Thirteenth Marcel Grossmann Meeting - MG13
Stockholm, July 1-7, 2012

Results from the Pierre Auger Observatory

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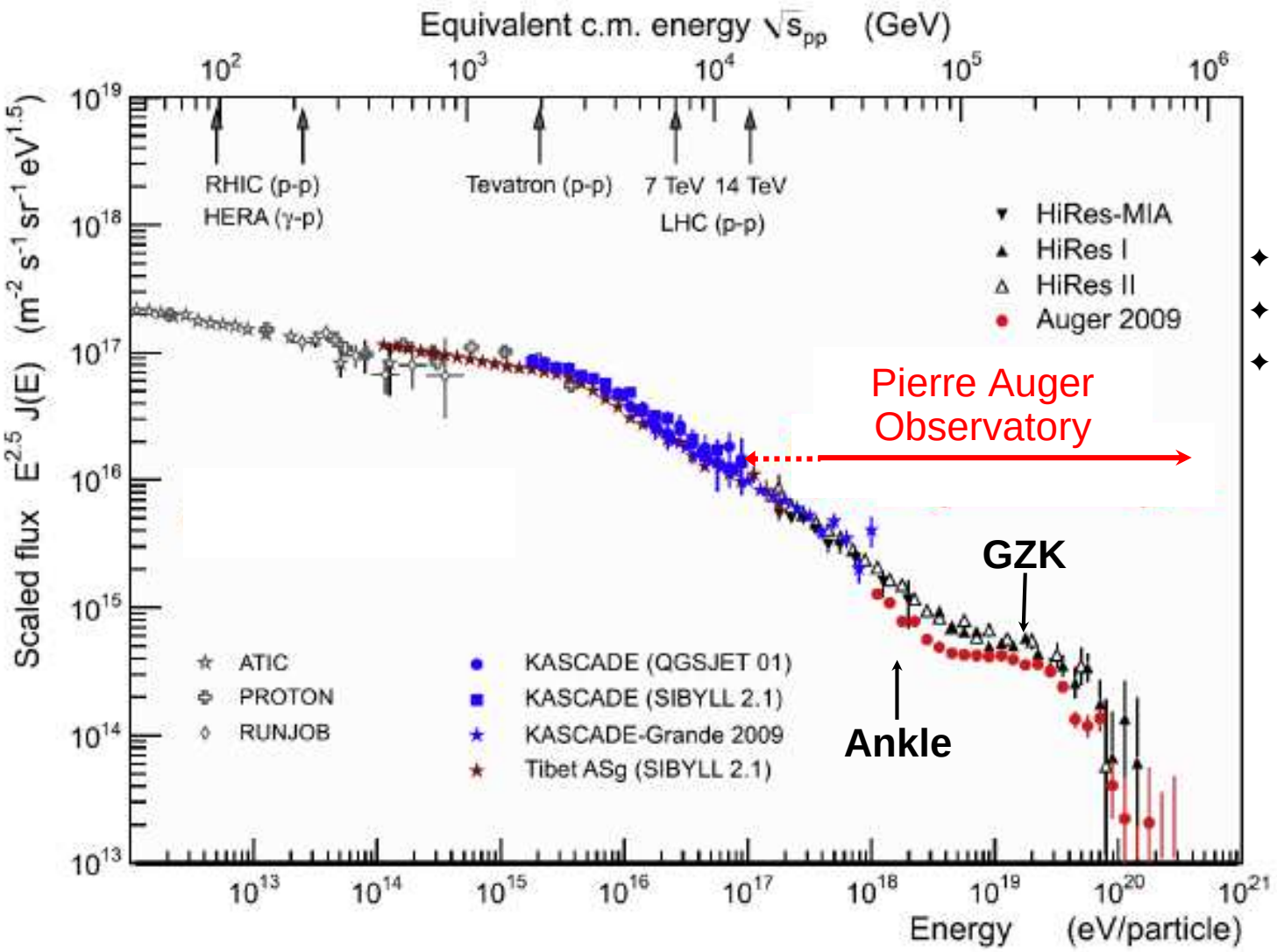
for the Pierre Auger Collaboration

Outline

- The Pierre Auger Observatory:
  the physics case and the hybrid detector

- Recent results on:
  - Energy spectrum
  - Mass composition
  - Arrival directions
  - Search for UHE photons and neutrinos
  - Hadronic interactions
  - ….

Investigating the Ultra-High Energy region



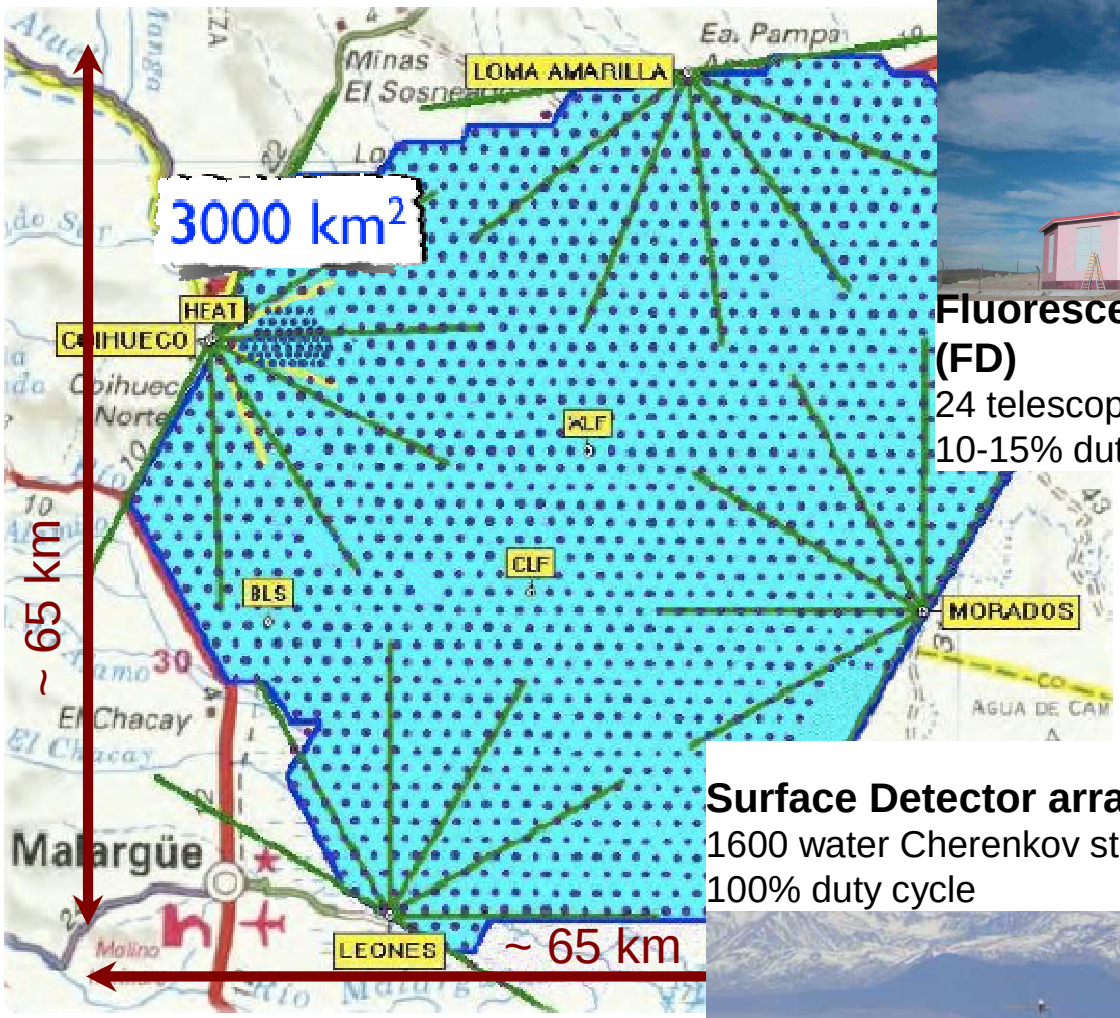
H. Bluemer et al, 2009

Physics Goals

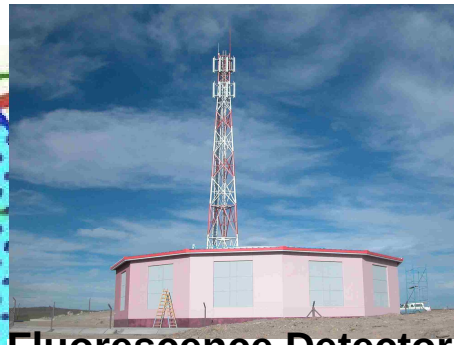
- Sources and Propagation
- Energy spectrum at UHE
- Mass composition

Need for huge exposures in order to have reasonable statistics

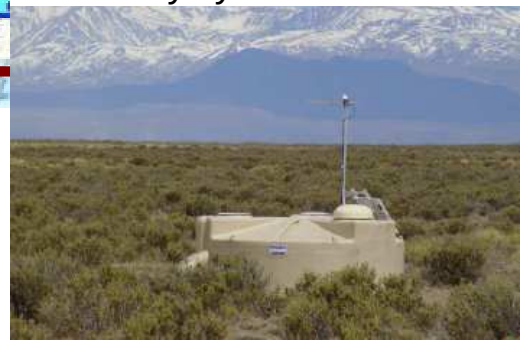
The Pierre Auger Observatory



Malargüe (Mendoza, Argentina)
1400 m s.l.



Fluorescence Detector (FD)
24 telescopes,
10-15% duty cycle

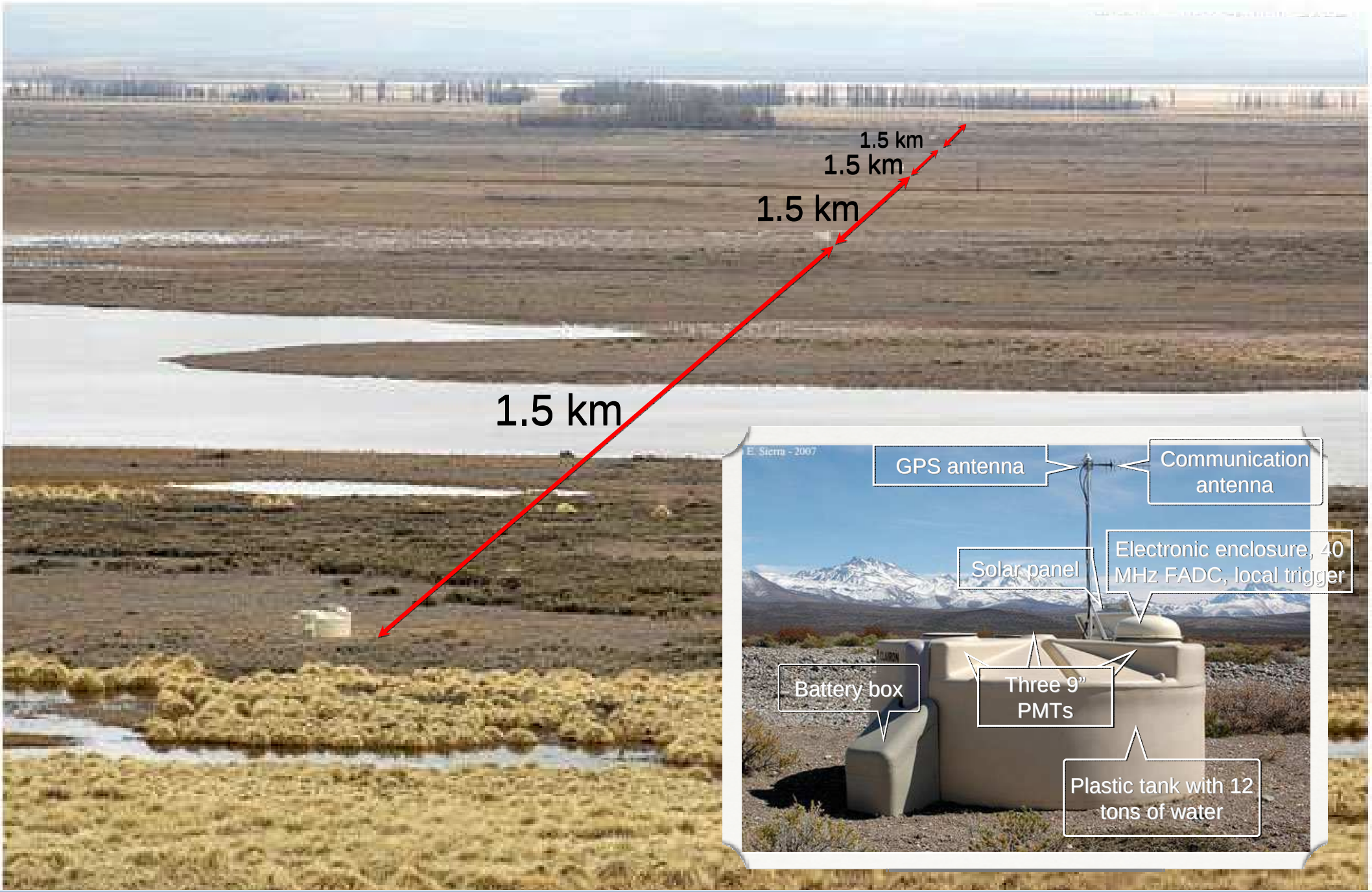


Surface Detector array (SD)
1600 water Cherenkov stations,
100% duty cycle

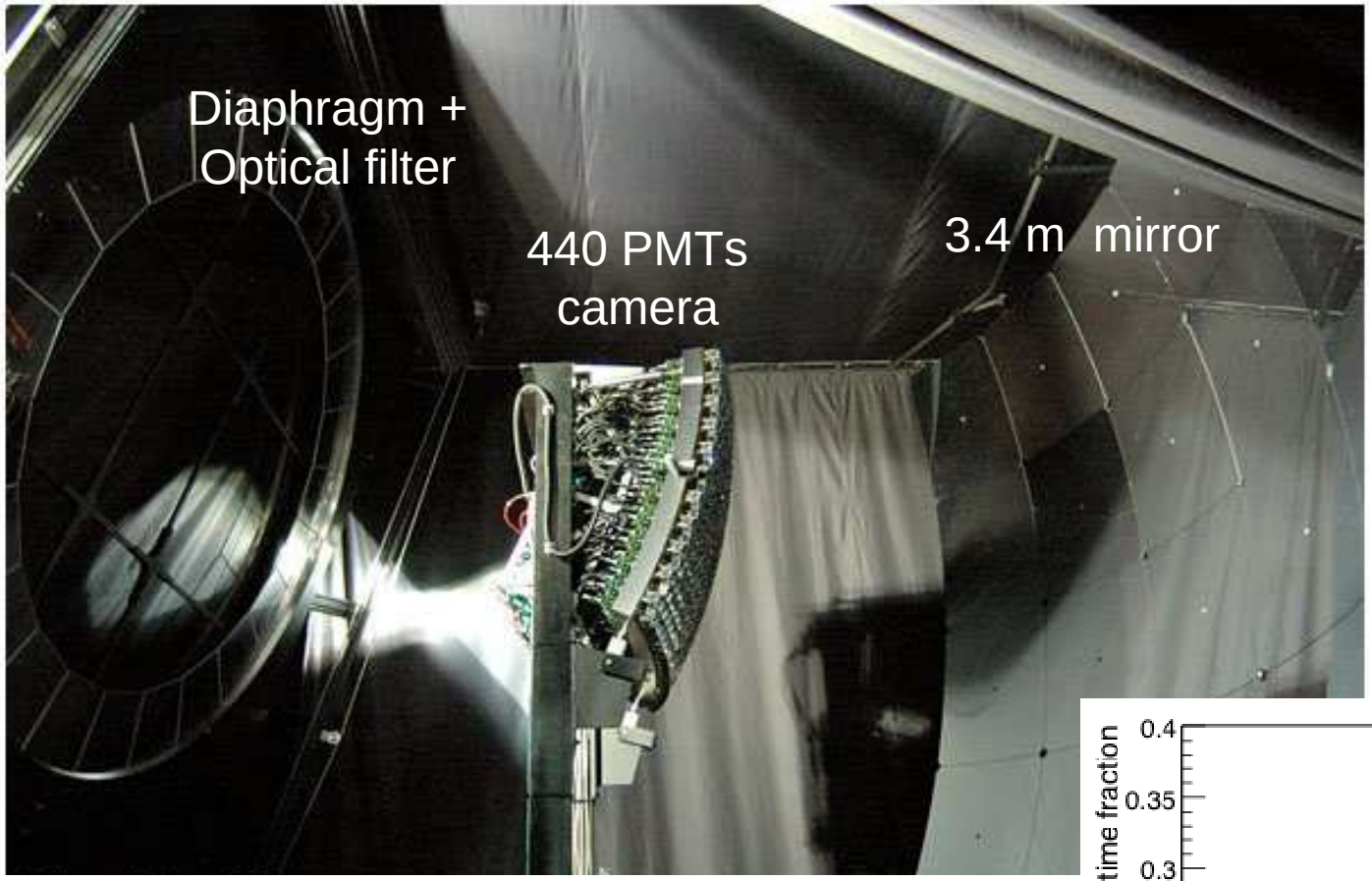
Investigate cosmic rays with E $\gtrsim 10^{17}$ eV

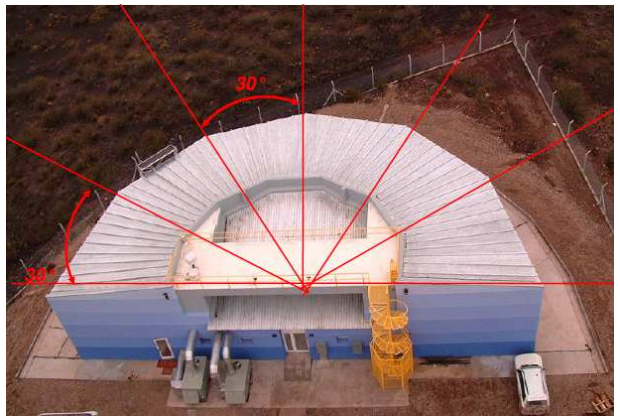
- Energy spectrum
- Mass composition
- Arrival direction

The Surface Detector (SD)

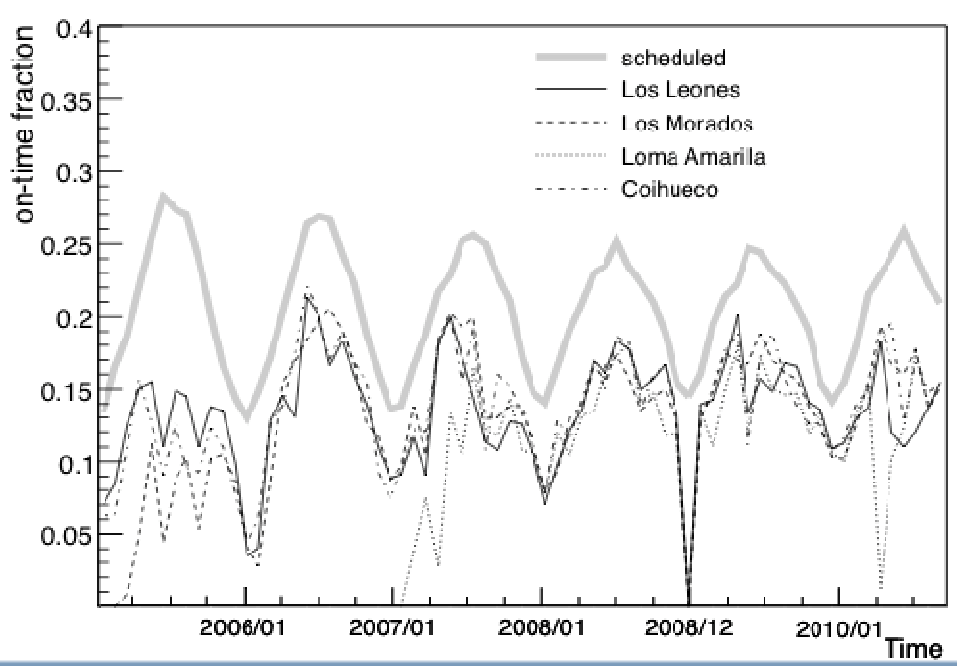


The Fluorescence Detector (FD)





- 24 telescopes in 4 sites
- Field of view:
  0-30º in elevation
  0-180º in azimuth
- 3 new telescopes (HEAT)

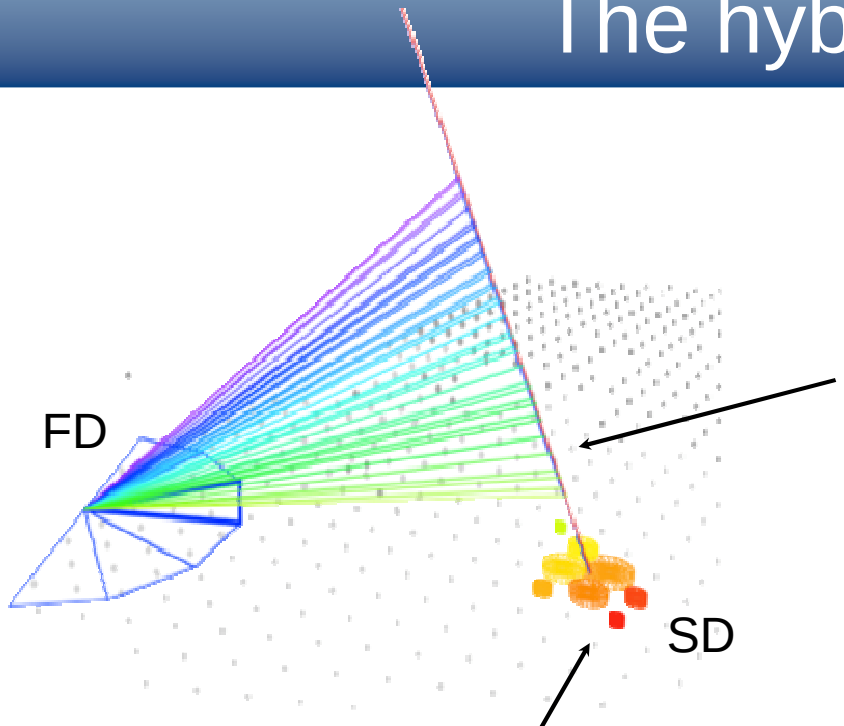


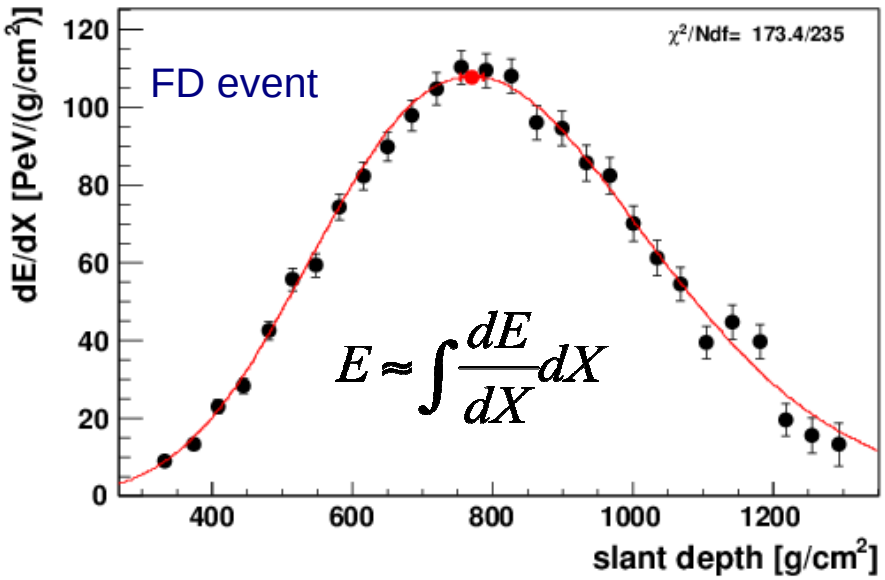
duty cycle ~ 12 - 15%

- DAQ ***scheduled:*** clear and moonless nights

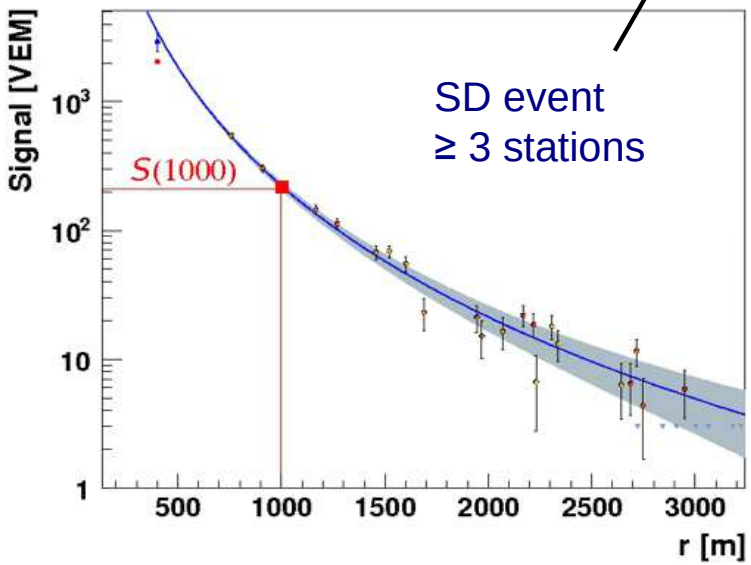
- ***on-time fraction:*** weather conditions + DAQ, detector and communication system efficiencies

The hybrid concept





- observation of *longitudinal profile*
- calorimetric energy (almost independent of hadronic interaction models)



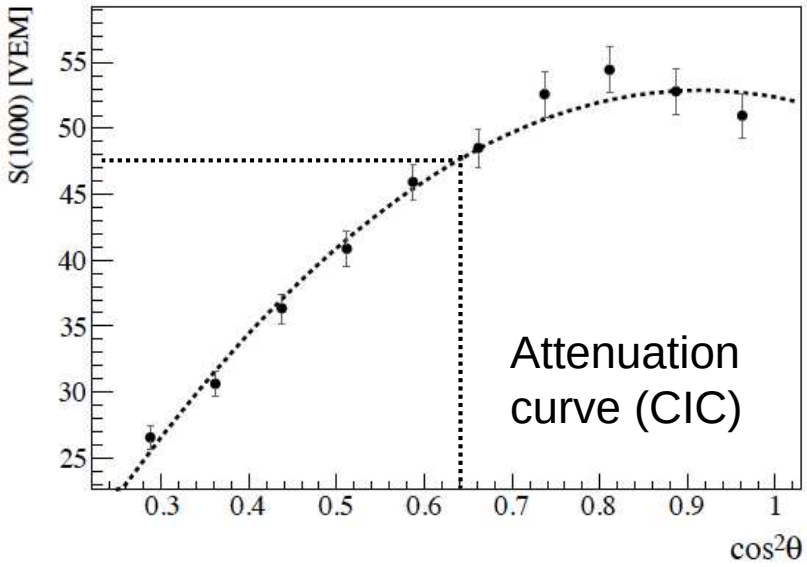
- *lateral distribution* of secondary particles
- energy proportional to the signal S(1000) at 1000 m

SD and FD combined in the ***hybrid mode***
(i.e. FD + at least 1 SD)

- accurate energy and direction measurements
- complementary mass sensitive parameters
- calibration of the energy scale for SD events using ***golden hybrid*** data (FD + ≥ 3 SD stations)

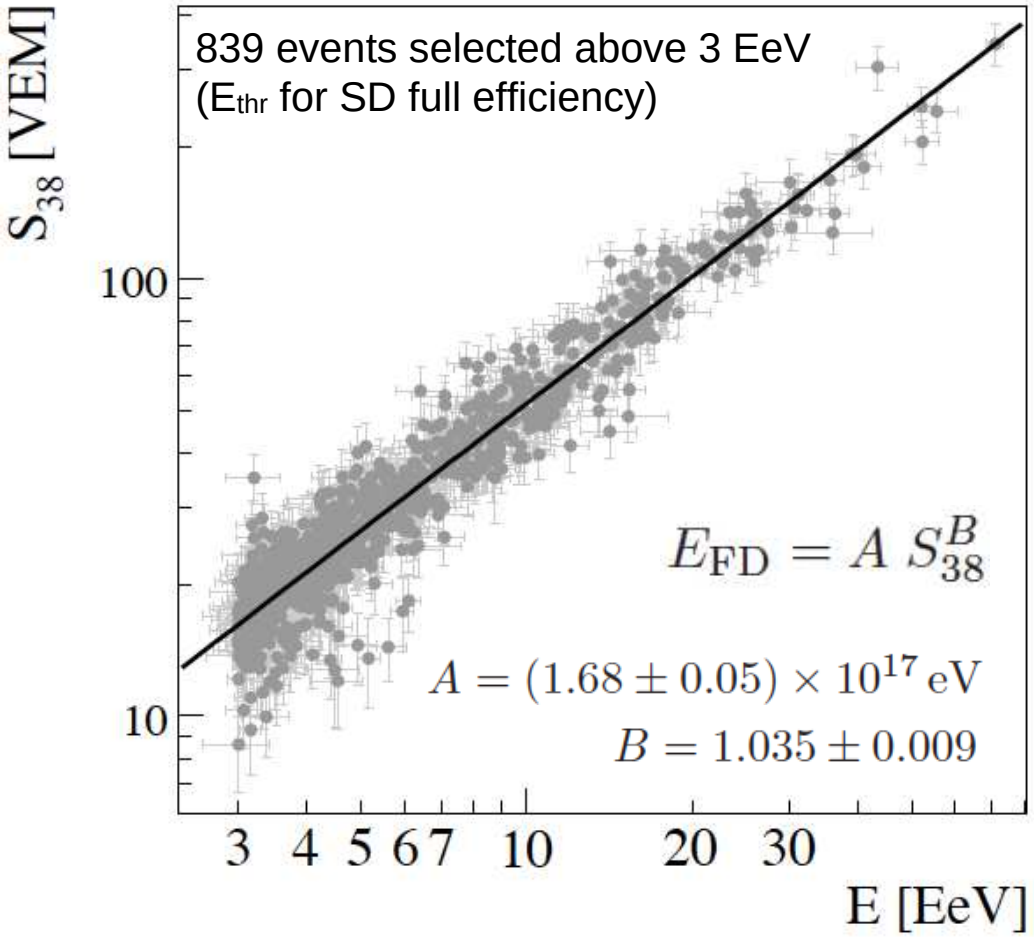
Calibration of the SD energy scale

SD energy calibrated with the calorimetric one measured by FD (almost independent of the hadronic interaction models) using the sub-sample of golden hybrid data



convert to S_{38}: *S1000 that a shower would have produced if it had arrived with a zenith angle of 38°*

R. Pesce for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4809

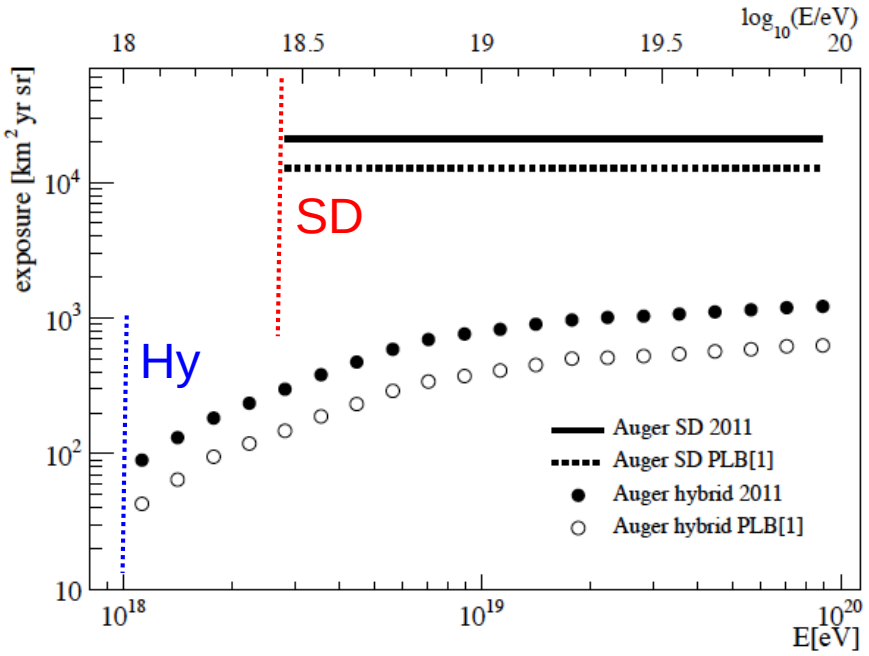


SD energy resolution: E_{SD}/E_{FD} ~ 15%

Systematic uncertainties:

- SD calibration: 7% at 10 EeV; 15% at 100 EeV
- FD energy scale: 22% (dominated by Fluorescence Yield)

Measurement of the energy spectrum

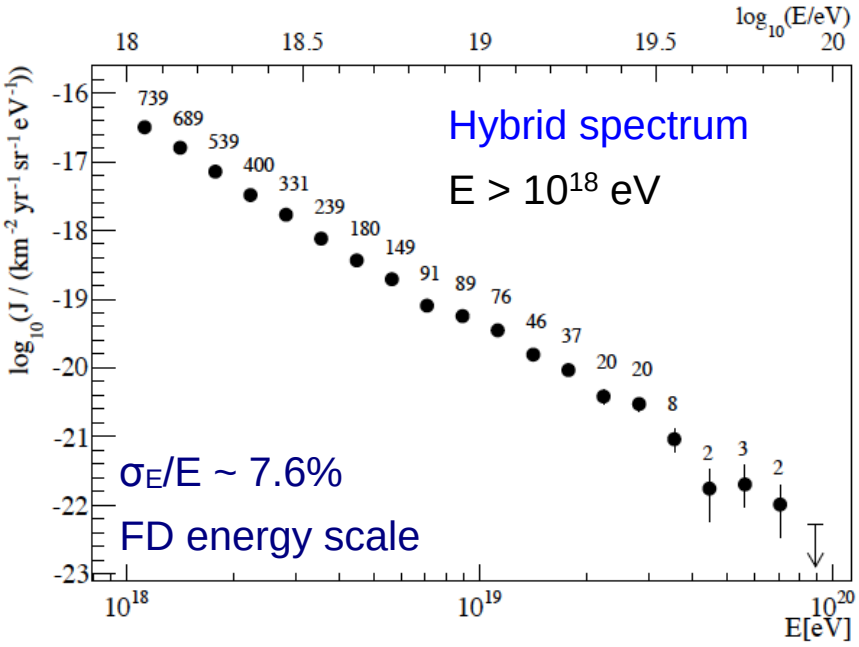


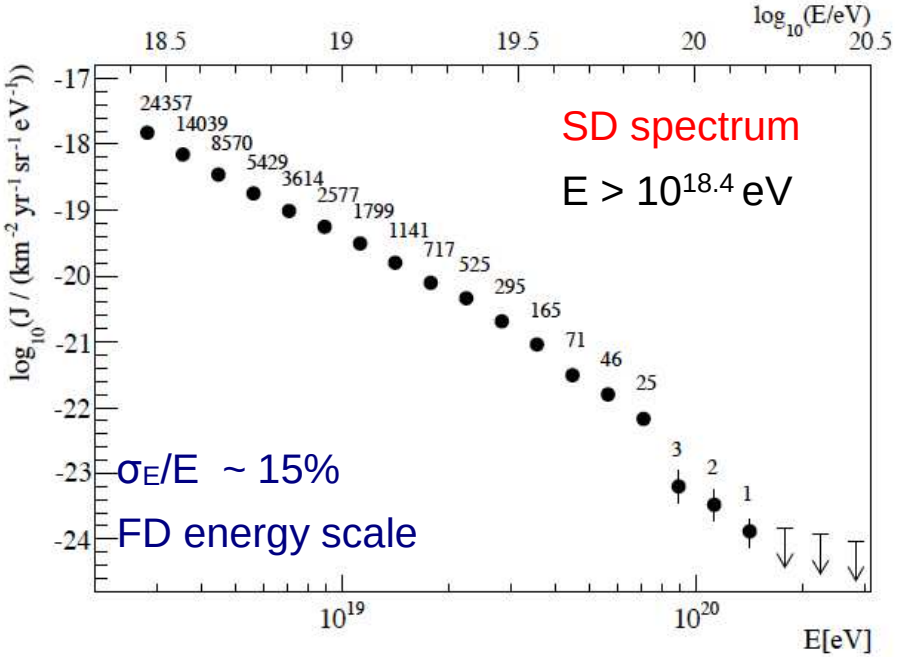
SD Exposure (01/2004-12/2010)

- geometrical calculation (~ 21000 km^2 yr sr)
- syst. uncertainties: ~ 3%

Hybrid Exposure (11/2005-09/2010)

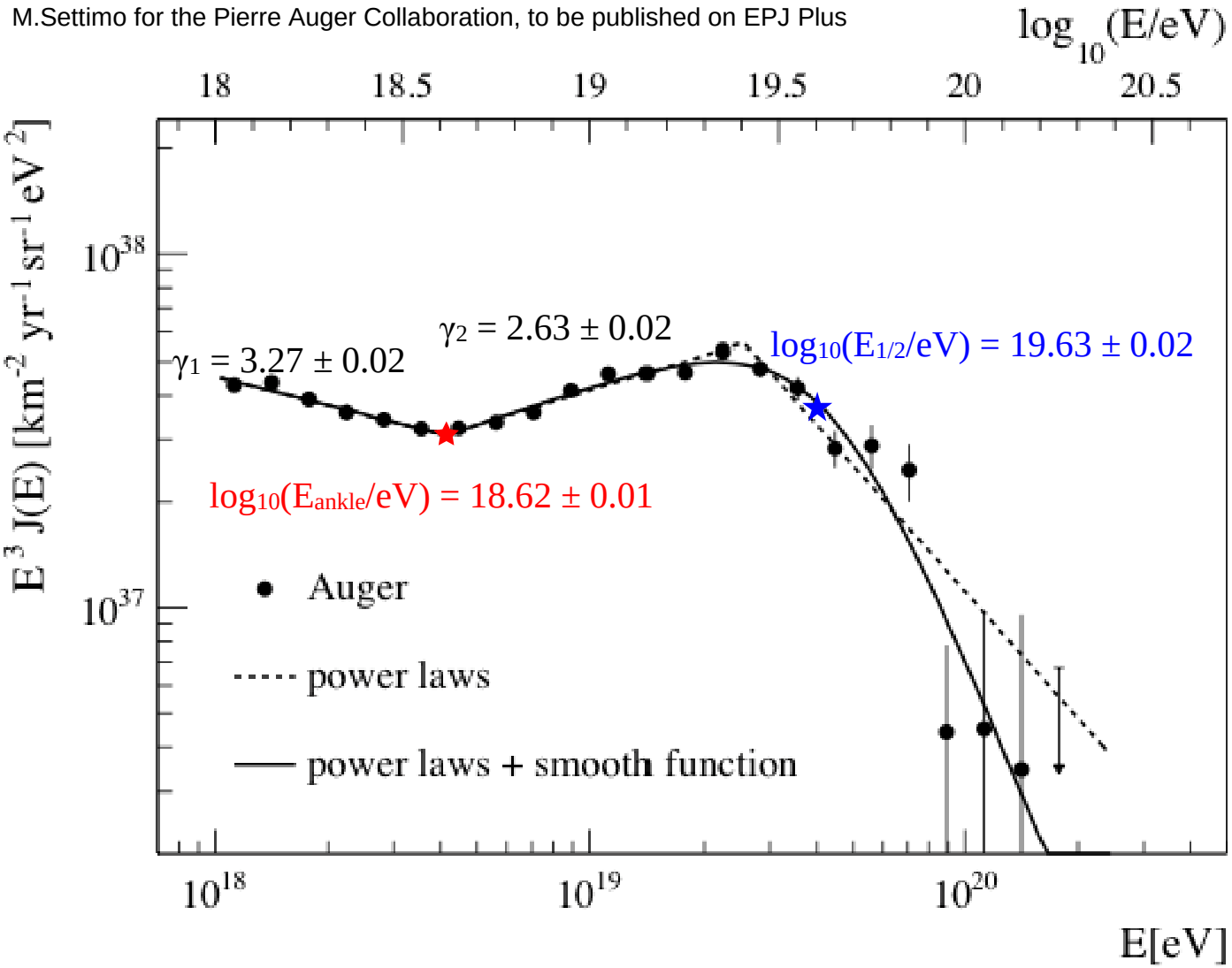
- time-dependent Monte Carlo simulations
- syst. uncertainties ~10% (6%) at 10^{18} eV (10^{19} eV)





Measurement of the energy spectrum

F. Salamida for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4809
M.Settimo for the Pierre Auger Collaboration, to be published on EPJ Plus



Combined Spectrum

- Hybrid: accurate energy measurement down to 10^{18} eV

- SD huge statistics ($E > 10^{18.5}$ eV)

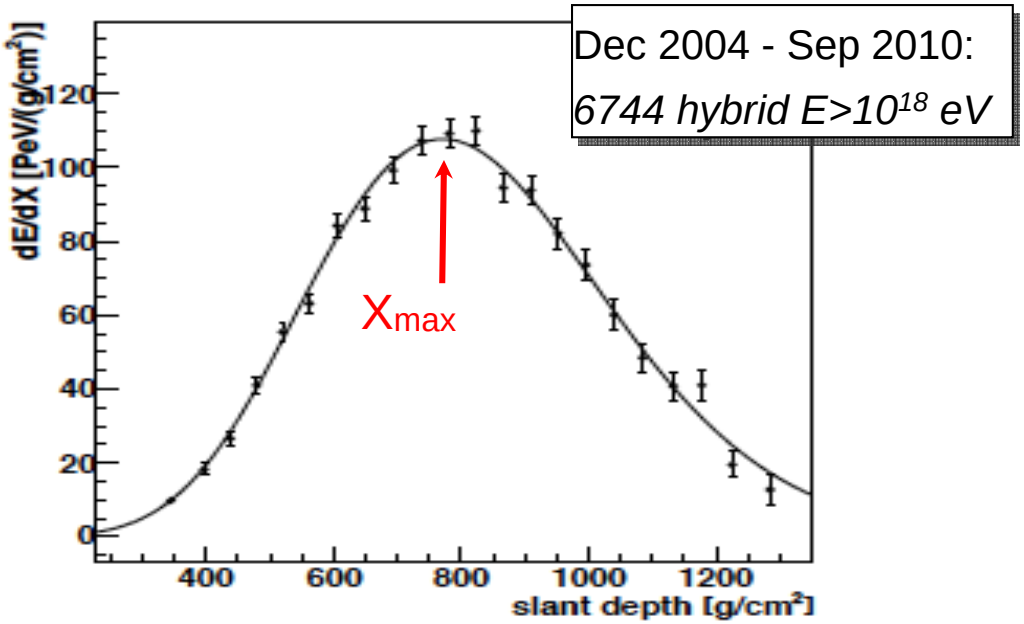
syst. FD energy scale 22%

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

- Ankle: may indicate a change in the origin of UHECR (galactic to extragal. composition)
- Flux suppression above $10^{19.5}$ eV found with 20 σ significance

Mass composition with FD

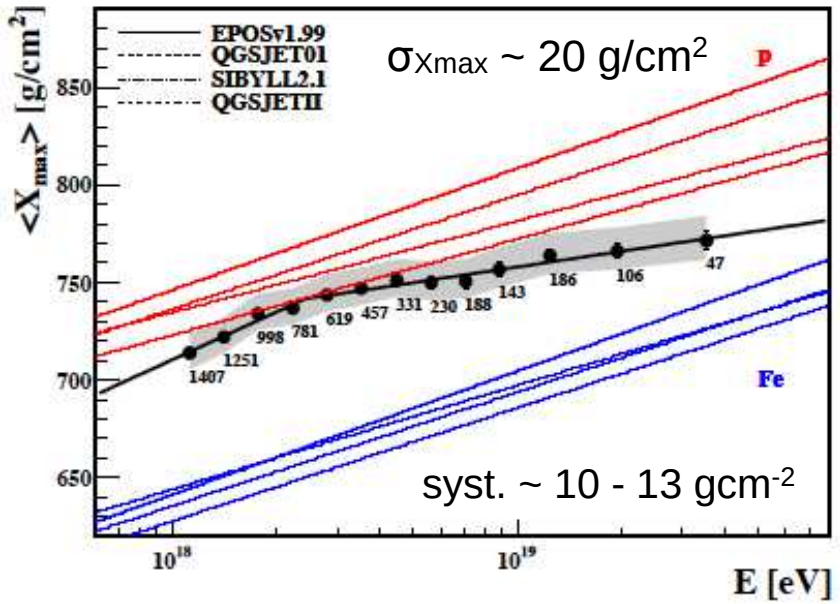
X_{max} and RMS(X_{max}) measured from the longitudinal profile observed by FD

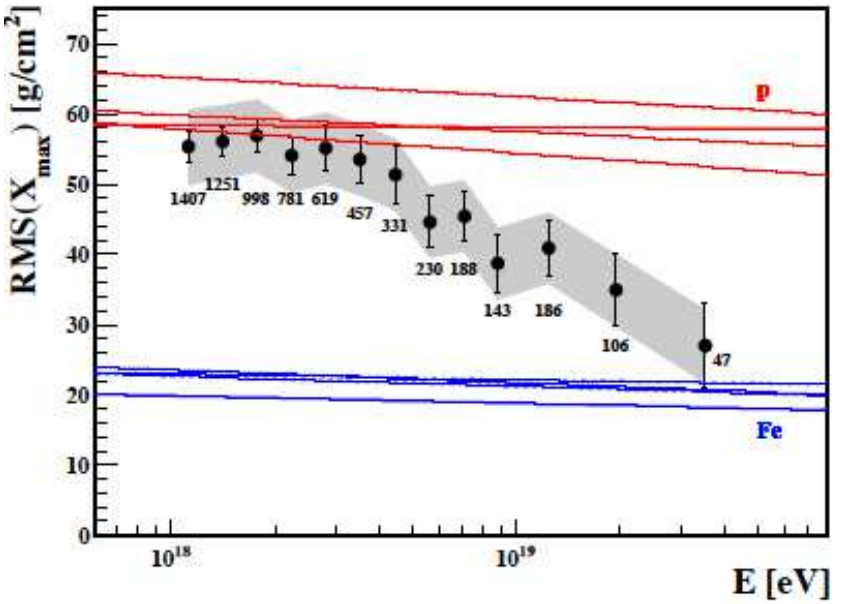


- Break of the elongation rate at ~ 2.4 x 10^{18} eV
- from light to heavier composition at high energy
- similar indication from RMS(X_{max}) and measurement using SD data

significant departure from the predictions of the hadronic models would modify this interpretation

P. Facal for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804

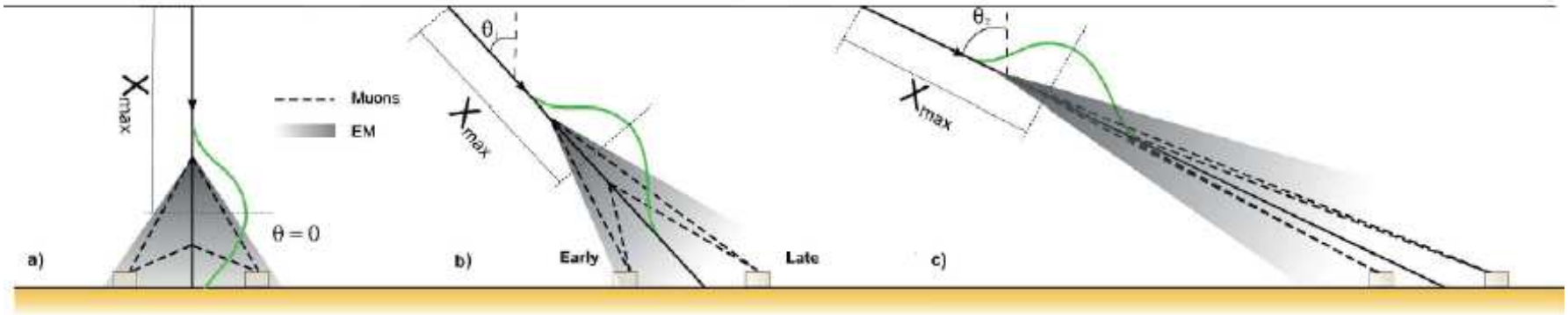




Mass composition with SD

From the Surface Detector:

- Θ_{max} Azimuthal asymmetry of the signal risetime



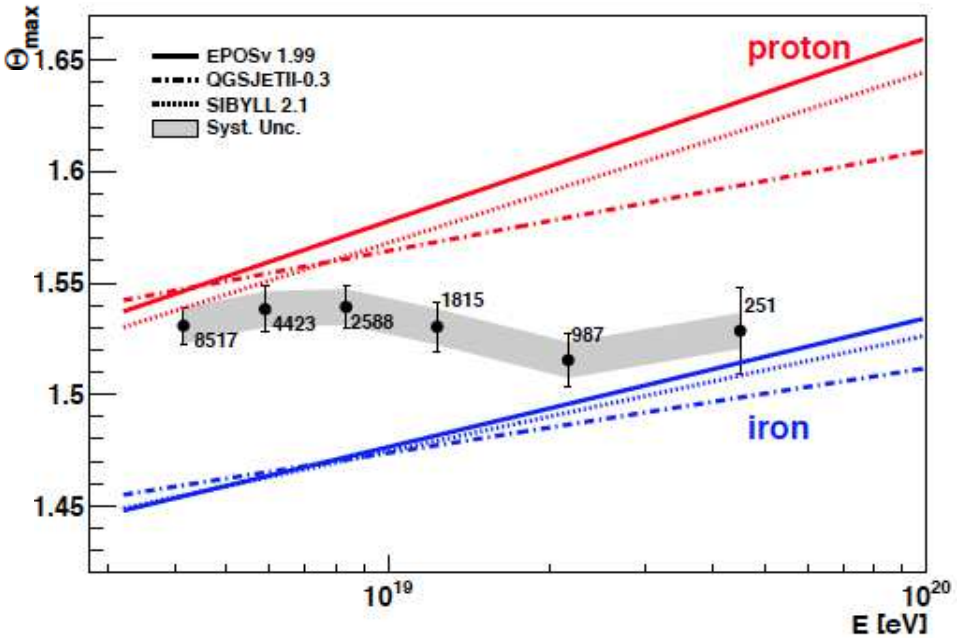
Vertical
symmetry in the signals

Inclined
asymmetry!!

Very inclined
no asymmetry

Θ_{max} is defined as the value of sec(θ) for the zenith angle that gives maximum asymmetry

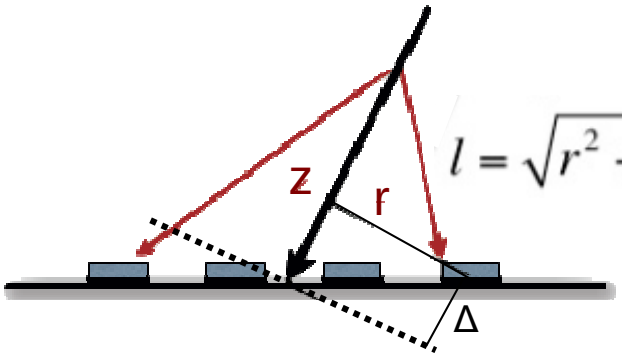
18581 SD events (Jan 2004 – Dec 2010)
$E > 3.16 \times 10^{18}$ eV, and $30° < \theta < 60°$



D. Garcia Pinto for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804

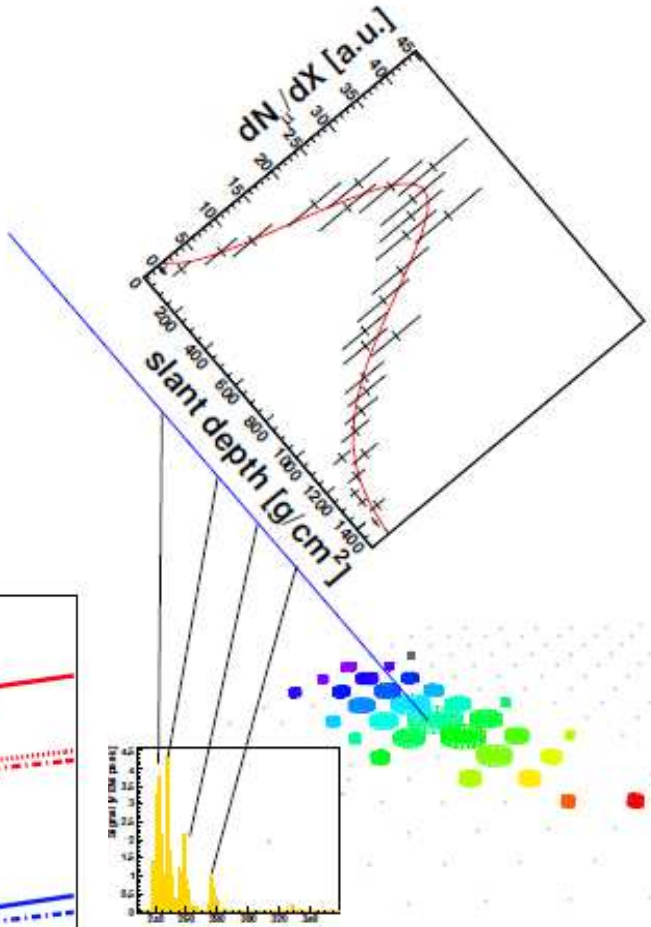
Mass composition with SD

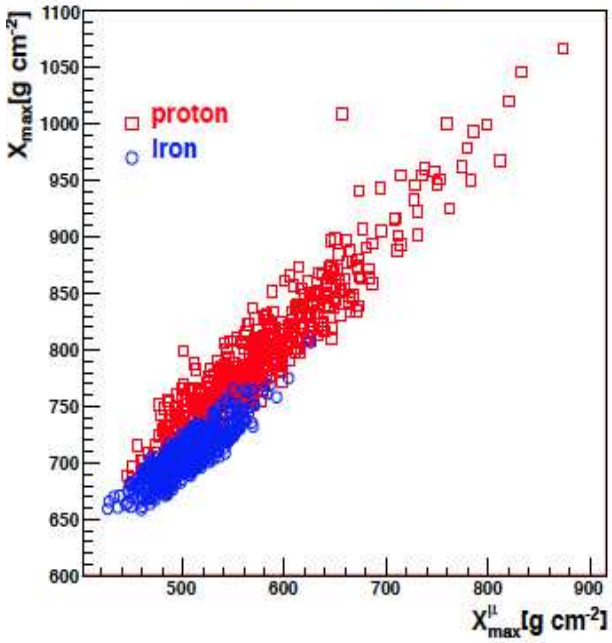
Muon Production Depth (MPD): the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals

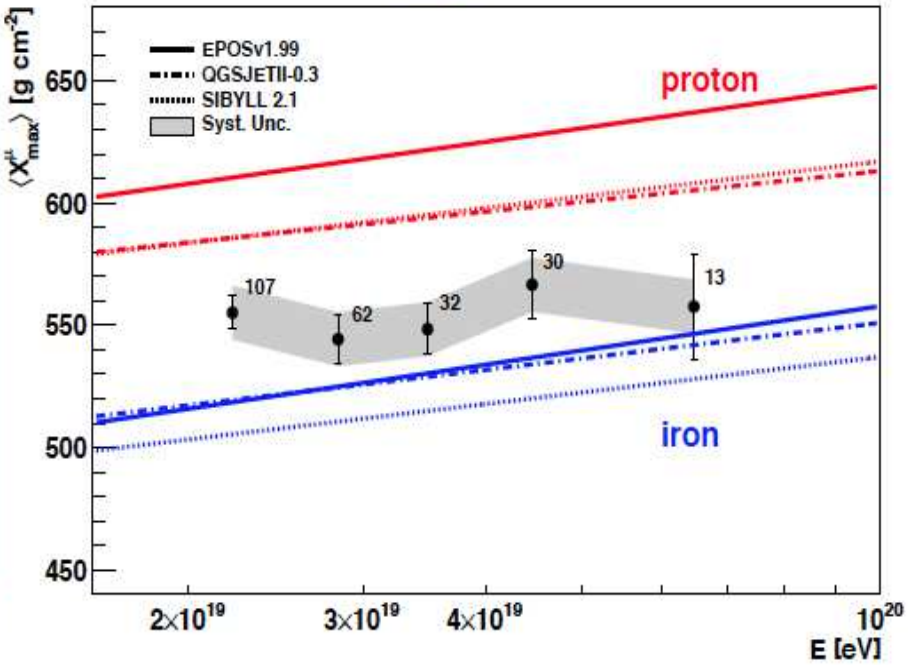


$$l = \sqrt{r^2 + (z - \Delta)^2}$$

Geometrical delay (t_g):The time difference between the arrival time of the muon and that of the time-reference shower plane







244 SD events

E > 20 EeV

55° < θ < 65°

Arrival direction and anisotropy

Search for anisotropy using nearby AGN (Veron-Cetty Veron Catalog)

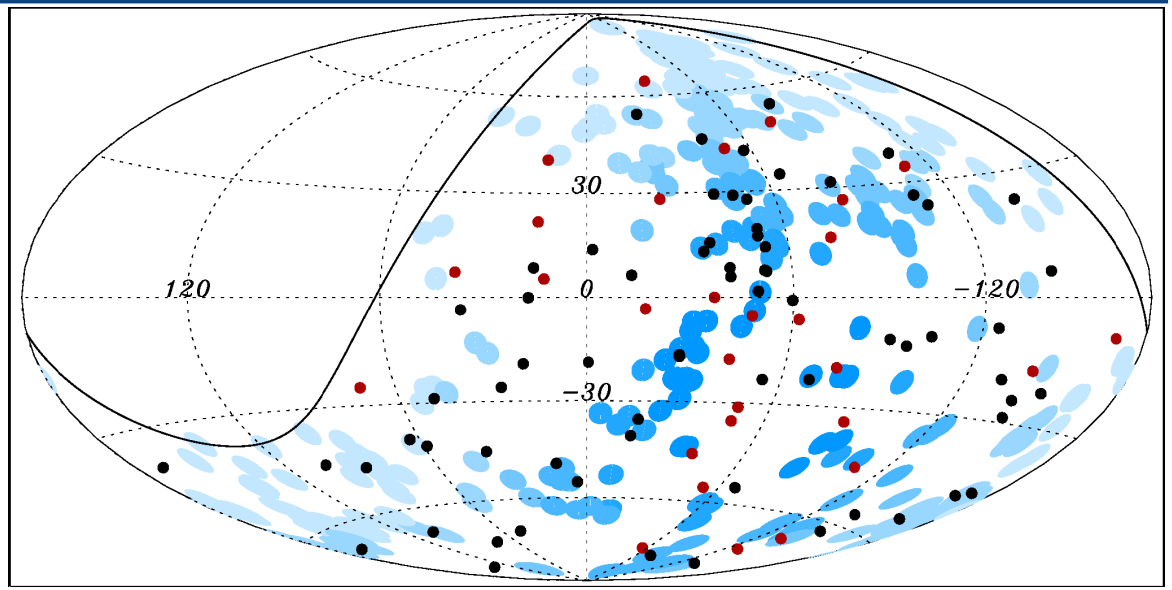
28 / 84 events (up to June 2011)

$E >$ 55 EeV

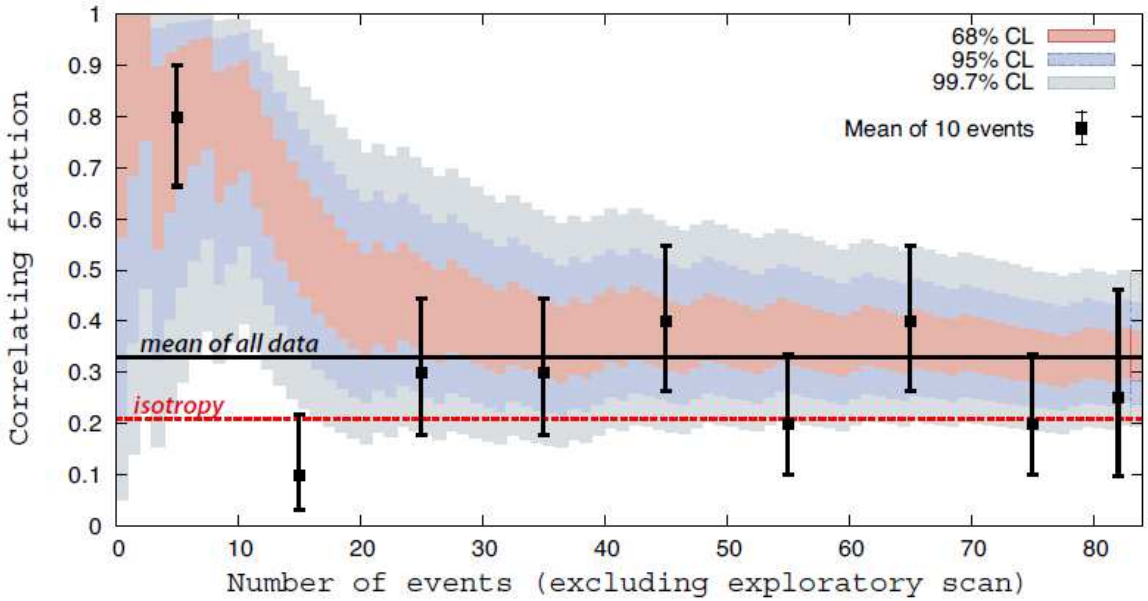
$\psi = 3.1^{o}$

$d_{max} = 75$ Mpc

12 events inside a window of 13º close to CenA



The Pierre Auger Collaboration, Astroparticle Physics 34 (2010) 314–326
K. H. Kampert for the Pierre Auger Collab., Highlight at ICRC 2011



fraction of correlating events

$P_{data} = 0.33 \pm 0.05$

The chance probability of observing such a correlation from a random distribution is below 1 %

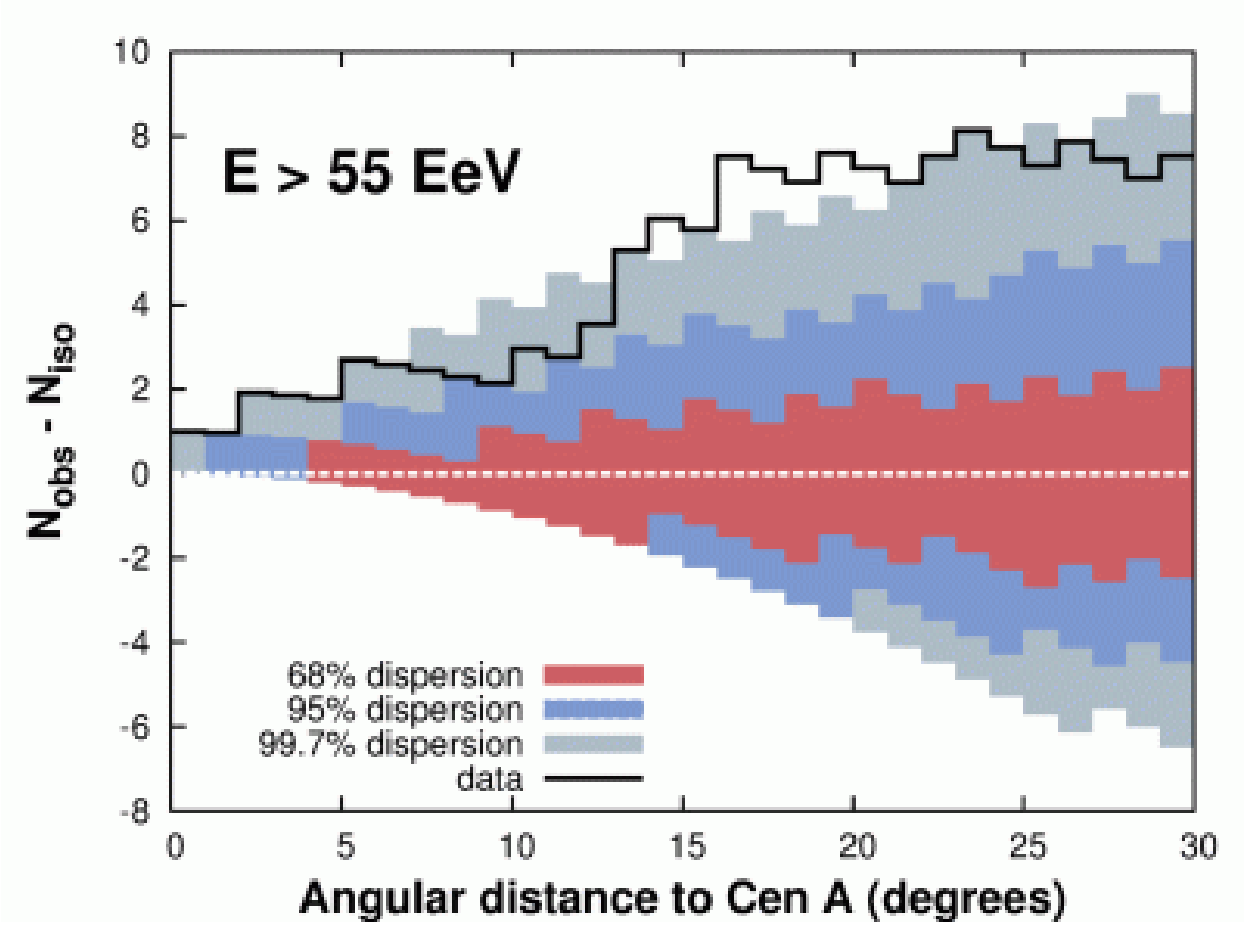
- VCV not a complete catalog

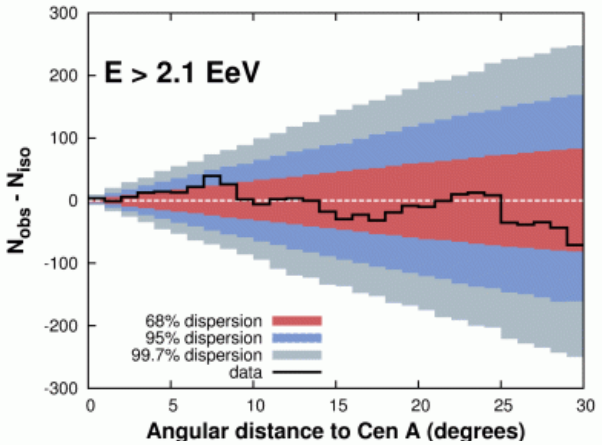
- AGN traces the matter distribution

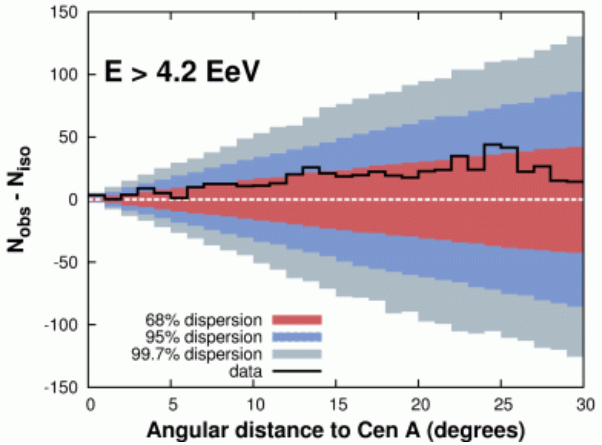
Arrival direction: Centaurus A (aka NGC 5128)

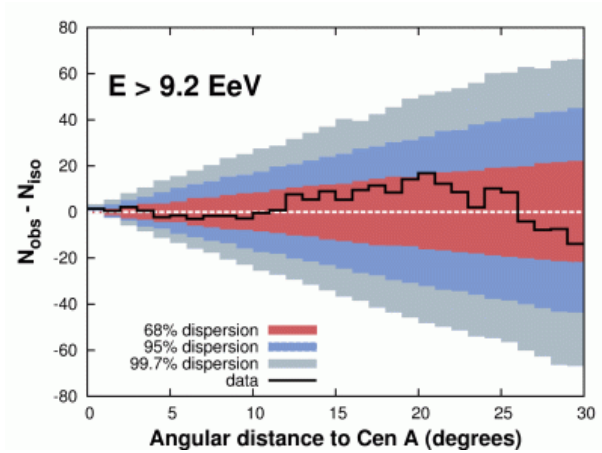
Search in the direction of Cen A, the closest AGN (at 3-5 Mpc)

Excess of correlating events at large energies



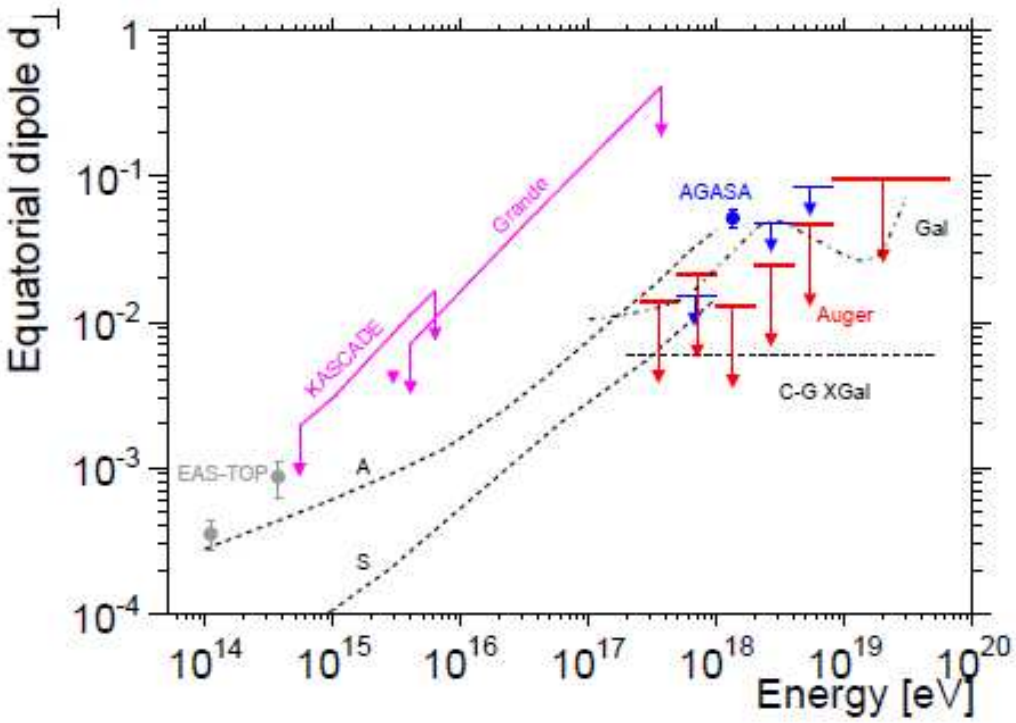






The Pierre Auger Collaboration, JCAP06 (2011) 022

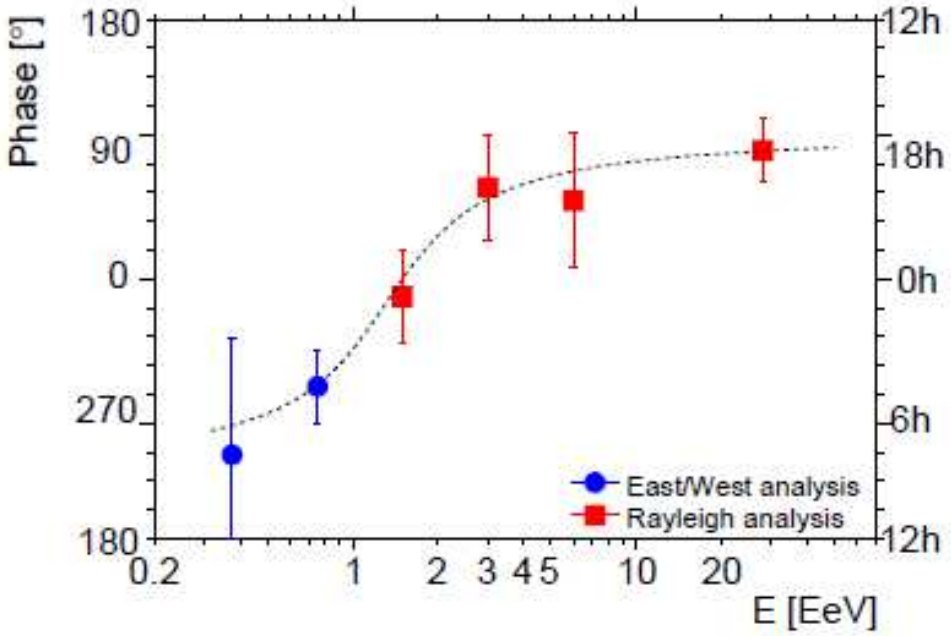
Large Scale Anisotropy



Upper limits on the equatorial dipole component start probing anisotropy models

Data on the phase of the first harmonic modulation in right ascension suggest an energy dependence

H. Lyberis for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4805



Search for UHE photons

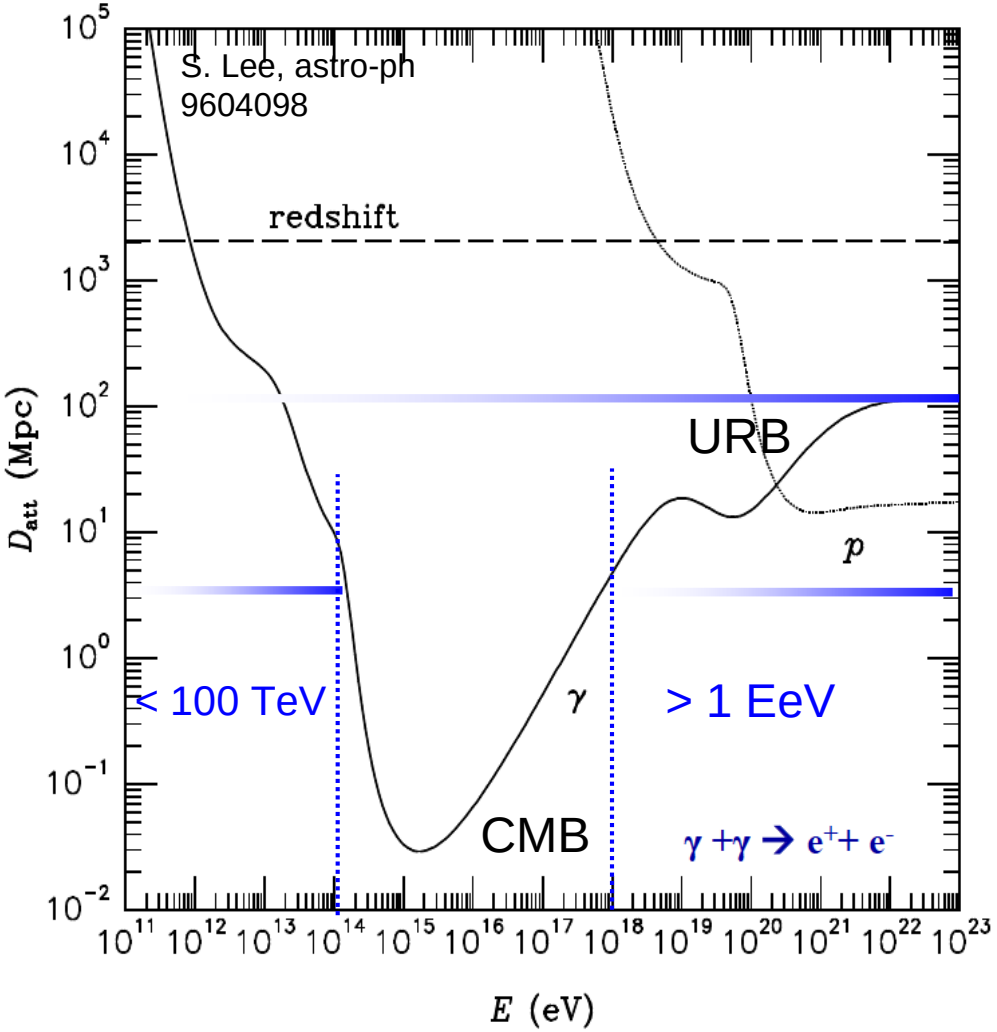
UHE photons mainly produced as:

- secondaries of the photo-pion production (**GZK effect**) of nuclei

photon fraction at Earth~ 0.1 - 1%

- product in **top-down models** for UHECR acceleration

photon fraction at Earth ≳ 10%



Photons interact with background radiation via e^+e^- production

← closest blazars

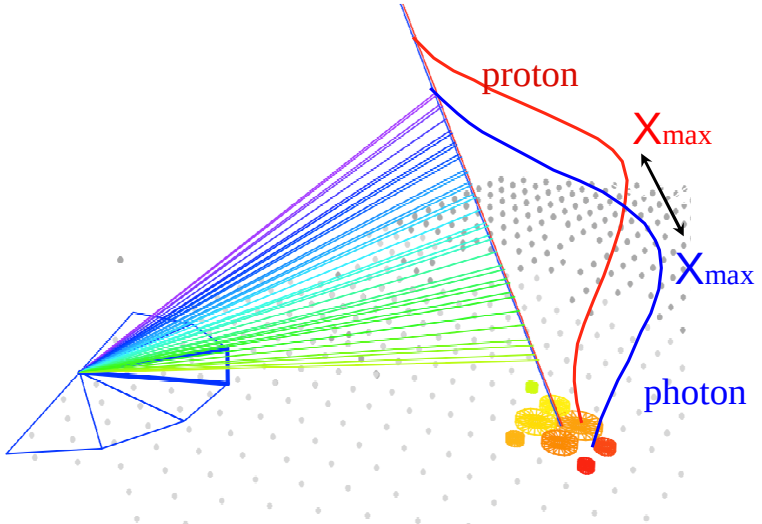
← closest AGN

← Galactic center
$\gtrsim 10^{14}$ eV photons absorbed on CMB

Search for photons with hybrid events

- **FD:**
  - **Deeper development of the air showers**

→ **Larger X_{max}**



M.Settimo for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

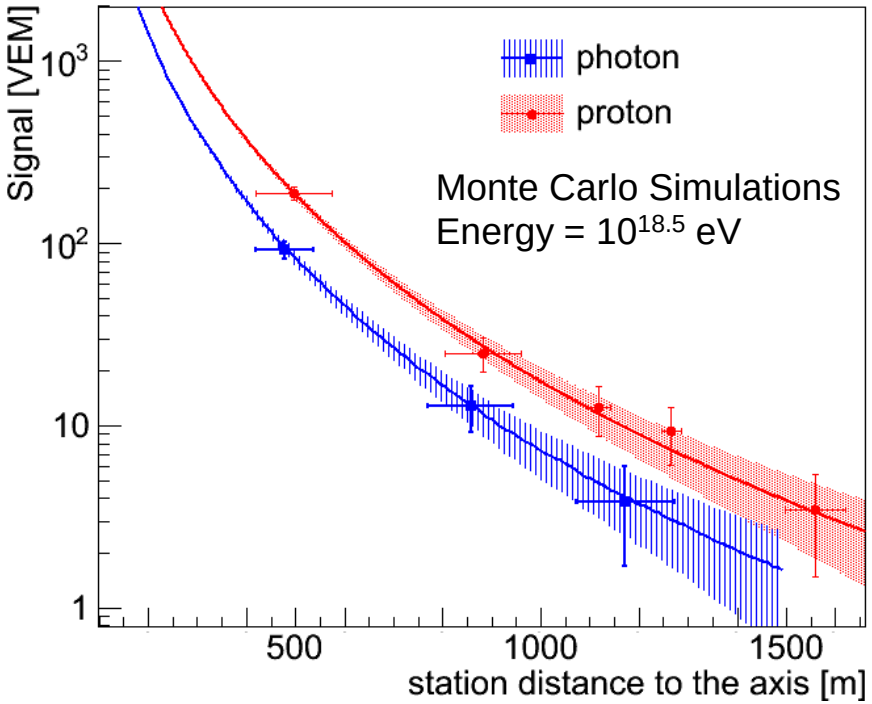
- **SD:**
  - **Smaller detected signal at a given distance**
  - **Fewer triggered stations**

$$S_b = \sum_i S_i \left(\frac{R_i}{1000}\right)^4$$

S_i : station signal [VEM]
R_i : station distance to the shower axis [m]

details on S_b: G. Ros et al., arXiv 1104.3399

→ **Smaller S_b**



Search for photons with SD

Different air shower development for photon primaries:

- deeper showers

- electromagnetic component

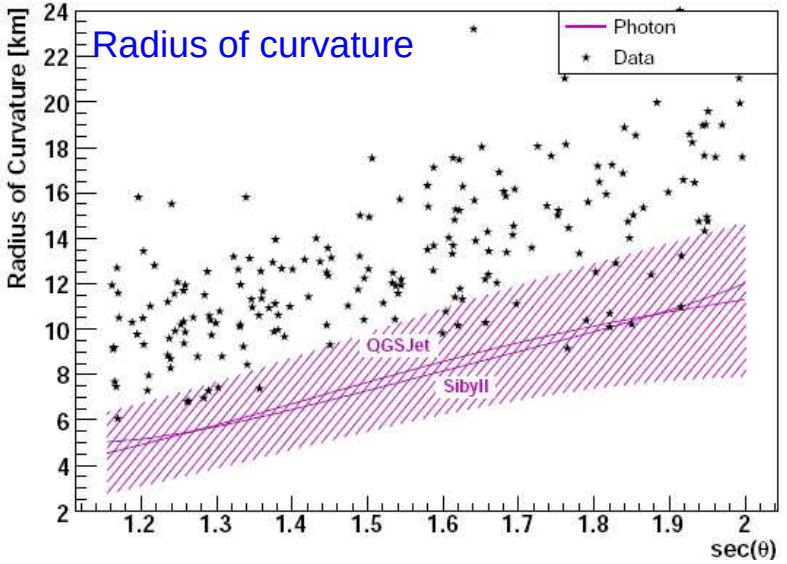
- Events observed by SD-alone

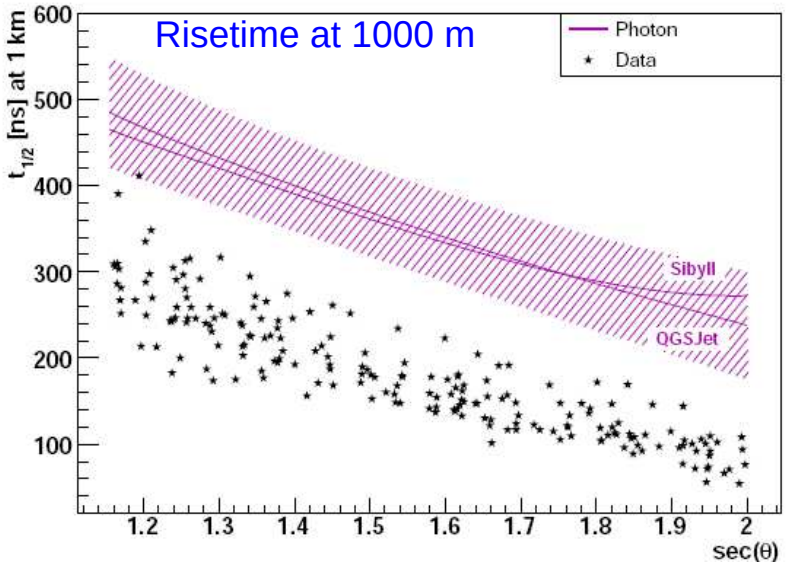
- radius of curvature R and risetime $t_{1/2}$ at 1000 m used for photons identification

Deviations of data from the mean value of R and $t_{1/2}$ expected for photon showers combined with a Principal Component Analysis

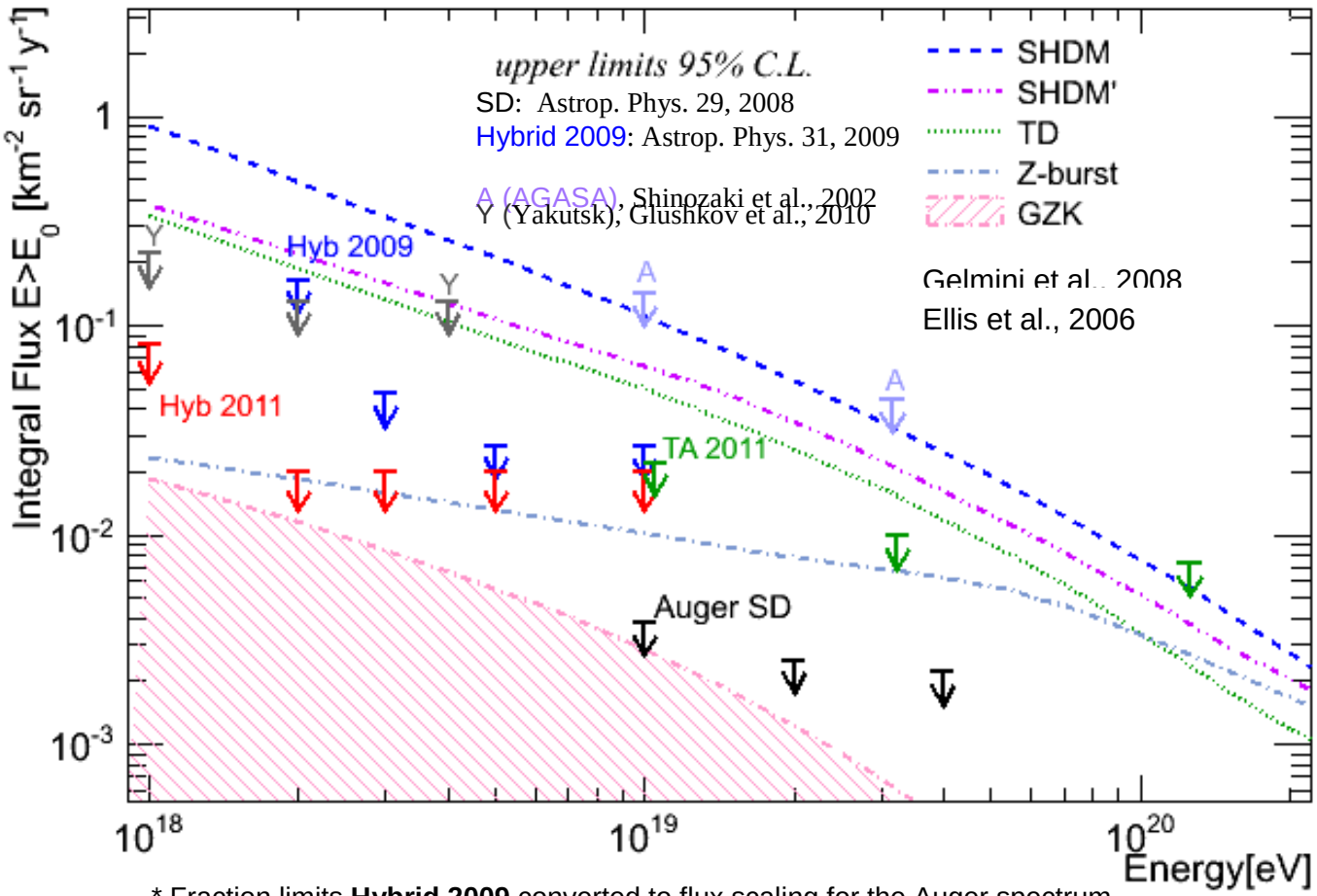
Data sample:
Jan 2004 - Dec 2006

No photon candidates found





Upper limits to photon flux



* Fraction limits **Hybrid 2009** converted to flux scaling for the Auger spectrum

E_0 [EeV]	Nγc	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

Impact of systematic uncertainties

(Exposure, ΔX_{max}, ΔS_b, Energy scale, hadronic interaction model and mass composition assumptions)

$$^{+20\%}_{-64\%} \; (E_0 = 1 \text{ EeV})$$

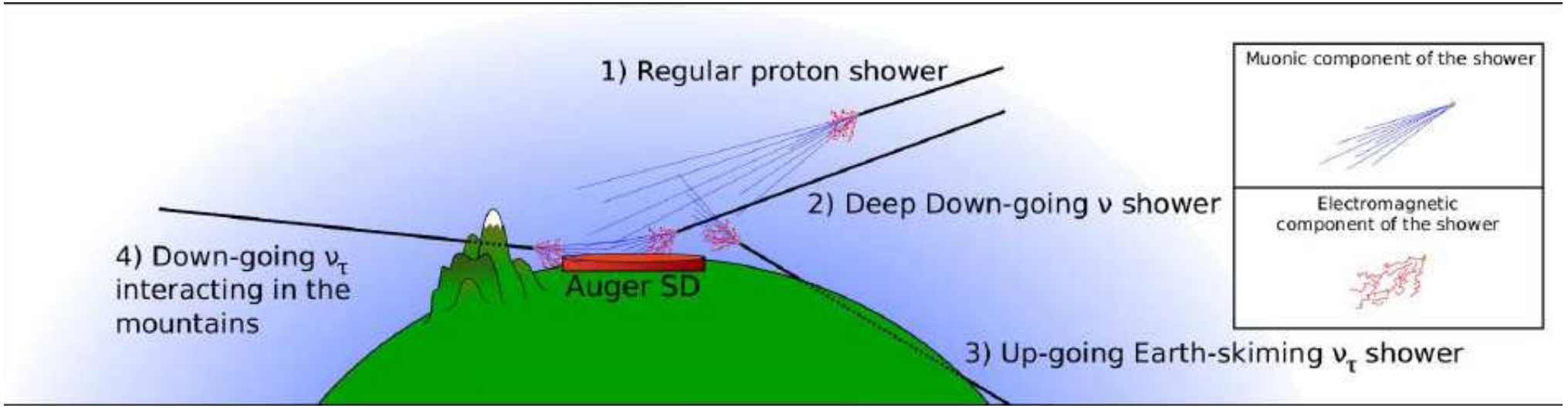
$$^{+15\%}_{-36\%} \; (E_0 > 1 \text{ EeV})$$

Upper limits to the integral photon fraction assuming the **Auger Spectrum**

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

M.Setimo for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

Search for neutrinos



Neutrinos/hadron discrimination:

- inclined events (elongated footprint at ground) with SD signals typical of
- young showers (large contribution of em component)

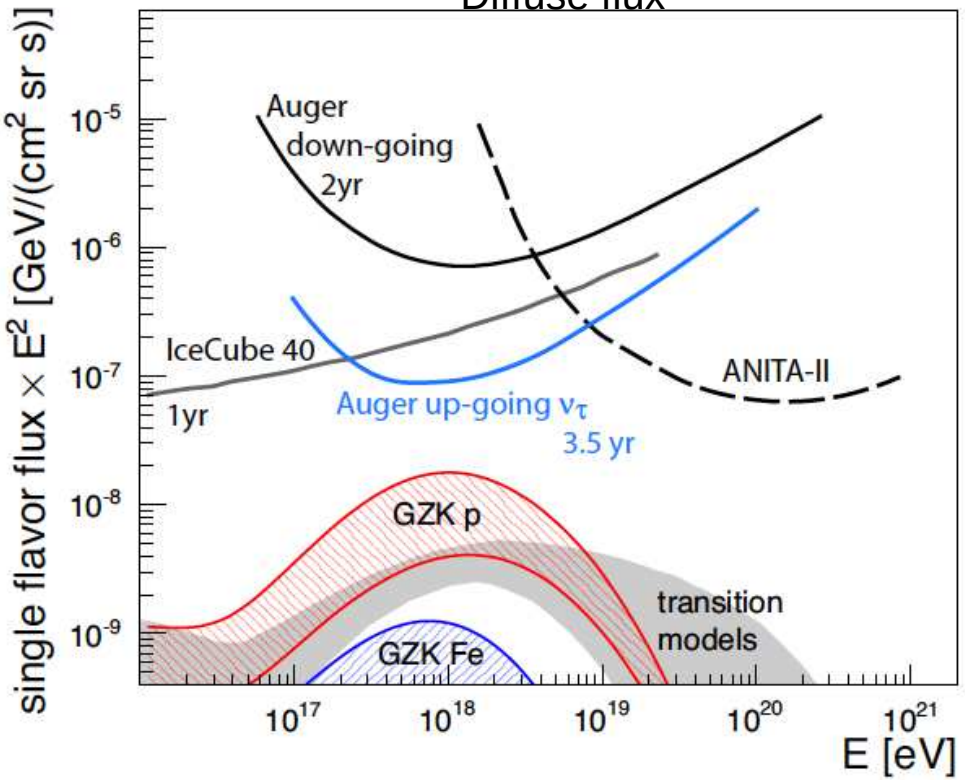
No candidate found so far

Limits to the diffuse neutrino flux

and to point-like sources

as a function of their declination

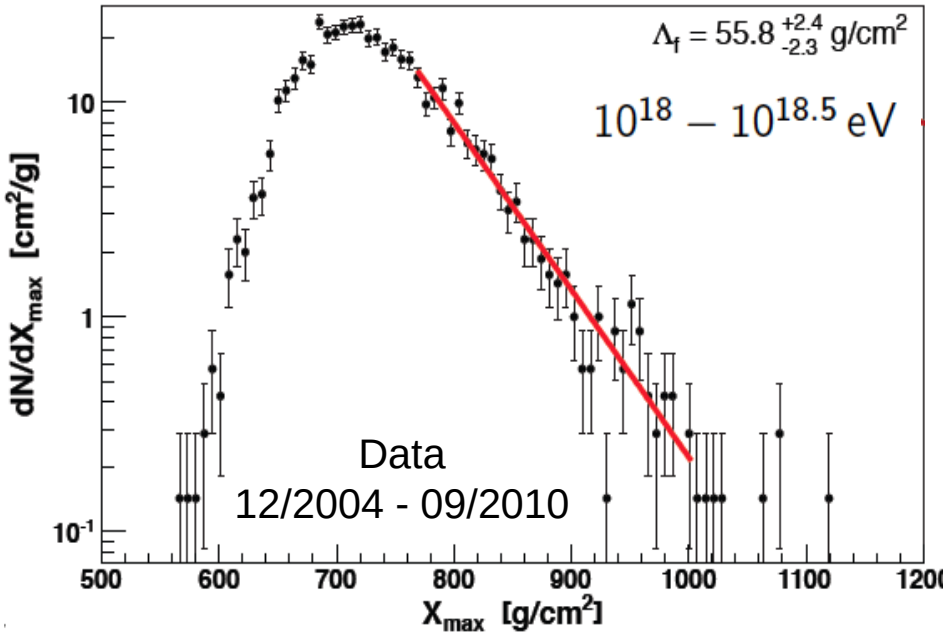
Diffuse flux

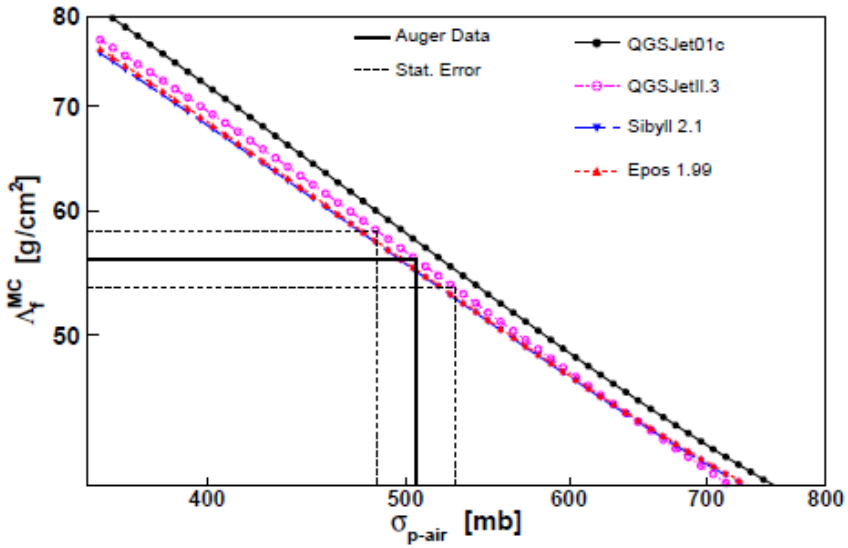


The Pierre Auger Collaboration, Astrophysical Journal Letters, in press, 2012

Measurement of the p-Air cross section

The exponential tail of the X_{max} distribution is sensitive to proton-air cross section.





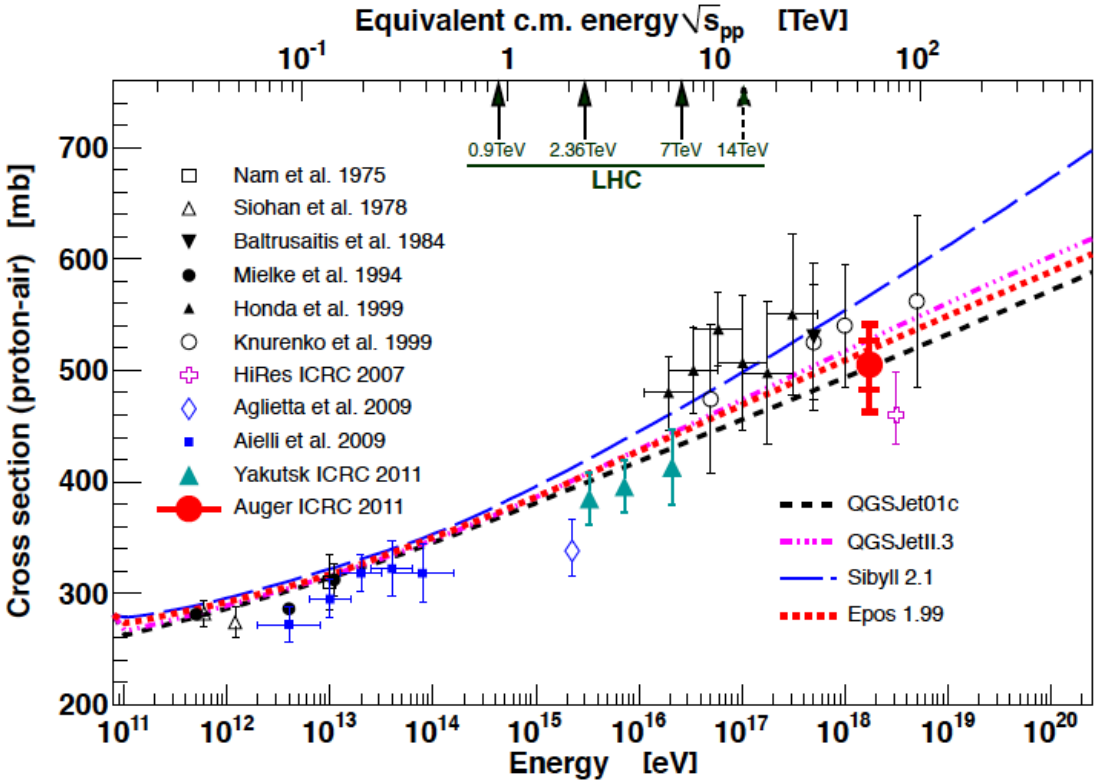
$$\sigma_{\mathrm{p-air}} = \left(505 \pm 22_{\mathrm{stat}} \ \left(^{+20}_{-15}\right)_{\mathrm{syst}}\right)\ \mathrm{mb}$$

Systematic uncertainties

- Λ systematics
- Energy scale
- Hadronic models + simulations
- Composition:

  < +10 mb for < 0.5% of photons

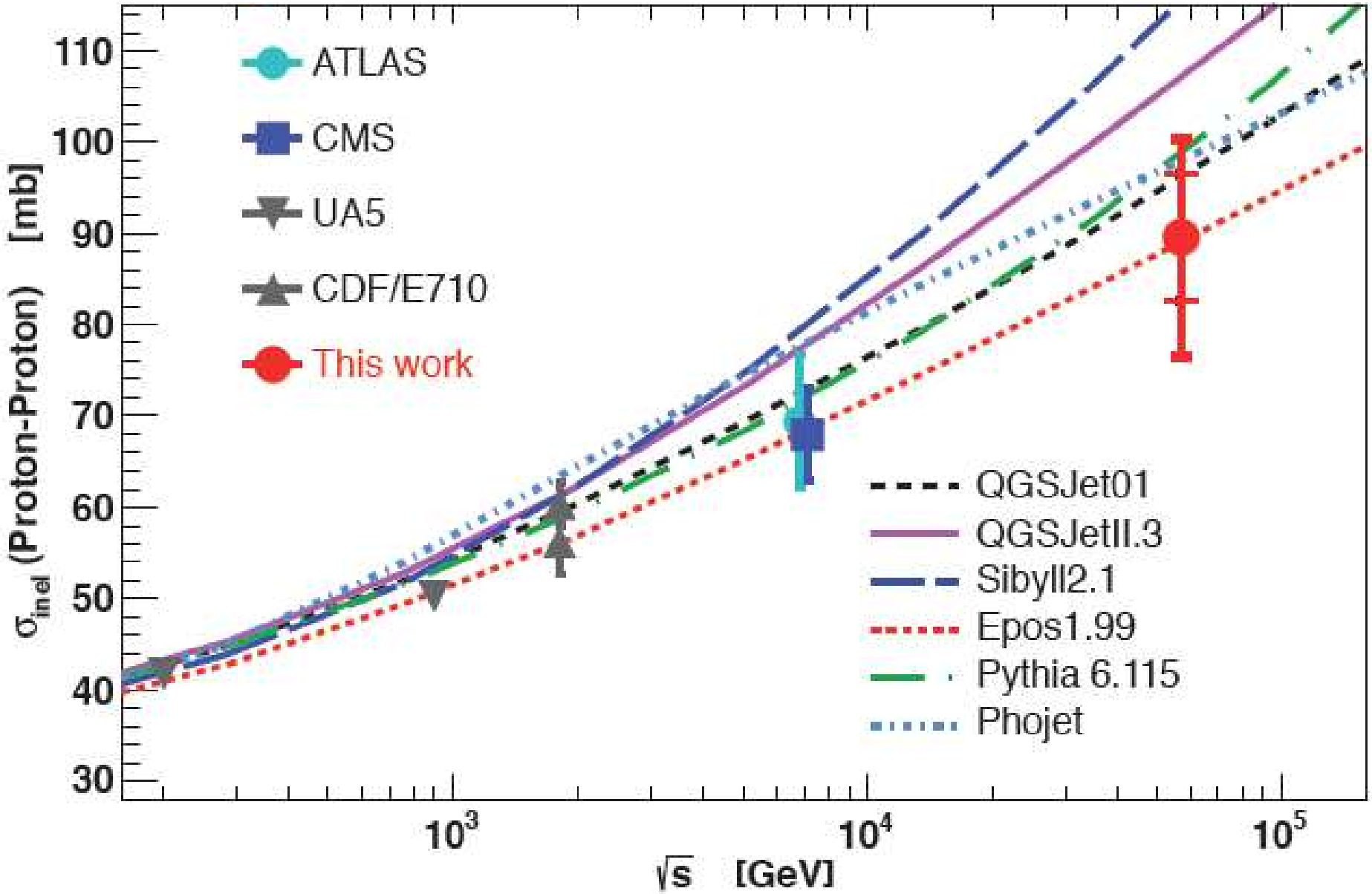
  -12mb (-80 mb) for 10% (50%) of He



R. Ulrich for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804

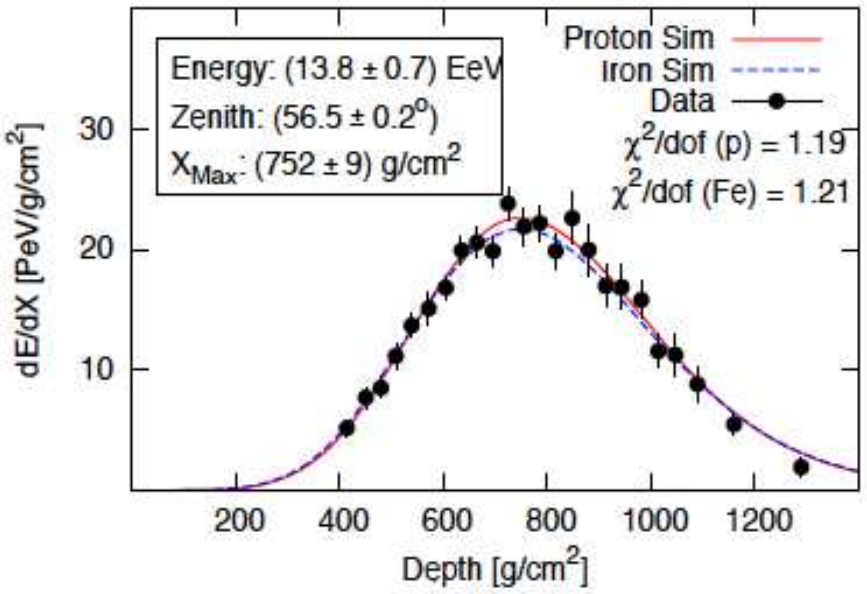
From p-Air to p-p cross section

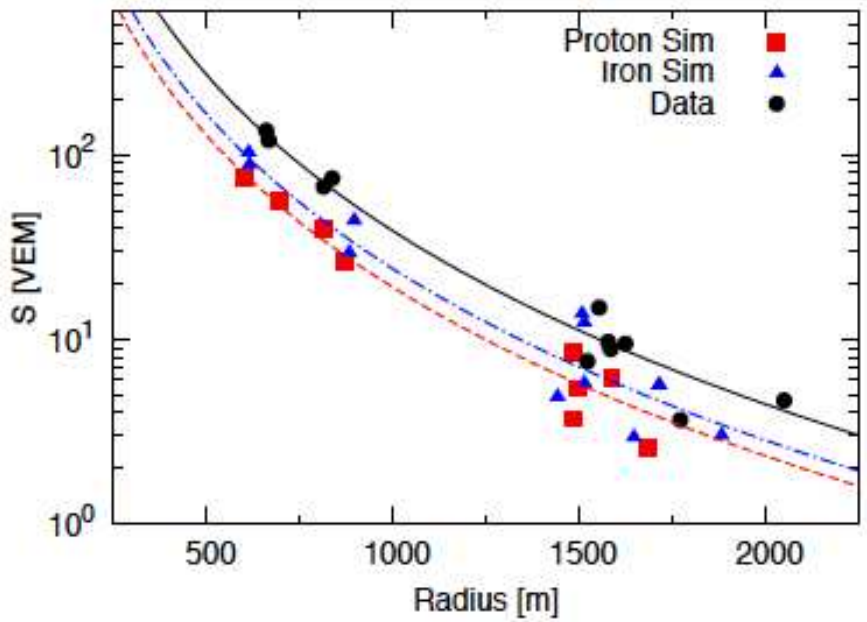
By using the Glauber formalism:



R. Ulrich for the Pierre Auger Collaboration, TAUP 2011

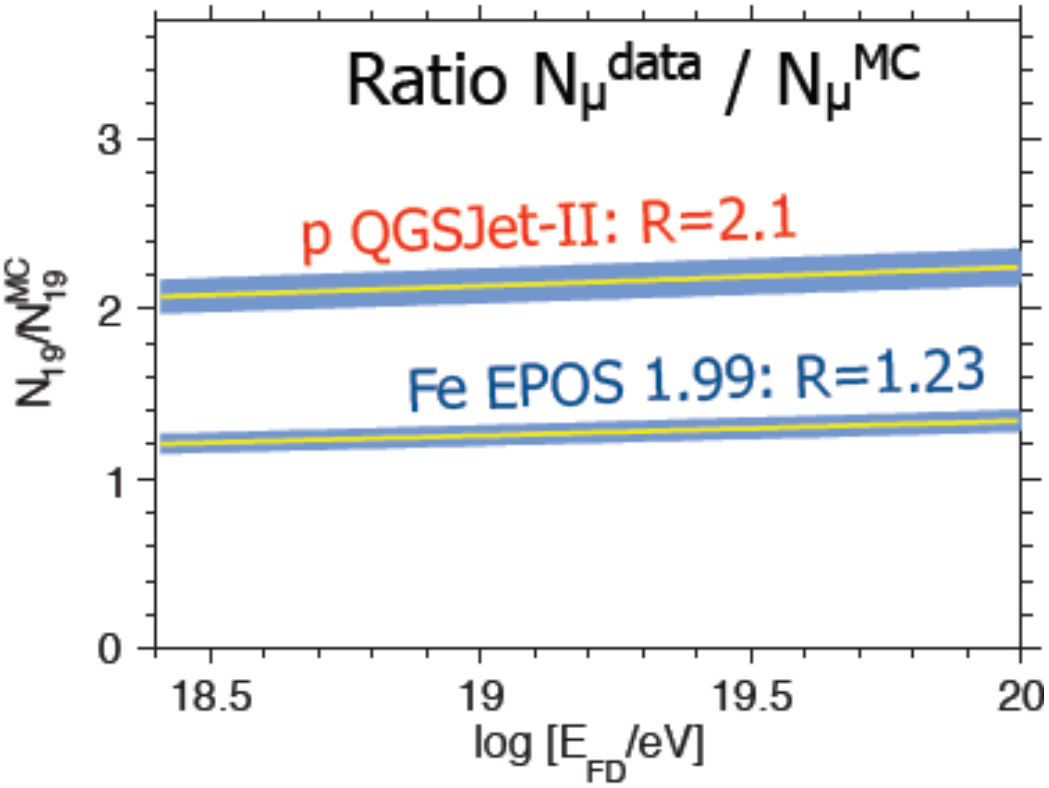
Test of hadronic interaction models





A deficit of muons observed comparing data and Monte Carlo:

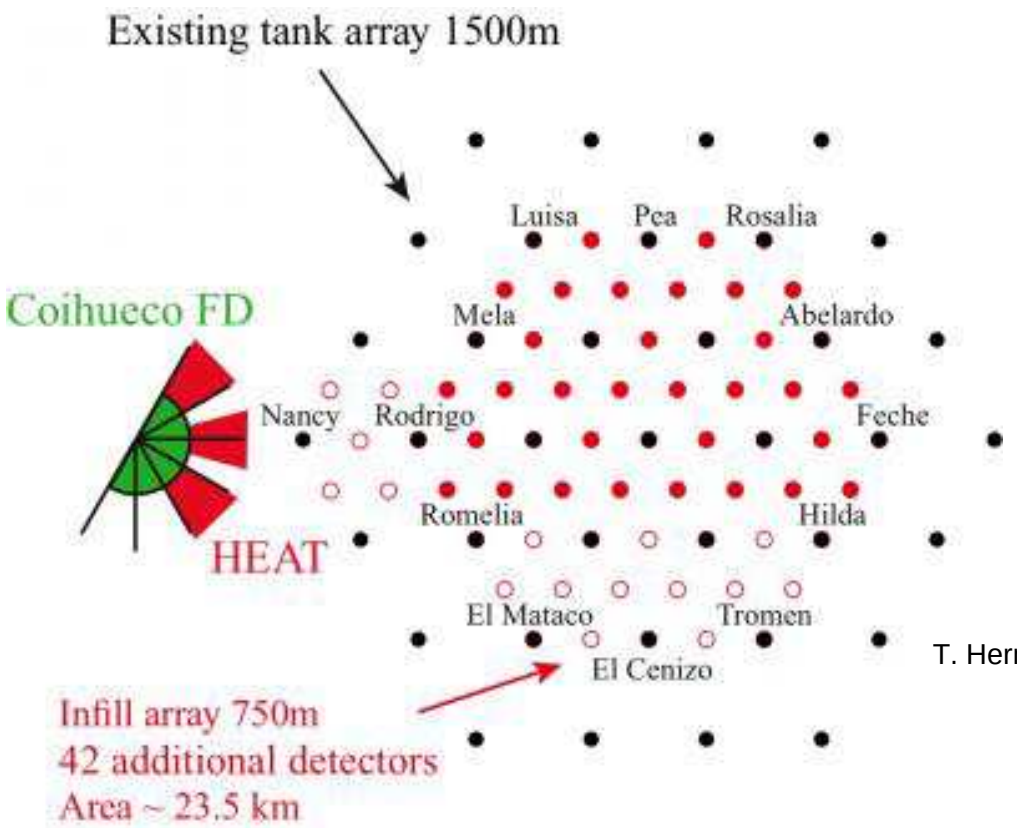
- from golden hybrid events
- from inclined events
- independent of the primary particle (i.e. not due to mass composition assumptions)

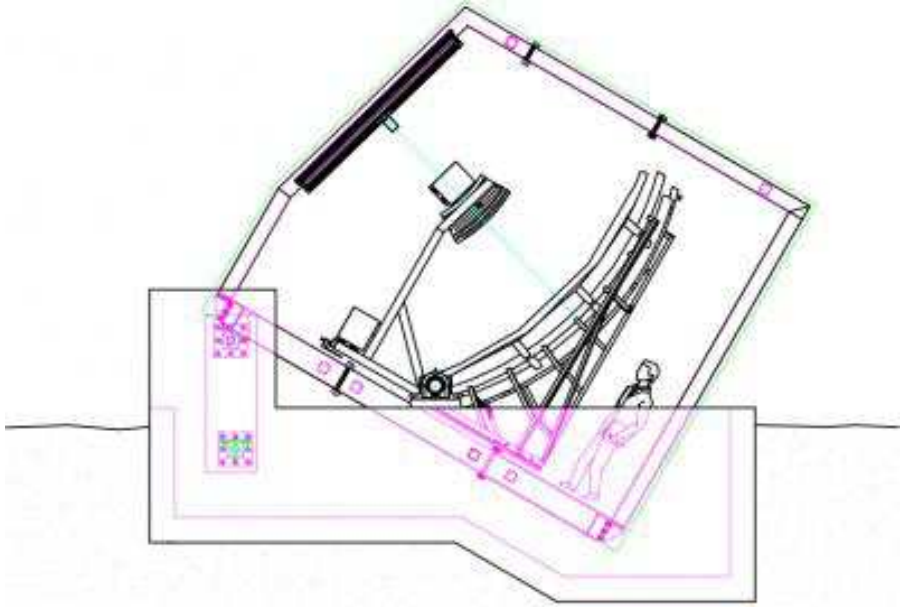


J. Allen for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804

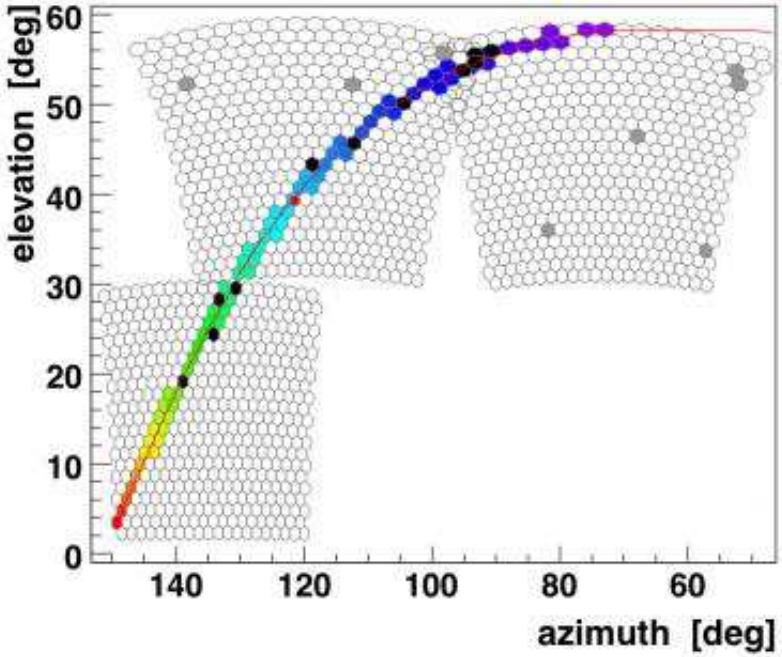
K.H. Kampert for the Pierre Auger Collaboration, Highlight talk ICRC 2011,

Enhancements and R&D Activities





T. Herman-Josef Mathes for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807



HEAT
Three additional telescopes at the Cohiueco site to look up to 60 deg in elevation (closer showers).

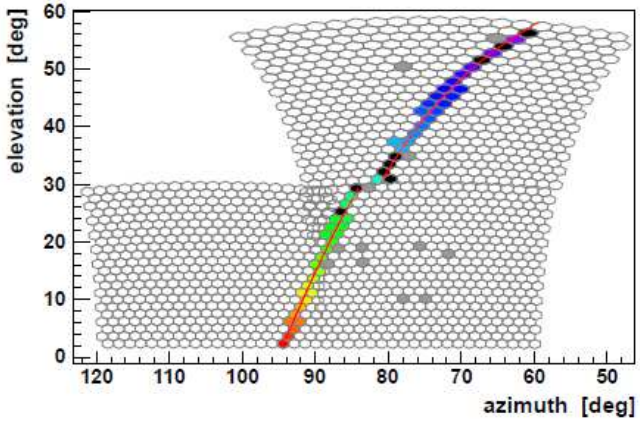
Infill array
42 additional SD detectors with 750 m spacing close by the Cohiueco site

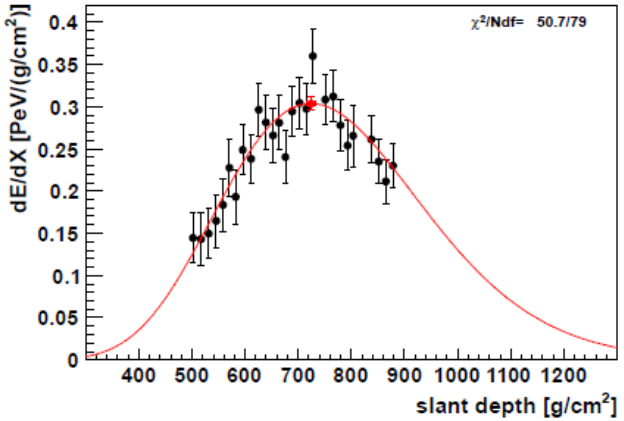
Enhancements and R&D Activities

Low energy event recorder by **HEAT** and Cohiueco:

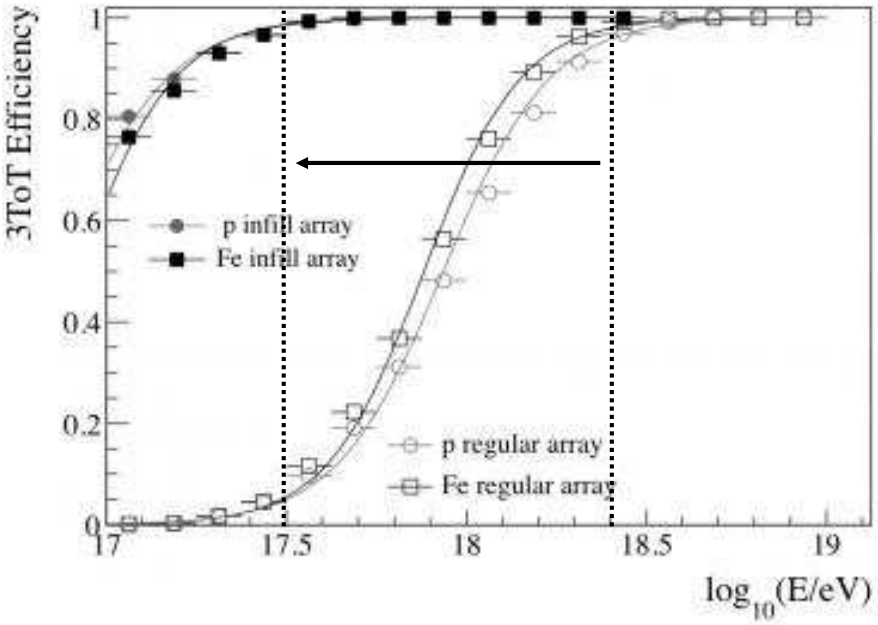
$E \approx 1.7 \cdot 10^{17}$eV ; $\theta \approx 19°$

T. Herman-Josef Mathes for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807

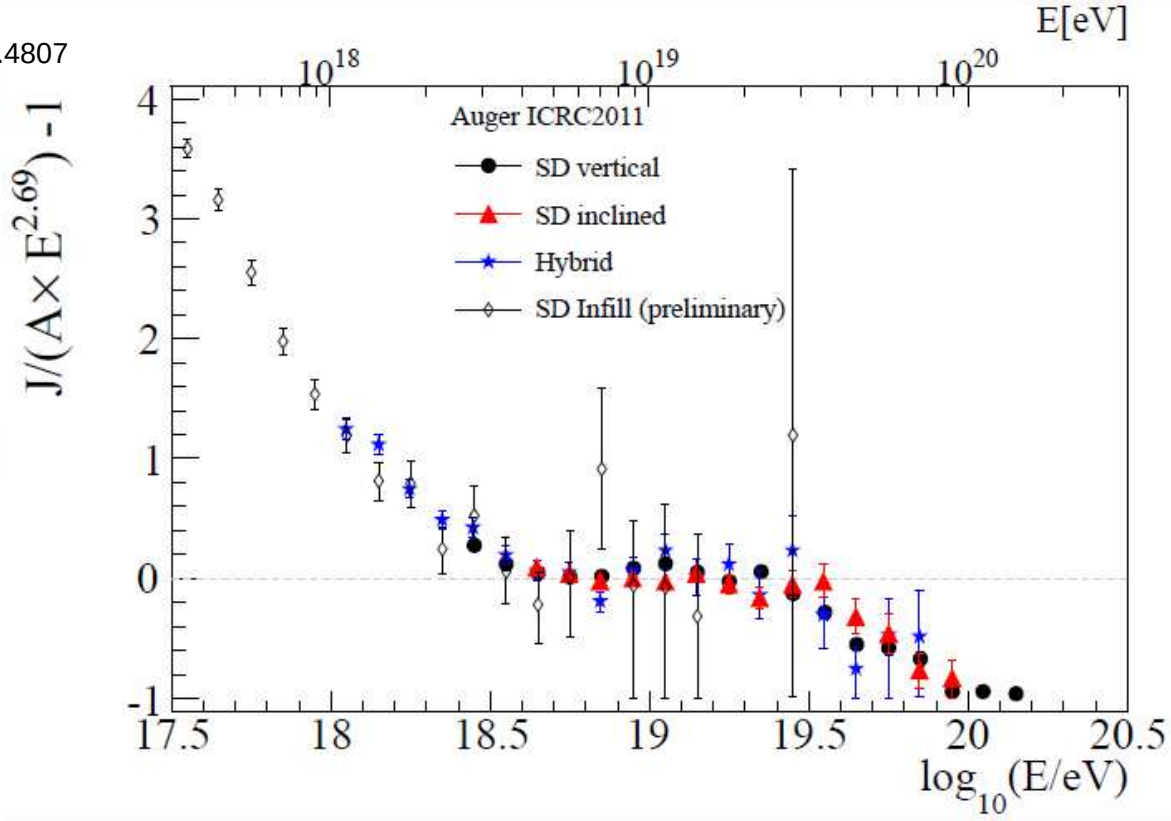




F. Sanchez for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807



The **Infill Array** allows extending the energy range down to $3 \cdot 10^{17}$eV

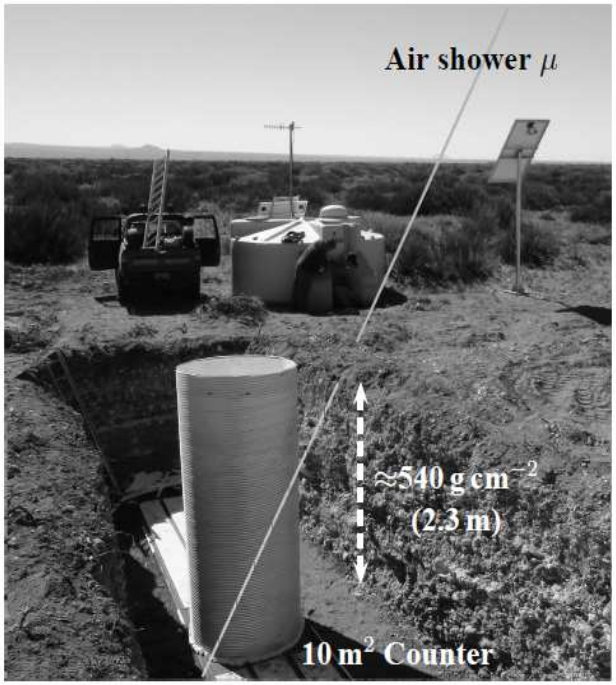


I. Maris for the Pierre Auger Collaboration,UHECR 2012, CERN Feb '12

Enhancements and R&D Activities

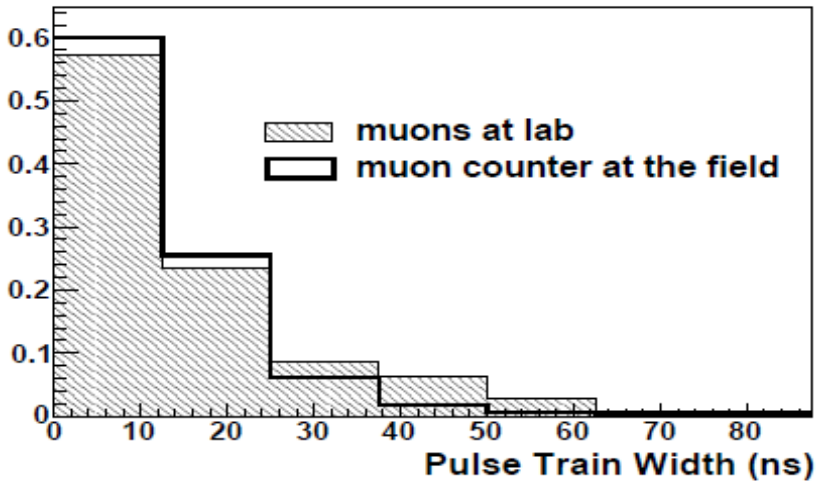
AUGER Muons and Infill on the Ground Array **AMIGA**

Infill SD tanks (see previous slides) and **scintillator muon detectors** 2.3 m below ground in the Cohiueco area

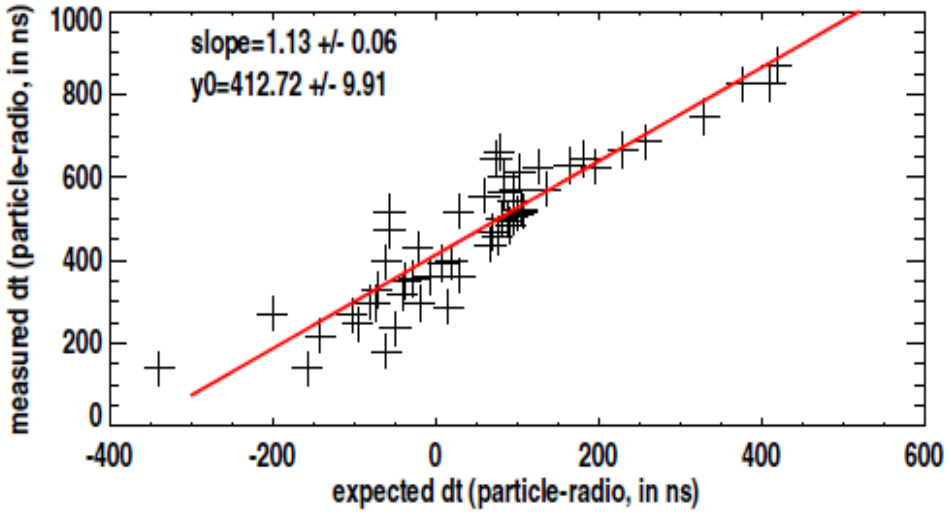


AUGER Engeneering Radio Array: **AERA**

Detection of shower **radio emission** in the VHF band with an array of 160 (21 already installed) antennas on a 20 km^2 area close by Cohiueco



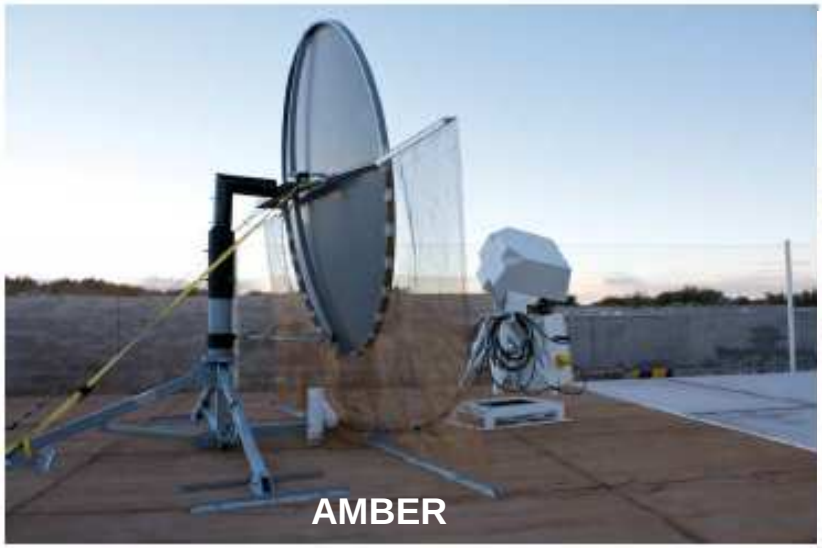
B. Wundheiler for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807



B. Revenu for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807

Enhancements and R&D Activities


MIDAS


AMBER


EASIER

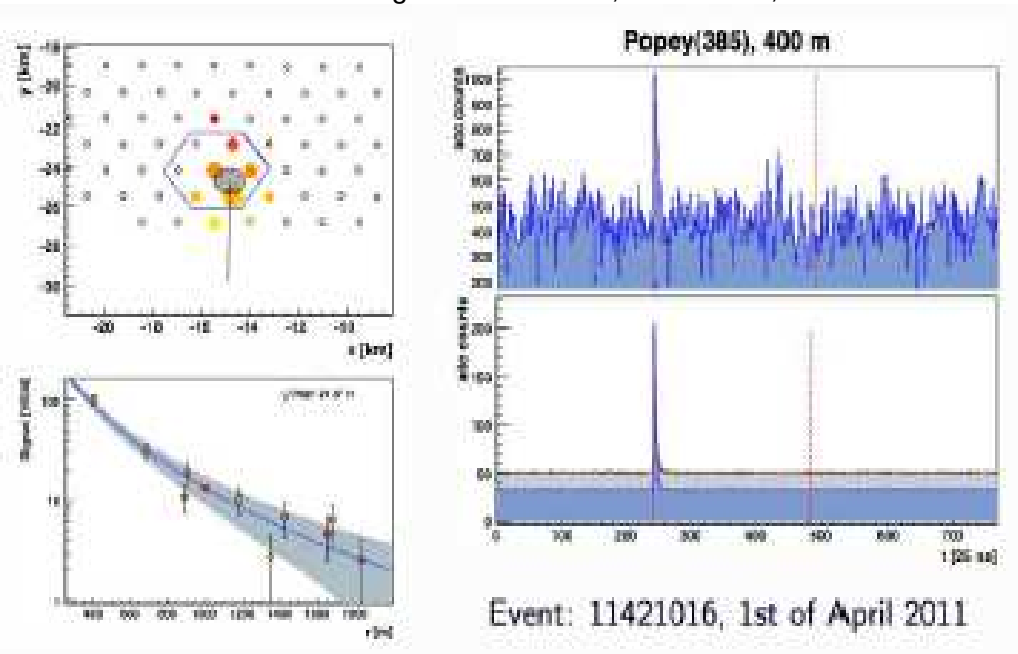
Many R&D activities related to the detection of shower microwave emission: **AMBER, EASIER,**

FDWAVE, MIDAS

New technologies for a novel tank design and a new telecomunication system for AUGER upgrades and/or a new giant UHECR detector

F. Sarazin for the Pierre Auger Collaboration et al., ICRC 2011, arXiv:1107.4807

P. Allision for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4807

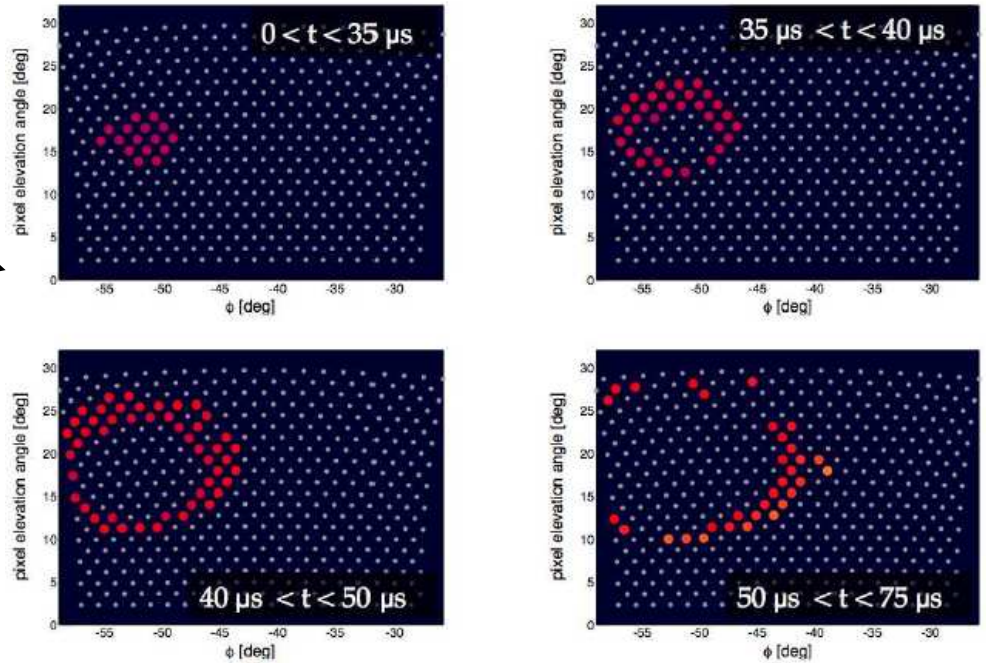


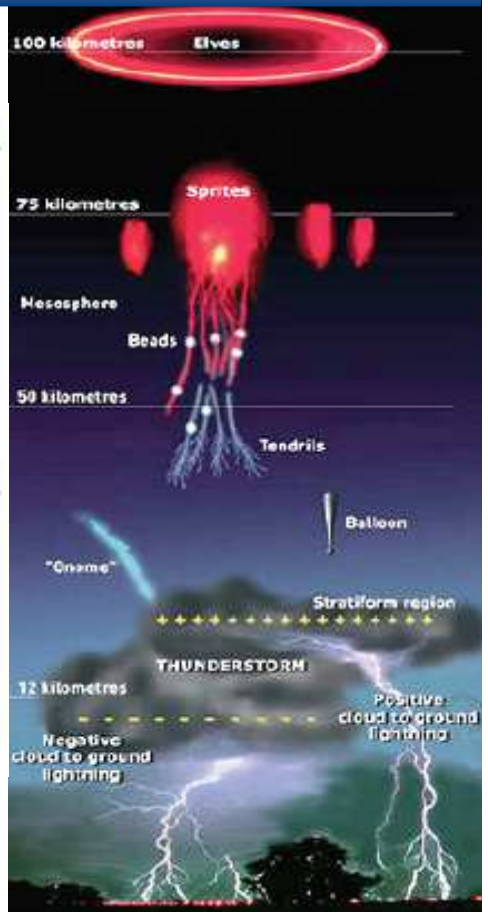
Cosmic ray envent seen by the SD and EASIER

Interdisciplinary activities and … Serendipity

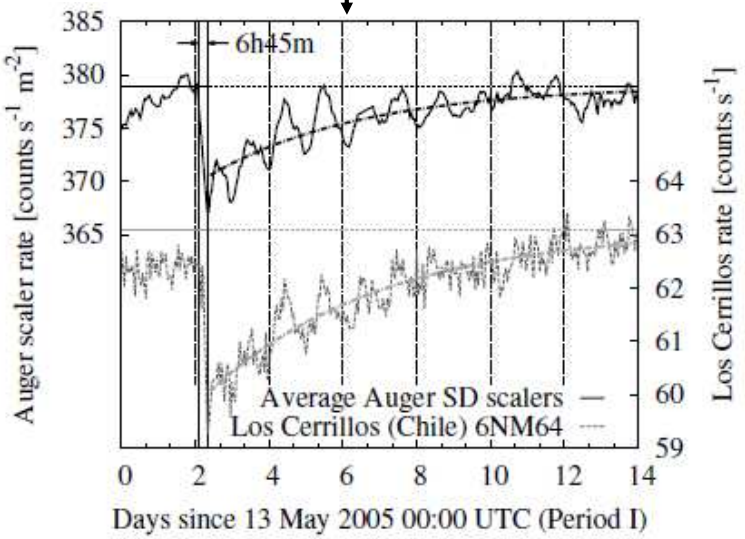
A. Tonachini for the Pierre Auger Collaboration et al., ICRC 2011, arXiv:1107.4806

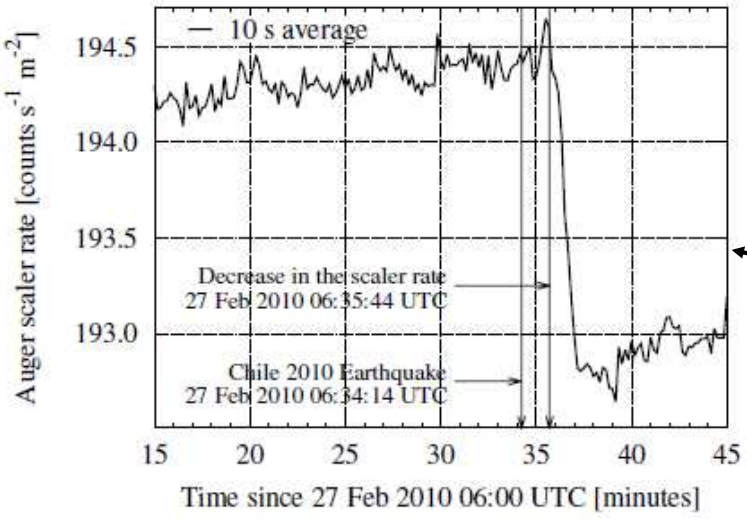
Detection of an **elve** located at 80km altitude at a distance of 580km





Detection of a **Forbush** decrease seen by SD in "scaler mode"





Variation in the SD in "scaler mode" connected with the Feb 27 2010 Chile 8.8 magnitude **earthquake**

H. Asorey for the Pierre Auger Collaboration et al., ICRC 2011, arXiv:1107.4805

Summary

Energy Spectrum Measurement

- **Ankle position** ($10^{18.62}$ eV) and **flux suppression** ($10^{19.4}$ eV) measured with high accuracy using SD and hybrid data

Arrival Direction

- **anisotropy** of the arrival direction of CR with E > 55 EeV measured with a p-value of 33%. Directional search and large scale anisotropy studied.

Mass Composition

- The $\langle X_{max} \rangle$ and the RMS(X_{max}) vs E indicates a **change from light to heavier** composition for increasing E. Interpretation of results relies on hadronic models.

Upper limits on **photon** fraction and **neutrino** fluxes

Hadronic Interactions

Measurement of the **p-Air cross section** and estimate of the **p-p cross section at 57 TeV** in c.m.s.
Muon deficit in model predictions compared to data

Enhancements

HEAT and Infill allow **lowering the energy threshold** down to about 10^{17} eV
Muon detector composition/hadint studies

R&D activities

Test of new detection techniques (**radio, microwave**) are in progress

Interdisciplinary science , ……