
N_{19} -> lateral muon density

Full agreement with flux from vertical showers

- **Energy > $4\ 10^{18}$ eV**
- **62° < Zenith< 80°**



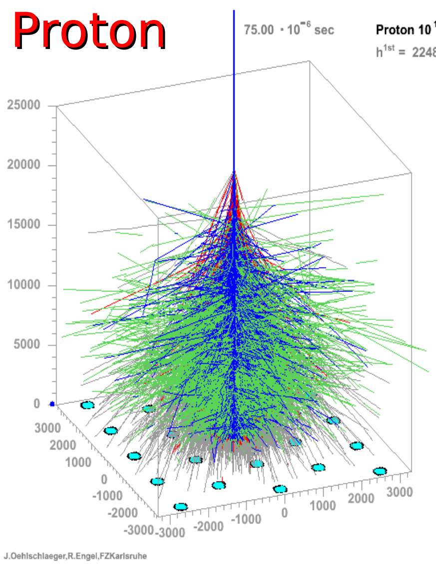
H.Dembinski @ **ICRC 2011**

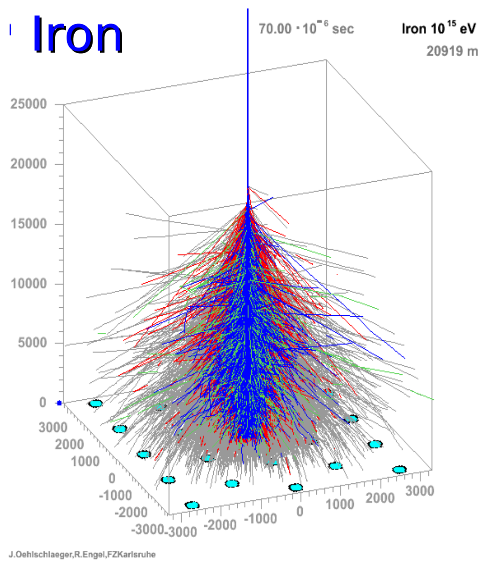
Results

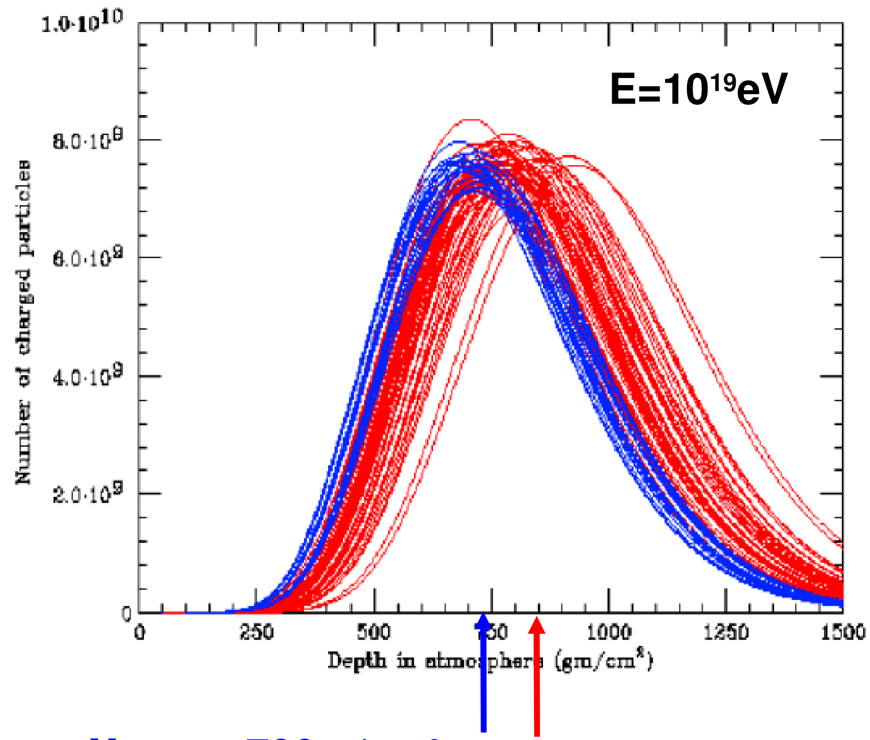
- Energy spectrum
- **Mass composition**
- Hadronic interactions
- Search for photons and neutrinos
- Astrophysics

X_{max} as indicator of mass composition

Atmospheric depth of shower maximum correlated with primary type
(Example: proton showers develop deeper than iron , $X_{max,pr} > X_{max,Fe}$)







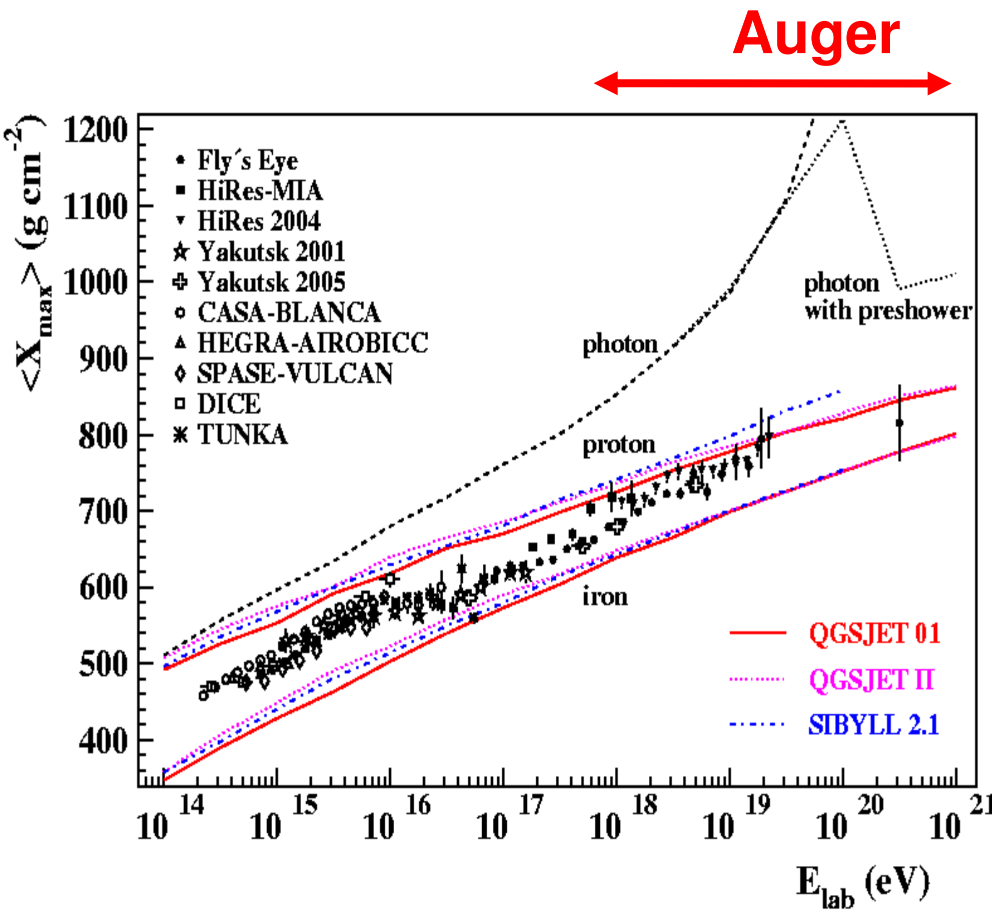
hadrons muons electrs neutrs

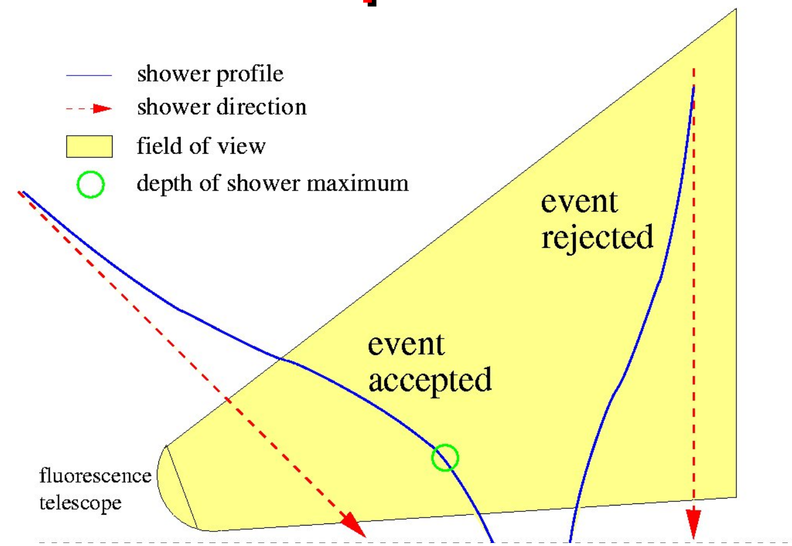
$X_{max,Fe}$ ~ 700 g/cm²

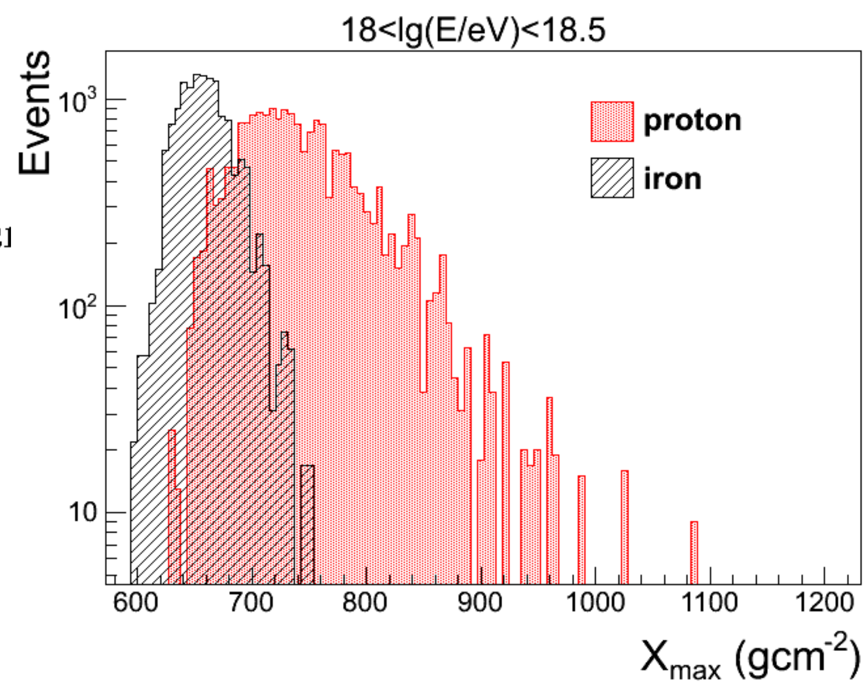
$X_{max,p}$ ~ 800 g/cm²

http://www-ik.fzk.de/corsika

Observation of longitudinal profile







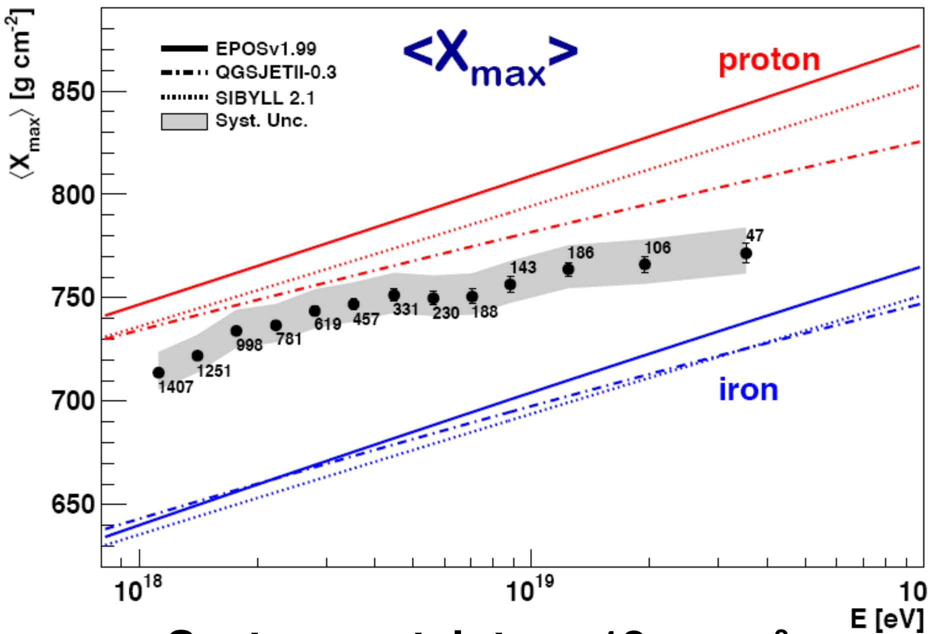
$$\langle X_{max}\rangle = \alpha(\ln E - \langle \ln A\rangle)+\beta$$

<Xmax> and its RMS

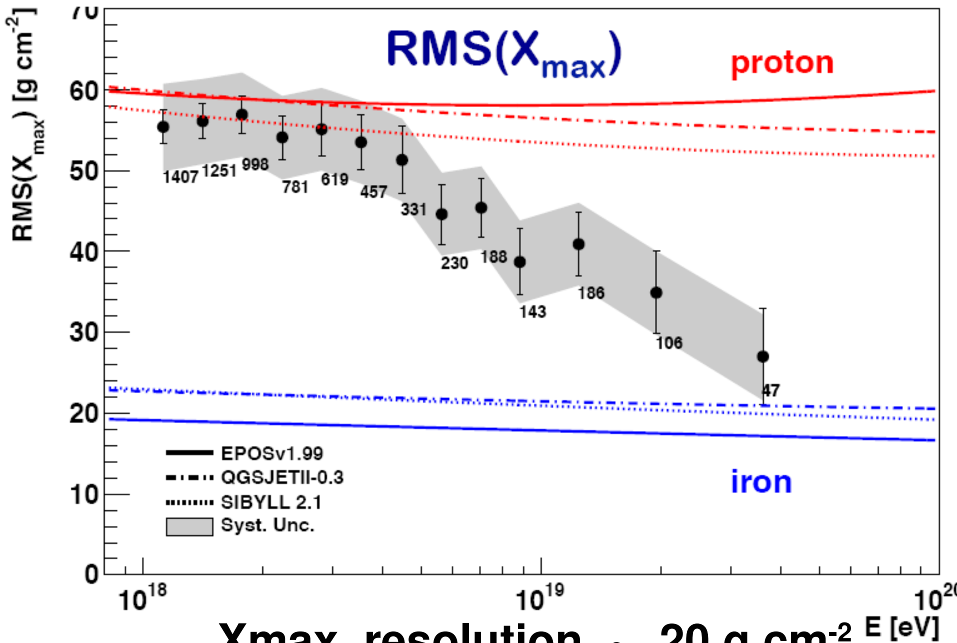
- sensitive to mass composition
- key observables for composition studies

Mass Composition: mean X_{max} and its RMS

G. Pinto, P.Facal @ **ICRC 2011**



Syst uncertainty < 13 g cm^{-2}

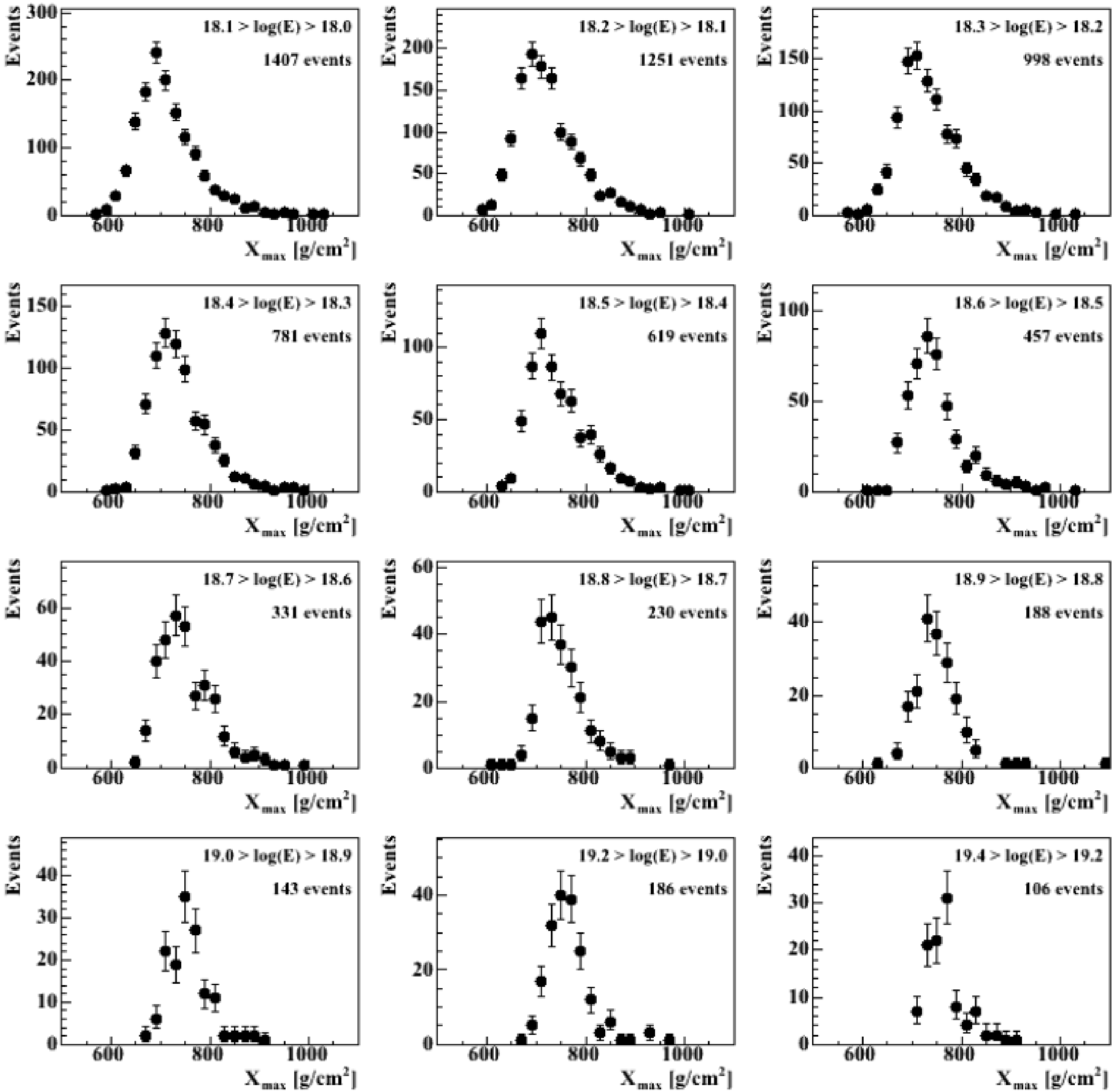


Xmax resolution ~ 20 g cm^{-2}

6744 hybrid events (Dec 2004 – Sept 2010) E > 10^{18} eV

- → **interpretation depends on hadronic interaction models**
- → **increase of the mean mass with the energy**
- → **Open issue: HiRes (and first results of TA) suggest a lighter composition**

X_{max} distributions

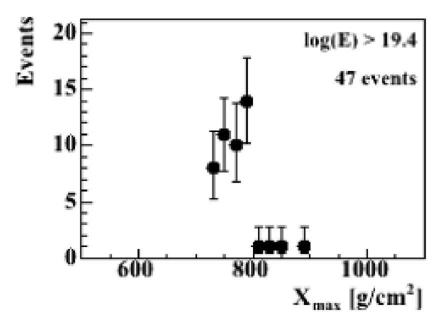


As the energy increases:

- distributions becom narrower, and

- deep X_{max} tail becomes less eviden

Interpretation, especially at high energy, is difficult since we have to rely on the extrapolation provided by the different models



Distributions – Shape

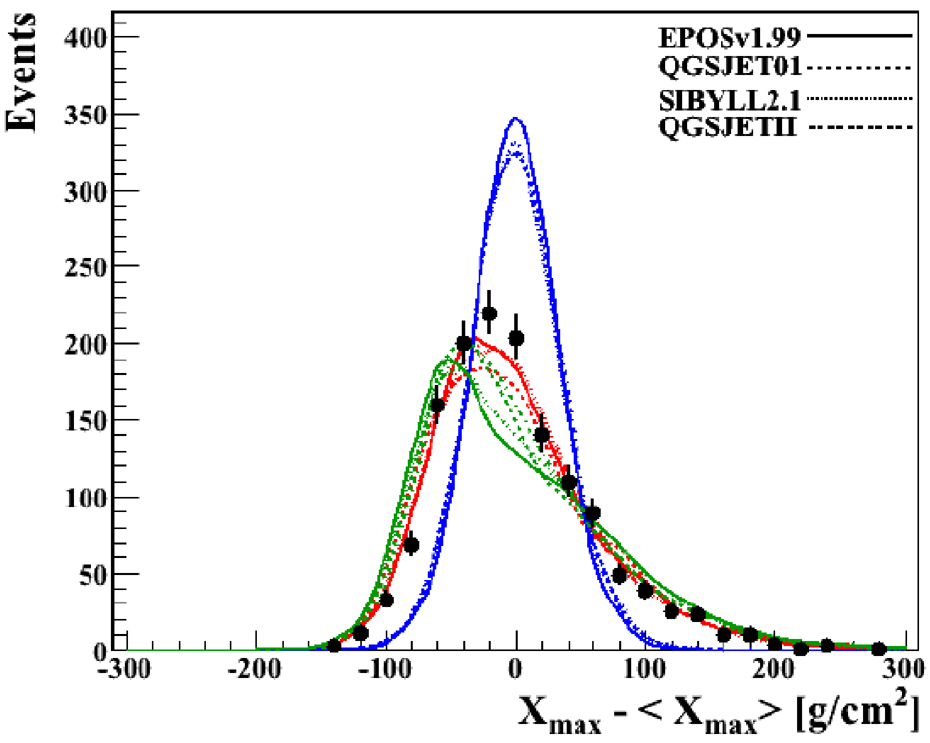
p Fe Mixed

Mixed: 50% p + 50% Fe

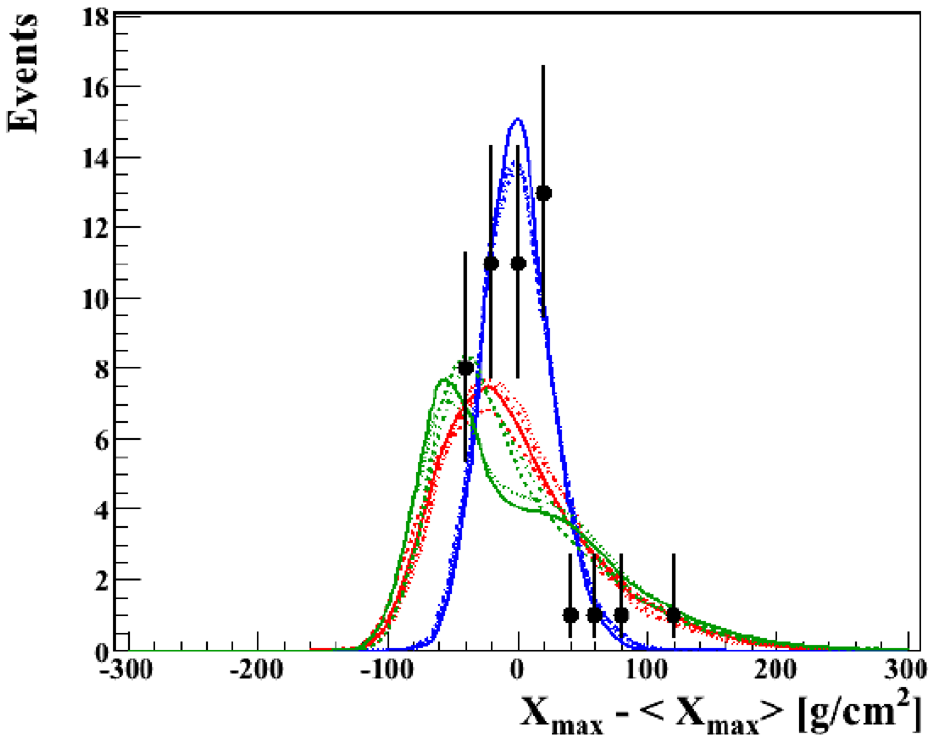
Subtract $<X_{max}>$ to each of the distributions and compare only the shapes

P.Facal @ **ICRC 2011**

18.1 > log(E) > 18.0



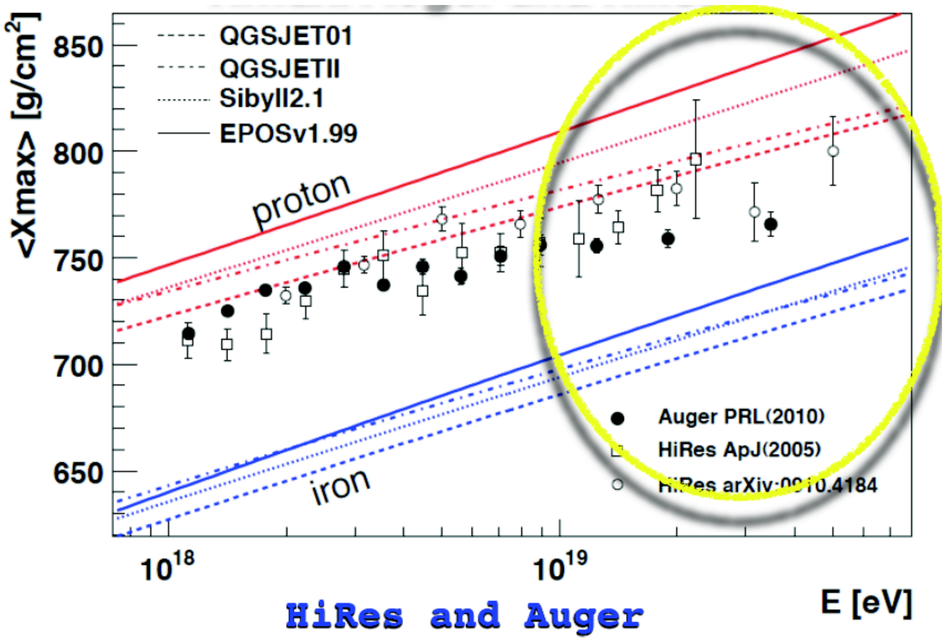
log(E) > 19.4

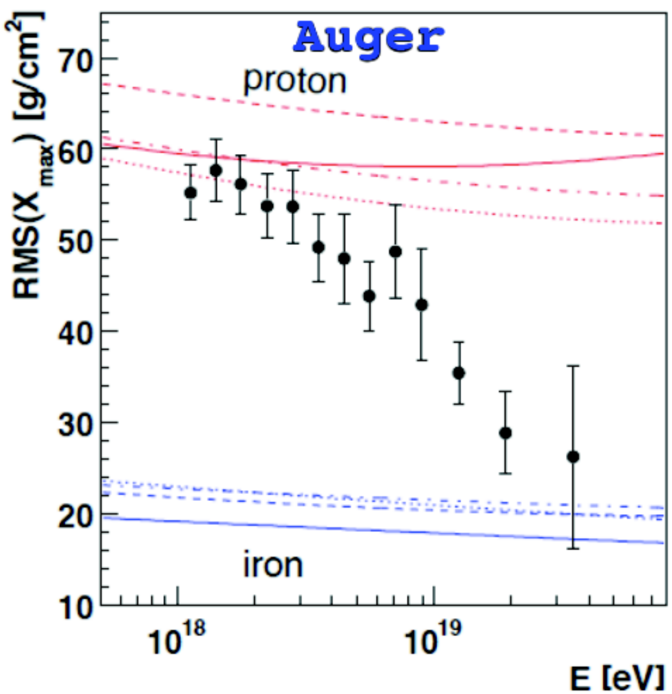


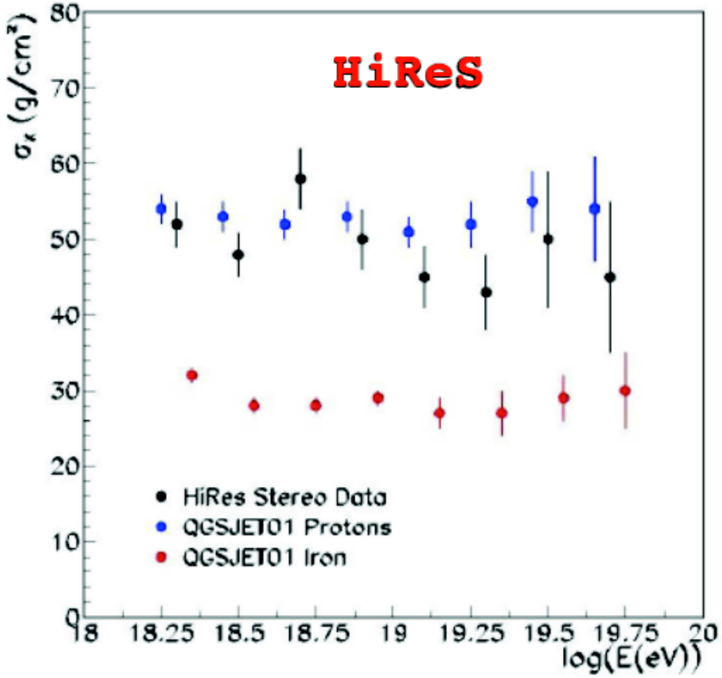
Fits light to heavier

HiRes vs Auger

Mass composition

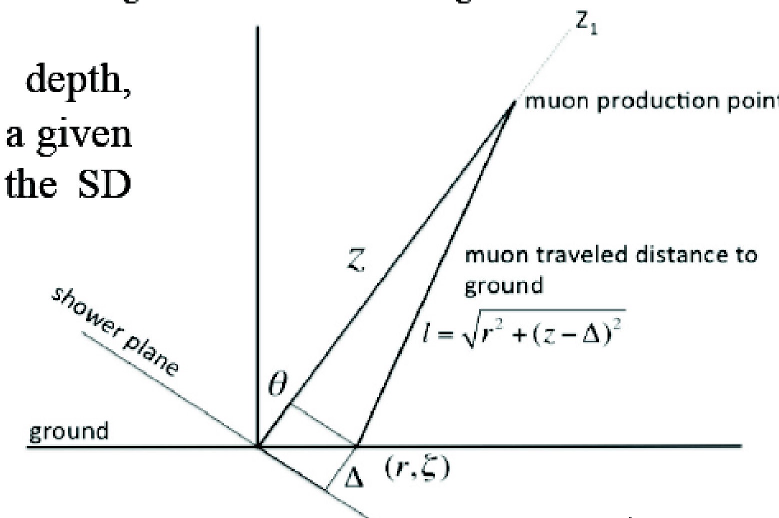




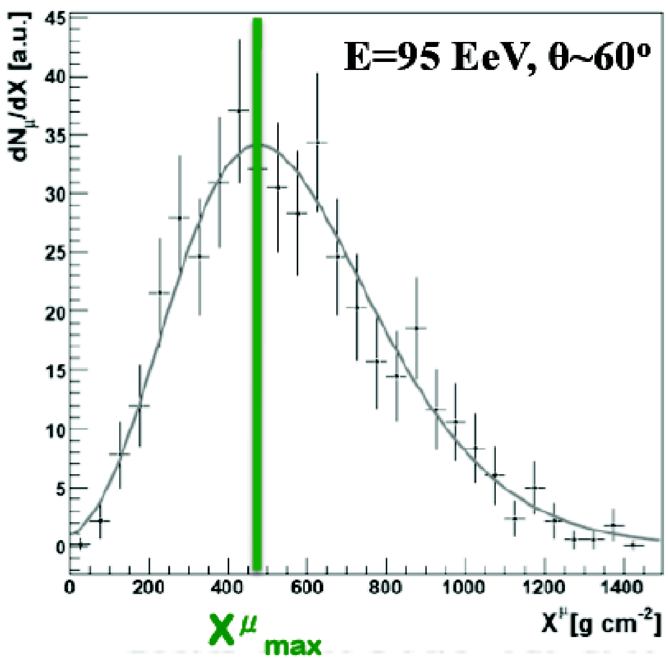


Muon Production Depth

Muons are produced within a narrow cylinder centered at the shower axis. They travel along straight lines, practically unaffected by multiple scattering and bremsstrahlung.



Muon Production Depth (MPD): the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals.



t_g, geometrical delay: the time difference between the arrival time of the muon and that of the time-reference shower plane.

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

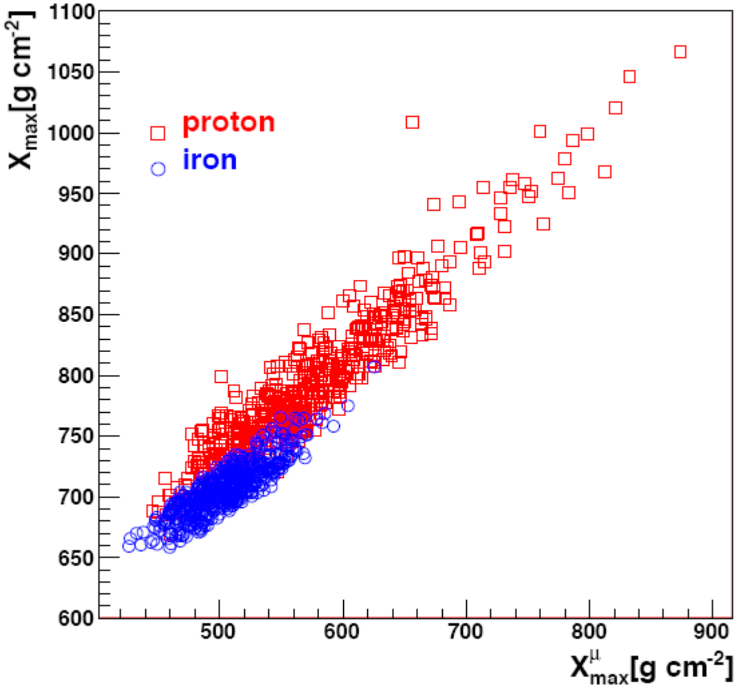
Event selection:

- $55° < \theta < 65°$
- $r > 1800$ m
- $E > 20$ EeV
- Gaisser-Hillas fit ⇨ X^μ_{max} (depth of maximum number of produced muons)
- Systematic uncertainty ≤ 11 g/cm^2

M.Monasor at TeVPa 2011

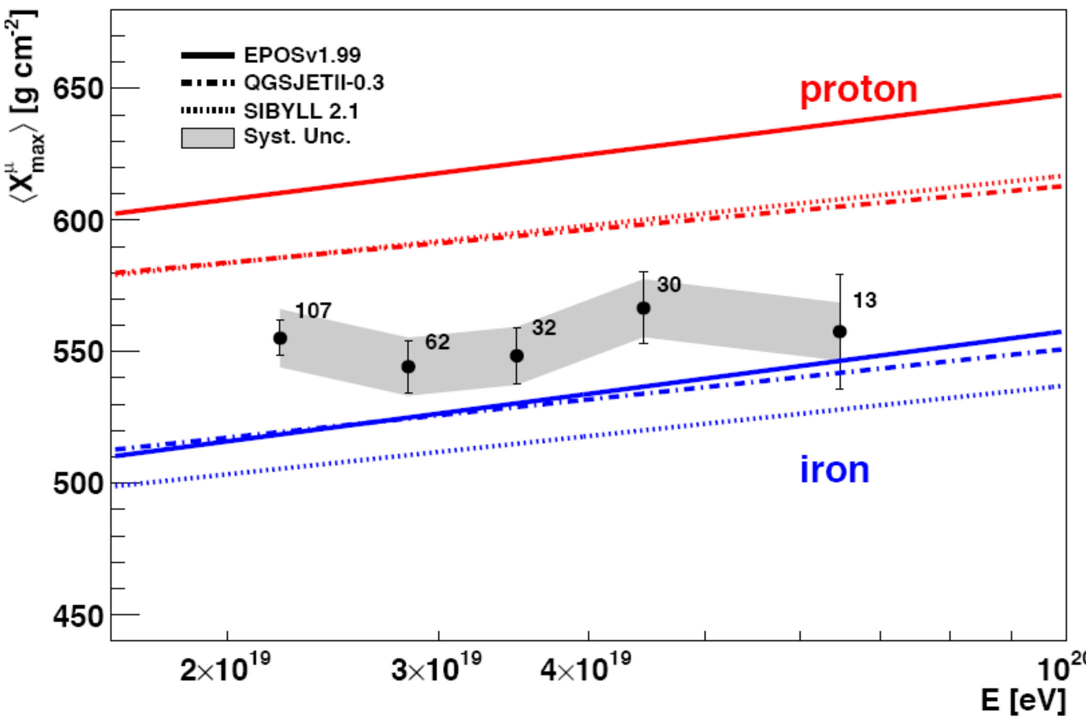
Mass Composition: X^{μ}_{max}

X^{μ}_{max} vs X_{max}



- MC hybrid events
- Correlation with X_{max}

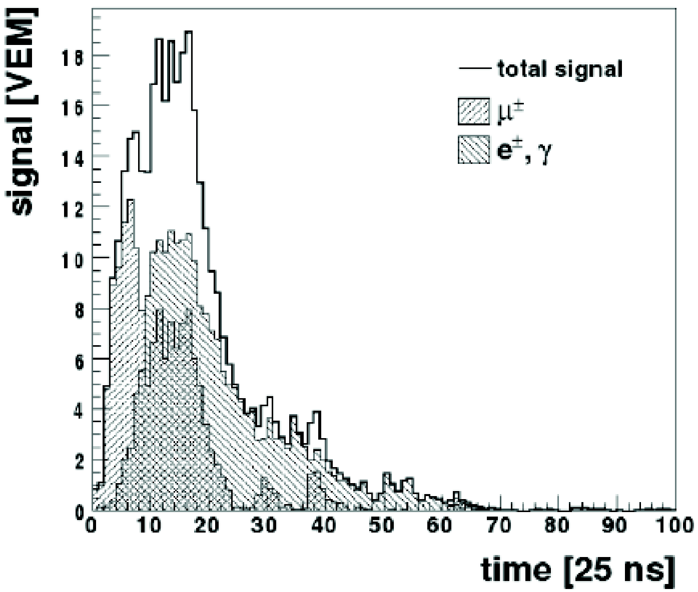
$\langle X^{\mu}_{max} \rangle$ vs E



- 244 SD events (Jan 2004 – Dec 2010)
- E > 20 EeV 55° < θ < 65°

Composition using the azimuthal asymmetry in SD signals

The time structure of SD signals has information about shower development:



μ: less interacting. Dominate first portion of the signal.

EM: multiple scattering. Spread out in time.

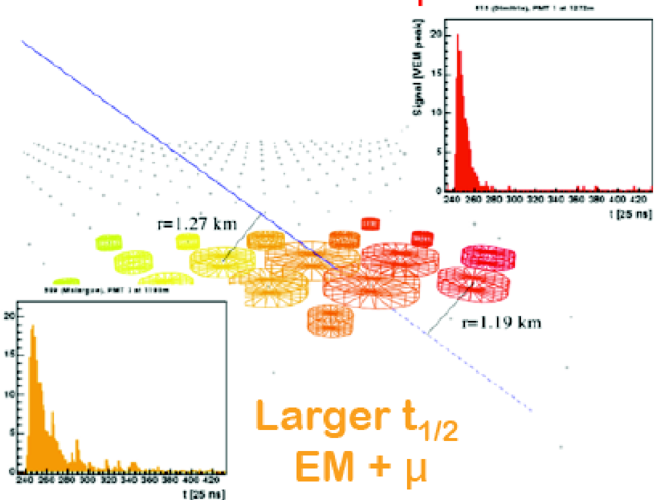
Risetime ($t_{1/2}$): time required to go from 10% to 50% of the total signal.

For non-vertical showers particles striking detectors in the different regions will have different stages of development because of the different path travelled.

LATE REGION

Shorter $t_{1/2}$

μ dominated

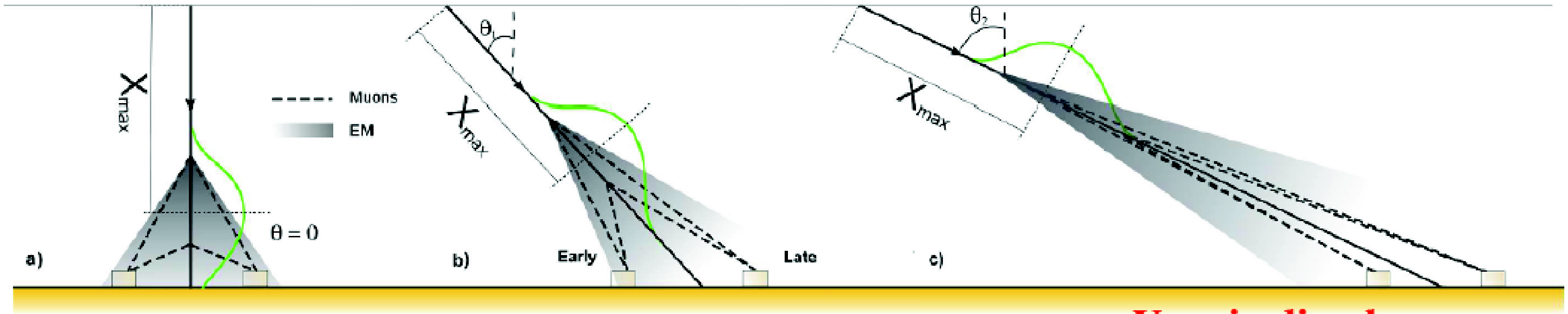


Larger $t_{1/2}$

EM + μ

EARLY REGION

Azimuthal asymmetry in SD signals



Vertical

symmetry in the signals

Inclined

asymmetry!!

Very inclined

no asymmetry

The early-late asymmetry as function of the zenith angle is expected to have a maximum which is correlated with X_{max}

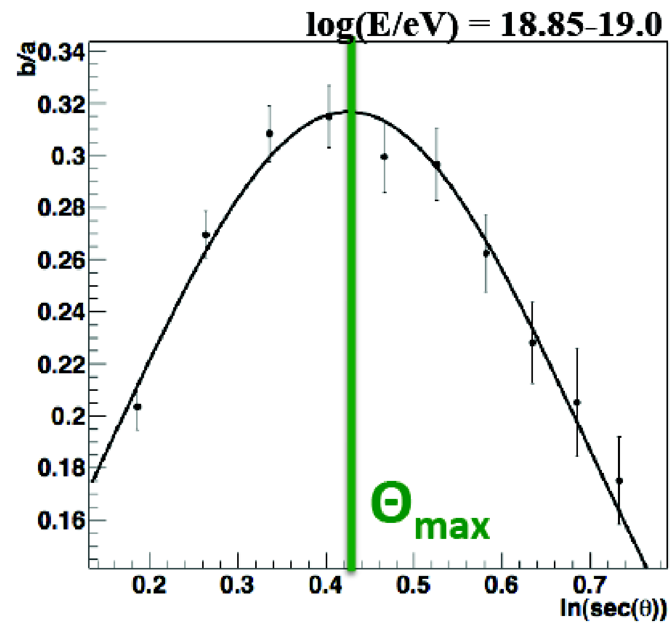
Observable: Θ_{max} : secθ for which b/a is maximum

Different primaries will have different asymmetry profiles.

Event selection:

- $30^o < \theta < 60^o$
- $500\ m < r < 2000\ m$

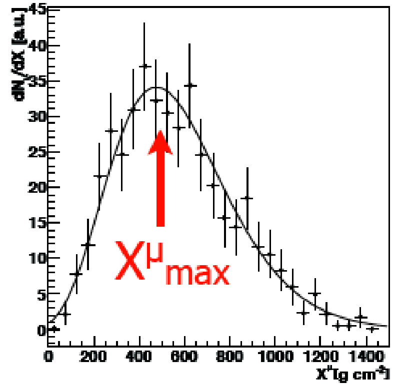
$$\langle t_{1/2}/r \rangle = a + b\cos\zeta$$



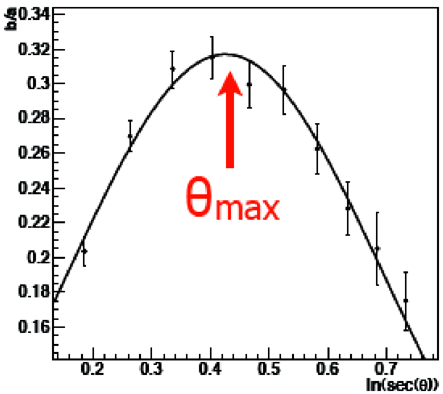
Systematic uncertainty ≈ 10% of p-Fe separation

Comparison of Methods

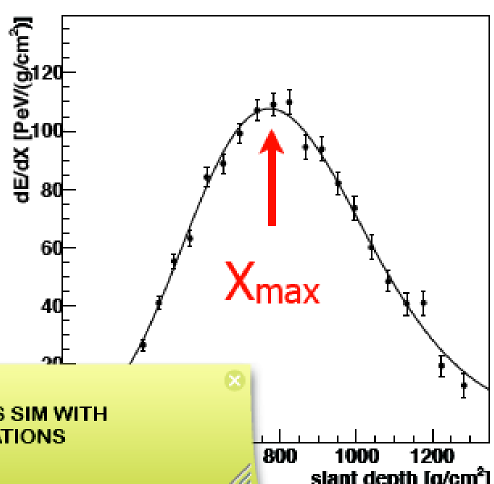
#709: Garcia Pinto



Muon Production Depth from timing differences

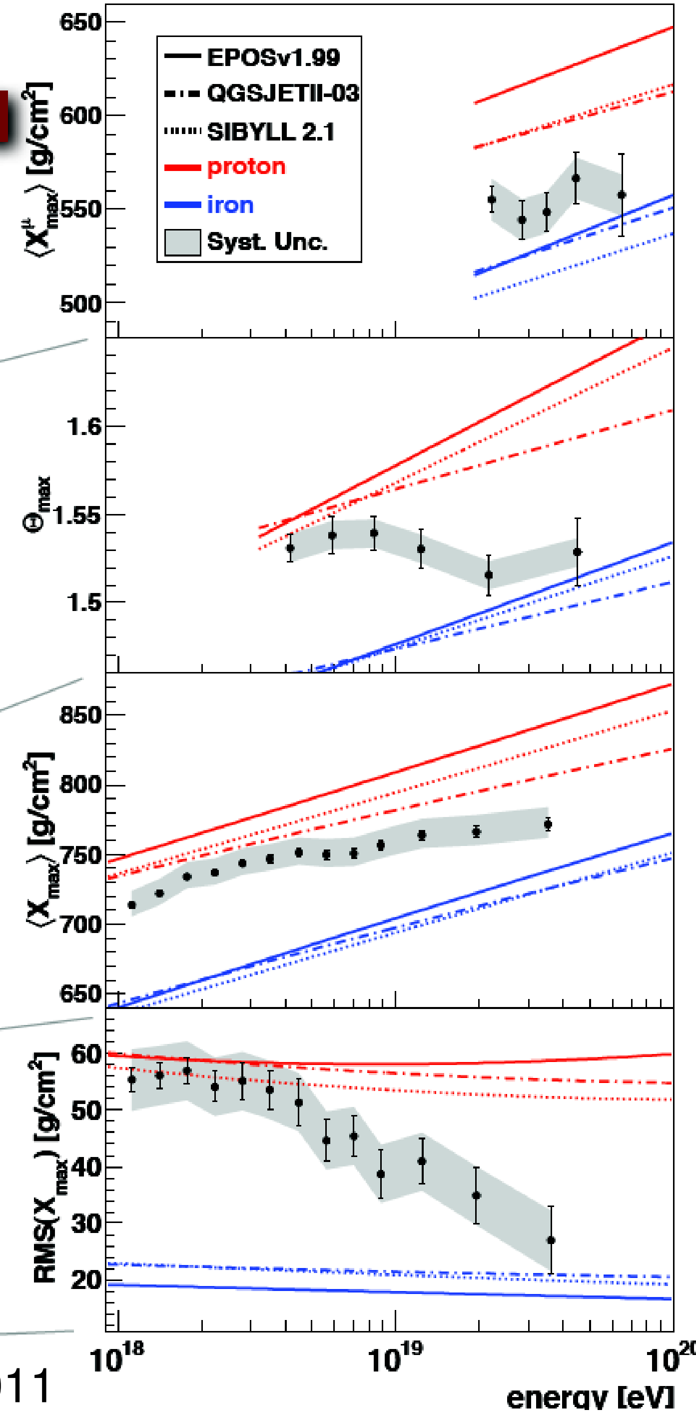


Shower Maximum from asymmetry of rise times



X_{max} from FD

RMS(X_{max}) from FD



PERHAPS SIM WITH
FLUCTUATIONS

K.H. Kampert @ICRC2011

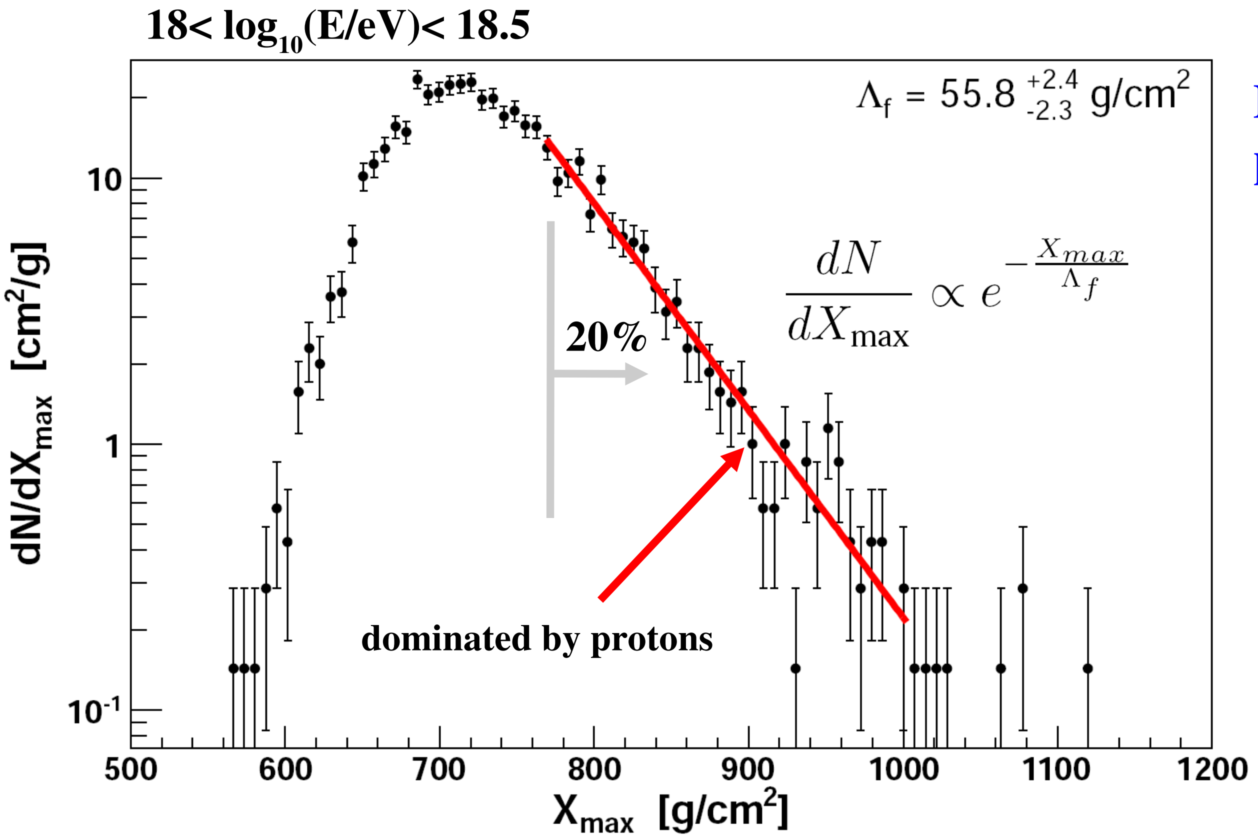
Results

- Energy spectrum
- Mass composition
- **Hadronic Interactions**
- Search for photons and neutrinos
- Astrophysics

Measurement of the p-air cross-section

Tail of the distribution of <X_{max}> sensitive to cross-section

Fly's Eye → Ellsworth et al. Phys. Rev. D26 (1982) 336
Baltrusaitis et al. Phys. Rev. Lett. 52 (1984) 1380



Dedicated analysis to select a proton-enriched data sample

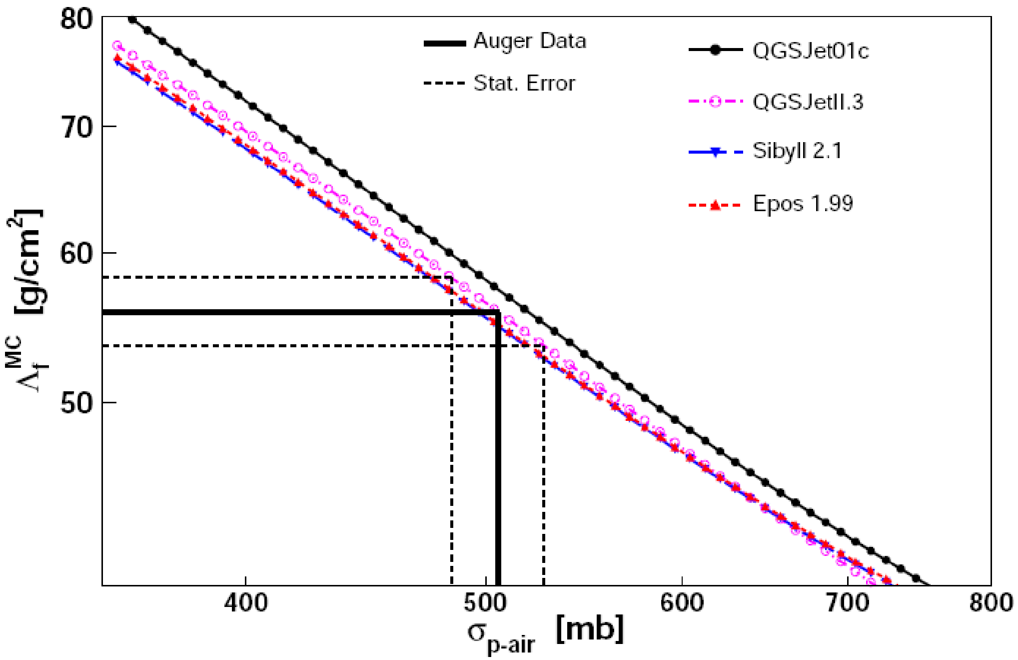
Why 20%?
15% helium contamination produces a bias at the level of the statistical uncertainties

Use simulations to correlate Λ_f^{MC} with cross-sections

Λ_f^{MC} adjusted to reproduce the measured Λ_f

R. Ulrich @ **ICRC 2011**

Retrieving cross-sections



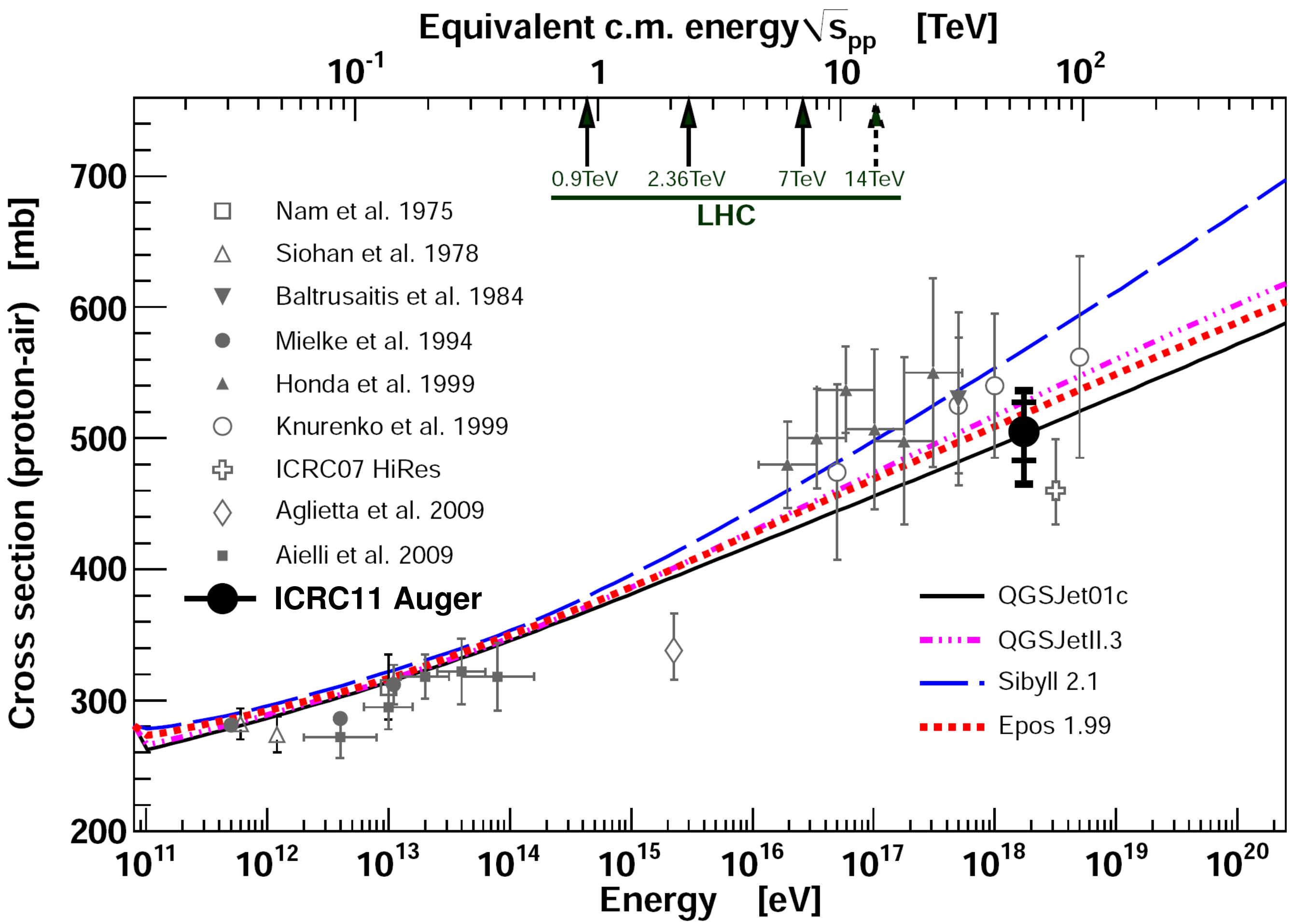
Correlation between Λ^{MC} and true cross-sections for different models

This method relies on simulations

Model	Rescaling factor at $10^{18.24}$ eV	σ_{p-air}/mb
QGSJet01	1.04 ± 0.04	524 ± 23
QGSJetII.3	0.95 ± 0.04	503 ± 22
SIBYLL 2.1	0.88 ± 0.04	497 ± 23
EPOS 1.99	0.96 ± 0.04	498 ± 22

$$m(E,\ f_{19}) = 1 + (f_{19} - 1)\,\frac{\lg\left(E/10^{15}\,\mathrm{eV}\right)}{\lg\left(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV}\right)},$$

Corrections to be applied to simulations (i.e. on true cross-sections) in order to match the measured Λ



Energy well above the LHC measurements

Systematic Uncertainties

- hadronic models
- energy scale
- simulations

Total: -15 mb, +20 mb

$$< E > \sim 1.7 \text{ EeV} \qquad \sqrt{s} = 57 \text{ TeV}$$

$$\sigma_{\text{p-air}} = (505 \pm 22_{\text{stat}} (^{+26}_{-34})_{\text{syst}}) \text{ mb}$$

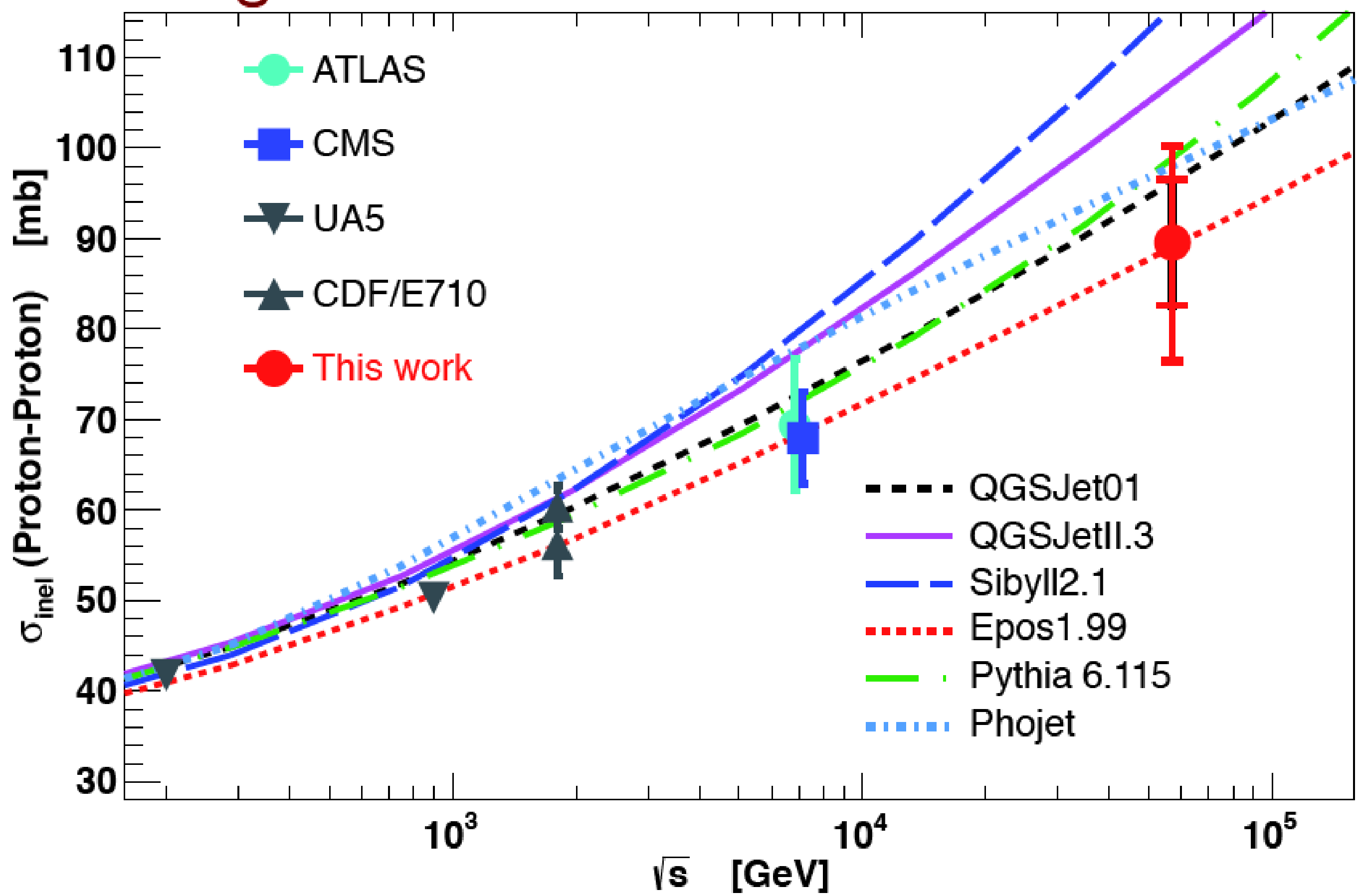
Additional Uncertainties due to diverse contaminations:

- **photon fraction 0.5% +10 mb**
- helium fraction 10% -12 mb
- **helium fraction 25% -30 mb**

p-p Cross Section at √57 TeV

#946: Ulrich

using Glauber model

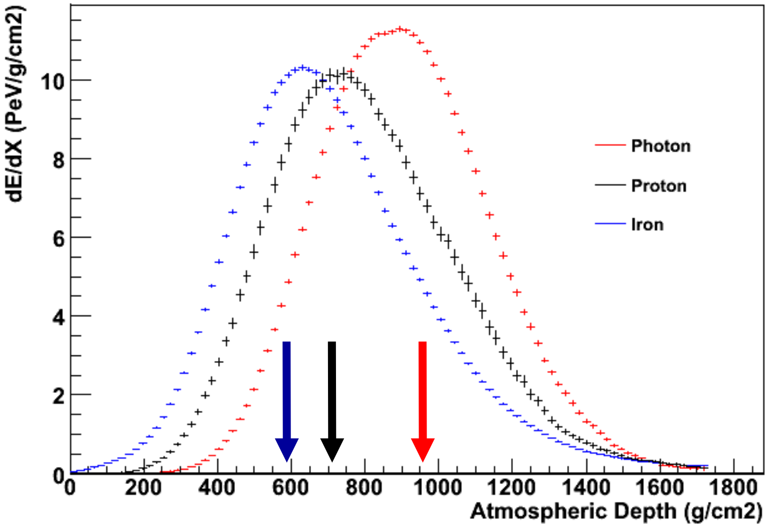


$$\sigma_{pp} = (90 \pm 7_{stat} \, (^{+8}_{-11})_{sys} \pm 1.5_{Glauber}) \text{ mb}$$

Results

- Energy
- Mass composition
- Hadronic Interactions
- **Search for photons and neutrinos**
- Astrophysics

Search for photon primaries

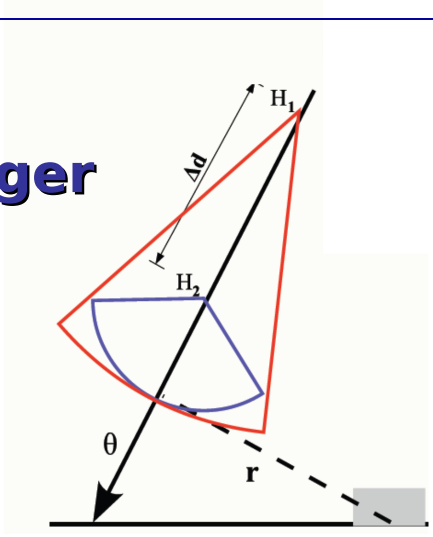


Photon showers develop deeper in the atmosphere

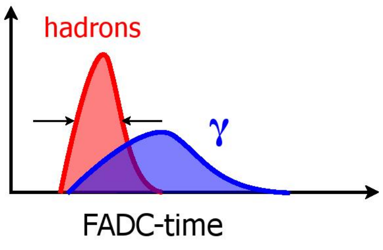
FD: search for events with deep Xmax

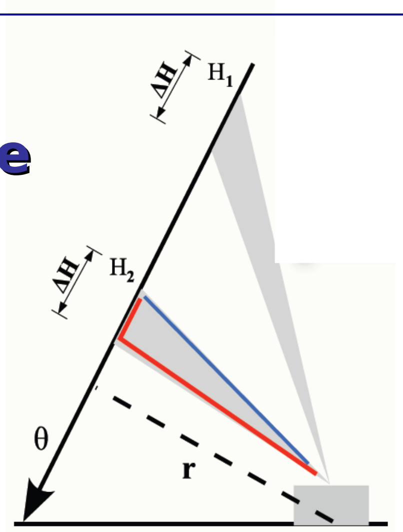
SD: search based on signal time structure

Deeper showers larger curvature

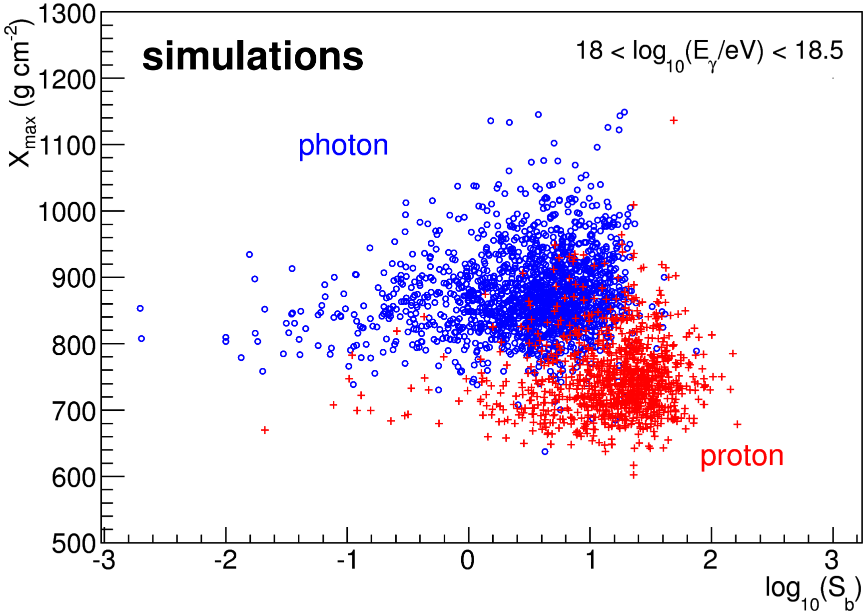


Slower signal, longer risetime





(hybrid) photon/hadron separation

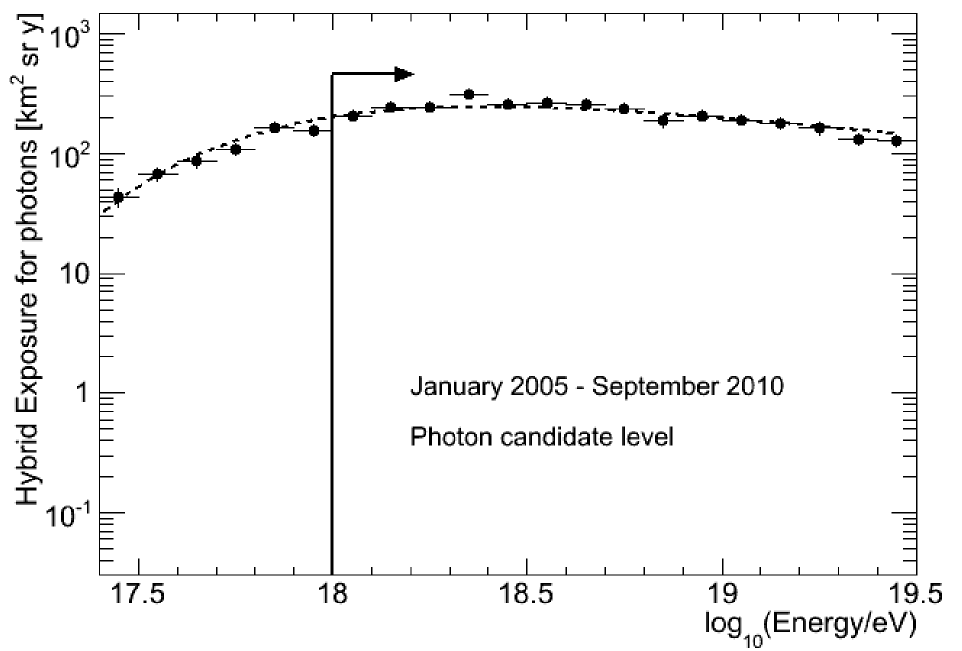


signal amplitude

- deep shower
large X_{max} (from **FD**)

- structure of the LDF
different time structure and smaller signal (from **SD**)

Hybrid Exposure for photons



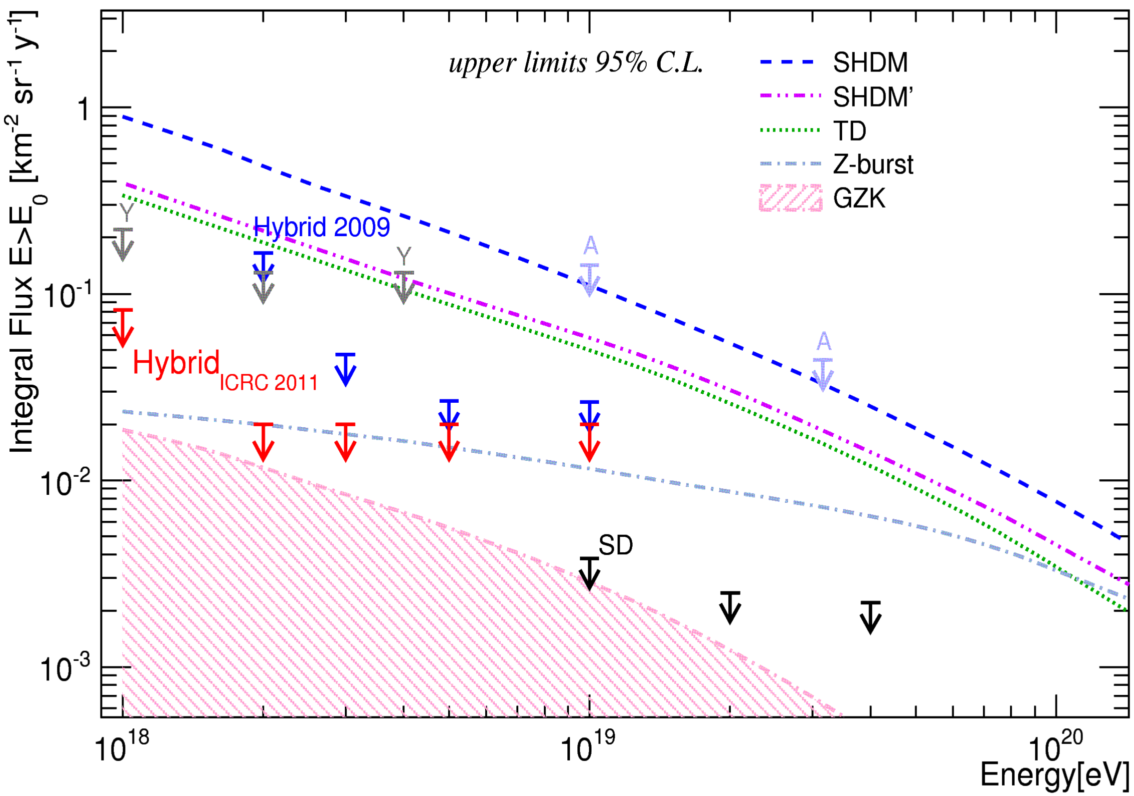
Realistic and time dependent

actual DAQ and atmospheric conditions taken into account (same approach used for the hybrid spectrum)

Proton background less than 1%

Upper limit to the integral photon flux

M. Settimo @ **ICRC 2011**



flux and fraction upper limits down to the EeV region

top-down models severely constrained

- favour astrophysical origin of UHECR
- reduce systematics in measurements of energy spectrum, p-air cross section, mass composition

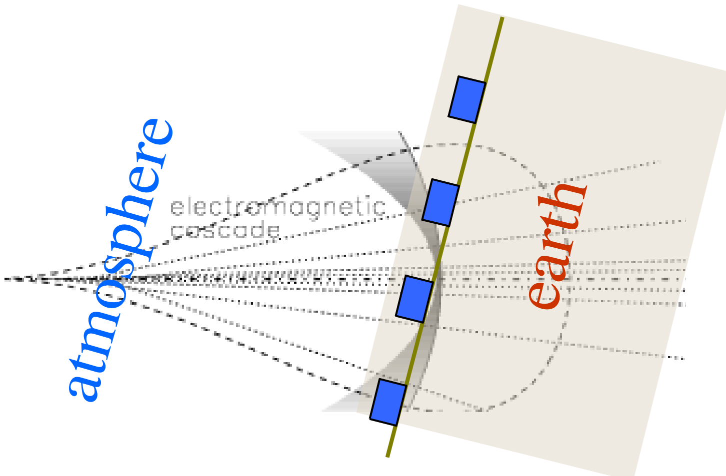
Upper limits to the integral photon fraction assuming the Auger Spectrum

0.4%, 0.5%, 1.0%, 2.6% and **8.9%** for E> **1, 2, 3, 5 and 10 EeV**

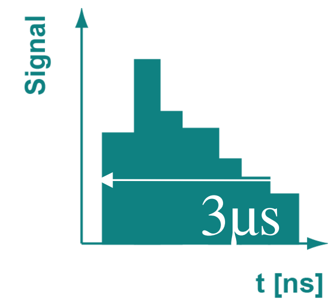
Number of candidates
6, 0, 0, 0, and 0 for E> 1, 2, 3, 5 and 10 EeV

GZK region within reach in the next years

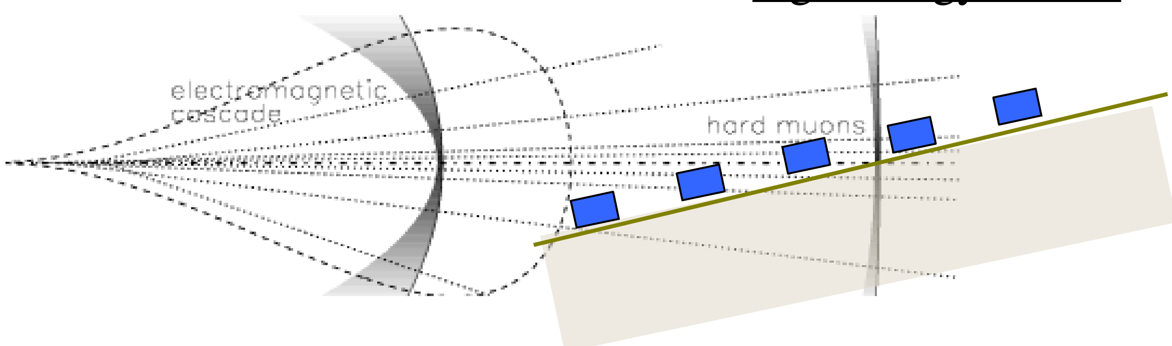
Search for neutrinos

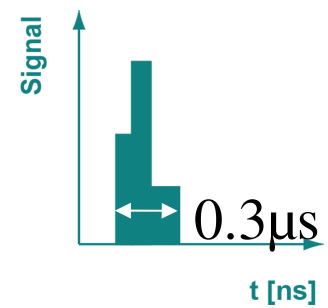


Almost vertical
muons + electromagnetic



Very inclined, thin flat front
high energy muons

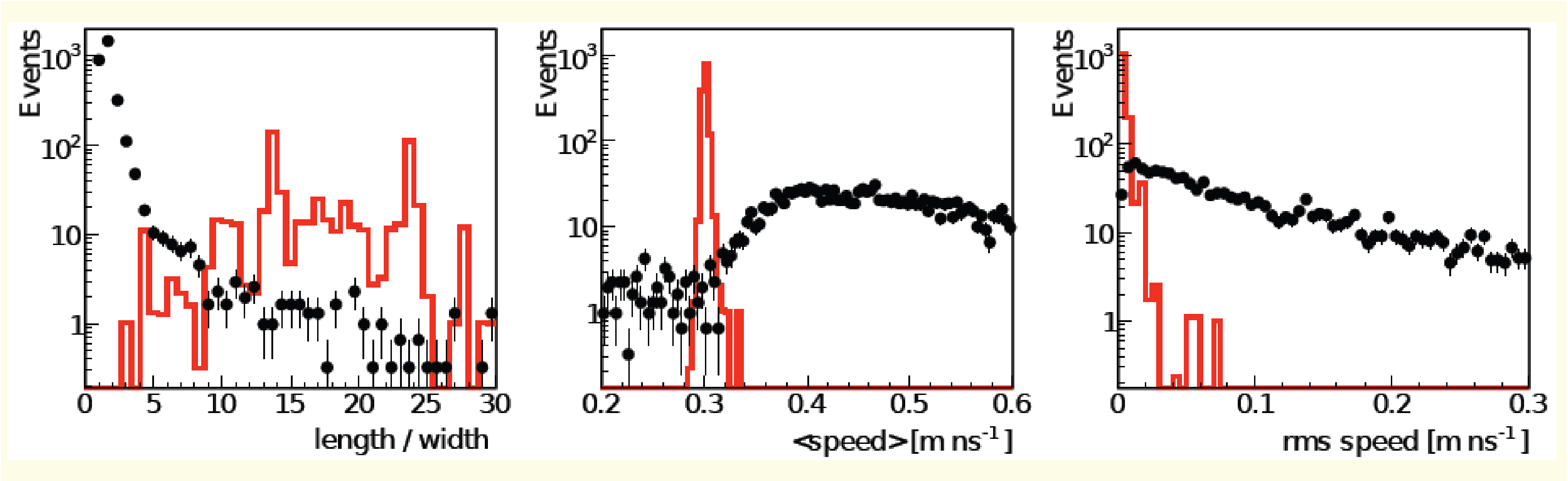




Important for neutrino detection: observable only if almost horizontal

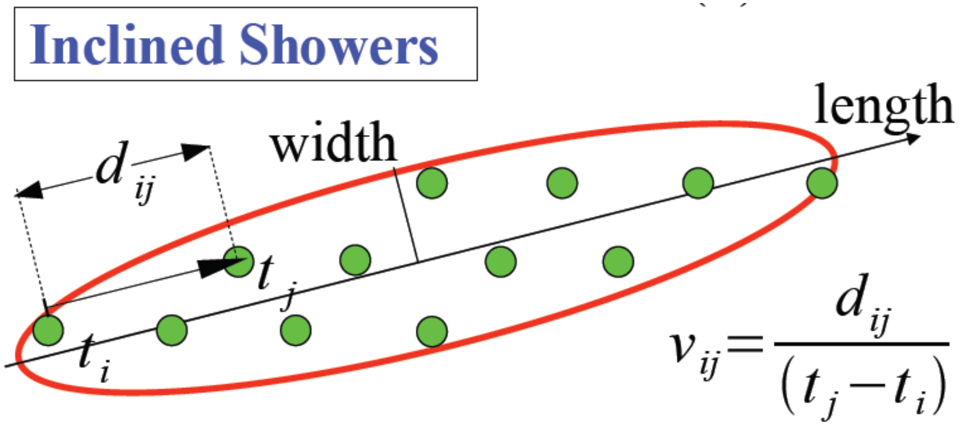
Neutrino signature: an inclined shower with large electromagnetic component

Neutrino-like event selection



Data

Simulated neutrino signal



Earth-skimming

Length/width >5

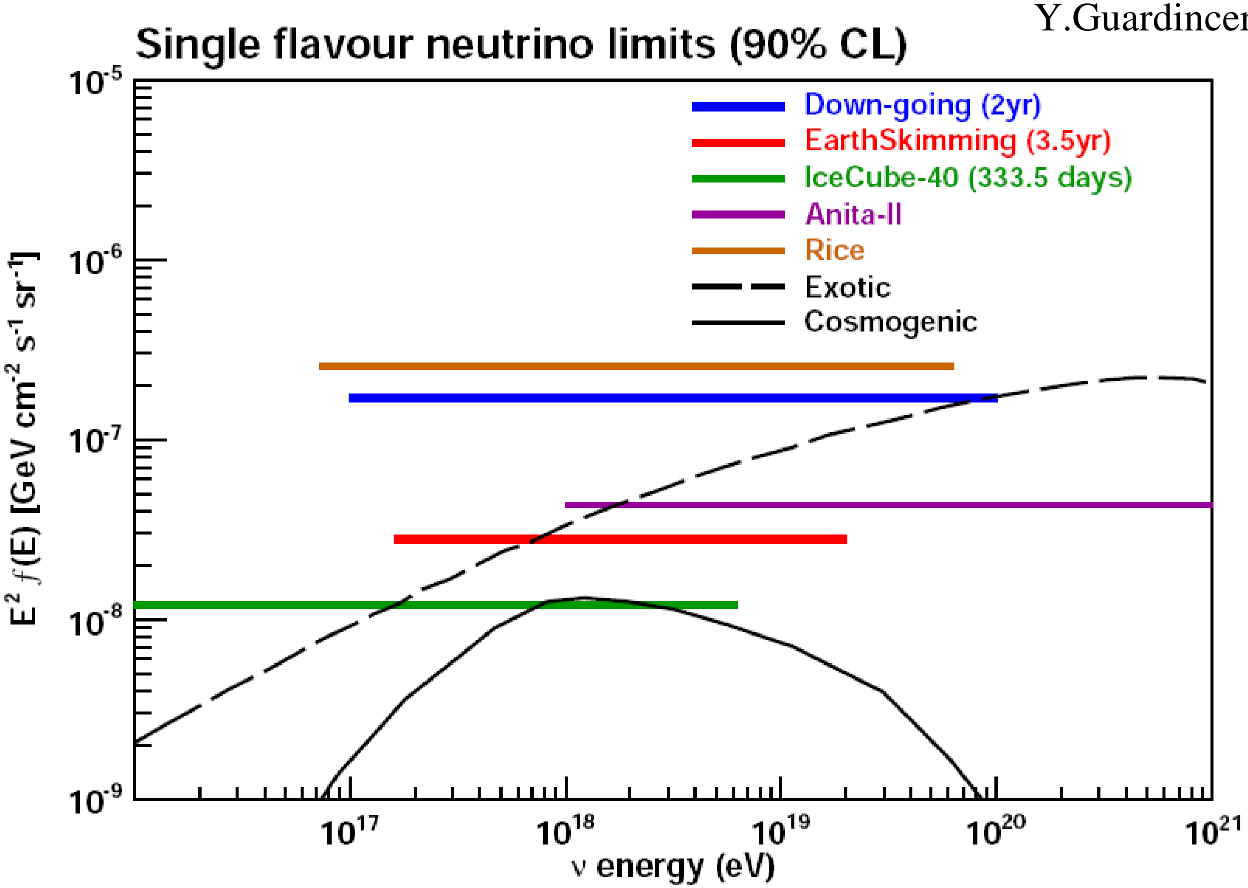
0.29< speed < 0.31 m/ns

rms< 0.08 m/ns

Similar selection rules for down-going

pper limit on the diffuse neutrino flux

Y.Guardincerri @ **ICRC 2011**



$k < 2.8 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} **in** 1.6×10^{17} eV $< E < 2.0 \times 10^{19}$ eV

$k < 1.7 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} **in** 1×10^{17} eV $< E < 1 \times 10^{20}$ eV

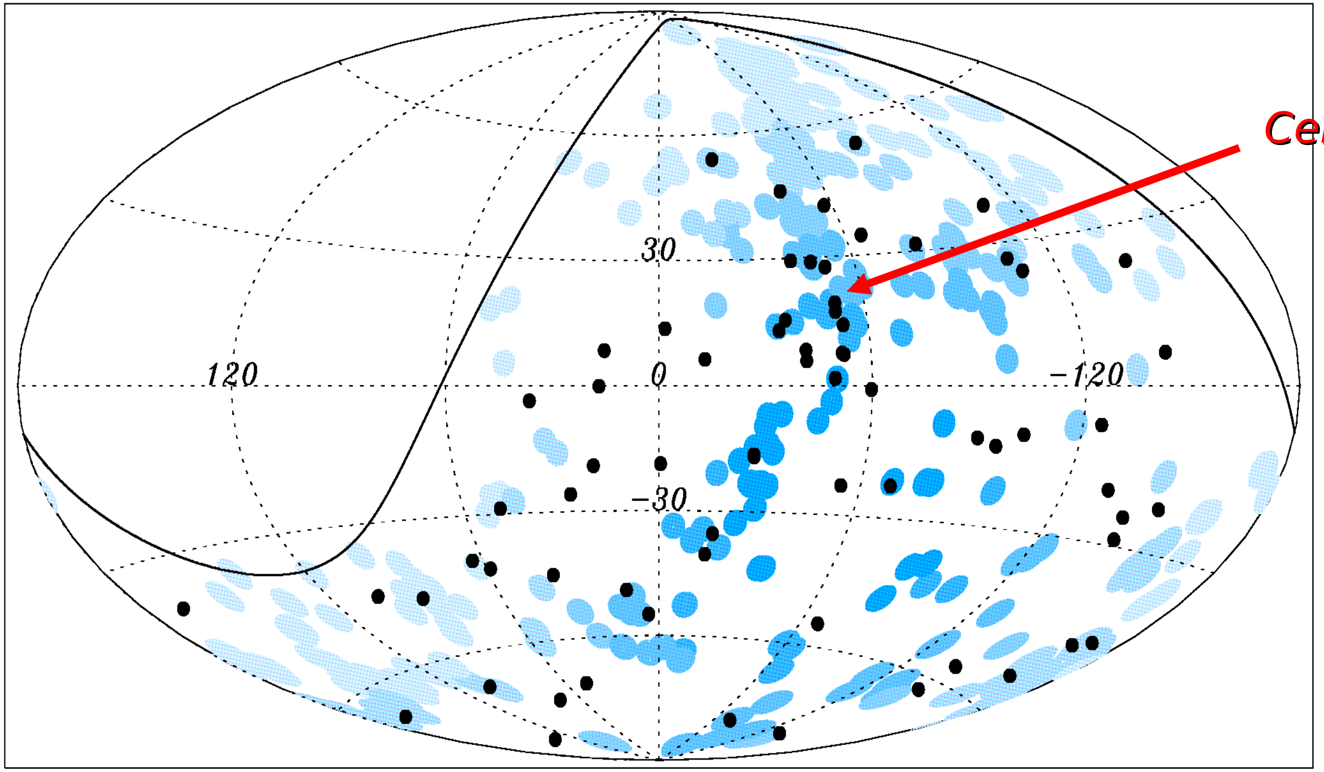
Results

- Energy spectrum
- Mass composition
- Hadronic Interactions
- Search for photons and neutrinos
- **Astrophysics**

Anisotropy at the highest energy

Astropart. Phys. 34 (2010) 314

Jan 2004
Dec 2009

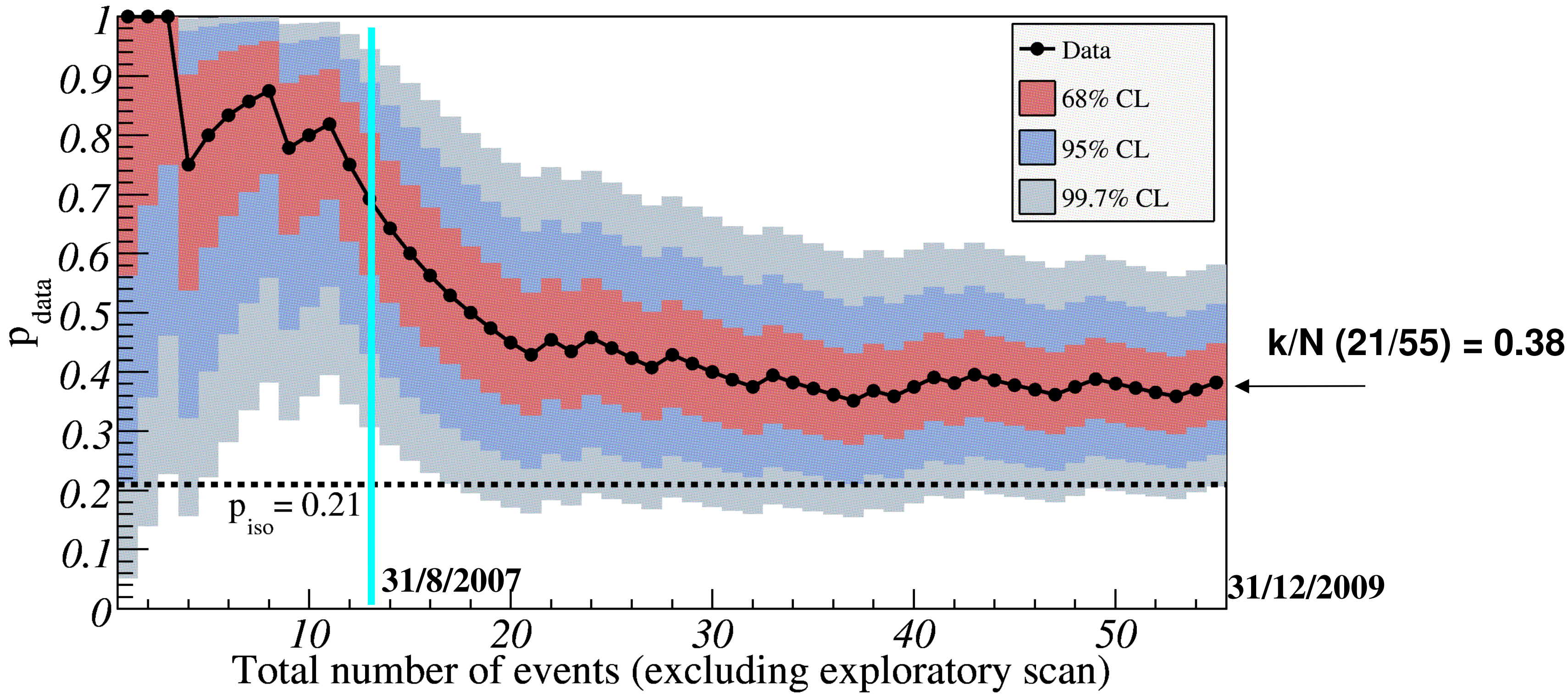


The 69 events with Energy > 55 EeV detected by the Pierre Auger Observatory
Blue circles of radius 3.1° centered at the positions of the 318 AGNs < 75 Mpc in the VCV catalog. The exposure-weighted fraction of the sky covered by the blue circles is 21% (fraction of correlating events under the hypothesis of isotropy)

Limitations of the catalogue: incomplete and inhomogeneous

Degree of correlation

Astropart. Phys. 34 (2010) 314



Degree of correlation p_data = k/N vs total number of time-ordered events:
the 68%, 95% and 99.7% confidence level intervals around the most likely value are shaded. The isotropic value is p_iso = 0.21. The current estimate of the signal is 0.38 (+0.07, -0.06).

Facts and open issues

- the degree of correlation has decreased (from 69% to 38%)
- probability from an isotropic distribution ~ 3 10^{-3}
- with the current degree of correlation about four years of new data are required for a 5 σ significance

Anisotropy consistent with a proton based composition

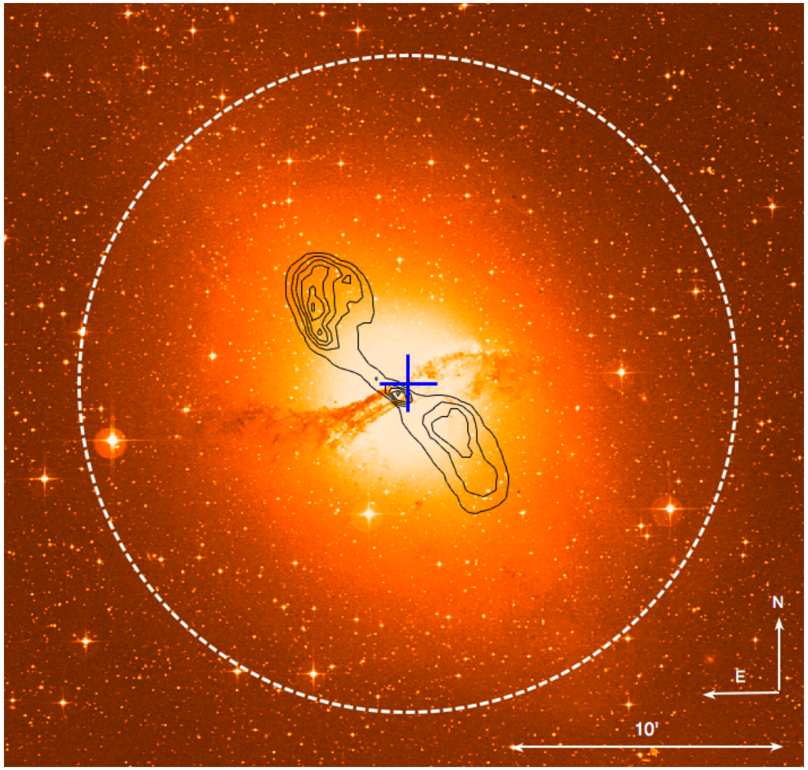
Xmax measurement suggest mixed composition (though not measured for E>55 EeV)

Anisotropy not confirmed by HiRes (lower statistics, northern Hemisphere)

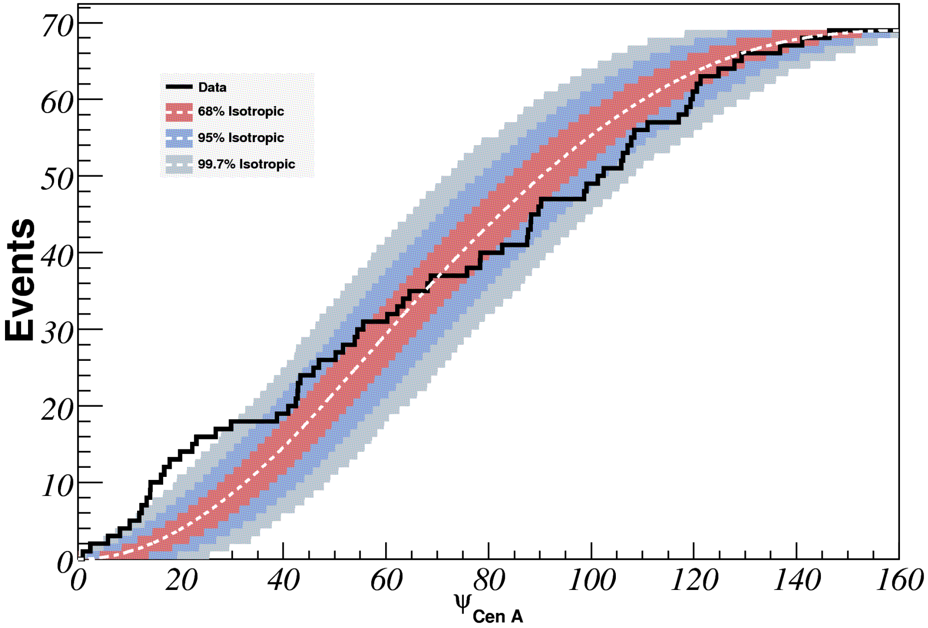
TA has a similar degree of correlation: 40% (8/20) con p_{iso}=25%

Centaurus A

Astropart. Phys. 34 (2010) 314



CEN A: optical image, radio contours (VLA), VHE best fit position and 95% C.L. (HESS). From http://arxiv.org/pdf/0903.1582v1



Cumulative number of events with energy E>=55 EeV as a function of angular distance from the direction of Cen A.

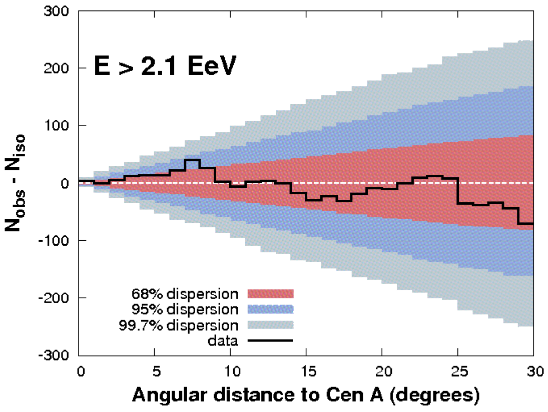
The bands correspond to the 68%, 95%, and 99.7% dispersion expected for an isotropic flux. 13 events fall in this area (18°) vs. 3.2 expected from isotropic flux.

Anisotropy and chemical composition

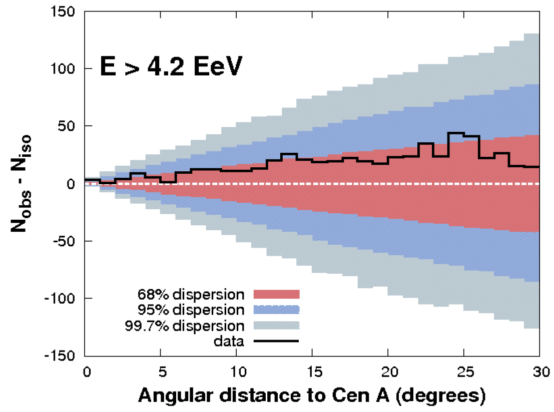
If the excess at E_{thres} > 55 EeV is due to nuclei (Z), the proton counterpart should be observed at energy above E_{thres}/Z

Lemoine & Waxman JCAP 11 (2009) 009

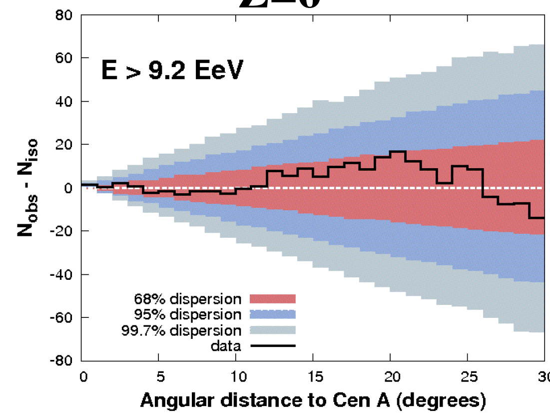
Z=26



Z=13

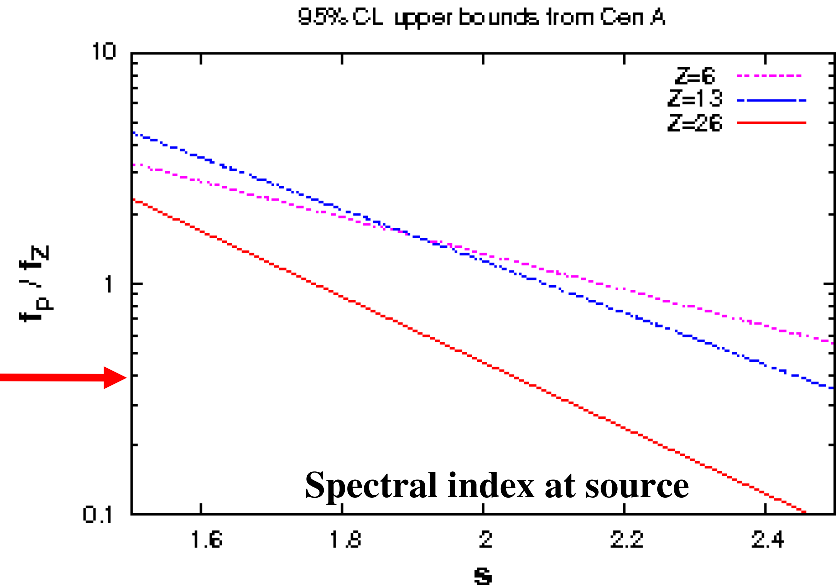


Z=6



No excess observed from CEN A at lower energies

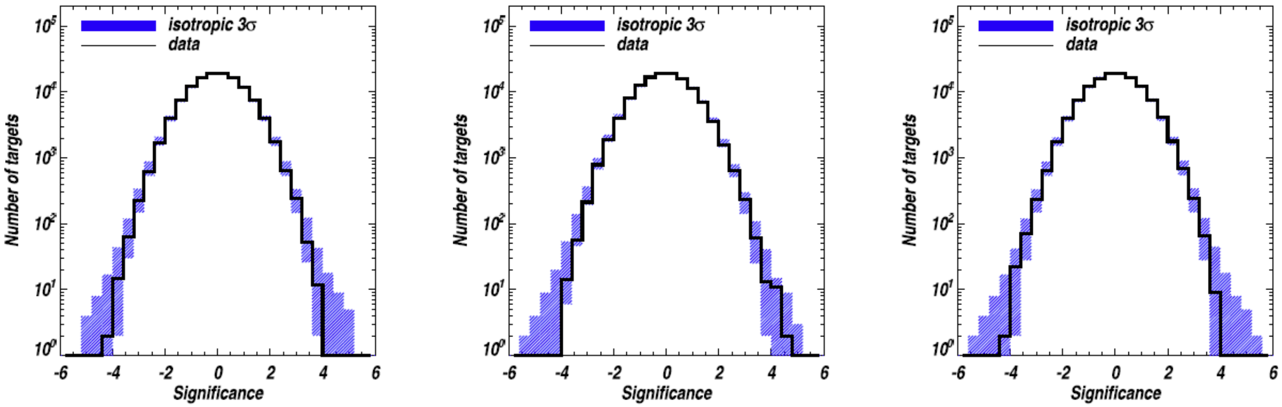
Upper limit to the proton fraction at the source (within the model assumption)



The Pierre Auger Collaboration, JCAP06 (2011) 022

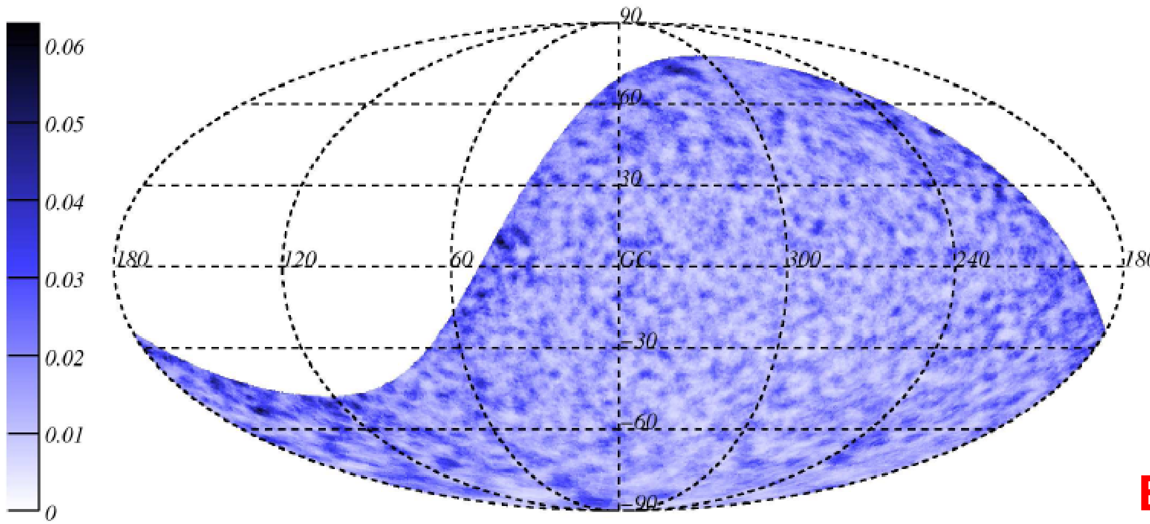
Search for neutron point-sources

Neutron mean decay length: $\lambda_n = (9.2 \times E)$ kpc $\longrightarrow$ **They could arrive from GC**



No significant excess observed

Upper limits 95% CL ($km^{-2}yr^{-1}$)



Galactic coordinates

E > 1 EeV

Enhancements and future plans

Extension towards the lower energies

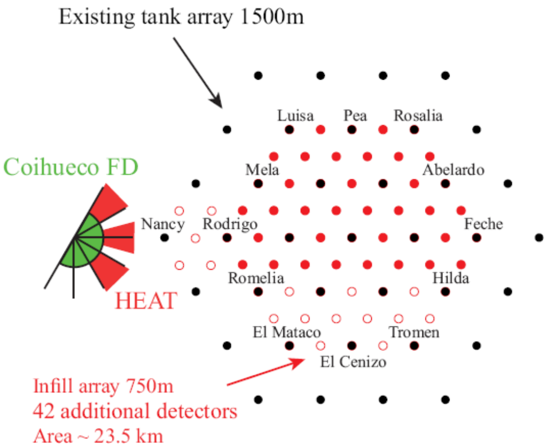
- improve detector performance at the transition to extragalactic component between ~10^{17} and 10^{18} eV (HEAT and AMIGA)
- cross calibration with other experiments

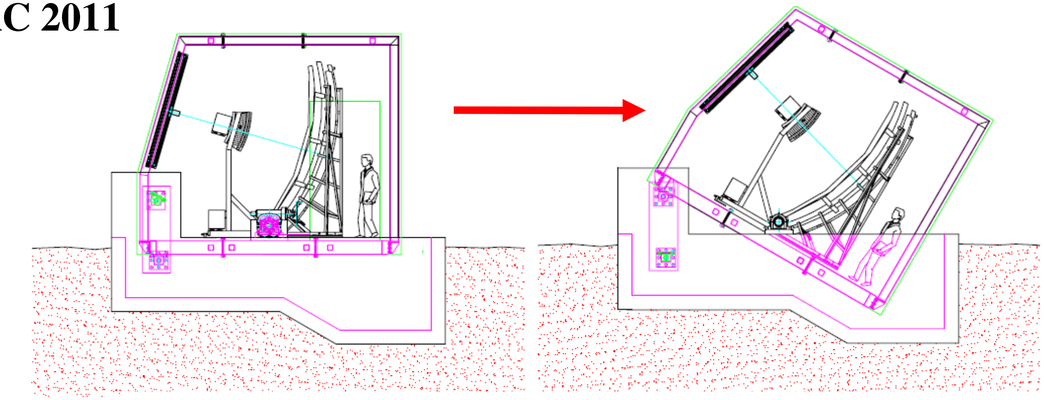
The Pierre Auger Observatory as an ideal site to test and develop new detection techniques

- Radio detection (AERA)
- Microwave detection (several projects)

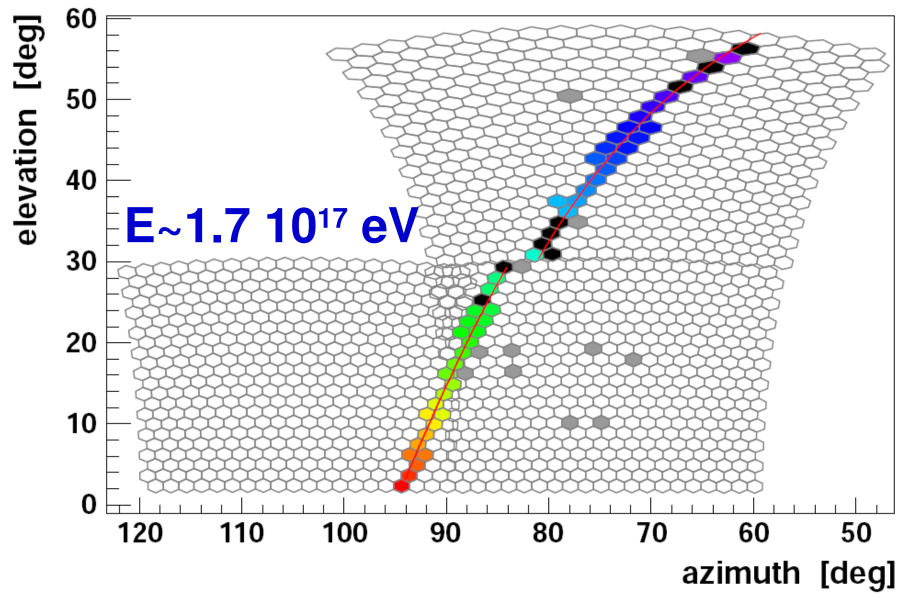
FD Auger enhancement: HEAT

H-J Mathes @ **ICRC 2011**





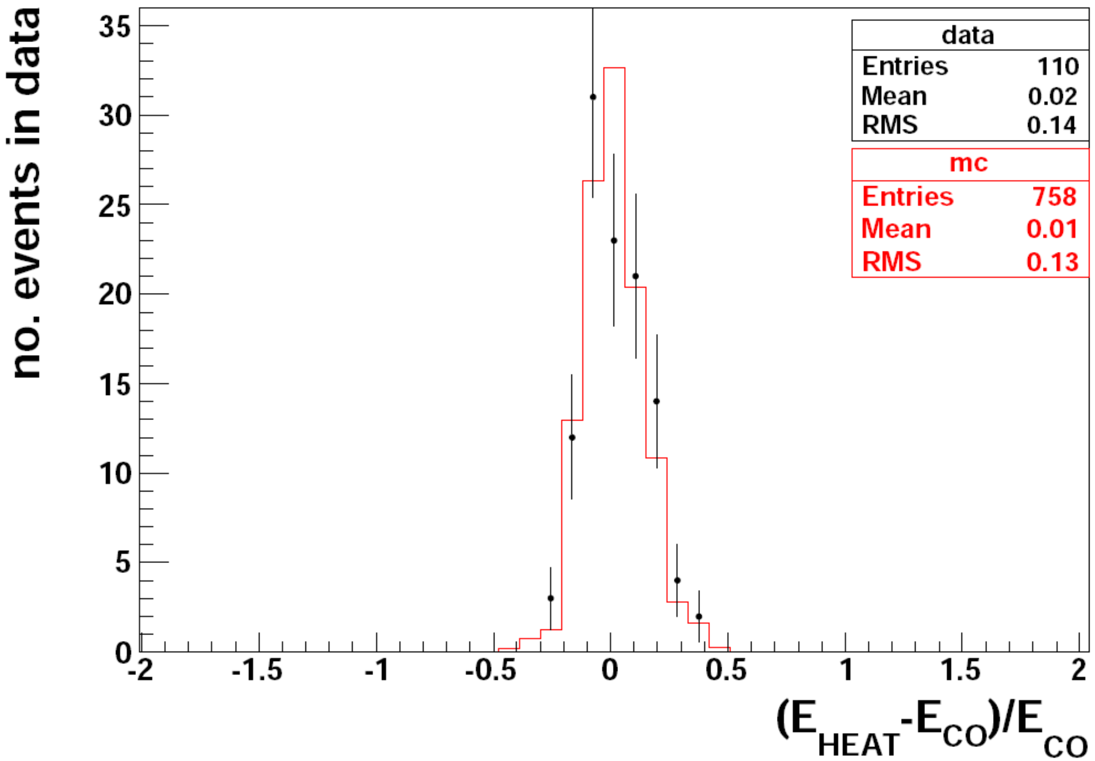
3 telescopes nearby Coihueco
30° up to 60° elevation



Taking data since Sept. 2009

Higher elevation
lower energies (~ 10^{17} eV) unbiased observation of longitudinal profile

First data used for alignment and calibration



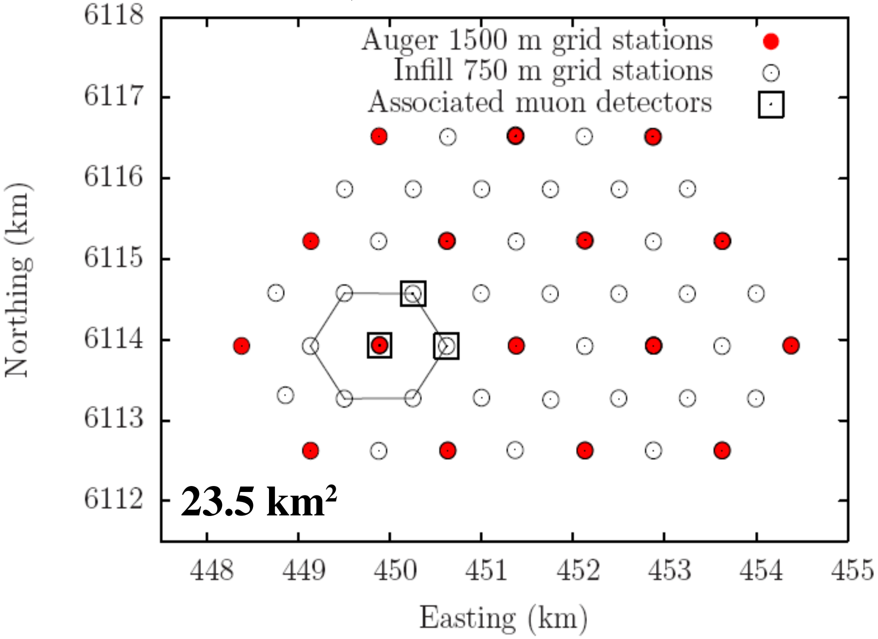
Energy reconstruction

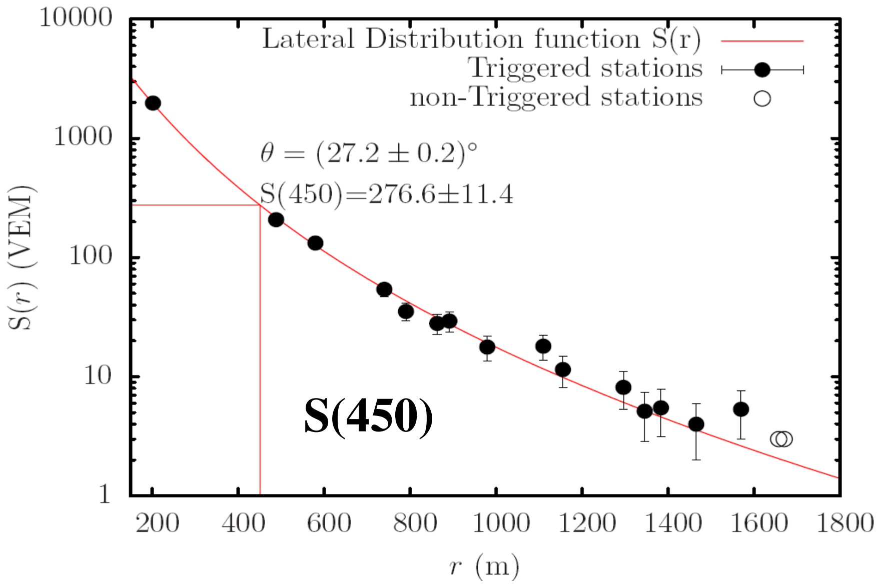
- cross-calibration of HEAT (working in downward mode) and Coihueco
- agreement with simulations

Plenty of new high-quality data are being collected

SD Auger enhancement: AMIGA

I.Maris, F. Sanchez @ **ICRC 2011**

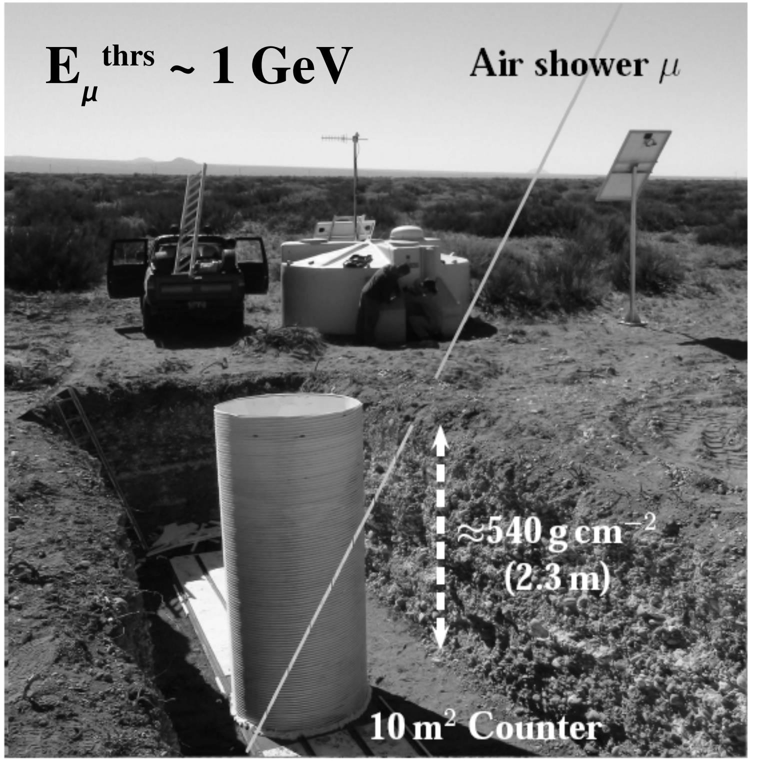




INFILL array (Cherenkov stations) and Muon detectors (scintillators)

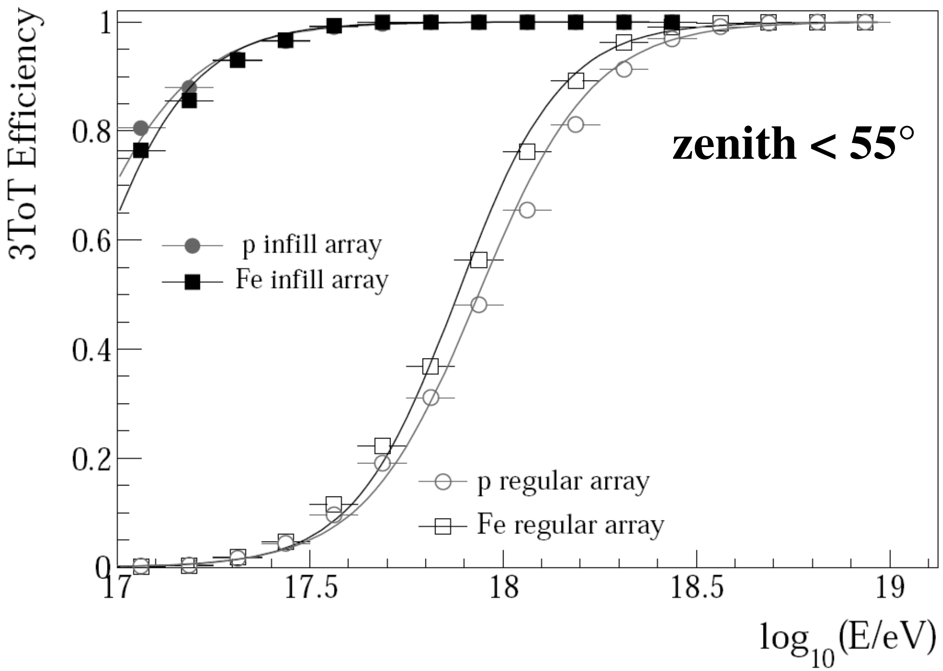
- 61 station with spacing 750 m deployed
- 4 buried scintillator modules installed

Exposure: (35.7 ± 1.3) km^2 sr yr



700 (20, 4) events/ month E > $10^{17.5\ (18,\ 18.5)}$ eV

Infill array performance



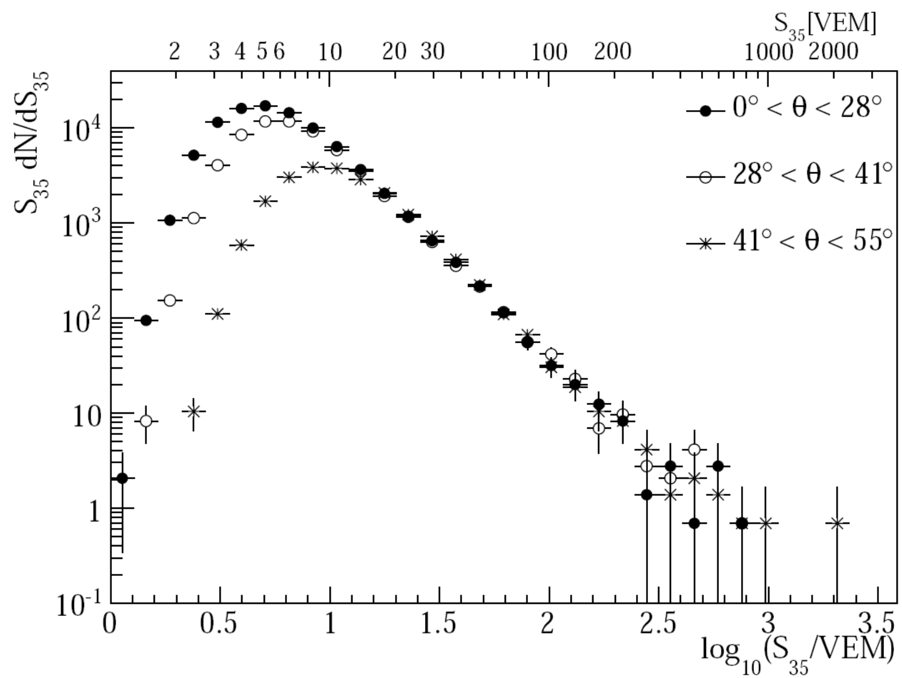
Full Efficiency above 3 10^{17} eV

Angular resolution

1.3° for at least four stations

1° for at least six stations

About 200.000 fiducial events collected



S(450) -> particle density at 450 m

- S35 corrected for the zenith angle dependence
- 22% (13%) uncertainty at 3 (10)VEM

Imminent result:

the energy spectrum down to 3 10^{17} eV

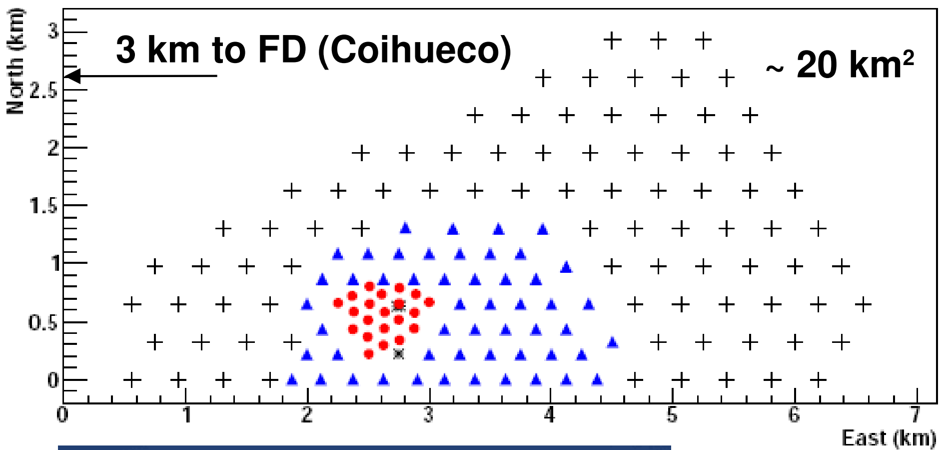
AERA: Radio detection

B. Revenu, J.L Kelley @ **ICRC 2011**

Observation of radio emission from electromagnetic cascade

- geomagnetic field
- charge separation

VHF band 10-100 MHz

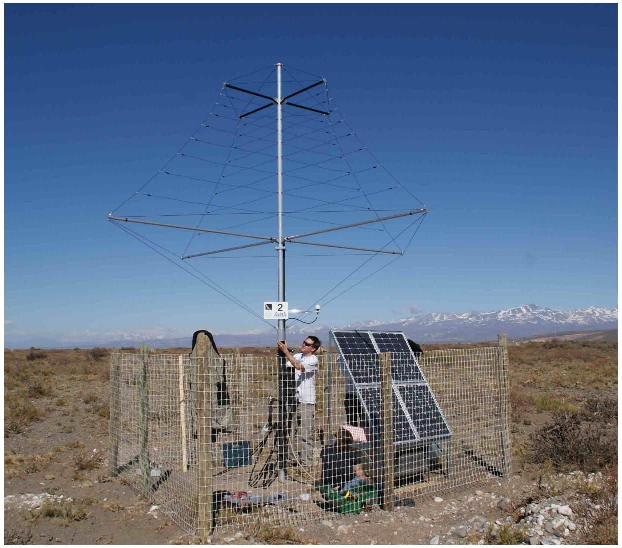


Deployed in 2010 (21 Radio stations, 150m)
stage 2 (250 m)
stage 3 (350 m)

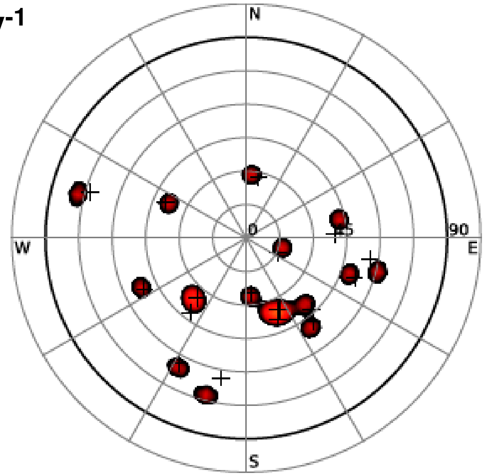
First physical radio-hybrid events

Radio/SD 0.5 day^{-1}

$E_{thres} \sim 10^{17}$ eV



Logarithmic periodic dipole antenna (two polarizations)



Polar plot, SD and radio reconstruction

First Radio/FD/SD super hybrid event observed

Microwave detection

Observation of microwave emission from electromagnetic cascade

Molecular Bremsstrahlung isotropic emission

P. Gorham et al., Phys. Rev. D, 2008, 78: 032007

Signal $\propto N_e^2$ quadratic scaling

Signal $\propto N_e$ linear scaling

~100% duty cycle – negligible atmospheric absorption

P. S Allison @ **ICRC 2011**

Radiometers in coincidence with SD

2.4 m off-axis parabola
C Band: 3.4 - 4.2 GHz
ku band: 10.95 14.5 GHz
Total FoV 7°x 7°
First test at Hawaii, then shipped to Argentina
Collecting first data

GhZ Antenna
C Band: 3.4 - 4.2 GHz
Total FoV 60° to zenith
First test at Paris, then shipped to Argentina
Collecting first data

Self-trigger same logic as FD

Observation of the longitudinal profile

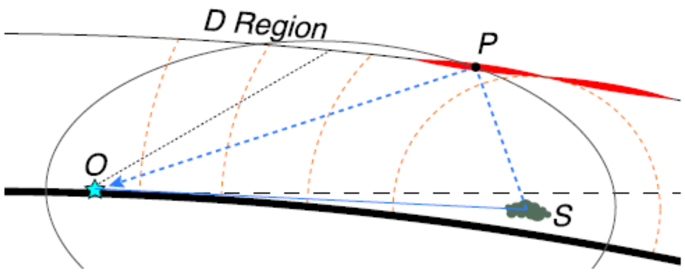
4.5 parabolic reflector with a 53 pixel camera
Total FoV 20°x 10°
C Band: 3.4 - 4.2 GHz
Data collected at Chicago, then shipped to Argentina

E_{thrs} ~ 2 10^{18} eV (quadratic scaling)
E_{thrs} ~ 1 10^{19} eV (linear scaling)

All operating (or very close to) at the Auger Site

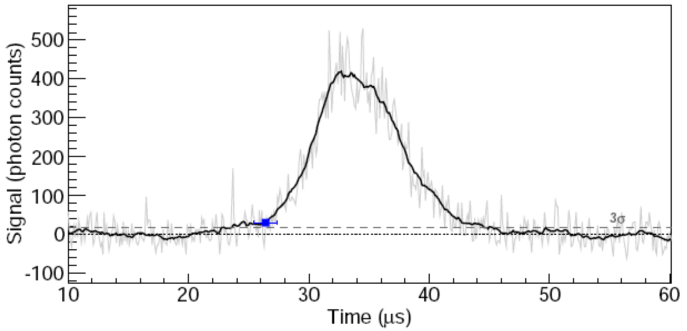
Observation of elves with FD

Transient phenomena in D-layer of the ionosphere at about 90 km (few ms long)

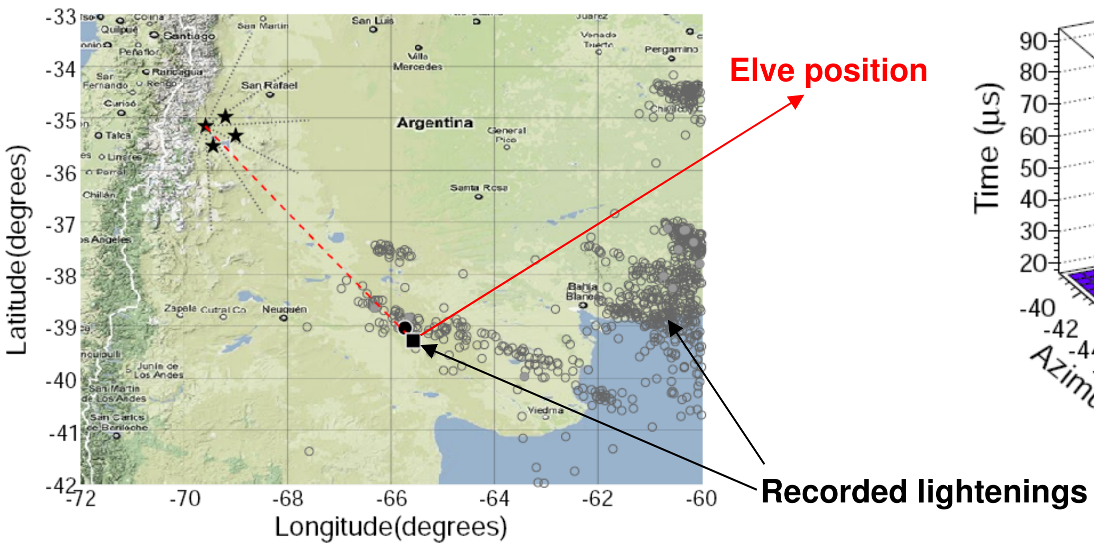


3 candidates observed in FD

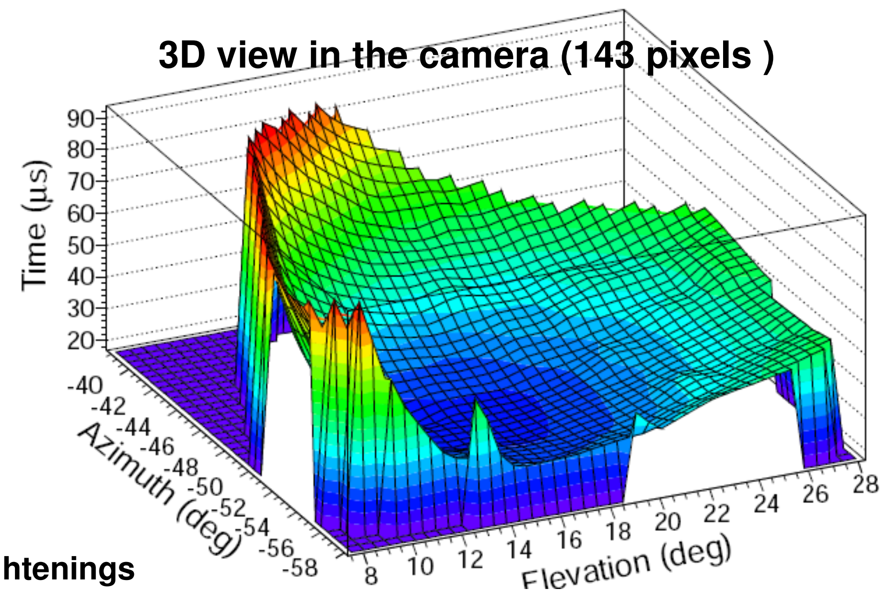
Site-Bay	GPS time	GMT time
$LM-6$	800414142	18 May 2005 01:15:29
$CO-3$	860806213	17 April 2007 00:49:59
$LL-1$	861081389	20 April 2007 05:16:15



Reconstruction performed with FD



3D view in the camera (143 pixels)



Summary of results

Spectrum

- flux suppression established ($E > 4\ 10^{19}$ eV)
- ankle observed at about $4\ 10^{18}$ eV

Composition

- mixed scenario: light dominated at low energies, heavier with increasing energy (interpretation is model dependent)

Hadronic interactions

- first measurement at $\sqrt{s}$ = 57 TeV

Arrival directions

- the degree of correlation with VCV catalog has decreased
- definitive conclusions must await additional data

Photons and neutrinos

- flux photon limits above 1 EeV (top-down model disfavored)
- updated limits on the diffuse flux

Outlook and future

The Pierre Auger Observatory takes data smoothly since 2004

- construction completed in 2008

Extensions towards the lower energies (HEAT and AMIGA) r

- study the transition from galactic to extragalactic CR component
- allow cross-calibration with other experiments

The Pierre Auger Observatory for new detection techniques

Radio detection (AERA), radio hybrid events collected

Microwave detection, several detectors being installed

"In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side."

V.H.Hess, Nobel Lecture, December 1936

Back-up slides

Anisotropy at the highest energy

<u>Data Set</u>

01/01/2004 – 31/08/2007

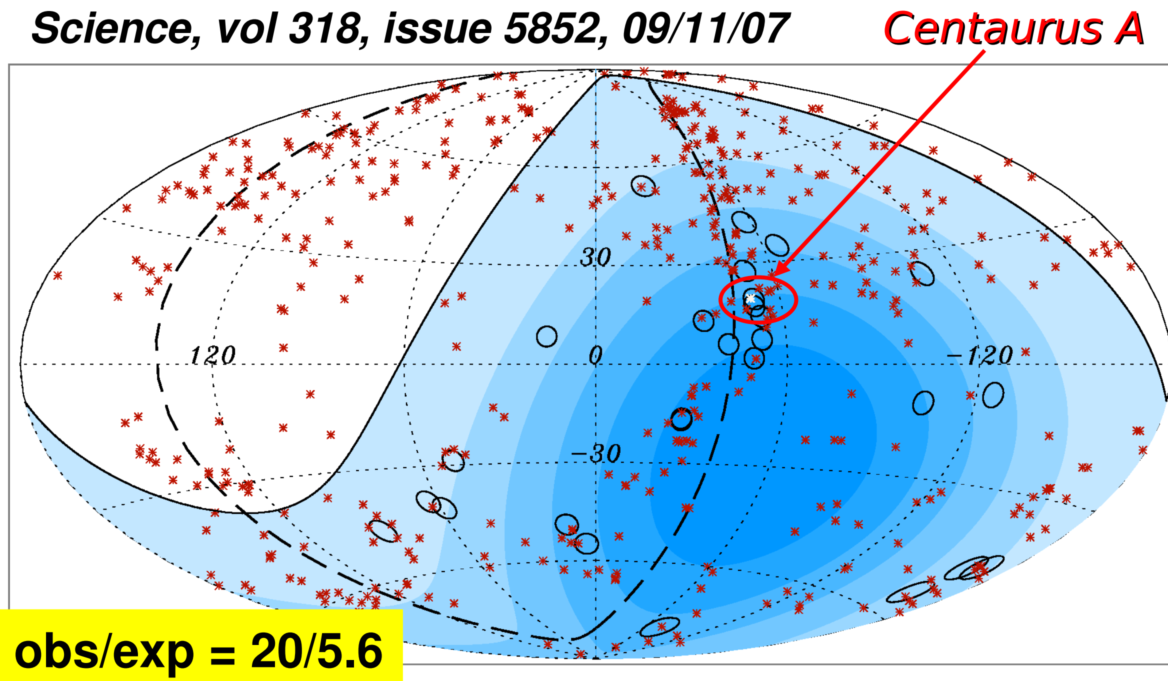
<u>27 high energy events</u>

E>57 EeV
Angular radius of 3.1°
Dmax=75 Mpc

Taking as reference the catalog by Véron-Cetty and Véron (2006)

20/27 events correlate with nearby AGN

Science, vol 318, issue 5852, 09/11/07



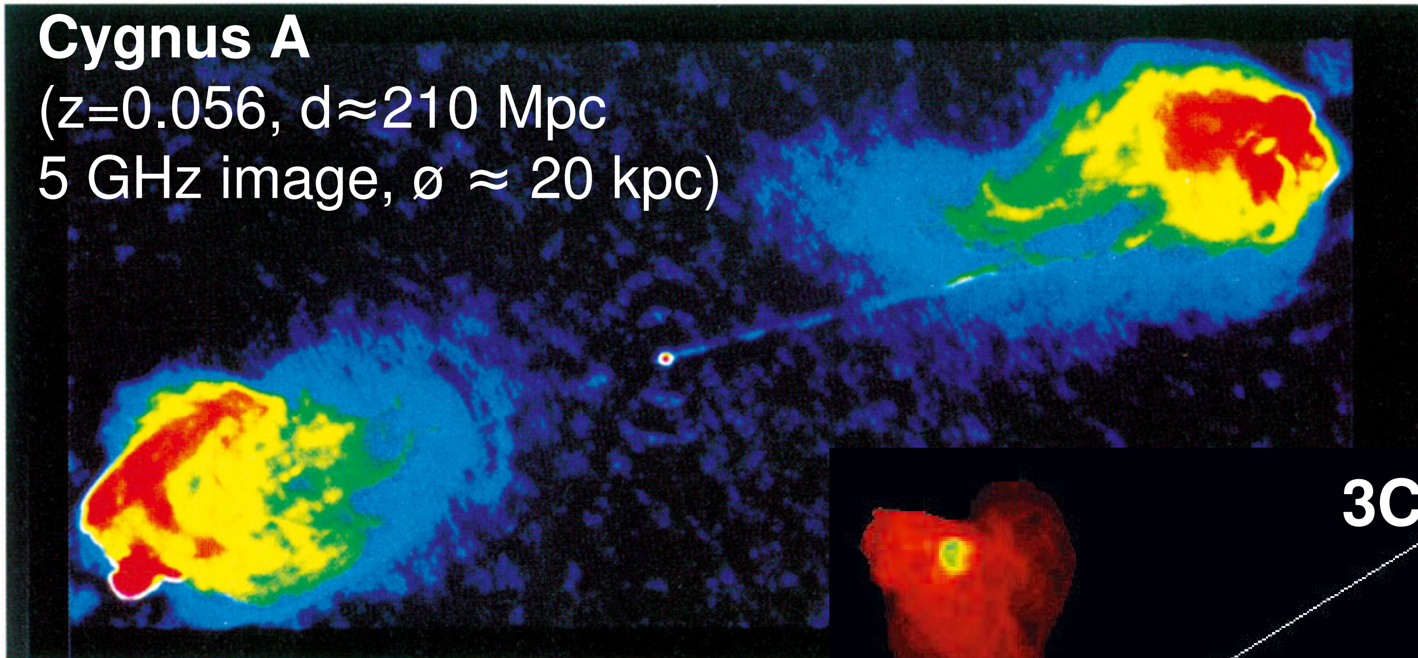
○ *events with E>57 EeV, angular radius ψ = 3.1°,*

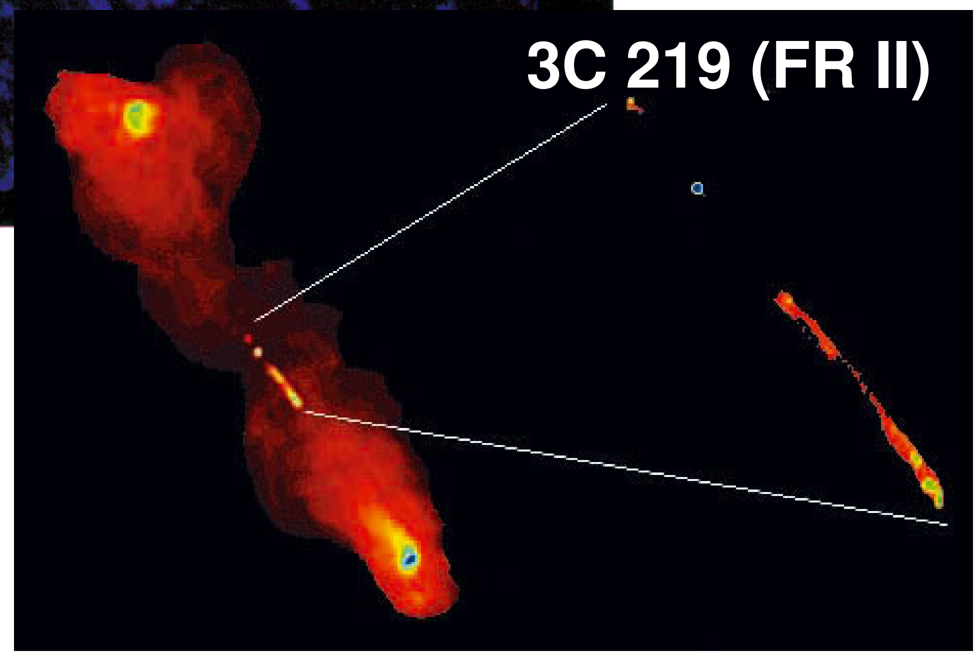
× *472 AGN within D_{max}=75Mpc (318 in the Auger FOV)*

Isotropic chance probability < 1%

Limitations of the catalogue: incomplete and inhomogeneous

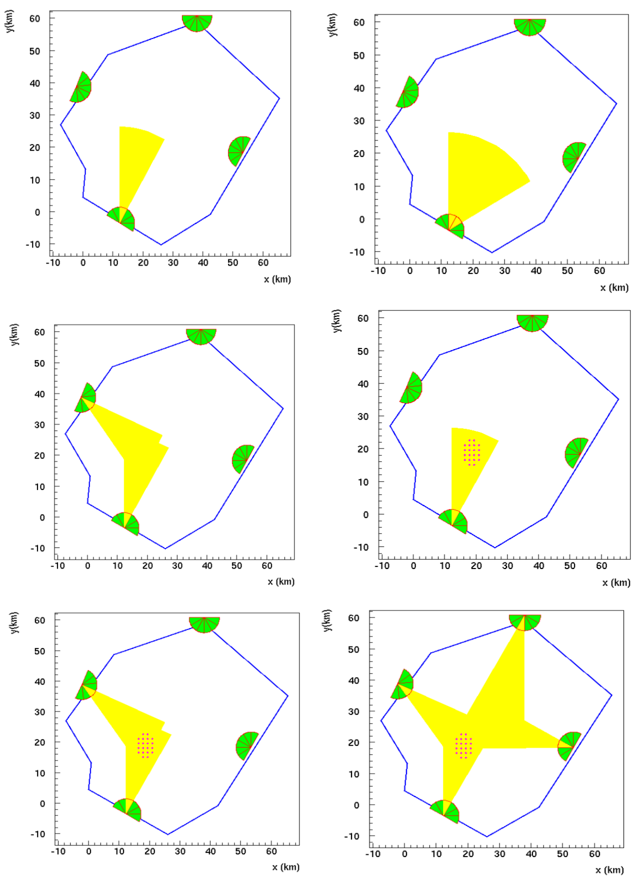
Cosmic Rays: astrophysical sources

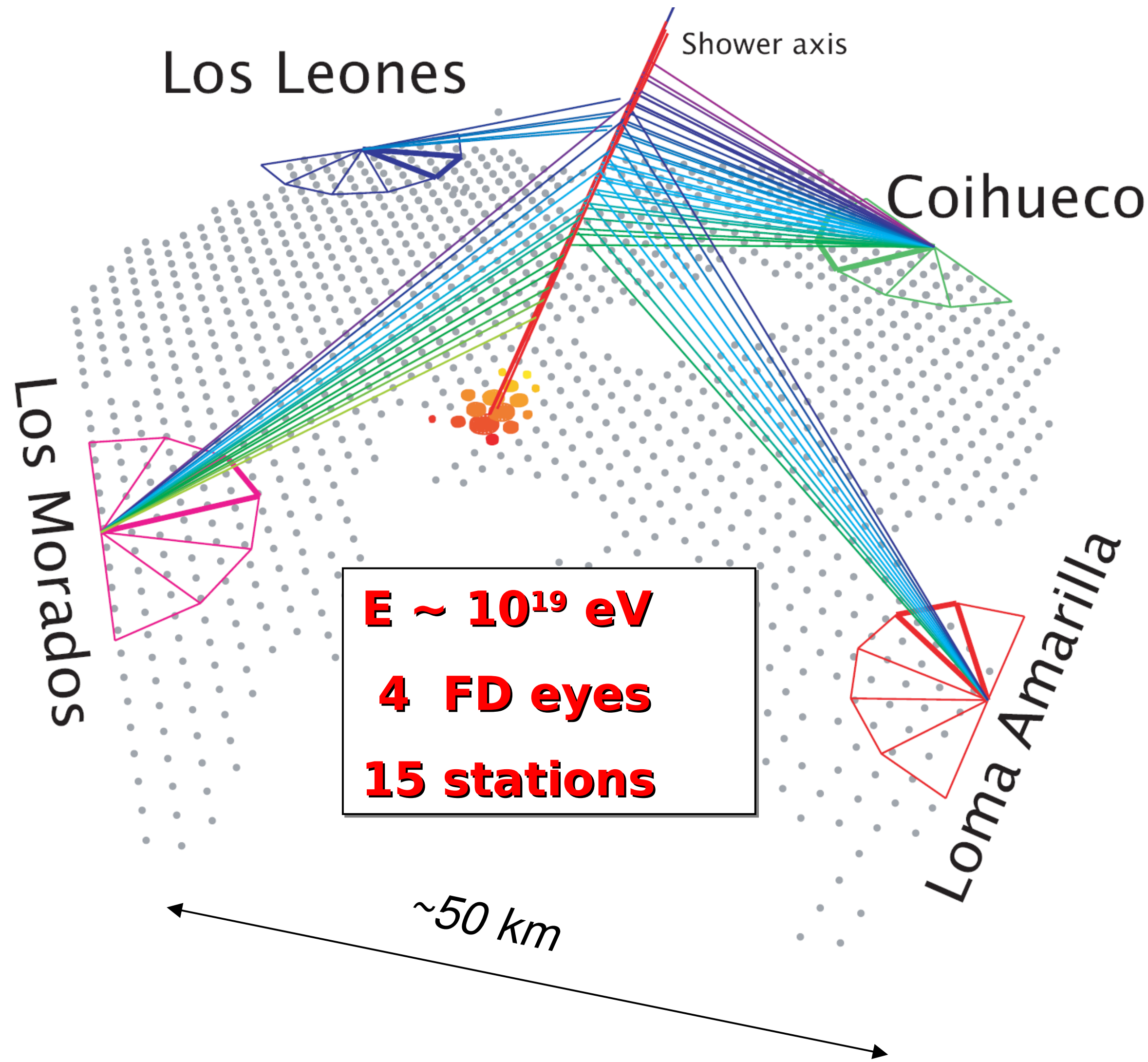




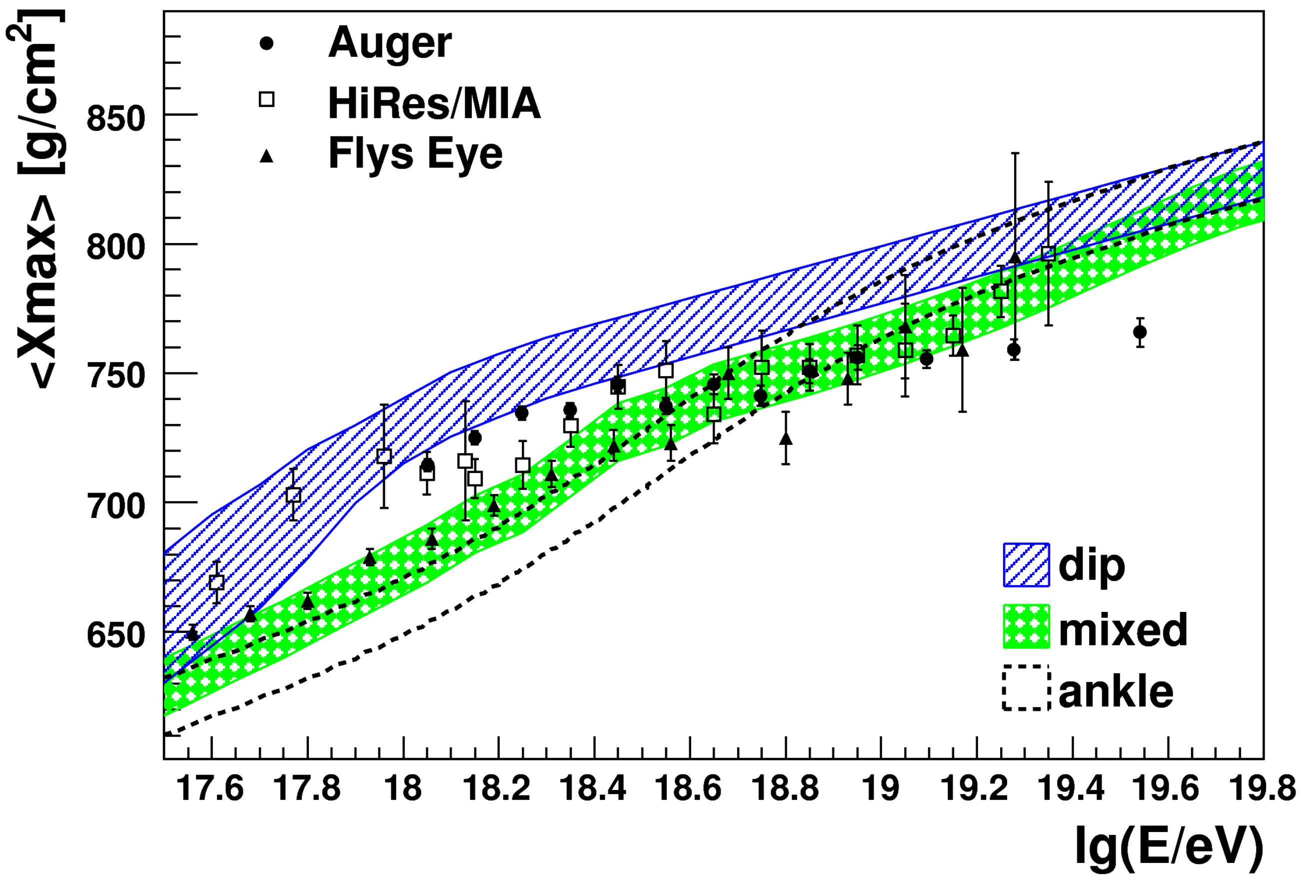
AGN radio-lobes:
(Rachen&Biermann,1993)
AGN Jets:
(Norman et al.,1995)

Event topologies





Data compared to models



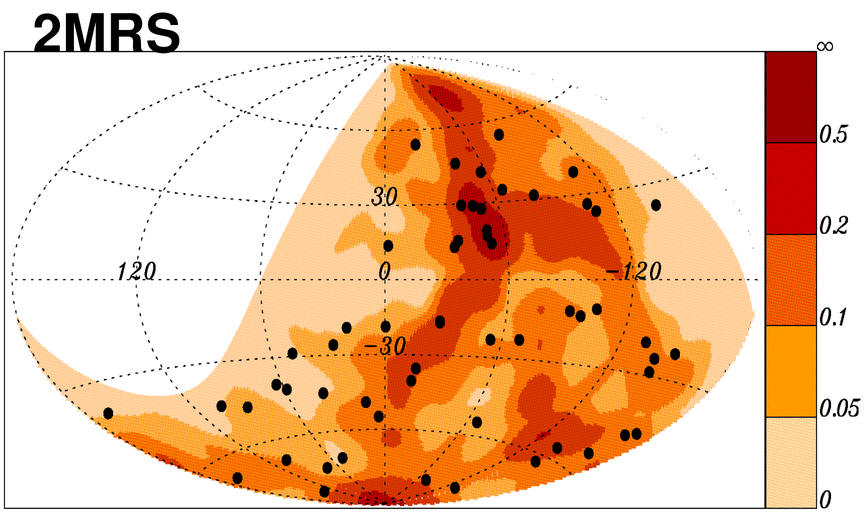
Courtesy of Michal Unger

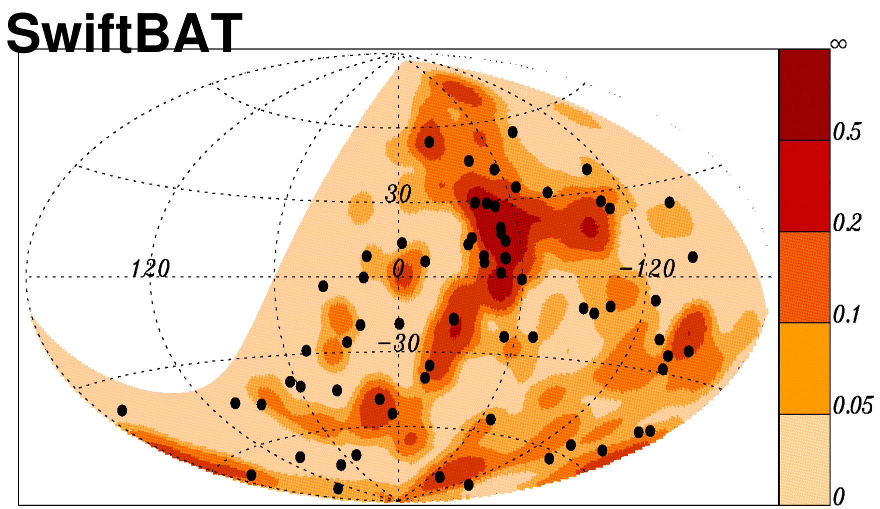
none of the model satisfactory explains data yet (shape, absolute value)

→ constraints by studying X_{max} distribution (known syst. unc.)

A posteriori searches

Astropart. Phys. 34 (2010) 314





5 σ detection requires more data (165 for P=6*10^{-7})
→ tests on other catalogues: 2MRS (IR) & SwiftBAT (X-rays)

Not only muons hit the tank!!!!

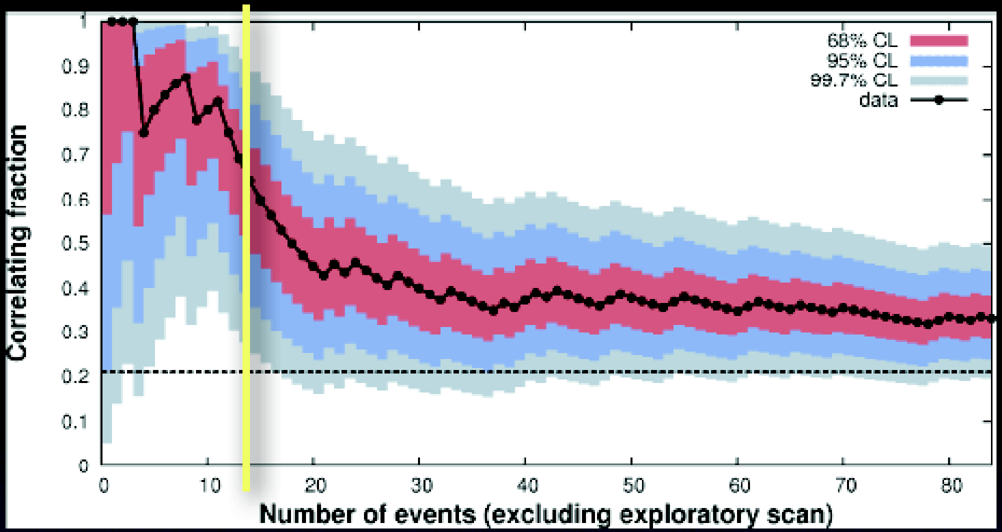
Bird droppings together with dry weather degrade solar panels.

Bird nests behind solar panels sometimes catch fire.

Frazione di eventi di E > 55 EeV che correlano con le posizioni degli AGN "vicini" del catalogo VCV

Pierre Auger Collaboration (2011) presentato ICRC 2011 (Bejing)

Science 318: 9/13 ~69% di eventi correlati



frazione = k/N
k: eventi che correlano
N numero di eventi totali

f = (33±5)%
f_{iso} = 21%, Totali 28/84
P = 0.006

frazione aumenta escludendo piano galattico
f = 46±6% (f_{iso} = 24%)

Telescope Array (2011)

frazione di correlati è 40% (8/20) mentre l'aspettazione da un flusso isotropo è il 25%

frazione degli eventi correlati del 69% (9/13) convertita nell'emisfero nord è il 73%