PIERRE AUGER OBSERVATORY

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

18th International Seminar on High Energy Physics

QUARKS-2014

Results from the Pierre Auger Observatory

Astroparticles at the High Energy Frontier

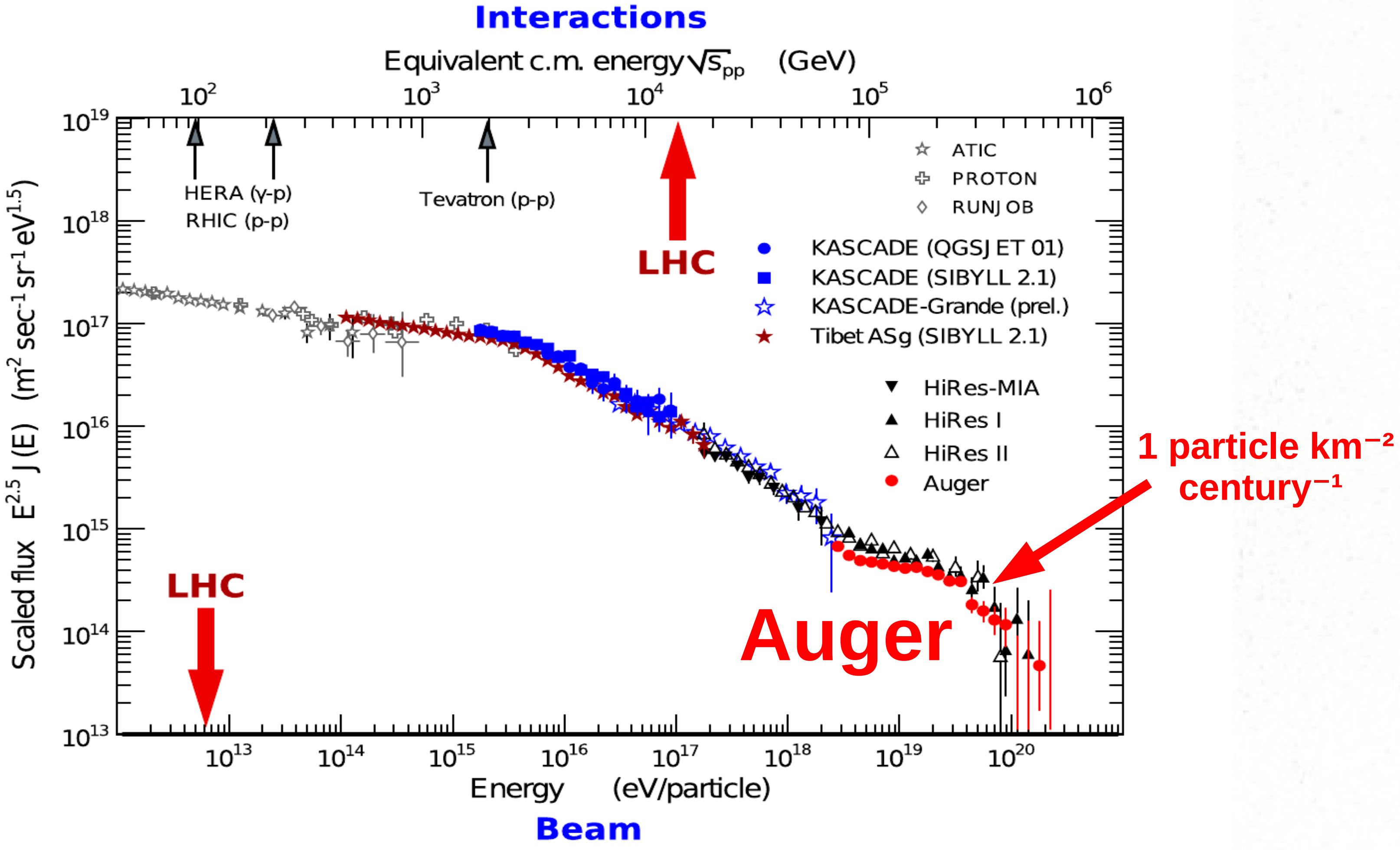
Gonzalo Parente for the Pierre Auger Collaboration

Universidade de Santiago de Compostela & IGFAE

Suzdal, 7 june 2014

The Pierre Auger Observatory

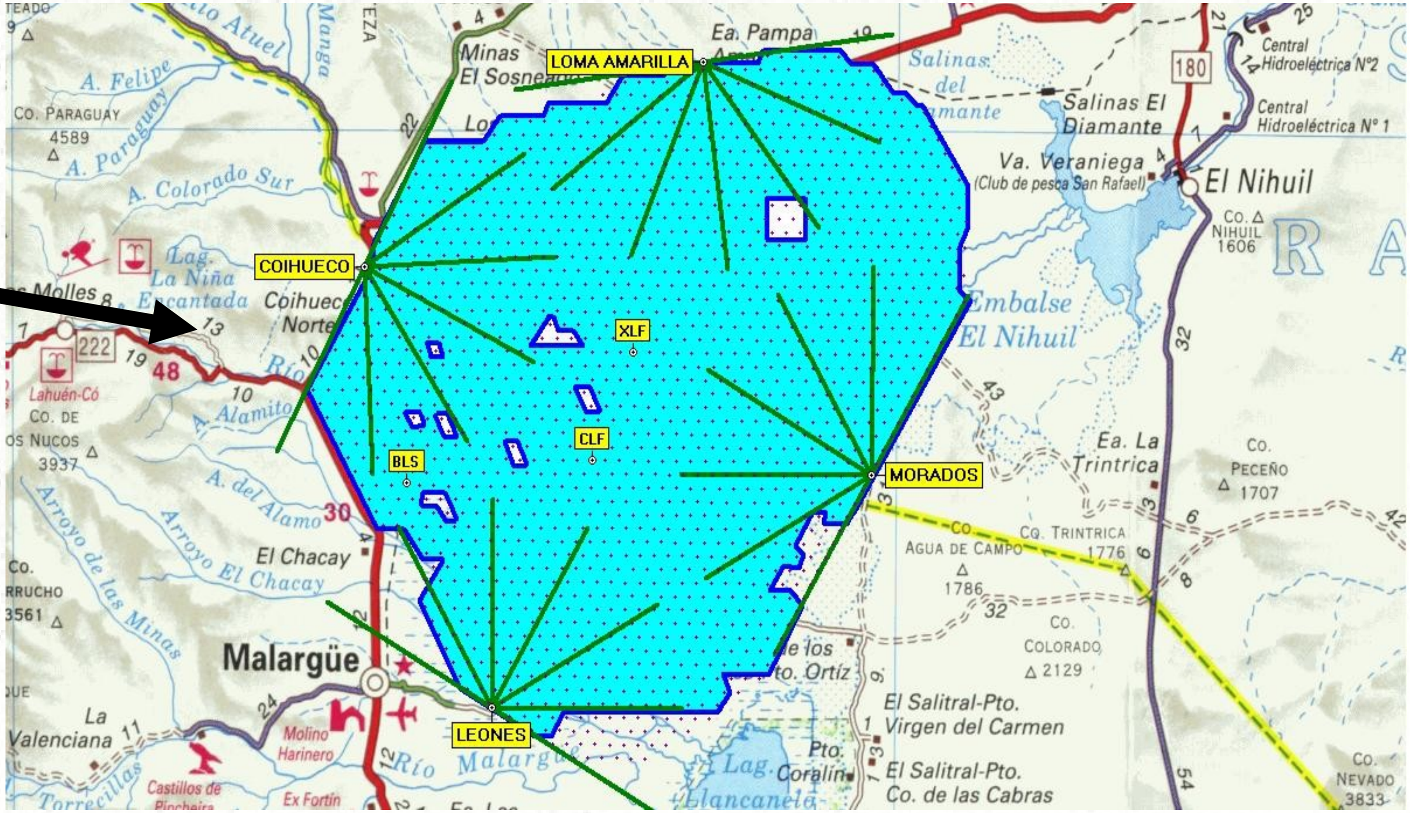
The High Energy Frontier

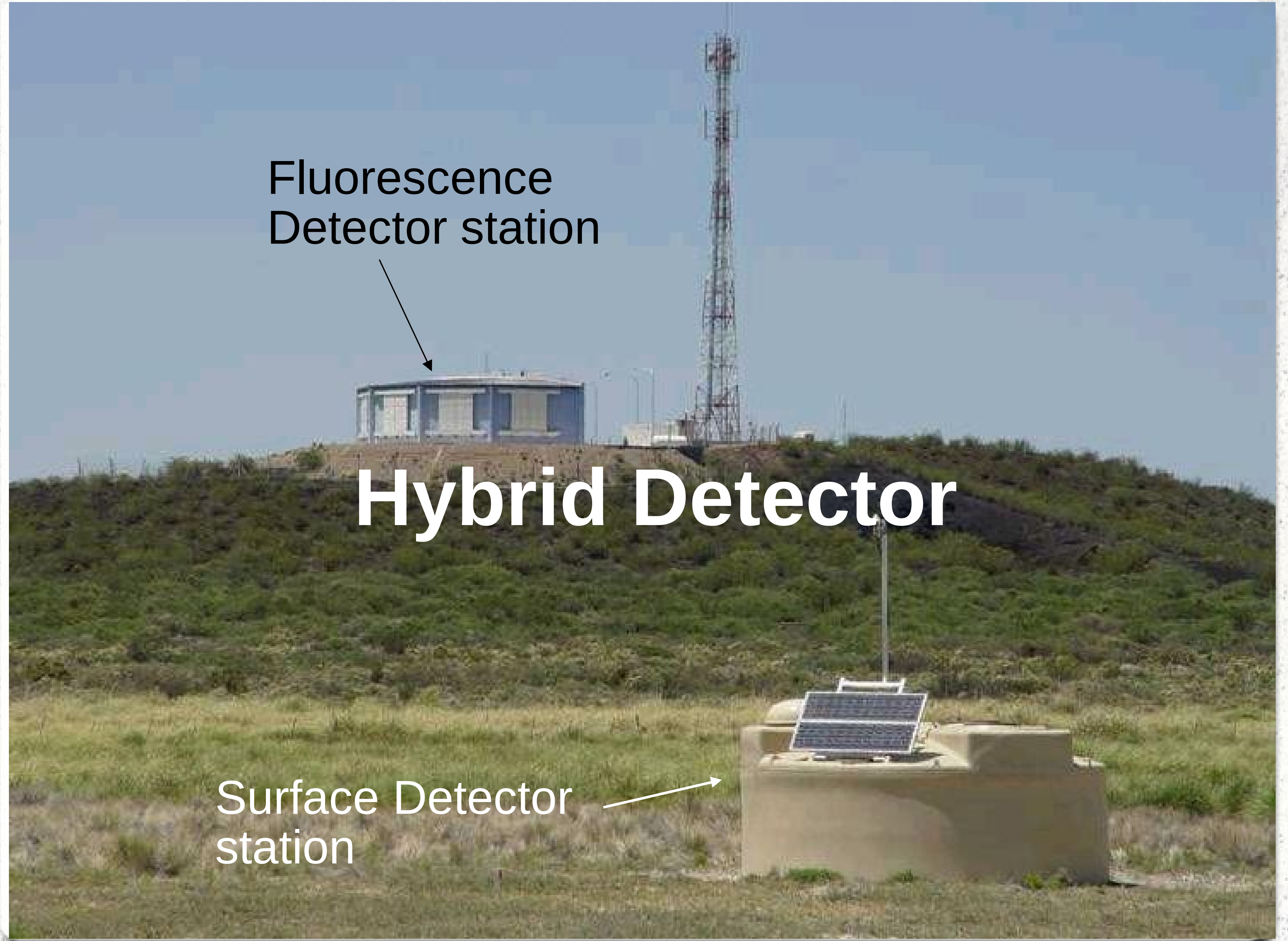


Pierre Auger Observatory

1660 water cherenkov stations (3000 km^2, 1.5 km grid)
4+1 fluorescence sites (24+3 telescopes)
130 radio antennas

500 collaborators
90 institutions
18 countries

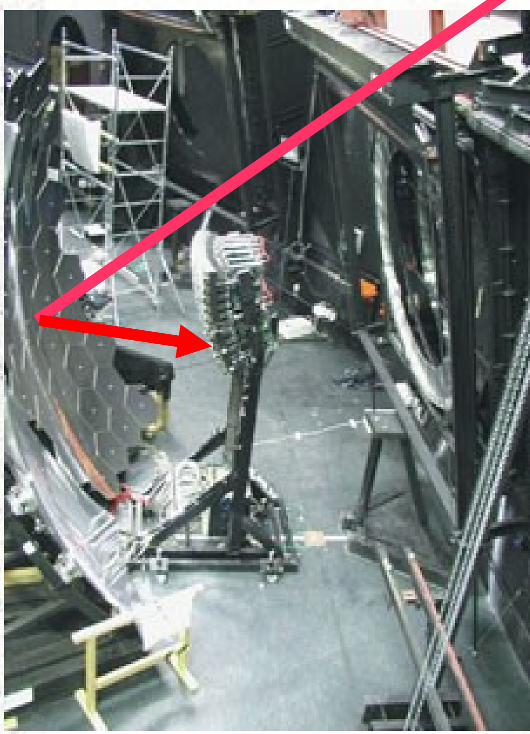


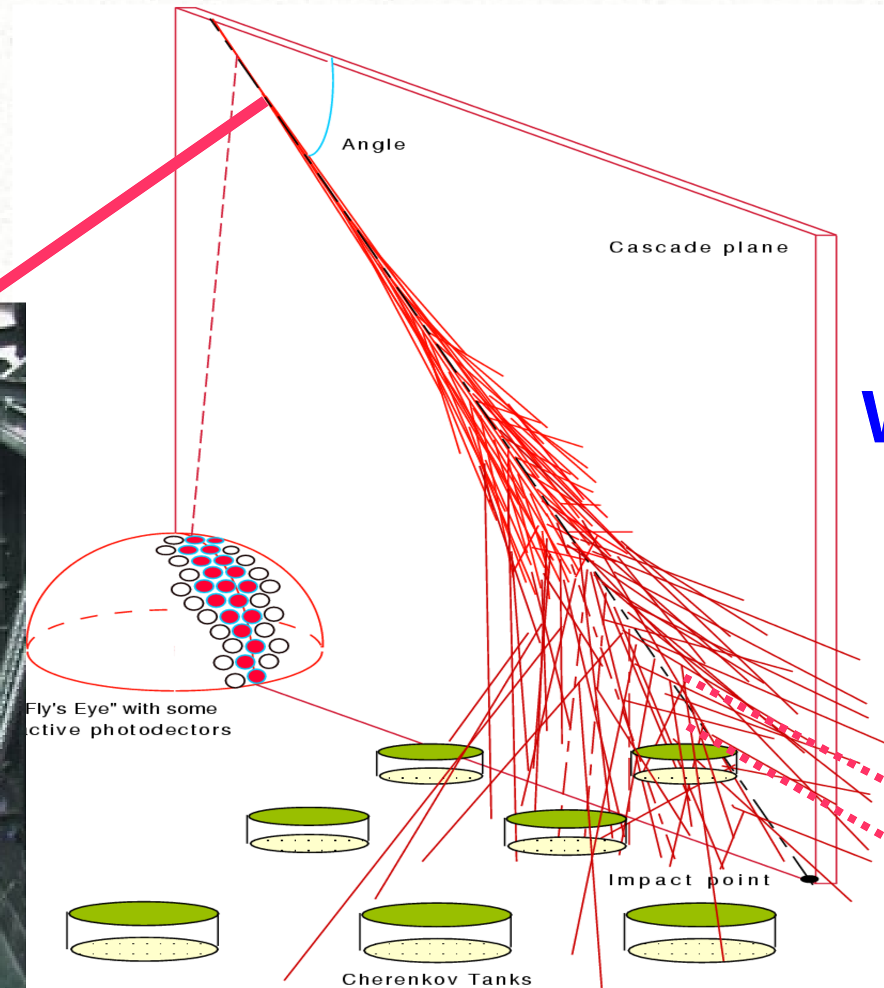

Fluorescence
Detector station
Hybrid Detector
Surface Detector
station

Two different techniques

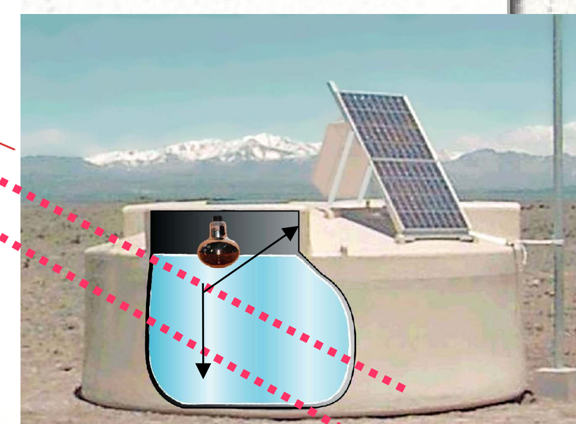
~ 10% of events are observed with both methods

Fluorescence telescopes



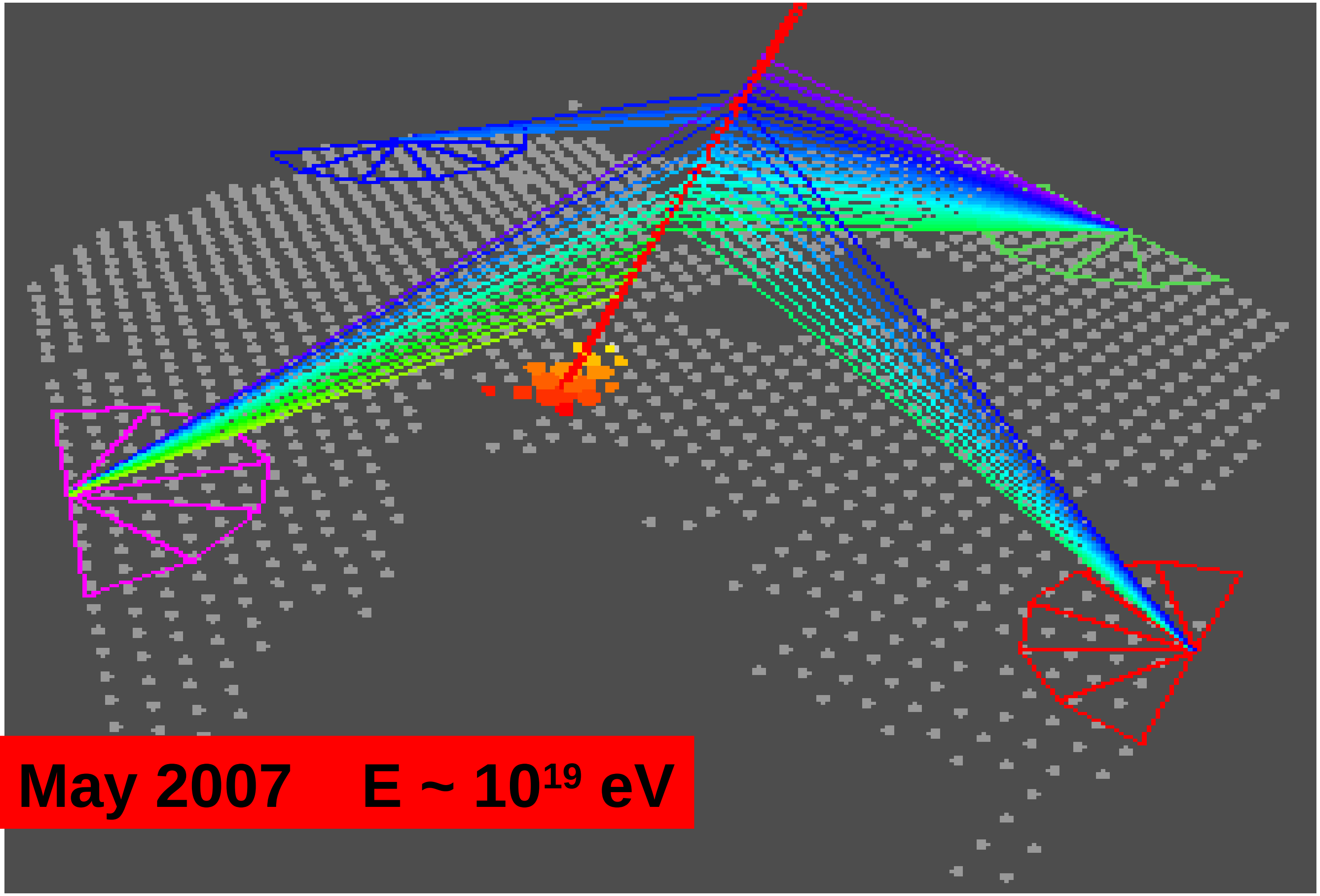


Water-Cherenkov stations



Example of hybrid event

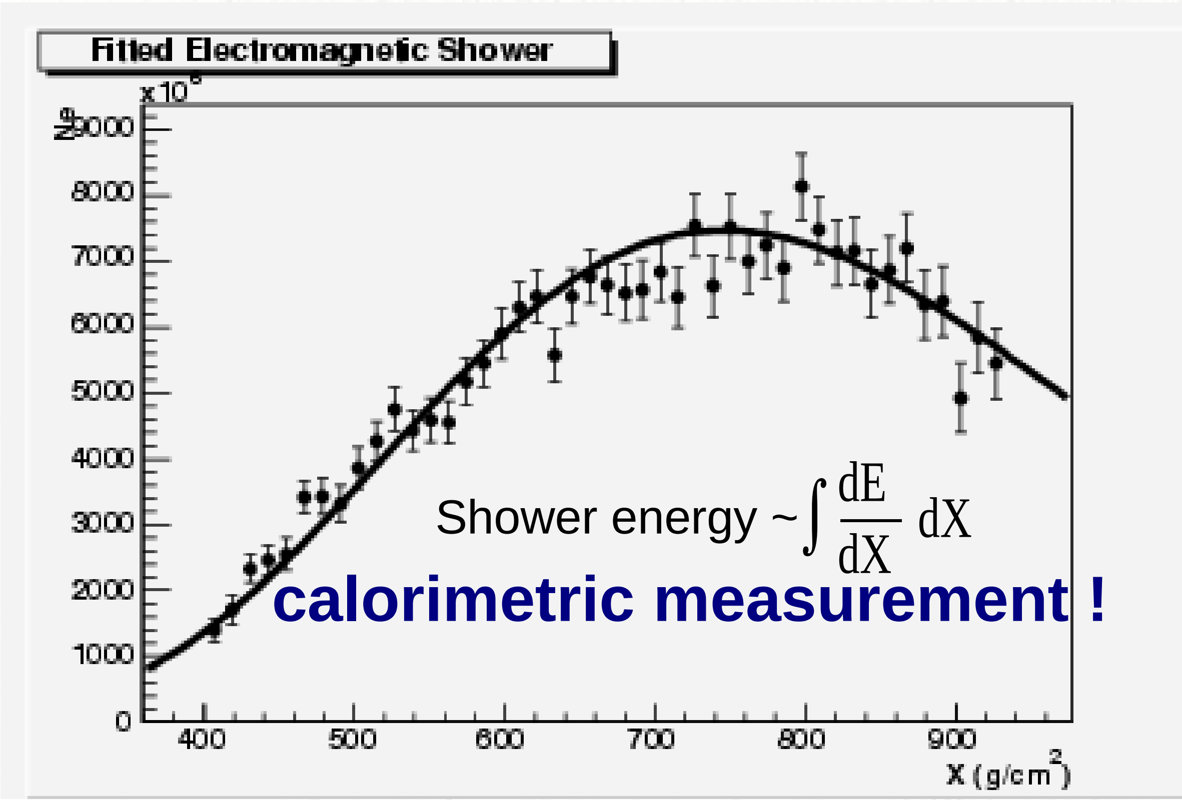
Detected in 4 fluorescence stations & the surface array



20 May 2007 E ~ 10^{19} eV

Energy reconstruction
(with the Fluorescence Detector)

Measured **fluorescence light vs depth** proportional to **dE_{ion}/dX vs X**



Shower energy $\sim \int \frac{dE}{dX} dX$

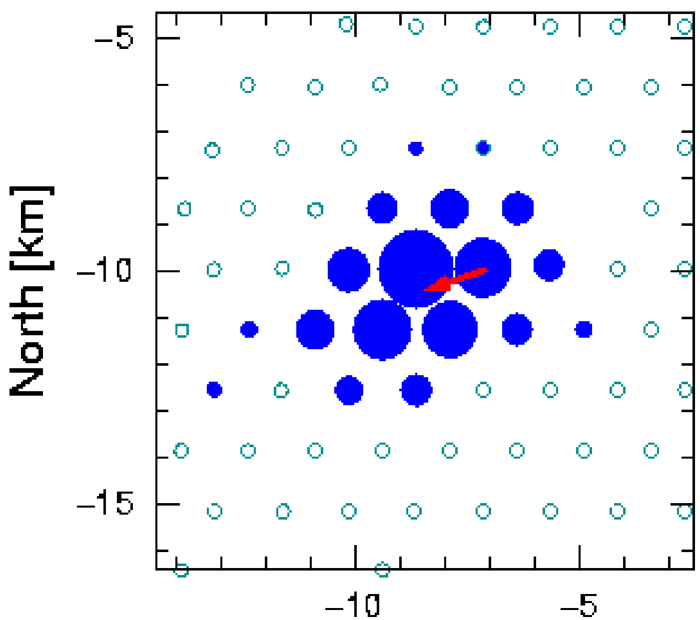
calorimetric measurement !

weakly dependent on hadronic model & composition (~ 5%) from missing energy (muons and neutrinos not seen by the fluorescence detector)

Energy reconstruction
(with the Surface Detector)

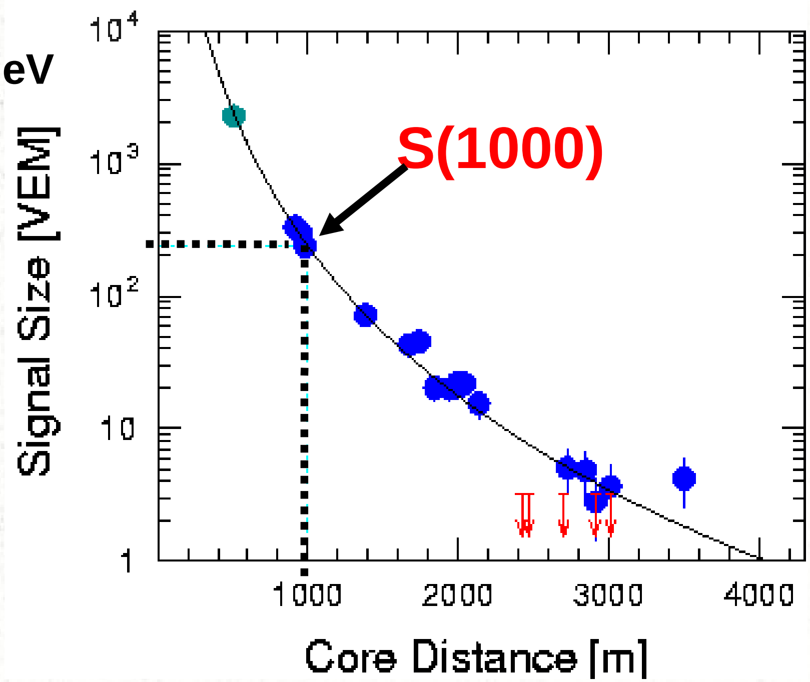
Energy estimator: S(1000) signal at 1000 m from the shower core

Footprint on the ground



Event 762238
θ ~ 48º
E ~ 7 x 10^{19} eV

Lateral density distribution

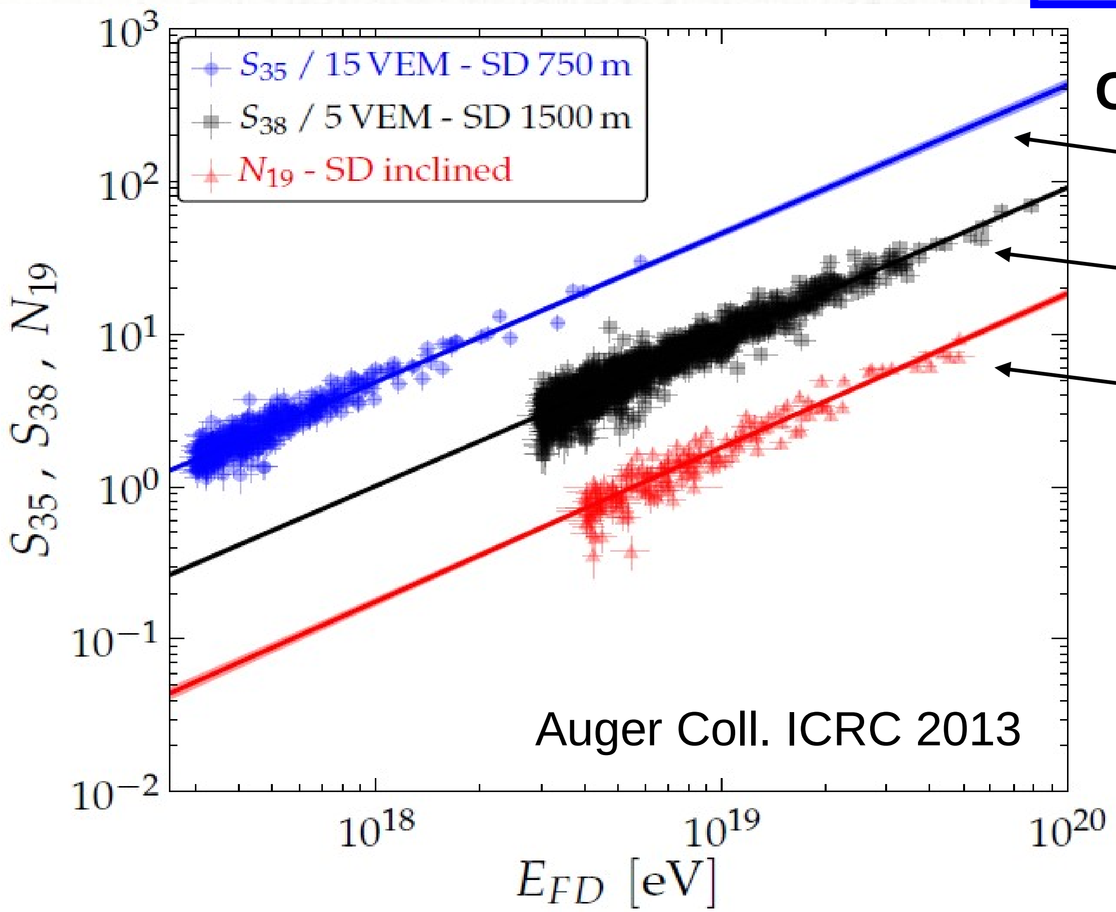


Needed relation of S(1000) with Energy

independent on had. models and composition

Energy calibration with hybrids

Minimises dependence on hadronic model and mass composition (~ 5%)



Correlation FD energy vs.

S(450) 750 m array

S(1000) 1.5 km array

N19 Inclined showers

Extrapolate calibration to events observed with the Surface Detector

Energy reconstruction
for inclined events (> 60 deg.)

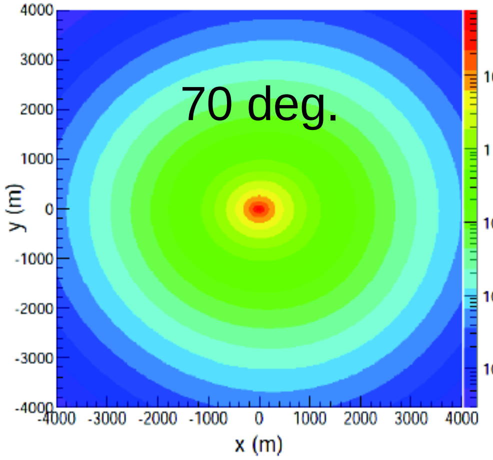
$$n_\mu = \rho_\mu(\vec{r})\, A_\perp(\theta) = N_{19}\, \rho_{\mu,19}(\vec{r};\theta,\phi)\, A_\perp(\theta)$$

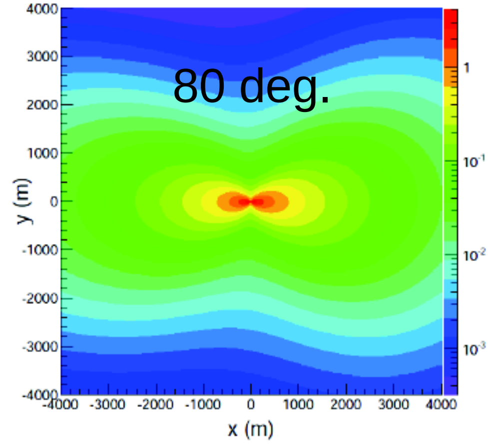
muonic signal

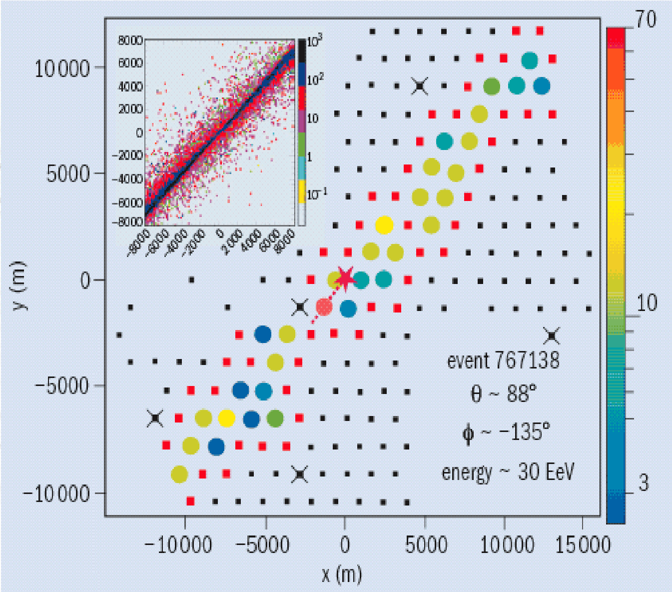
energy estimator

muon density profile used as reference
10 EeV – proton - QGSJetII-03

Contour plot of the muon density in the shower plane

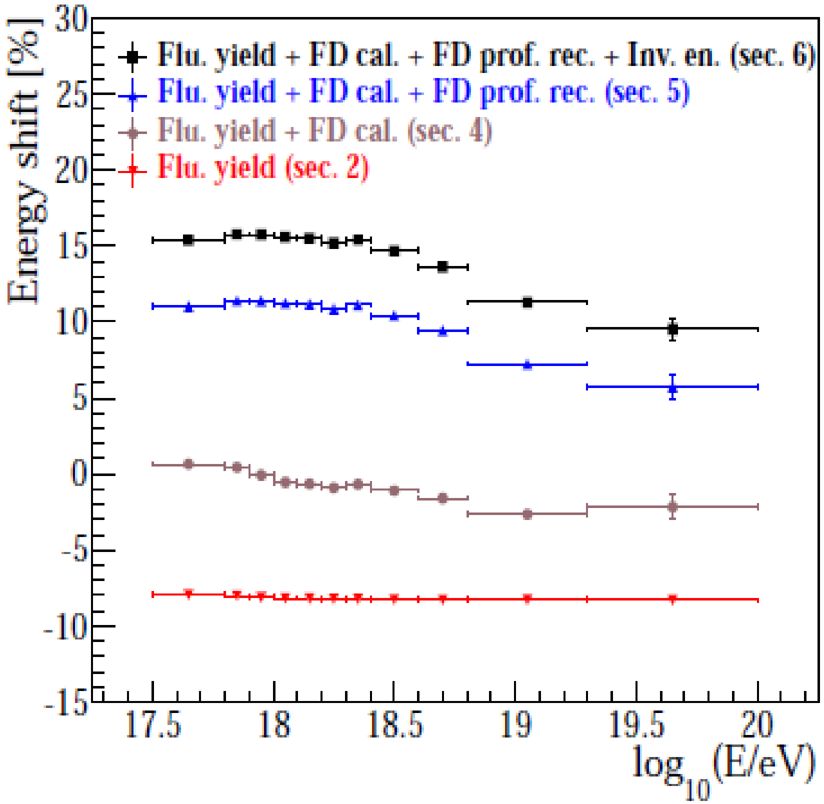






Auger energy scale have changed in 2013

Energy scale shift

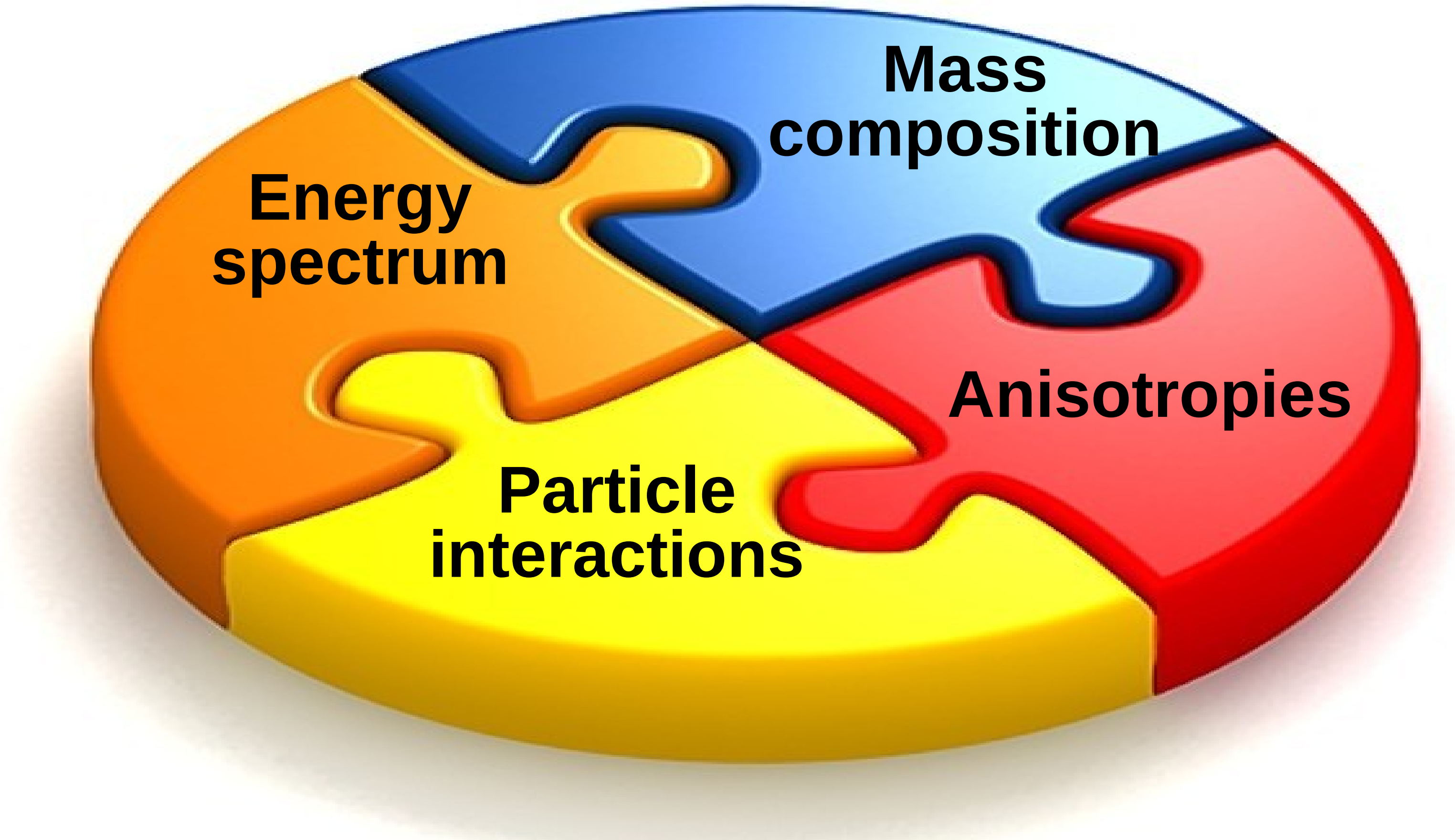


Auger Coll. ICRC 2013

Systematic uncertainty decreases from 22% to 14%

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

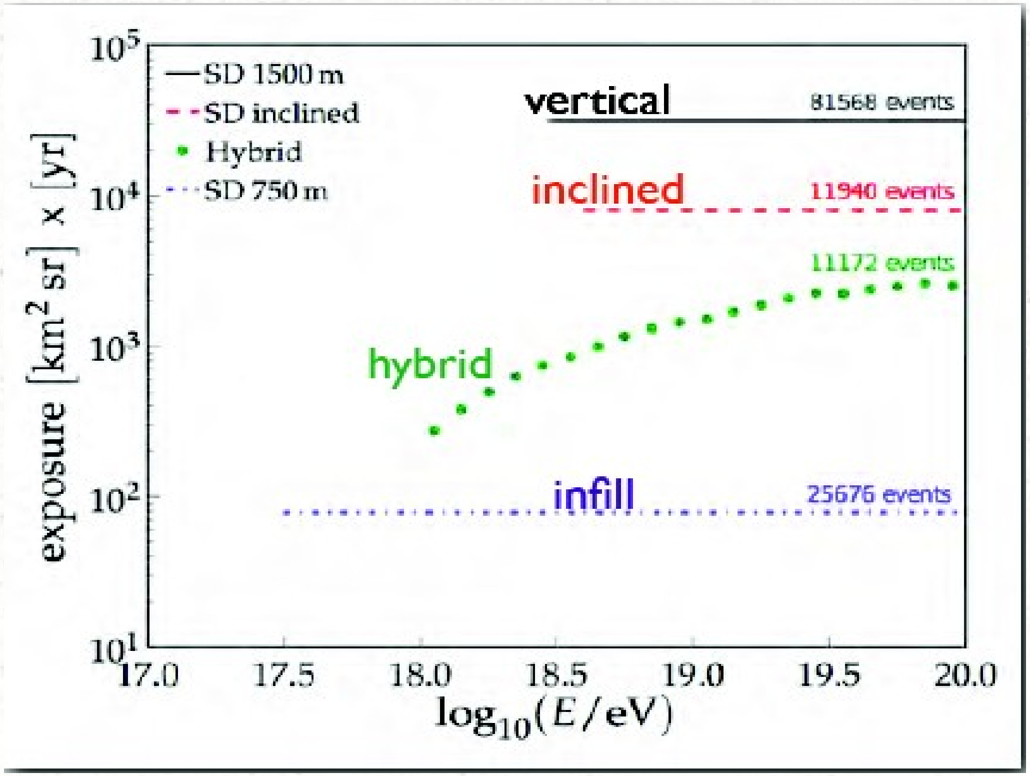
Overview of selected results
(after 6 years of operation)



and also Neutrinos & Photons

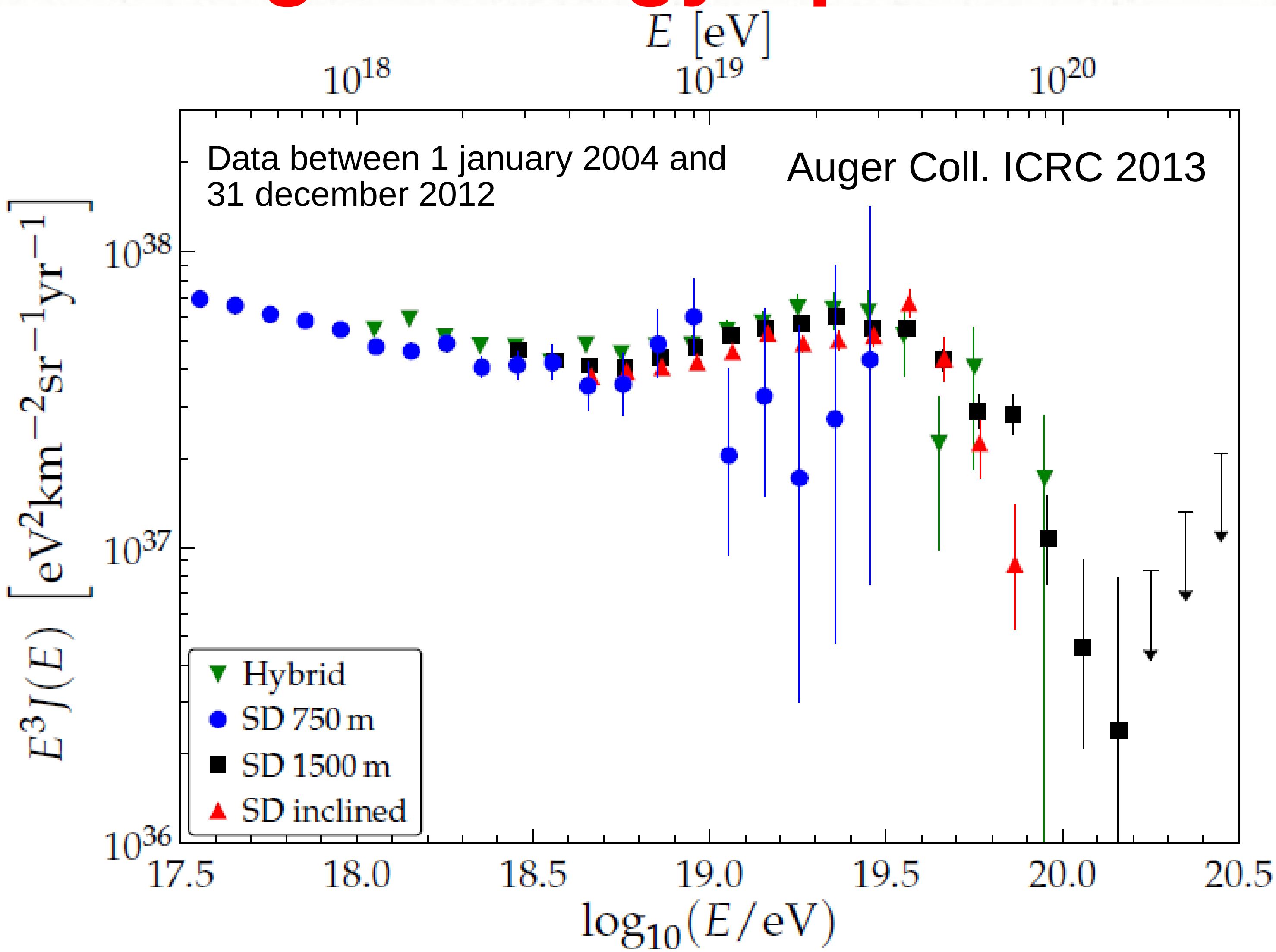
Energy spectrum

Exposure (km² sr yr)

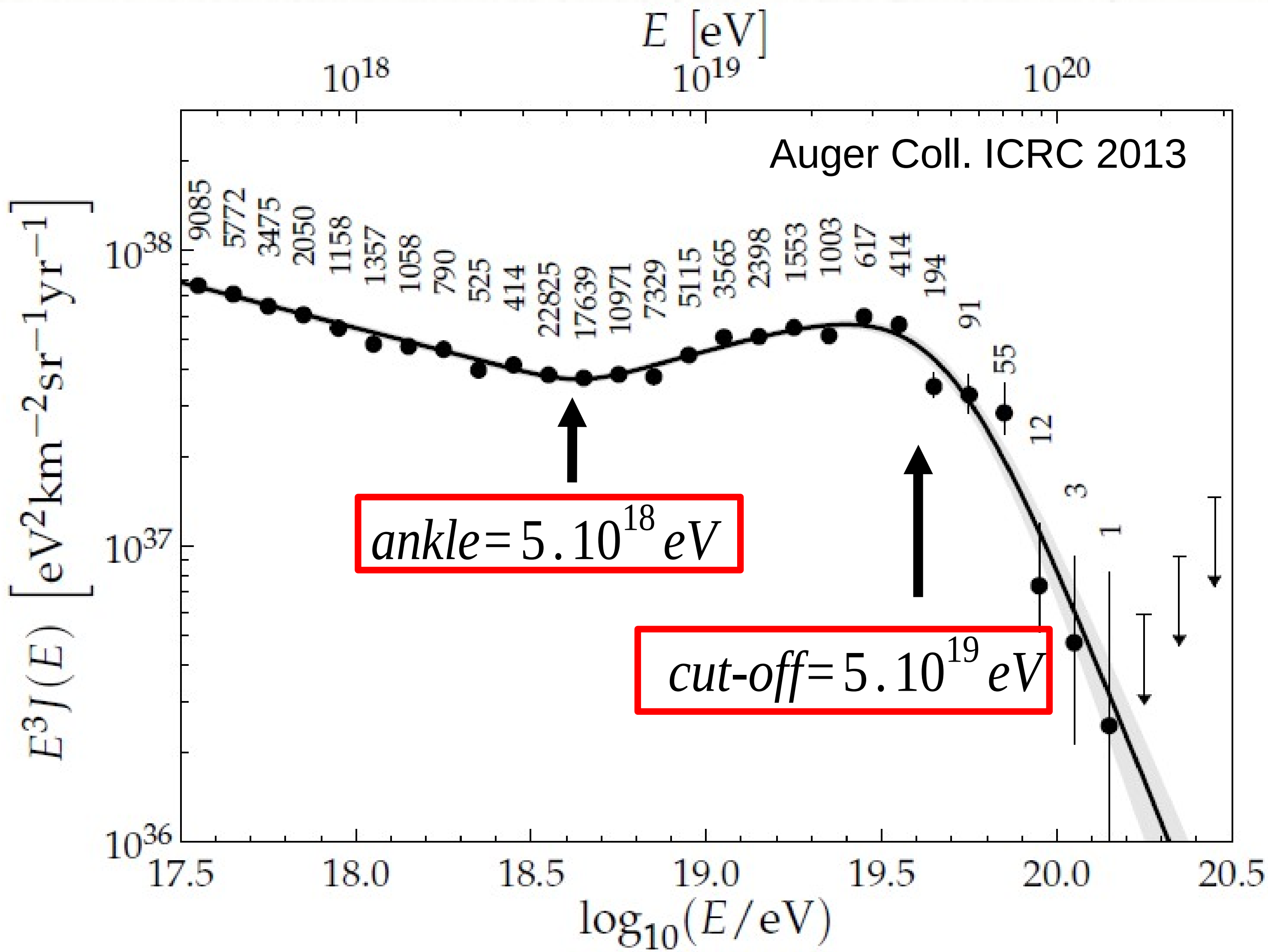


Auger Coll. ICRC 2013

Auger energy spectrum

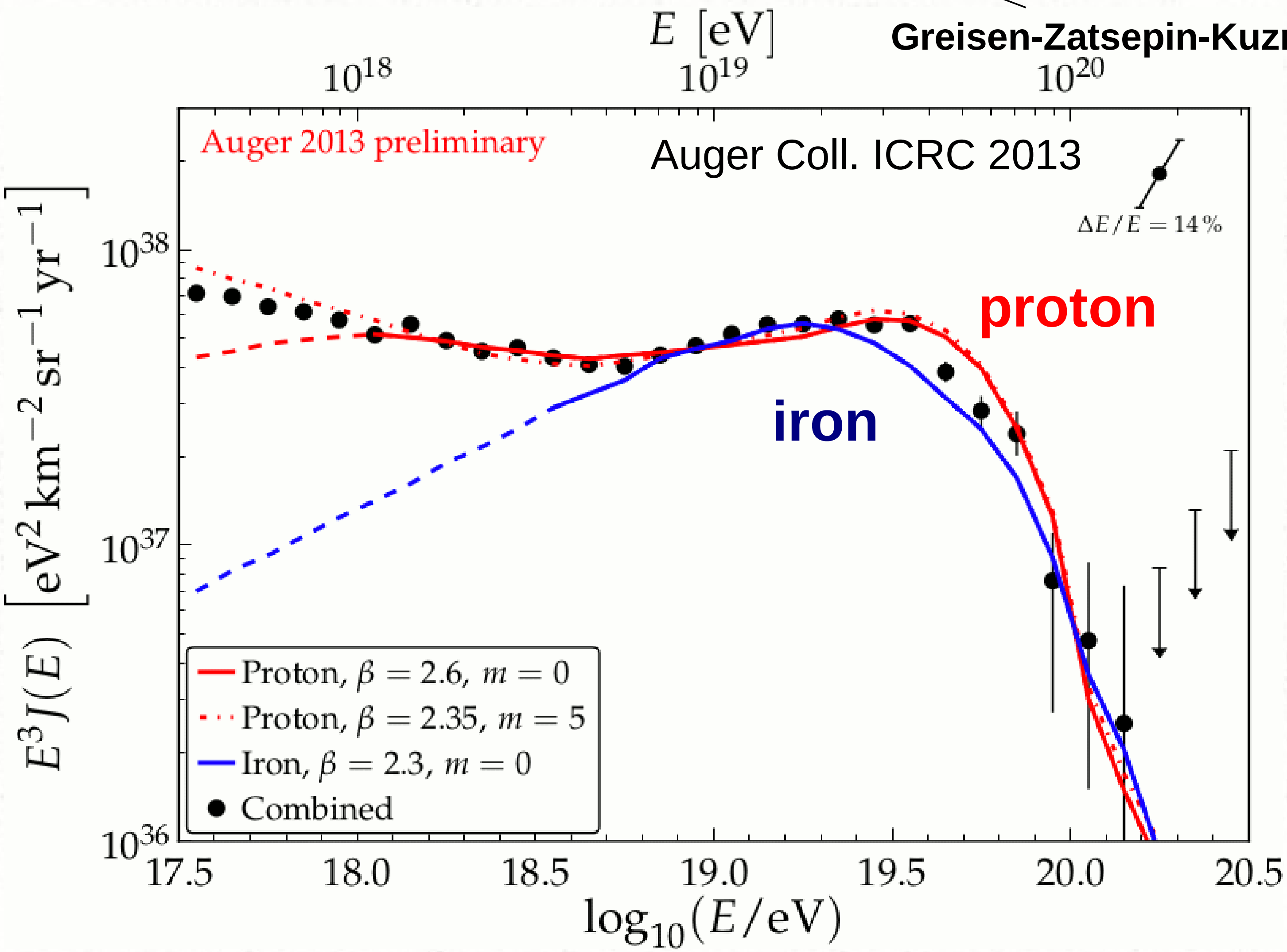


Combined spectrum



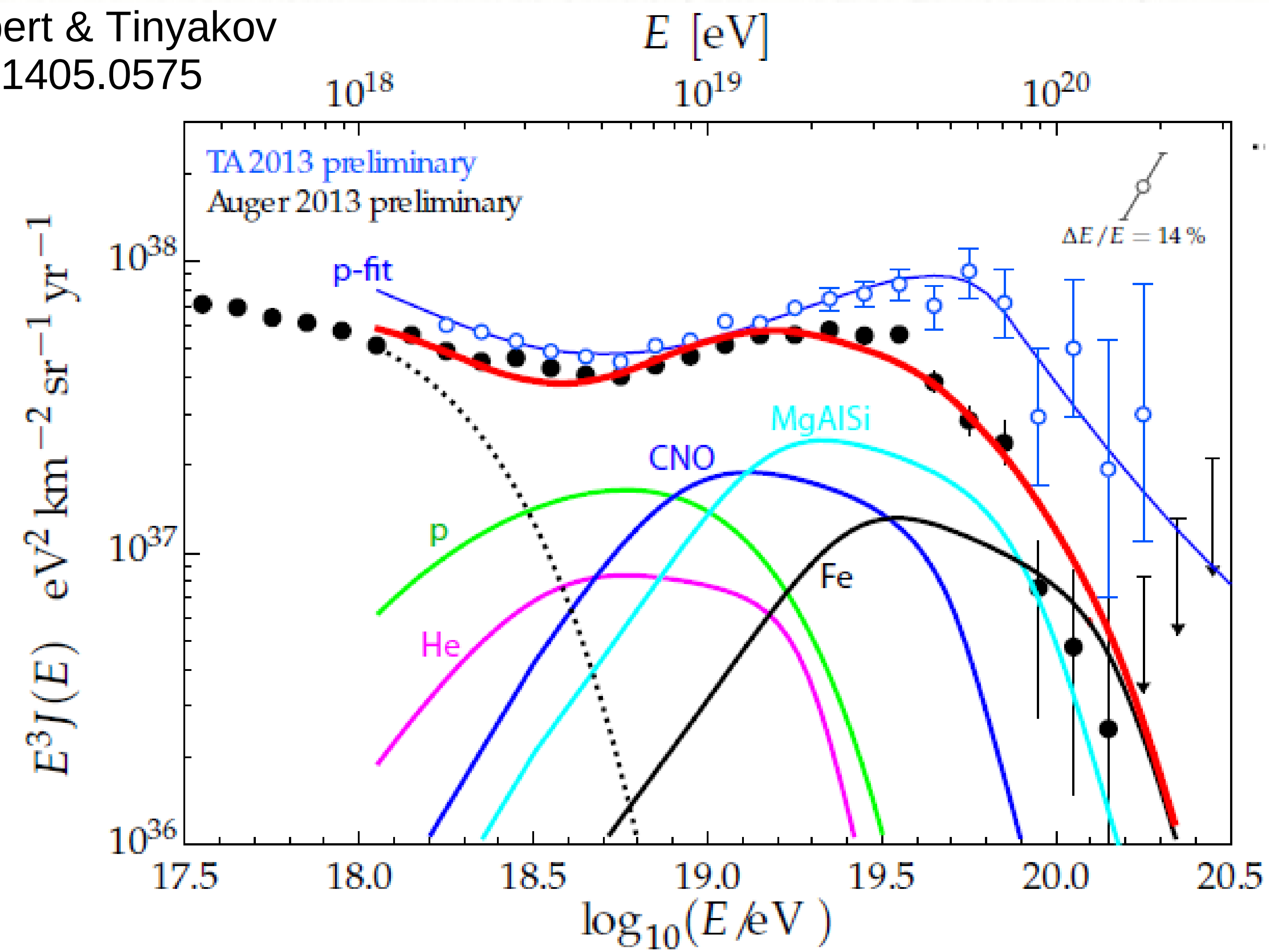
Is the cut-off due to GZK effect ?

Greisen-Zatsepin-Kuzmin (1966)



… or it is due to acceleration limits

Kampert & Tinyakov
arXiv:1405.0575

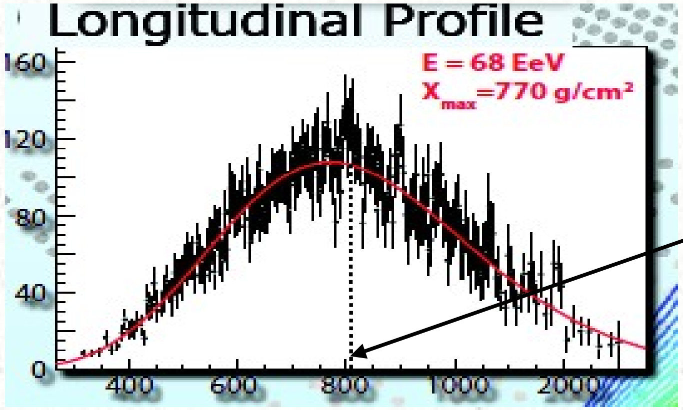


Mass composition

Traditional Method

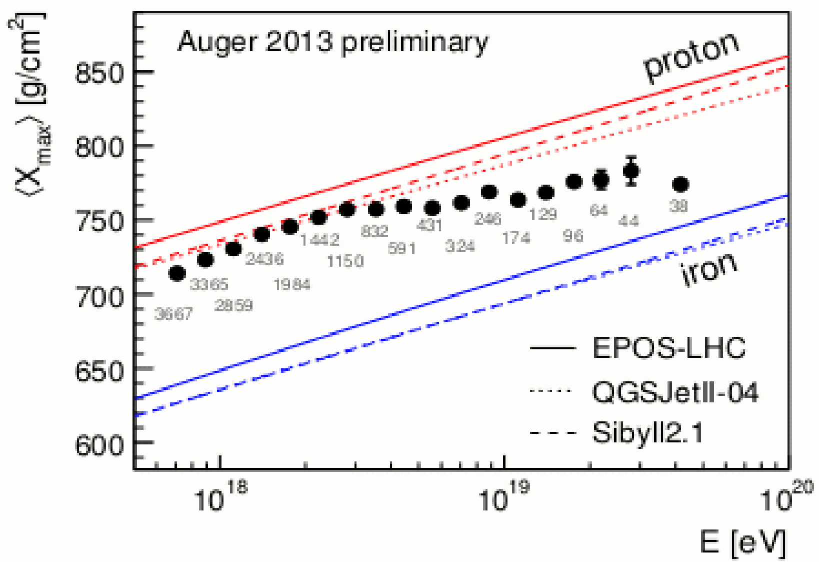
with the Fluorescence Detector

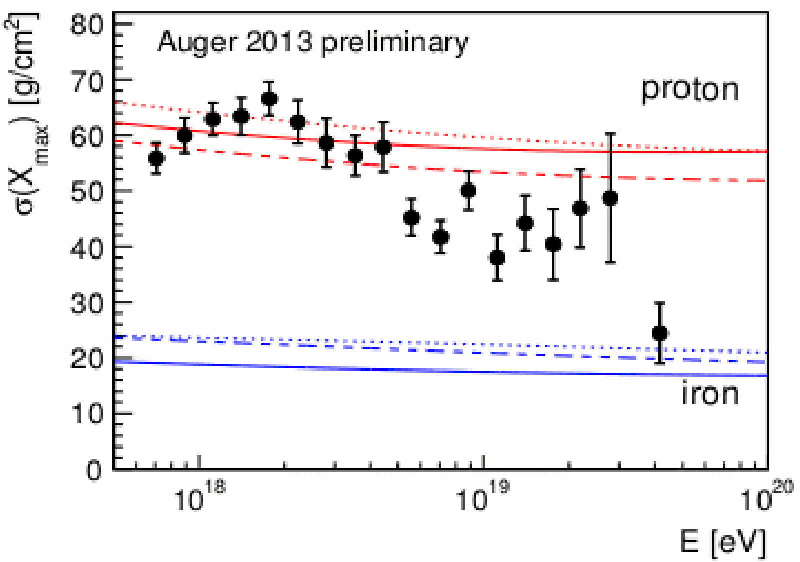
Depth of Shower Maximum (Xmax)



Xmax

<Xmax>   Auger Coll. ICRC 2013   RMS(Xmax)



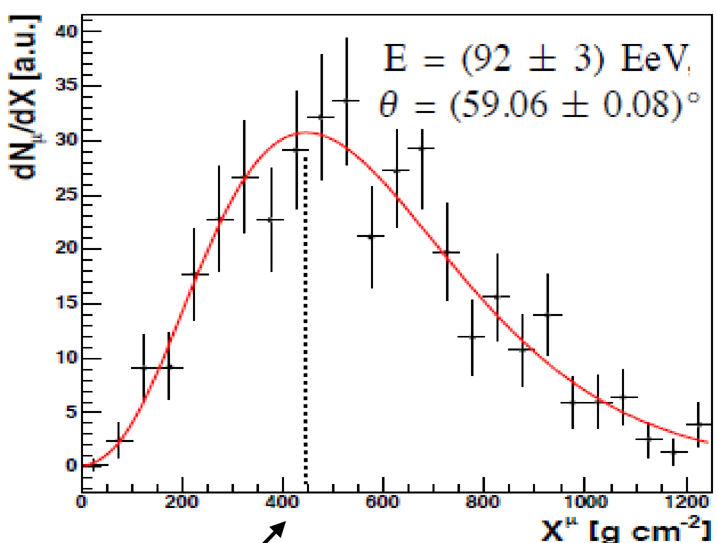


New Method

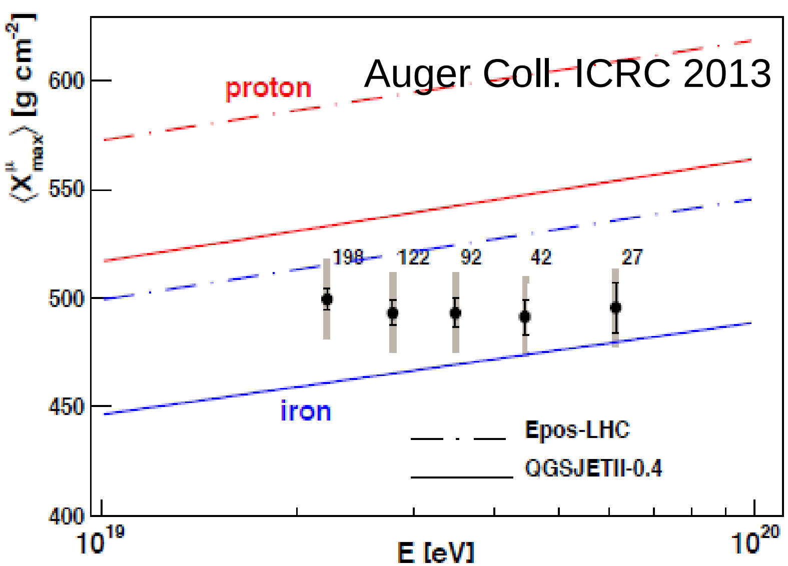
with the Surface Detector

Determining the muon production depth
from timing of FADC traces in SD stations

Longitudinal development of the muonic component



$<X^\mu_{max}>$

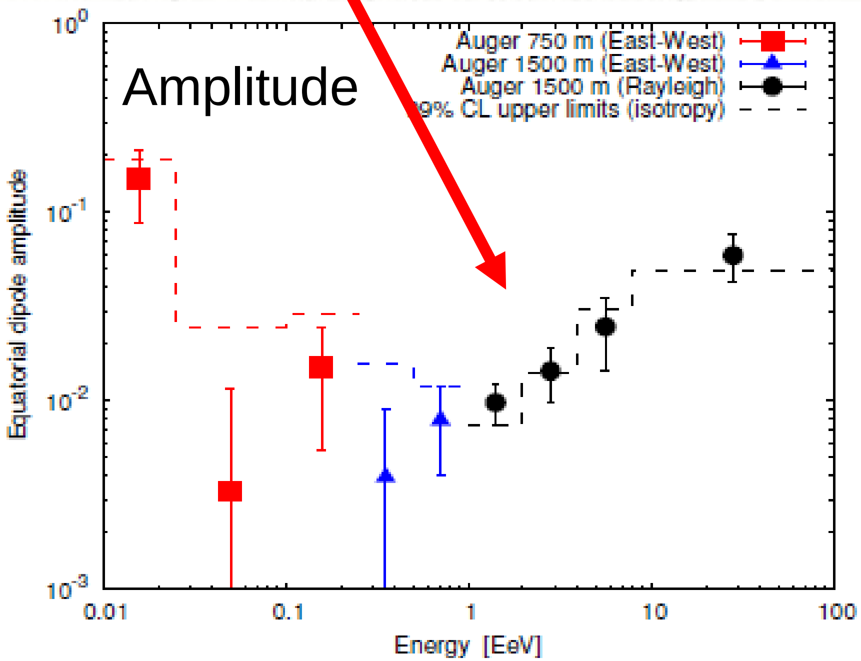


X^μ_{max}: depth where the number of muons reaches maximum

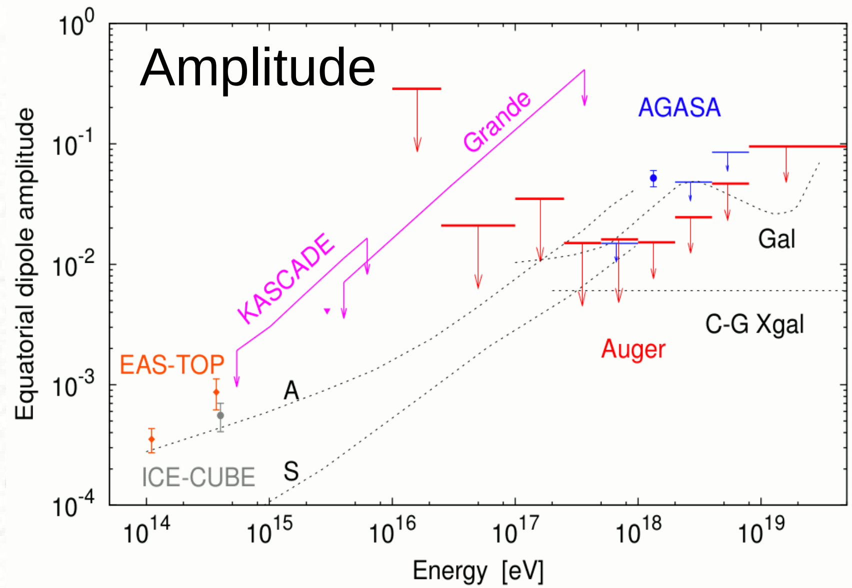
Anisotropies

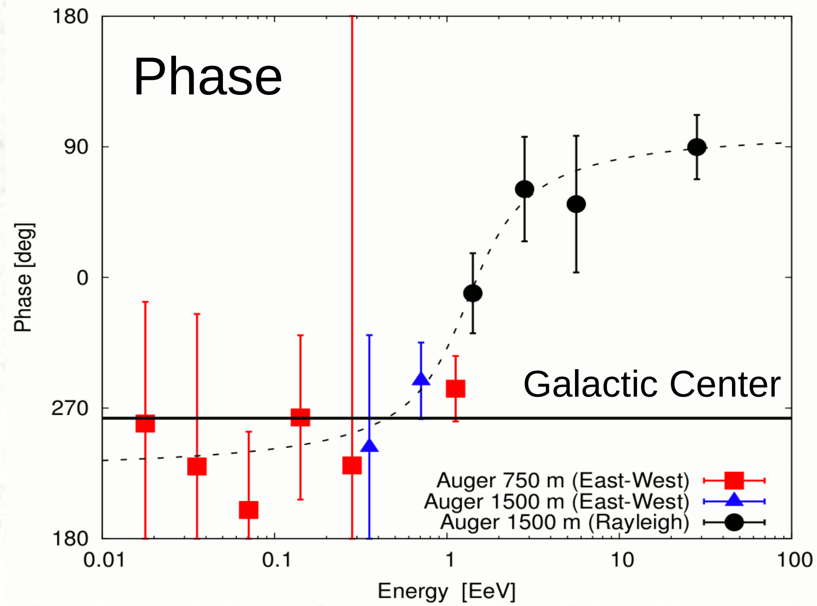
Dipolar anisotropies

For **E > 1 EeV** chance probability of isotropy < 1%

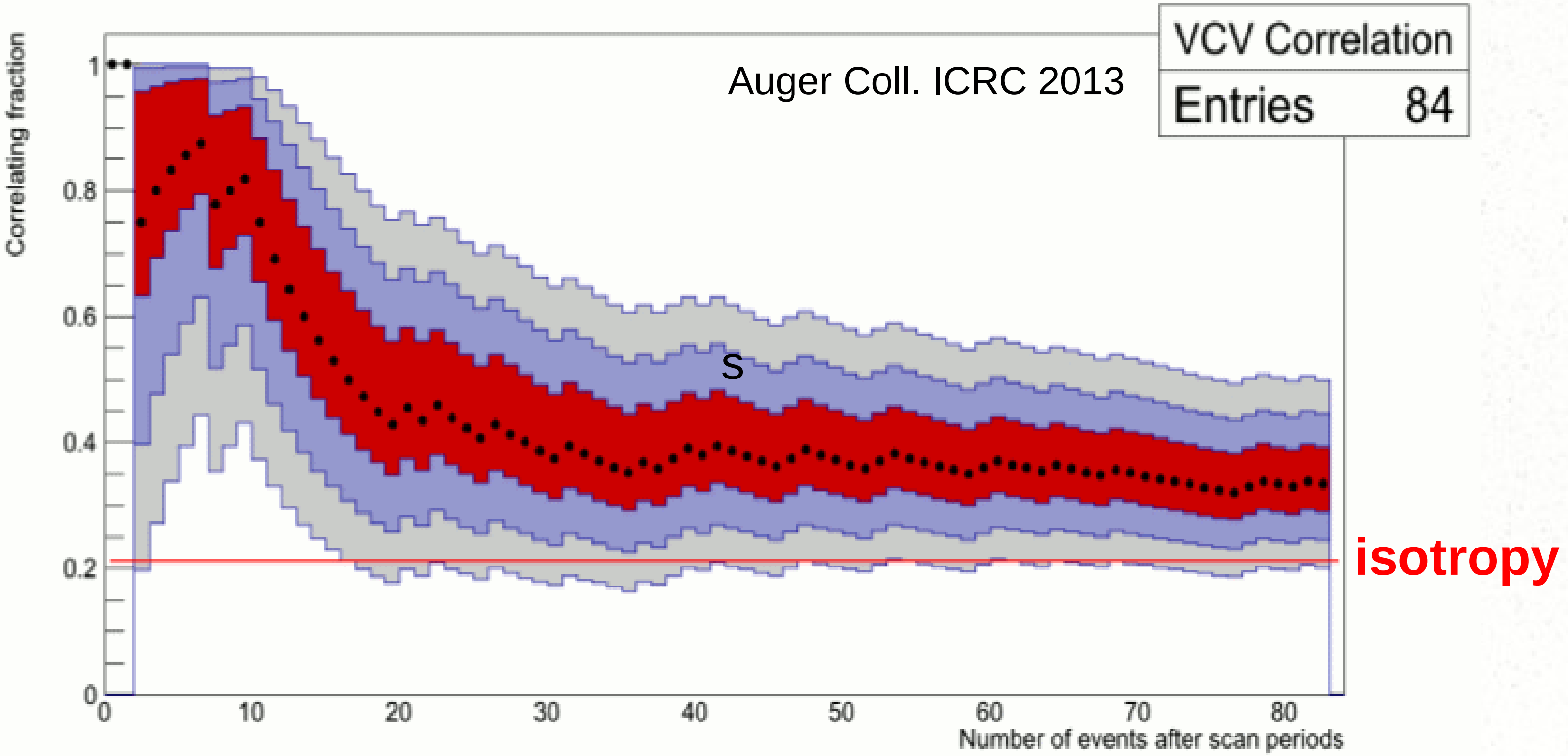


Auger Coll. ICRC 2013





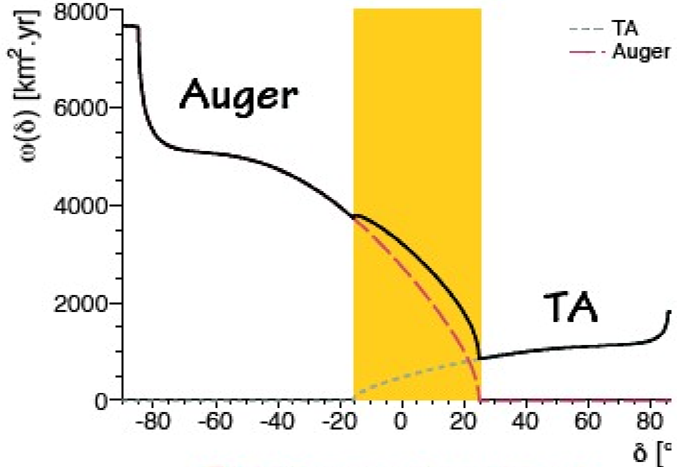
VCV Correlation



Full-sky large scale anisotropy at E>10 EeV

First Combined Auger and TA Analysis

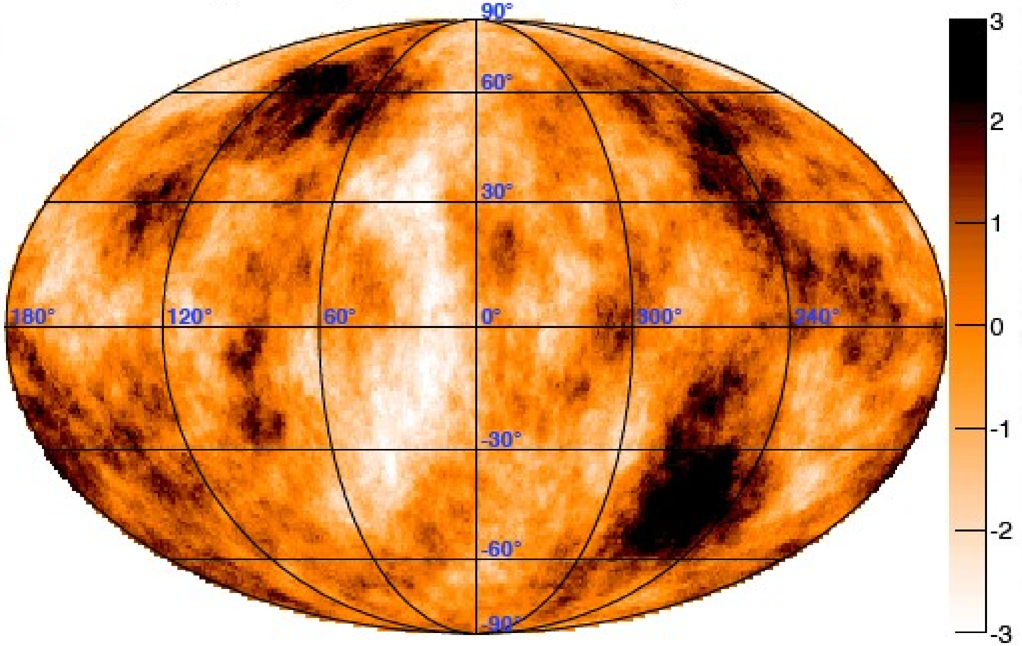
Journal paper ready for submission



Overlap region used to match E-scale

$E > 10^{19}$ eV ; 15° smoothing galact. coord.

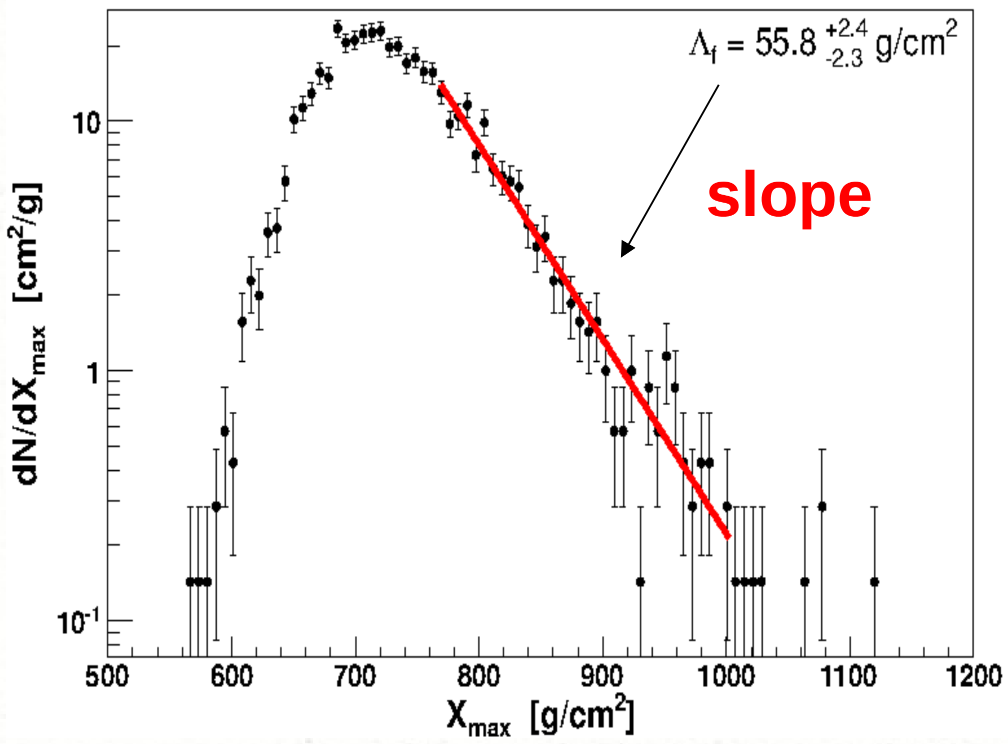
using multiploar expansion up to ℓ=4

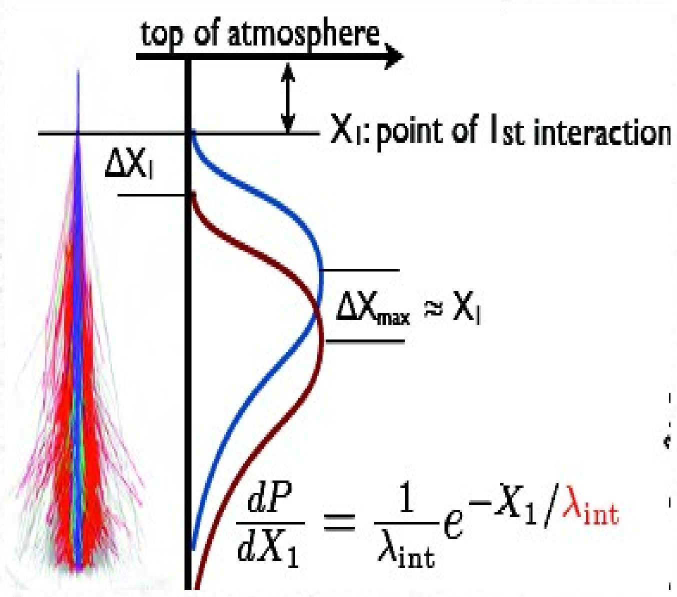


Hadronic interactions

Extraction of the p-Air Cross-Section

Xmax distribution **(10^{18} eV < E < $10^{18.5}$ eV)**

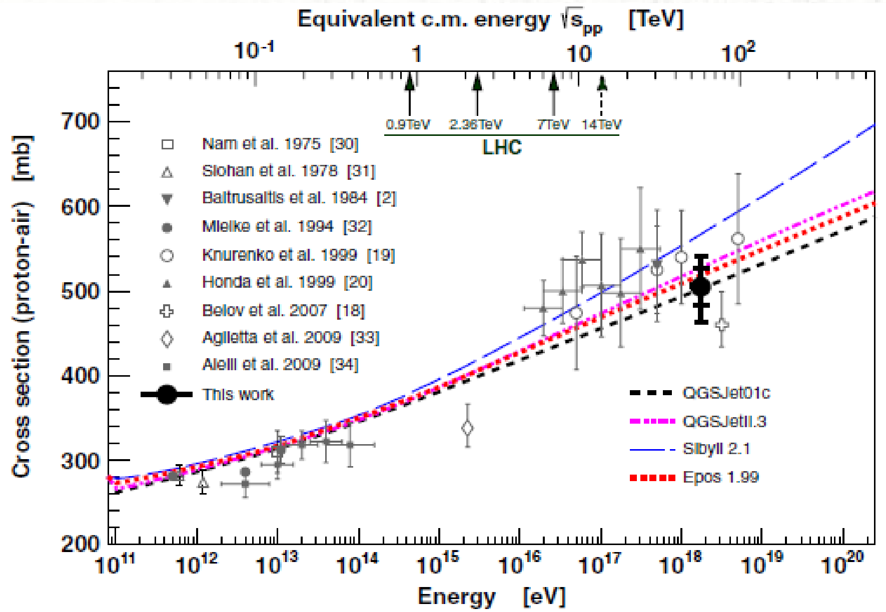


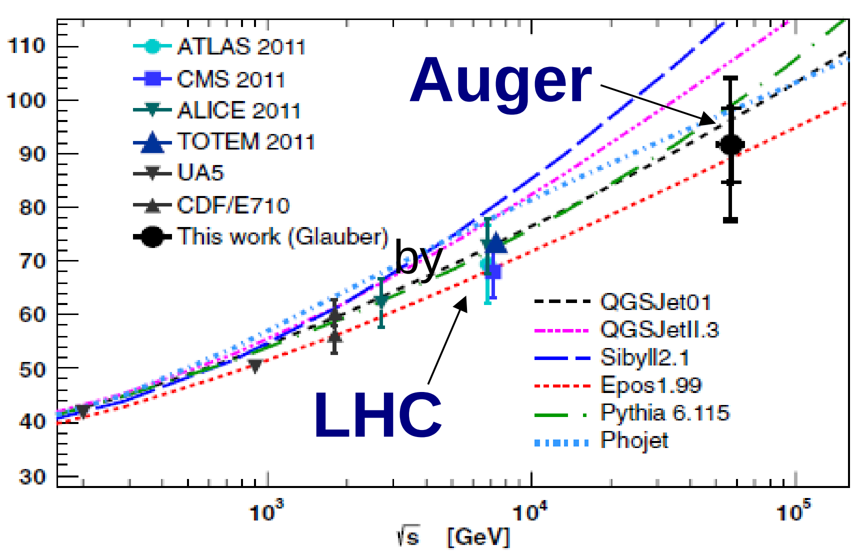


p-Air & pp Cross-Section at 57 TeV

by Glauber approach

p-Air → **pp**



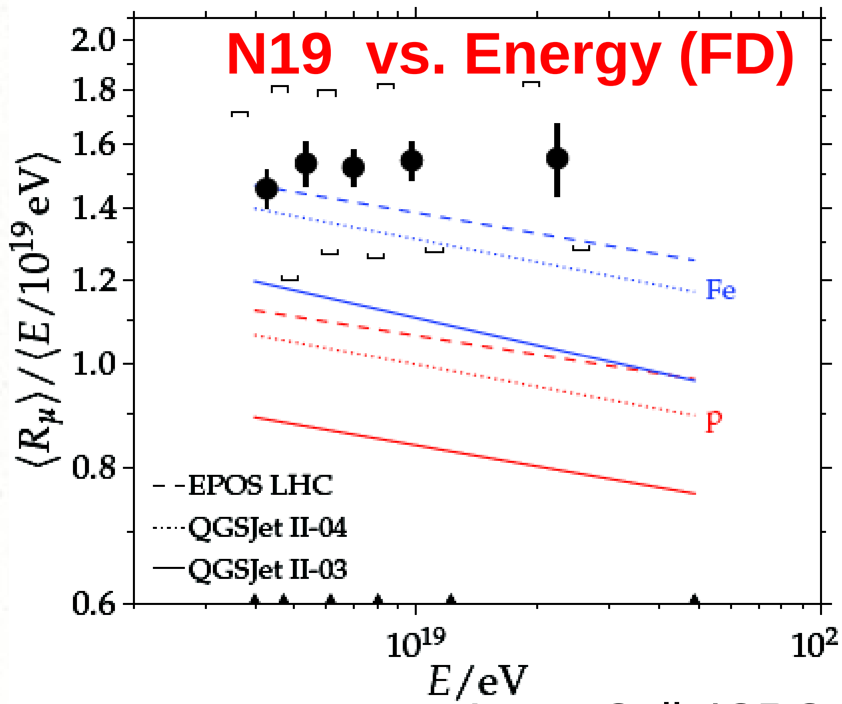


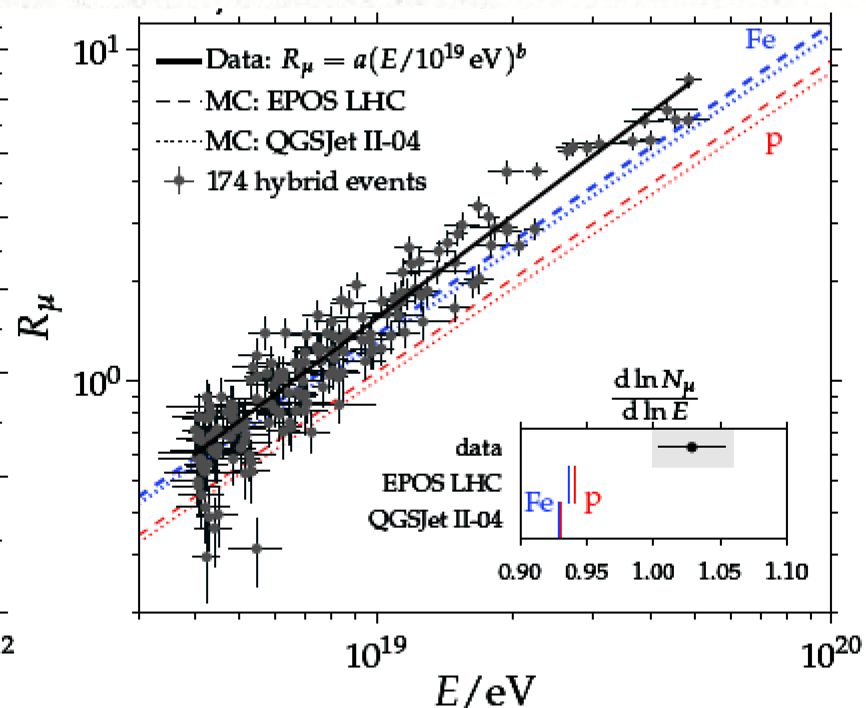
Auger Coll. PRL 109 (2012)

Muon Content
(from inclined events 62-80 deg)

N19 parameter provides a **direct measurement of the number of muons** relative to a reference muon distribution

Up to 55 % muon deficit in interaction models

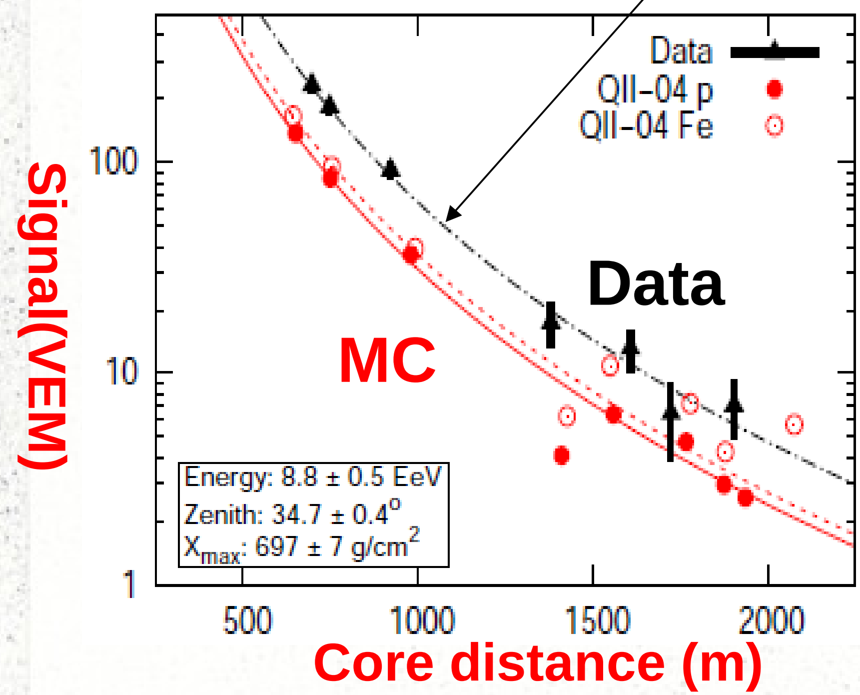




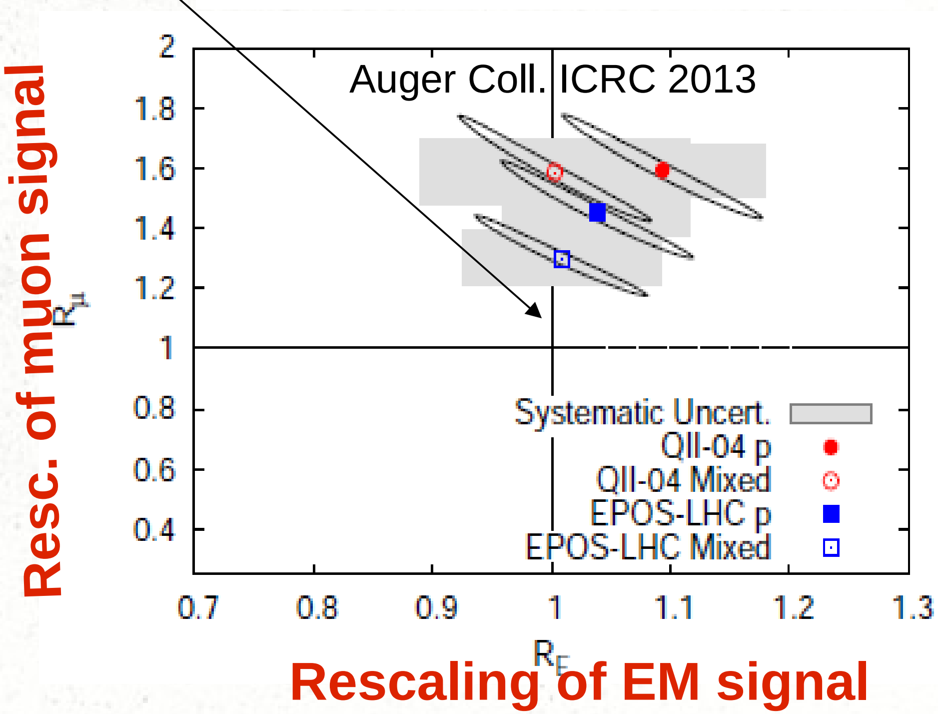
Auger Coll. ICRC 2013 & new article submitted.

Muon Content
(from vertical events 0-60 deg)

30–60 % muon deficit in interaction models



$$S_{\rm resc}(R_E,R_\mu)_{i,j} \equiv R_E\,S_{{\rm EM},i,j} + R_E^\alpha\,R_\mu\,S_{\mu,i,j}$$

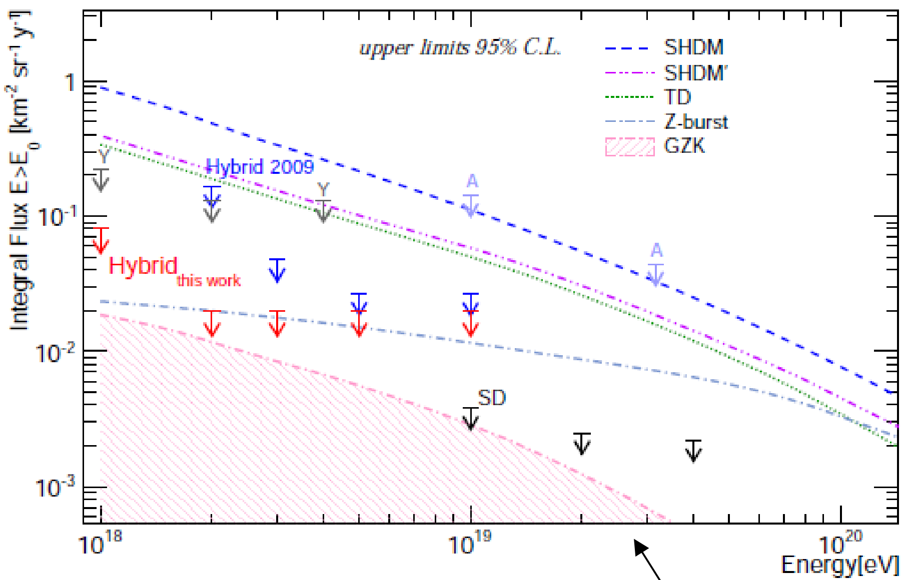


Photons

Upper limits on photons

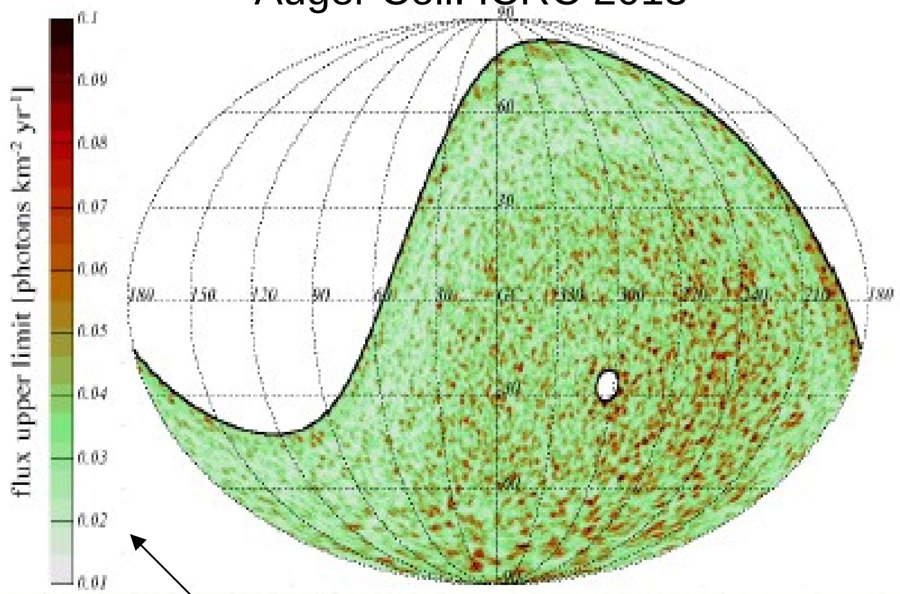
Diffuse flux

Auger Coll. ICRC 2011



Directional search

Auger Coll. ICRC 2013



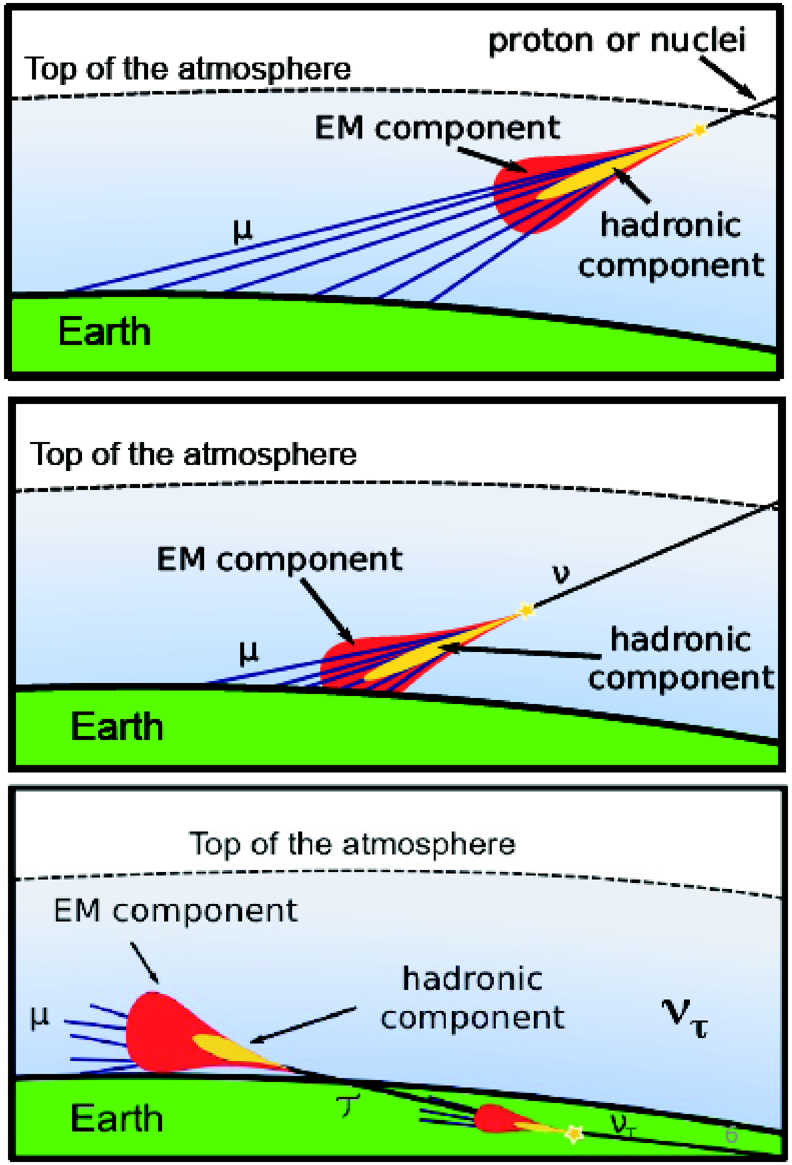
Photons km^{-2} yr^{-1}

Severe constraints of top-down models

Neutrinos

Inclined showers & UHE neutrinos

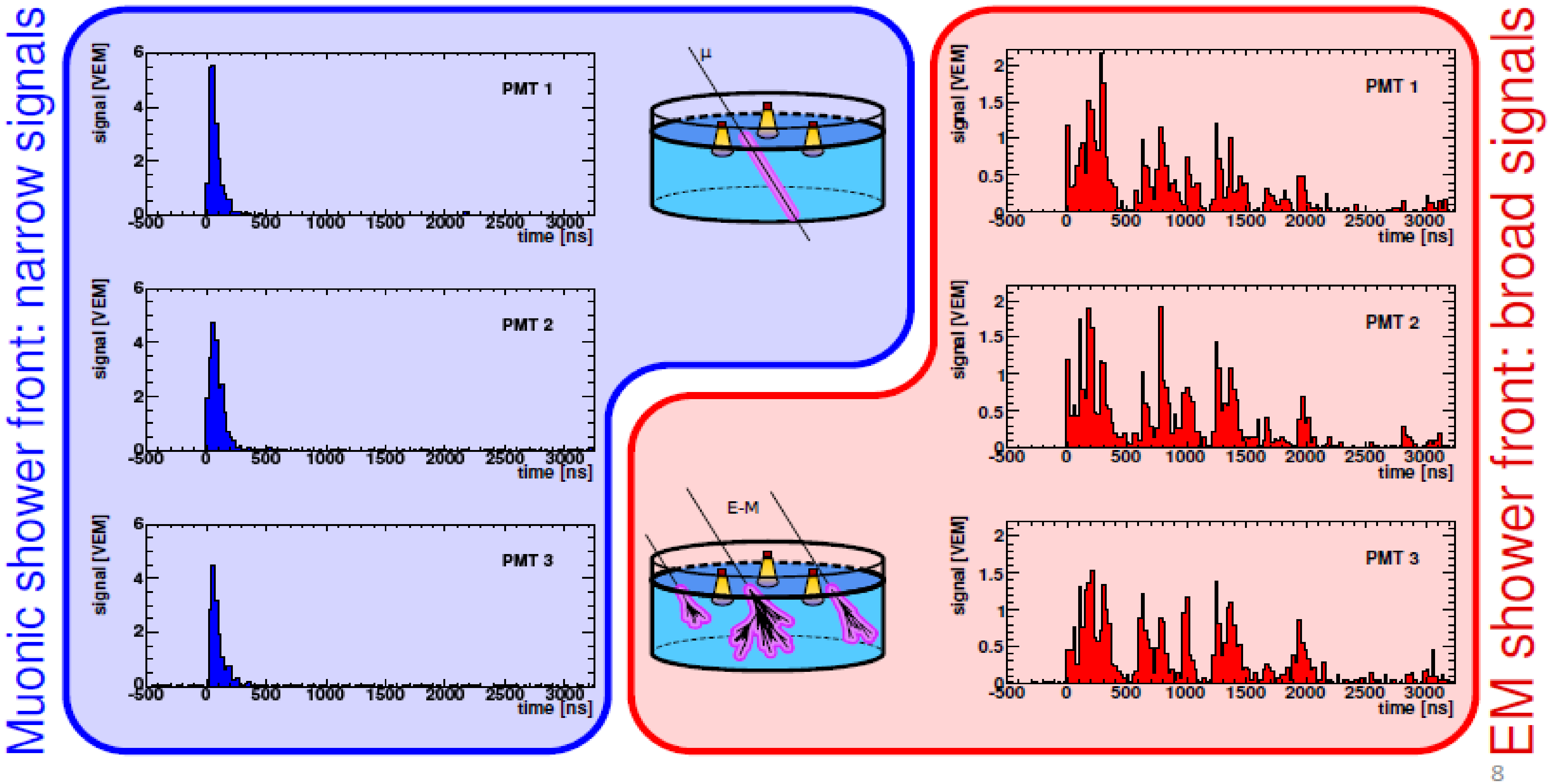
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



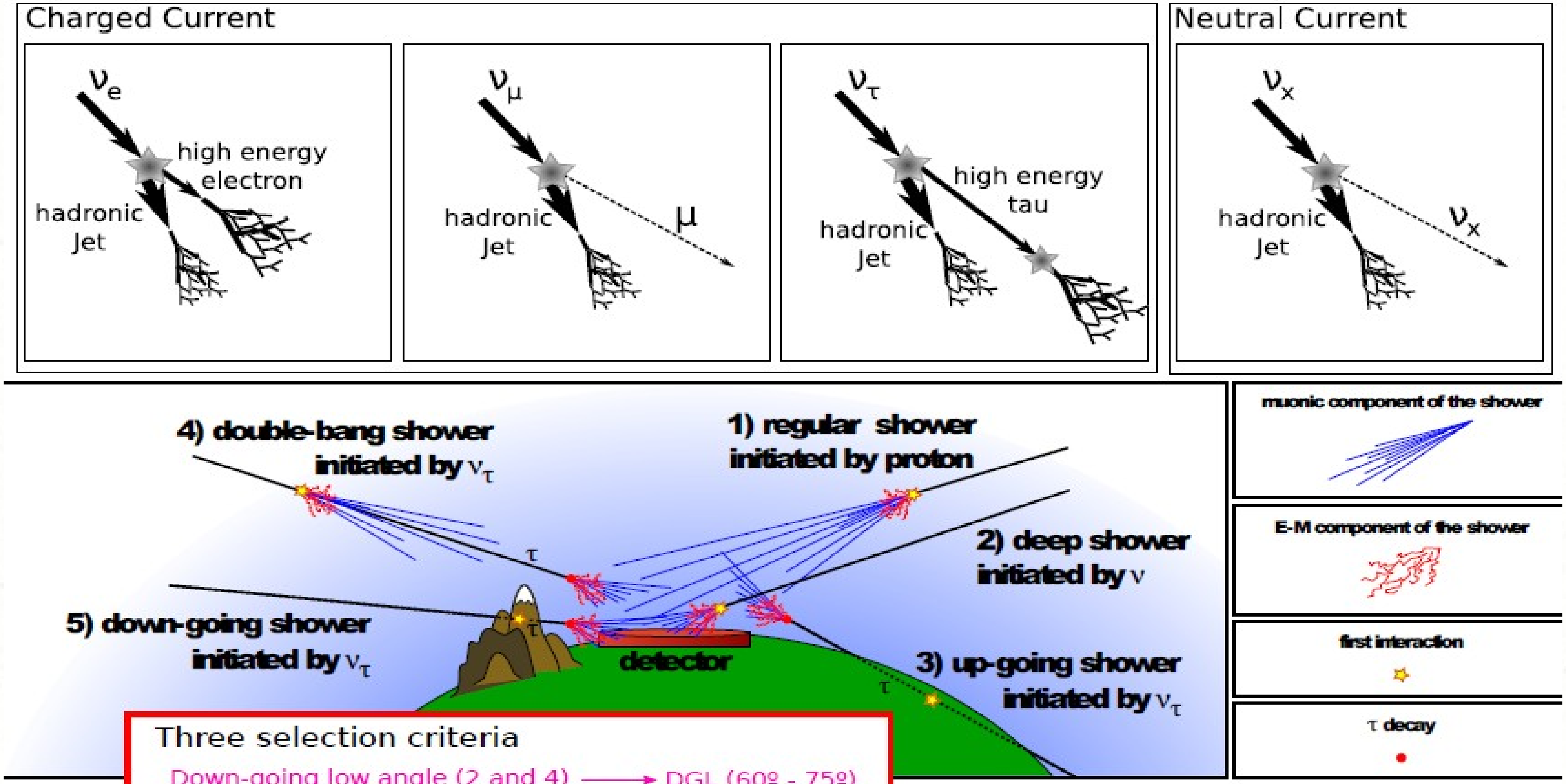
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

Identifying νs in data collected at SD

With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signals in the water Cherenkov stations).



Sensitivity to all flavours & channels

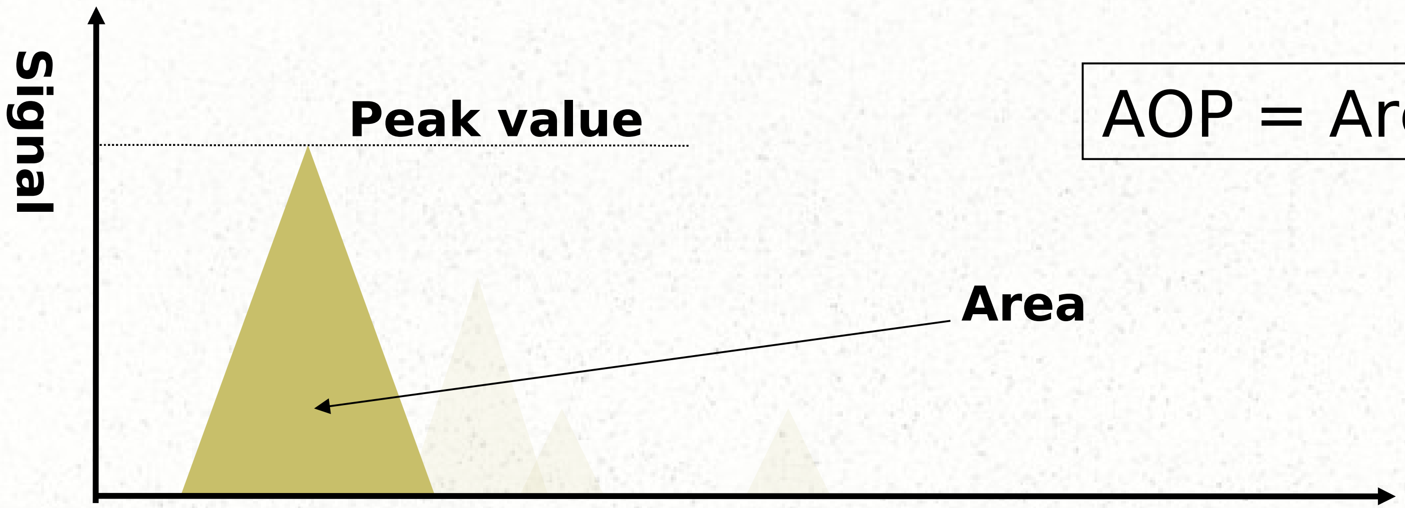


Three selection criteria

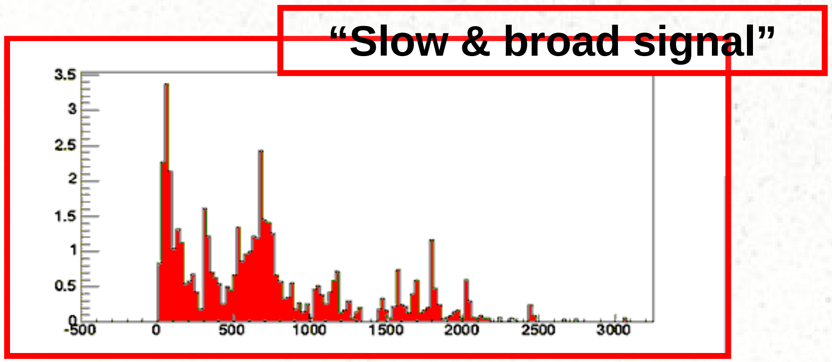
Down-going low angle (2 and 4) → DGL (60º - 75º)
Down-going high angle (2, 4 and 5) → DGH (75º - 90º)
Earth-skimming (3) → ES (90º - 95º)

Looking for broad signals: Area Over Peak (AOP)

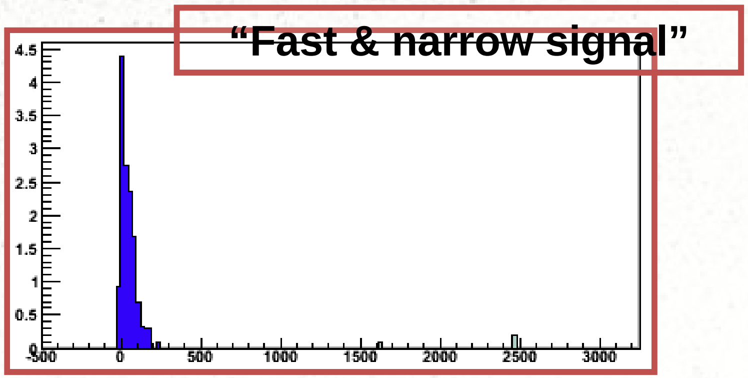
FADC trace



AOP = Area/Peak

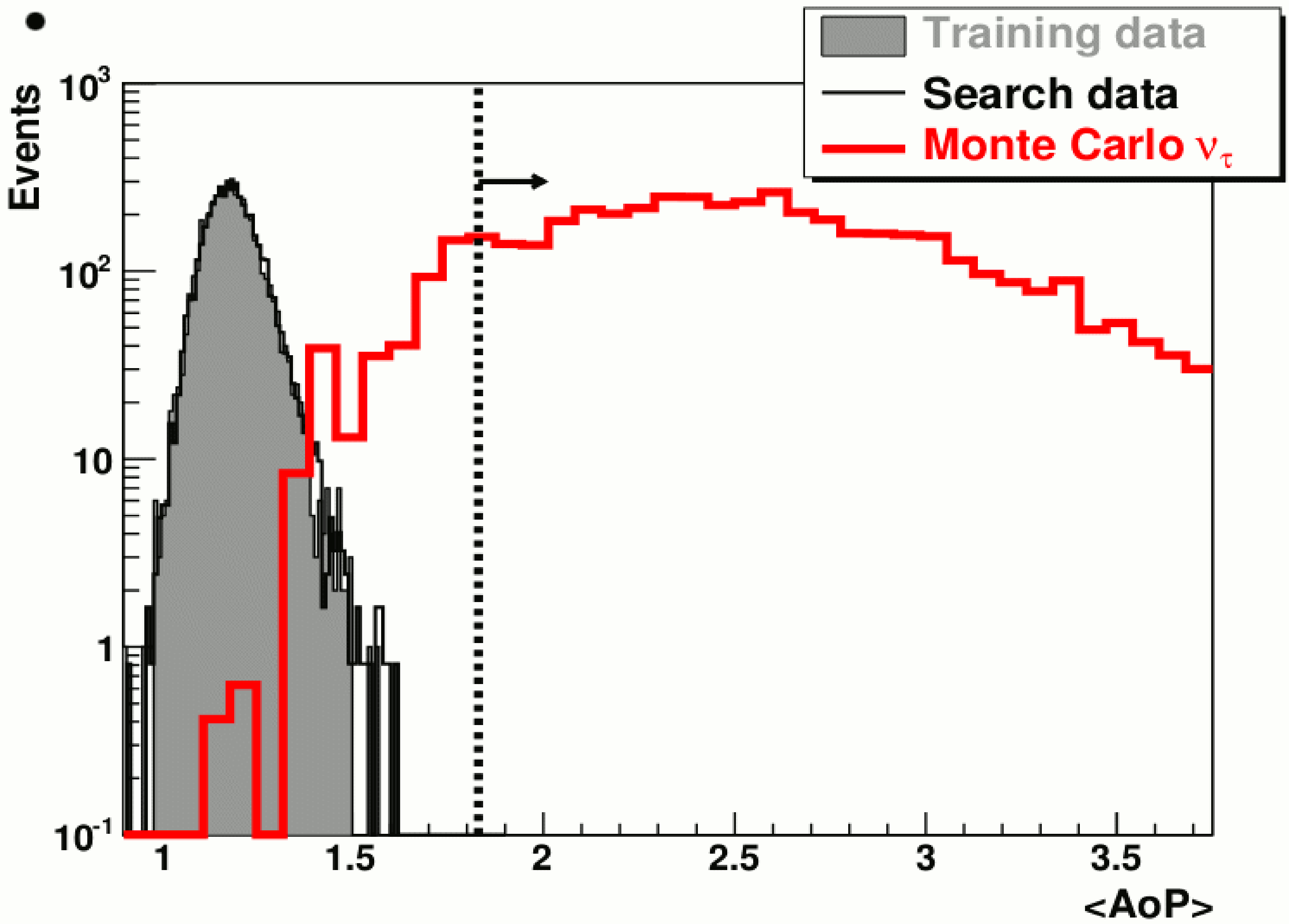


Large AOP (> 3)



Small AOP (~ 1)

•

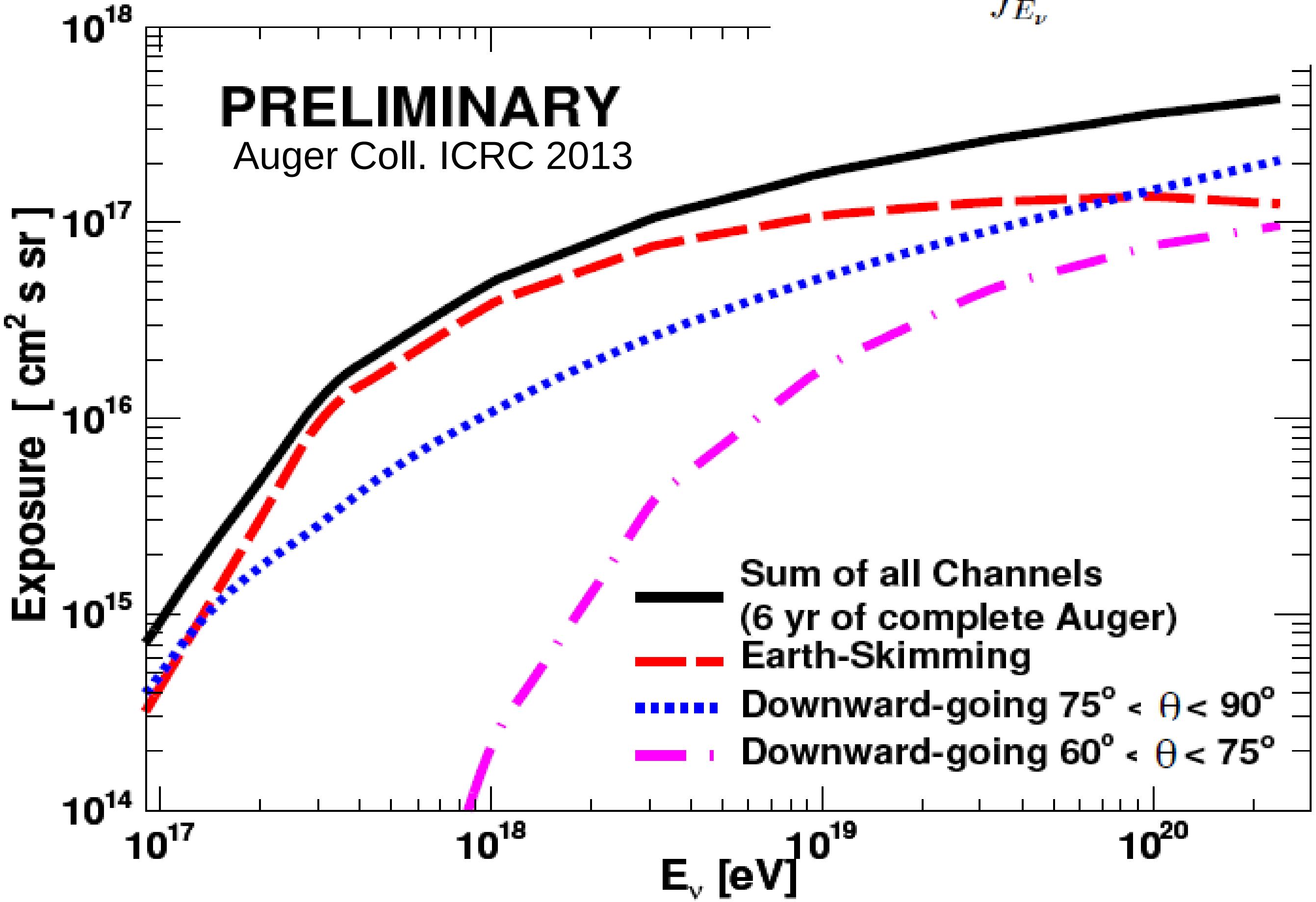


Training data
Search data
Monte Carlo ν_τ
Events
10^3
10^2
10
1
10^{-1}
1
1.5
2
2.5
3
3.5
<AoP>

Exposure: 1 Jan 04 – 31 Dec 12

(excluding training data periods)

$$N_{\text{events}} = \int_{E_\nu} \Phi(E_\nu)\, \varepsilon_{\text{tot}}(E_\nu)\, \mathrm{d}E_\nu$$



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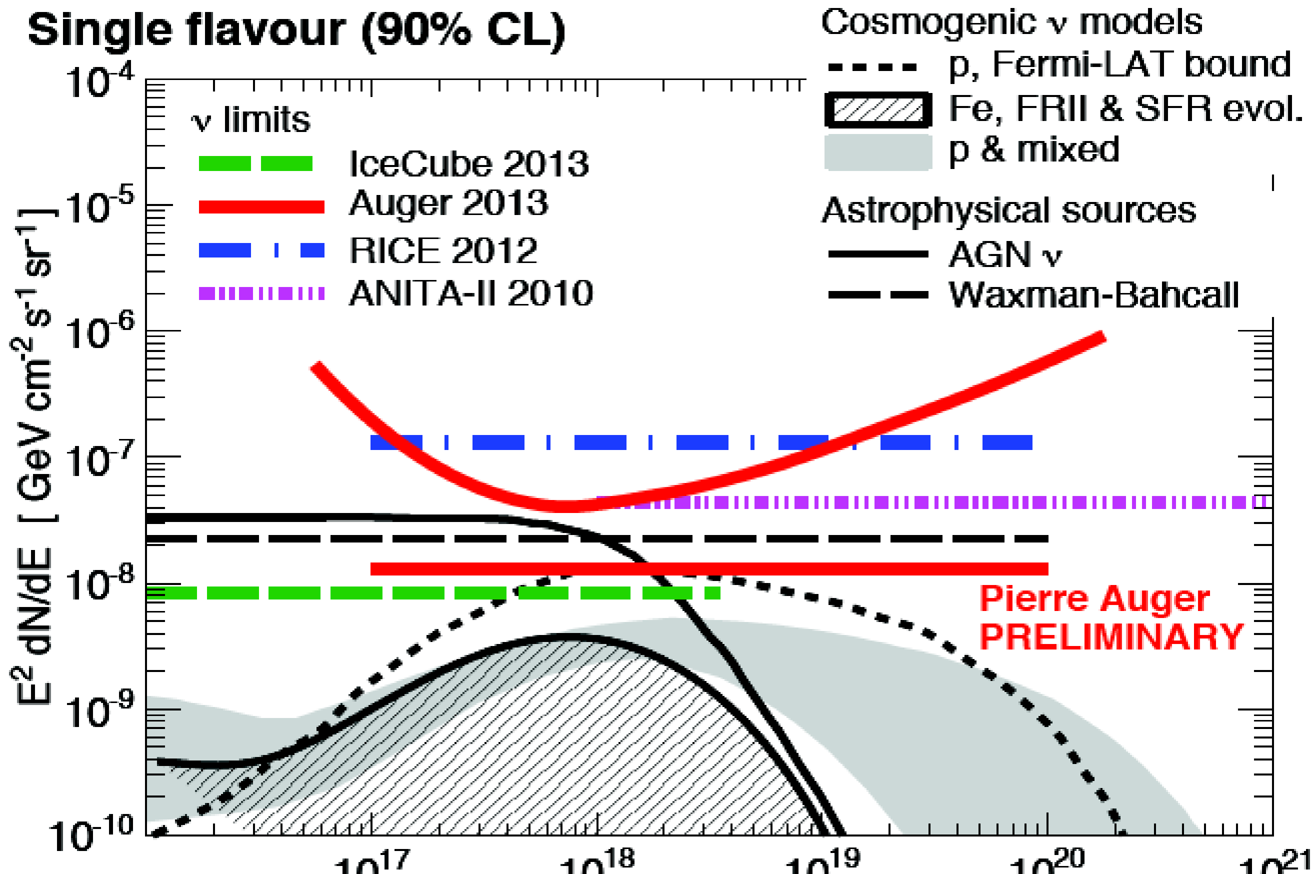
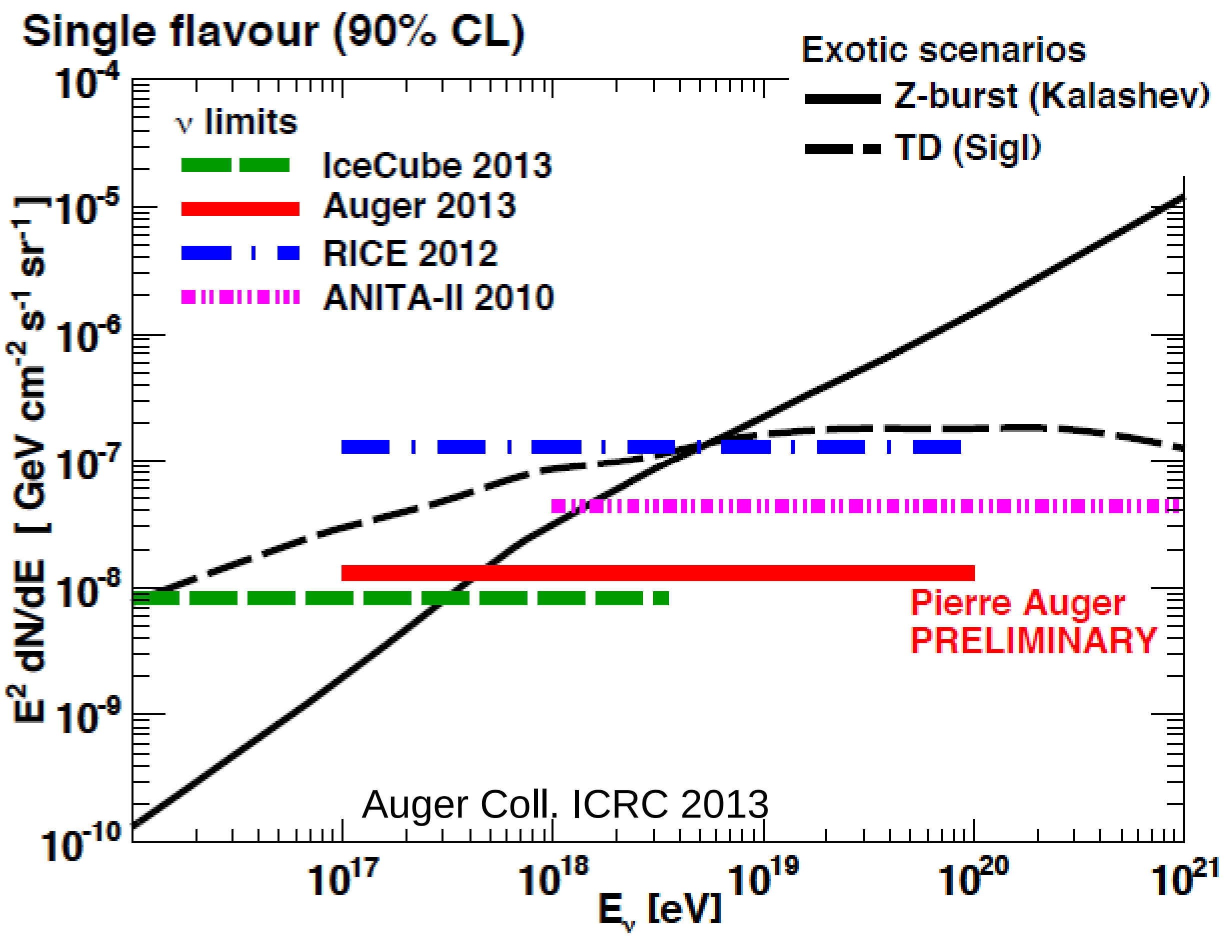
Limits to diffuse flux of UHEν



Auger Coll. ICRC 2013

$dN/dE = k\,E^{-2} \longrightarrow k \sim 1.3 \times 10^{8}$ GeV cm^{-2} s^{-1} sr^{-1} - 90% C.L. - 10^{17} eV < E < 10^{20} eV


Single flavour (90% CL)
Exotic scenarios
Z-burst (Kalashev)
TD (Sigl)
ν limits
IceCube 2013
Auger 2013
RICE 2012
ANITA-II 2010
Pierre Auger
PRELIMINARY
Auger Coll. ICRC 2013
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}

Summary of Main Auger Achivements (6 yr)

Clear **knee** at 5 EeV

Strong flux **suppression** (@10 sigma) above 50 EeV

Hints of **directional correlation** to nearby matter

Change in the shower elongation rate (**composition)**

pp cross-section at 57 TeV

Muon deficit (30-60 %) in models tuned to LHC

Strongest **limits to the photon** fraction at UHE

Strongest **bounds to** diffuse UHE **neutrinos**

Future

We still do not know the **origin of the flux suppression,** neither the **sources** and **nature** of UHE cosmic rays. In addition **interaction models** do not describe properly the muon content of the showers observed by Auger.

The **detailed study of composition** will permit to disentangle all these interconnected results

This will be done with the **Upgrade of the Surface Detector** (2015-16). The separation of the EM and muonic component of the showers will provide **10 times more statistics** for composition studies than the FD.

Also we should wait for more data (x3 in 10 yr)


Thank you!
G. Parente 2014