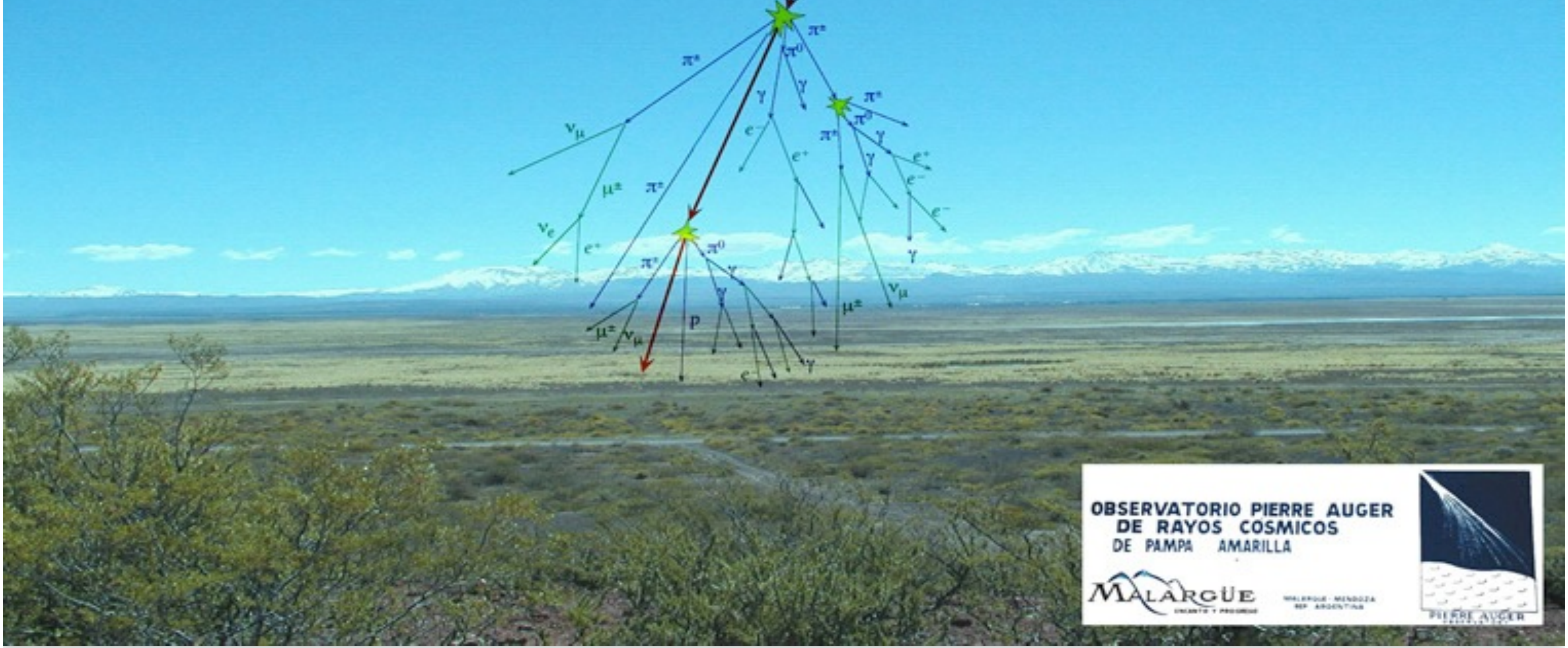
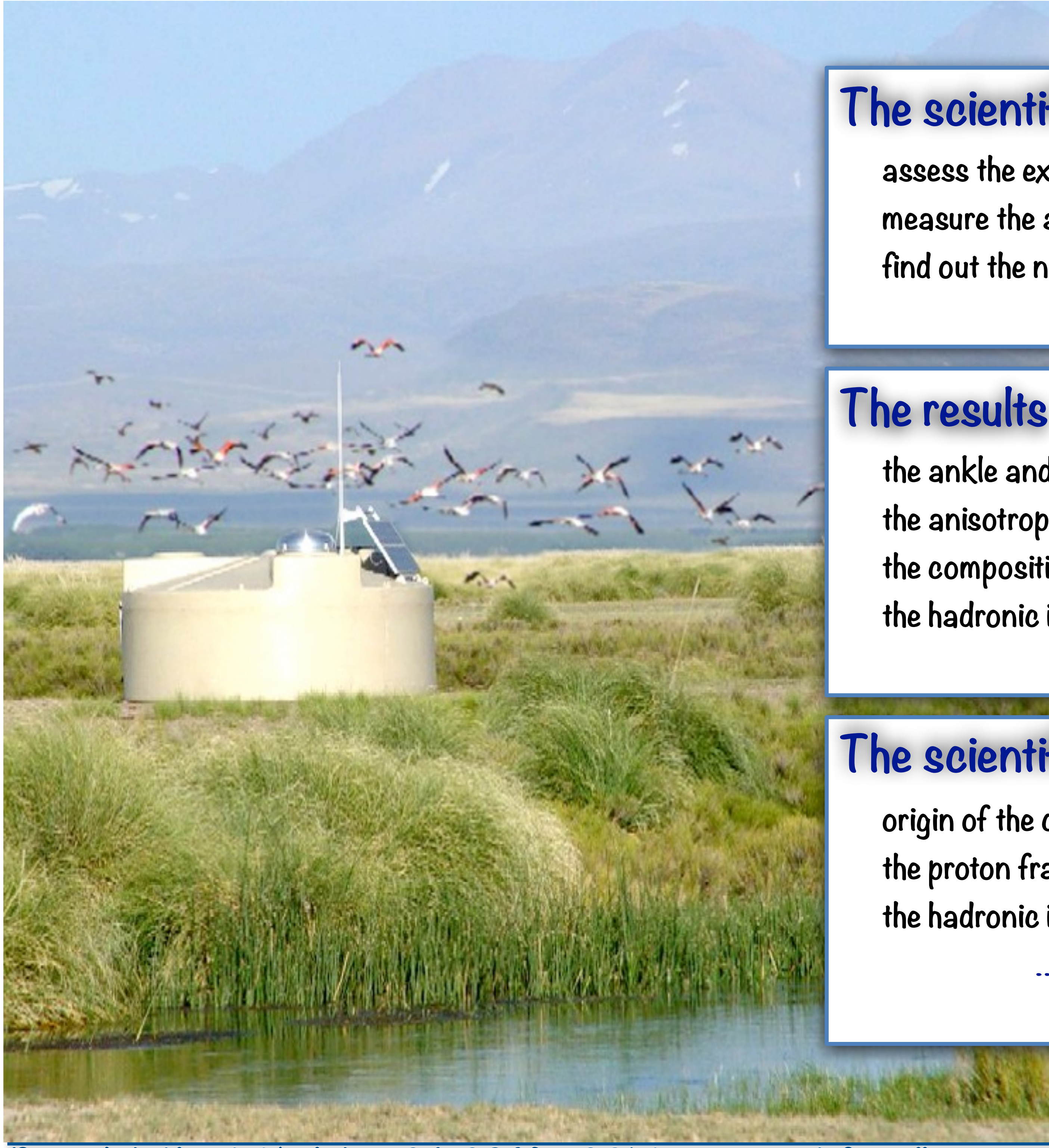


The Pierre Auger Observatory:
results, open questions and future prospects

Antonella Castellina

INFN & INAF, Torino, Italy

for the Pierre Auger Collaboration



The scientific case for Auger

assess the existence or absence of the cut-off

measure the anisotropy in the quest for the sources

find out the nature of the primary cosmic rays

... with a hybrid detector

The results

the ankle and the cut-off clearly measured

the anisotropy : LSA, point sources, etc.

the composition: primary nuclei, photons, neutrinos

the hadronic interactions: muons, p-p cross section

... a wealth of info on UHECRs

The scientific case : beyond 2015

origin of the cut-off : GZK or reach of E_{max} ?

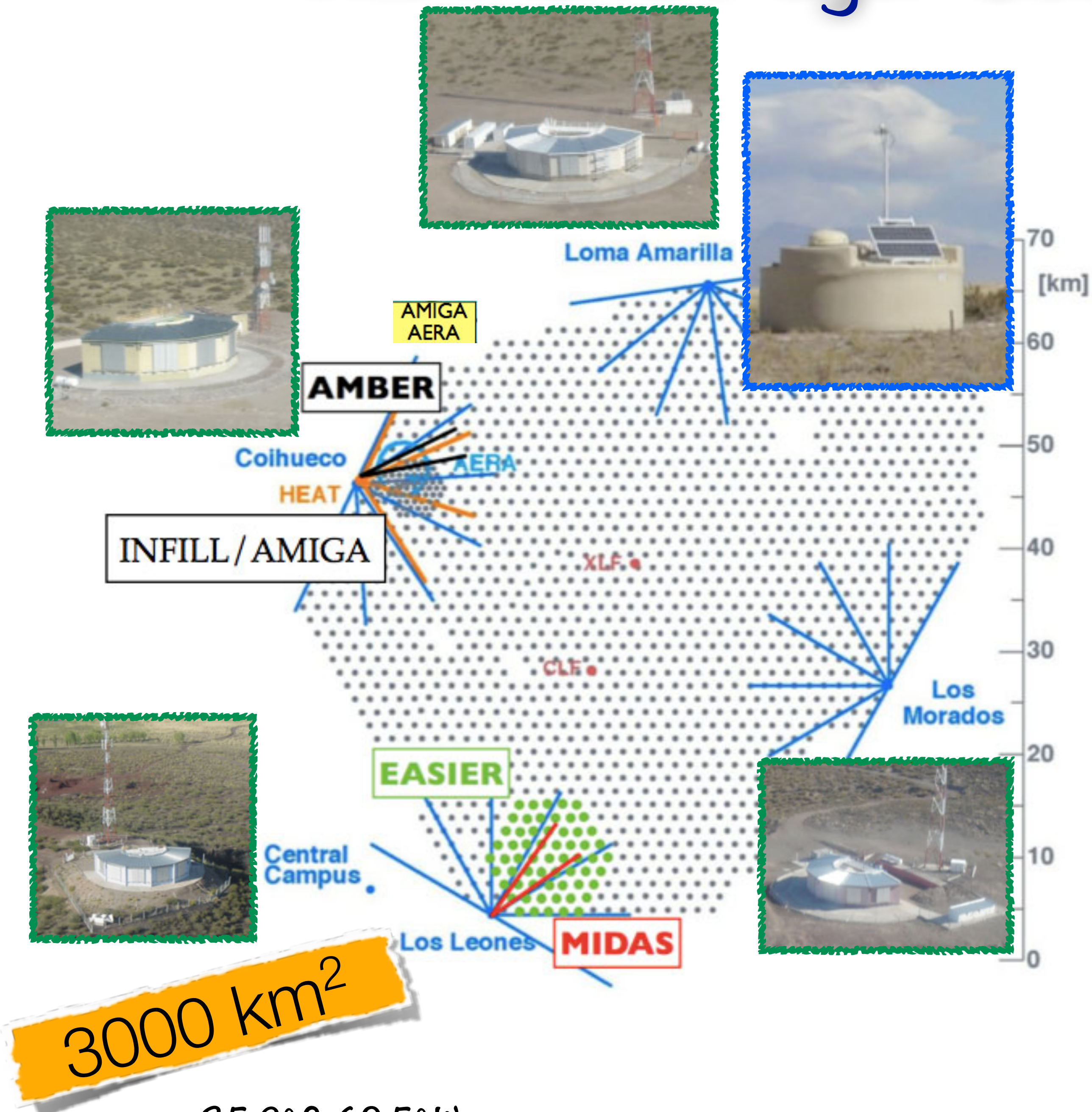
the proton fraction at UHE : particle astronomy ?

the hadronic interactions and new physics

... improving the composition knowledge

...increasing the statistics

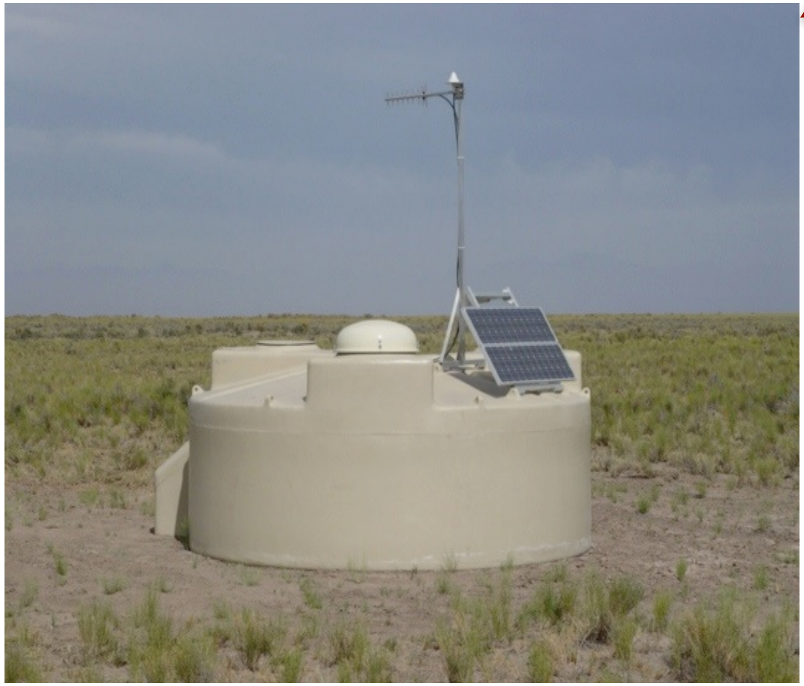
The Pierre Auger Observatory

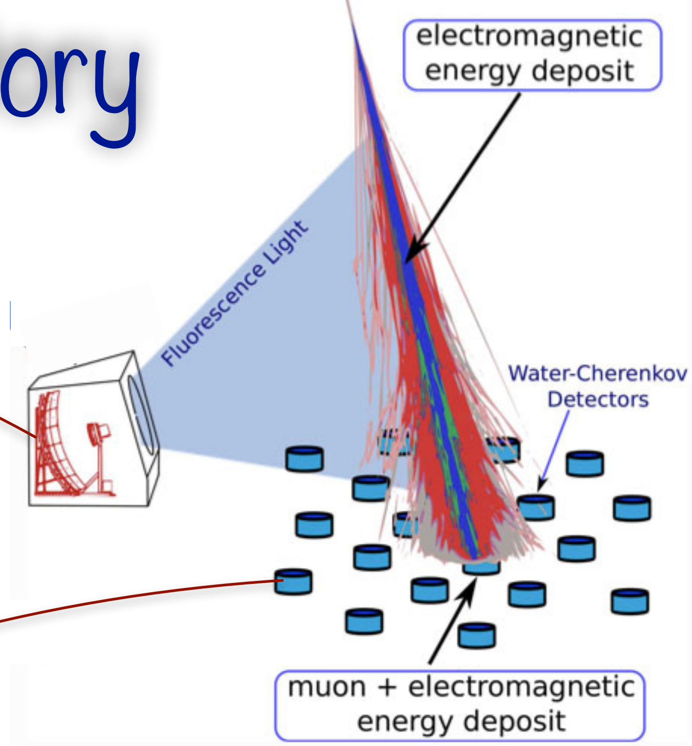


35.2° S, 69.5° W,

- Water-Cherenkov tanks
  - 1660 in a 1.5 km standard grid
  - 71 in 0.75 km infill grid (~30 km^2)
- Fluorescence Telescopes
  - 24 in 4 buildings overlooking SD
  - 3 in 1 building overlooking the Infill
- Muon detectors
  - engineering array phase - 61 aside the Infill stations
- AERA radio antennas (MHz)
  - 124 in the Infill region (~6 km^2)
- R&D GHz antennas
  - AMBER - MIDAS (2 imaging radio telescopes)
  - EASIER (61 radio sensors)

The Pierre Auger Observatory





Simultaneous detection of UHE cosmic rays by means of

SD : 100% duty cycle - precise determination of aperture and exposure

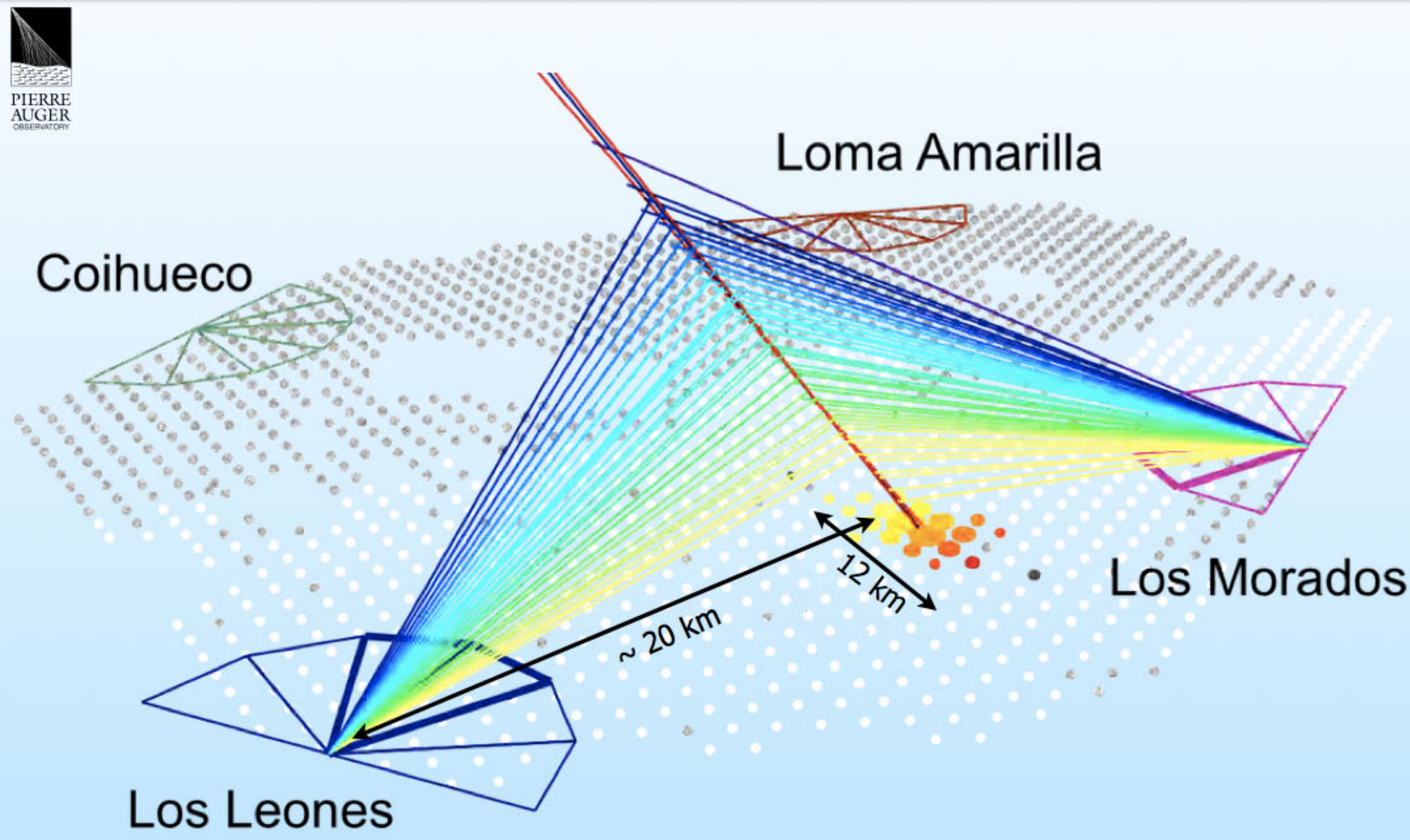
FD : 10% duty cycle - almost calorimetric measure of energy

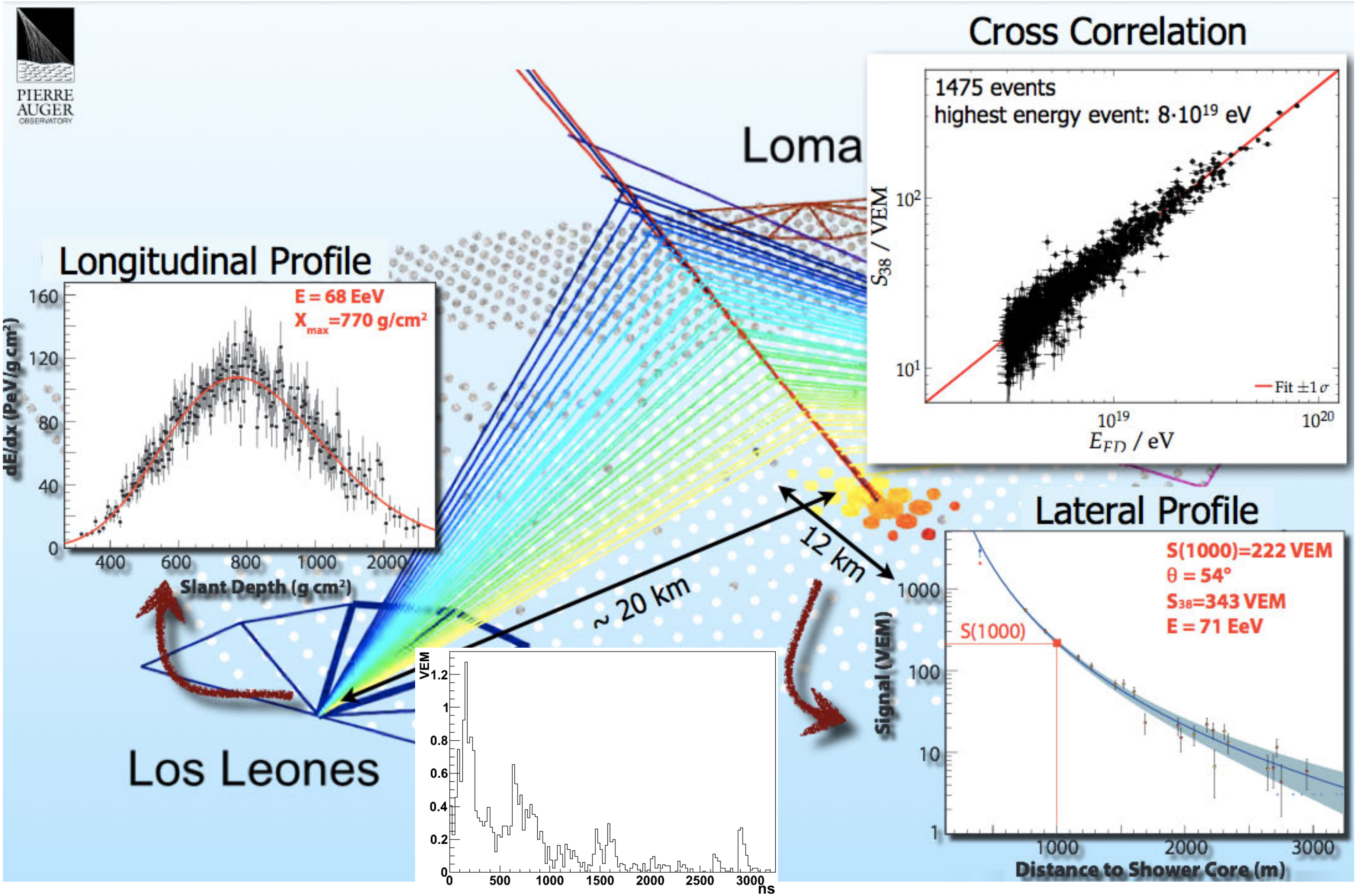
Two complementary techniques:

different shower parameters contribute to identify the primary arrival direction, energy and nature

Different techniques:

measurements redundancy and cross checks

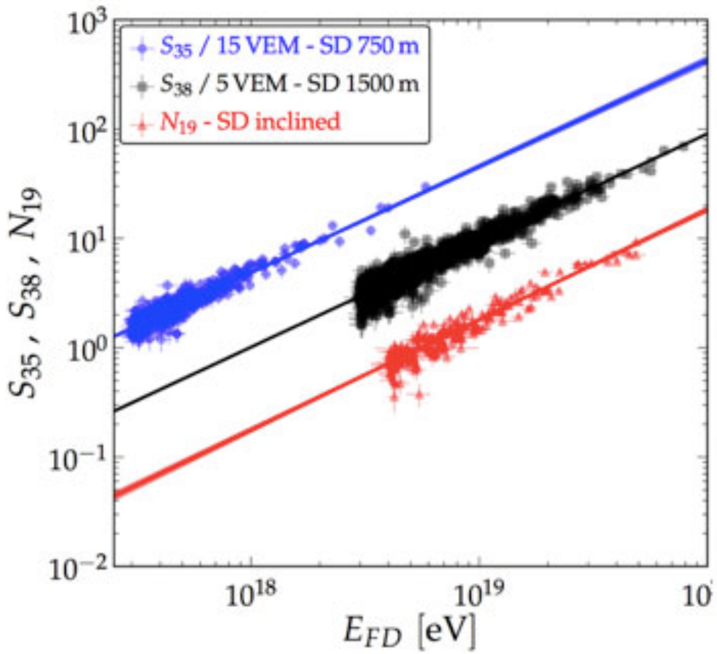

PIERRE
AUGER
OBSERVATORY
Loma Amarilla
Coihueco
Los Morados
12 km
~ 20 km
Los Leones

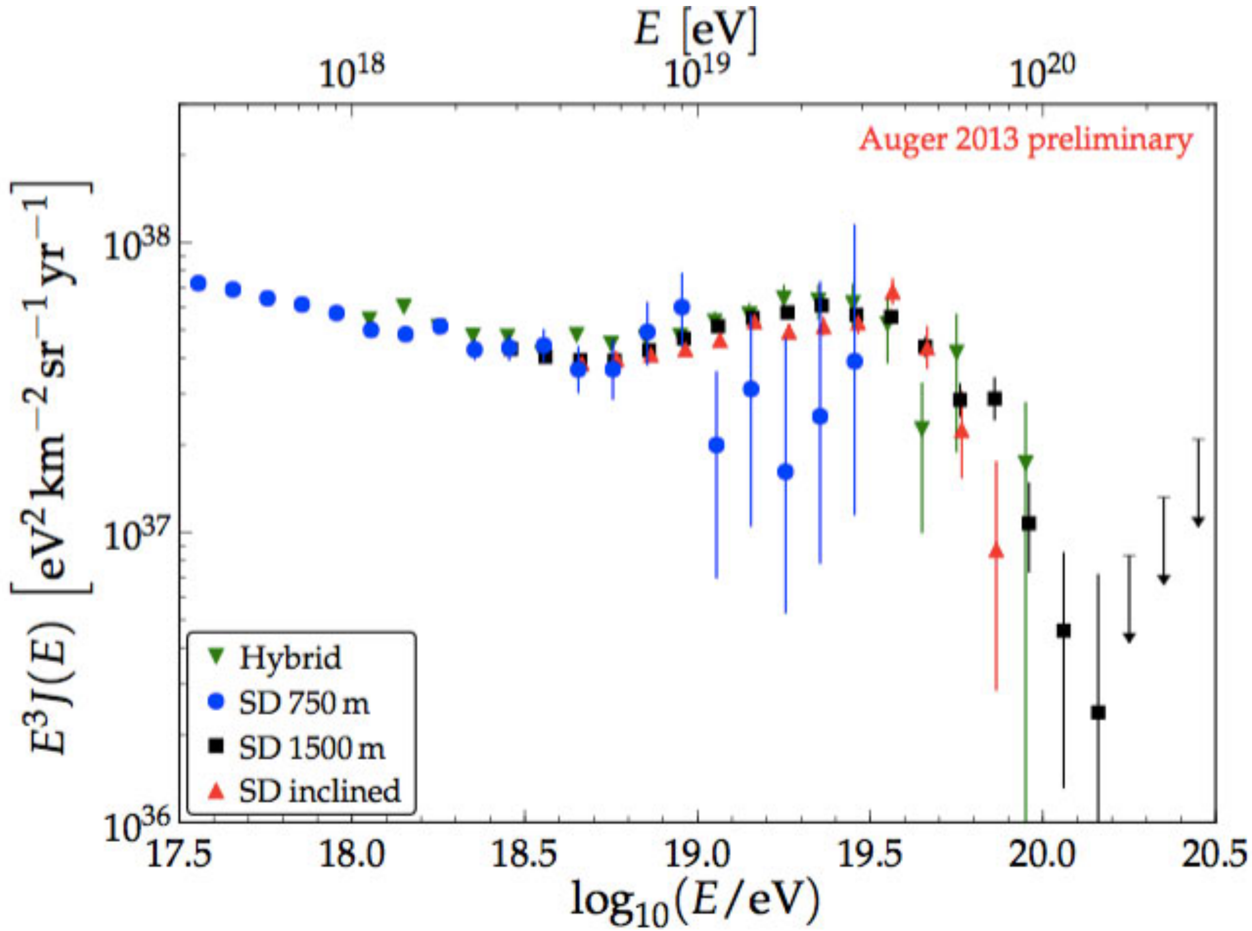

PIERRE AUGER OBSERVATORY
Cross Correlation
1475 events
highest energy event: 8·10^19 eV
S38 / VEM
E_FD / eV
Fit ±1σ
Loma
Longitudinal Profile
E = 68 EeV
Xmax=770 g/cm²
dE/dx (PeV/g cm²)
Slant Depth (g cm²)
Lateral Profile
S(1000)=222 VEM
θ = 54°
S38=343 VEM
E = 71 EeV
S(1000)
Signal (VEM)
Distance to Shower Core (m)
12 km
~ 20 km
Los Leones
VEM
ns

Energy spectrum

Overall uptime

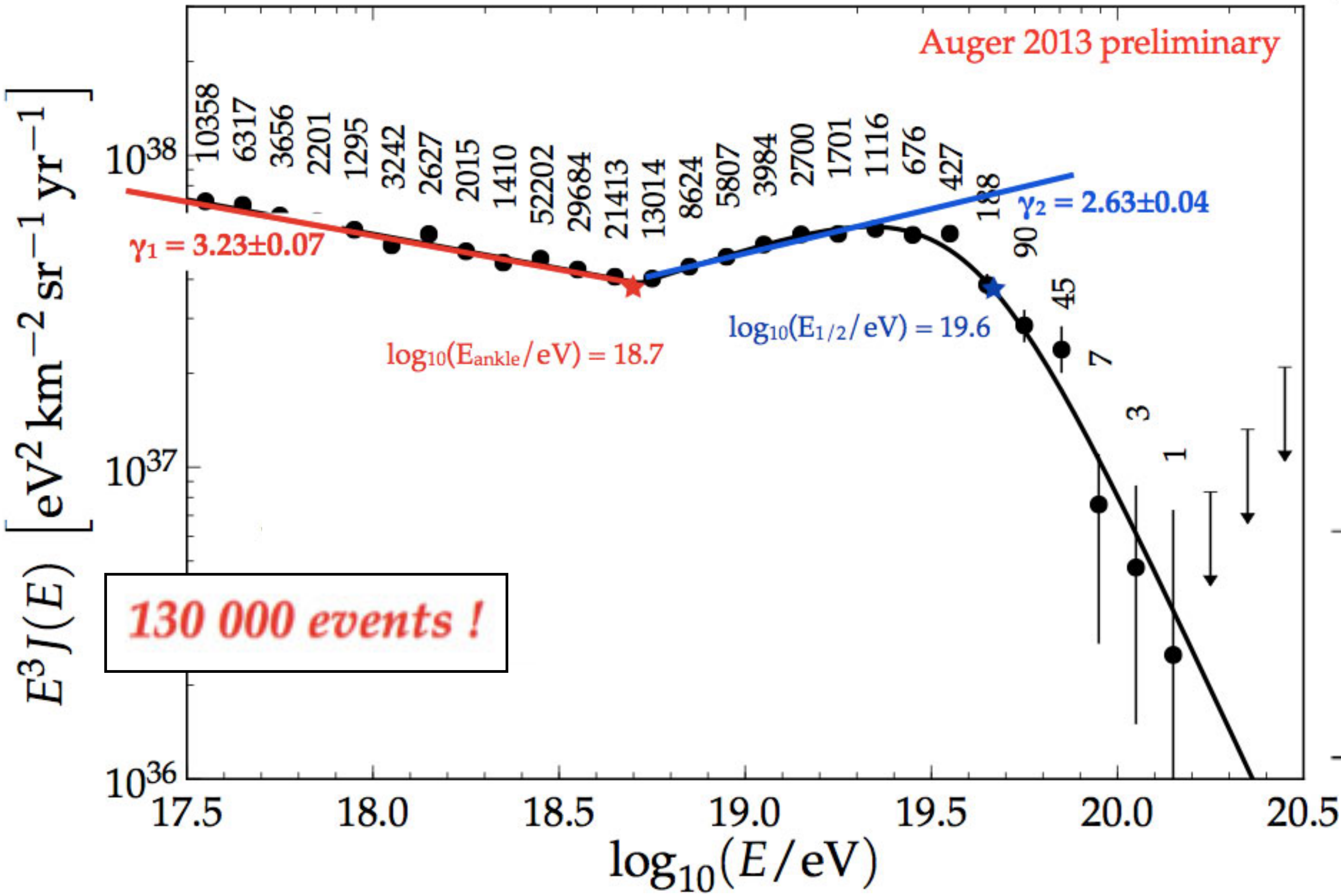
- ~ 98% for SD
- ~ 13% for FD





- SD (1500 m and infill) and FD provide 4 independent measurements
- the 4 spectra agree within statistical and systematic uncertainties

Energy spectrum



Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
$\log_{10}(E_a/\mathrm{eV})$	$18.72 \pm 0.01 \pm 0.02$
γ_1	$3.23 \pm 0.01 \pm 0.07$
γ_2	$2.63 \pm 0.02 \pm 0.04$
$\log_{10}(E_{1/2}/\mathrm{eV})$	$19.63 \pm 0.01 \pm 0.01$
$\log_{10} W_c$	$0.15 \pm 0.01 \pm 0.02$

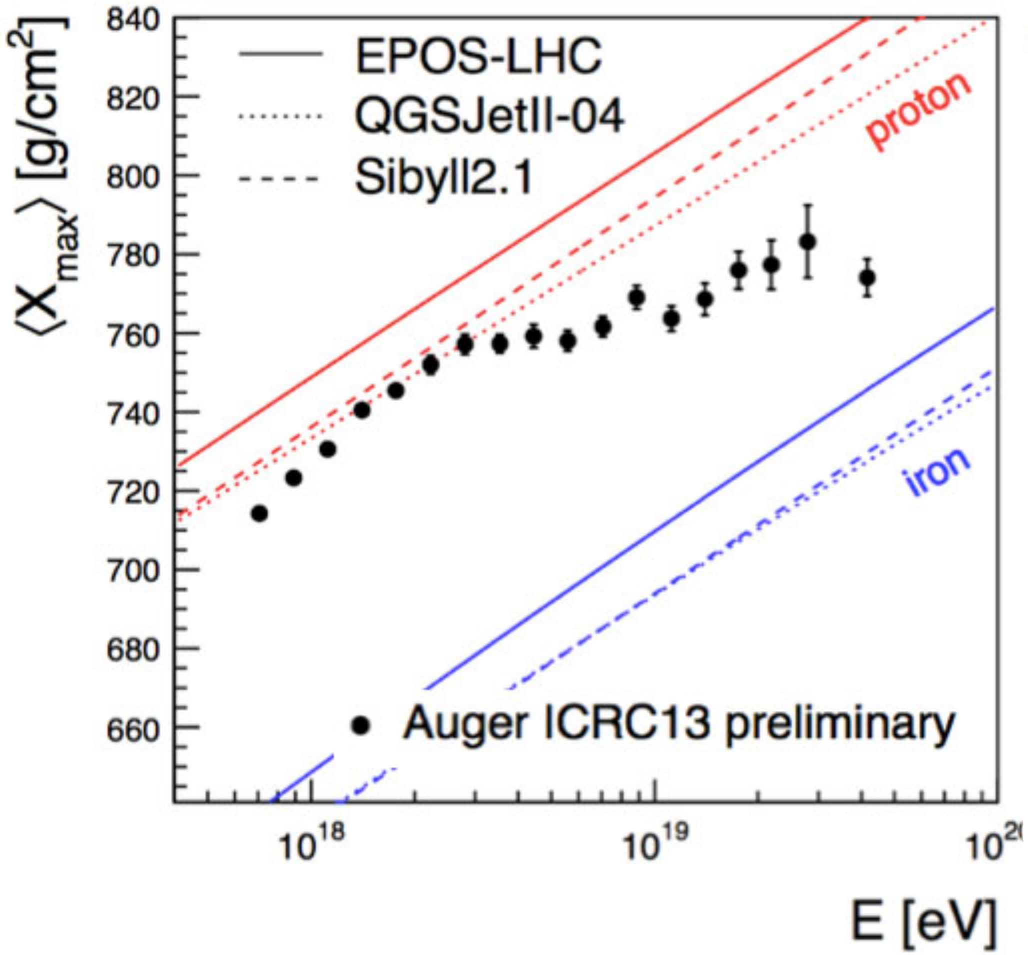
Energy systematic uncertainty

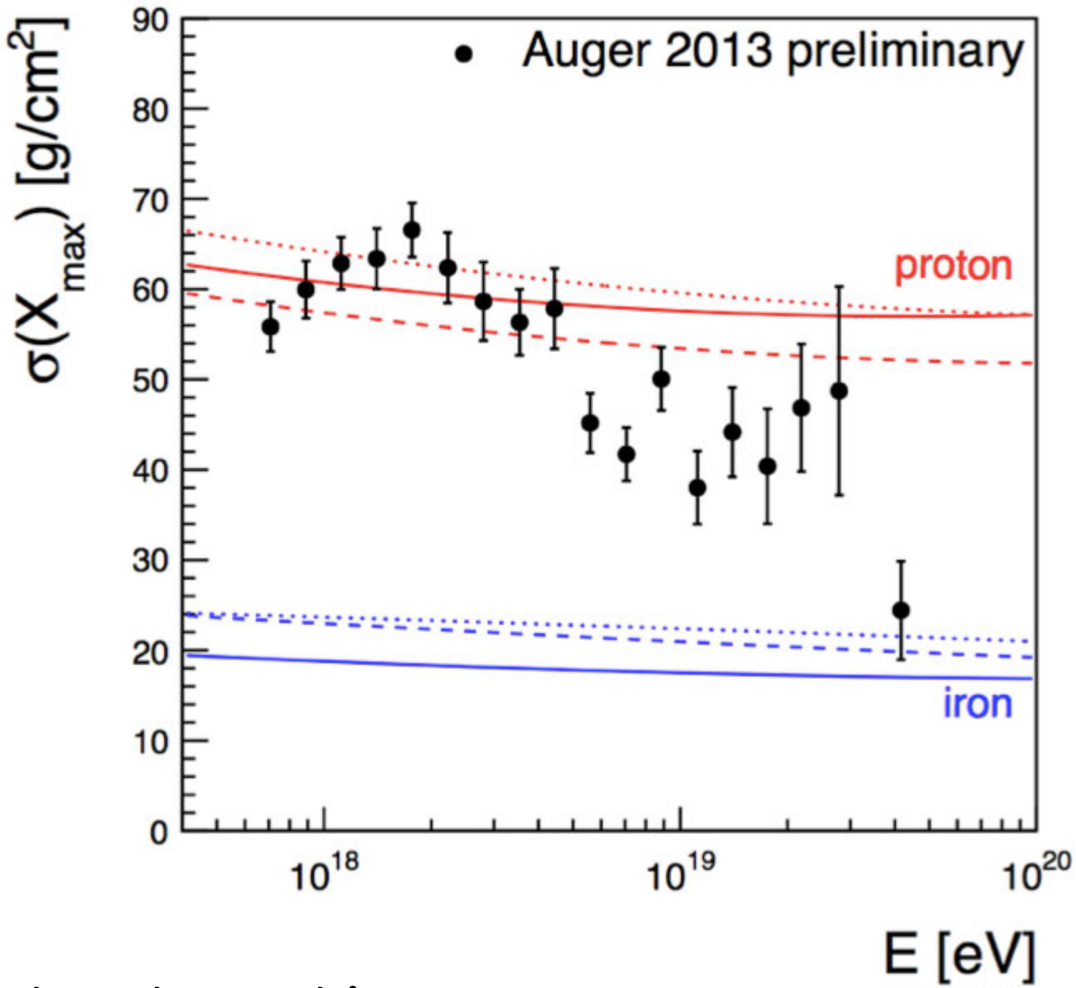
- FD energy scale 14%
  - absolute calibration 9%
  - fluorescence yield 4%
  - shower reconstruction 6%
  - atmospheric corrections 3-6%
  - invisible energy 6%

Flux systematic uncertainties

- SD vertical 6%
- hybrid 6-10% (from 1 to 10 EeV)

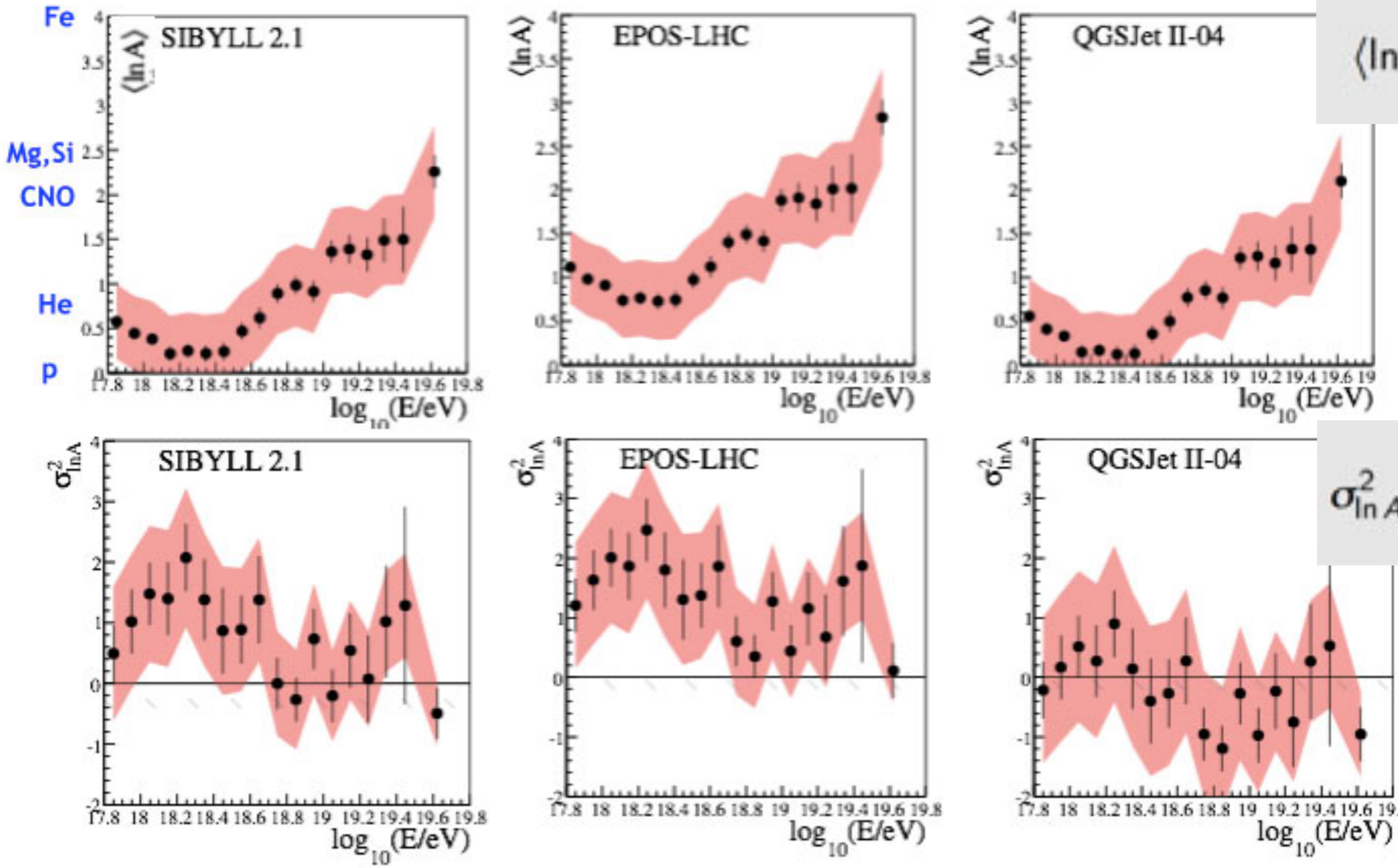
Mass composition - X_{max}





- high quality hybrid data set: anti-bias cuts for a direct data-model comparison
- need of very high statistics

Mass composition - X_{max}



$$\langle \ln A \rangle = \frac{\langle X_{max} \rangle - \langle X_{max} \rangle_p}{f_E}$$

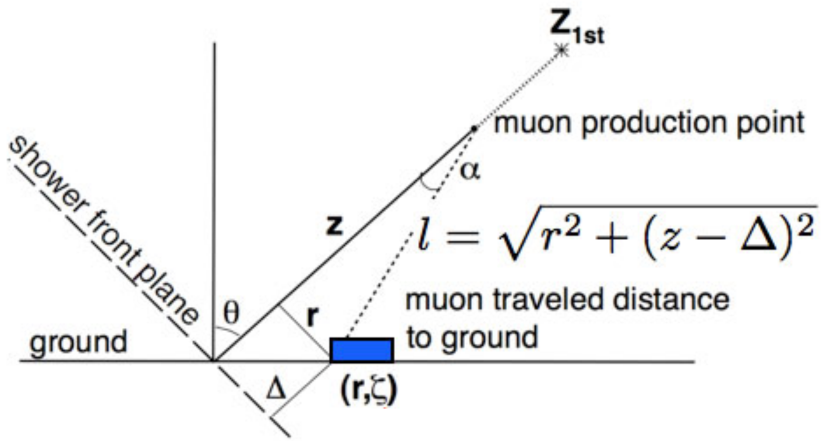
info on average composition

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{max}) - \sigma^2_{sh}(\langle \ln A \rangle)}{b\sigma^2_p + f^2_E}$$

dispersion of masses at Earth: spread at the sources AND propagation effects

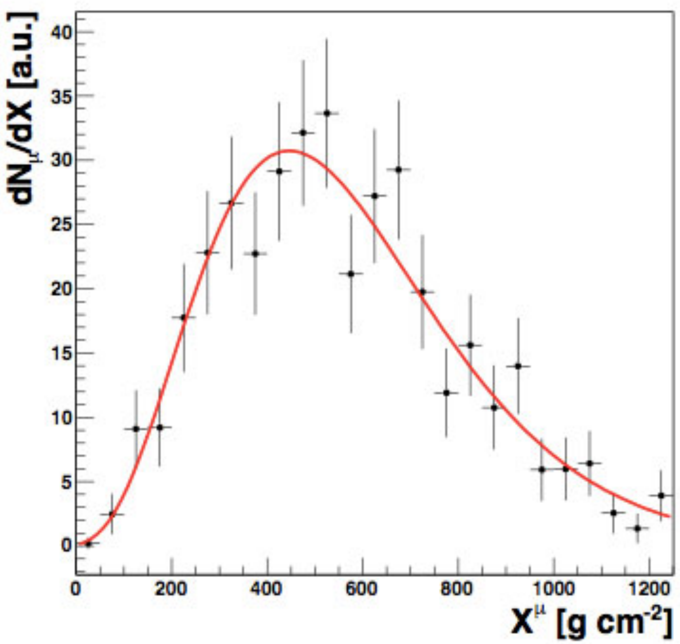
- energy evolution common to all models: <lnA> increasing from light to medium
- $\sigma^2{}_{max}$ ~1 : the mix is within intermediate nuclei (not p:Fe)
- negative variance within systematics

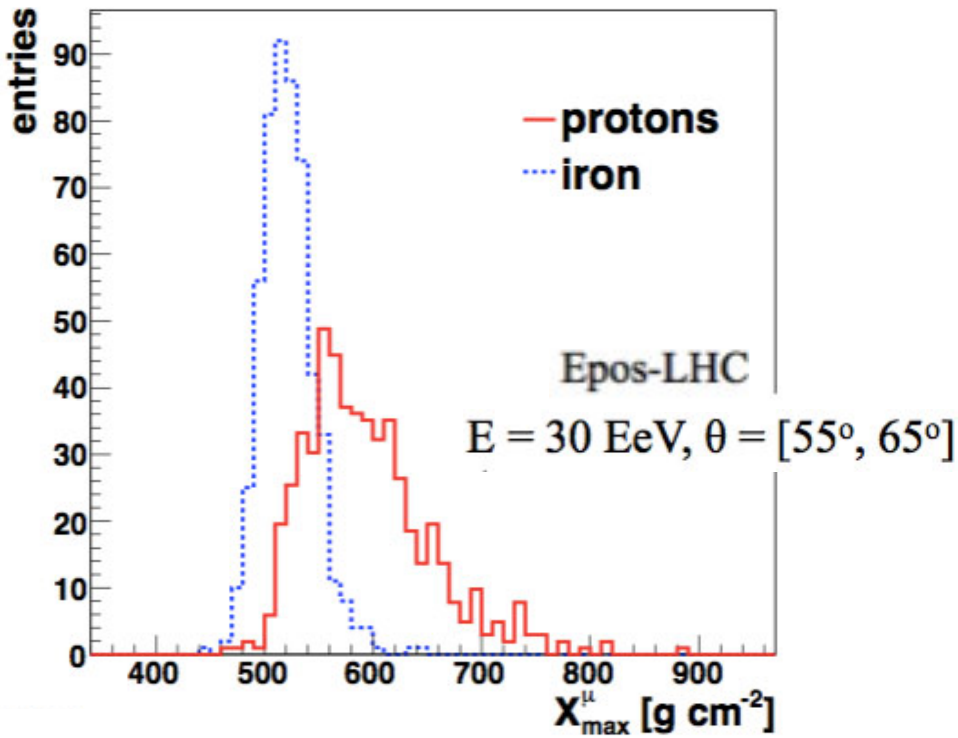
Mass composition - MPD_μ



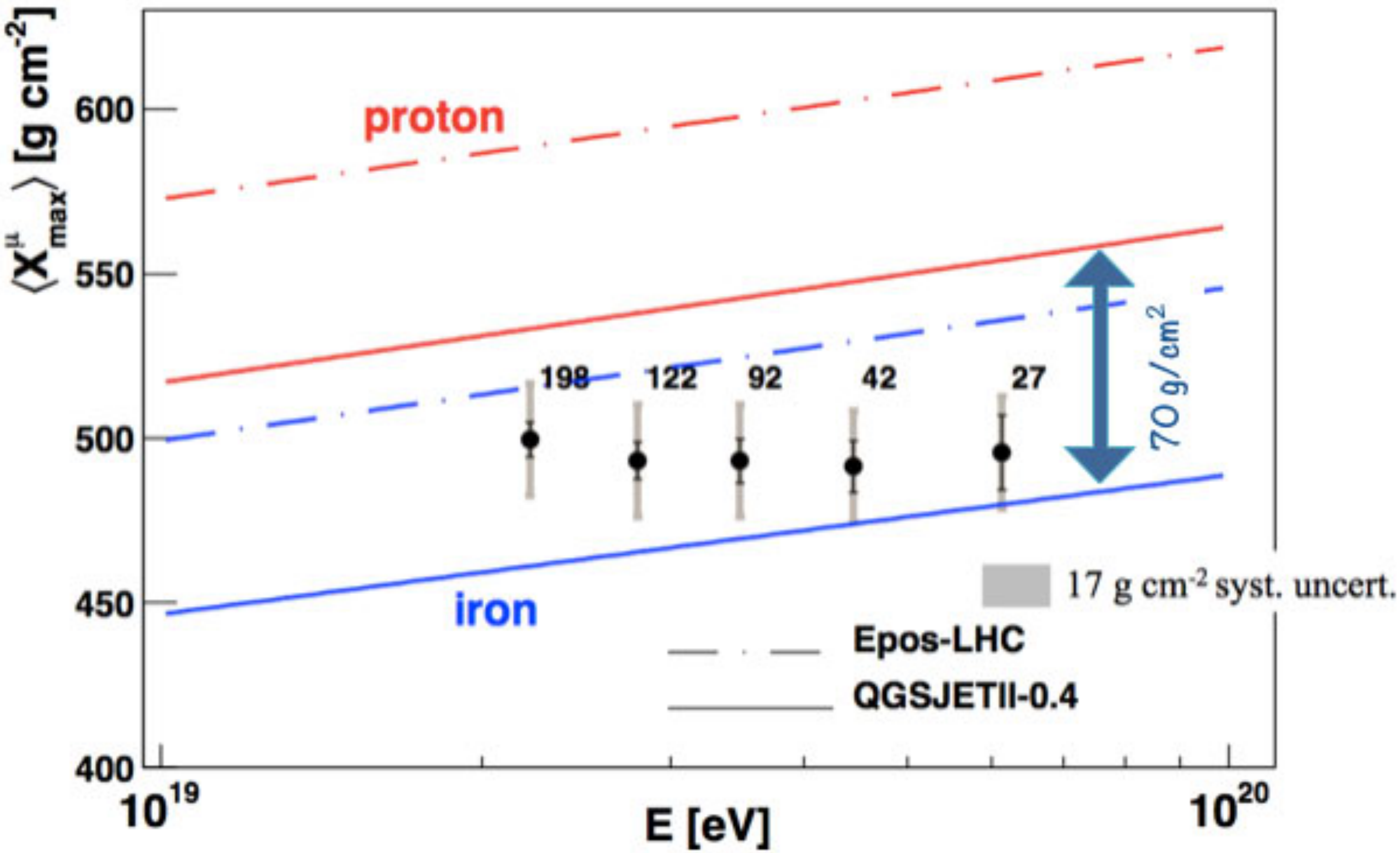
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta \quad \longrightarrow \quad X^\mu = \int_z^\infty \rho(z')dz'$$

$$t_g \simeq t - < t_\varepsilon >$$





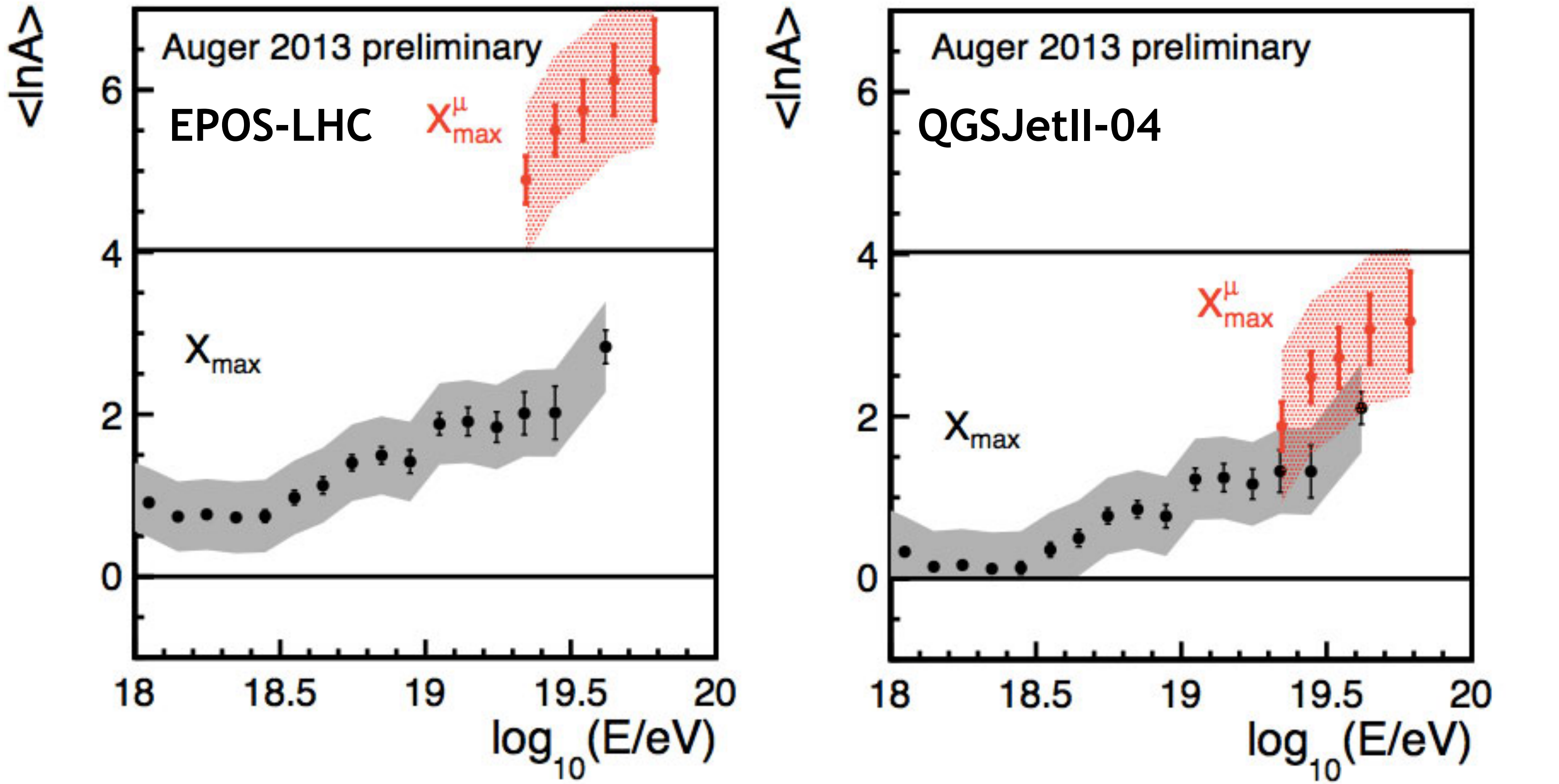
Mass composition - MPD_μ



- novel approach to study the longitudinal distribution of the hadronic component of EAS
- agreement with the conclusion from Xmax (but still compatible with constant comp.)
- here, E>20 EeV, $\vartheta > 55^0$, only stations far from the core. Analysis can be extended to lower angles and energies if able to tag the EM contamination

Interpreting X_{max} and X^{μ}_{max}

$$\langle \ln A \rangle = \ln 56 \frac{X^{p}_{max} - \langle X_{max} \rangle}{X^{p}_{max} - X^{Fe}_{max}} \qquad \langle \ln A \rangle^{\mu} = \ln 56 \frac{X^{\mu p}{}_{max} - \langle X^{\mu}{}_{max} \rangle}{X^{\mu p}{}_{max} - X^{\mu Fe}{}_{max}}$$

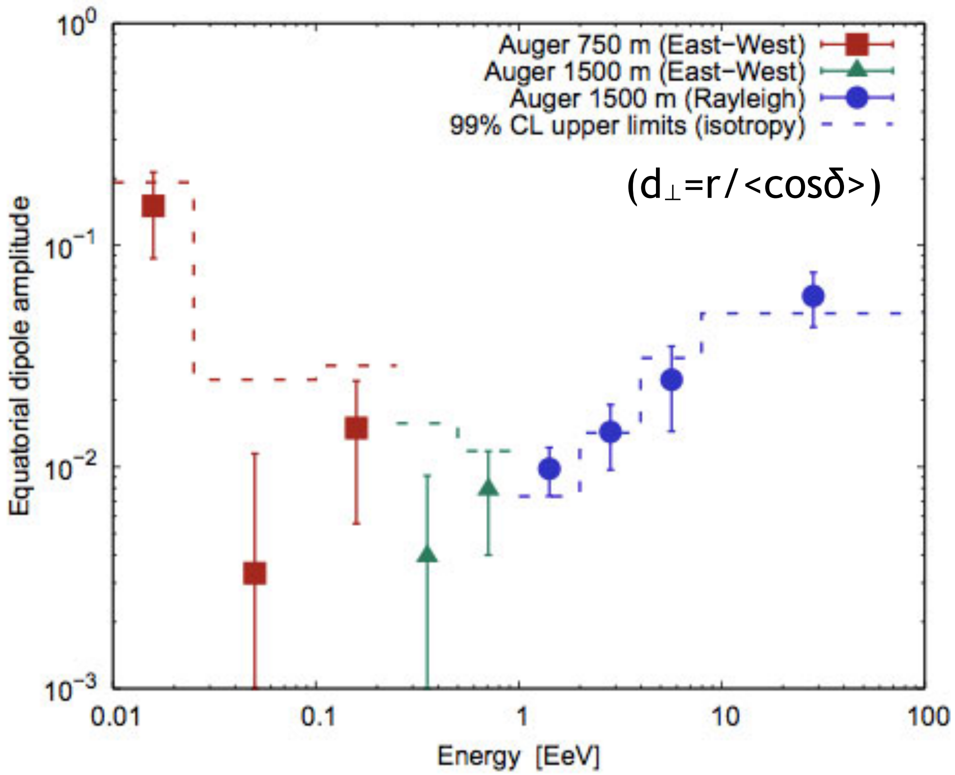


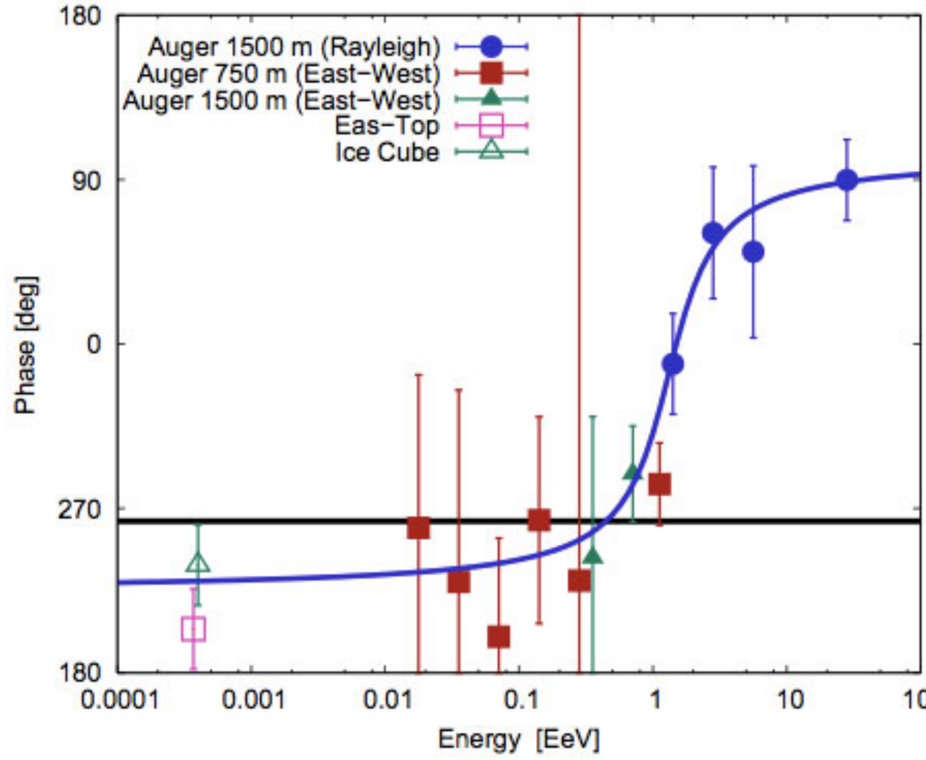
the consistency between the two Xmax can help to constrain hadronic interaction model

Large Scale Anisotropy

- Transition galactic/extragal. origin should induce a significant change in their LS angular distribution
  - if Galactic at 10^{18} eV: %-level modulation (depending on GMF, comp., distr. of sources, ...)
  - if extra-gal. at 10^{18} eV: no structure except for a CMB-dipole (~ 0.6 %)
  - ➡ dipole expected: escape from the Galaxy or extra-gal. CG
  - ➡ quadrupole expected: sources distributed on galactic or super galactic plane or rotation of Galaxy could produce anisotropy by virtue of moving magnetic field (i.e. GMF could transform the extra-gal CG dipole into a quadrupole)
- First harmonic modulations are small
  - ➡ Rayleigh analysis to accounts for spurious modulation (experimental & atmospheric)
  - ➡ East-West method (not sensitive to these effects). Need high statistics

Large Scale Anisotropy

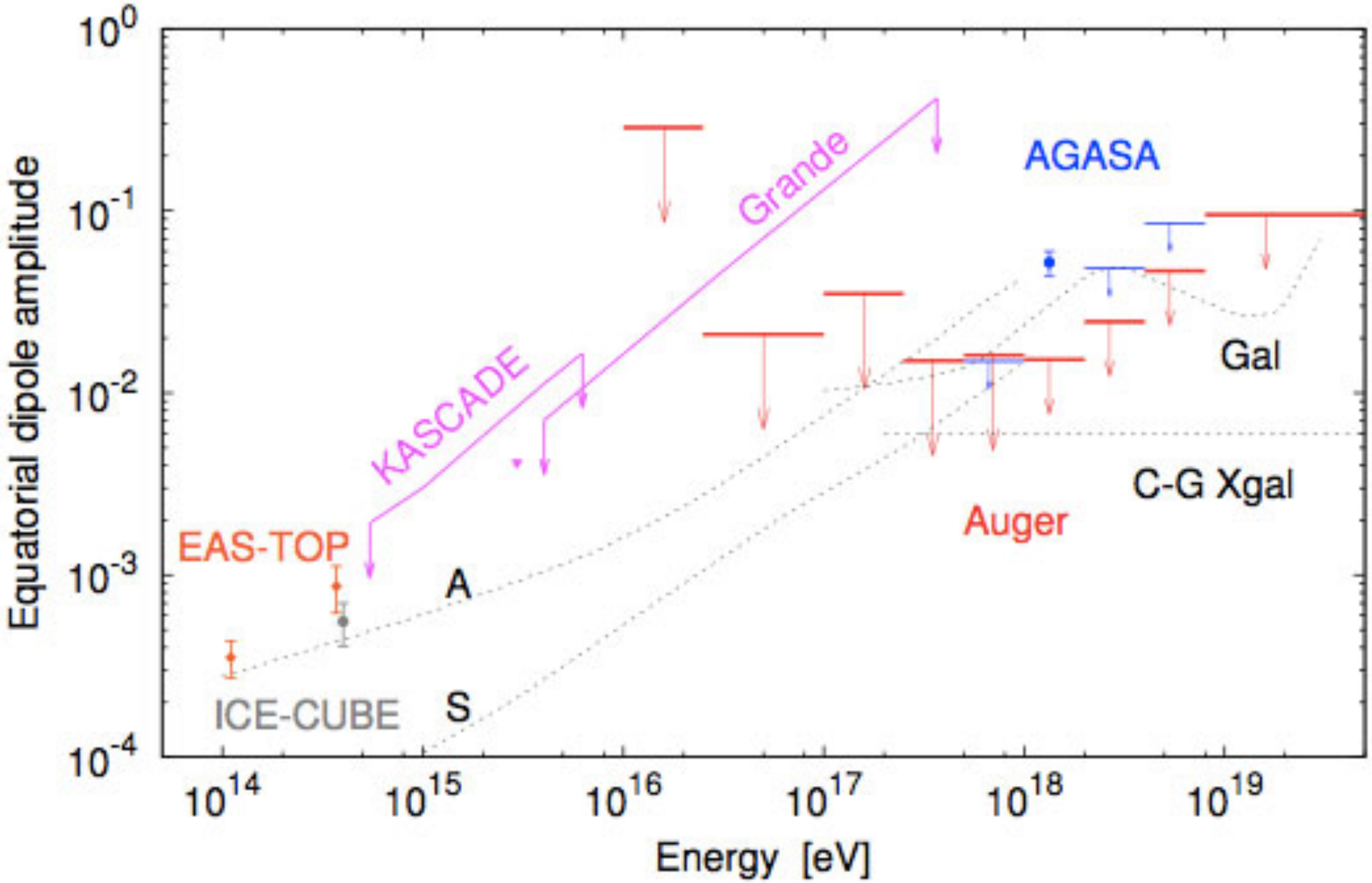




The anisotropy is found to be very small (% level)

- no clear evidence of anisotropy, but 3 points with chance probability <1%
- hint for a smooth transition in phase from 270° below 1 GeV (Galactic origin?) to 90° above 4 EeV (random phase expected from isotropy)

Large Scale Anisotropy



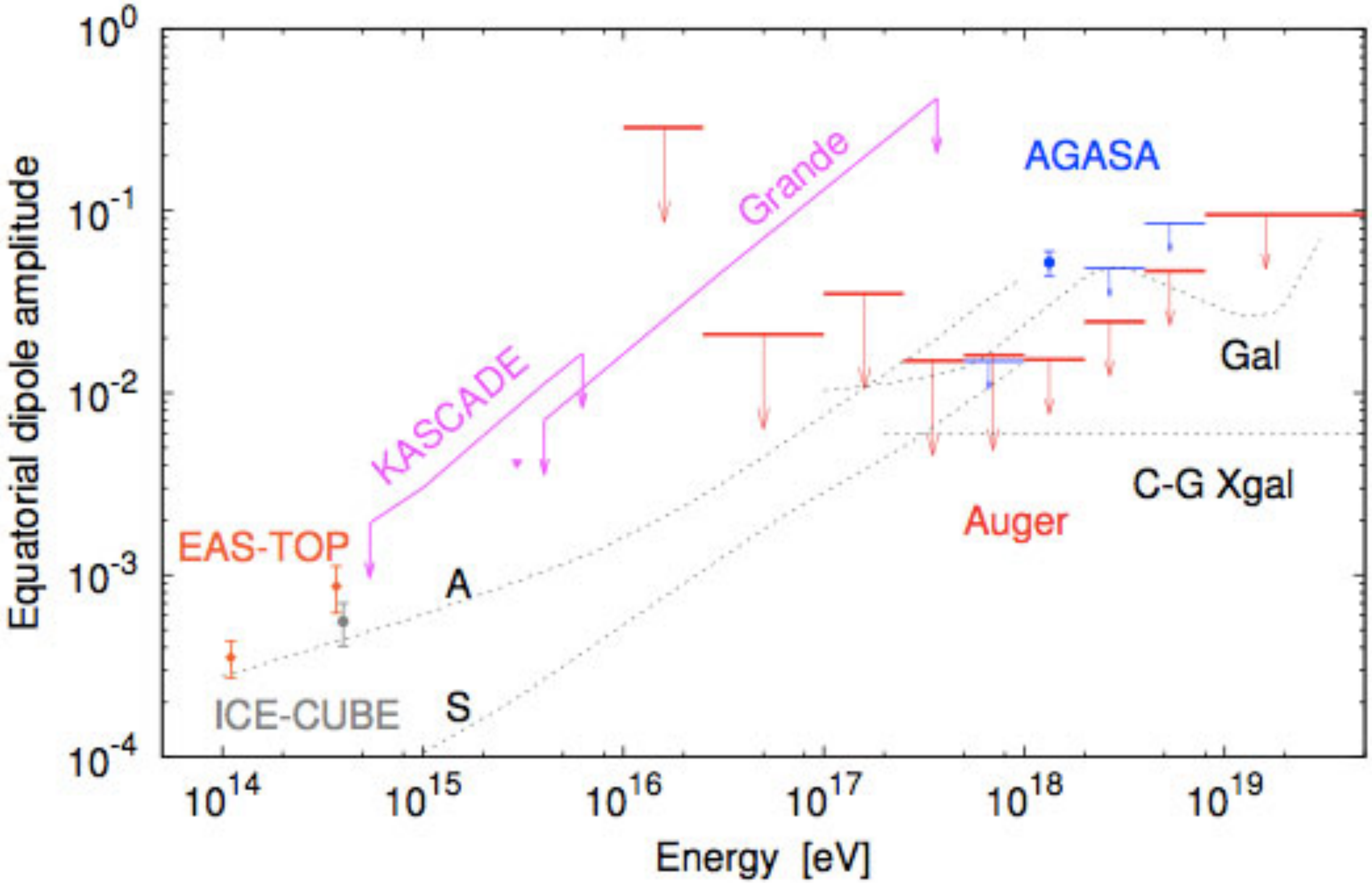
($d_{\perp}=r/\langle\cos\delta\rangle$)

A/S: Gal CRs at EeV, anis due to their escape by diffusion/drift. A/S = antisymm./symm. halo field

Gal: Gal CRs are galactic at all energies, anisotropy caused by diffusion due to the turbulent component of the GMF

C-G Xgal: Compton-Getting effect for extragal. CRs (motion of our Galaxy wrt the frame of extragal. isotropy,CMB)

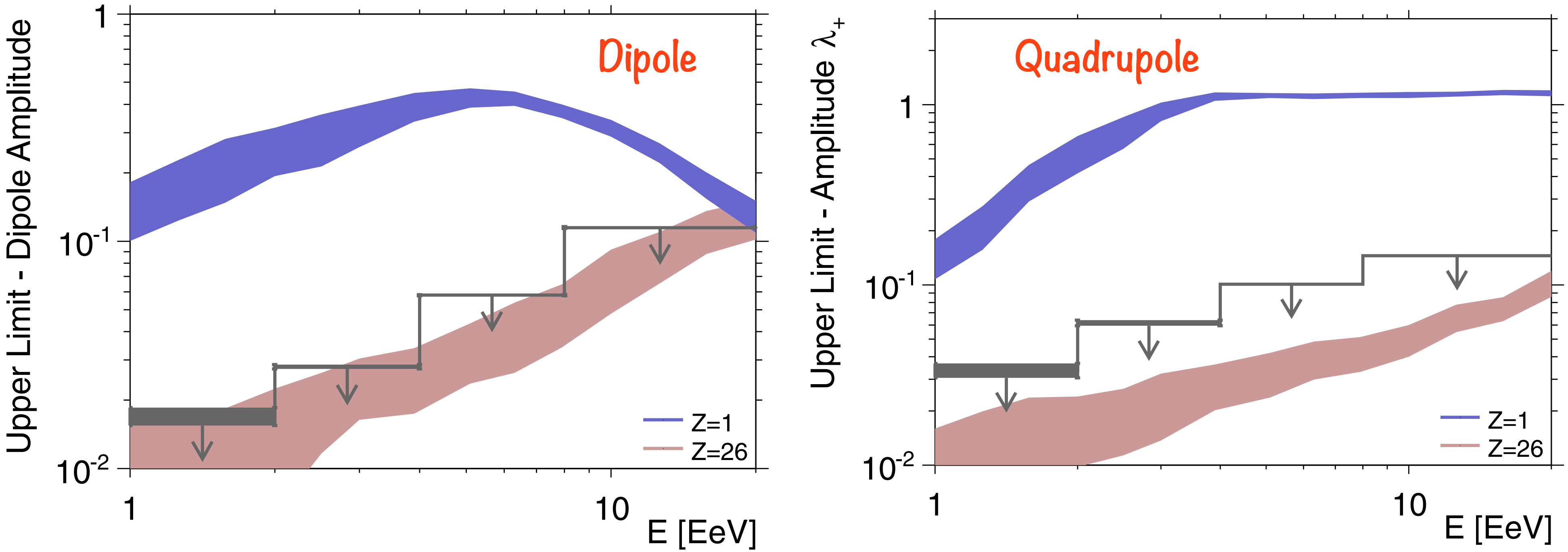
Large Scale Anisotropy



Upper limits on equatorial dipole

- exclusion of models with antisymmetric halo magnetic field >0.25 EeV
- exclusion of Galactic model at few EeV

Dipolar and quadrupolar patterns

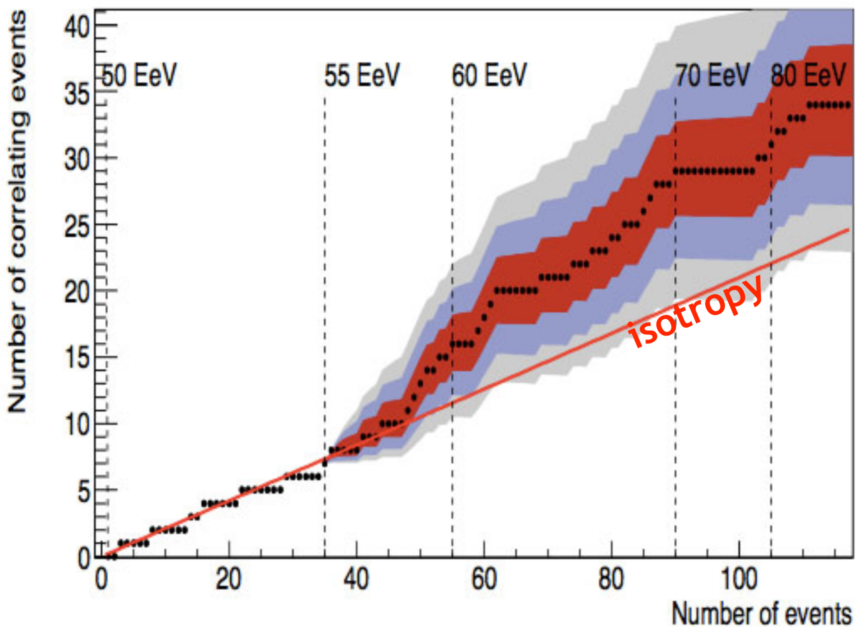


- Generic estimates of the amplitudes expected from stationary galactic sources

- GMF = regular (BSS disk field and anti-symmetric halo field) + turbulent field (according to a Kolmogorov power spectrum)

➡ these upper limits challenge an origin of CRs from galactic stationary sources distributed in the disk and emitting predominantly light particles in all directions at EeV energy ranges (unless the strength of the GMF is much higher than in the picture used here)

Point source searches

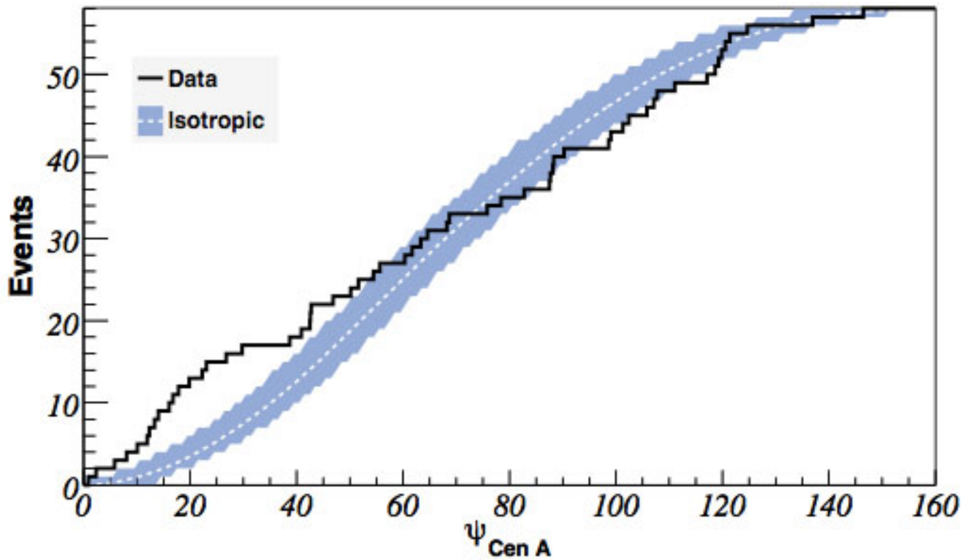


VCV Catalog

- fraction of correlating events (33 ± 5) %
- the content in protons at UHE is small : consistency with X_{max} indication, exhaustion of sources?

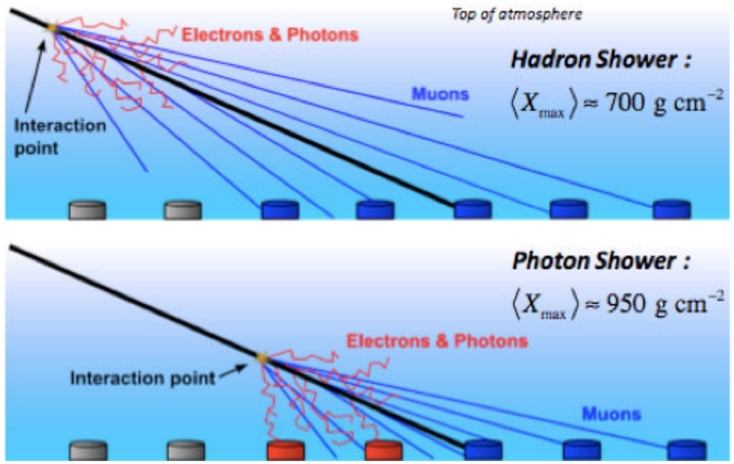
Centaurus-A

- Excess of events from a regione close to CenA (l=-50.5°, b=19.4°)
- 19 events in a 24° circular window vs 7.6 expected
- KS test: max departure from isotropy ≥ that of observed events only in 4% of isotropic realizations



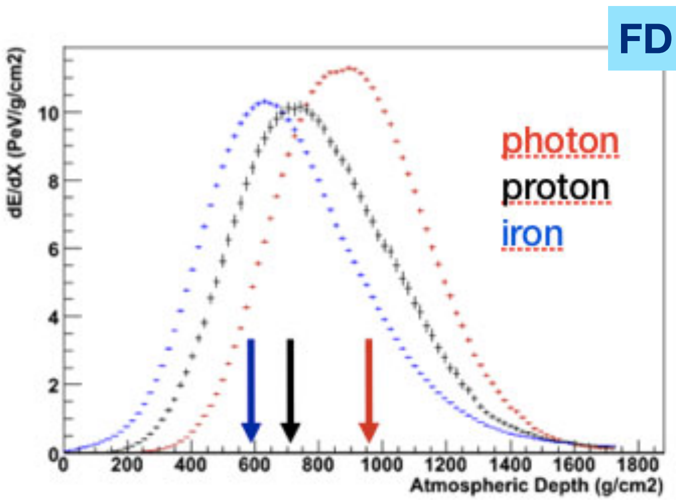
Photons

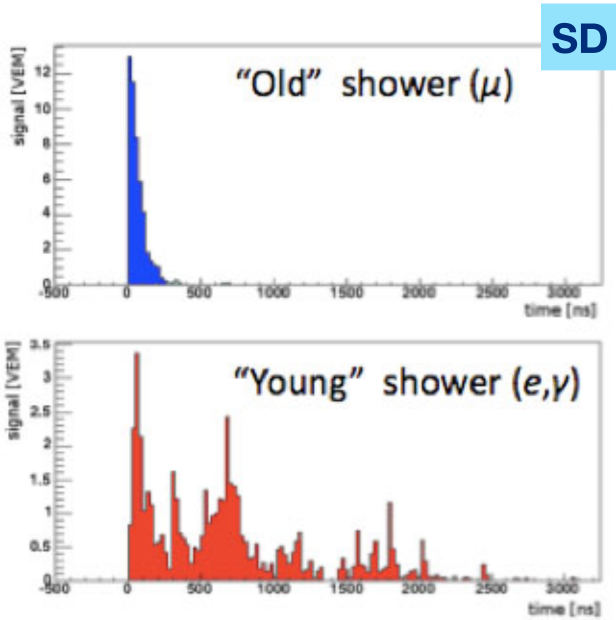
- to set limits on top-down mechanisms
- to search for GZK photons
- to fix the maximum photon fraction in the primary flux

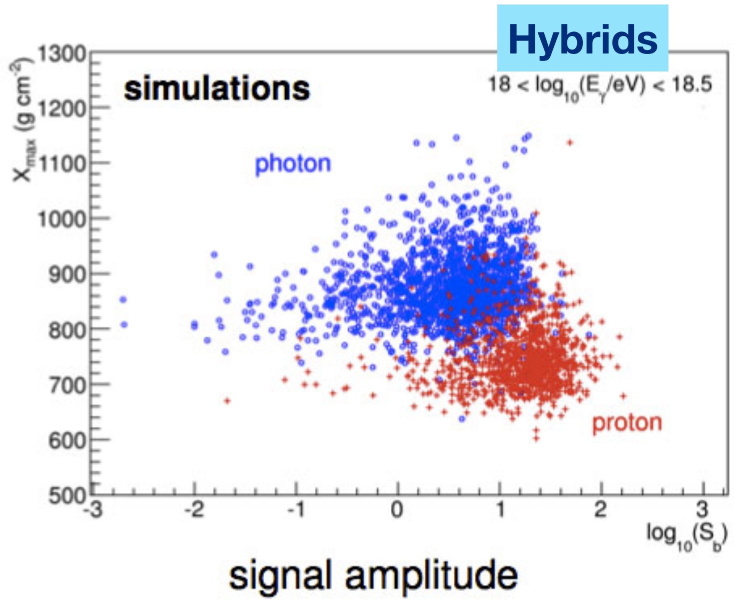


Exploit observable differencies between γ and hadrons

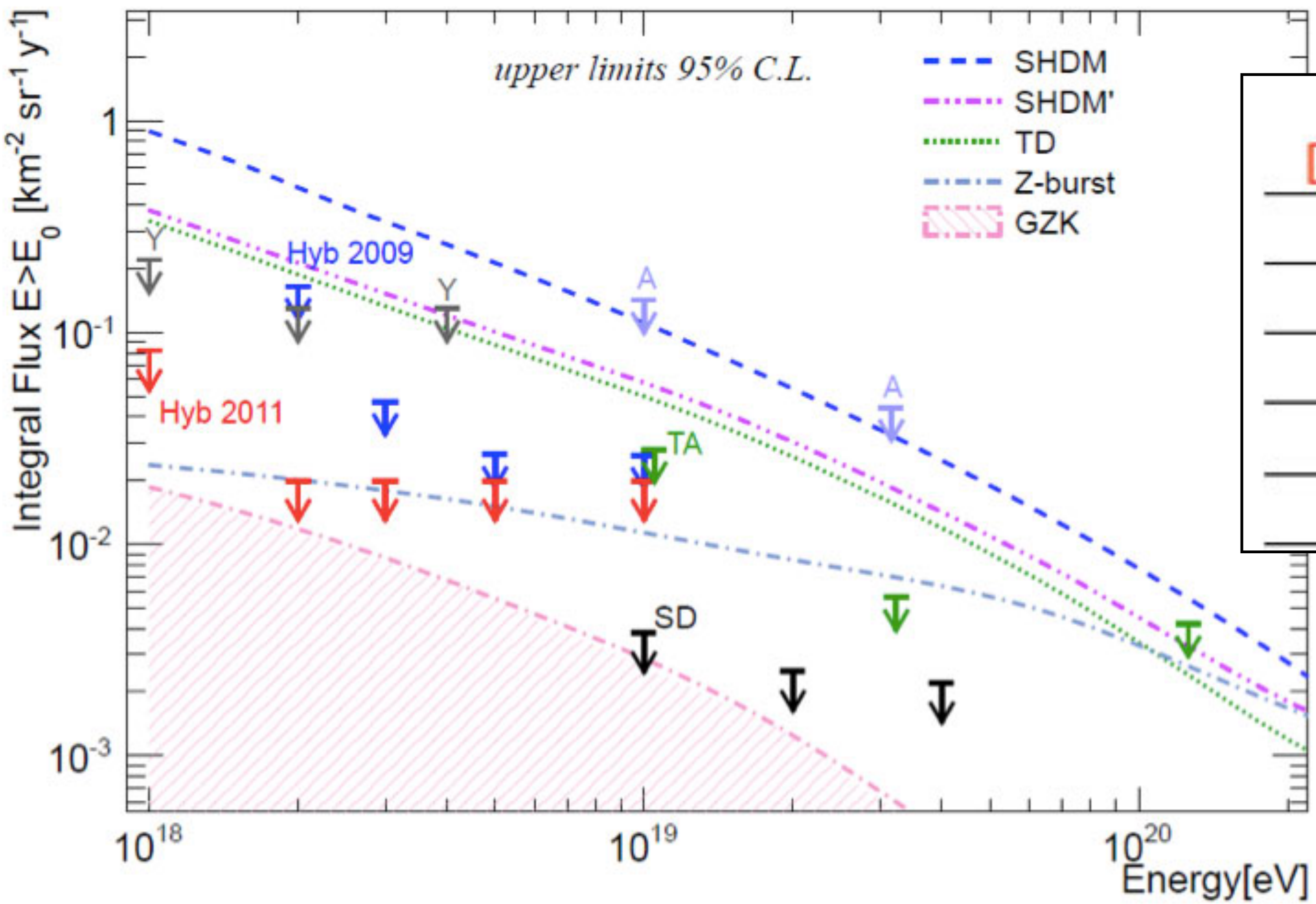
- γ EAS develop deeper in atmosphere: larger Xmax
- γ EAS look young: larger rise time, smaller radius of curvature







Diffuse photons

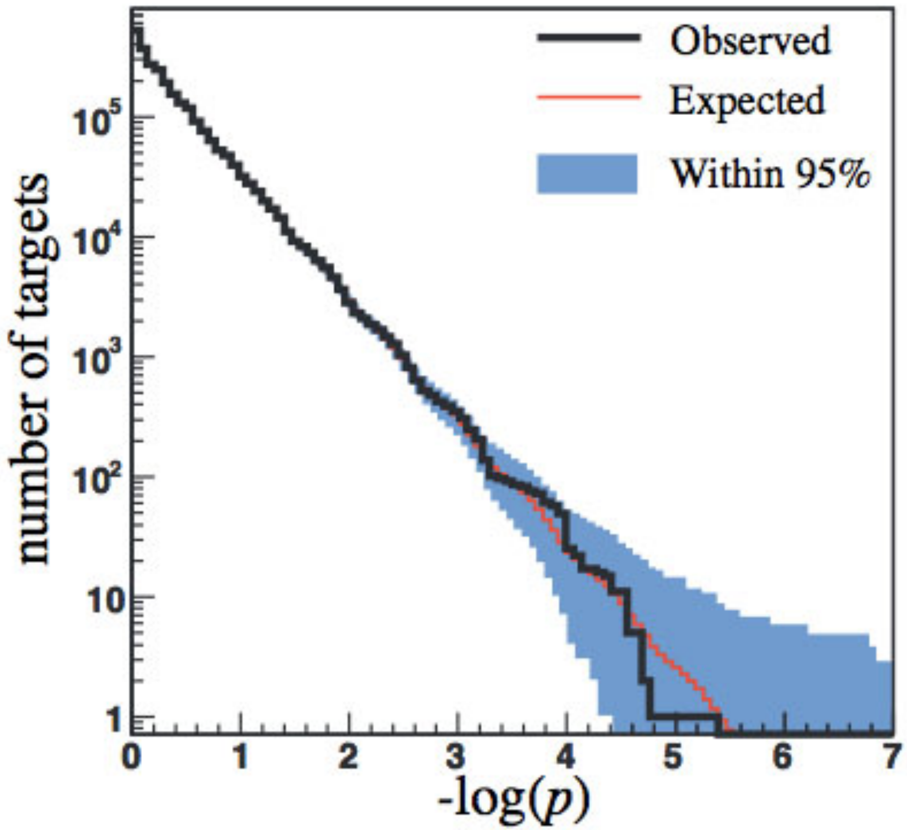


E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

- exotic models disfavoured down to 1 EeV
- GZK region within reach in the near future
- the primary composition is truly barionic

EeV Photon point sources

- Protons near the ankle produce photons ~ 1 EeV : can we find them?
- as the energy flux in TeV γ rays exceeds 1 eV cm^{-2} s^{-1} for some sources (CenA, Galactic center) with this energy spectrum, we expect similar flux at EeV (as sources with spectrum ~ E^{-2}, put the same energy flux/decade)



No point sources of EeV photons is found.

For $d\phi/dE \sim E^{-2}$

$\phi_\gamma < 0.25$ eV cm^{-2} s^{-1}

well below expectations

No Galactic sources of protons IF

—> they are not transient

—> they do not emit in jets towards Earth

—> they are too faint

What did we learn from Auger ?

Spectrum

The ankle is clearly seen at $10^{18.72}$ eV
The cut-off is established (>20σ), $E_{1/2} = 10^{19.63}$ eV

Composition

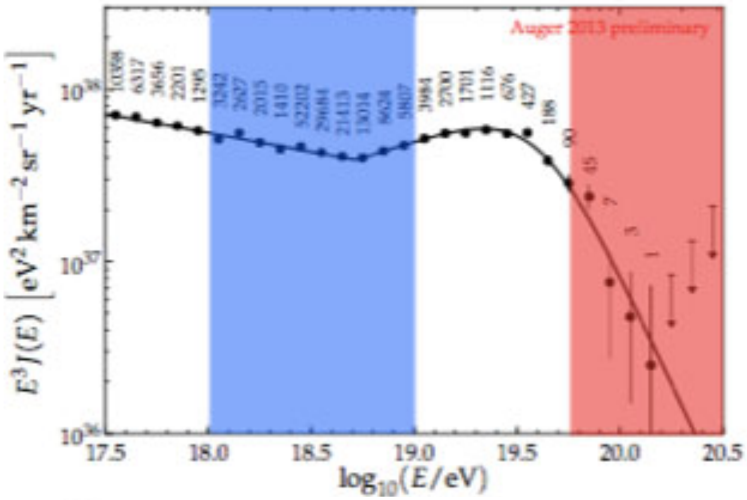
The composition gets heavier for increasing energy
No primary photons: exclusion of top-down models
No photons/neutrons form Galactic sources
Neutrinos constraints on astrophisical models

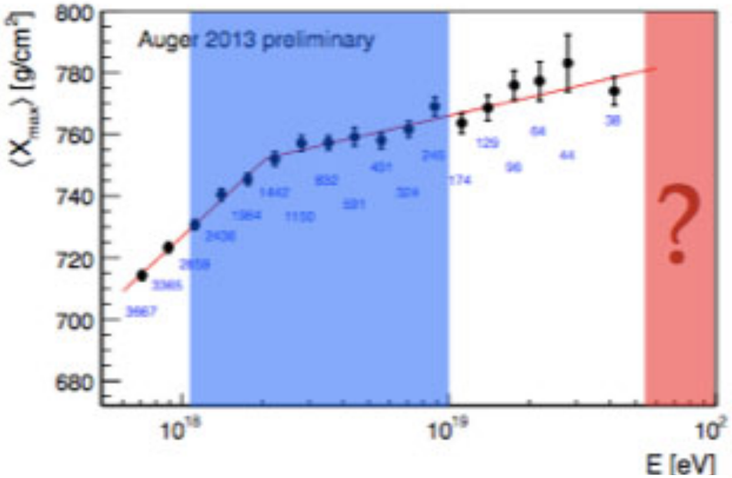
Anisotropy

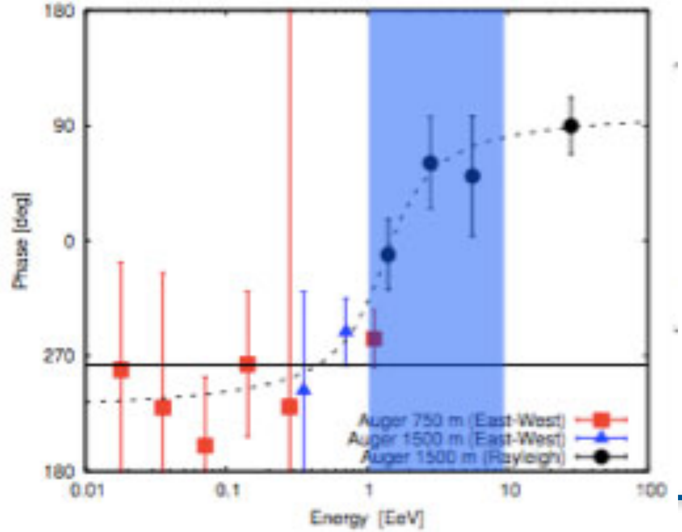
No LSA above 1-2%
exclusion of antisymmetric models of Galactic MF
exclusion of Galactic models above few EeV
Hints for Gal-XGal transition from dipole phase
Point source anisotropy above 55 EeV (3σ level)

Hadronic interactions

smooth growth of the pp cross section (meas.57 TeV)
muons put constraints to the hadronic interaction models







Questions and answers from Auger results

protons

Is there a proton component (~10%) at UHE?

above 55 EeV, some indication for anisotropy

Are there Galactic protons at the ankle ?

the composition is light, but we do not have anisotropy >few %;

extreme assumptions on Galactic magnetic fields could reconcile the two info

No evidence from n and γ flux limits, but sources could be transient, or faint...

cut-off

Is it due to propagation or source E_{max}?

the cut-off energy $E_{1/2}$ is lower than expected from GZK

composition is mixed and getting heavier

future detection of cosmological photons and neutrinos as a direct evidence

hadronic interactions

Can we get information on hadronic interactions at UHE ?

smooth grow of the pp cross section, measured at 57 TeV

muon content of EAS

other info

Are UHECR produced in top-down mechanisms?

excluded from photon and neutrino limits

....

Astrophysical scenarios

photo-disintegration

sources accelerate nuclei to a maximum energy
light elements are fragments of heavier nuclei

- cut-off: energy loss processes of nuclei (photo-disintegration)
- light elements appear at E shifted by $m_{daughter}/m_{parent}$
- N-Si nuclei in the sources, no protons

maximum energy

sources accelerate nuclei to a maximum energy $\propto Z$
composition in the source similar to the Galactic one

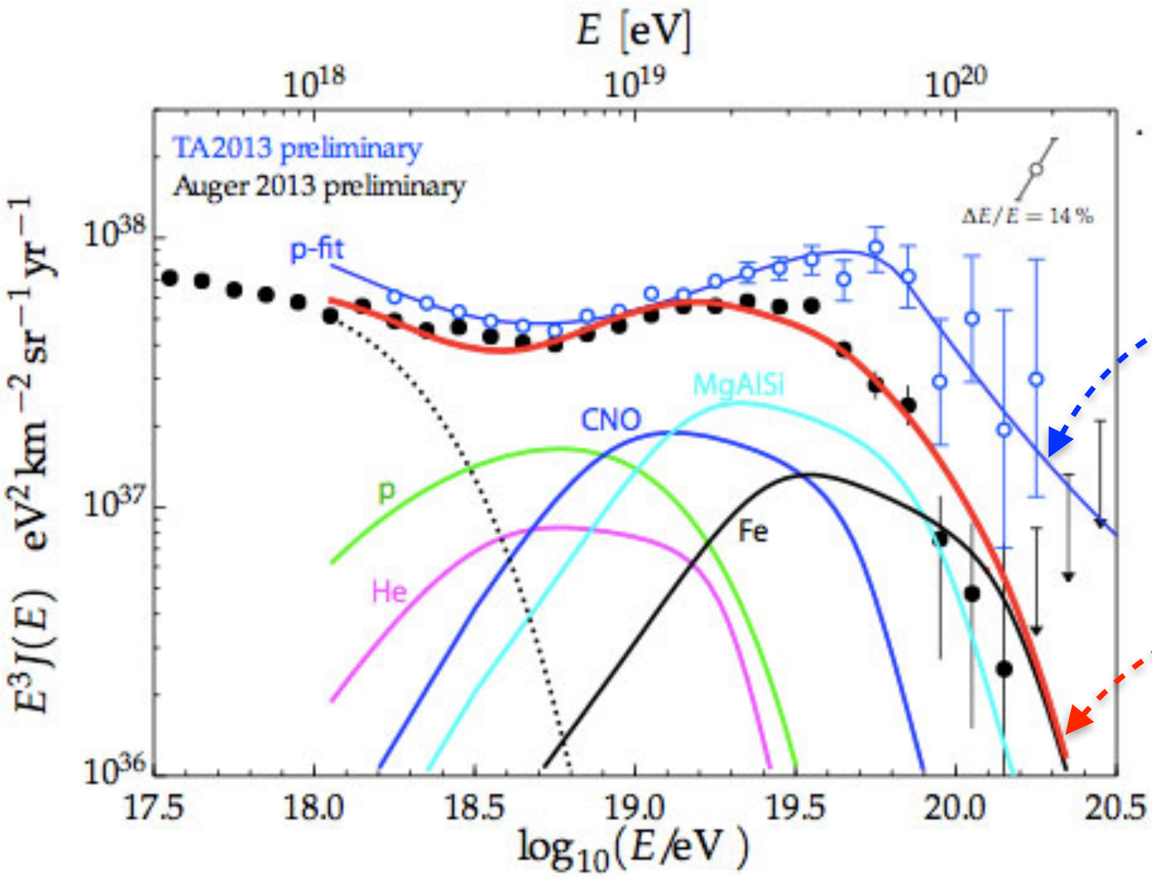
- cut-off: E_{max} reached in the source
- composition getting heavier for increasing energy
- protons at the ankle are extragalactic, no GZK γ or ν

proton dominance

the all particle flux consists of extragalactic protons
the source has a cut-off energy

- cut-off: energy loss processes for protons (pion-photoproduction)
- ankle due to pair production of protons on CMB
- new physics to explain heavier composition at UHE

Example scenario



- extragalactic proton sources
- sources distribution $(1+z)^{4.4}$
- injection spectrum $E^{-2.36}$

- Emax ~ $2 \times 10^{18.7}$ eV
- very hard injection spectrum E^{-1}
- enhanced Galactic component

(from arXiv:1312.7459)

- hard spectra: acceleration in rapidly rotating neutron stars, accretion disks with unipolar induction, etc. (high metallicity)
- good fit to Auger only above 5 EeV. Below
  - ✓ Galactic spectrum extending up to 5 EeV
    BUT if light, disfavoured by anisotropy results, if heavy by X_{max}
  - ✓ extraGal. (ad-hoc) sources injecting p, He. In agreement with Kascade-Grande and IceTop results
    BUT too much Fe at 1 EeV wrt Xmax result

The science case for an upgrade beyond 2015

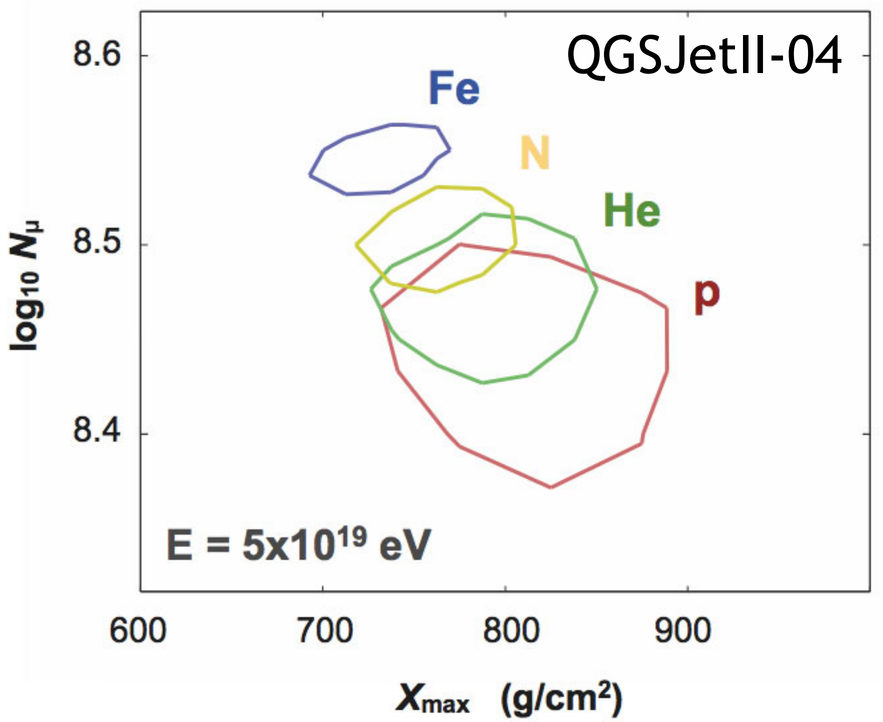
1. the origin of the cut-off : GZK or E_{max} ?
2. the proton component at UHE: what is its fraction ?
3. the hadronic interactions : particle physics beyond accelerators ?

operate Auger until 2023 (x 3 statistics)
with improved detector composition sensitivity : MUONS

Discrimination of muons vs EM component in SD will give

- composition info in the cut-off region
- increase our knowledge in the ankle region
- help in disentangling composition and hadronic interactions systematics

The science case for an upgrade beyond 2015

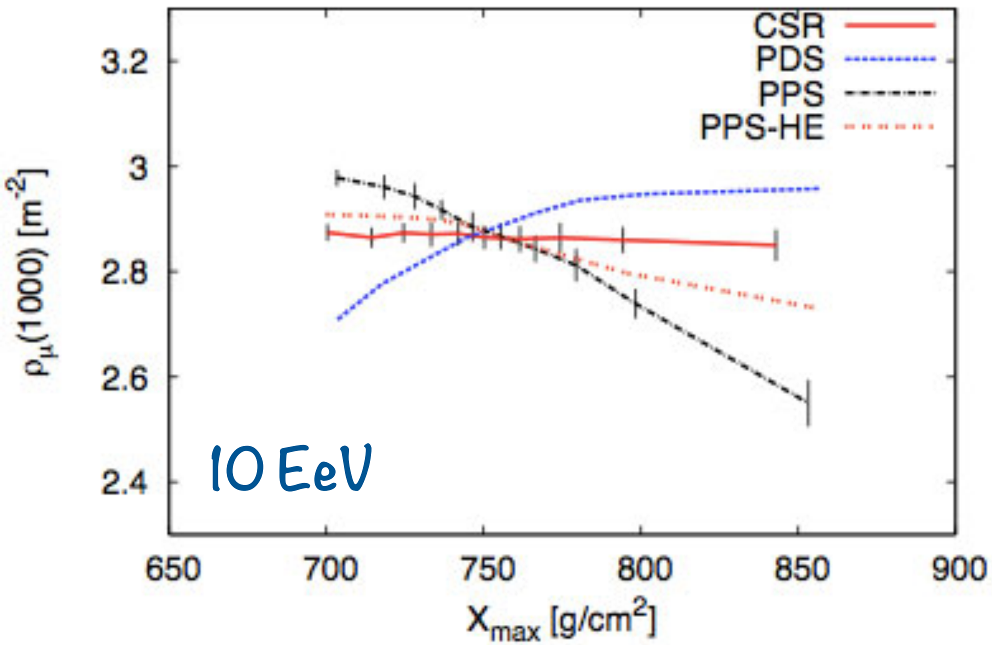


We can distinguish different primaries if N_μ only affected by shower-to-shower fluctuations

Are hadr.int.models failing in predicting the fraction of E_{EM} ?

N_μ —> m, f_{EM}, A

X_{max} —> σ, κ, m, A

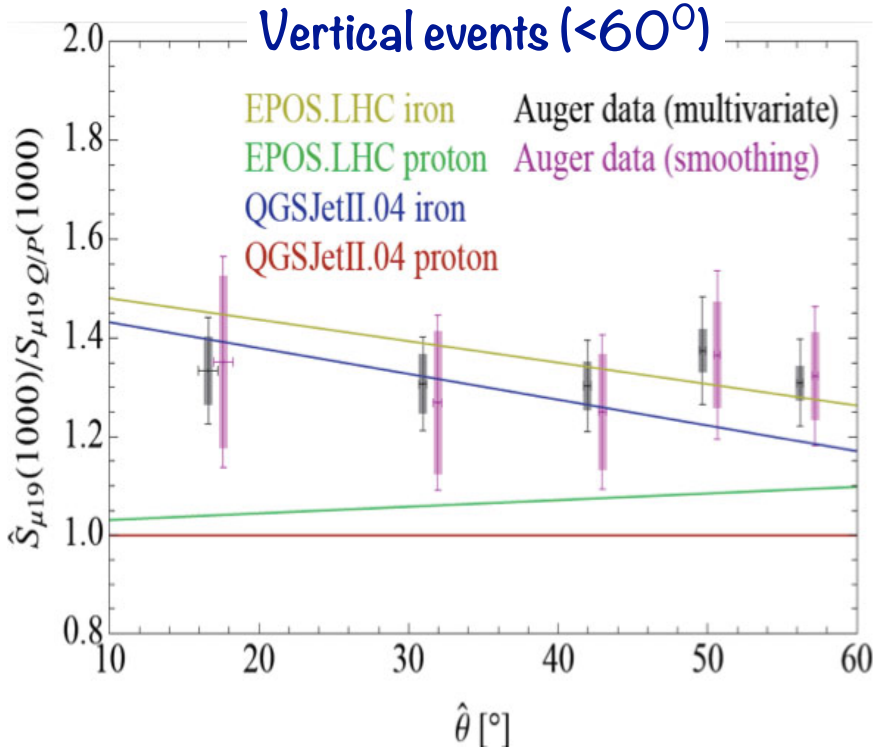


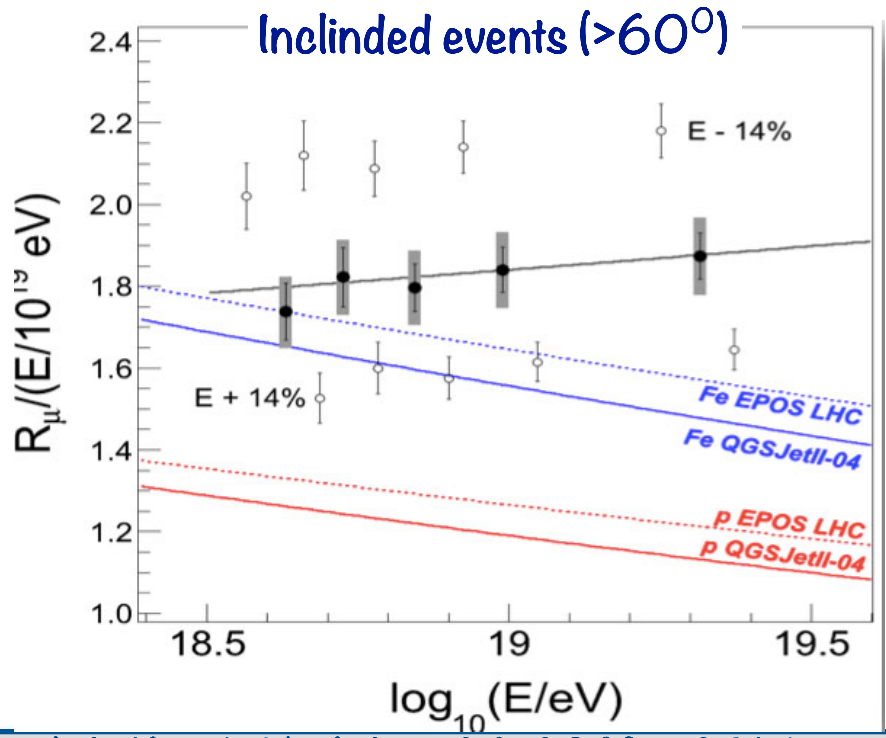
UHE physics case is strong
Auger is the biggest running observatory

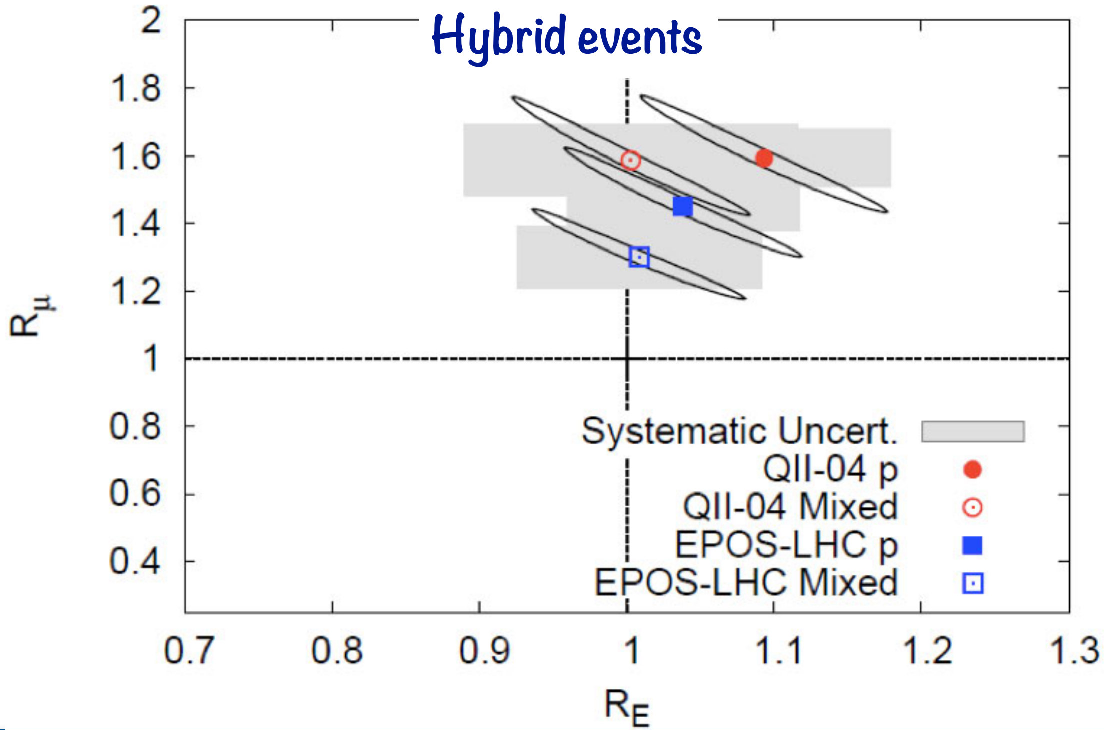
- ✓ a very fruitful collaboration is going on between Auger and TA
- ✓ the results from the current and upgraded observatories will guide the proposed or planned future experiments

Backup slides

Muon deficit in simulations







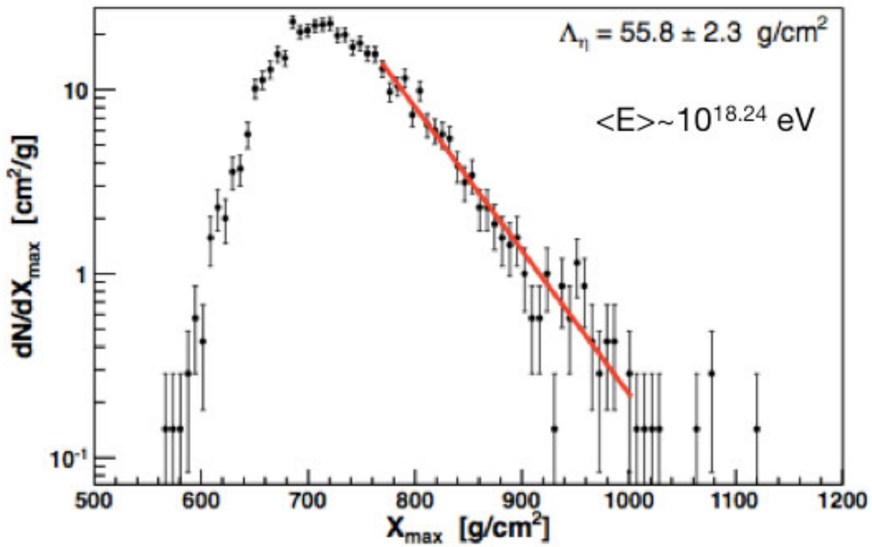
The p-Air cross section

Distribution of the depth of first interaction

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{p-air}} e^{-X_1/\lambda_{p-air}},$$

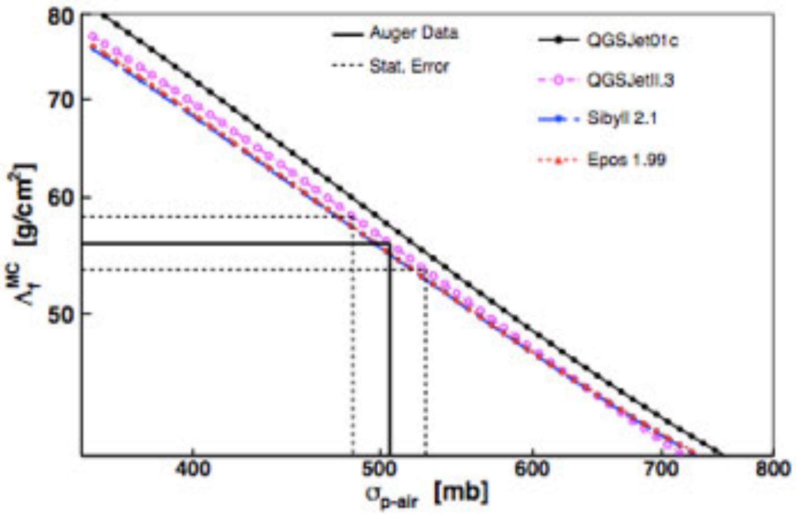
Mean $\langle X_1 \rangle$ and its shower-to-shower fluctuations directly linked to the p-Air cross section:

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{p-air}}$$ with $\langle m_{air} \rangle \sim 14.5\, m_p$



X_{max} shape from fluorescence

$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_X} \qquad \Lambda_X = k_F \lambda_{p-Air}$$



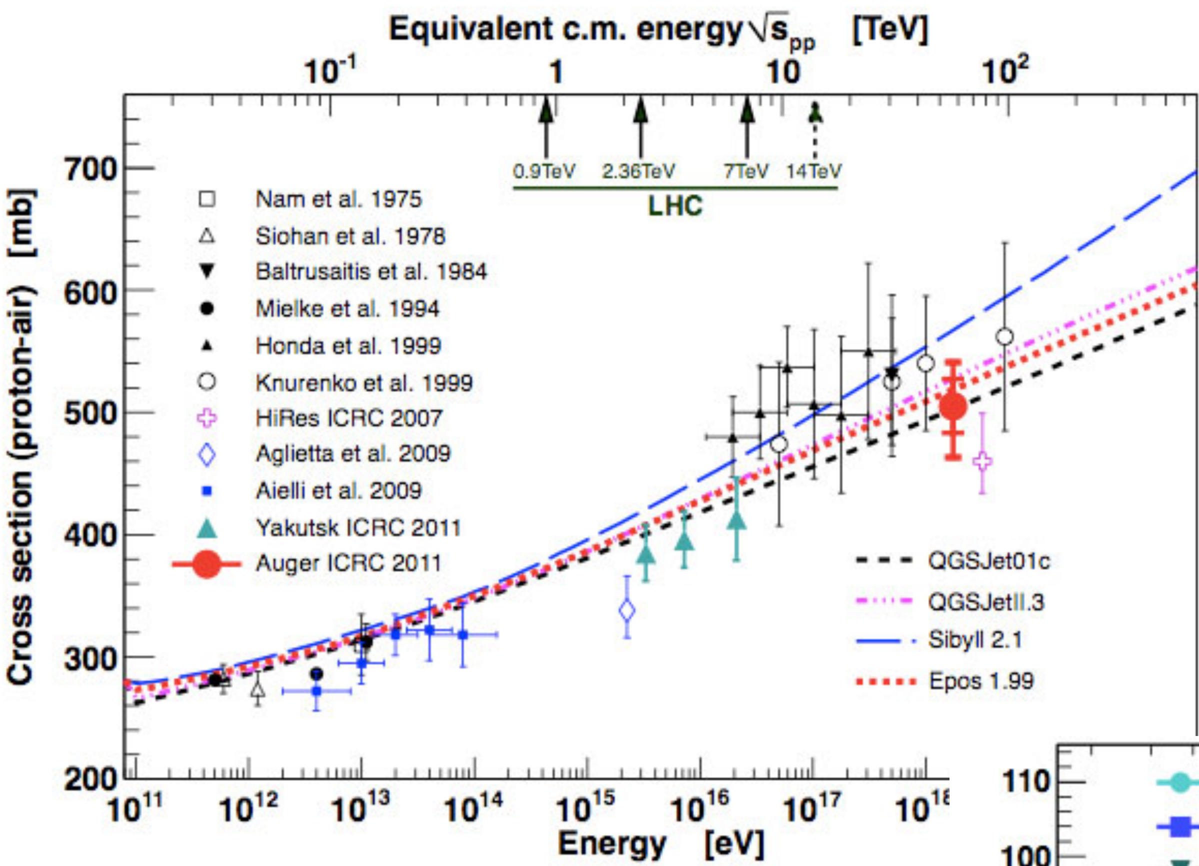
Main challenges:

reduce the mass composition systematic
subtract shower fluctuation

$RMS(X_1) \sim RMS(X_{max}-X_1)$

$\Lambda_X = (55.8 \pm 2.3^{stat} \pm 1.6^{syst})$ g cm^{-2}

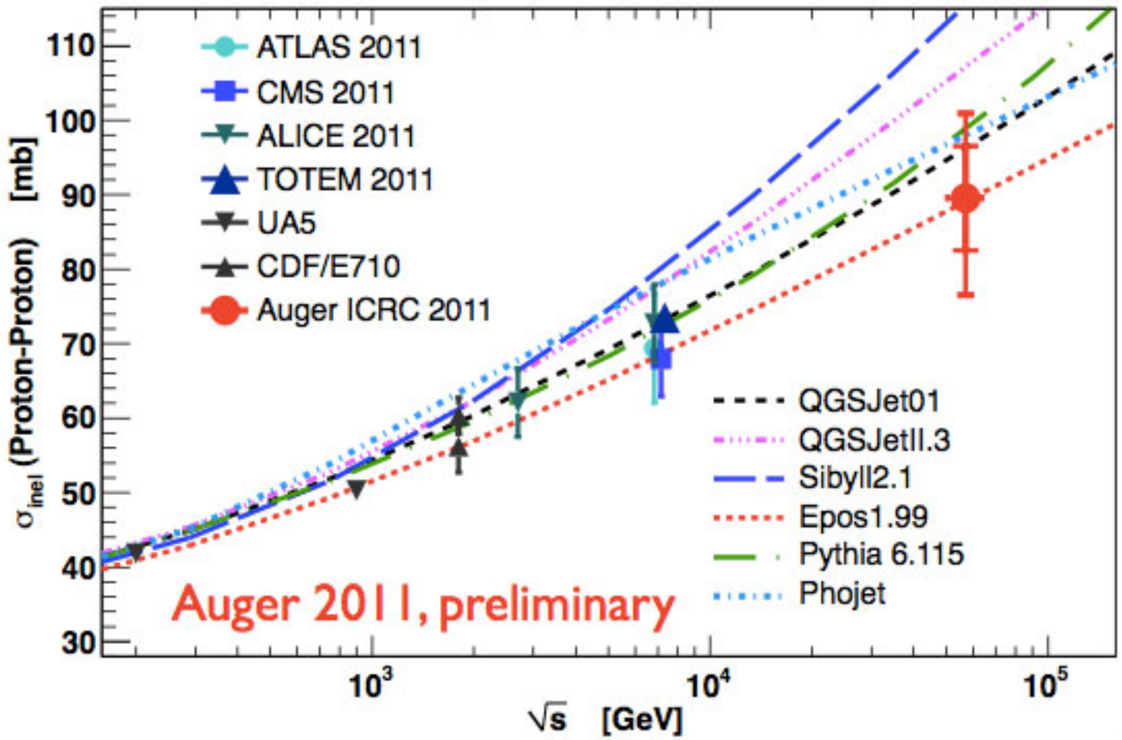
Cross section



$$\sigma_{p-Air} = [505 \pm 22(stat)^{+28}_{-36}(sys)]\ \ mb$$

To compare with accelerator results, use Glauber formalism to find σ_{pp}

$$\sigma^{inel}_{p-p} = [133 \pm 13(stat)^{+17}_{-20}(sys) \pm 16(Glauber)]\ \ mb$$



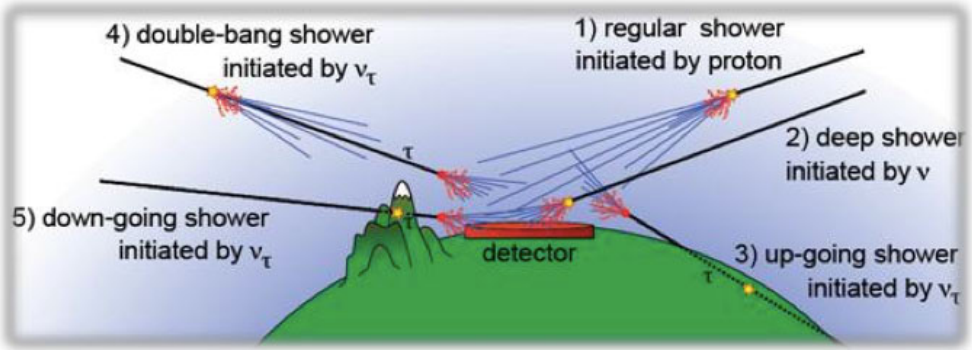
	Auger SD			Auger hybrid
	1500 m vertical	**1500 m inclined**	**750 m vertical**	
Data taking period	01/2004 - 12/2012	01/2004 - 12/2012	08/2008 - 12/2012	11/2005 - 12/2012
Exposure [km^2 sr yr]	31645 ± 950	8027 ± 240	79 ± 4	-
Zenith angles [°]	$0-60$	$62-80$	$0-55$	$0-60$
Threshold energy E_{eff} [eV]	3×10^{18}	4×10^{18}	3×10^{17}	10^{18}
No. of events ($E > E_{eff}$)	82318	11074	29585	11155
No. of events (golden hybrids)	1475	175	414	-
Energy calibration (A) [EeV]	0.190 ± 0.005	5.61 ± 0.1	$(1.21 \pm 0.07)\cdot10^{-2}$	-
Energy calibration (B)	1.025 ± 0.007	0.985 ± 0.02	1.03 ± 0.02	-

Table 1: Summary of the experimental parameters describing data of the different measurements at the Pierre Auger Observatory.

$\log_{10}(E/eV)$	$dN/dt\|_{infill}$ [yr^{-1}]	$dN/dt\|_{SD}$ [yr^{-1}]	$N\|_{infill}$ [2017-2023]	$N\|_{SD}$ [2017-2023]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1	100	7	700
19.8	-	9	-	60
20.0	-	$\sim$1	-	$\sim$9

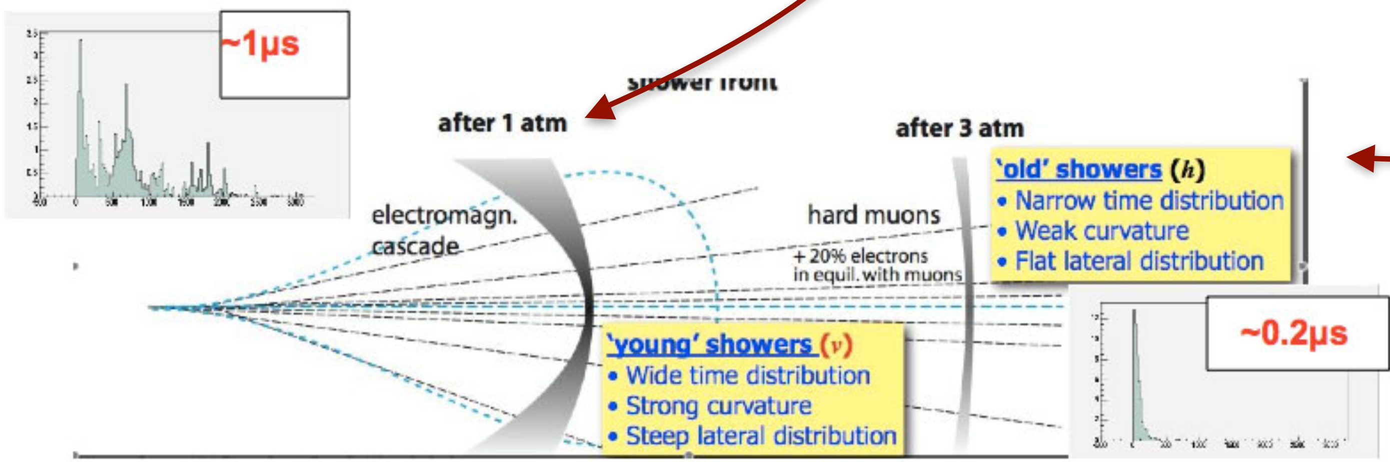
upgrade

Neutrinos



(1) inclined hadronic shower

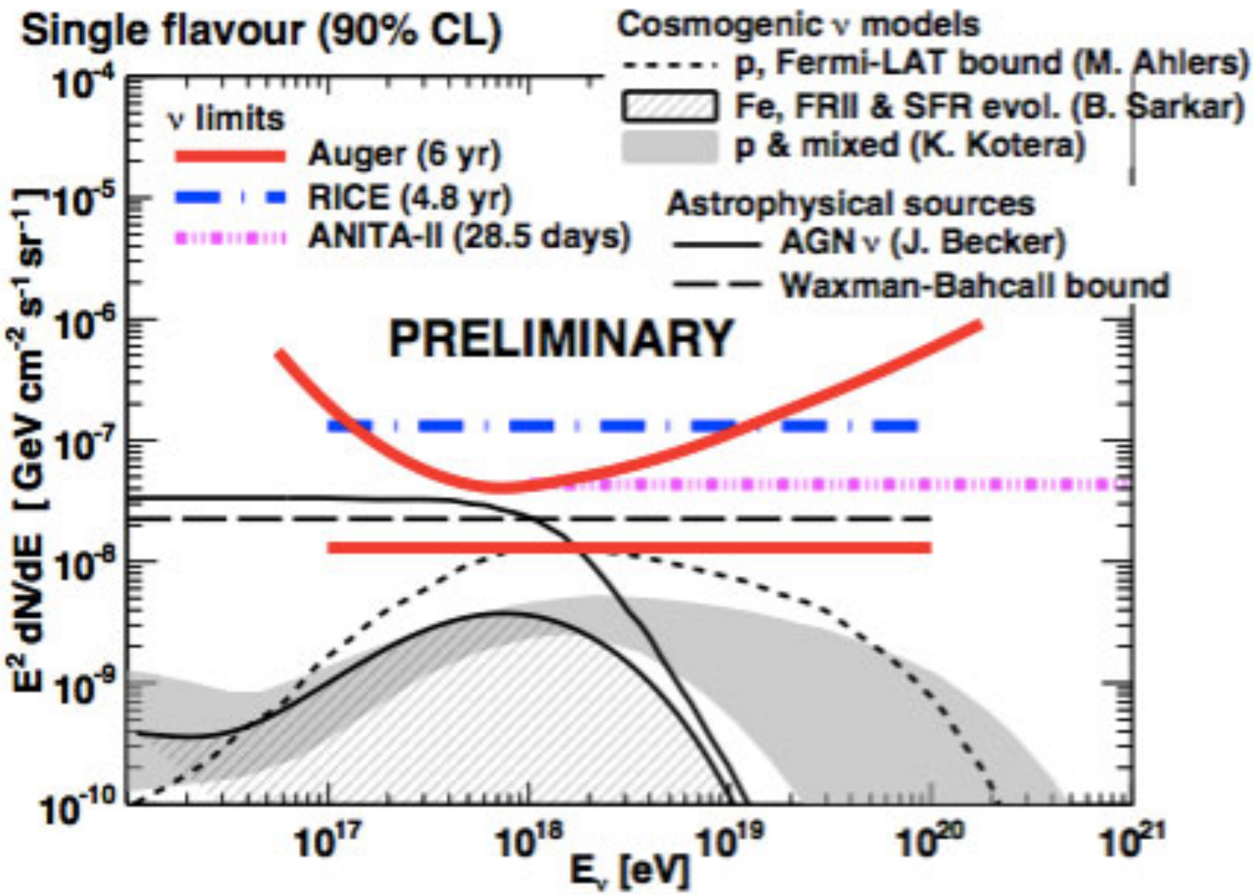
(2-5) neutrino induced showers



Neutrinos in Auger:

- Earth-skimming: ν_τ CC (90-95°)
- down-going : all flavours CC&NC

Neutrinos



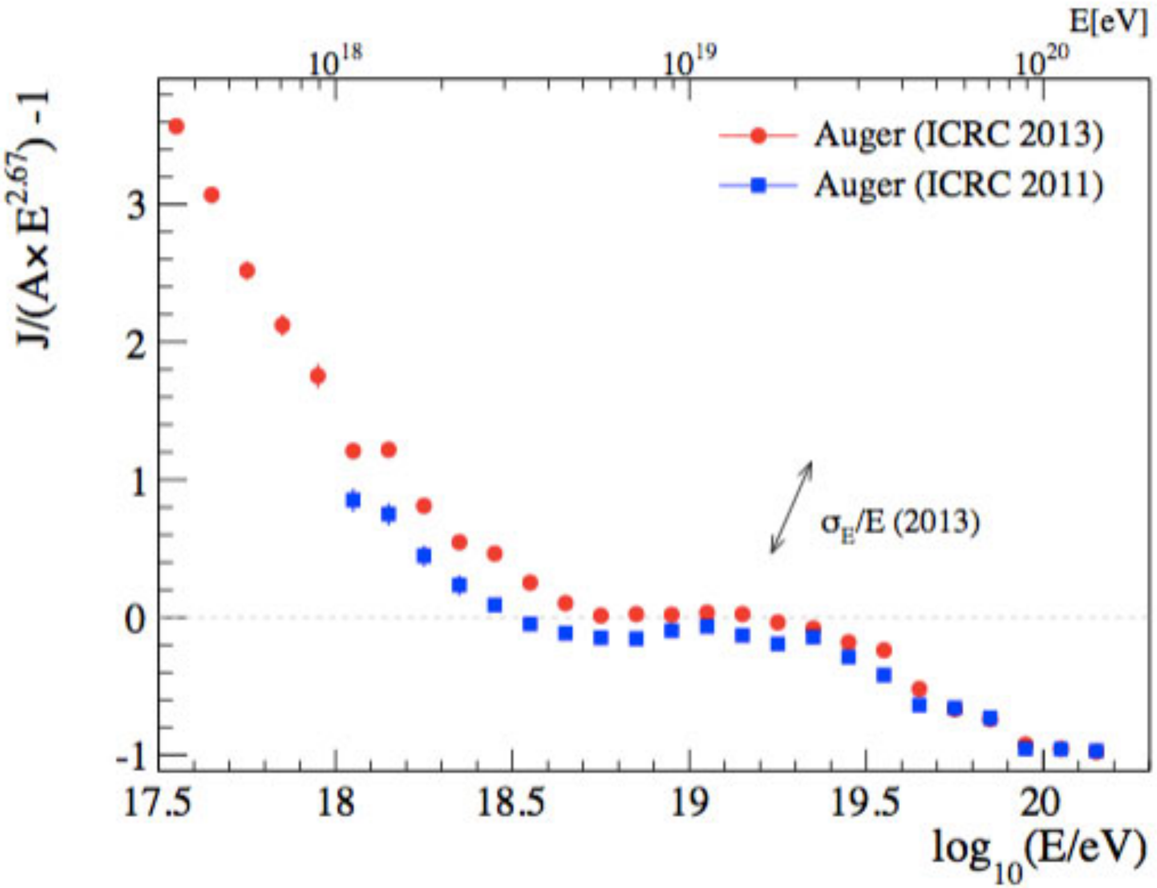
For a flux $\Phi(E_\nu)=kE_\nu^{-2}$

$$k = \frac{N_{up}}{\int_{E_{min}}^{E_{max}} E_\nu^{-2}\, \mathcal{E}_{tot}(E_\nu)\, dE_\nu}$$

k_{up}=1.3 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
at 90% CL
between 10^{17} and 10^{20} eV
(Jan 2004 - Dec 2012)

- constraints on astrophysical source models (AGN ν)
- Auger limit below Waxmann-Bahcall upper limit
- GZK region within reach in the near future
- the 2 neutrino events from IceCube are compatibile with an E^{-2} flux with normalized to $E_\nu^2 F_\nu$=1.2 10^{-8} GeV $cm^{-2} s^{-1} sr^{-1}$: extension of this upper limit to the flux at 10^{20} eV excluded (2.2 events expected, 0 detected)

Comparison of parameters



2011 spectral parameters

$\log_{10}(E_a/\text{eV}) = 18.62 \pm 0.01$

$\gamma_1 = 3.27 \pm 0.01$

$\gamma_2 = 2.63 \pm 0.02$

$\log_{10}(E_{1/2}/\text{eV}) = 19.63 \pm 0.02$

$\log_{10} W_c = 0.15 \pm 0.02$

2013 spectral parameters

$\log_{10}(E_a/\text{eV}) = 18.72 \pm 0.01$

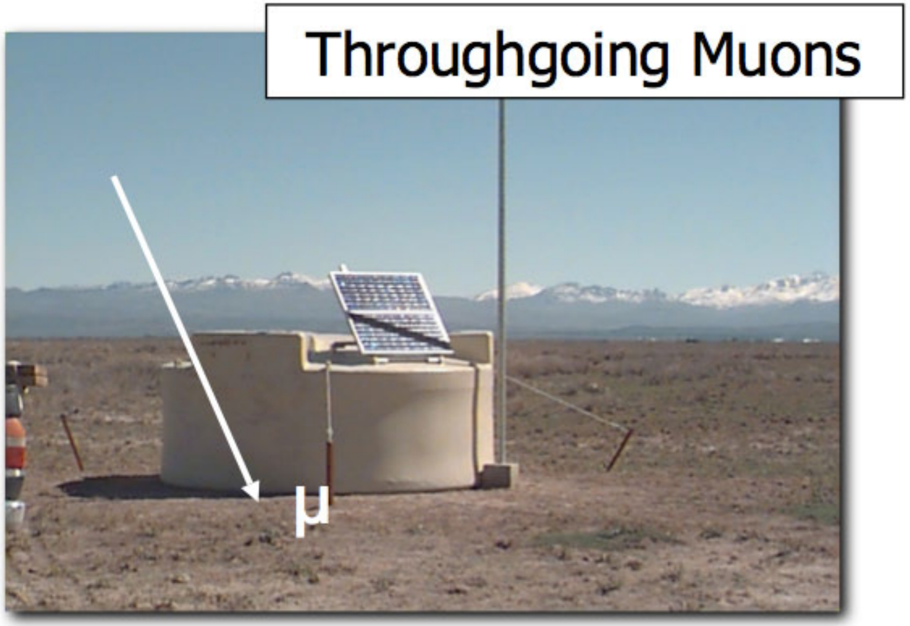
$\gamma_1 = 3.23 \pm 0.01$

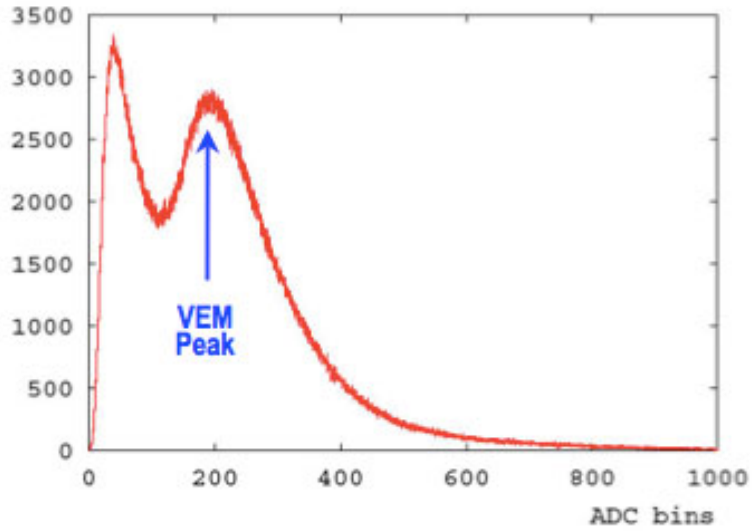
$\gamma_2 = 2.63 \pm 0.02$

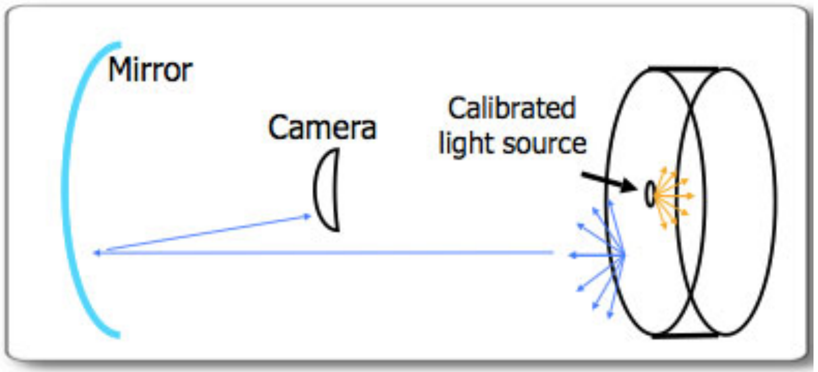
$\log_{10}(E_{1/2}/\text{eV}) = 19.63 \pm 0.01$

$\log_{10} W_c = 0.15 \pm 0.01$

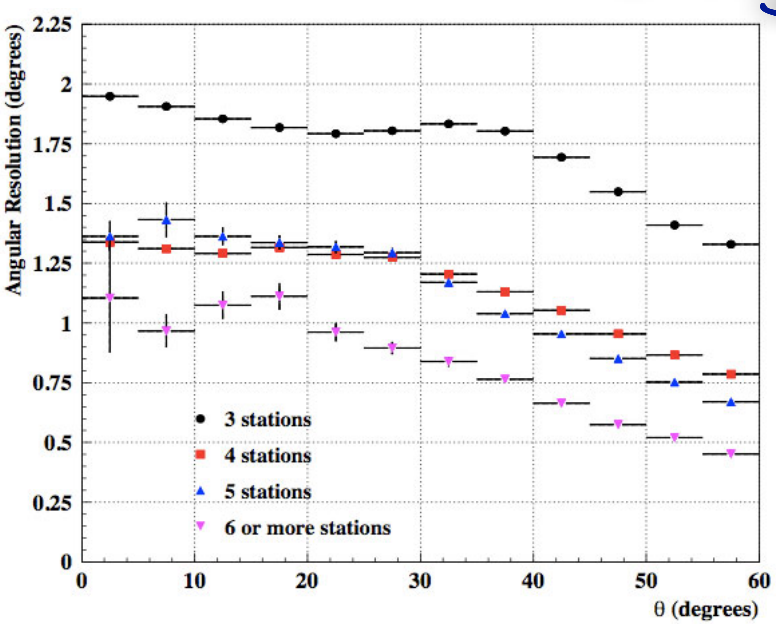
Calibration





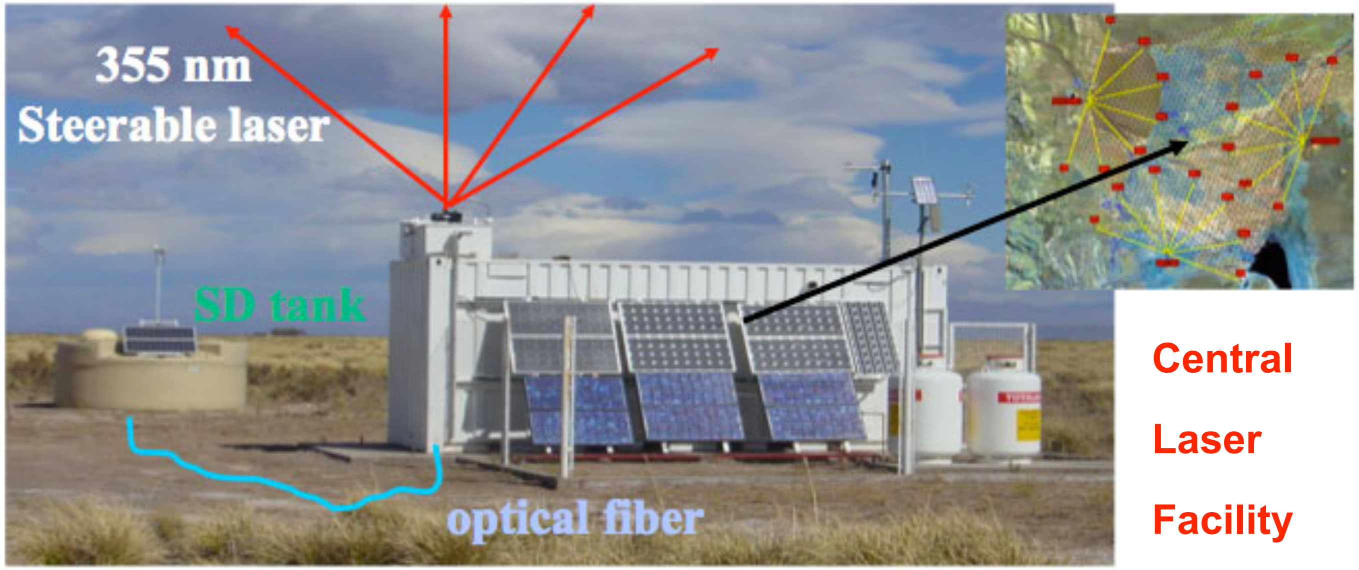


Angular resolution



SD Events
better than 1^0 for ≥ 6 stations (>10 EeV)

Hybrid events:
0.6^0 after correction for the true shower geometry



Central

Laser

Facility

Atmospheric monitoring

Lidar
Atmospheric profiling, "shoot-the-shower" for atm. measurements along the shower path

Central Laser Facility
Atmospheric monitoring,timing and calibration
Vertical optical depth
Relative timing between FDs and between FD-SD

Balloon borne
- measure T,P, humidity…
- measure of the deviation of g/cm^2 with respect to US std atmosphere