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

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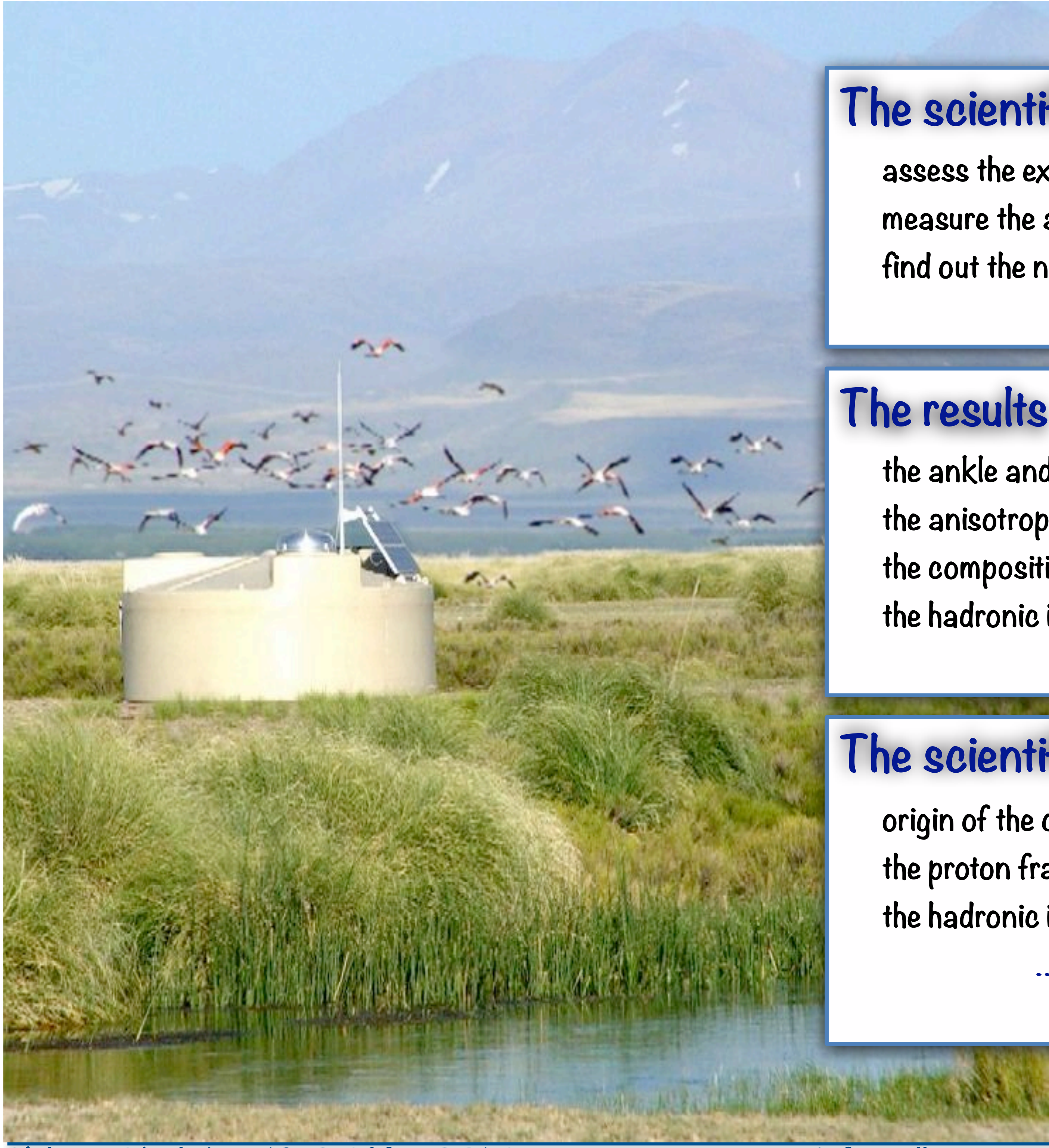
for the Pierre Auger Collaboration

Vulcano Workshop, 18-24 May 2014



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} ?

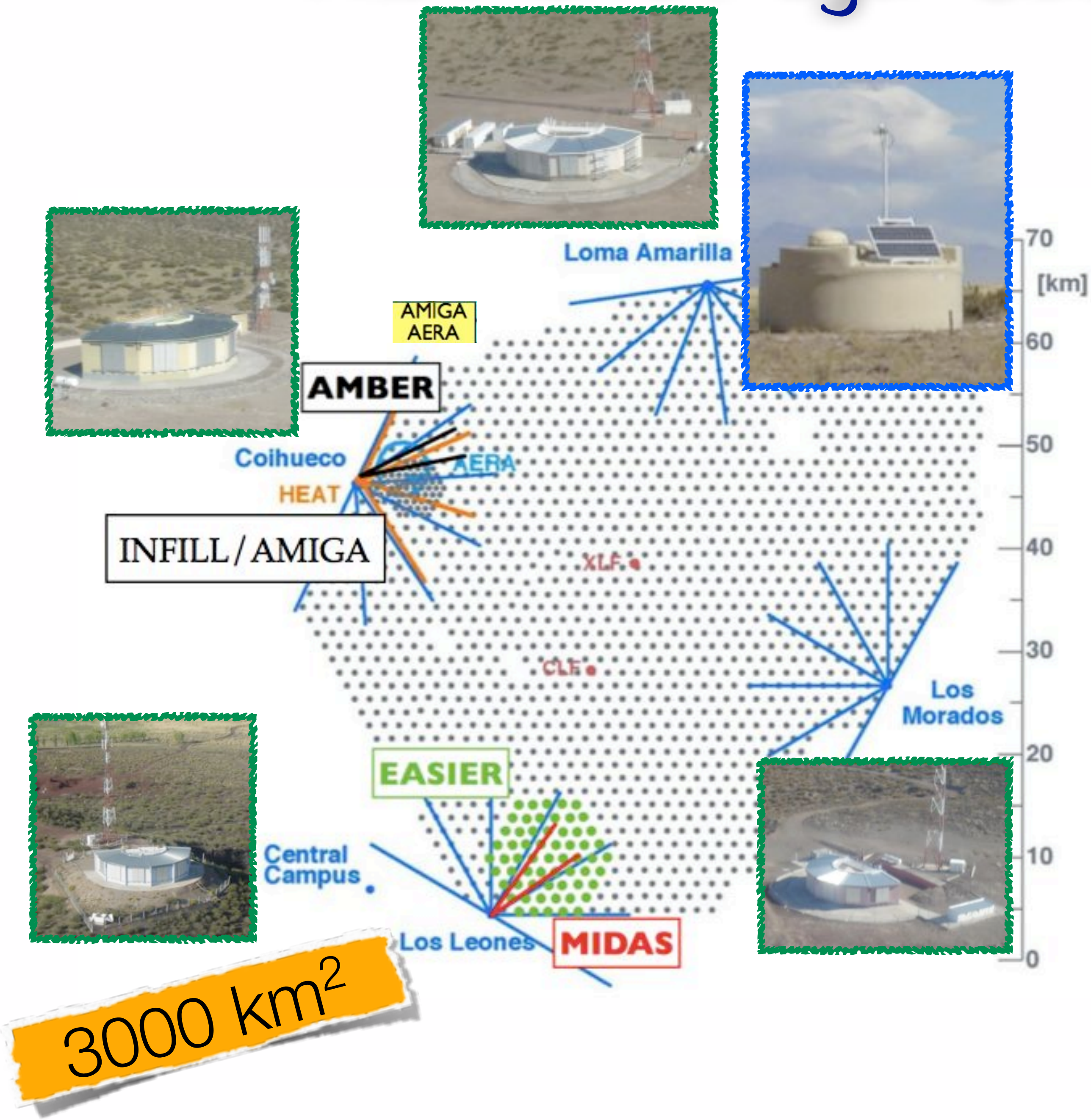
the proton fraction at UHE : particle astronomy ?

the hadronic interactions and new physics

... improving the composition knowledge

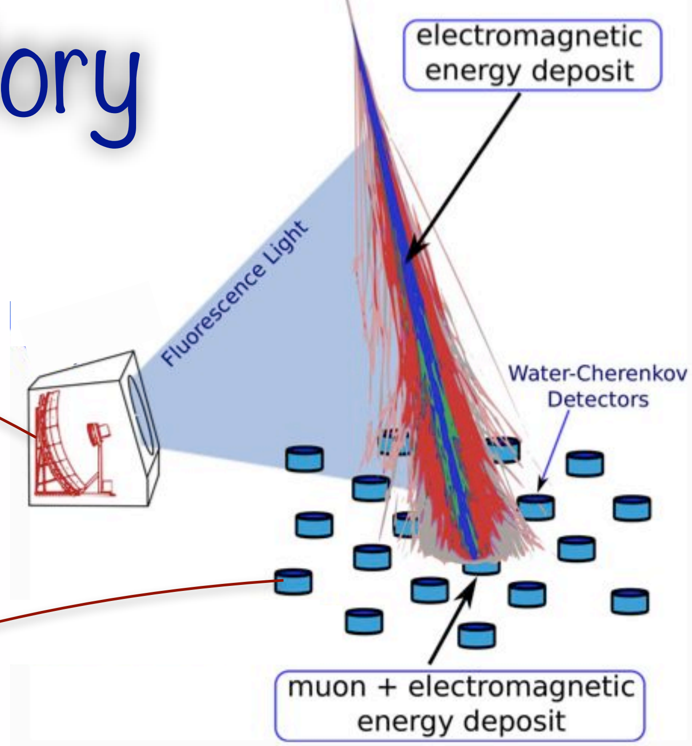
...increasing the statistics

The Pierre Auger Observatory



- 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

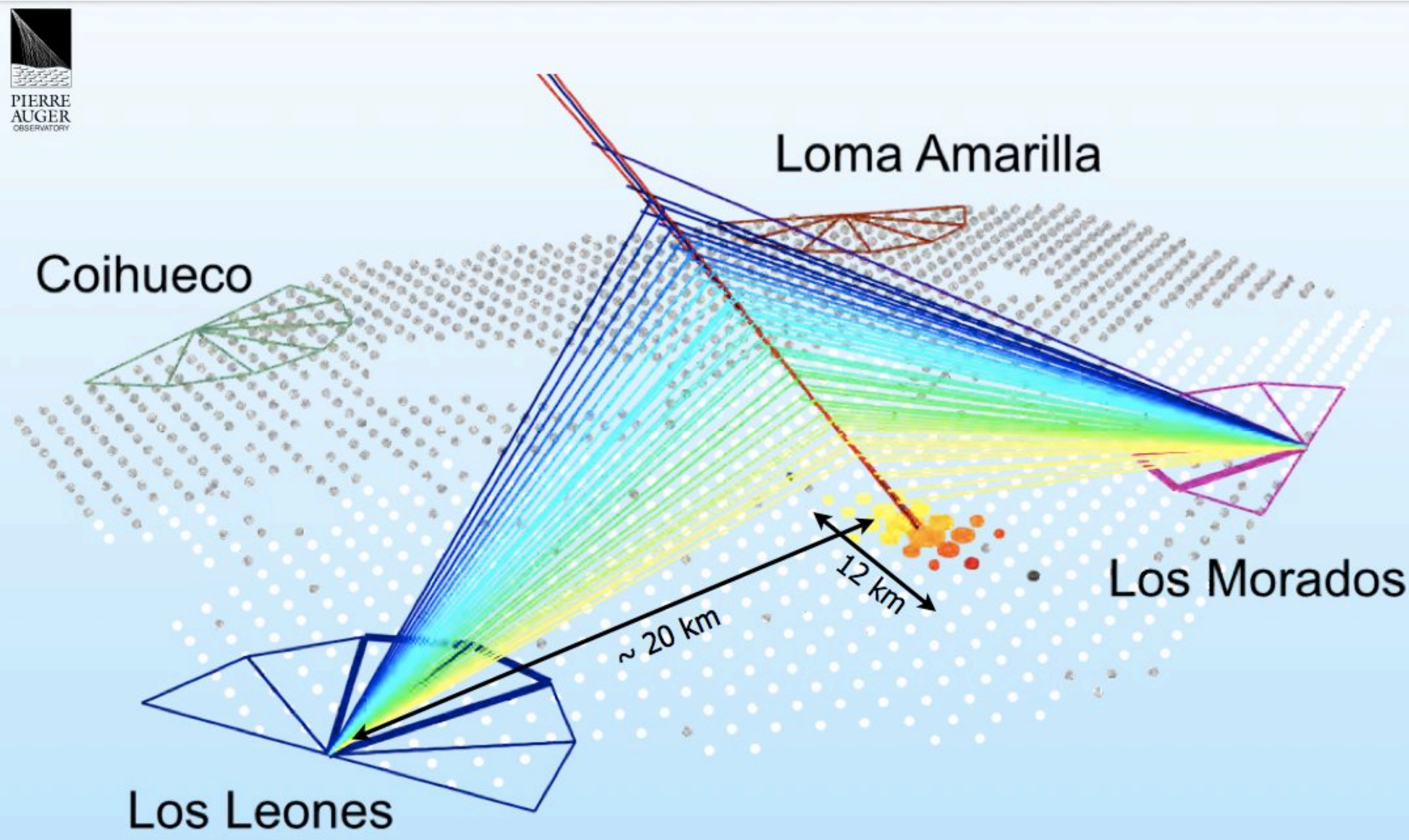
FD : 10% duty cycle - almost calorimetric measure of energy

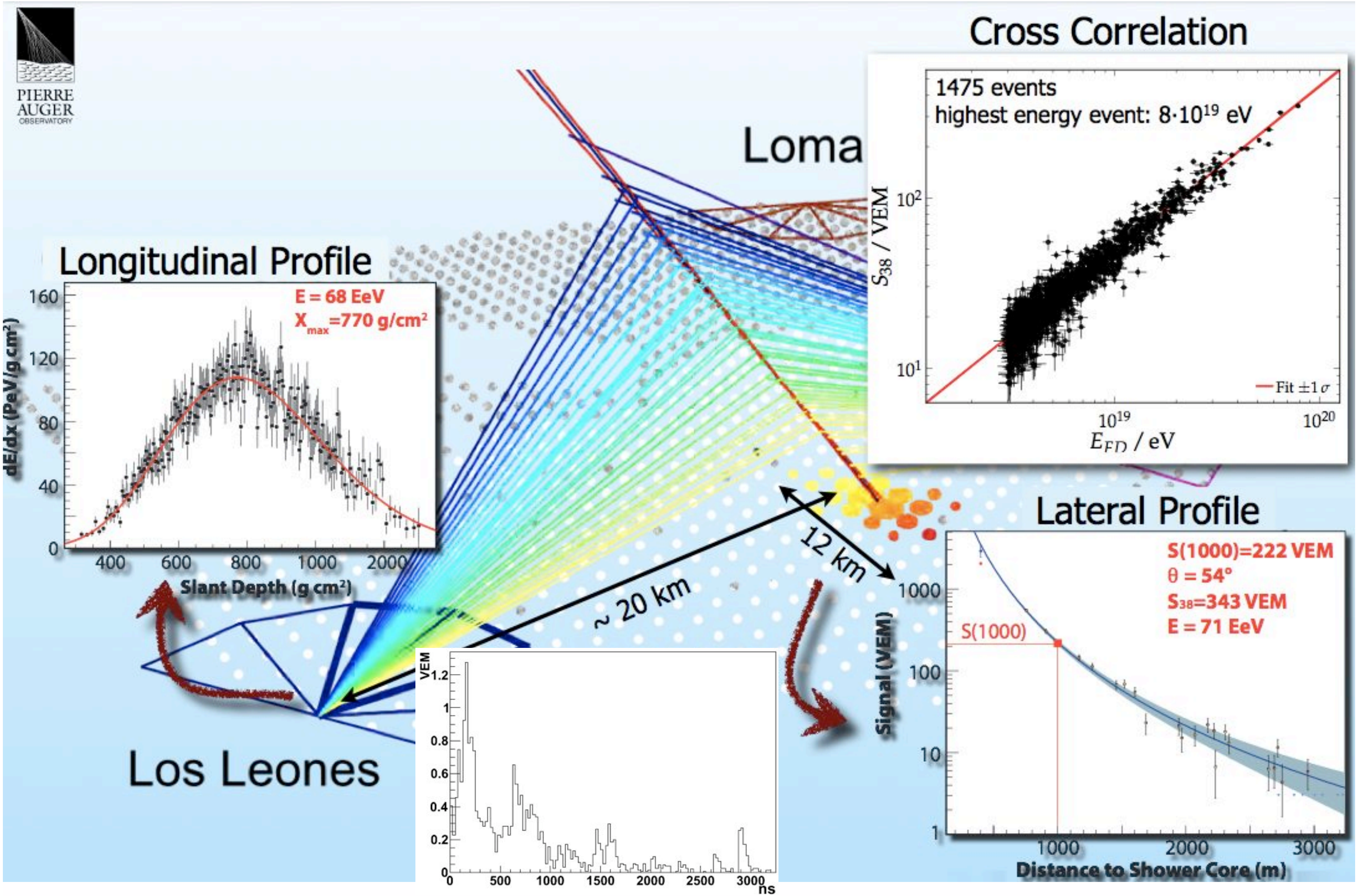
Two complementary techniques:

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

Different techniques:

measurements redundancy and cross checks


Loma Amarilla
Coihueco
Los Morados
Los Leones
~ 20 km
12 km

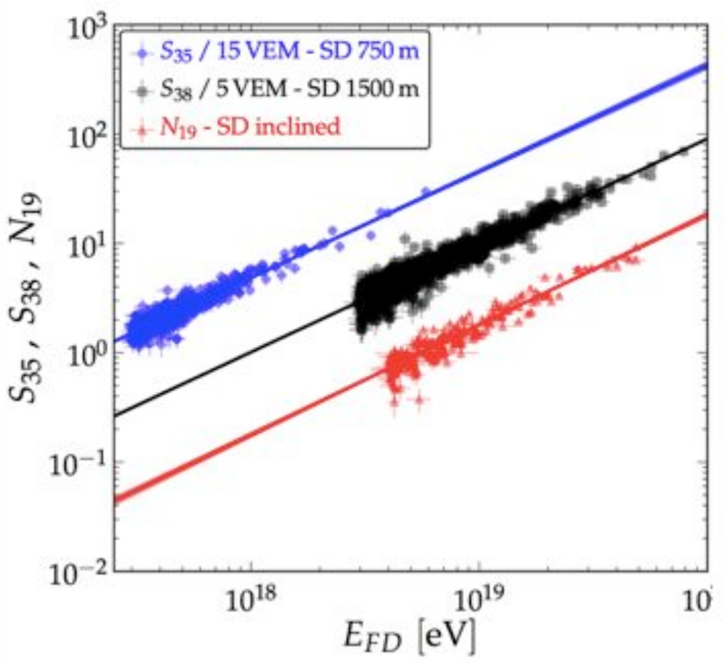


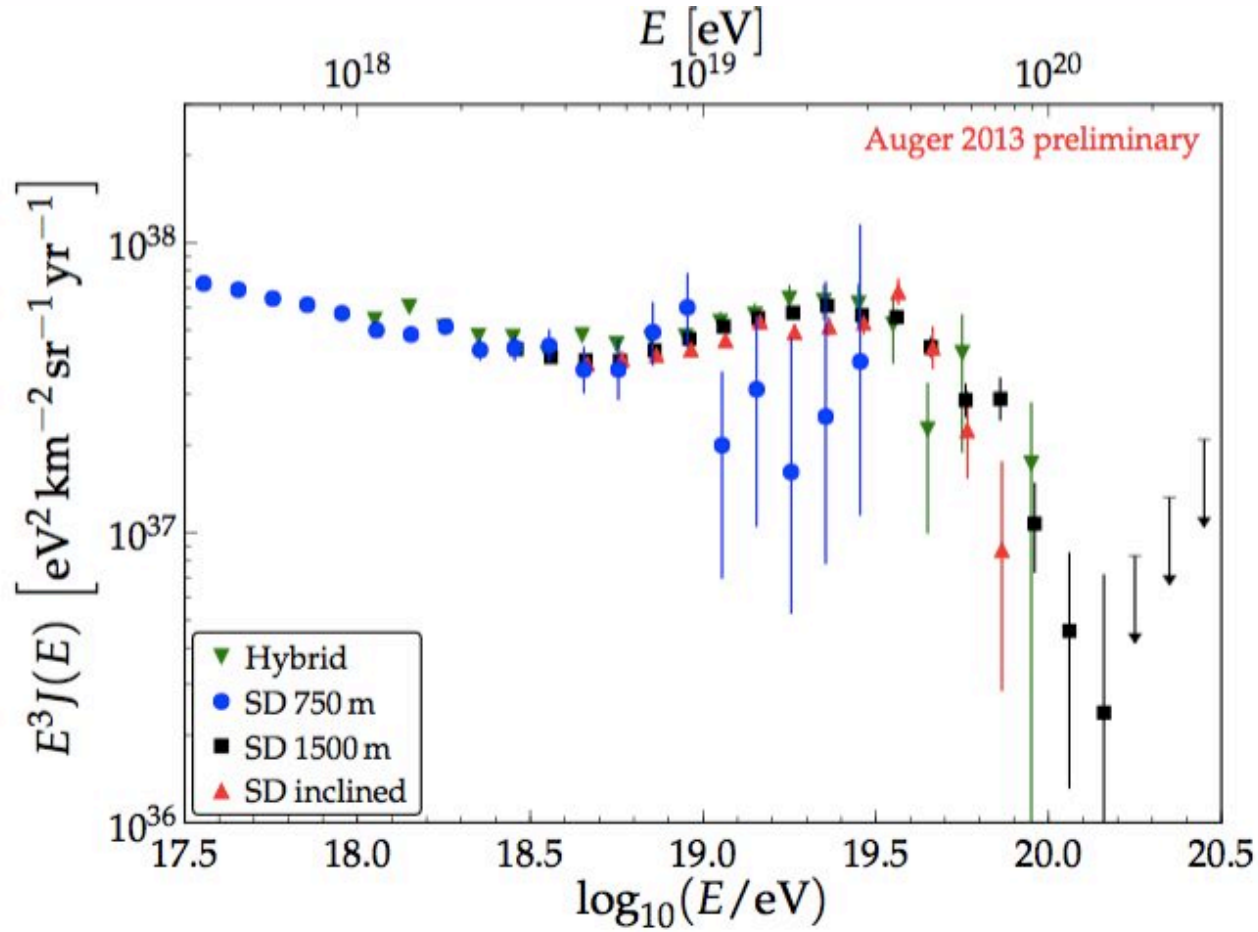
PIERRE AUGER OBSERVATORY
Cross Correlation
1475 events
highest energy event: 8·10^19 eV
S38 / VEM
E_FD / eV
Fit ±1σ
Loma
Longitudinal Profile
E = 68 EeV
X_max=770 g/cm²
dE/dx (PeV/g cm²)
Slant Depth (g cm²)
~ 20 km
12 km
Lateral Profile
S(1000)=222 VEM
θ = 54°
S38=343 VEM
E = 71 EeV
S(1000)
Signal (VEM)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

Energy spectrum

Overall uptime

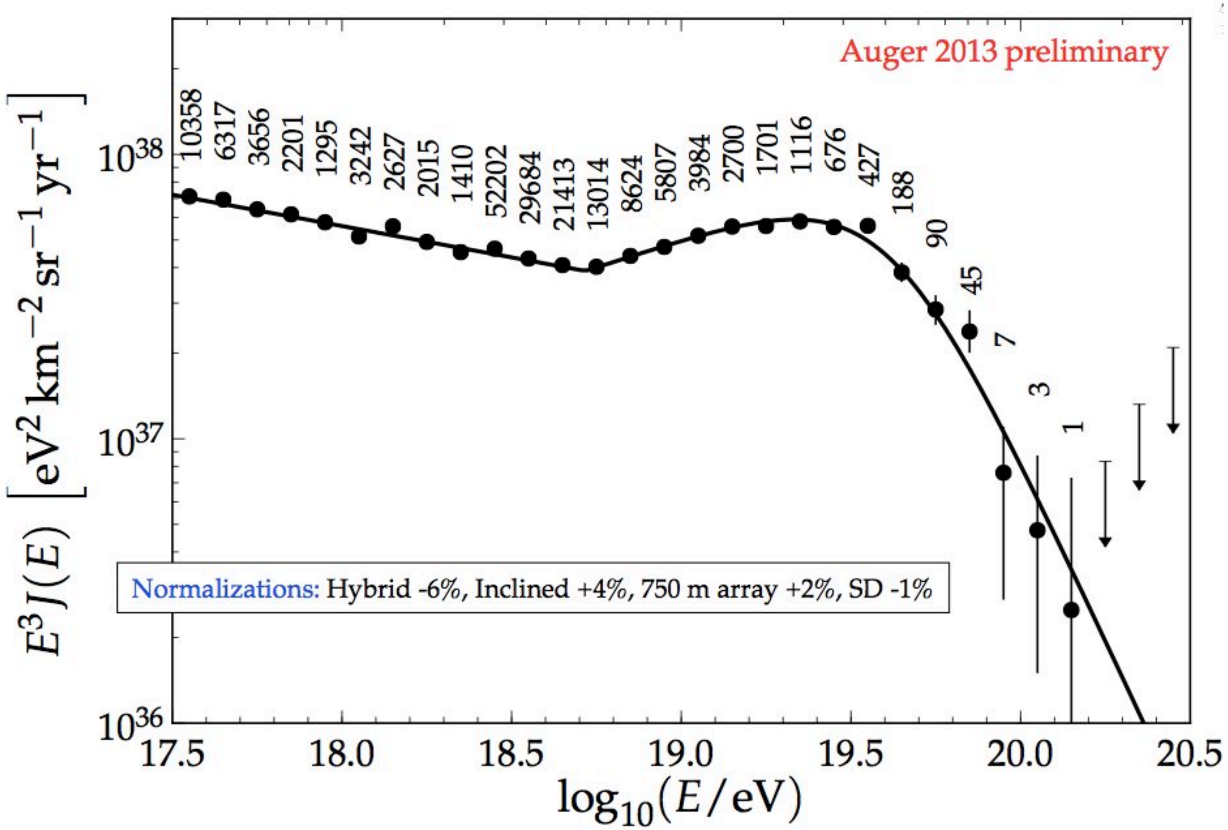
- ~ 98% for SD
- ~ 13% for FD





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

Energy spectrum combined fit



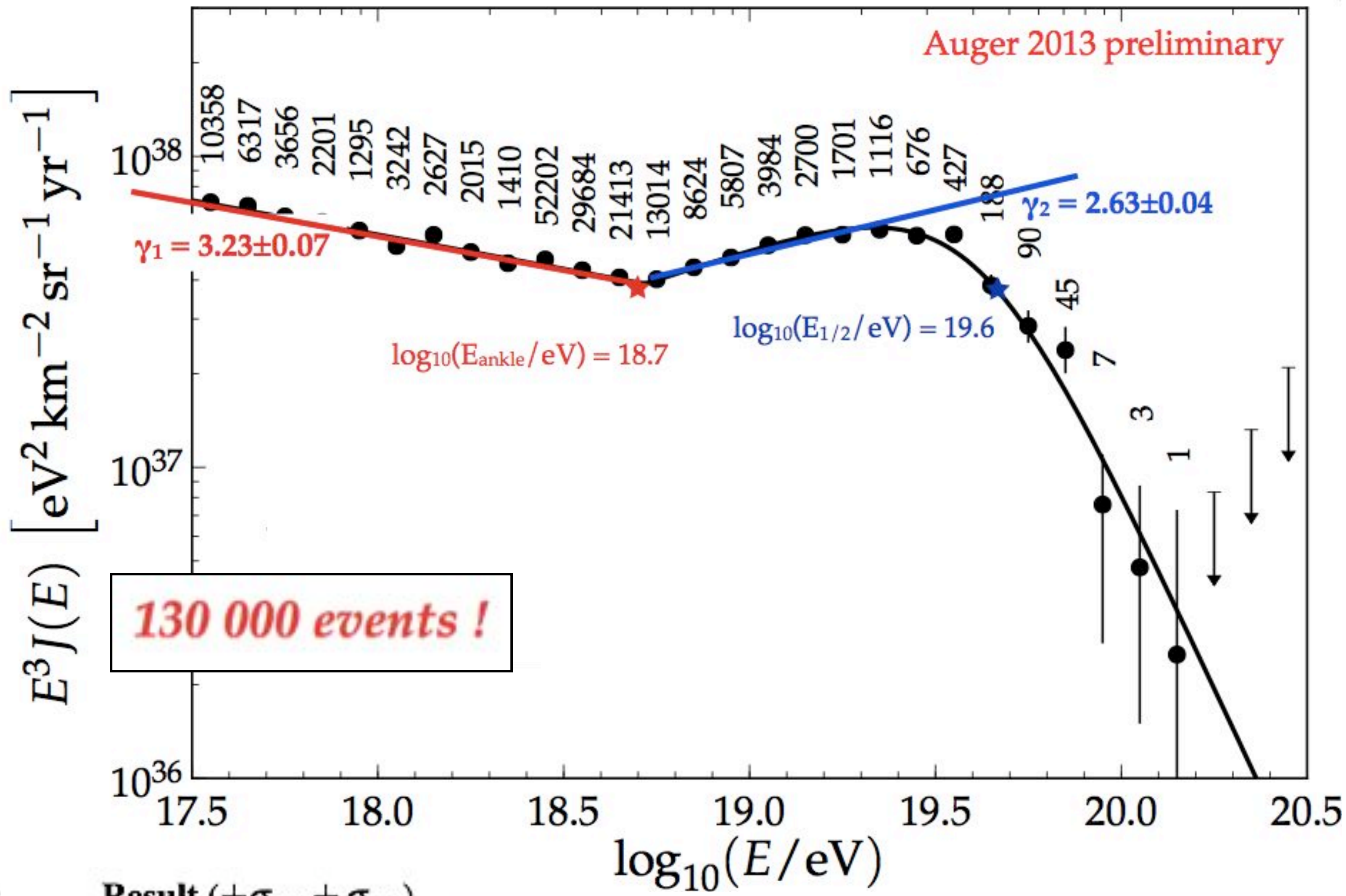
$$J(E; E > E_a) \propto E^{-\gamma_2}\left[1+\exp\left(\frac{\log_{10}E - \log_{10}E_{1/2}}{\log_{10}W_c}\right)\right]^{-1}$$

Energy systematic uncertainty

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

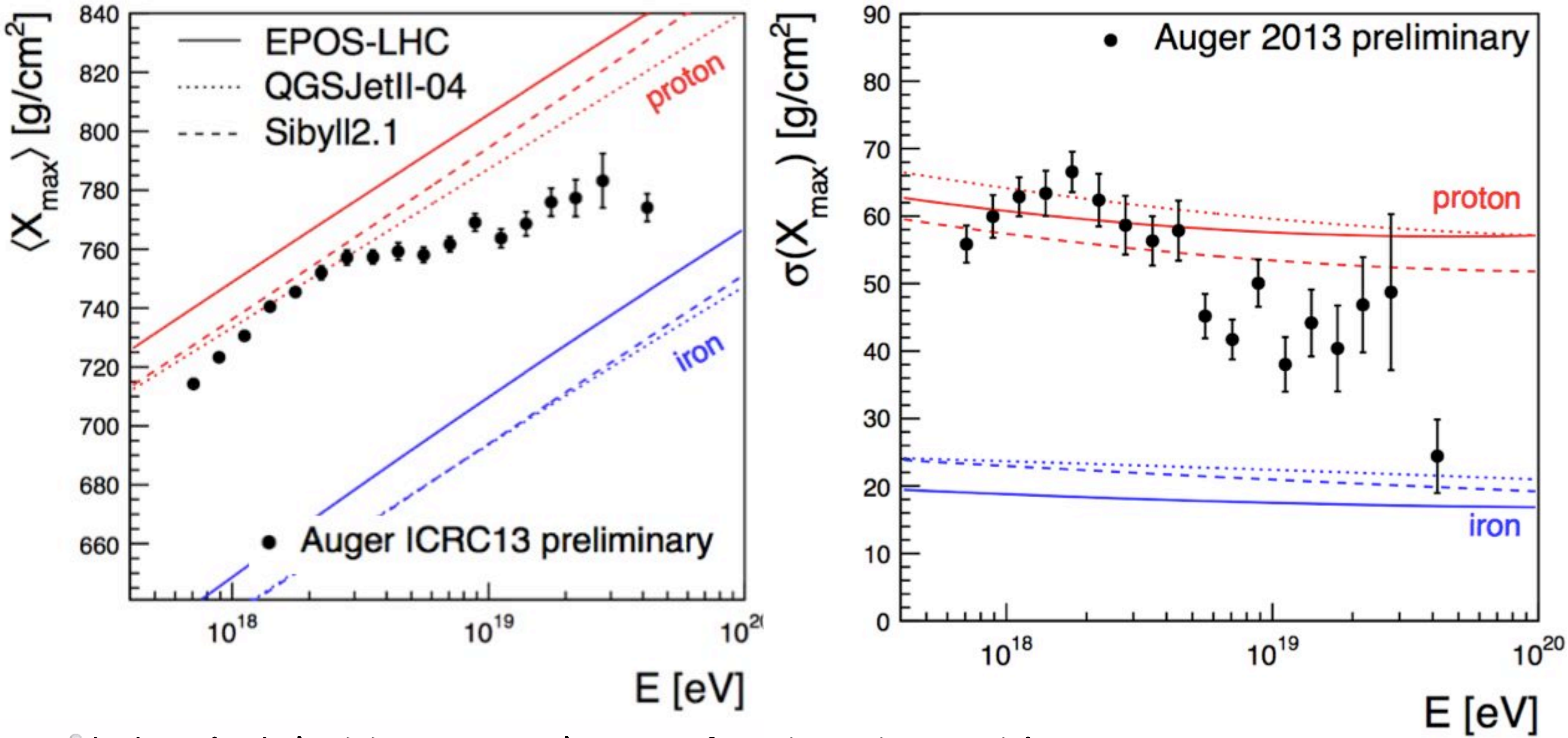
Flux systematic uncertainties

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



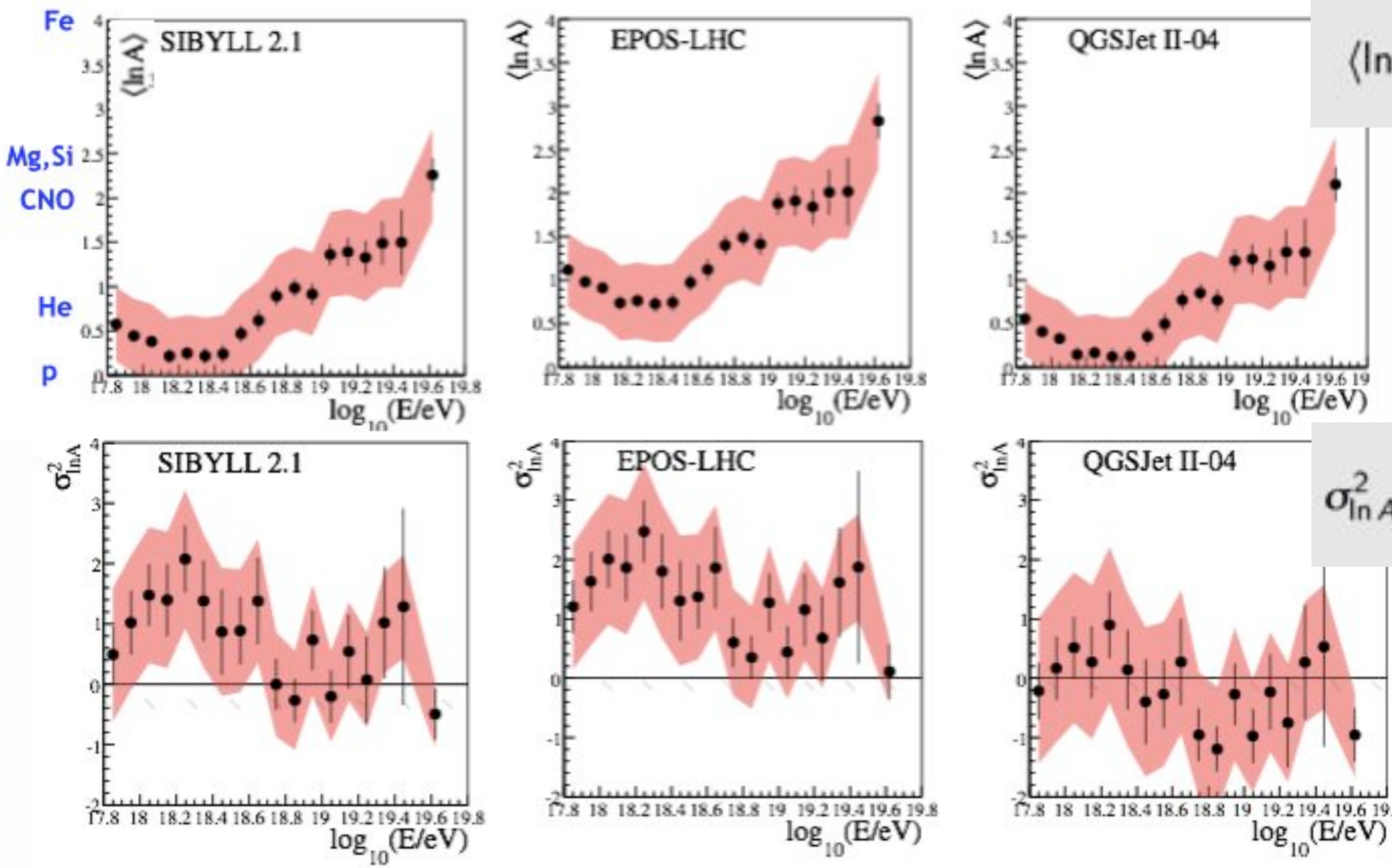
Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
$\log_{10}(E_a/\mathrm{eV})$	$18.72 \pm 0.01 \pm 0.02$
γ_1	$3.23 \pm 0.01 \pm 0.07$
γ_2	$2.63 \pm 0.02 \pm 0.04$
$\log_{10}(E_{1/2}/\mathrm{eV})$	$19.63 \pm 0.01 \pm 0.01$
$\log_{10} W_c$	$0.15 \pm 0.01 \pm 0.02$

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}



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

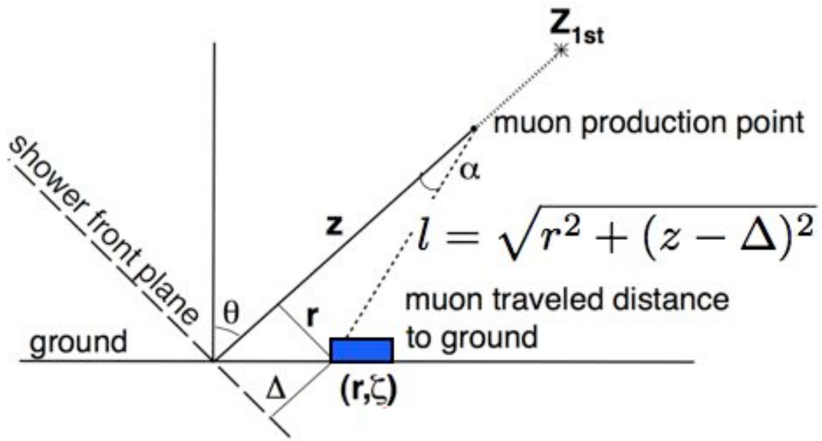
info on average composition

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

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

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

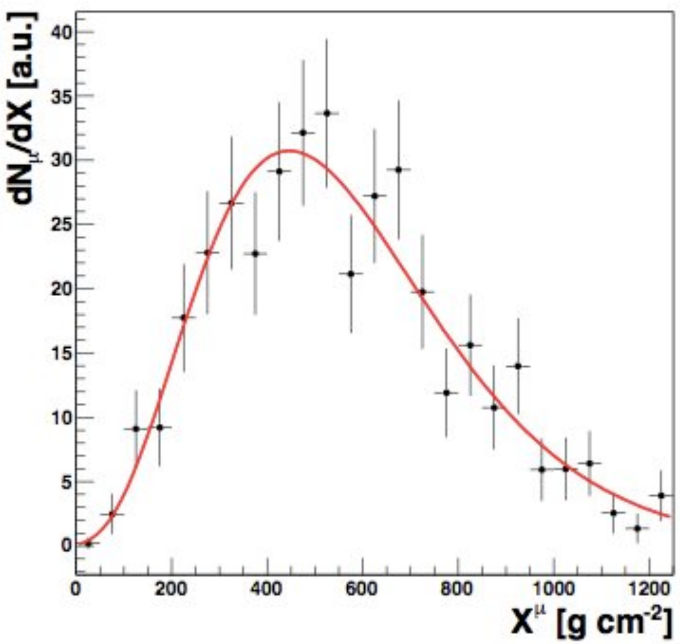
Mass composition - MPD$_\mu$

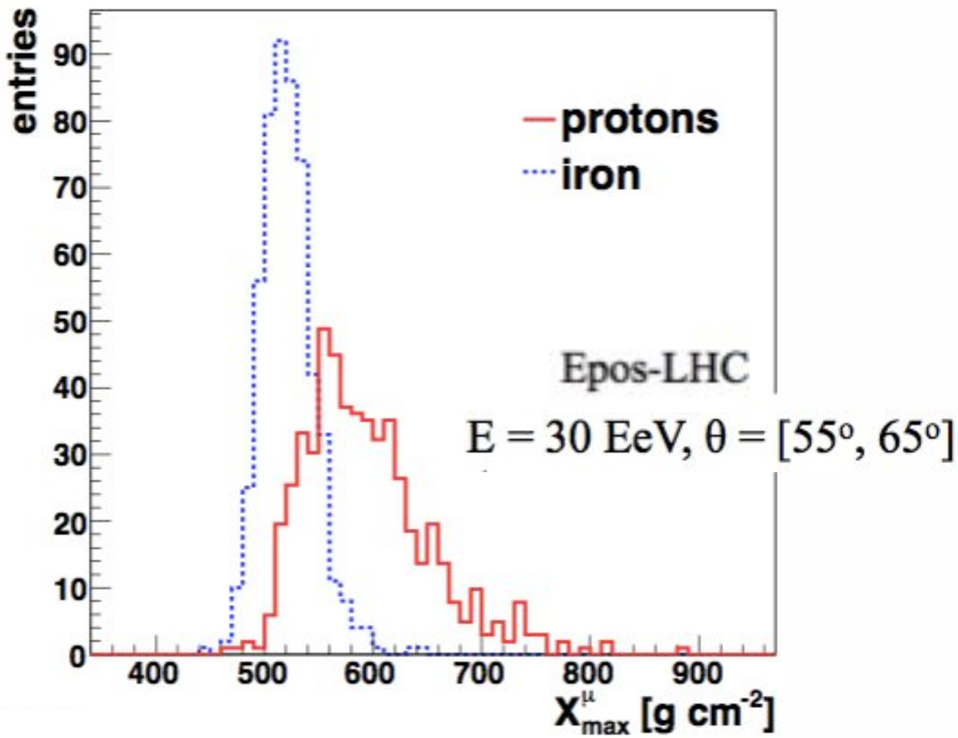


$$l = \sqrt{r^2 + (z - \Delta)^2}$$

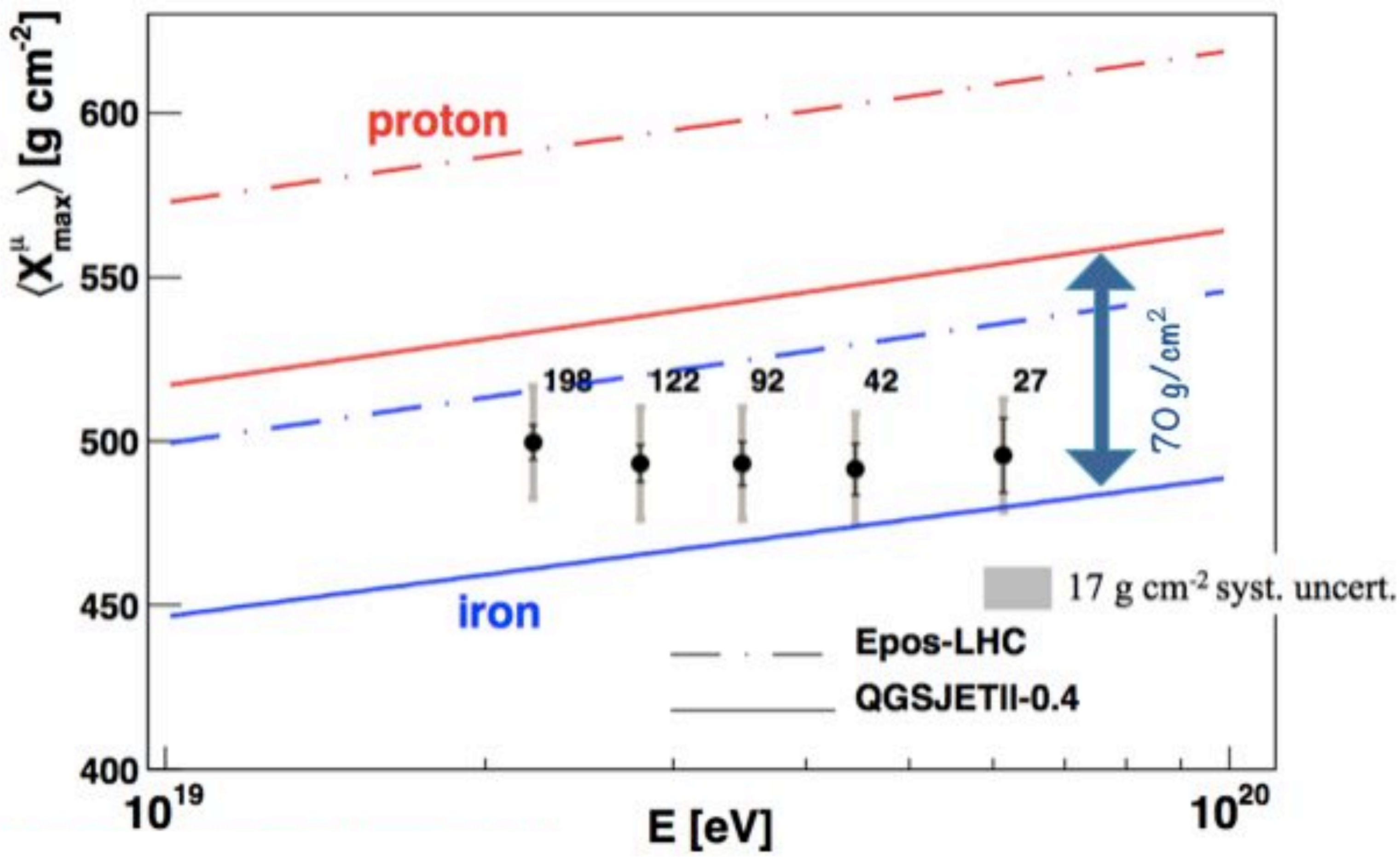
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta \rightarrow X^\mu = \int_z^\infty \rho(z')dz'$$

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





Mass composition - MPD_μ

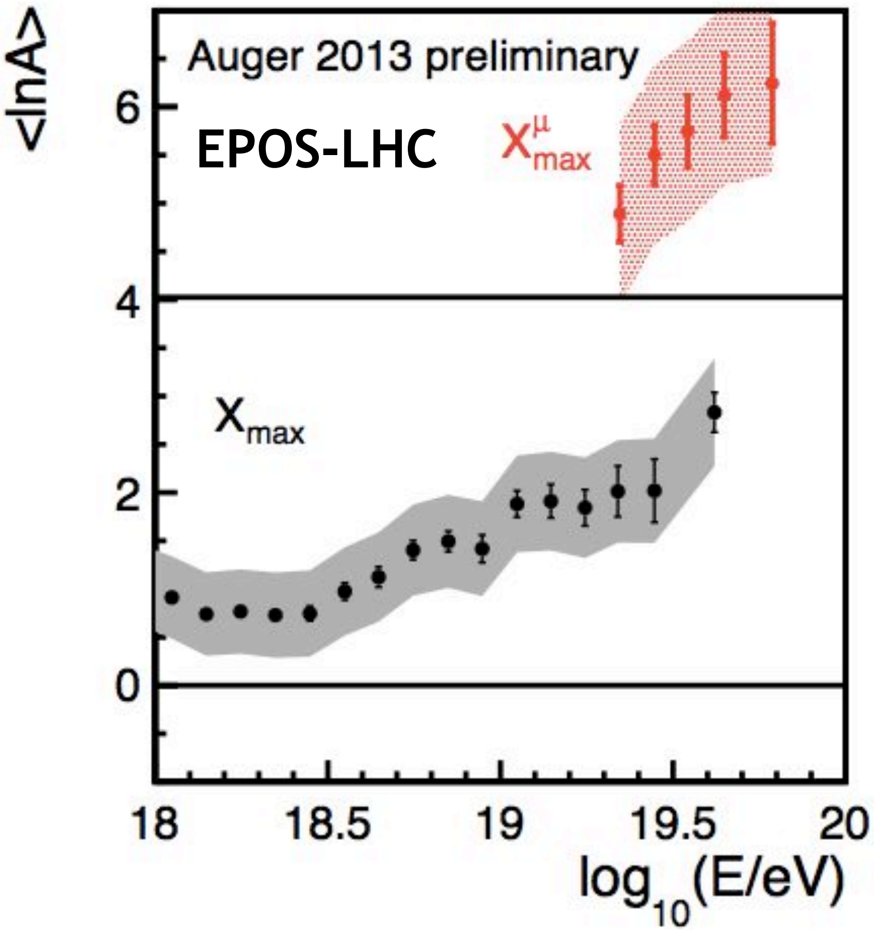


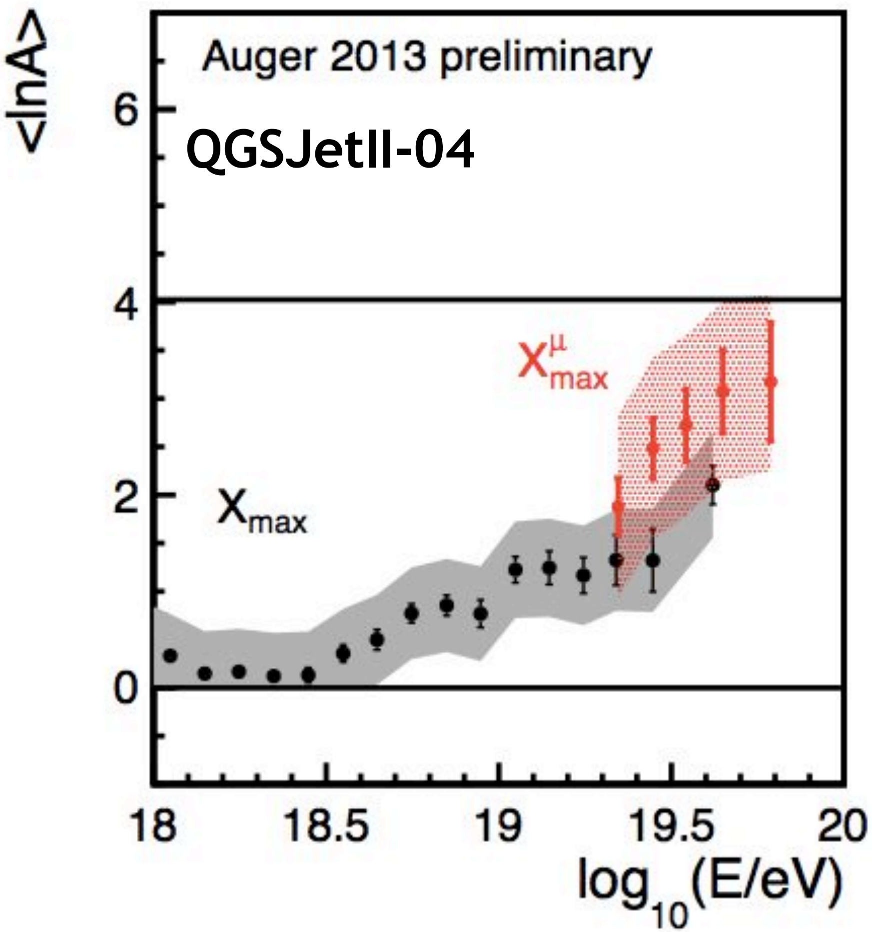
- novel approach to study the longitudinal distribution of the hadronic component of EAS
- agreement with the conclusion from Xmax (but still compatible with constant comp.)
- here, E>20 EeV, ϑ >55^0, only stations far from the core. Analysis can be extended to lower angles and energies if able to tag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

Interpreting X_{max} and X^{μ}_{max}

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

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



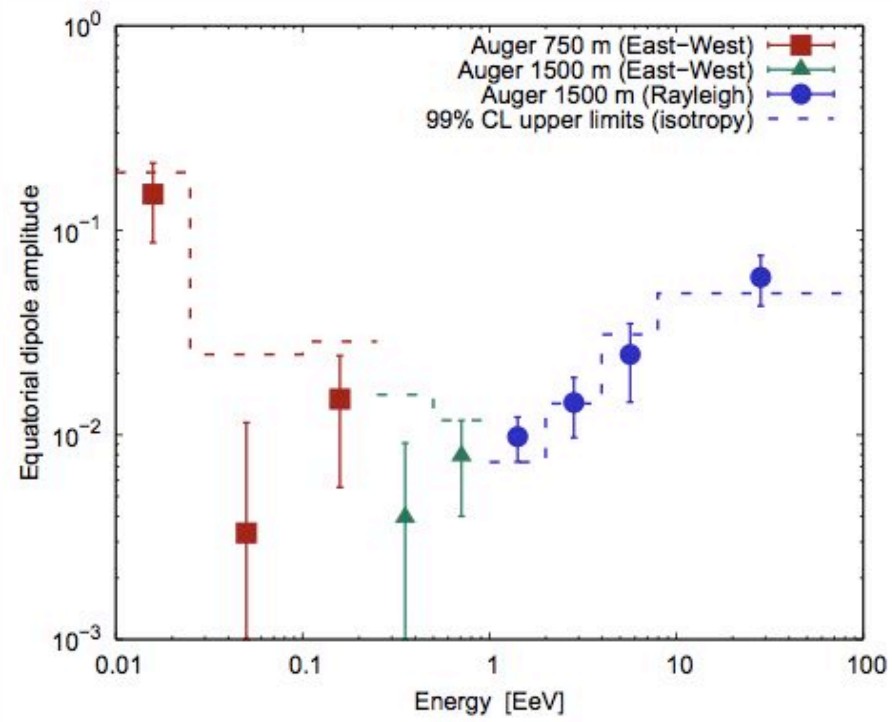


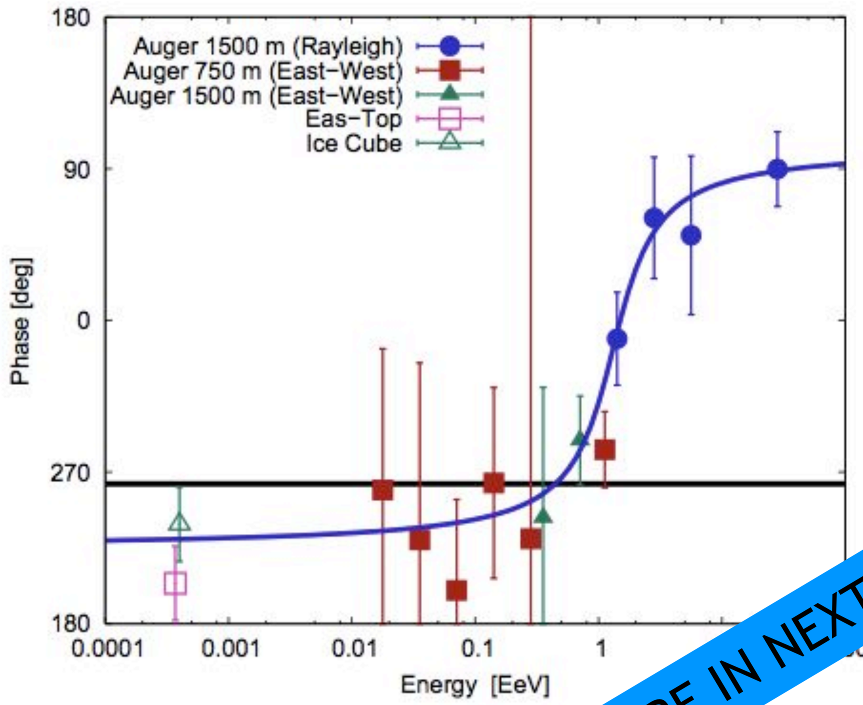
the consistency between the two Xmax can help to constrain hadronic interaction model

Large Scale Anisotropy

Change expected in transition region: e.g. at 1 EeV

- % modulation if Galactic,
- ~0.6% if extragalactic (CMB dipole)



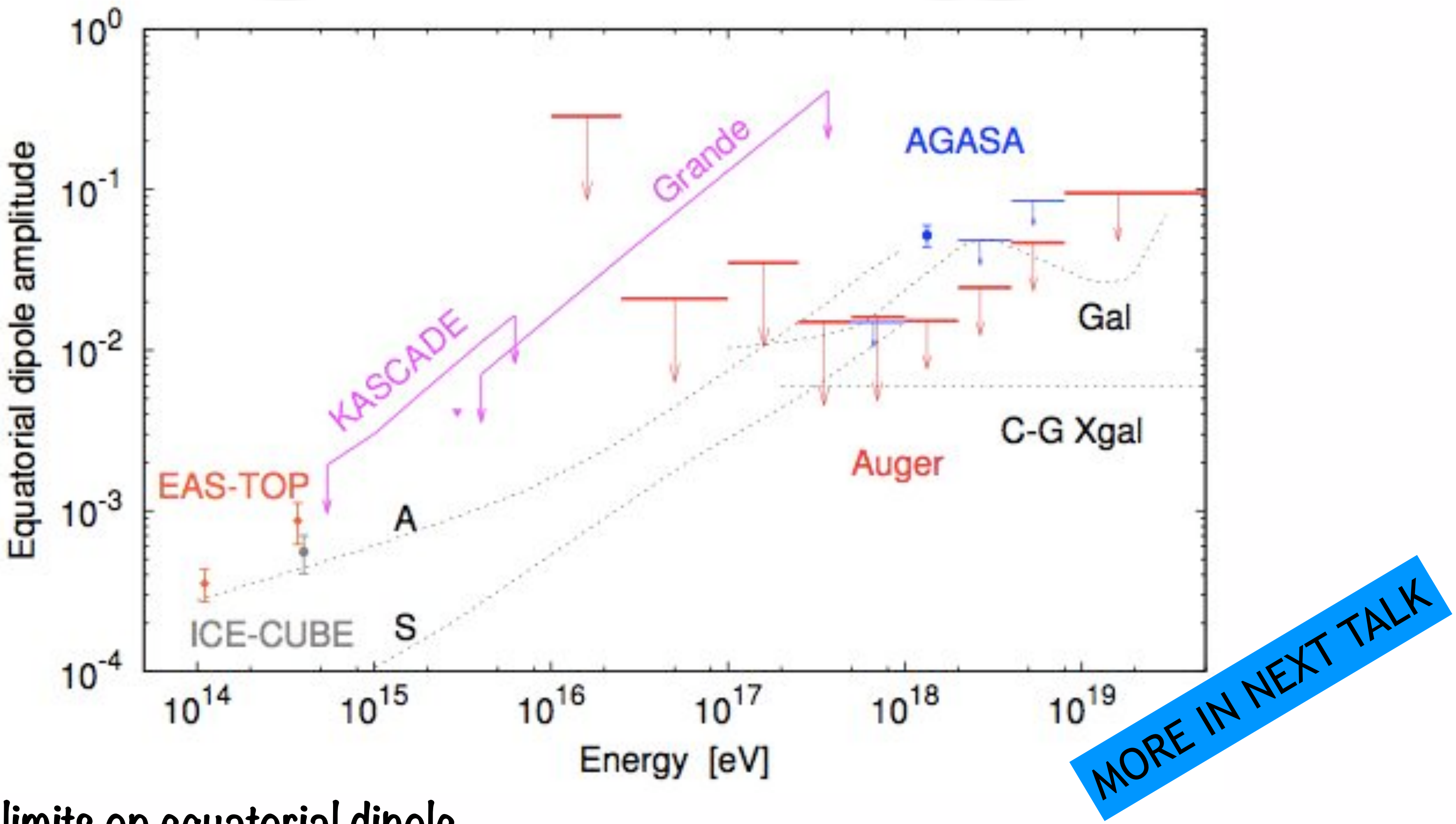


MORE IN NEXT TALK

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

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

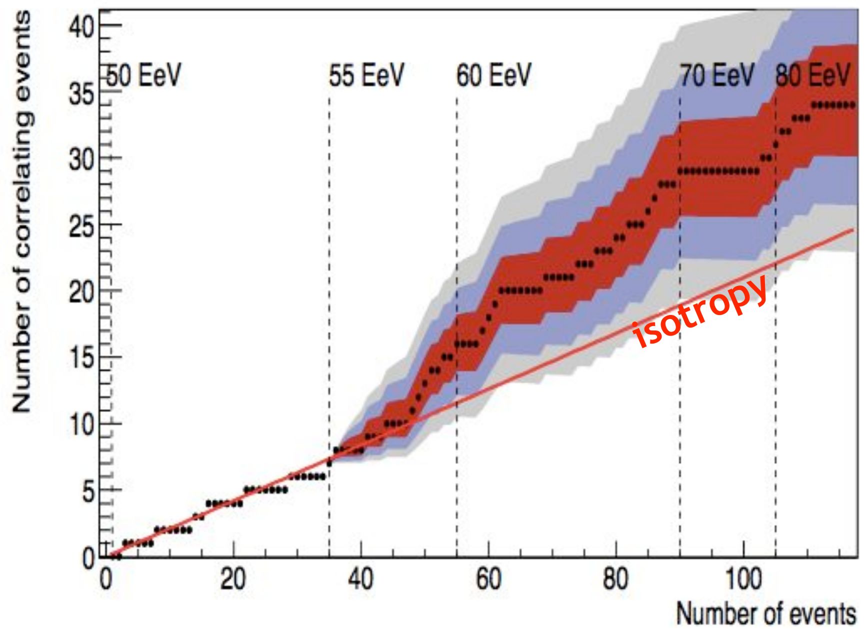
Large Scale Anisotropy



Upper limits on equatorial dipole

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

Point source searches



VCV Catalog

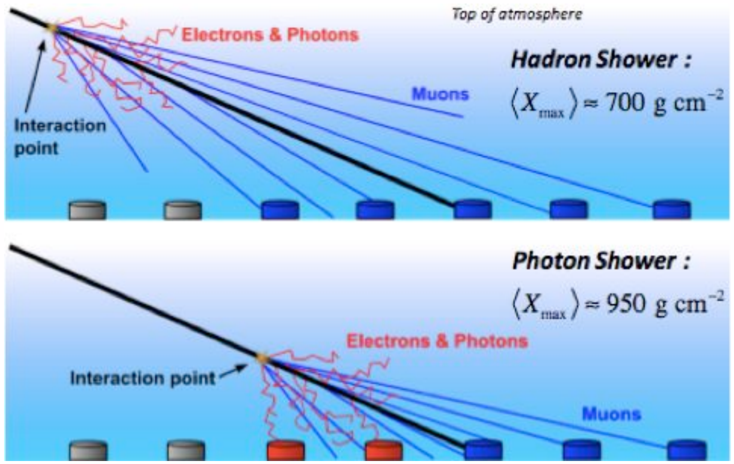
- fraction of correlating events (33 ± 5) % (21% from isotropy)
- the content in protons at UHE is small : consistency with X_{max} indication, exhaustion of sources?

Galactic neutron sources

- EeV neutrons searched for in the Galaxy (λdec~ (9.2 E_{EeV}) kpc) : different sources (HESS, Fermi sources, Galactic Plane and Galactic center, magnetars, microquasars, etc.)
- no candidate found with significant excess : $\phi_{neutrons}$<0.0114 km^{-2} yr^{-1} (> 1 EeV)
- challenge the hypothesis of EeV proton sources in the Galaxy, unless they are transient, or emitting in jets, or too faint...

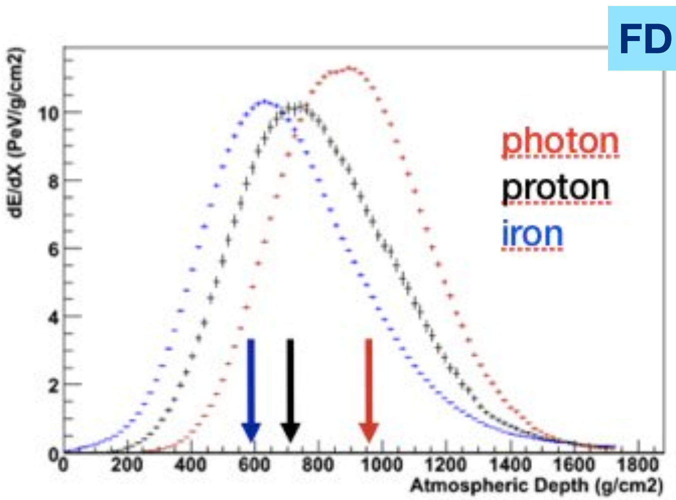
Photons

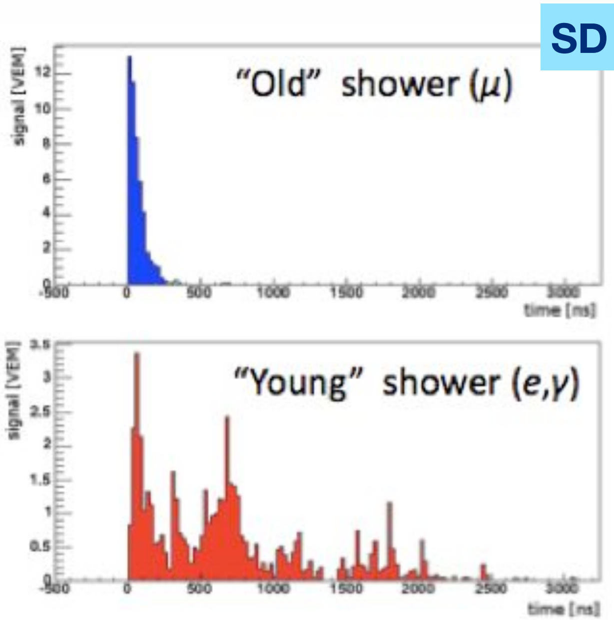
- to set limits on top-down mechanisms
- to search for GZK photons
- to fix the maximum photon fraction in the primary flux

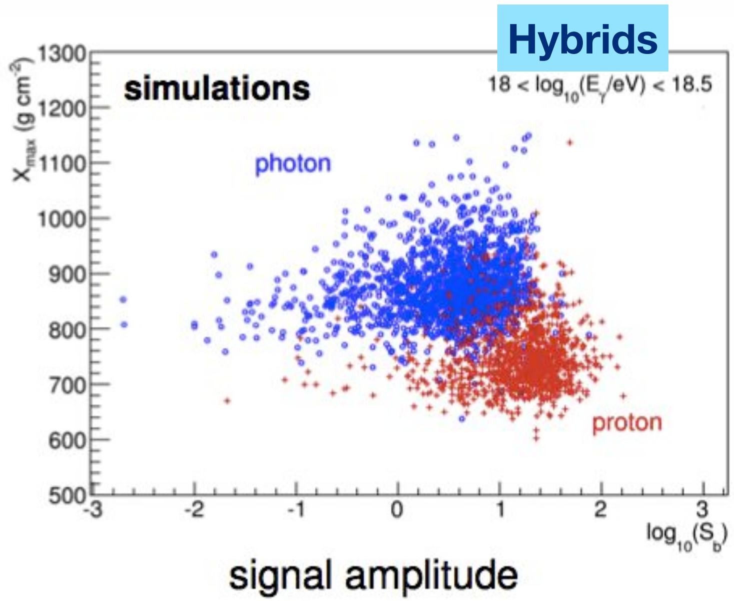


Exploit observable differencies between γ and hadrons

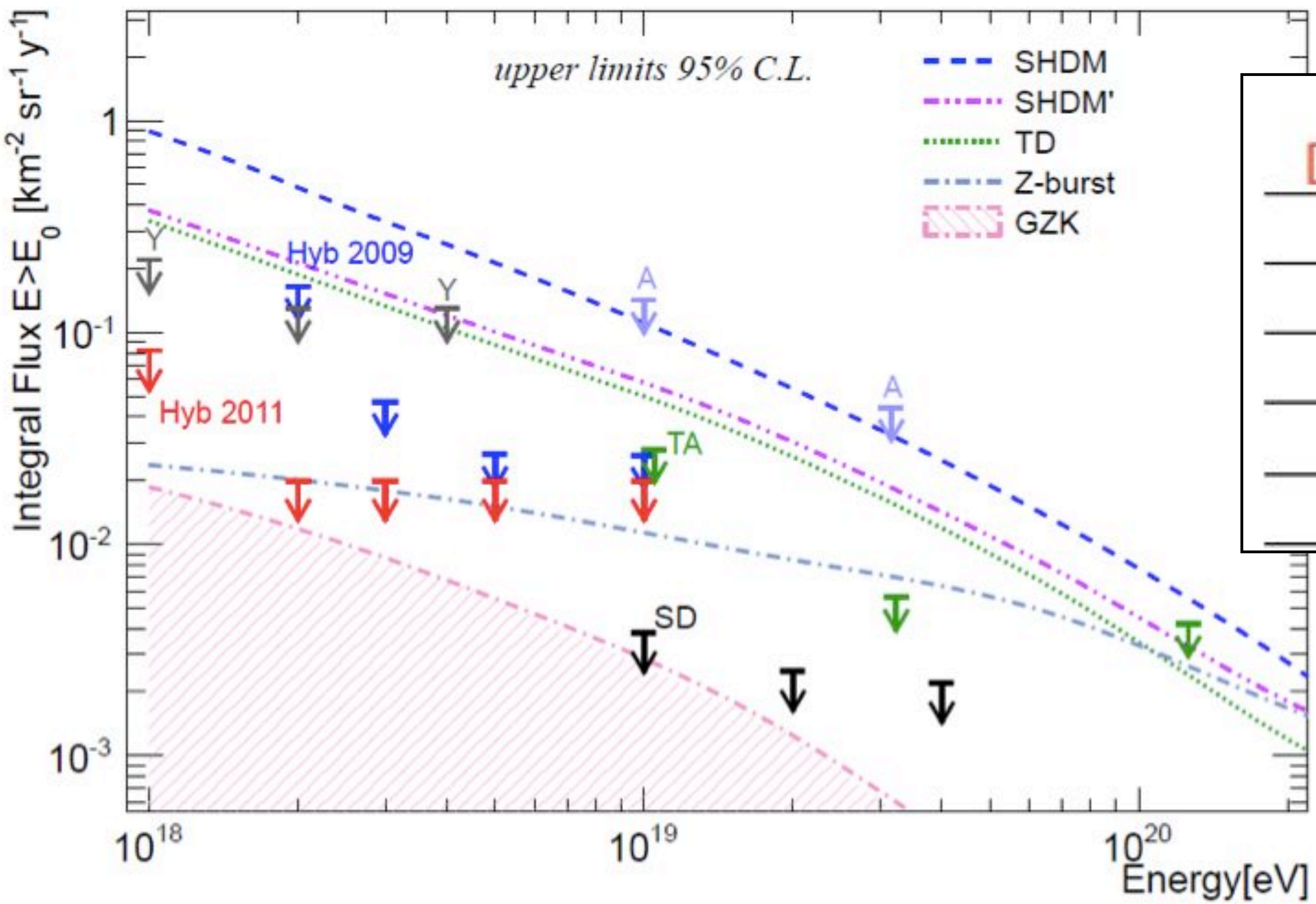
- γ EAS develop deeper in atmosphere: larger Xmax
- γ EAS look young: larger rise time, smaller radius of curvature







Diffuse photons

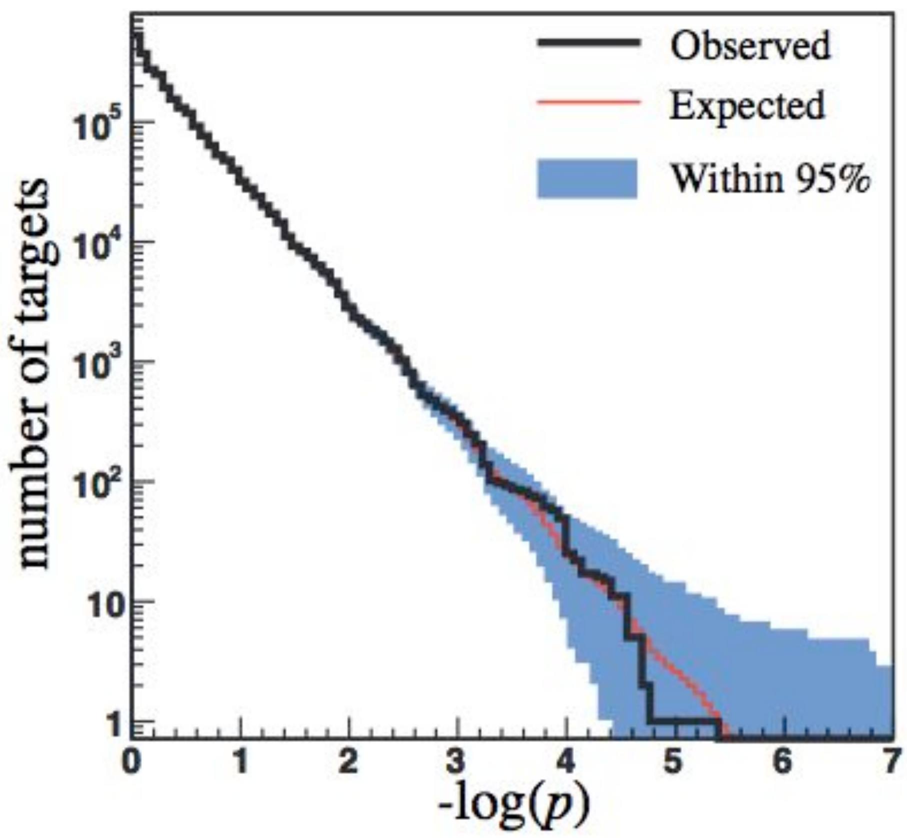


E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

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

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

well below expectations

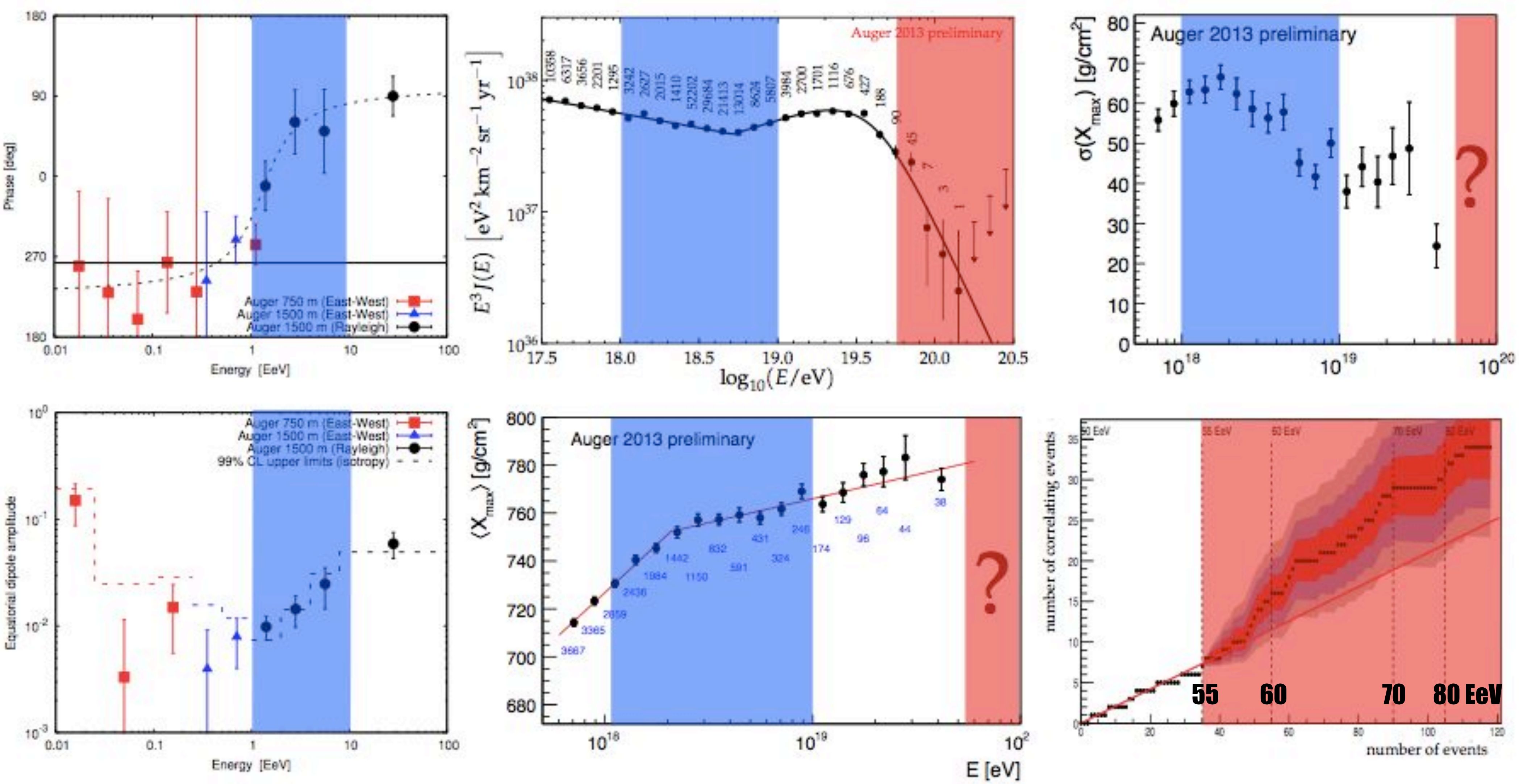
No Galactic sources of protons IF

—> they are not transient

—> they do not emit in jets towards Earth

—> they are too faint

The overall view



- **Ankle** : change in composition, hints of anisotropy on large scale
- **Cut-off** : 3 events above 10^{20} eV, no data from X_{max}, point source anisotropy at 3σ level

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 **Do EeV proton sources exist in our Galaxy ?** 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 **Are there information on quantum-gravity structures and possible LIV ?** see talk...

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

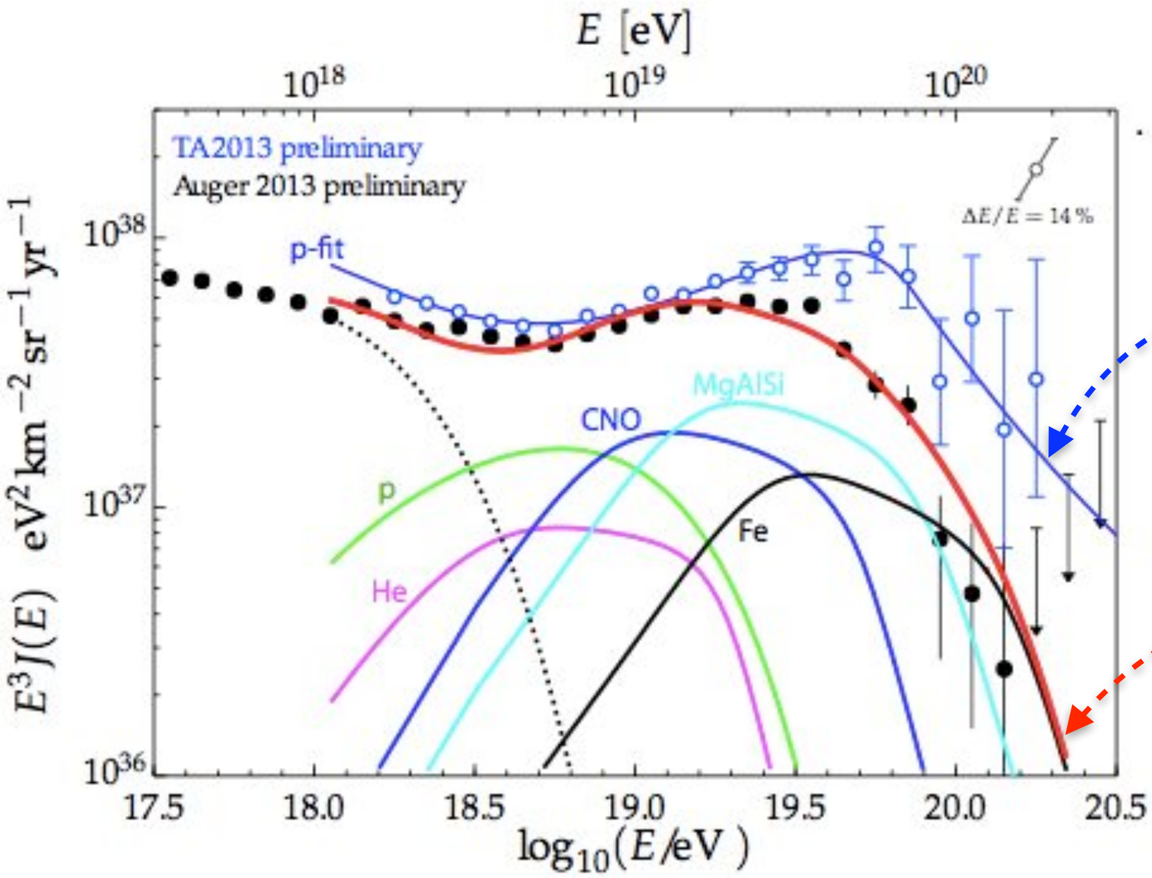
proton dominance

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

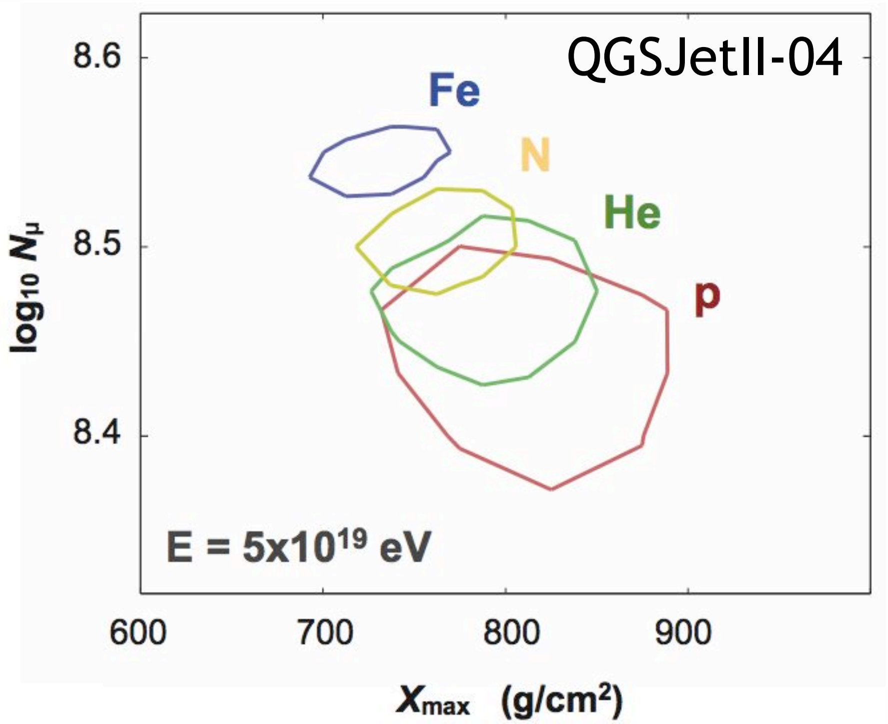
1. the origin of the cut-off : GZK or E_{max} ?
2. the proton component at UHE: what is its fraction ?
3. the hadronic interactions : particle physics beyond accelerators ?

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

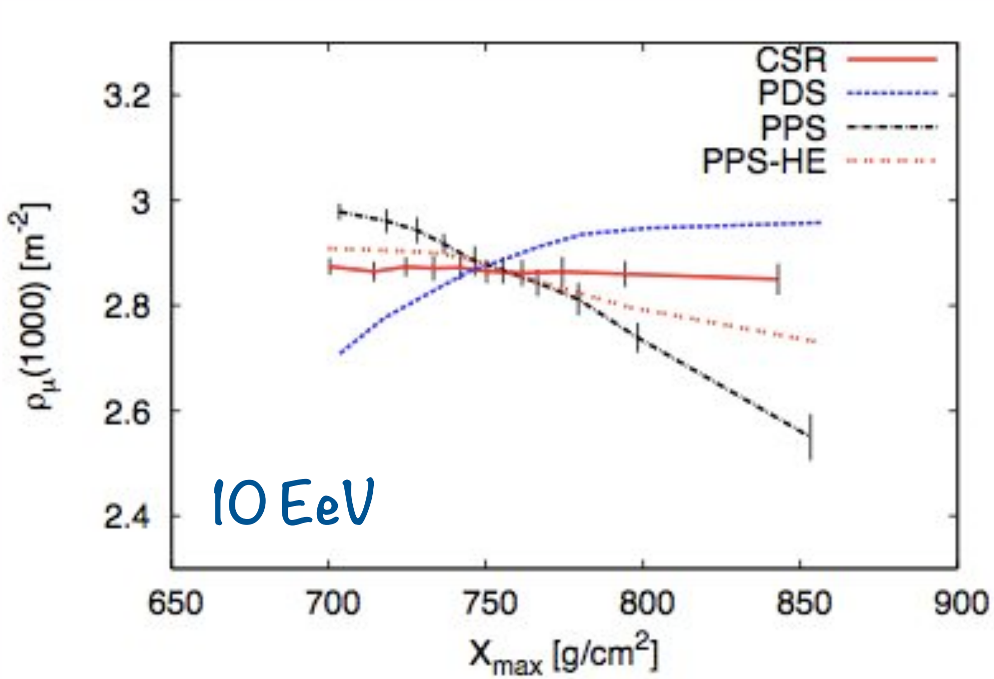


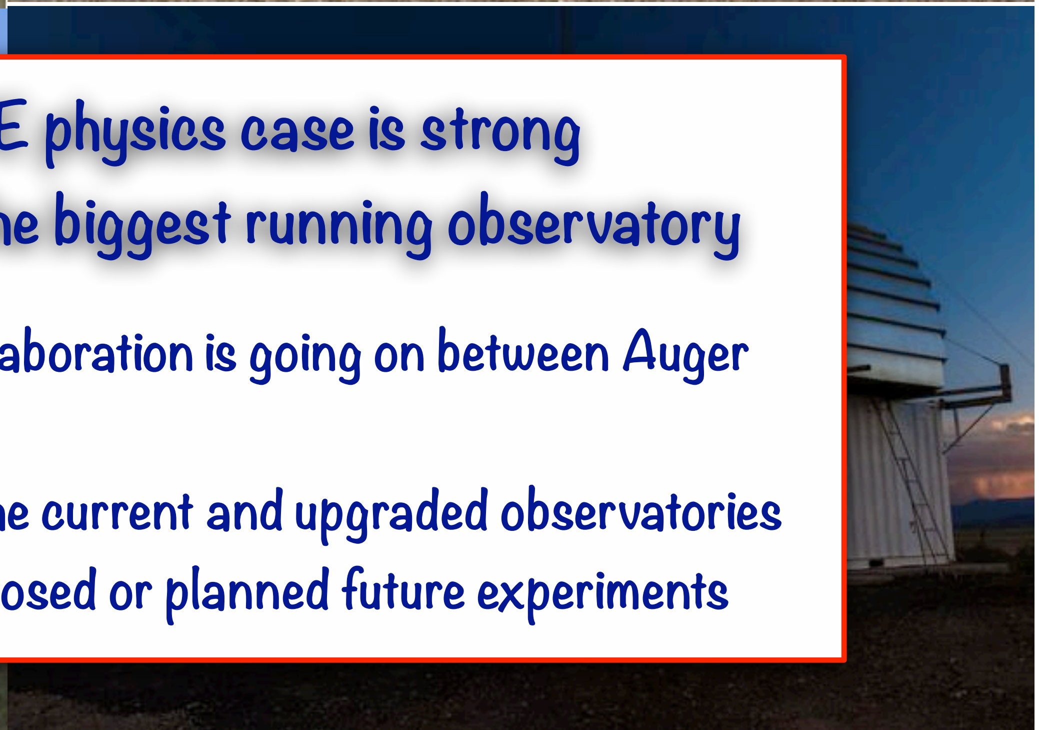
We can distinguish different primaries if N_μ only affected by shower-to-shower fluctuations

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

N_μ —> m, f_{EM}, A

X_{max} —> σ, κ, m, A





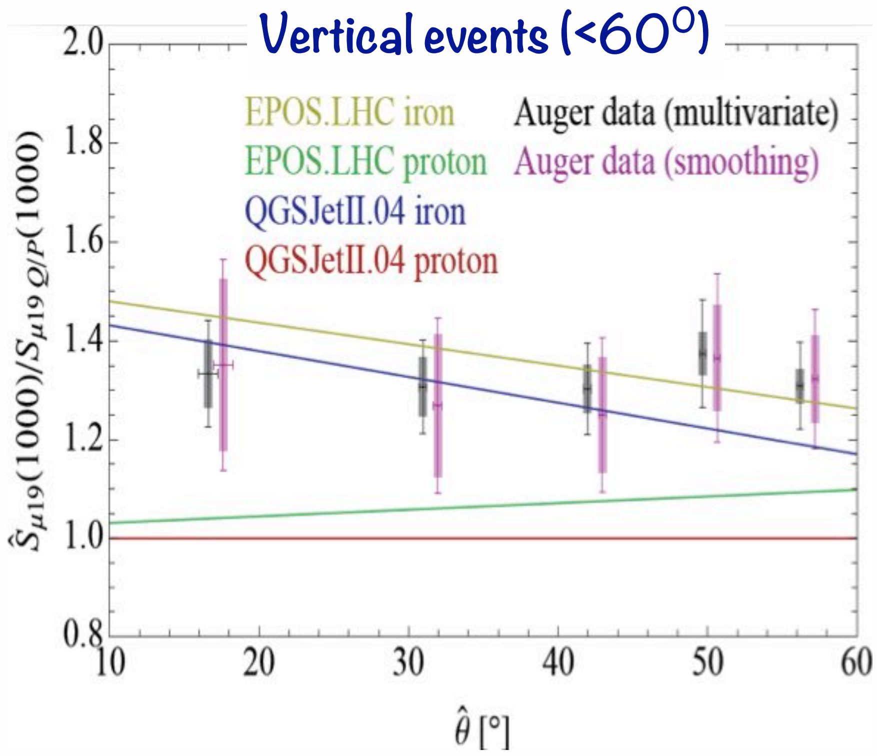
UHE physics case is strong

Auger is the biggest running observatory

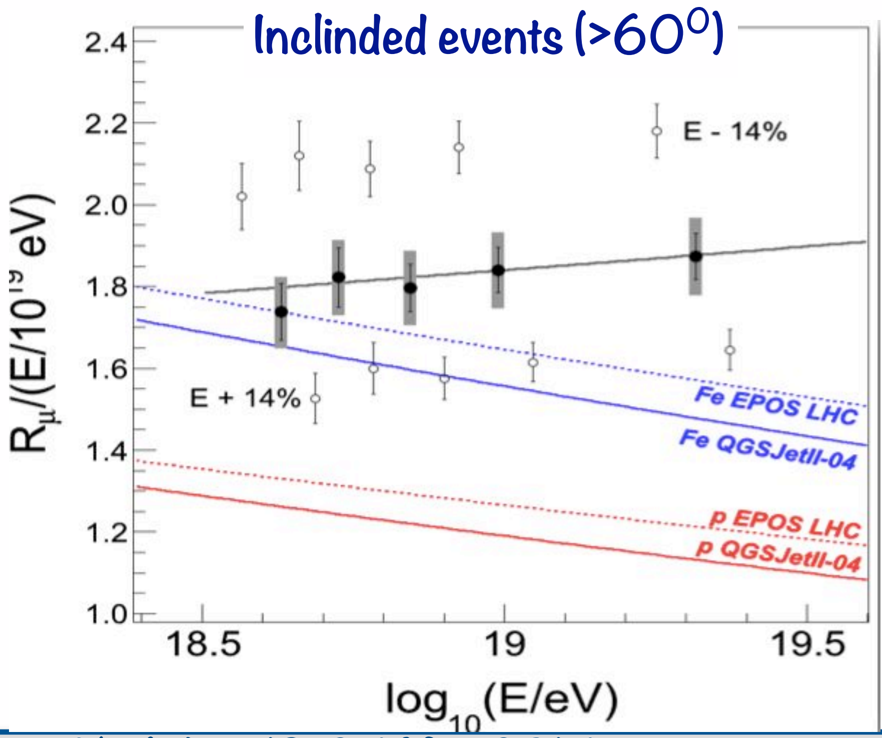
✓ a very fruitful collaboration is going on between Auger and TA

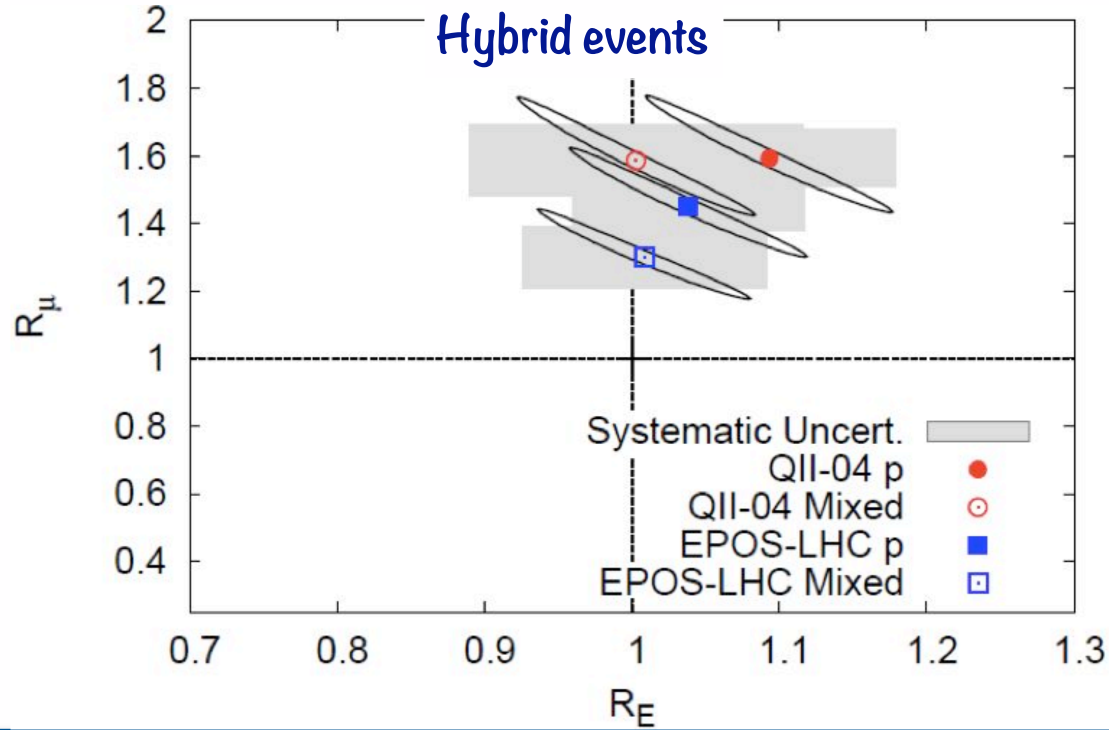
✓ the results from the current and upgraded observatories will guide the proposed or planned future experiments

Backup slides



Muon deficit in simulations





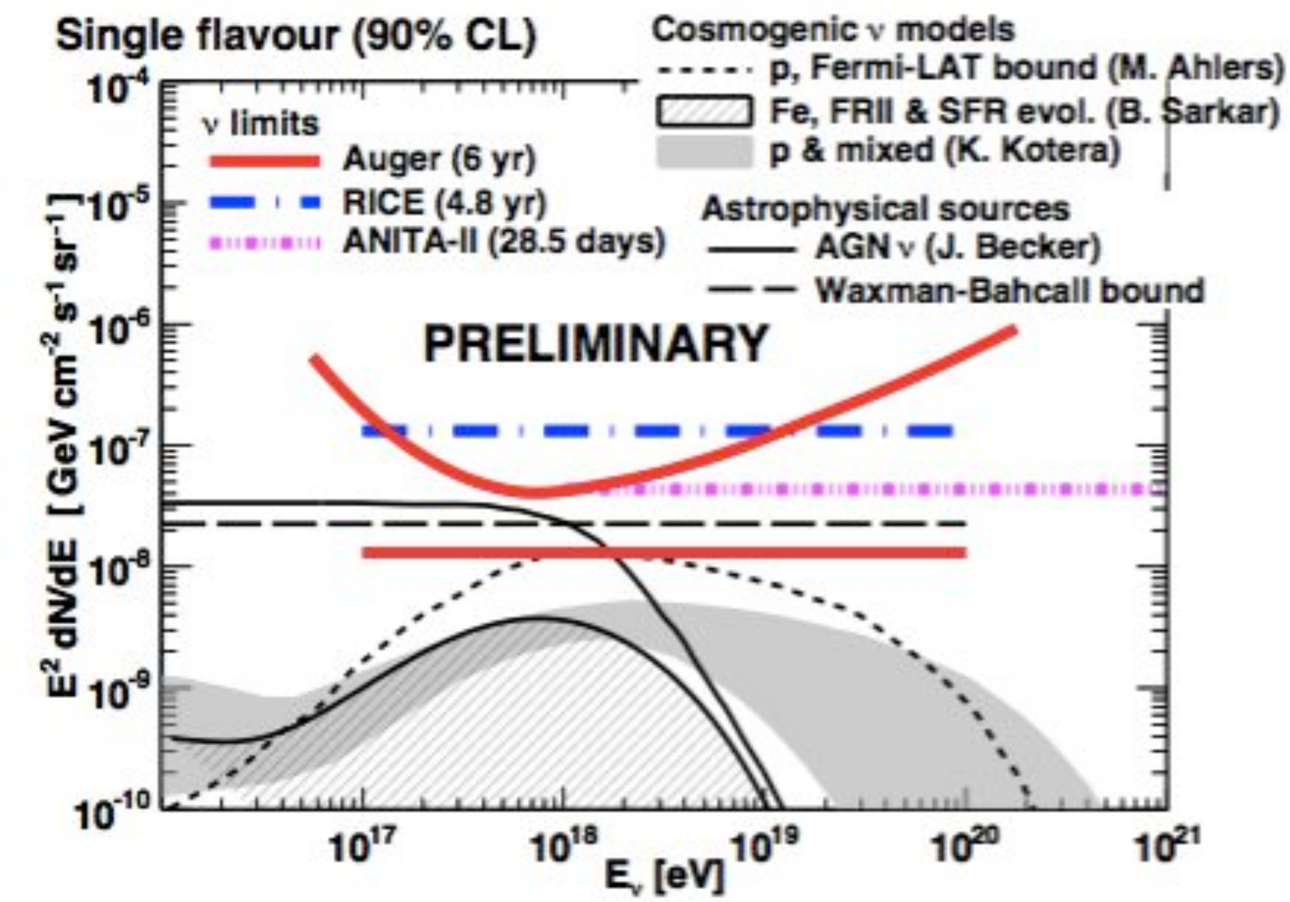
	Auger SD			Auger hybrid
	1500 m vertical	**1500 m inclined**	**750 m vertical**	
Data taking period	01/2004 - 12/2012	01/2004 - 12/2012	08/2008 - 12/2012	11/2005 - 12/2012
Exposure [km^2 sr yr]	31645 ± 950	8027 ± 240	79 ± 4	-
Zenith angles [°]	$0 - 60$	$62 - 80$	$0 - 55$	$0 - 60$
Threshold energy E_{eff}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

$\log_{10}(E/\mathrm{eV})$	$dN/dt\|_{\mathrm{infill}}$ [yr^{-1}]	$dN/dt\|_{\mathrm{SD}}$ [yr^{-1}]	$N\|_{\mathrm{infill}}$ [2017-2023]	$N\|_{\mathrm{SD}}$ [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



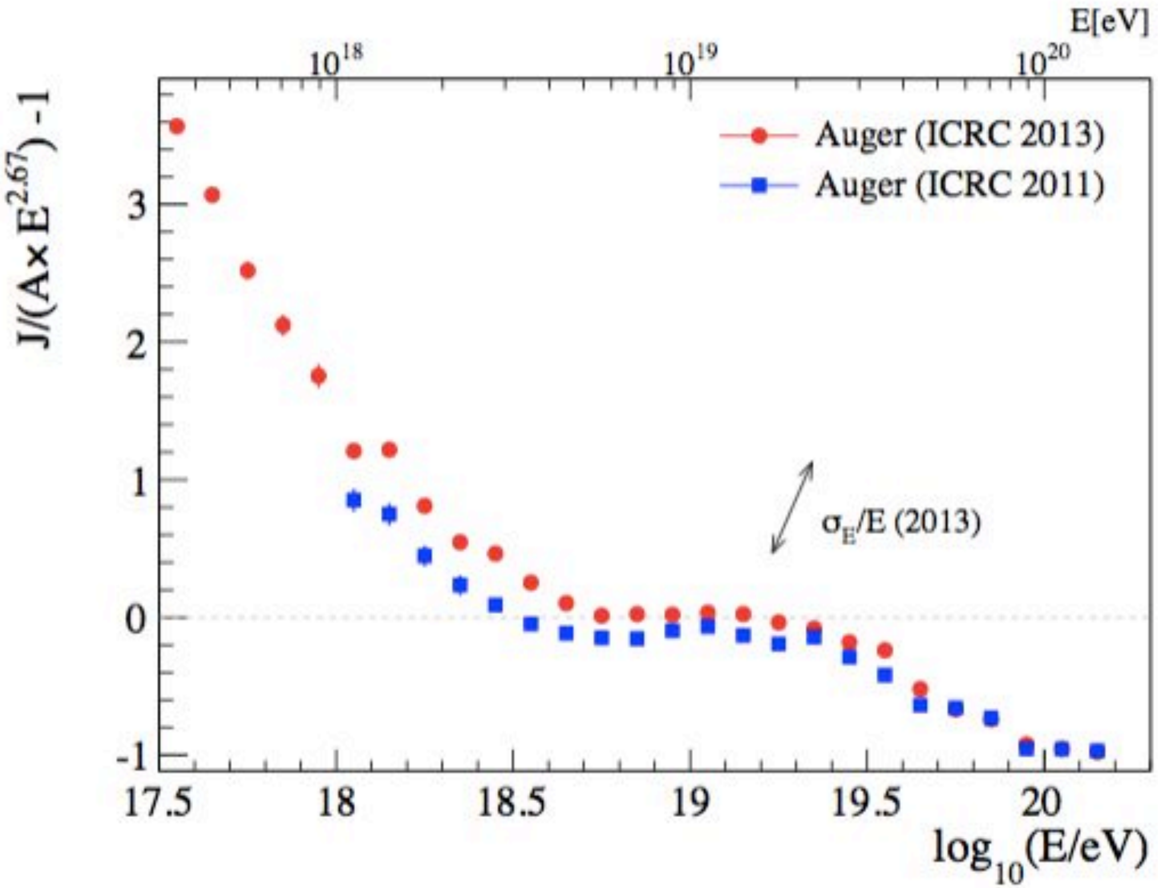
For a flux $\Phi(E_\nu)=kE_\nu^{-2}$

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

$k_{up}=1.3\ 10^{-8}$ 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



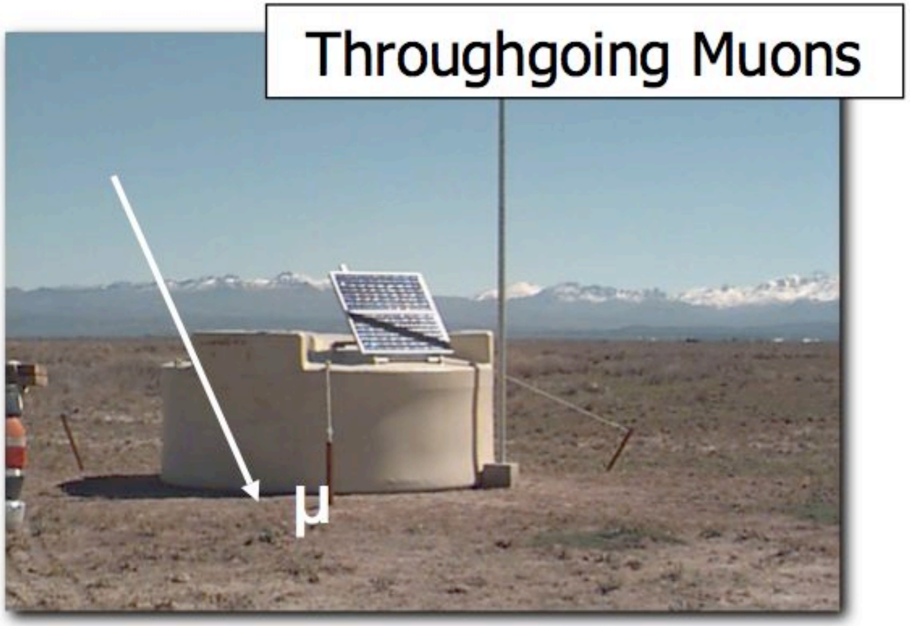
2011 spectral parameters

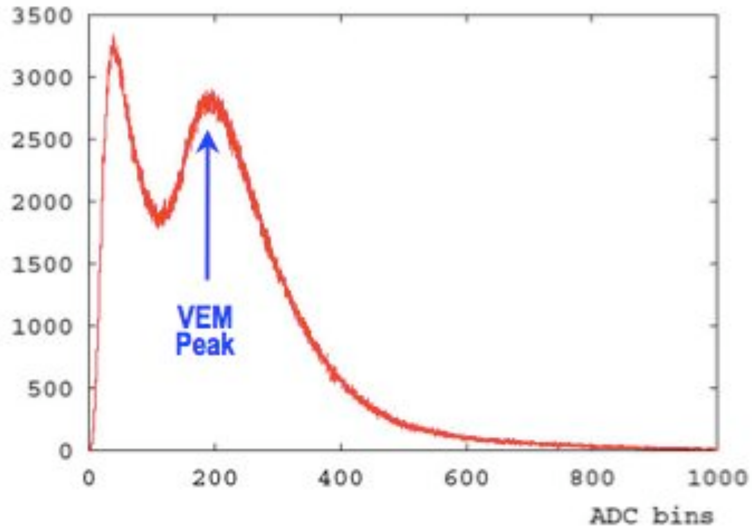
$$\log_{10}(E_a/\mathrm{eV}) = 18.62 \pm 0.01$$
$$\gamma_1 = 3.27 \pm 0.01$$
$$\gamma_2 = 2.63 \pm 0.02$$
$$\log_{10}(E_{1/2}/\mathrm{eV}) = 19.63 \pm 0.02$$
$$\log_{10} W_c = 0.15 \pm 0.02$$

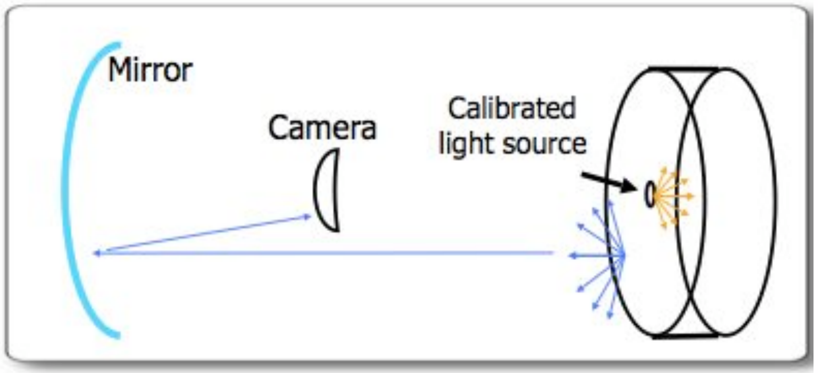
2013 spectral parameters

$$\log_{10}(E_a/\mathrm{eV}) = 18.72 \pm 0.01$$
$$\gamma_1 = 3.23 \pm 0.01$$
$$\gamma_2 = 2.63 \pm 0.02$$
$$\log_{10}(E_{1/2}/\mathrm{eV}) = 19.63 \pm 0.01$$
$$\log_{10} W_c = 0.15 \pm 0.01$$

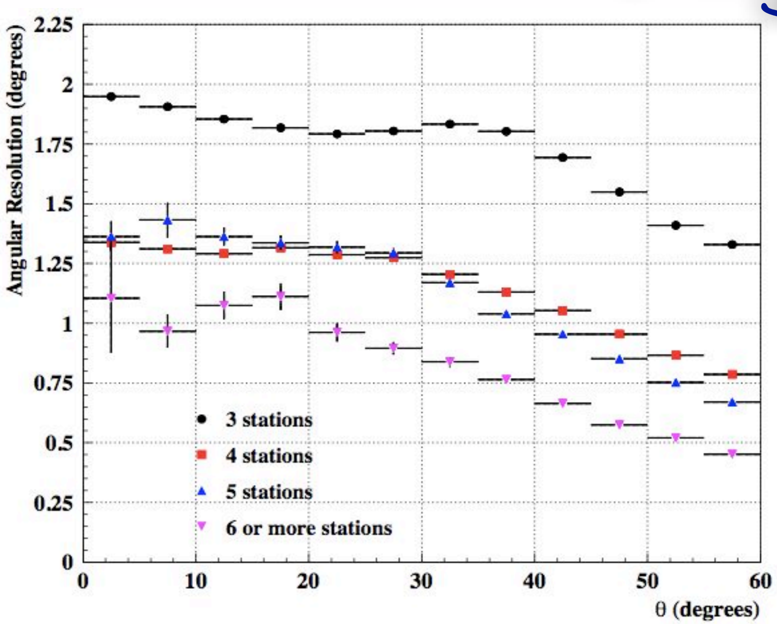
Calibration





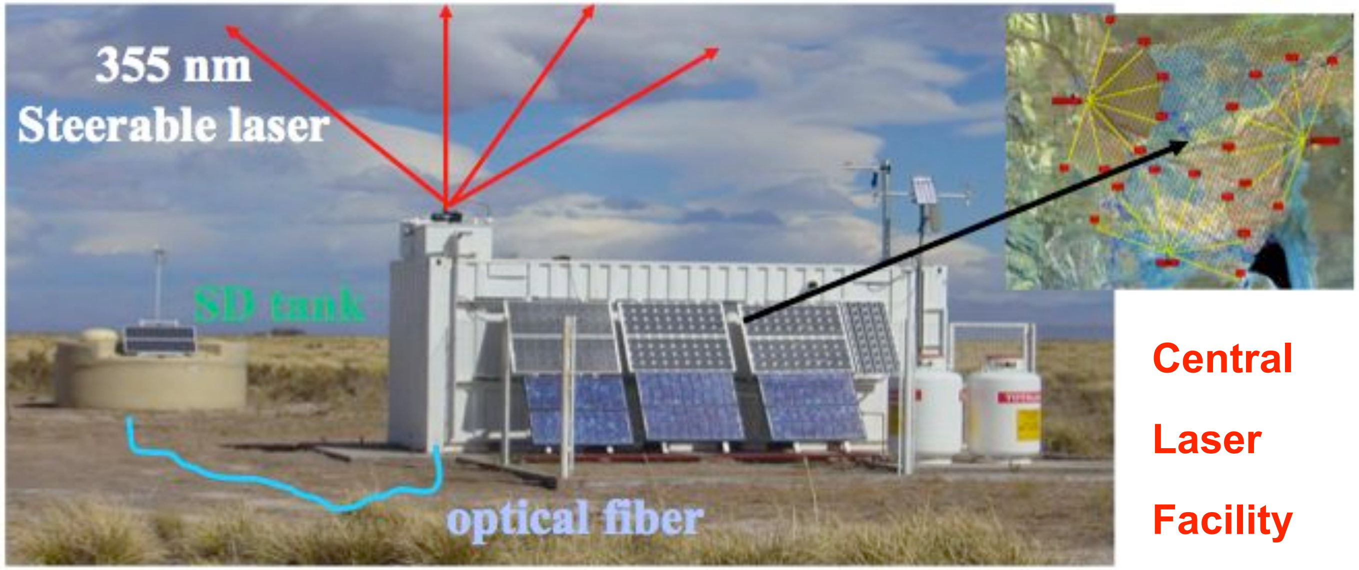


Angular resolution



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