PIERRE AUGER OBSERVATORY

Aspen Workshop on Cosmic Ray Physics

April 15-19, 2007 Aspen, Colorado

Status and results from the Pierre Auger Observatory

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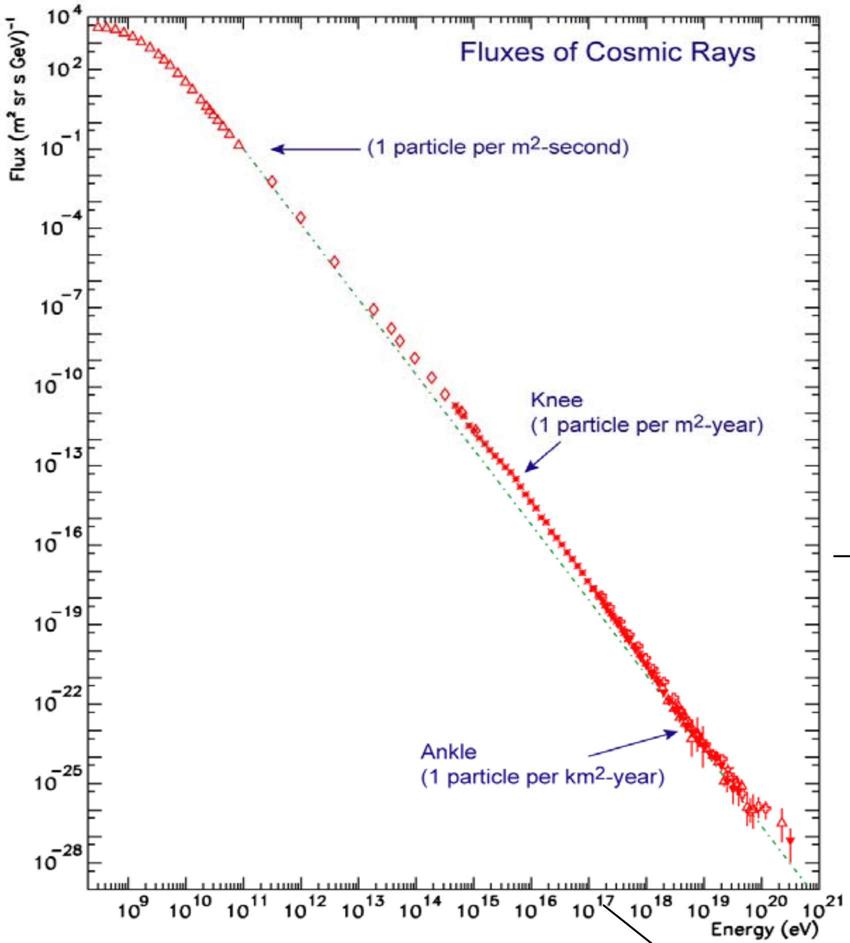
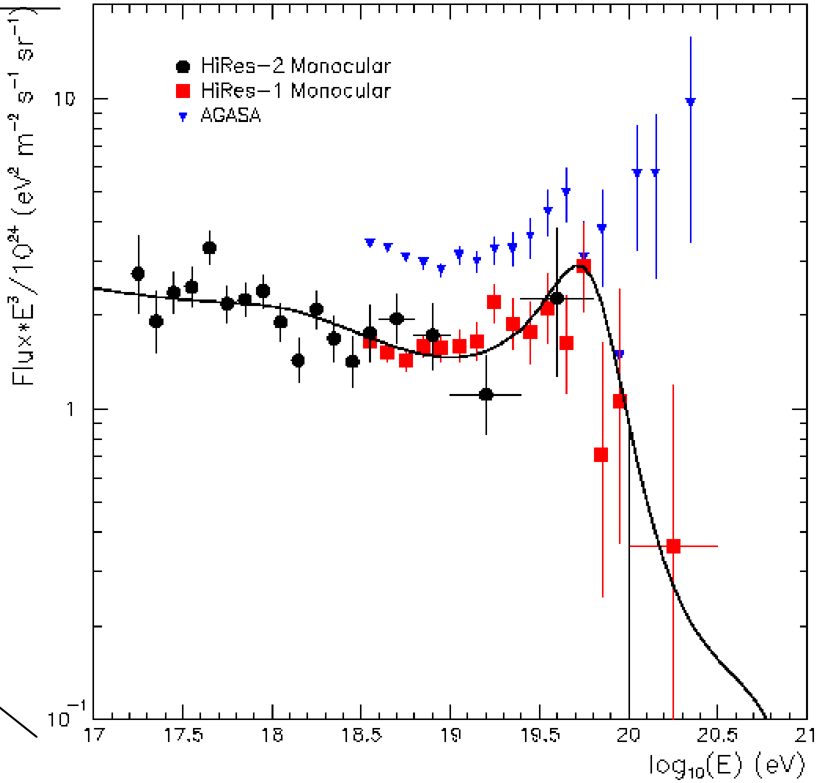
The Physics Case: highest energy cosmic rays



E>10^{19} eV: low statistics and results from different experiments/techniques slightly controversial
Partially statistics, probably also energy measurement systematics

Auger



E=10^{20} eV 1 event/ km^2/ century

3000 km^2 30 events / year

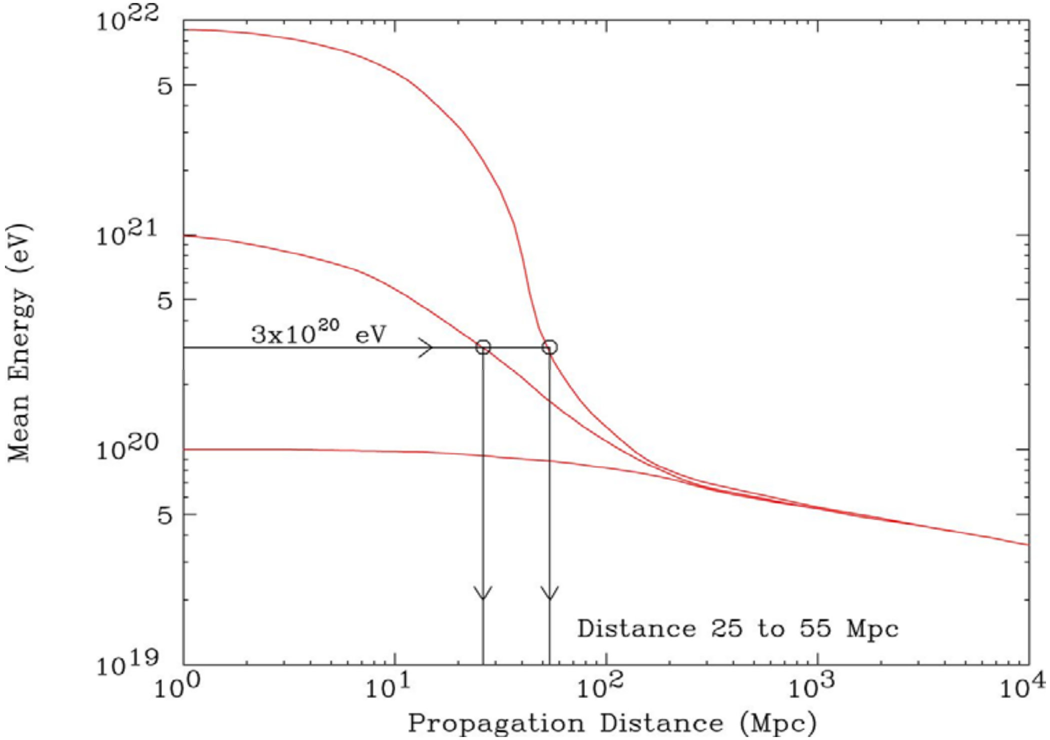
Need huge collecting area!

Standard astrophysical models hardly account for CR at energy $E>10^{20}$ eV

GZK cutoff at $E > 10^{19.5}$ eV

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

But CR with $E > 10^{20}$ eV exist



If GZK is observed :

Near sources should be identified

high magnetic rigidity of particles allows astronomy

GZK shape-> source distance distribution

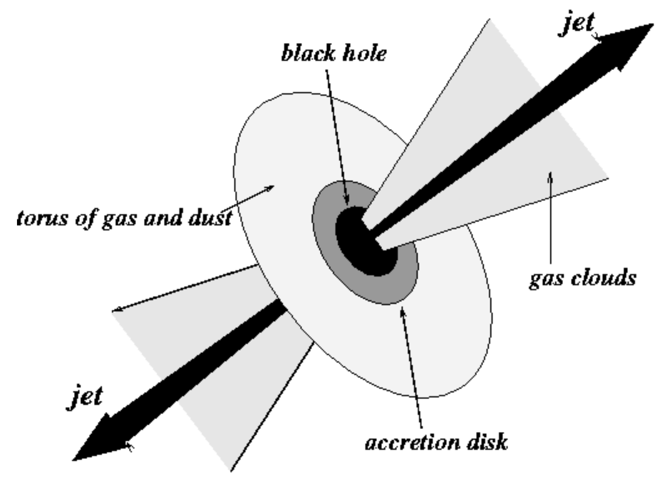
If GZK is NOT observed :

sources are nearby

other scenarios

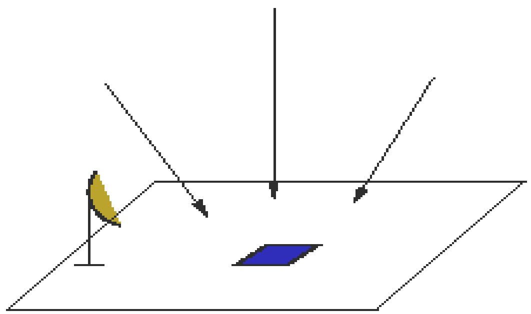
TD models, violation of Lorentz invariance,...

Which sources, where and how far are they?



How do cosmic rays propagate?

dN/dEdSdtdΩ



and which primary particles?

Observables: signal shapes with a given time, from different techniques.

Science goals

spectrum ``phenomenology''
arrival directions
chemical composition

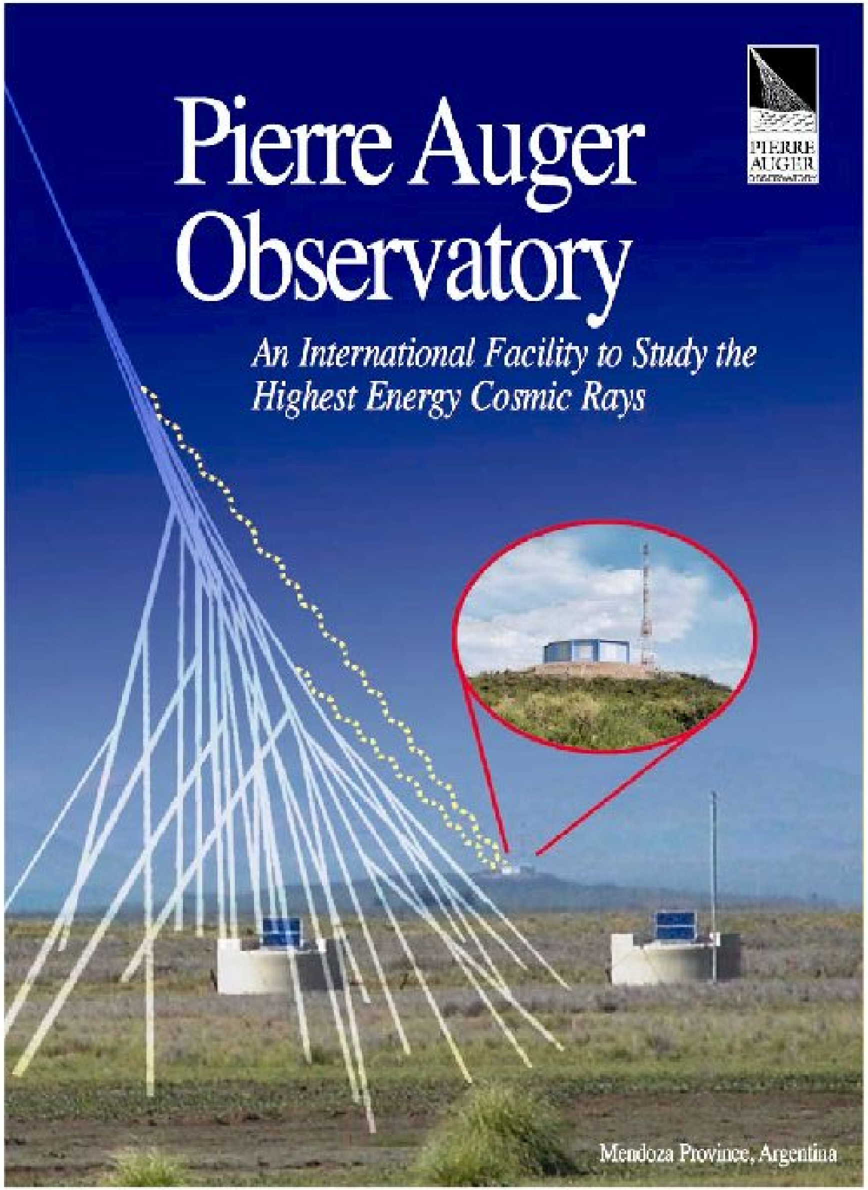
The Pierre Auger Collaboration

17 Countries

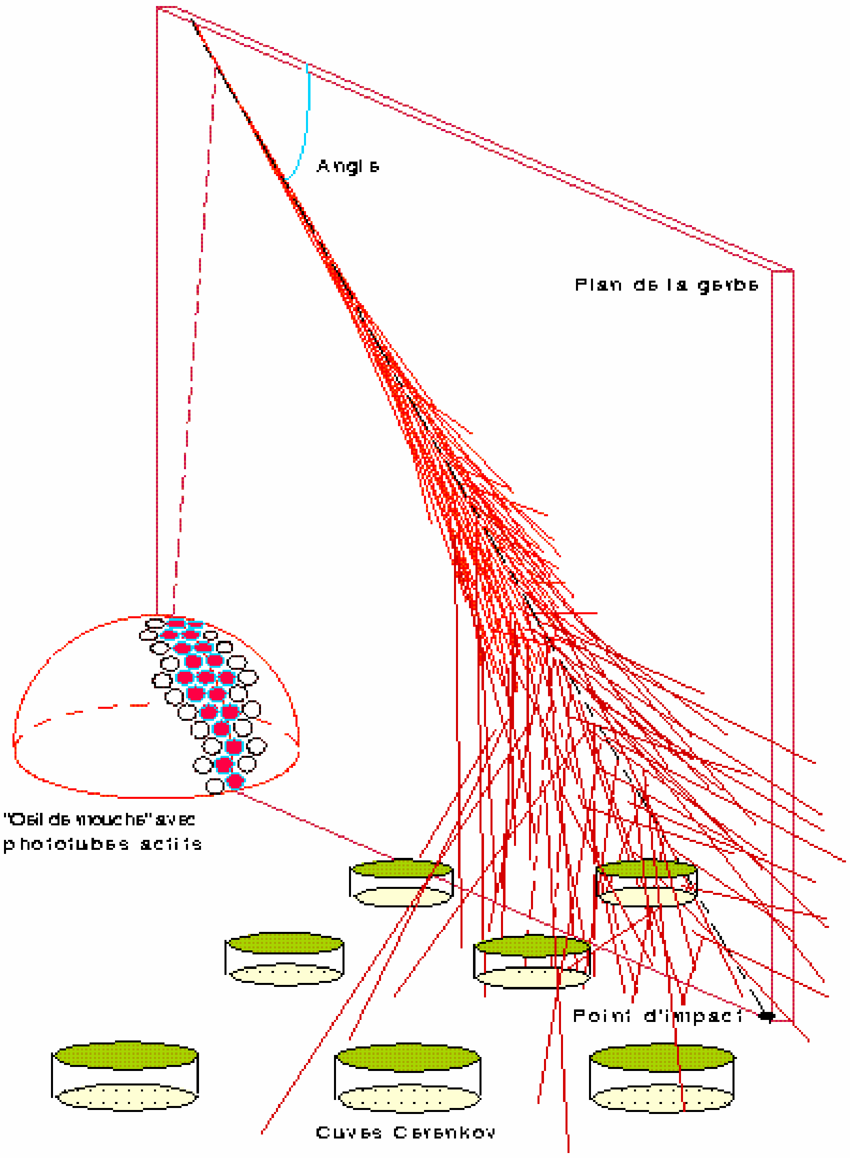
63 Institutions

~ 350 members

Argentina,
Australia,
Bolivia,
Brazil,
Czech Rep.,
France,
Germany,
Italy,
Mexico,
Netherlands,
Poland,
Portugal,
Slovenia,
Spain,
UK,
USA,
Vietnam.



The Hybrid Concept



The Auger Observatory combines independent measurement techniques

Surface Detector Array

Air Fluorescence Detectors

-more reliable energy 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

Southern Observatory (Argentina)

Very flat region

"Pampa Amarilla" Malargüe (Argentina)

35º S latitude 69º W longitude

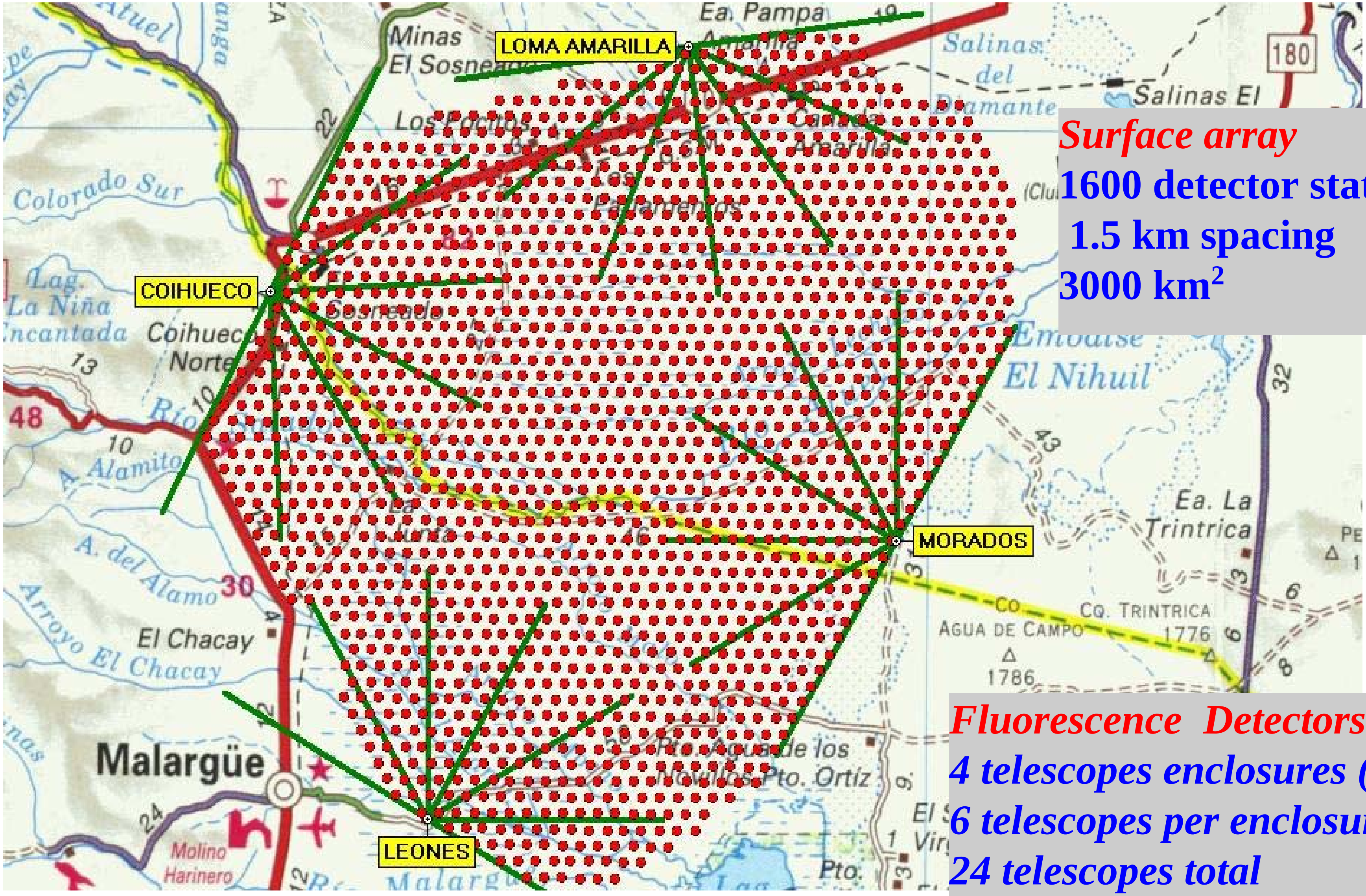
≈ 1400 m height ≈ 875 g/cm^2

Very low population density (< 0.1 / km^2)

Very good atmospheric conditions (clouds, aerosol…)

Future plan for Northern Observatory in Colorado (USA)

The Pierre Auger Observatory



Surface array

1600 detector stations

1.5 km spacing

3000 km^2

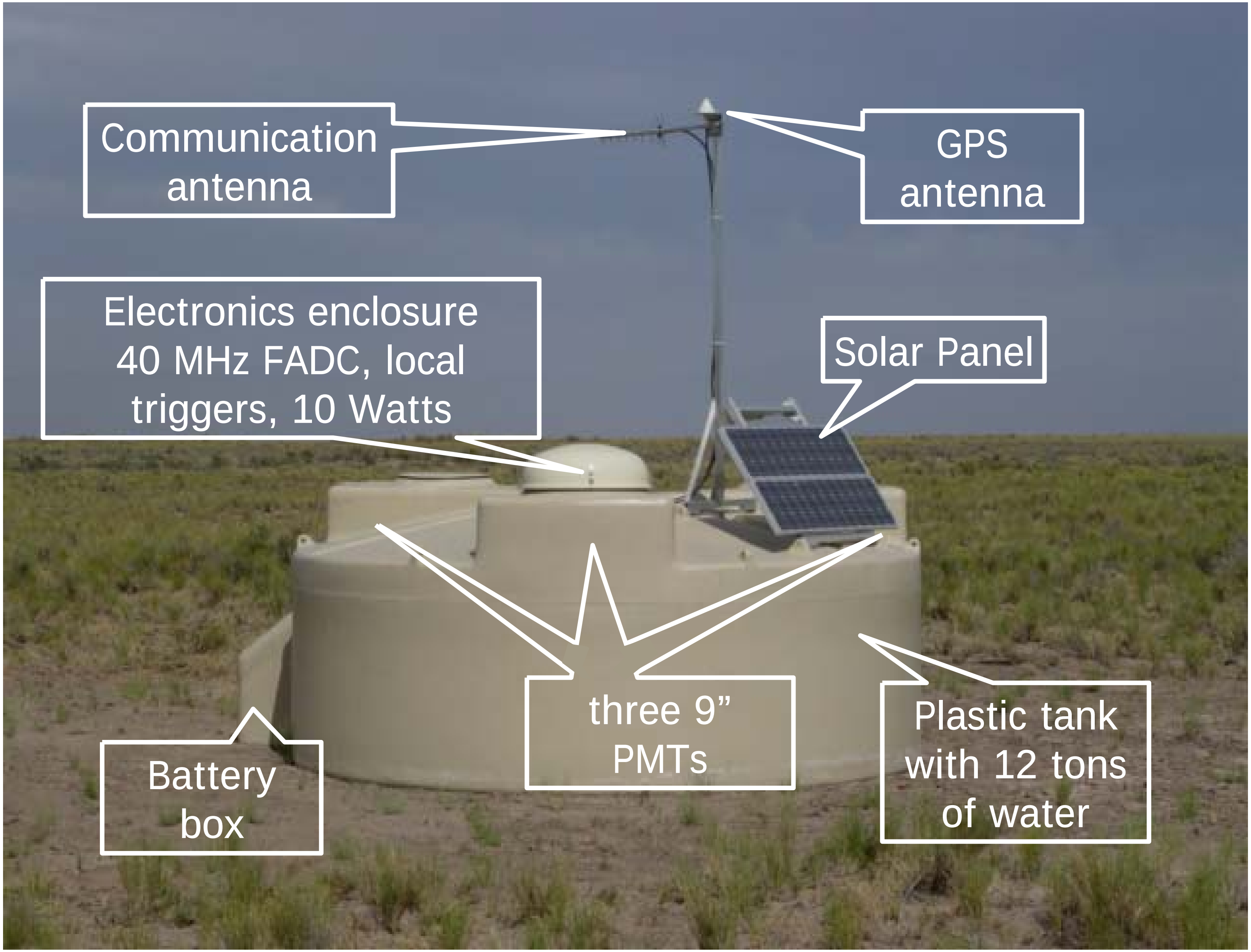
Fluorescence Detectors

4 telescopes enclosures (``Eyes'')

6 telescopes per enclosure

24 telescopes total

A water tank deployed in the Pampa



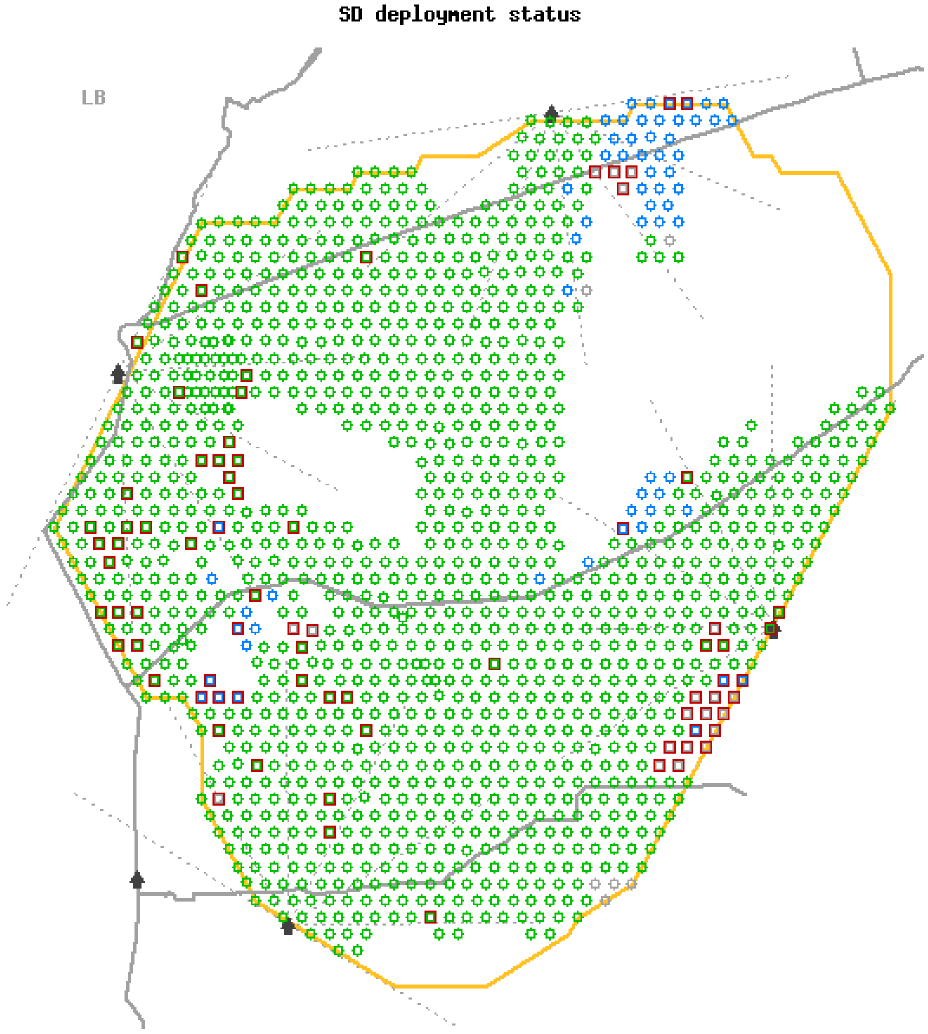
Auger Status: Sd (last Friday)

There are 1299 tanks deployed, 1273 with water and 1211 with electronics

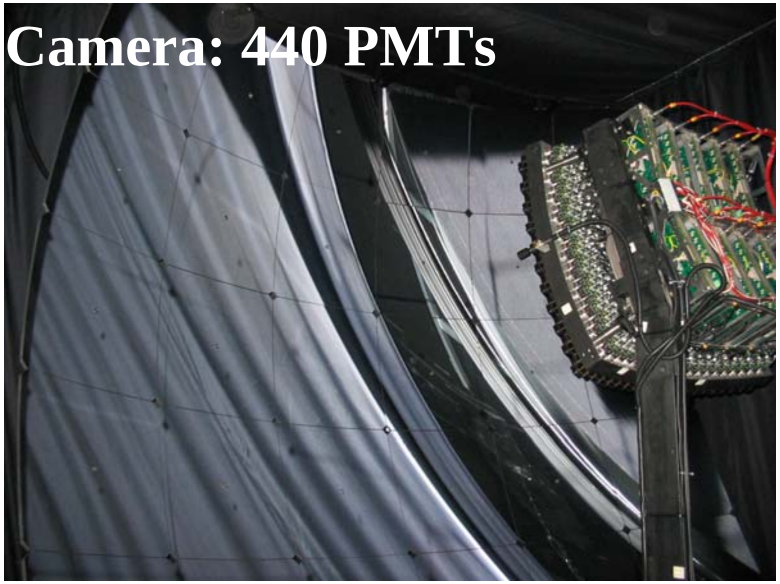
To be completed at beginning 2008

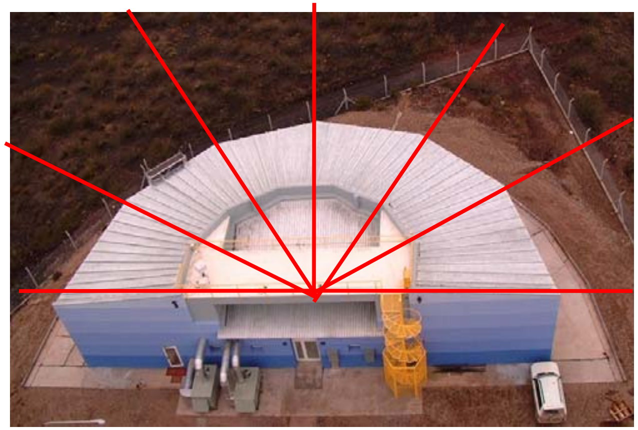
Routine data collected since January 2004

Exposure is already more than 3 times that of AGASA

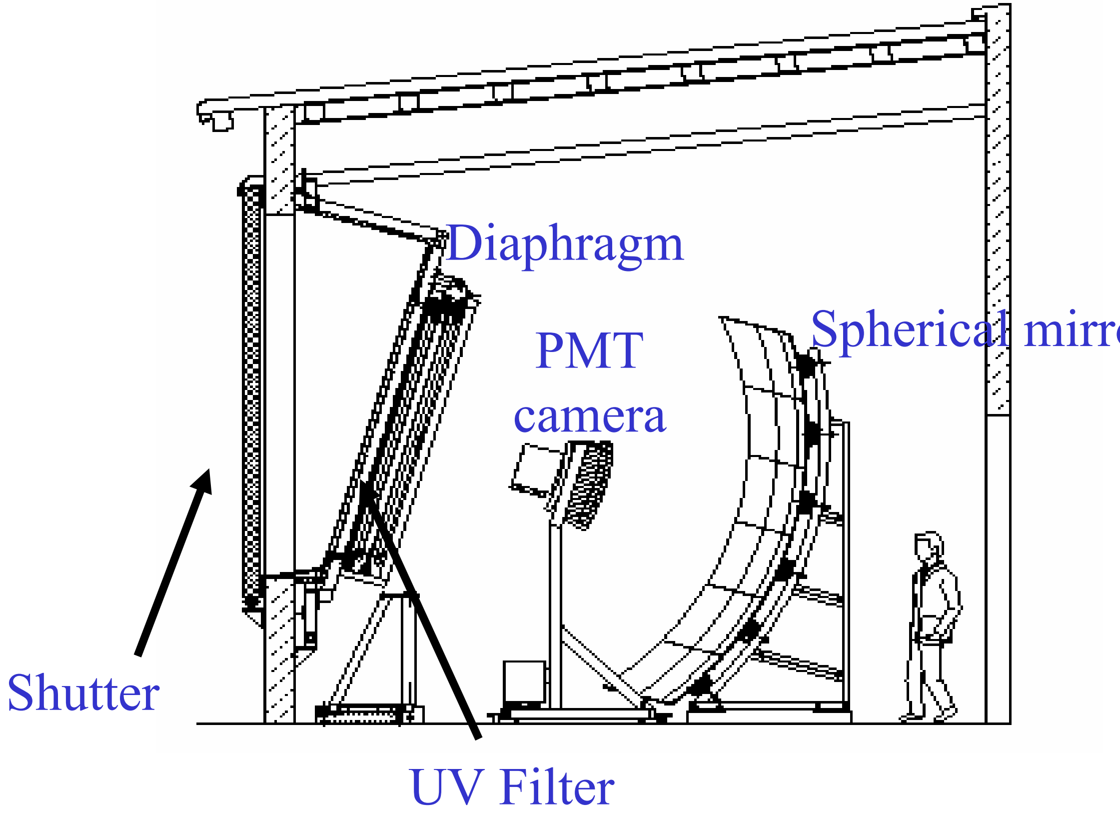


Fd Detector





field of view: 30°x 30° each



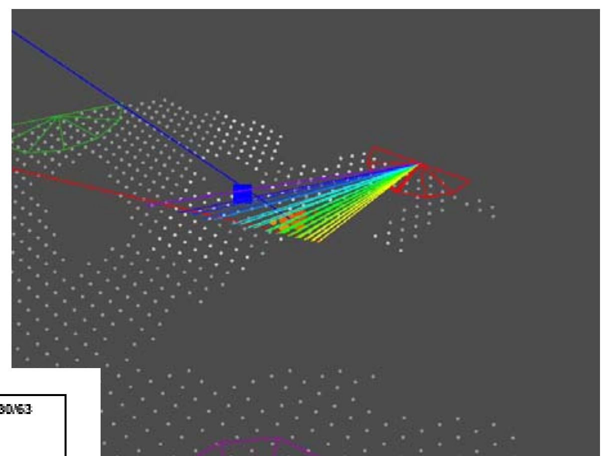
Auger Status: Fd

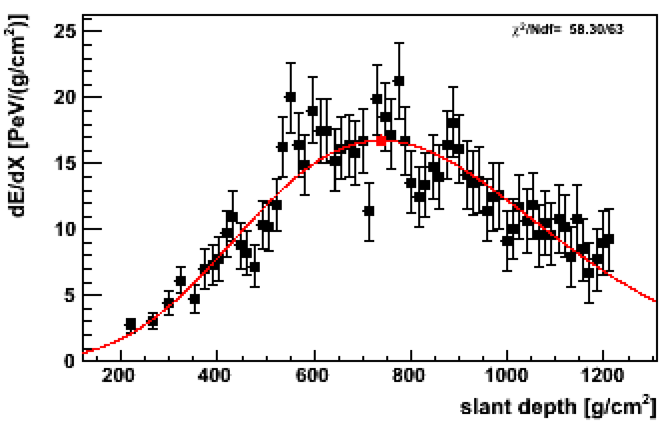
Los Leones

Coihueco

Los Morados

A Loma Amarilla hybrid event from last March



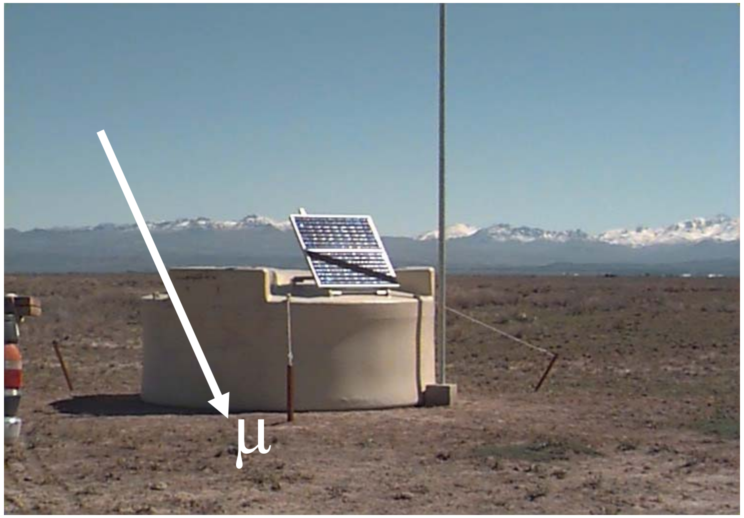


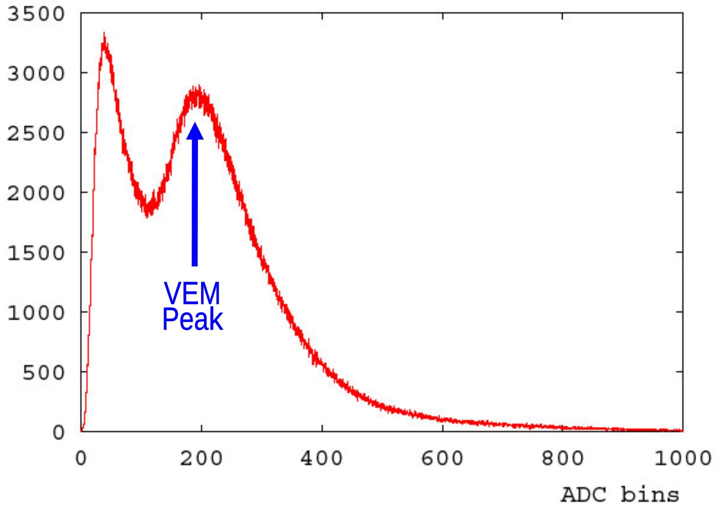
Loma Amarilla

Regularly taking data since February 23rd

Calibration

Sd

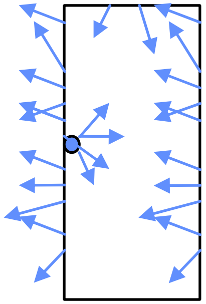




Through-going cosmic muons

Fd

light flux measured by absolutely calibrated PMT

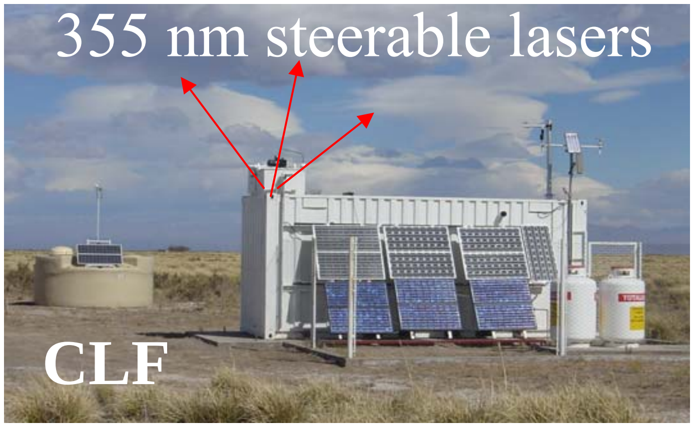


light diffusing Tyvek walls

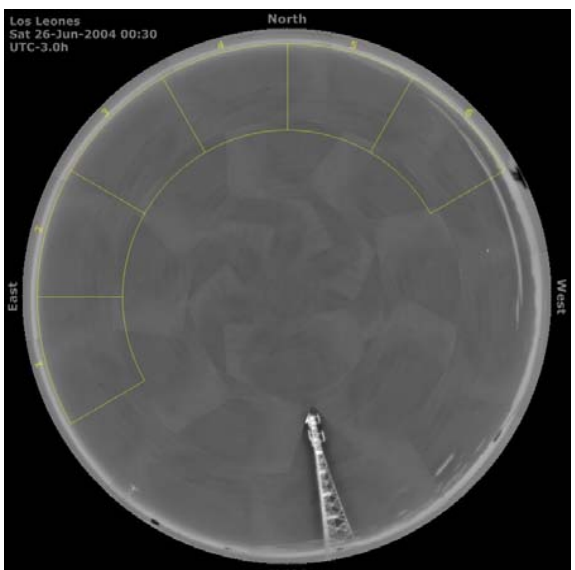
Drum: uniform camera illumination

Atmospheric Monitoring

Fd test beam



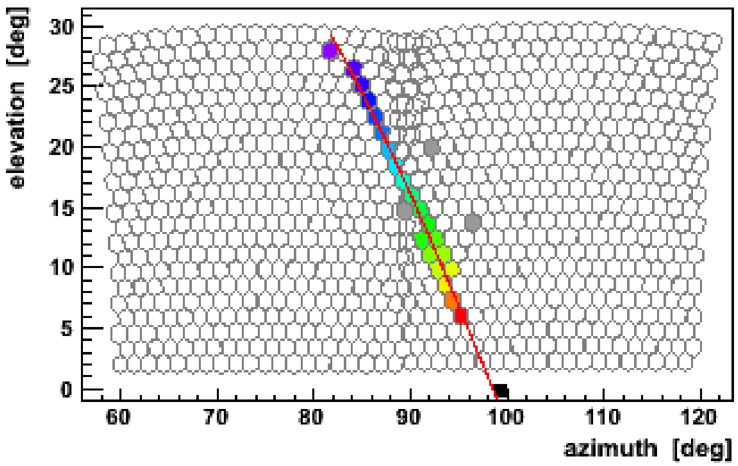
Balloons launches

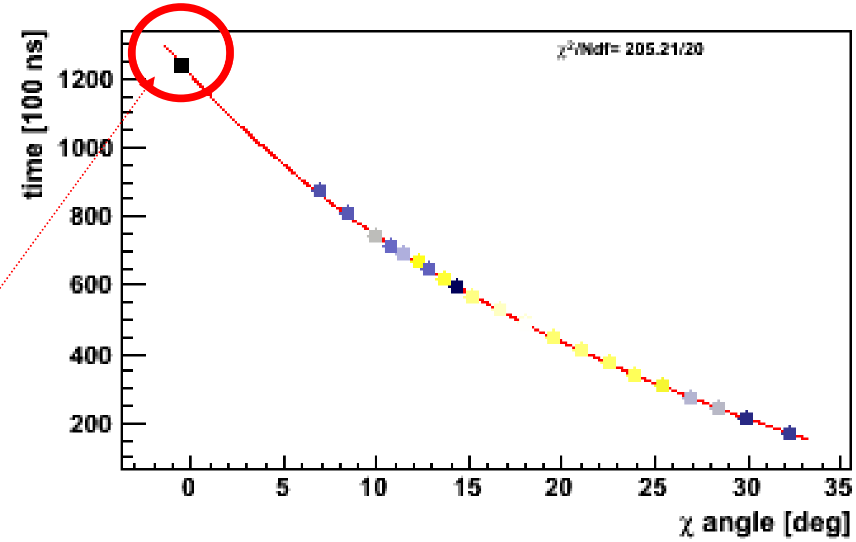


One cloud monitor per eye

One Lidar station per eye

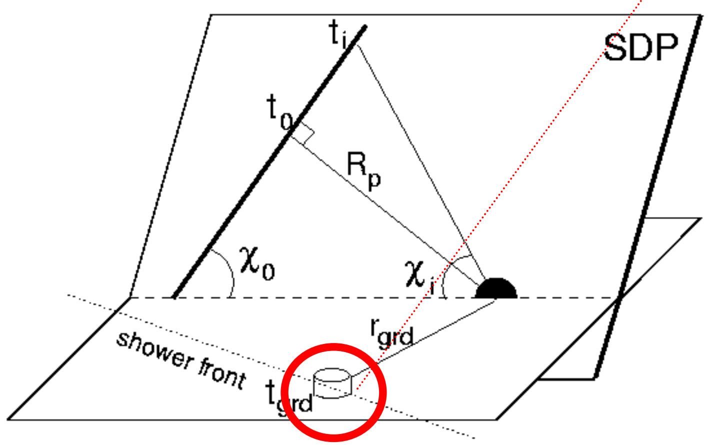
Fd (Hybrid) reconstruction



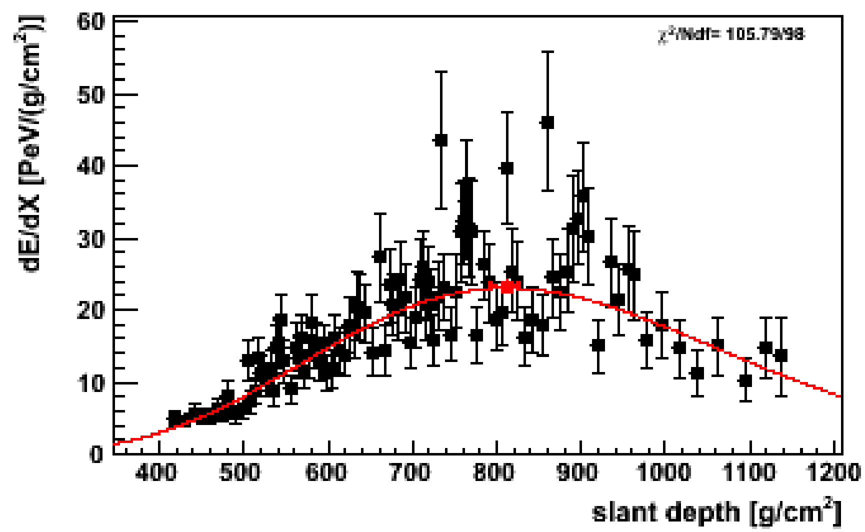


$$\chi^2_{SDP} = \Sigma_i w_i (\vec{n}_{SDP} \bullet \vec{r}_i)$$

$$t_i - t_0 = \frac{R_p}{c} \tan\left(\frac{\pi - \chi_0 - \chi_i}{2}\right)$$



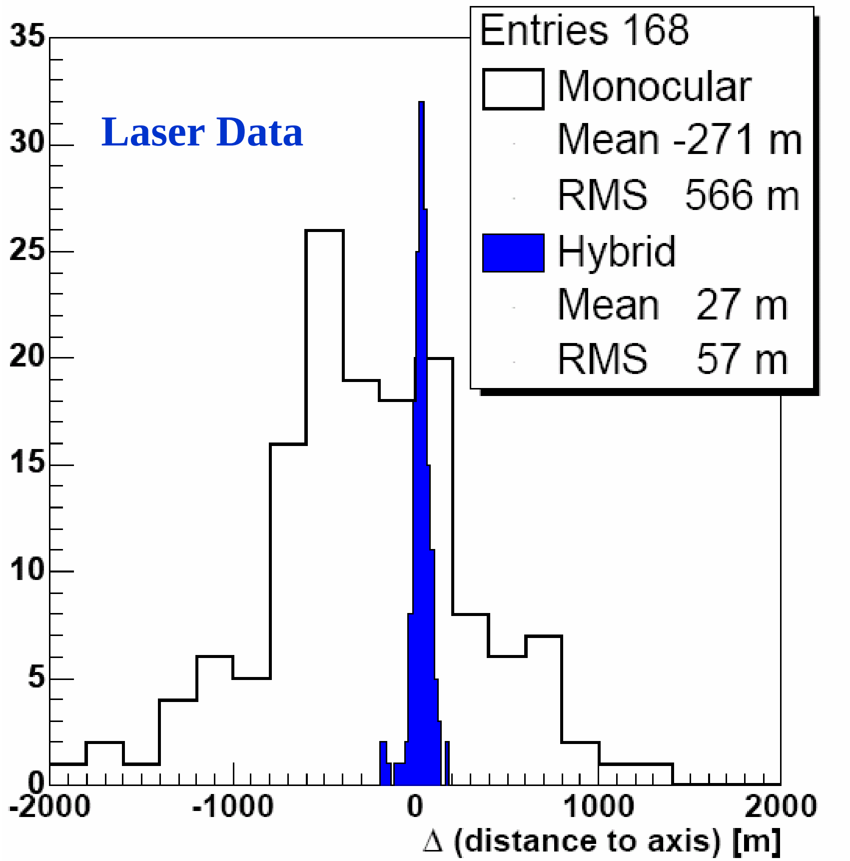
Longitudinal



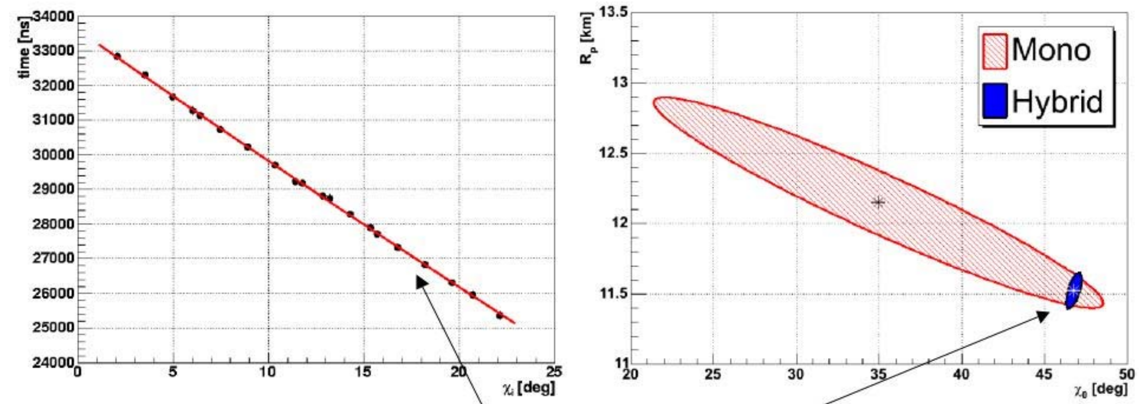
Energy: $E_{em} = \frac{E_c}{X_r} \int n_e(X)\, dX$

correct for the ``missing energy''

Hybrid vs Monocular



Laser position – Hybrid and FD only (m)



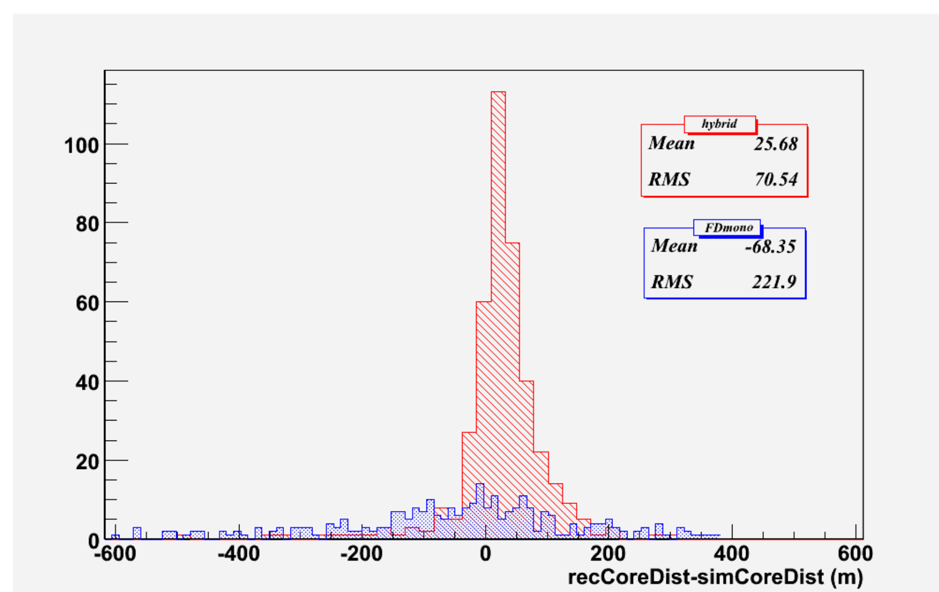
≈ line but

3 free parameters

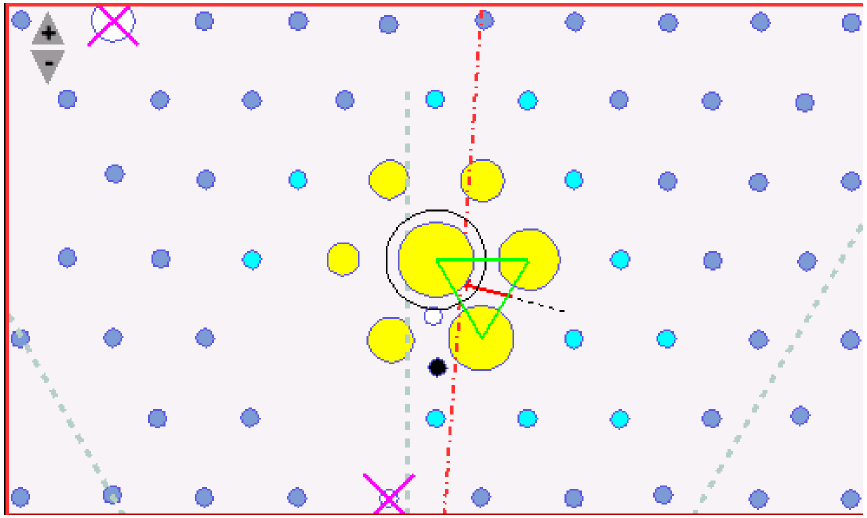
T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

Full hybrid simulations with Corsika showers

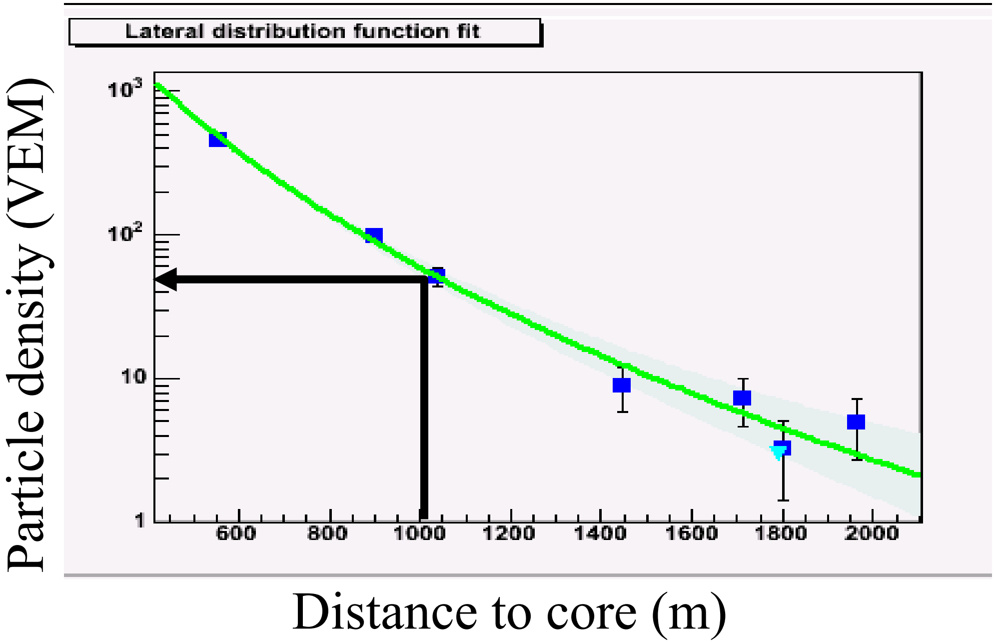


Sd reconstruction



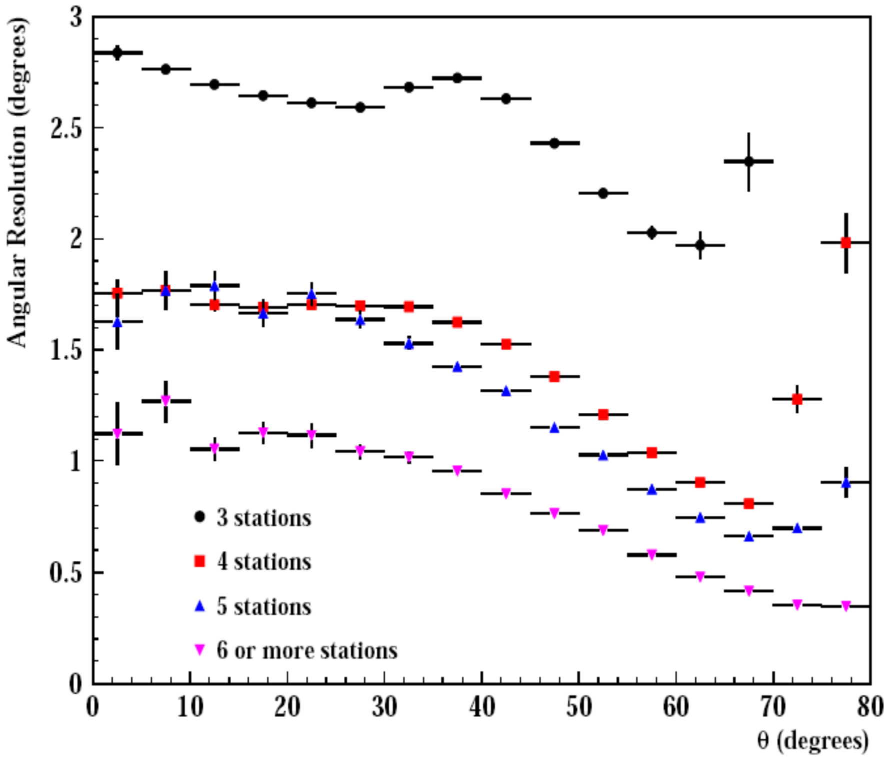
Geometry from the arrival time sequence

Lateral distribution and determination of the energy estimator S(1000) through simulations

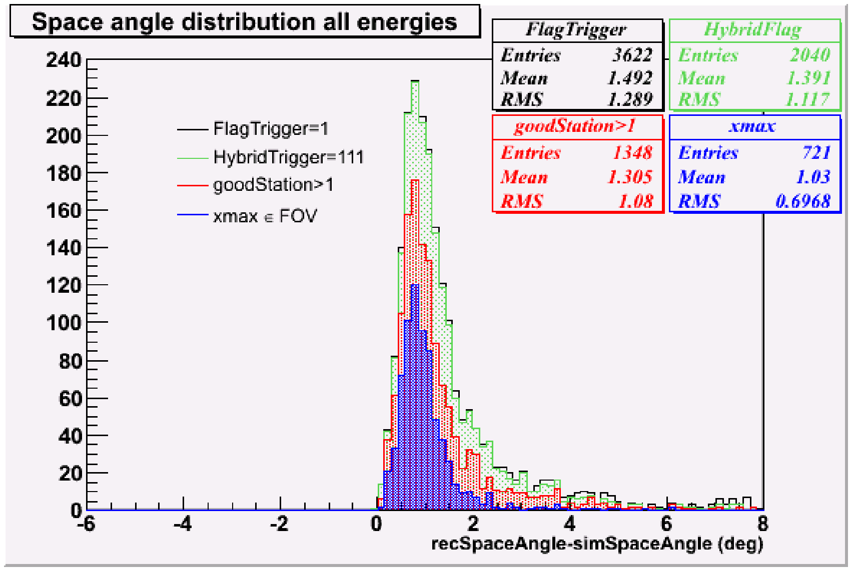


Large systematics expected on the energy:
- 30% from the high-energy hadronic interactions models
- 10-20% from low energy hadronic interaction models

Sd vs Hybrid angular resolution



Sd Angular resolution is a function of arrival direction and tank multiplicity (i.e. of energy)

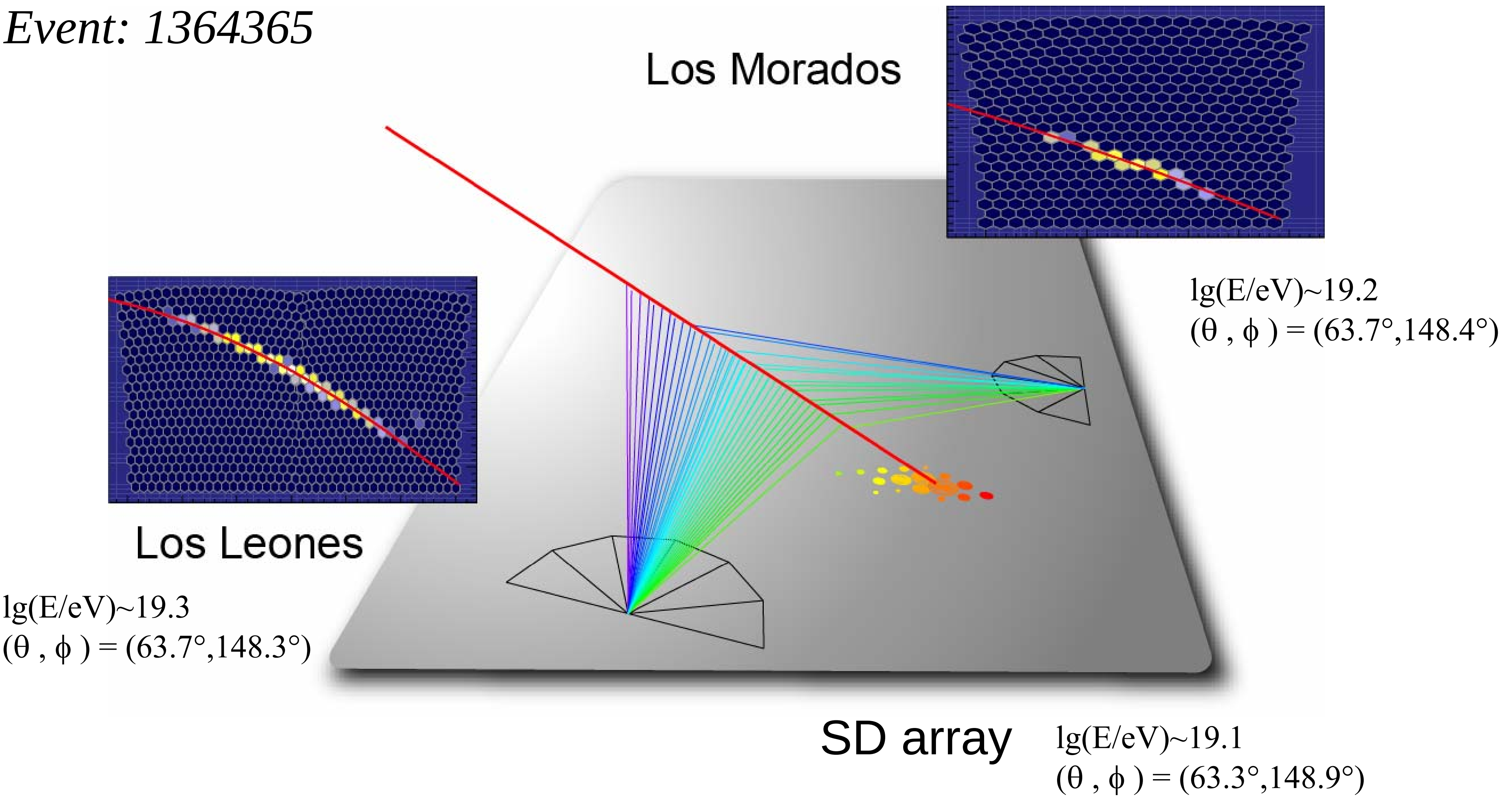


Improved for hybrids: within 1° down to $10^{17.5}$ eV

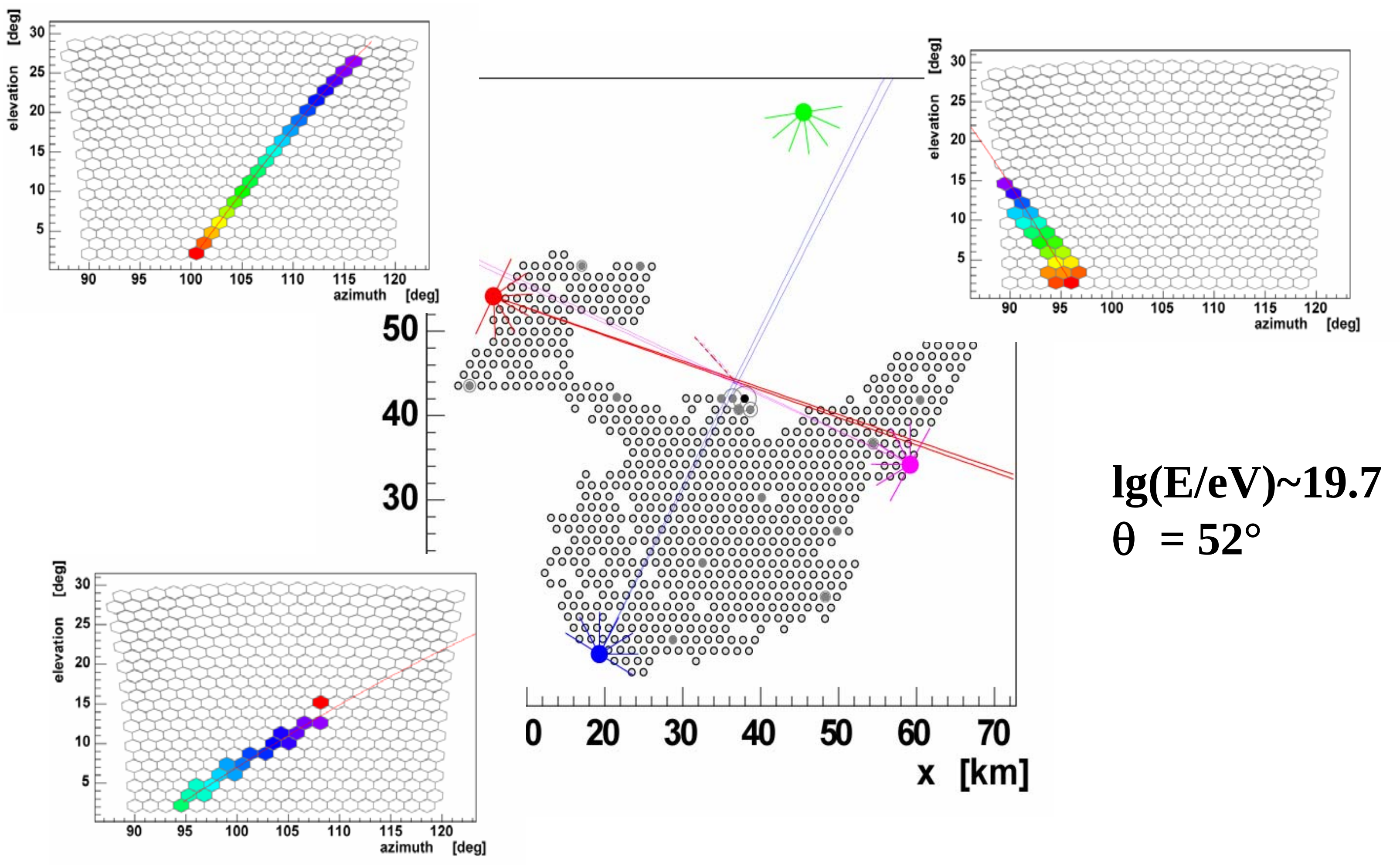
Full hybrid simulations with Corsika showers
Hybrid Reconstruction at different levels

space angle (deg) between true and reconstructed shower axis direction

A stereo hybrid event



A three-fold hybrid event (I)



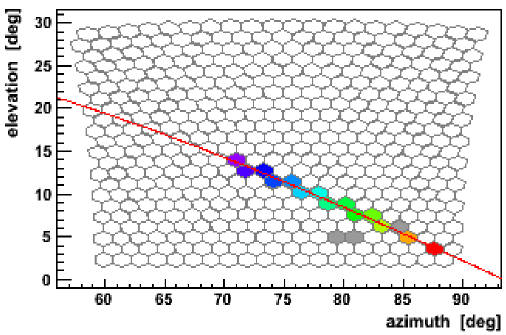
lg(E/eV)~19.7
θ = 52°

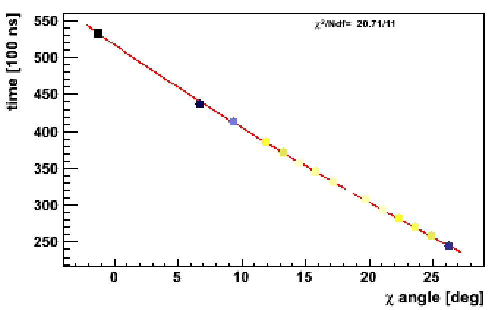
A three-fold hybrid event (II)

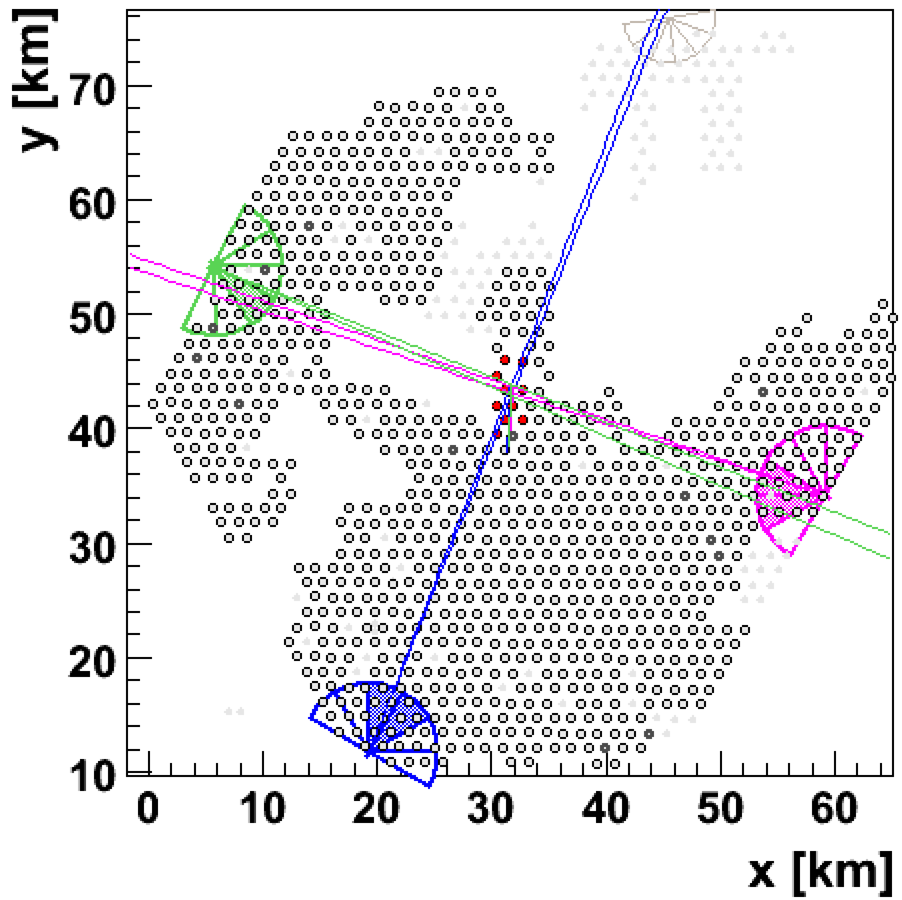
Event: 2619464

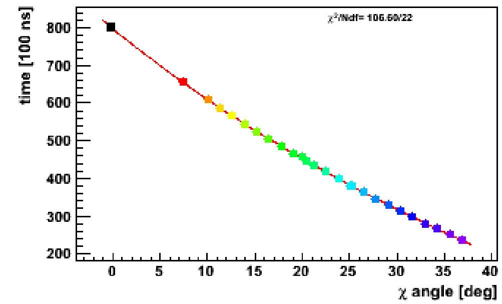
30/8/2006

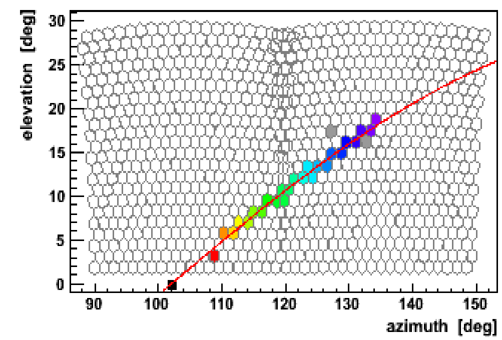
Coihueco









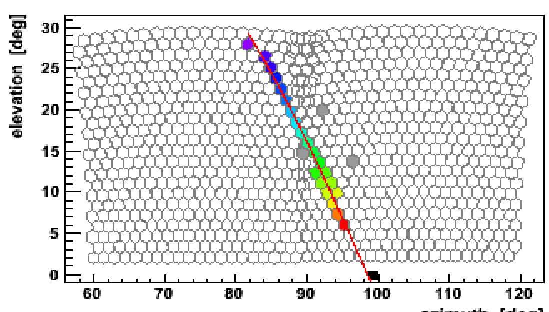


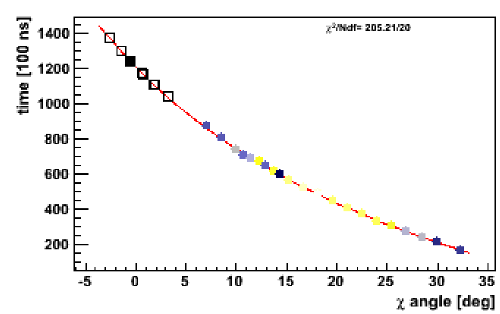
Los Morados

lg(E/eV)~19

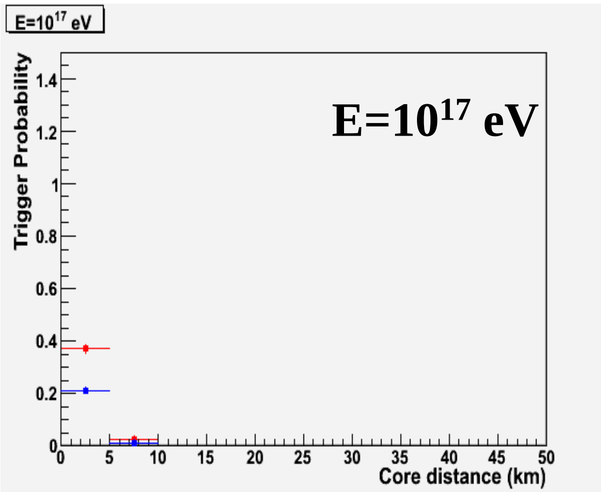
θ = 59°

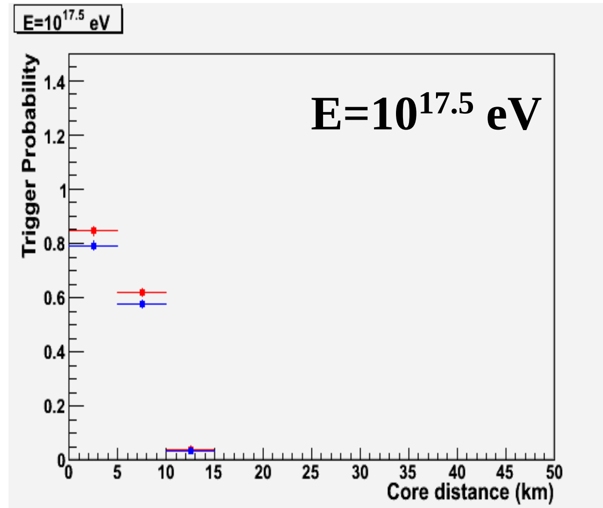
Los Leones

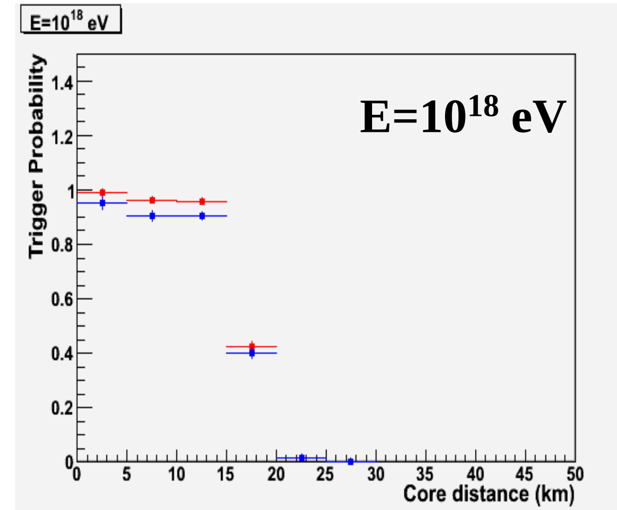




Hybrid trigger efficiency



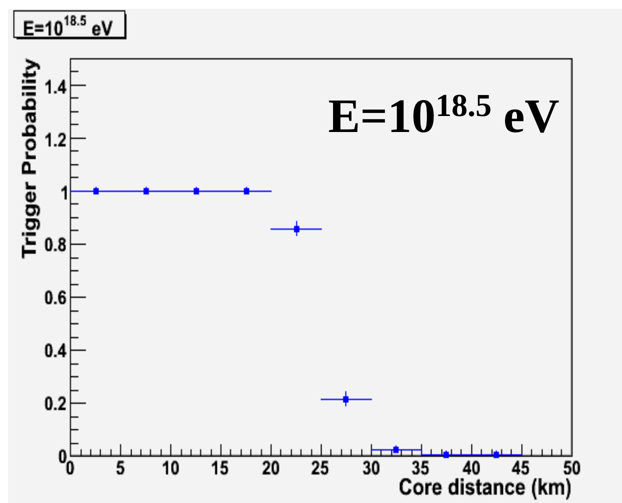


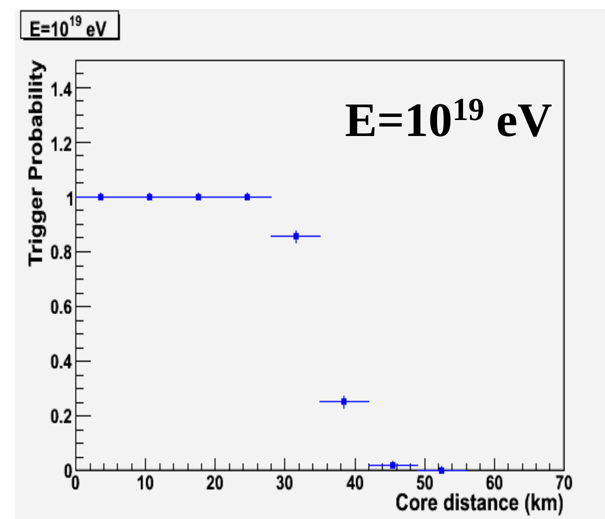


core distance to eye

Fd ——

Fd+1 Tank ——





Full hybrid simulations with Corsika showers - protons
Hybrid Reconstruction at different levels

Fd

Benefits: energy determination doesn't rely on theoretical assumptions (only for missing energy)

Drawbacks: 10-14% duty cycle, monocular reconstruction may poorly perform

Sd

Benefits: Large exposure, almost 100% duty cycle

Drawbacks: energy determination relies on theoretical assumptions

Hy

- Timing of at least one tank improves dramatically the FD monocular geometry reconstruction (hybrid sample).
- Down in energy below Sd threshold

- Energy scale from Fd with a hybrid reconstruction. It provides a calorimetric measurement for all Sd events (large statistics)

Energy Spectrum(I)

The energy scale is based on fluorescence measurements without relying on a specific interaction model or an assumption about the composition

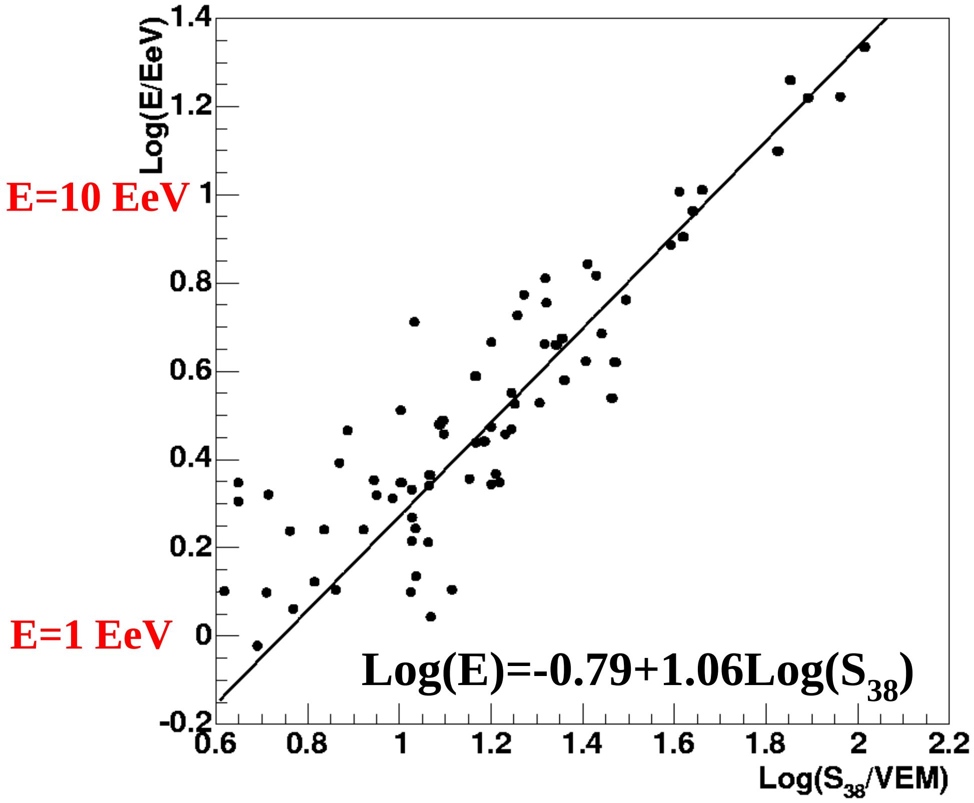
The energy ``calibration''

Compare ground parameter S(1000) with the fluorescence detector energy for hybrid events

Correct for S(1000) dependence on zenith angle at a given energy

Transfer the energy converter to the surface array only events

Sommers et al. (Auger Coll.) 29th ICRC 2005



S38 = the S1000 a shower would have if it came at a zenith angle of 38 deg

Energy Spectrum (II)

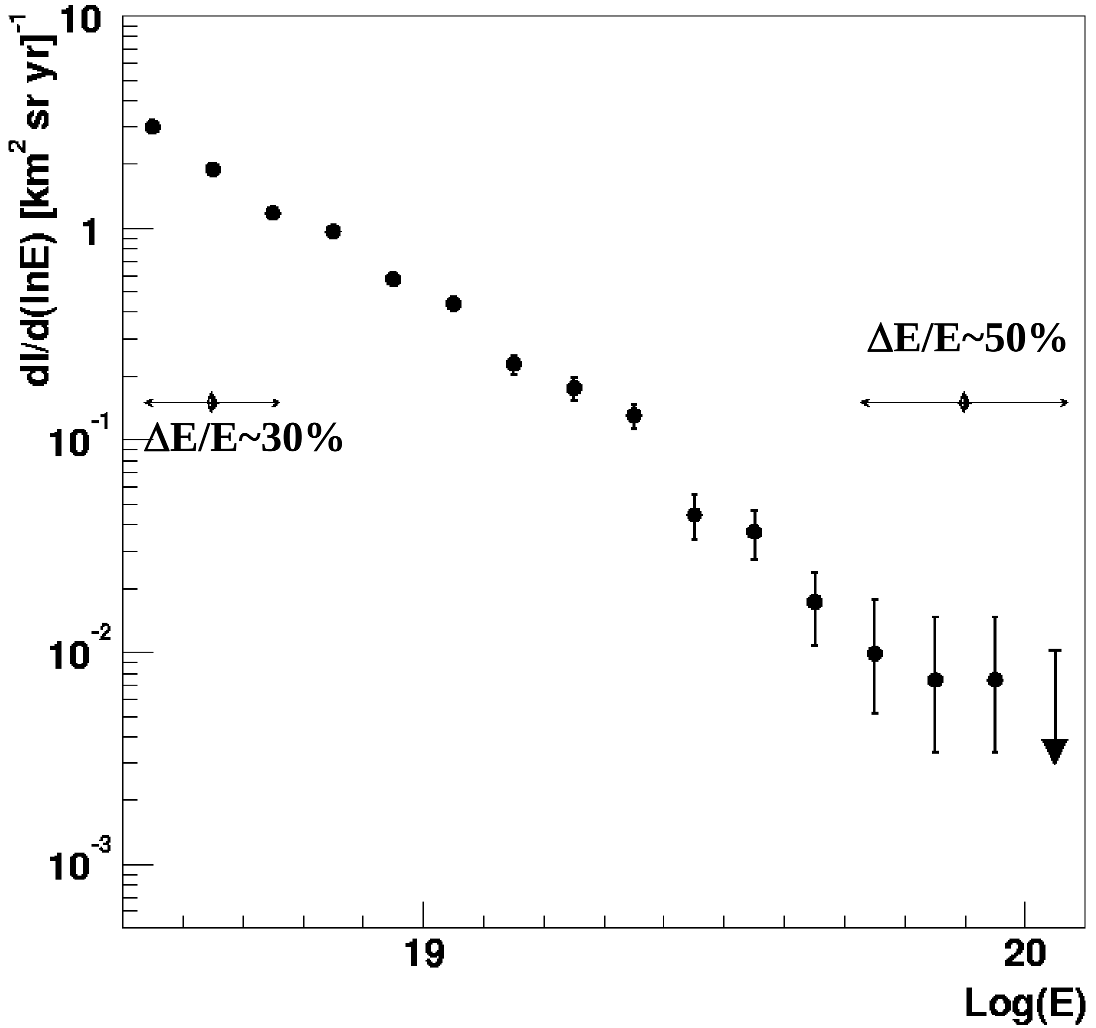
Combines the benefits from each technique

- Fd (Hybrid Energy) +
- Sd large exposure/statistics

Vertical bars: *statistical* errors

Horizontal bars: *systematical* due to Fd energy determination (~25%) & *statistical* from Sd calibration with Fd energy scale

Sommers et al. (Auger Coll.) 29th ICRC 2005



Data set:

Collection period – 1 January 2004 to 5 June 2005

Zenith angles - 0 – 60º Total acceptance – 1750km² sr yr (~ AGASA) – E > 3 EeV (Sd fully efficient)

Energy Spectrum (III)

Compared to other experiments

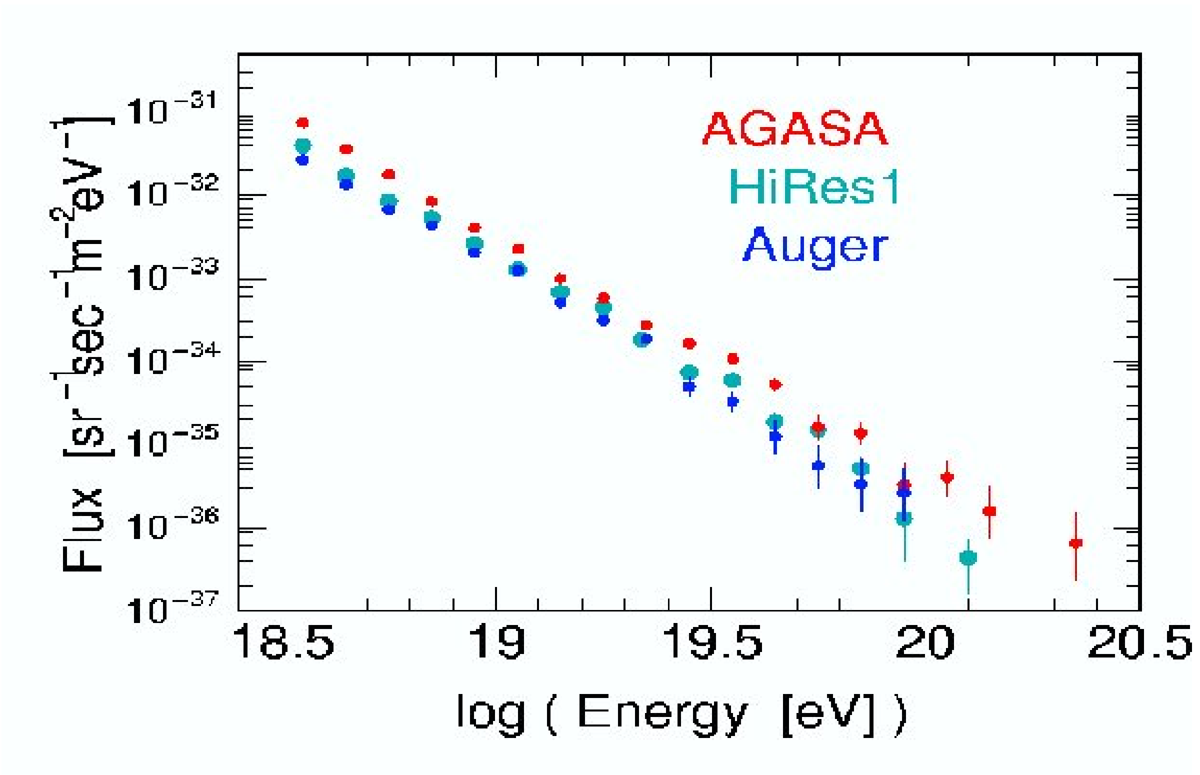
M. Takeda et al. Astroparticle Physiscs 19 (2003) 447

R.U. Abbasi et al. Phys. Lett B (to be published)

Sommers et al. (Auger Coll.) 29th ICRC 2005

No events above 10^{20} eV yet

Similar shape to the HiRes spectrum



Study of excess from the Galactic Center (I)

The Pierre Auger Coll., Astroparticle Phys. 27 (2007) 244

Data set:

Collection period – 1 January 2004 to 30 March 2006

Zenith angles - 0 – 60º – E > 0.8 EeV (Sd data calibrated with Fd Hybrid data)

Comparison to AGASA

Energy interval (1.0 – 2.5 EeV)
angular scale: 20° around GC

$n_{obs} / n_{exp} = 2116 / 2159.5$
Auger: 0.98 ± 0.02(stat) ±0.01(sys)

AGASA: 1.22 ±0.05(stat)
22% excess would give $n_{obs} = 2634$ and a 10 σ excess

Comparison to SUGAR

Energy interval (0.8 – 3.2 EeV)
angular scale: 5° around GC

$n_{obs} / n_{exp} = 286 / 289.7$
Auger:0.98 ± 0.06(stat) ±0.01(sys)

SUGAR: 1.85±0.29(stat)
85% excess would give $n_{obs} = 536$ and a 14.5 σ excess

No excess found

Search for a point-like source in the direction of Sagittarius A^*: upper bound derived

Study of excess from the Galactic Center (II)

The Pierre Auger Coll., Astroparticle Phys. 27 (2007) 244

The galactic plane

AGASA 20° search radius

SUGAR 5° search radius

Galactic center (Sagittarius A*)
(α, δ) = (266.3°, -29.0°)

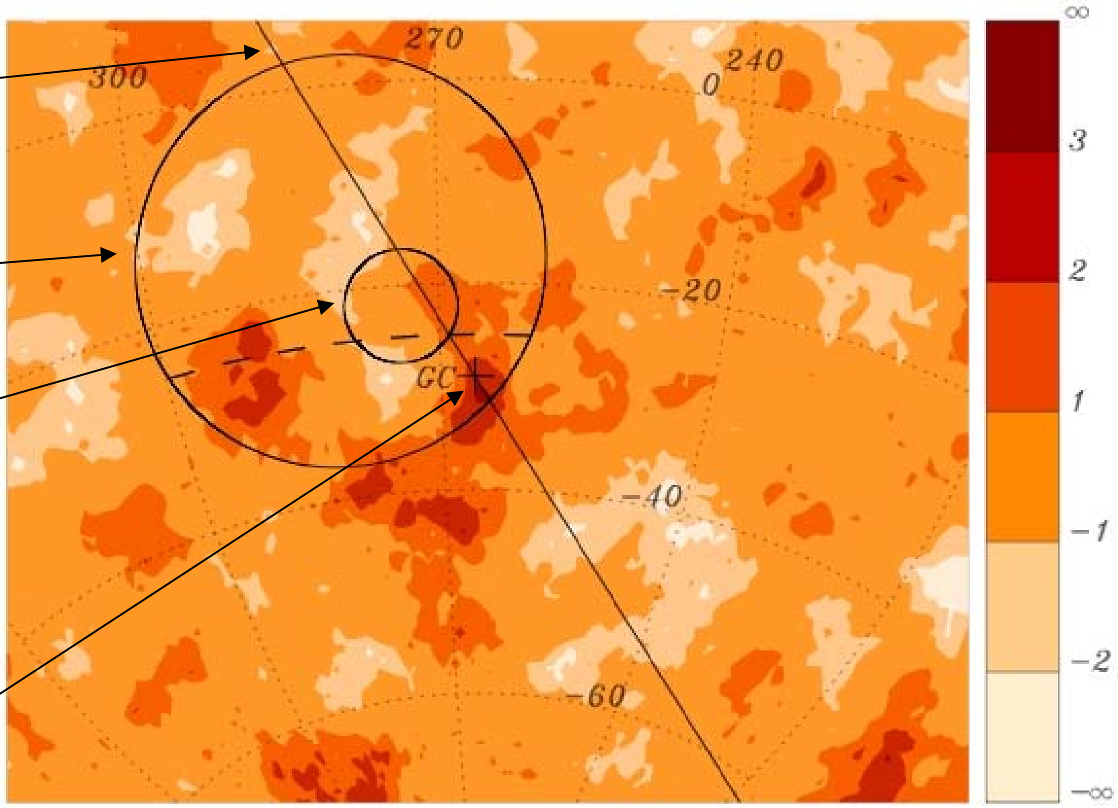


Figure 1: Map of CR overdensity significances near the GC region on angular scales of 5° radius. The GC location is indicated with a cross, lying along the galactic plane (solid line). Also the regions where the AGASA experiment found their largest excess as well as the region of the SUGAR excess are indicated.

An upper limit to the photon fraction (I)

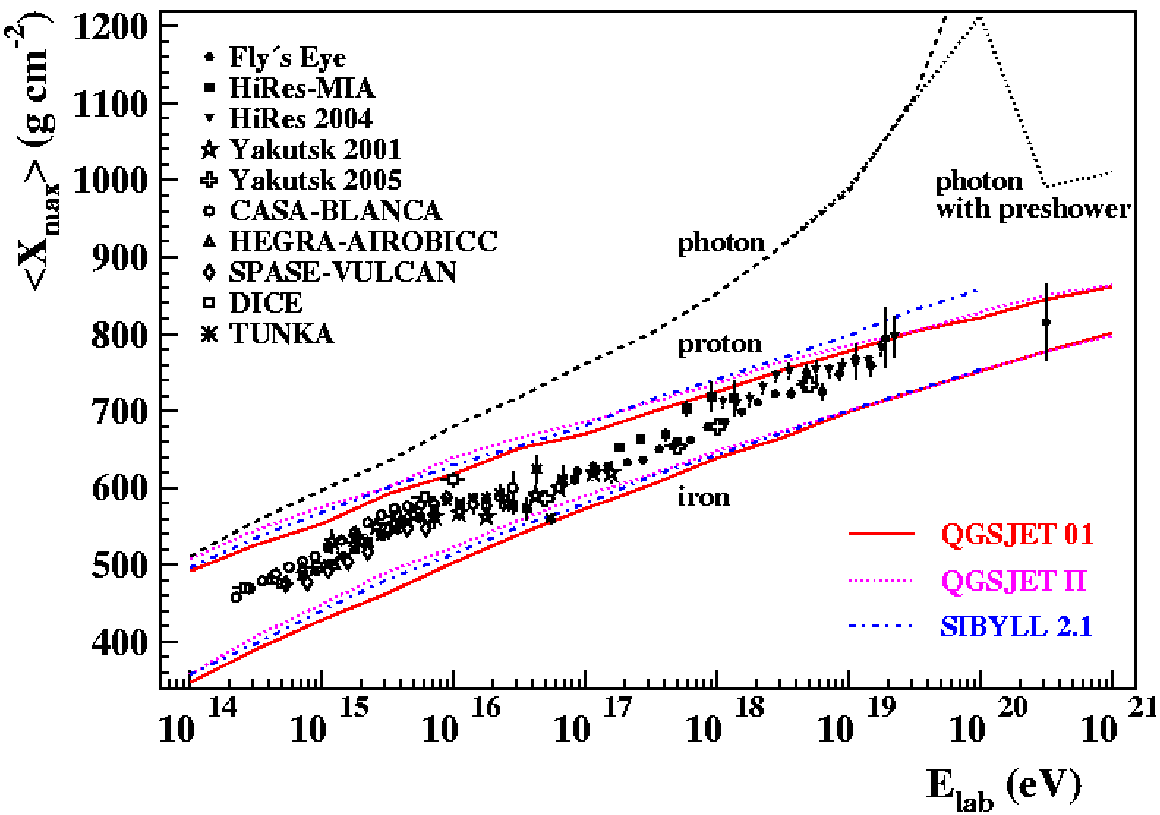
The Pierre Auger Coll., Astroparticle Phys. 27 (2007) 155

Data set:

Collection period – 1 January 2004 to 28 February 2006 (Fd Hybrid data)

Direct observation of the shower longitudinal profile, using the depth of shower maximum X_{max} as discriminator

Auger



Photons develop deeper in the atmosphere than protons or heavier nuclei

The method

For each event, the observed X_{max} is compared to the corresponding (same energy, geometry) average value from simulation with photon primaries

An upper limit to the photon fraction (II)

Event selection:
- geometry and longitudinal profile well reconstructed
- $E > 10^{19}$ eV
- X_{max} observed
- small Cherenkov light fraction
- good atmospheric conditions

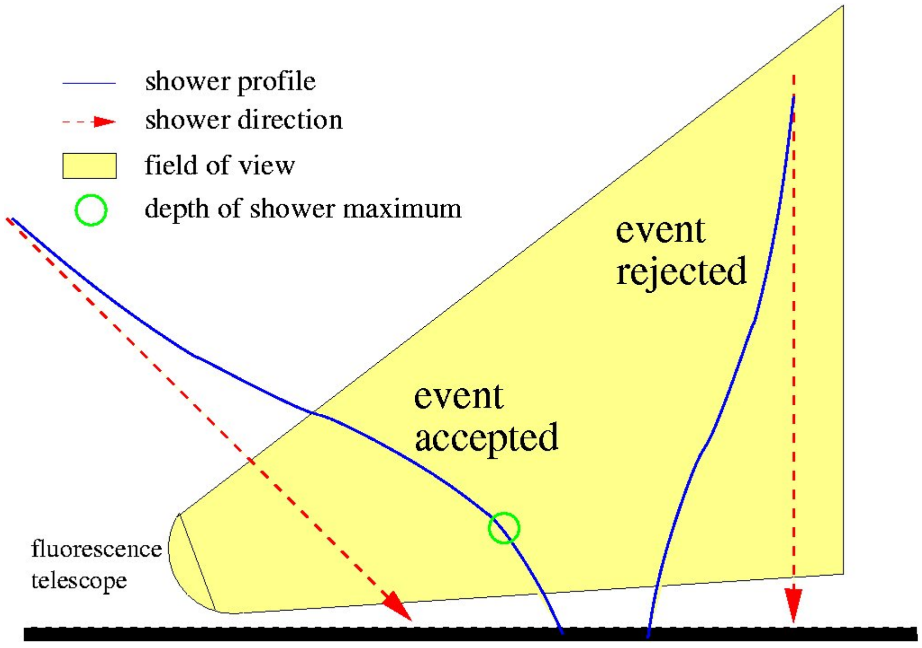
29 events survive the selection

Events with Xmax within a fiducial volume are accepted:

- Xmax well visible; vertical events are rejected as they may land underground (if they were photons)

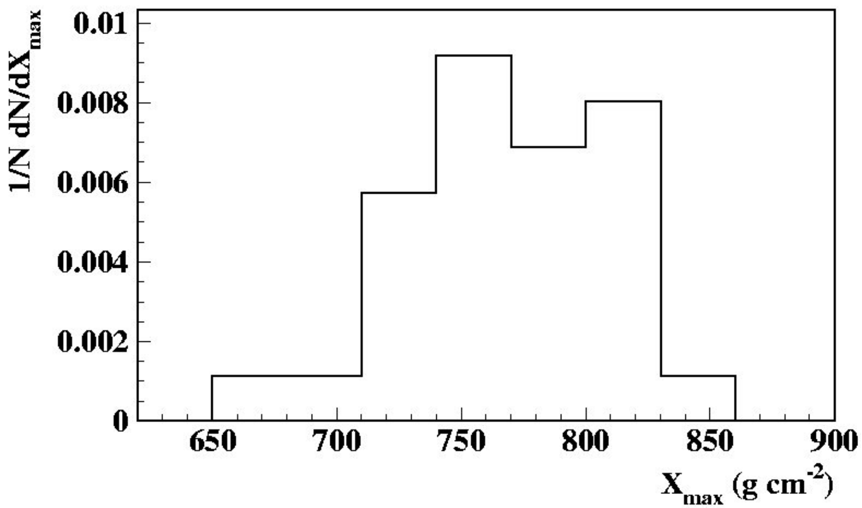
- events far away are rejected as the detector response depends on primary

Goal: an un-biased detector aperture

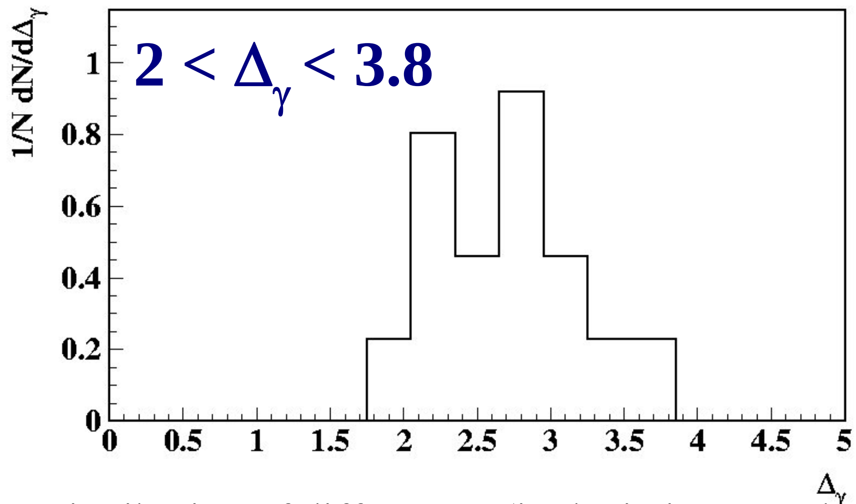


An upper limit to the photon fraction (III)

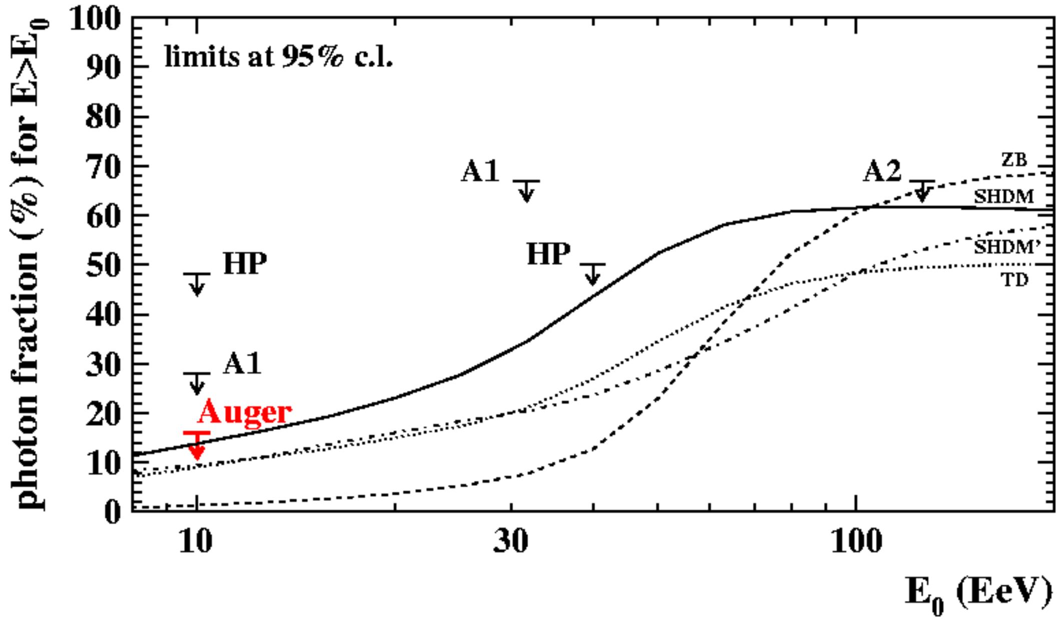
The Pierre Auger Coll., Astroparticle Phys. 27 (2007) 155



Normalized distribution of X_{max} of the 29 events



Distribution of differences (in deviation standard units) between data and simulation for the 29 events



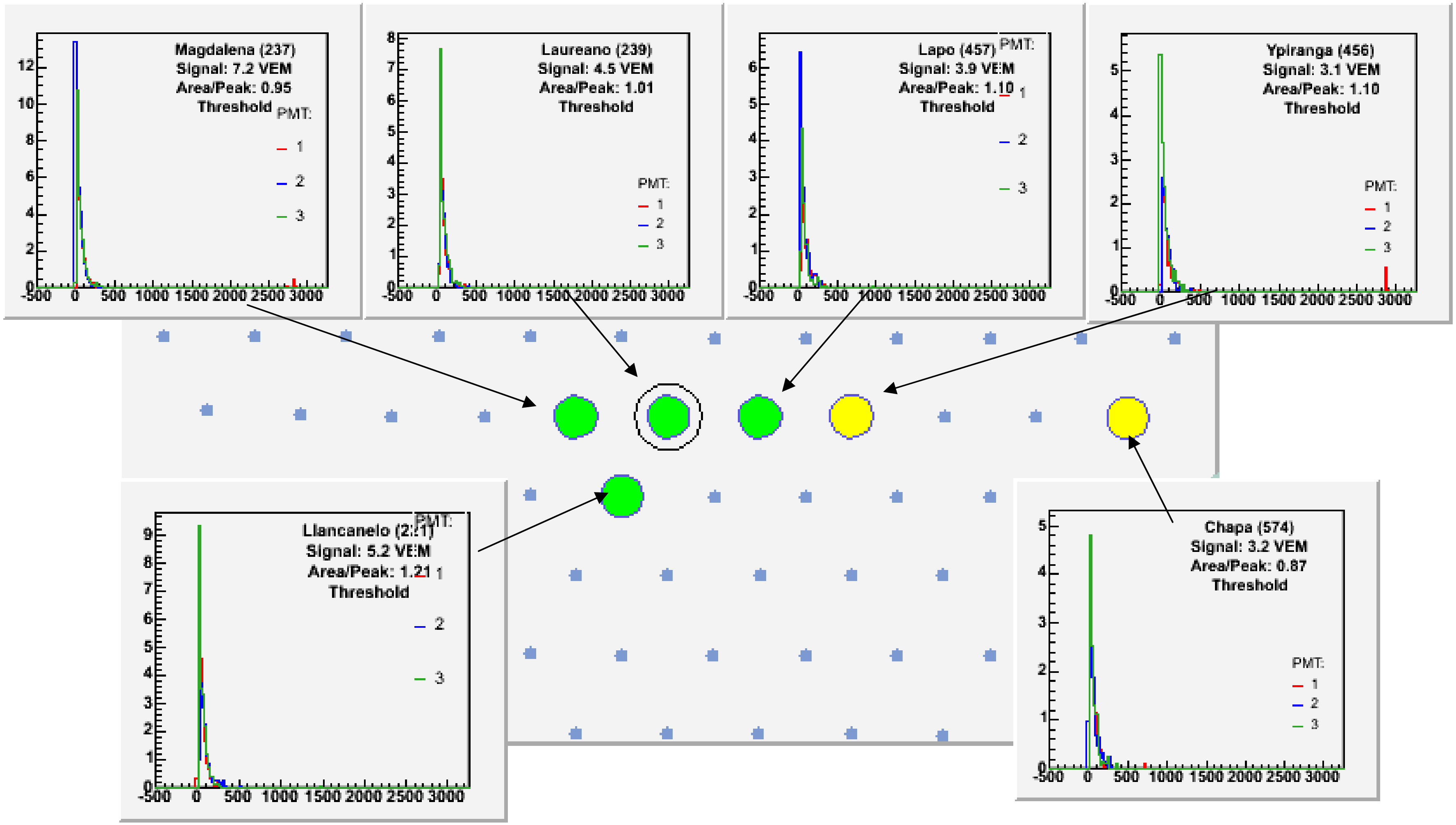
16% upper limit for the photon fraction

Most of the events have E < 20 EeV

$\Delta X_{max} = 28(\text{stat}) \pm 23(\text{sys})$ g cm^{-2}

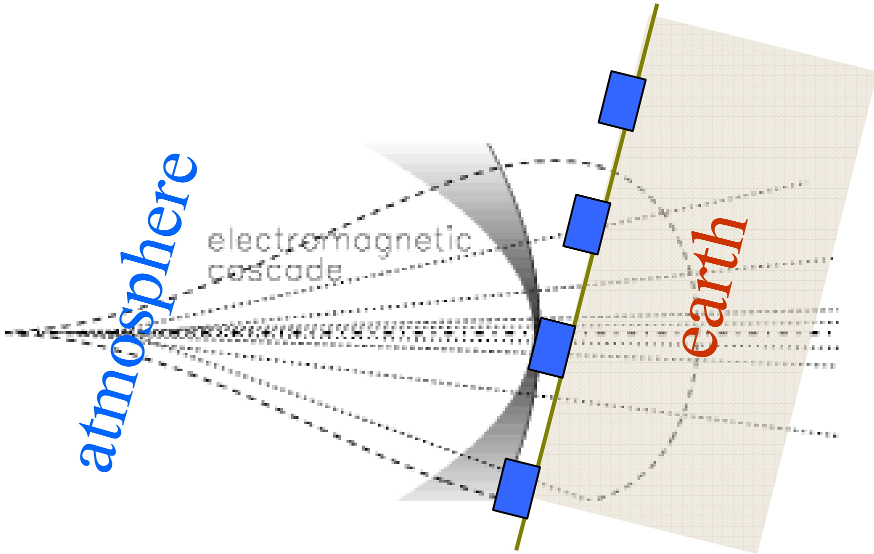
Inclined events (I)

Zenith ~ 80°



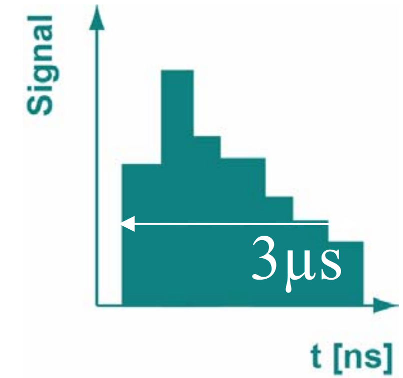
Single peaks, fast rise, accidental background are similar!

Inclined events (II)



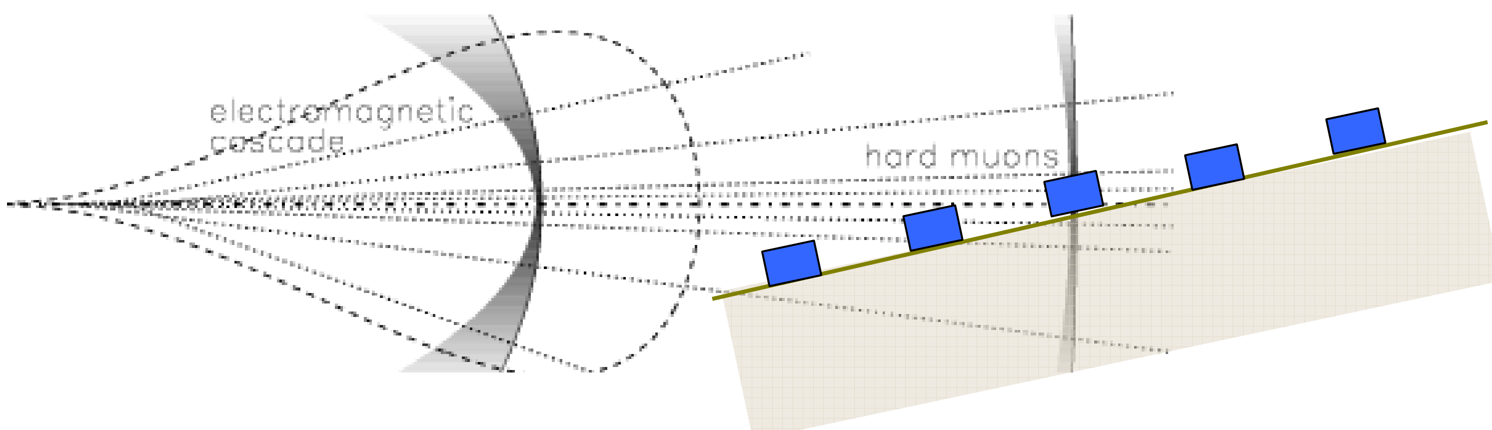
Almost vertical

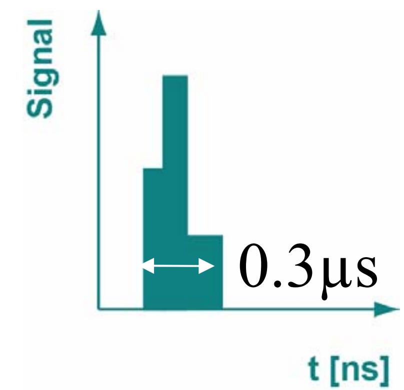
muons + electromagnetic



Very inclined, thin flat front

high energy muons





Important for neutrino detection: observable only if almost horizontal

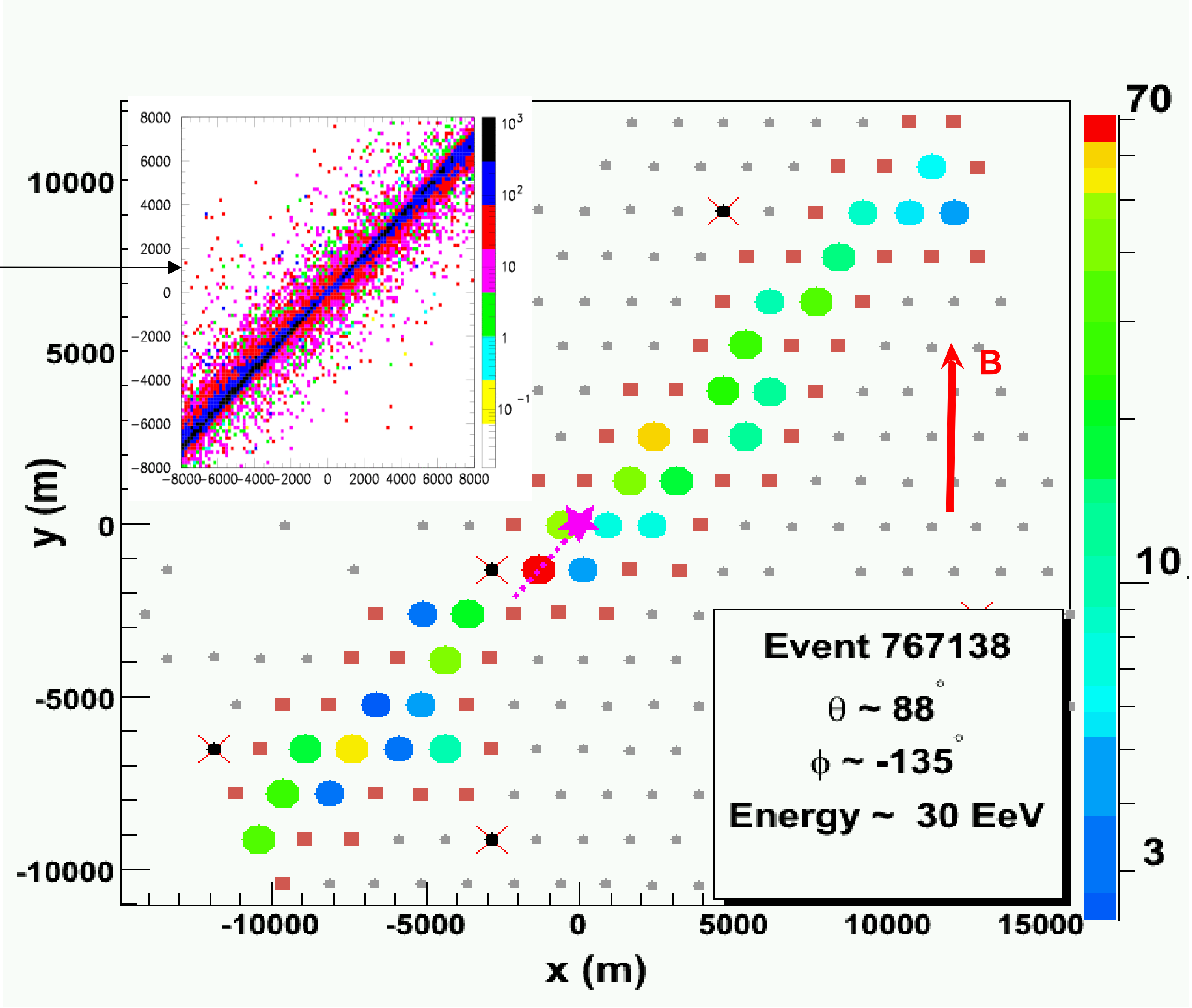
signature would be an inclined shower with large electromagnetic component

Inclined events (III)

31 tanks triggered extending on scale-lenght of about 30 km at ground

Simulated muon map corresponding to the reconstructed zenith and azimuth angles

Separation between μ^+ and μ^- due to the effect of the geomagnetic field



Conclusions

- Auger Data set is growing fast.

- *The southern Observatory will be ready at the beginning of 2008*

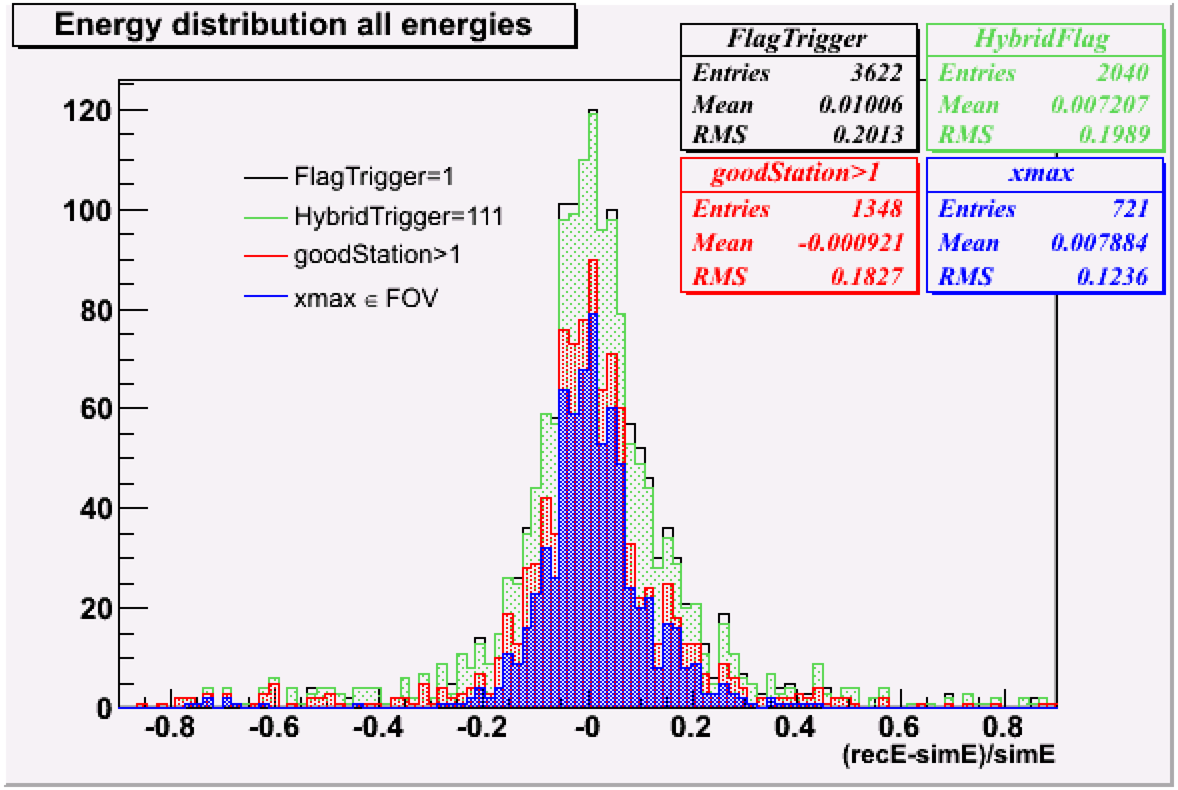
- The benefits of a hybrid measurement have been extremely useful for each analysis

- New results are imminent. Some of them:

  update Sd hybrid-calibrated spectrum
  pure hybrid spectrum
  spectrum for inclined events
  chemical composition (elongation rate)

- *Plans for the Observatory in the northern hemisphere are well advanced*

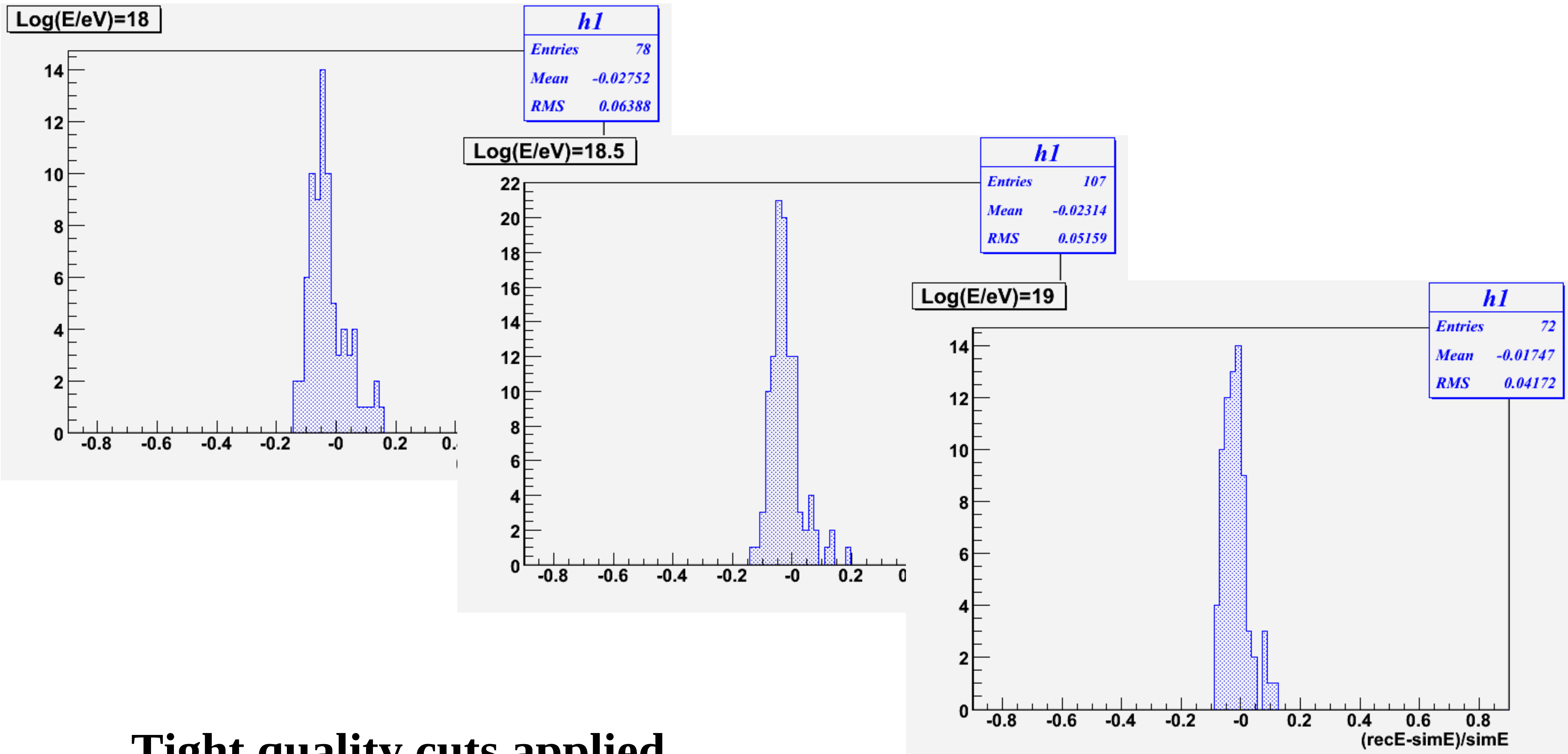
Energy resolution (hybrid sim/rec)



Basic cuts applied

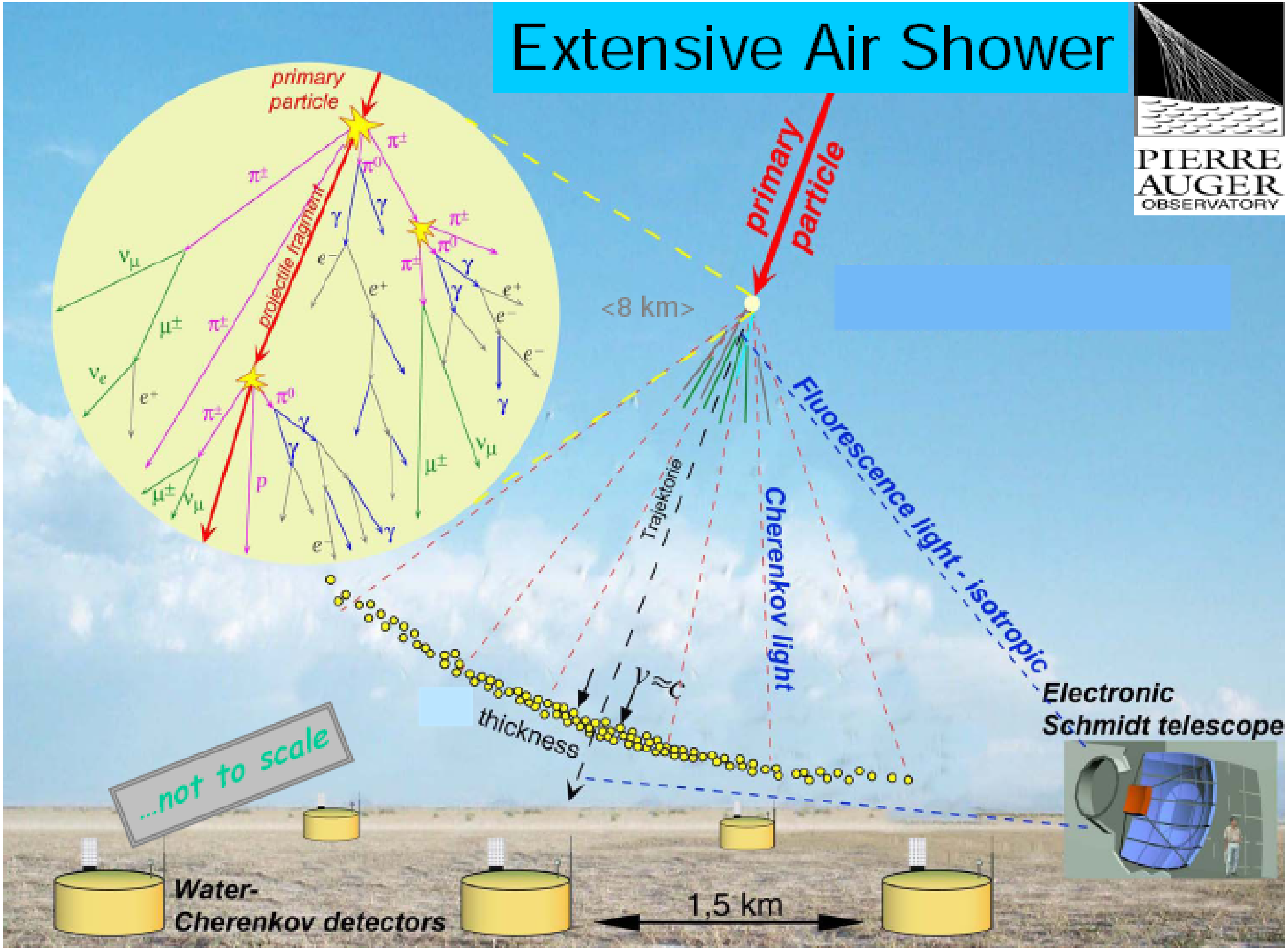
Full hybrid simulations with Corsika showers (fixed energies 10^{17} eV 10^{19} eV) - protons
Hybrid Reconstruction at different levels

Energy resolution (hybrid sim/rec)

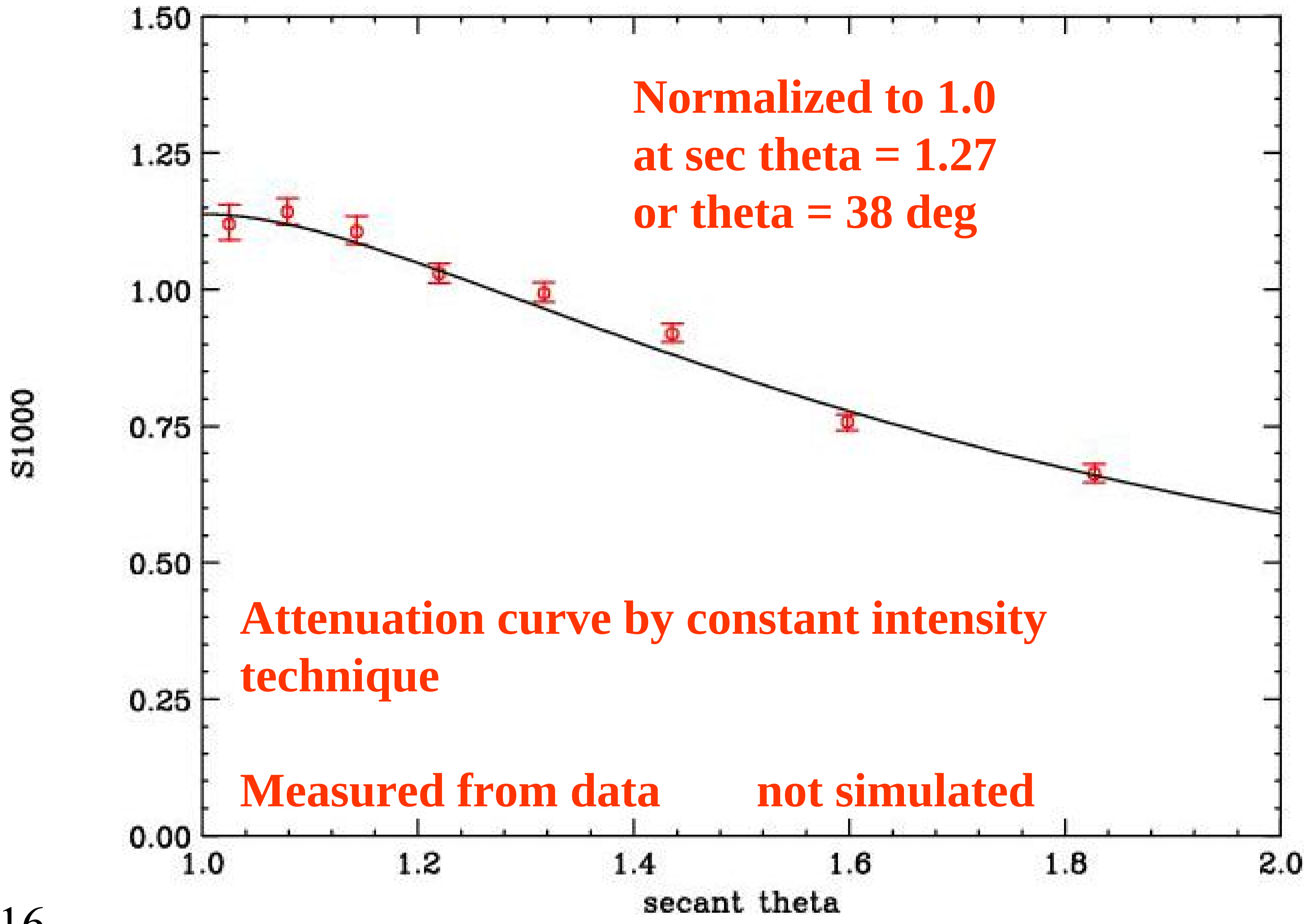


Tight quality cuts applied

Full hybrid simulations with Corsika showers (fixed energies 10^{17} eV 10^{19} eV) - protons
Hybrid Reconstruction at different levels

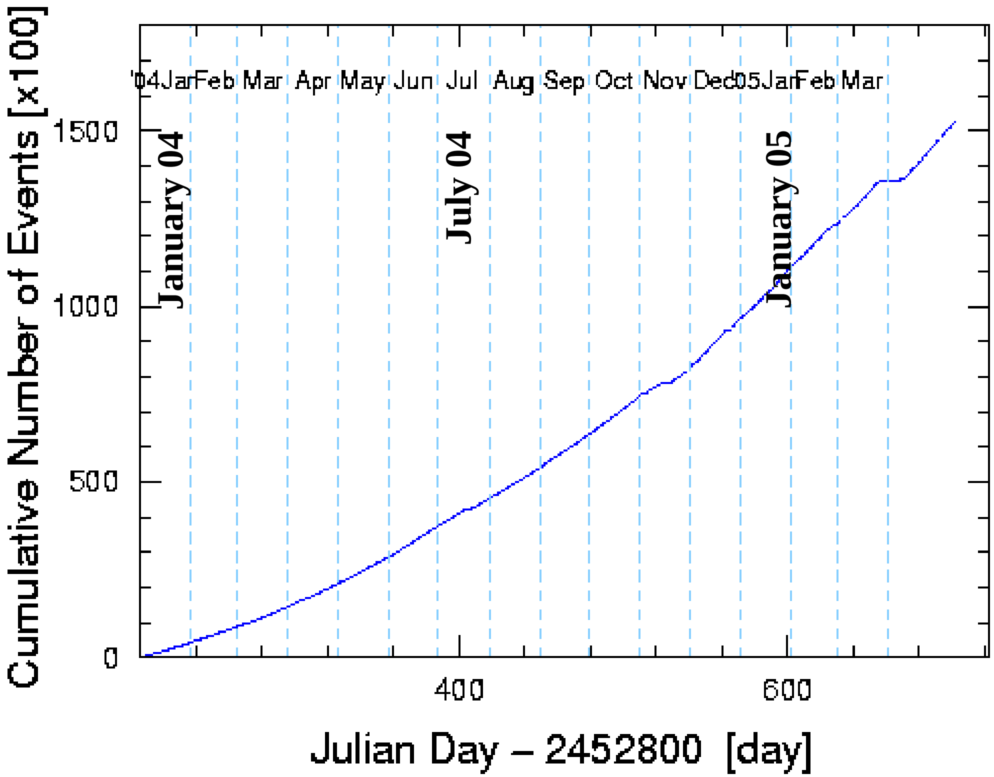


Extensive Air Shower
PIERRE
AUGER
OBSERVATORY
primary particle
primary particle
projectile fragment
<8 km>
Fluorescence light - isotropic
Cherenkov light
Trajektorie
v≈c
thickness
...not to scale
Electronic
Schmidt telescope
Water-
Cherenkov detectors
1,5 km


1.50
1.25
1.00
0.75
0.50
0.25
0.00
S1000
1.0
1.2
1.4
1.6
1.8
2.0
secant theta
Normalized to 1.0
at sec theta = 1.27
or theta = 38 deg
Attenuation curve by constant intensity
technique
Measured from data not simulated

The First Data Set

Cumulative number of events



Collection period – 1 January 2004 to 5 June 2005

Zenith angles - 0 - 60º

Total acceptance – 1750km^2 sr yr (~ AGASA)

Surface array events (after quality cuts)

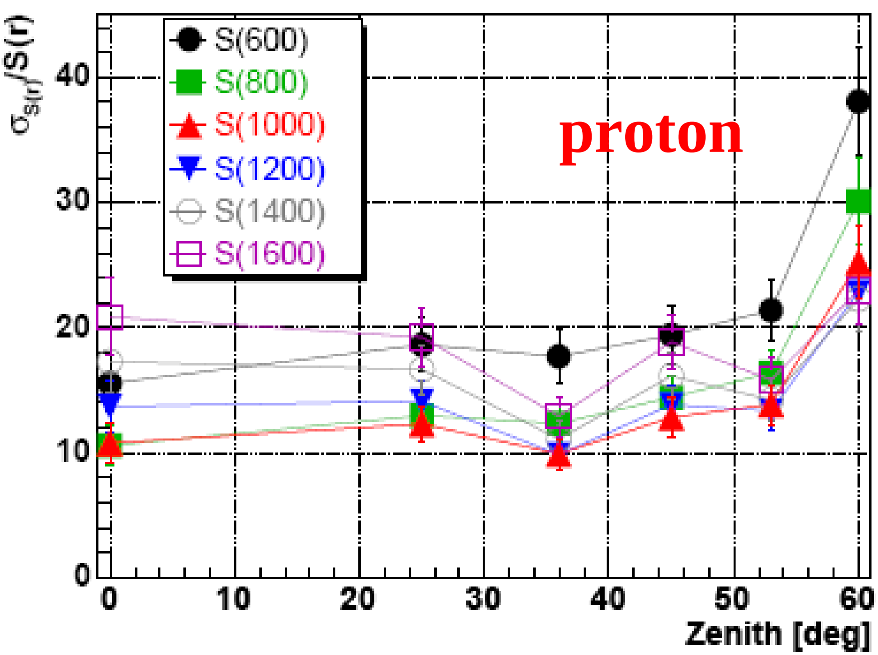
- Current rate - 18,000 / month
- Total -~180,000

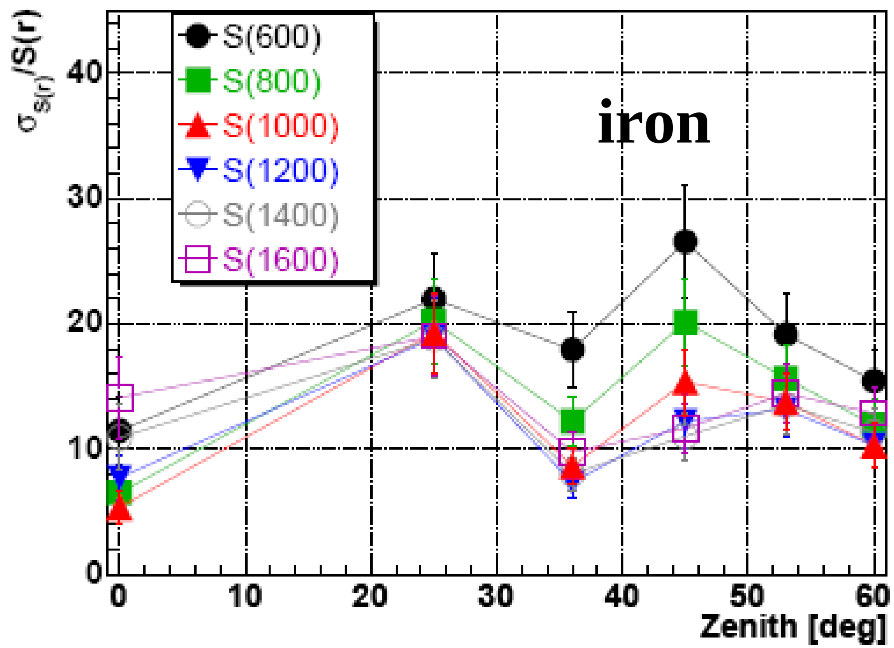
Hybrid events (after quality cuts)

- Current rate – 1800 / month
- Total ~ 18000

SD reconstruction (II)

Why S1000?
It's the distance that minimizes the relative error (given the surface detector tank spacing)





Large systematics expected on the energy:
- 30% from the high-energy hadronic interactions models
- 10-20% from low energy hadronic interaction models