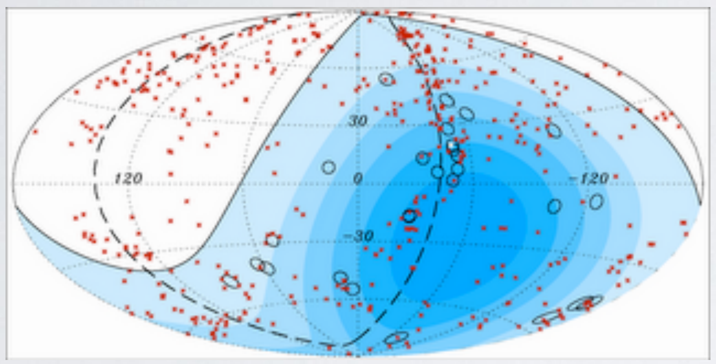
PRESENT AND FUTURE DIRECTIONS IN THE OBSERVATION OF ULTRA-HIGH ENERGY COSMIC RAYS WITH THE PIERRE AUGER OBSERVATORY

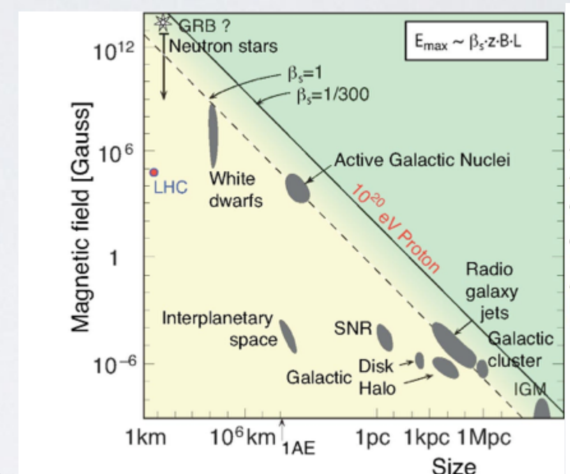
Antonio Bueno on behalf of the Pierre Auger Collaboration
(University of Granada)

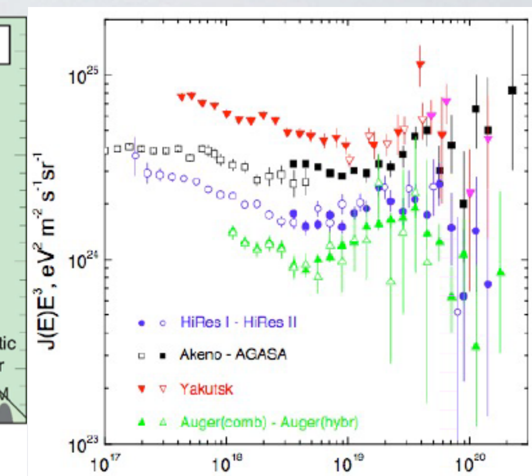
MOST ENERGETIC PARTICLES EVER OBSERVED

- Production sources



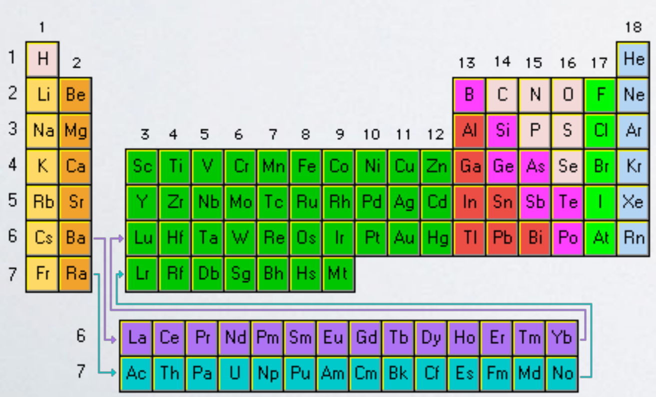
- Acceleration mechanisms



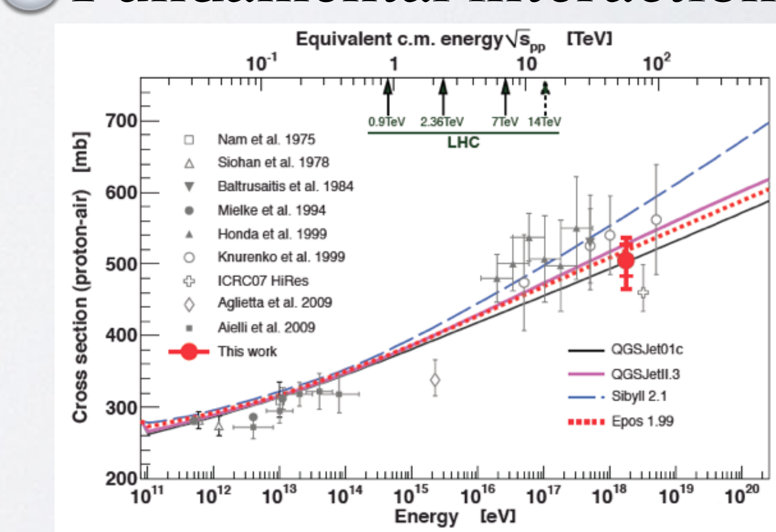


Ultra-High Energy Cosmic Rays:
Unanswered questions

- Mass composition



- Fundamental interactions



DETECTOR REQUISITES FOR AIR SHOWER MEASUREMENTS ABOVE 1 EeV

- Particle flux is extremely small (1 particle per km^2 per century for energies around 10^{20} eV)

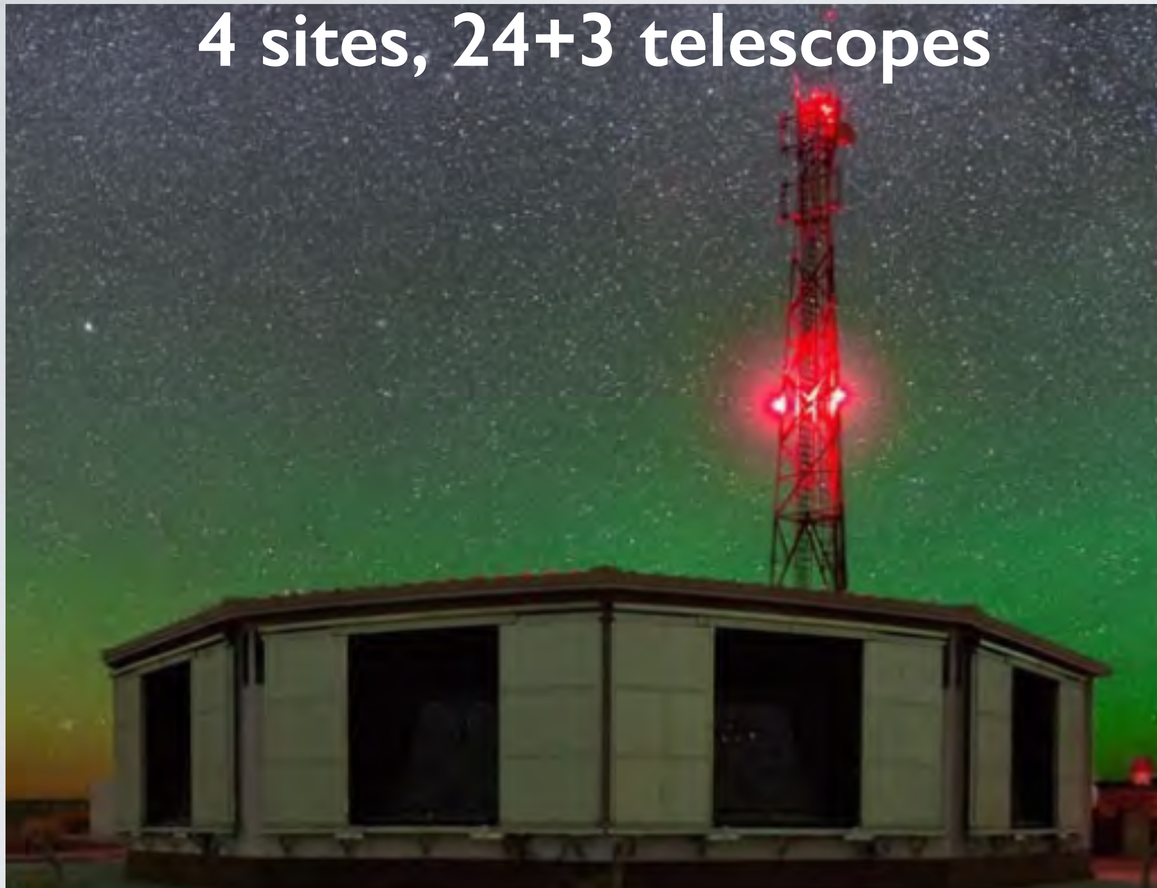
  - **Large areas required!**

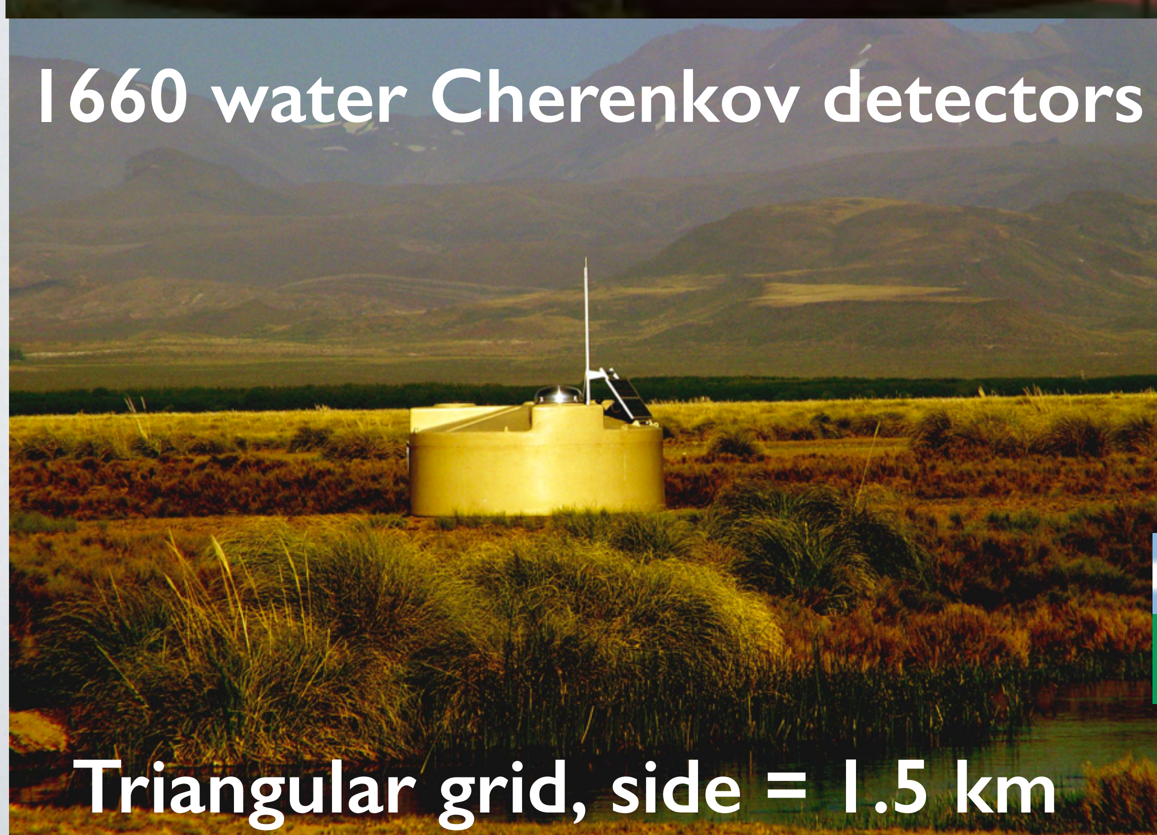
- Hybrid detector required for excellent measurement capabilities

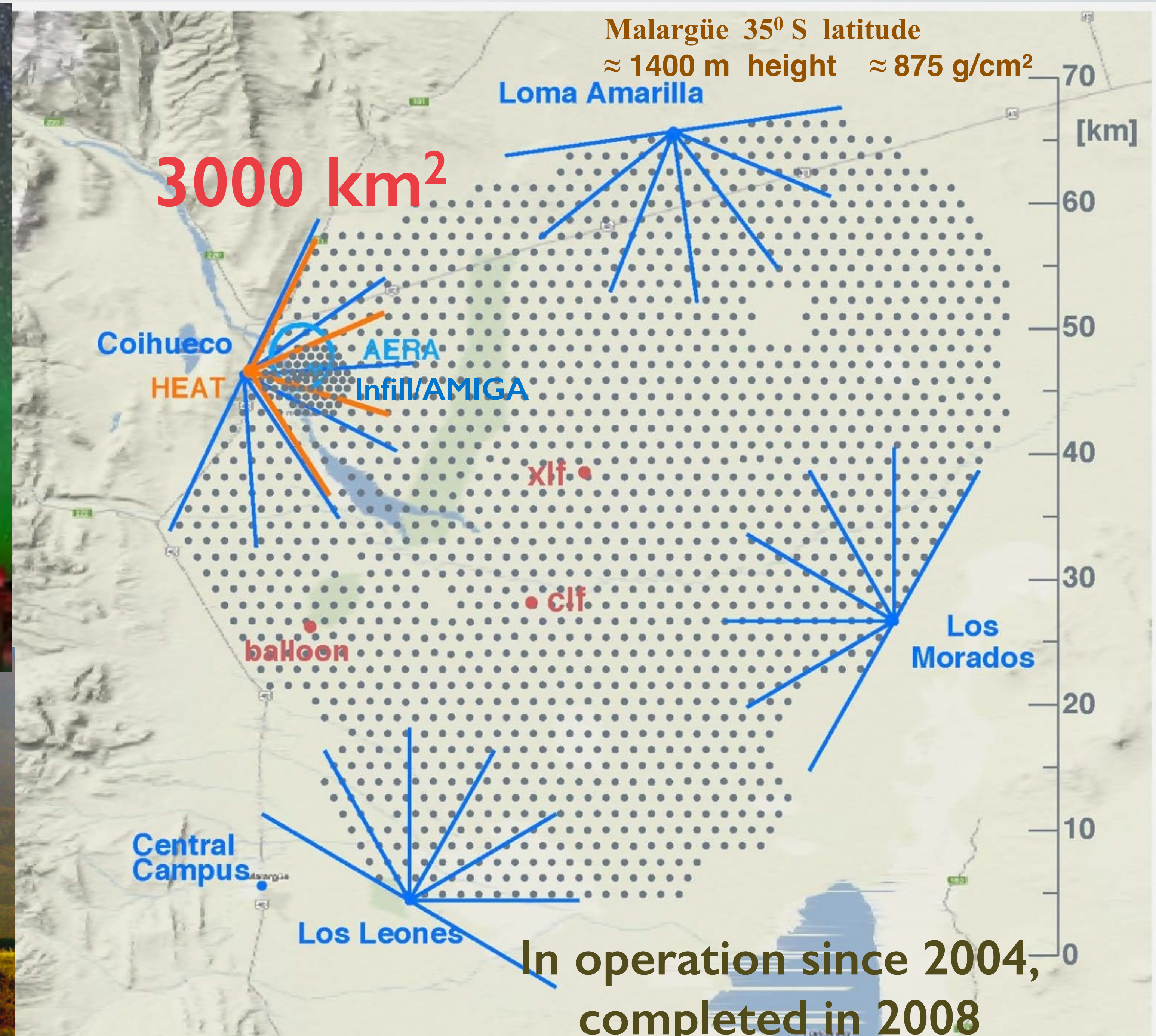
  - **Combination of ground array (particle detectors, 100% duty cycle) & optical devices (atmospheric fluorescence, 13% duty cycle)**

  - **Data-driven calibration of the ground array**

PIERRE AUGER OBSERVATORY

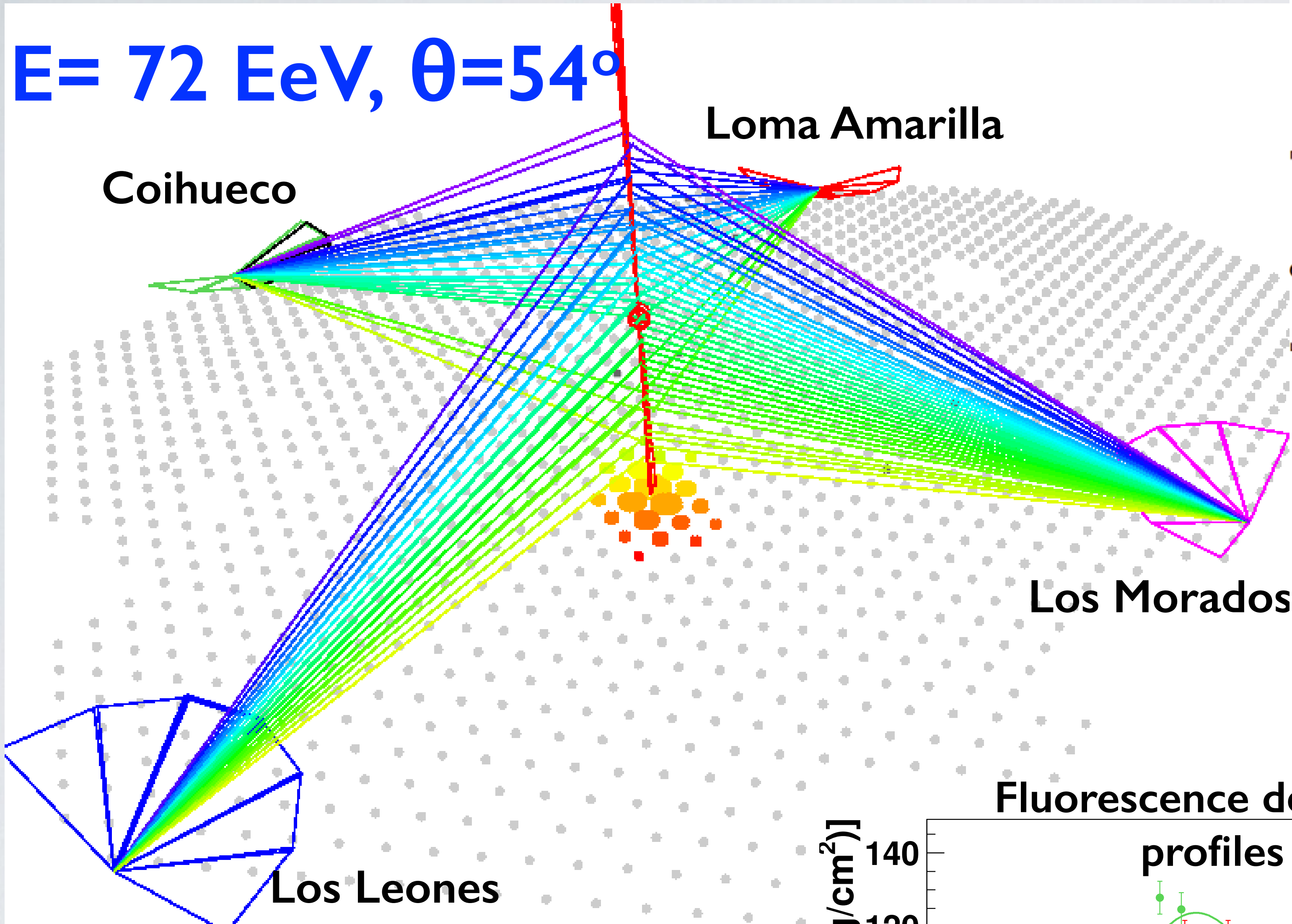


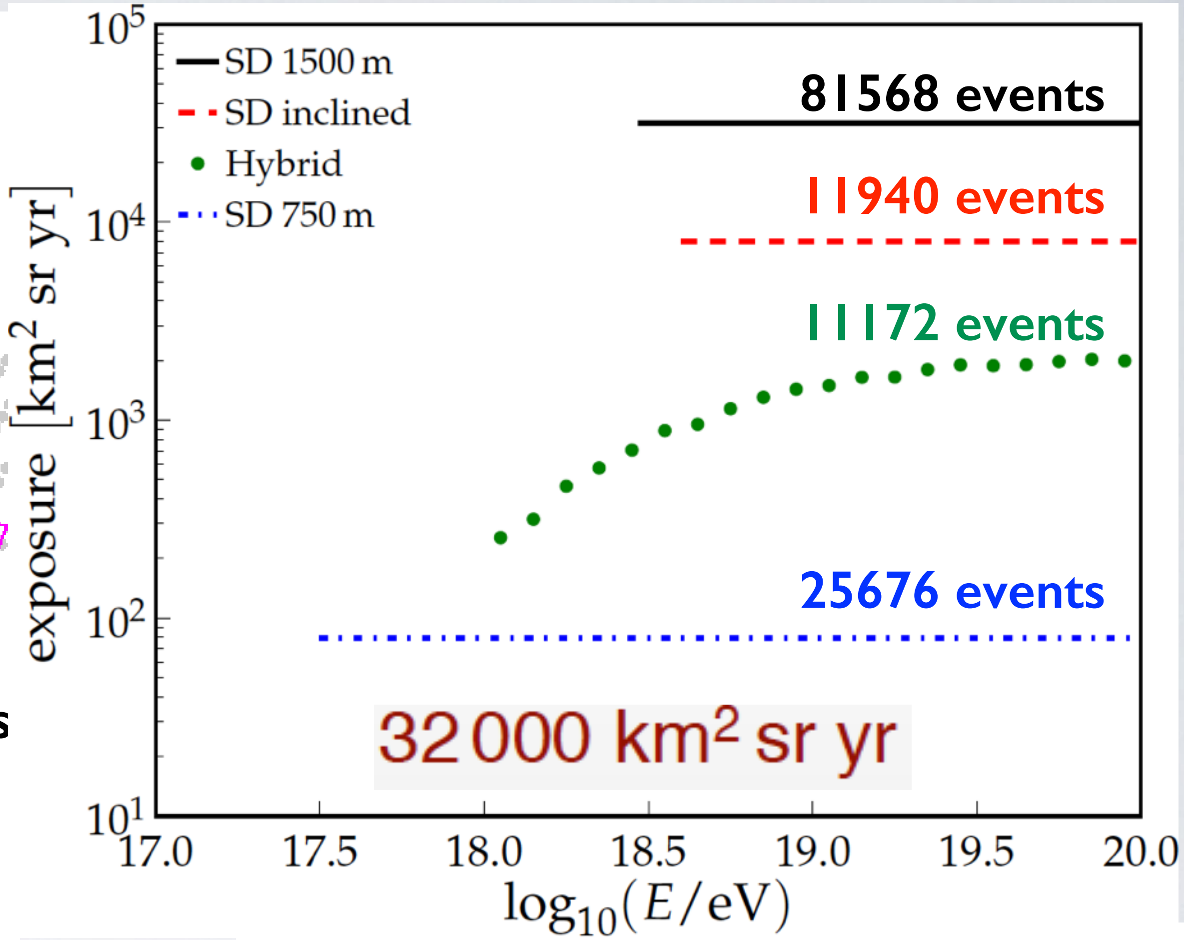


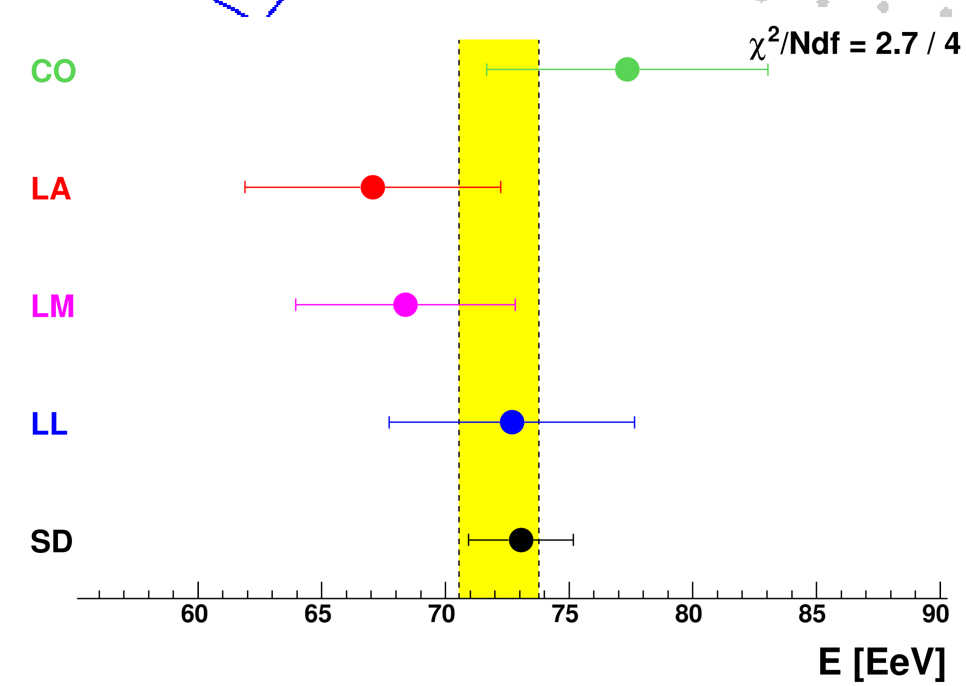


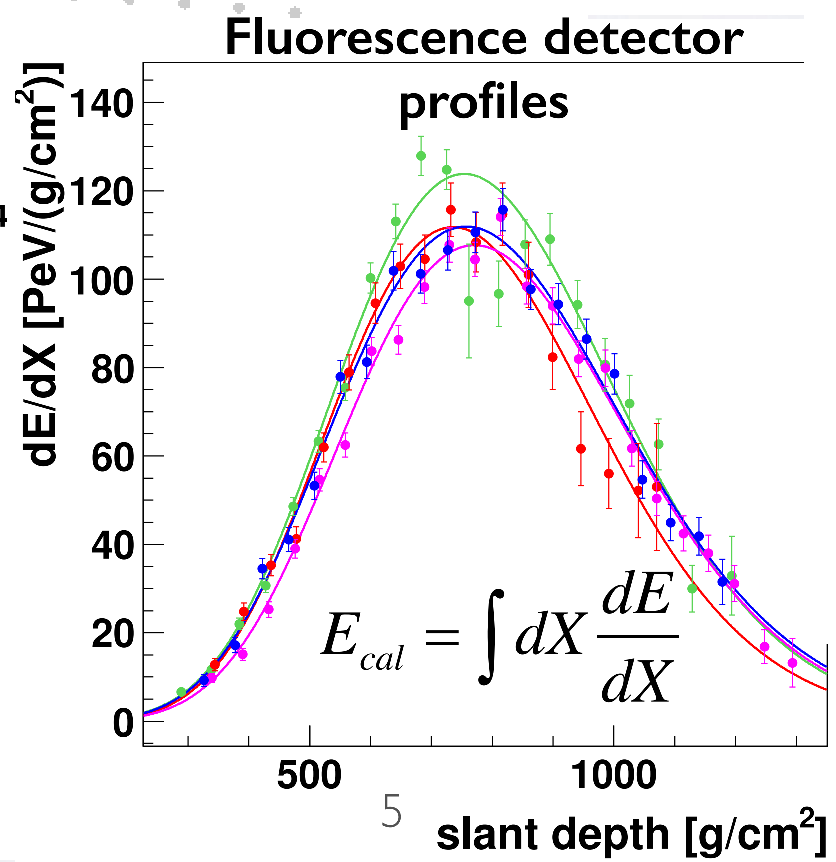
18 countries
94 institutions
> 500 collaborators

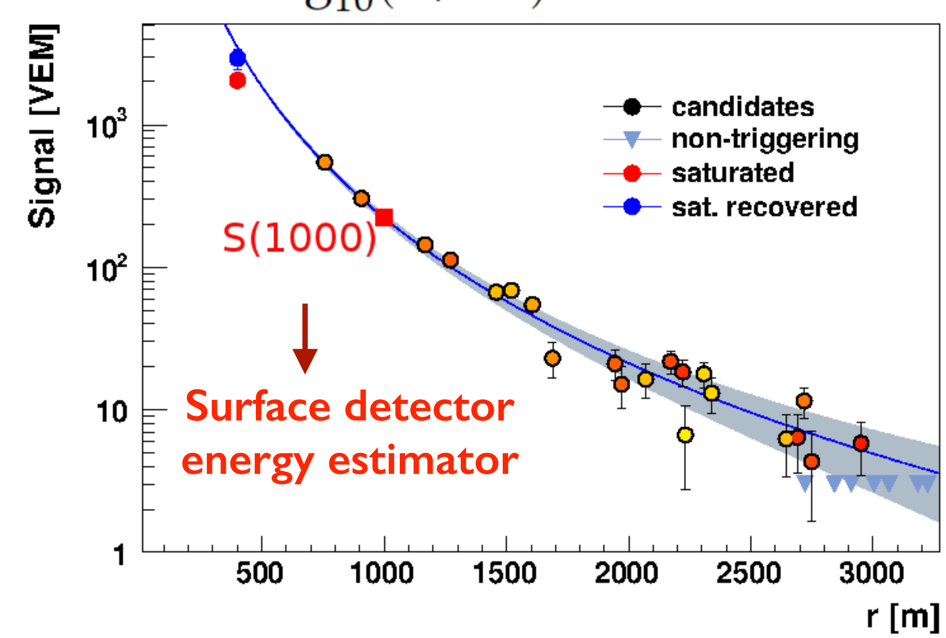
HYBRID DETECTION











SCIENTIFIC ACHIEVEMENTS

40 publications, 3260 citations, 81 citations/article

UHECR Flux Suppression

Restrictive limits γ on and ν fluxes

Heavier composition above the ankle

Spectrum & CR Phenomenology

Composition

PIERRE AUGER OBSERVATORY

p-air cross section measurement at $\sqrt{s}$ = 57 TeV

Hints of anisotropy for E>55 EeV

Arrival Directions

Fundamental Interactions

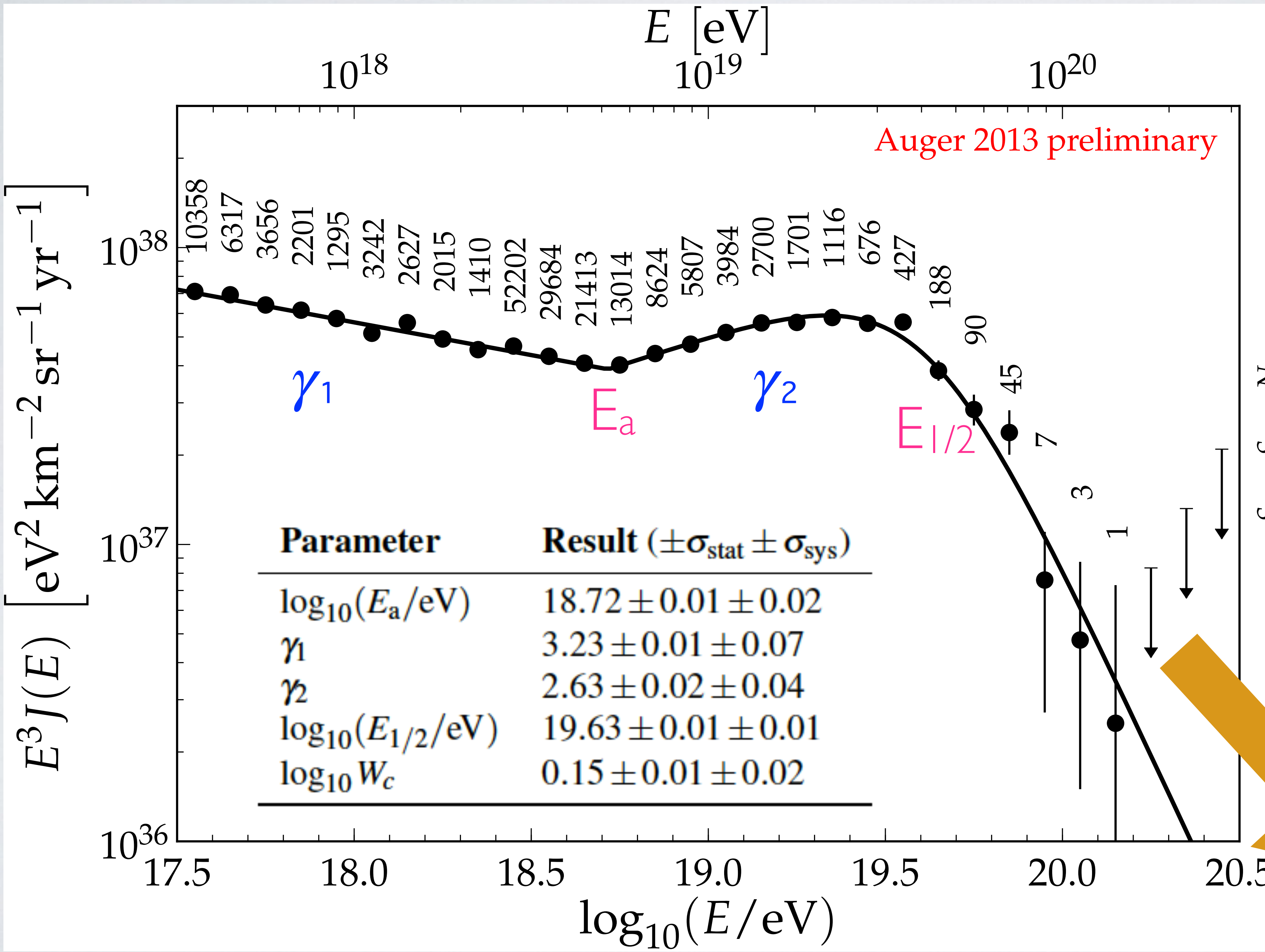
Interdisciplinary Science

Strongest bounds on large scale anisotropies

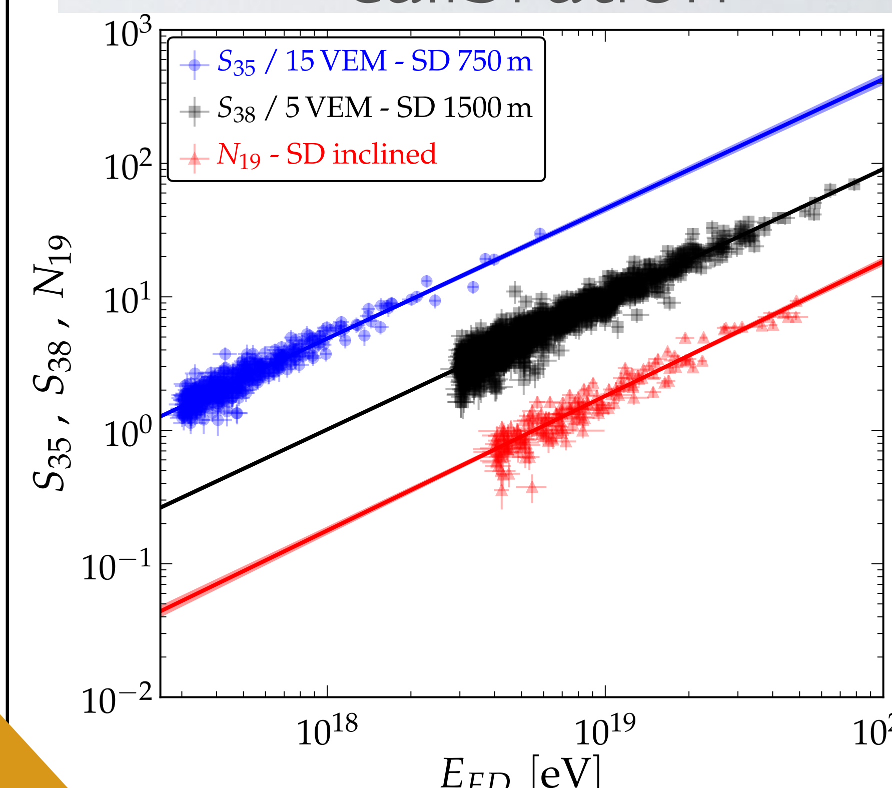
Muon deficit in models of hadronic interactions

Solar & Atmospheric Physics

ALL-PARTICLE SPECTRUM



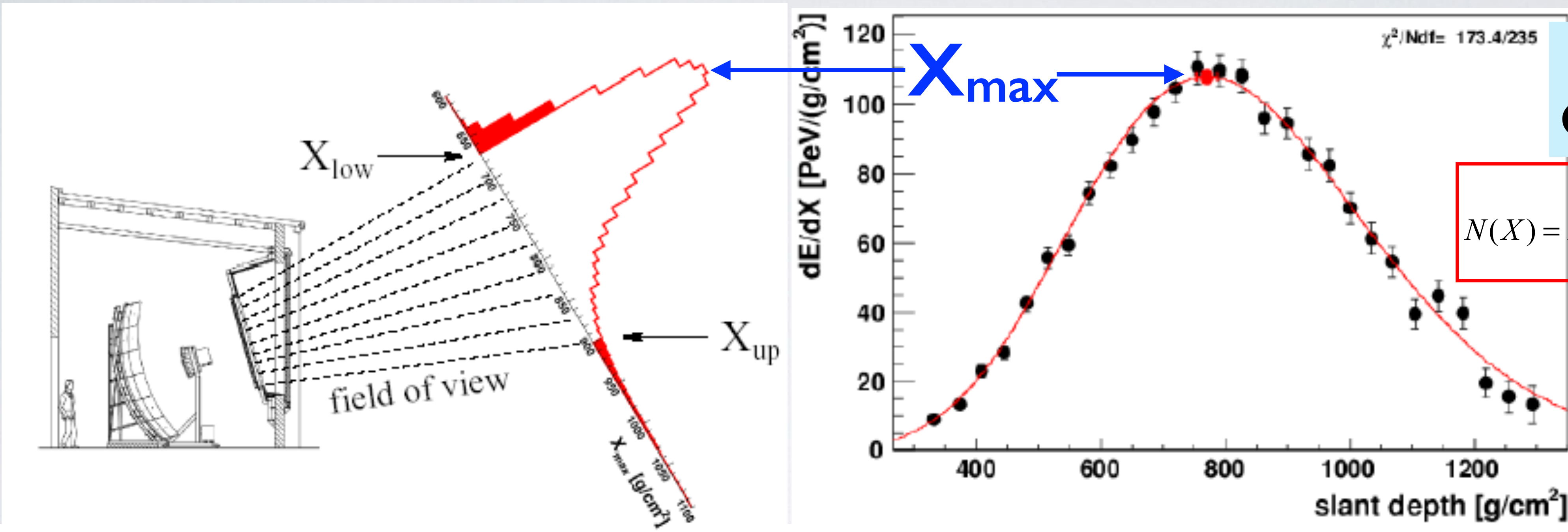
Data-driven calibration



~130 000 events

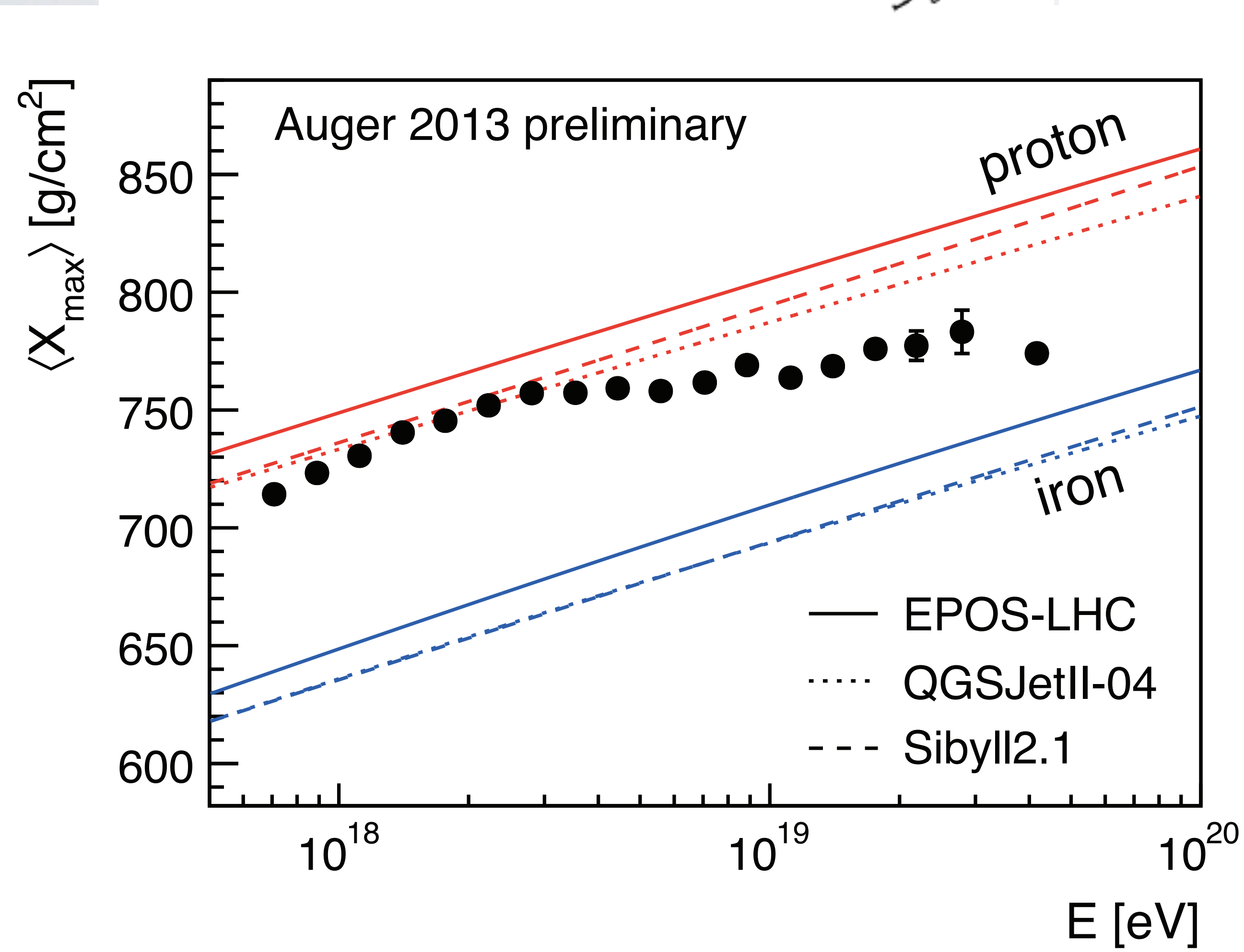
Flux suppression established!

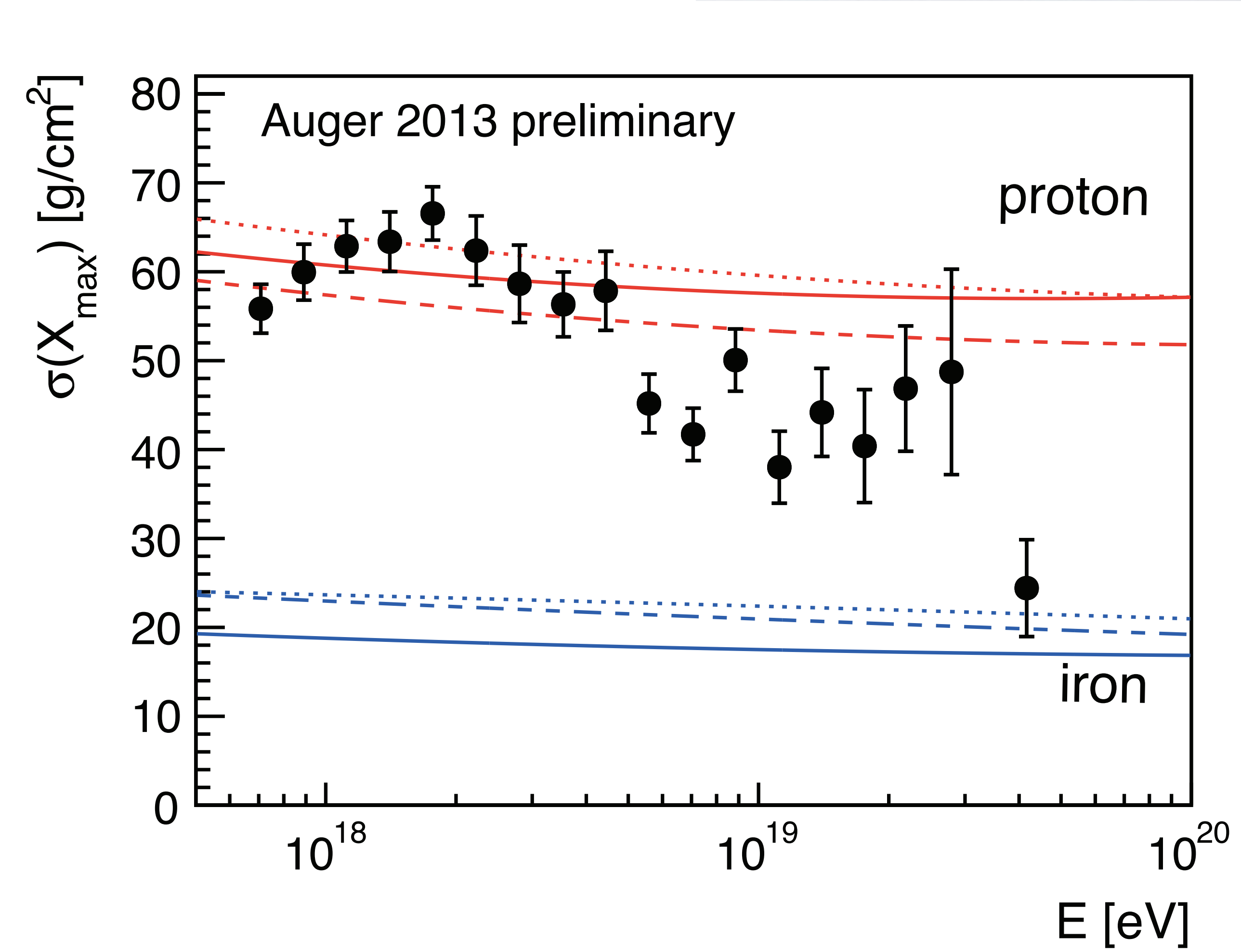
MASS COMPOSITION



Fit with empirical Gaisser-Hillas formula

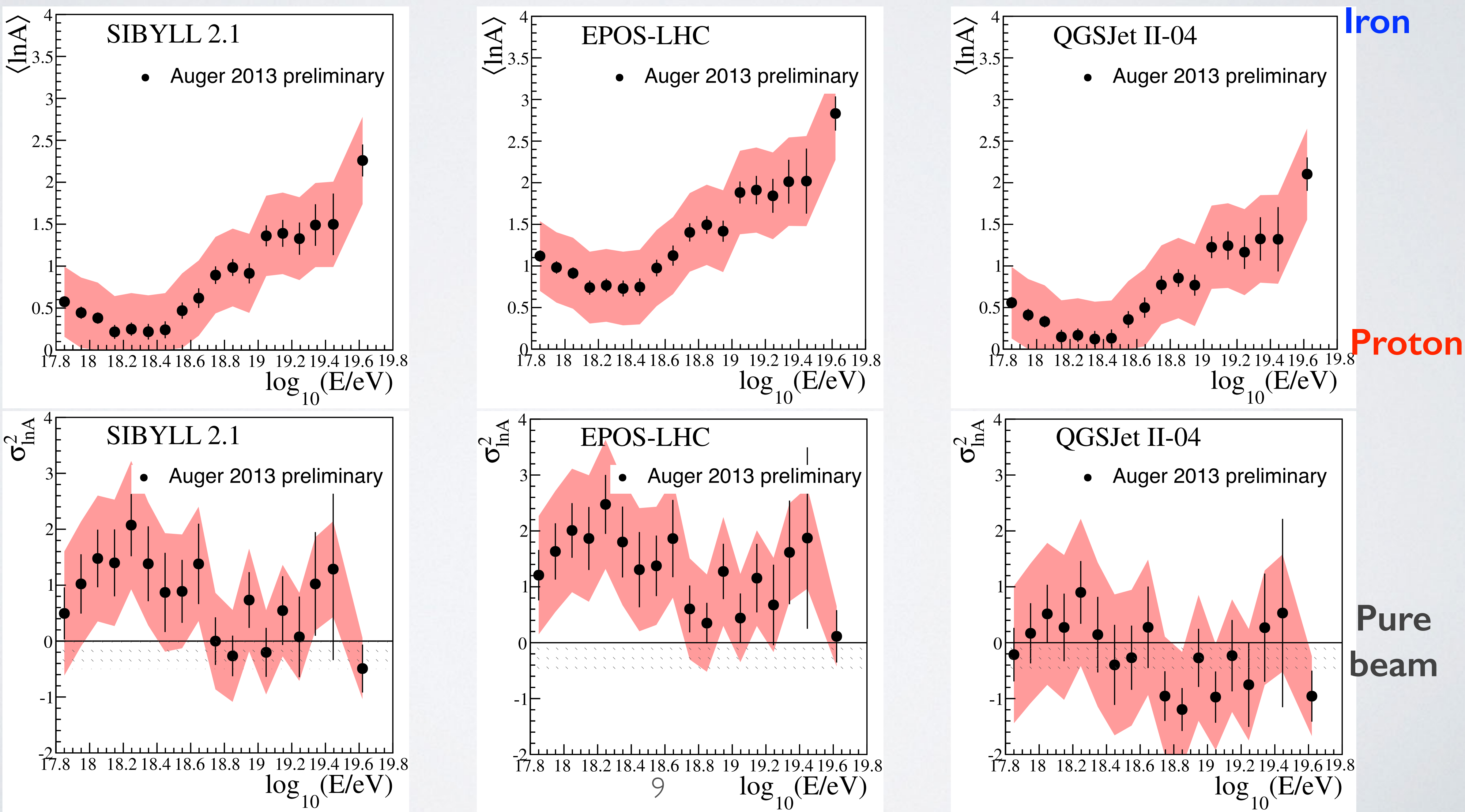
$$N(X) = N_{\max}\left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max}-X_0}{\Lambda}} \exp\left(\frac{X_{\max} - X}{\Lambda}\right)$$





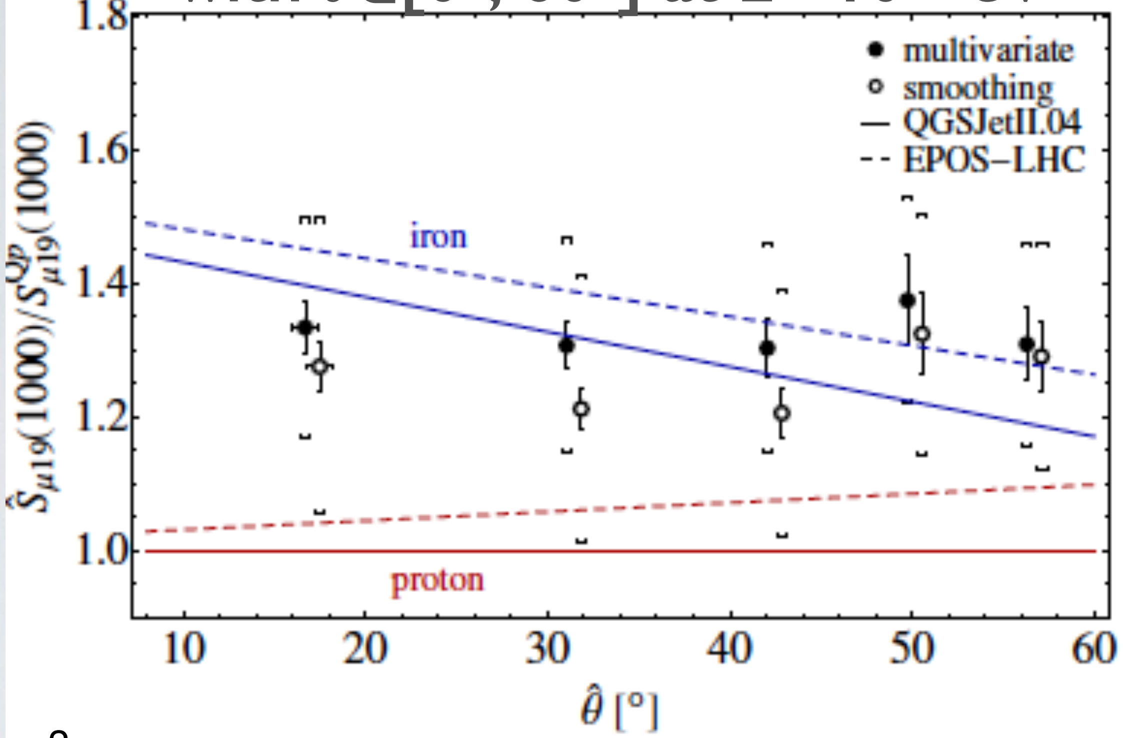
INTERPRETATION IN TERMS OF <LN A>

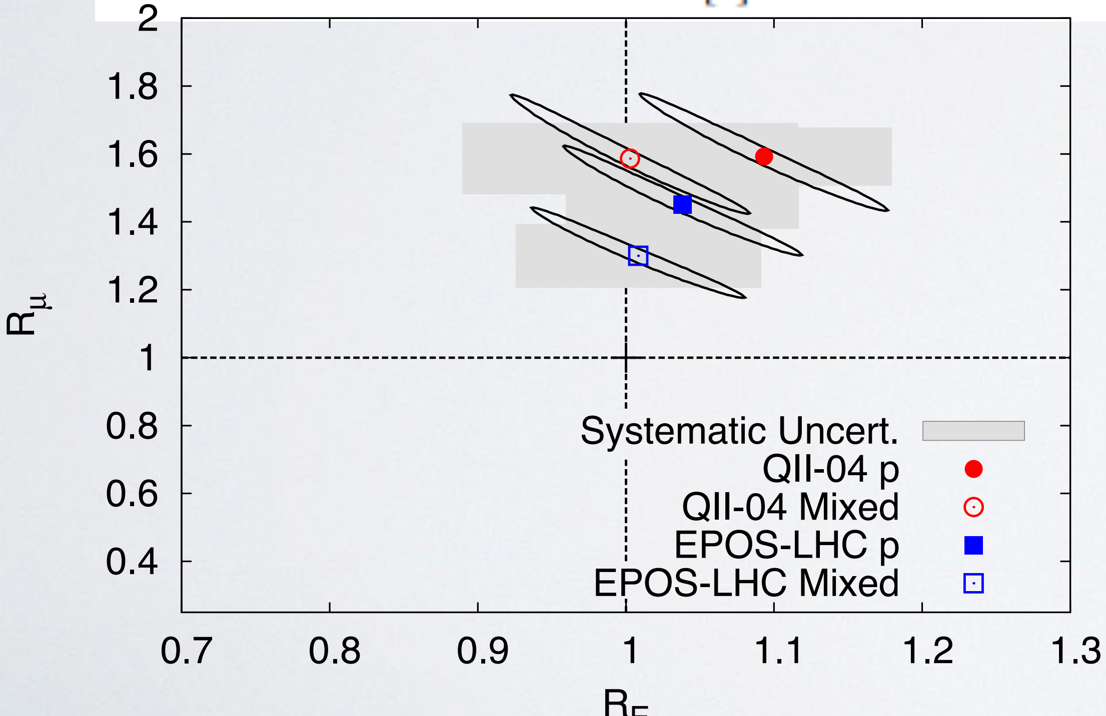
$$\langle X_{max} \rangle \approx \langle X^{p}_{max} \rangle - D_p \langle \ln(A) \rangle$$
$$\sigma^2[X_{max}] \approx \langle \sigma_i^2 \rangle + D_p^2 \sigma^2[\ln(A)]$$



HADRONIC INTERACTIONS

Muon counting from FADC for events with $\theta \in [0^o, 60^o]$ at E= 10^{19} eV

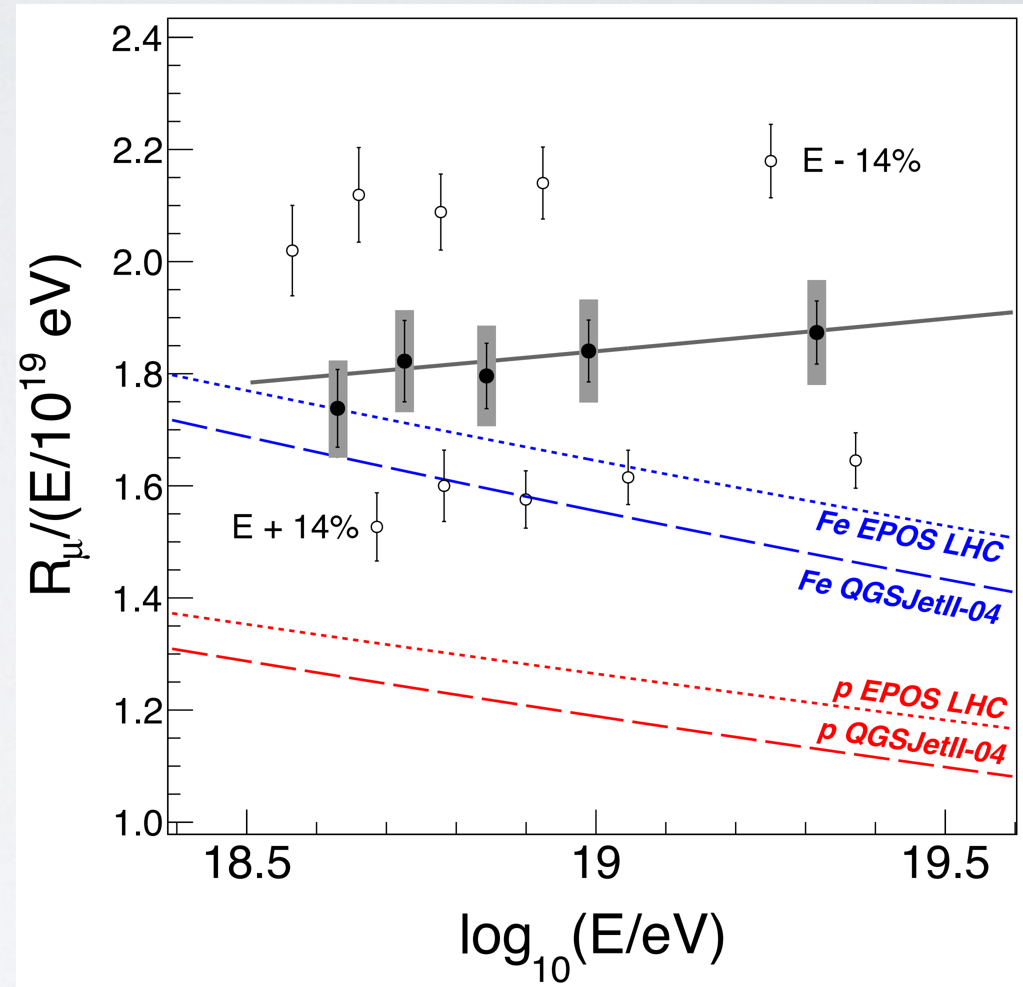




Scale factor to properly describe Auger data at E= 10^{19} eV

Inclined showers (i.e. θ>62°)

Signal dominated by muons



Muon discrepancy between data and models of hadronic interactions

ADVANCING THE UNDERSTANDING OF UHECR

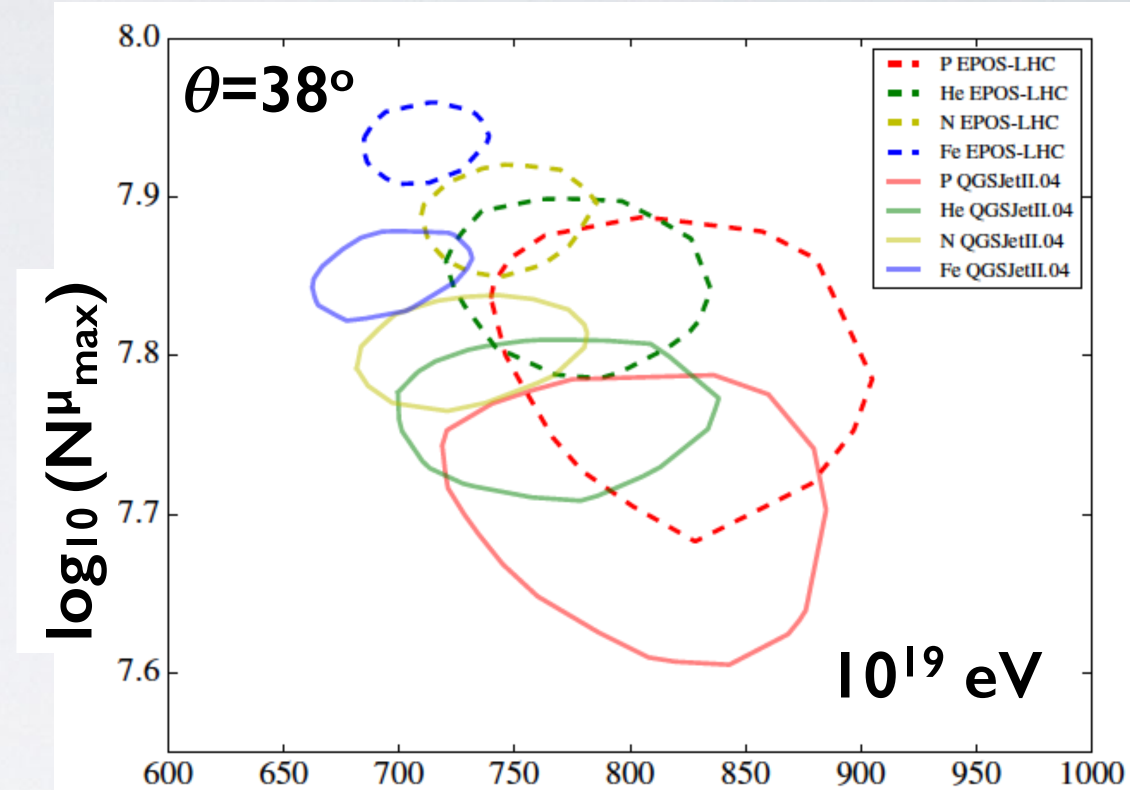
Importance of enhanced composition sensitivity

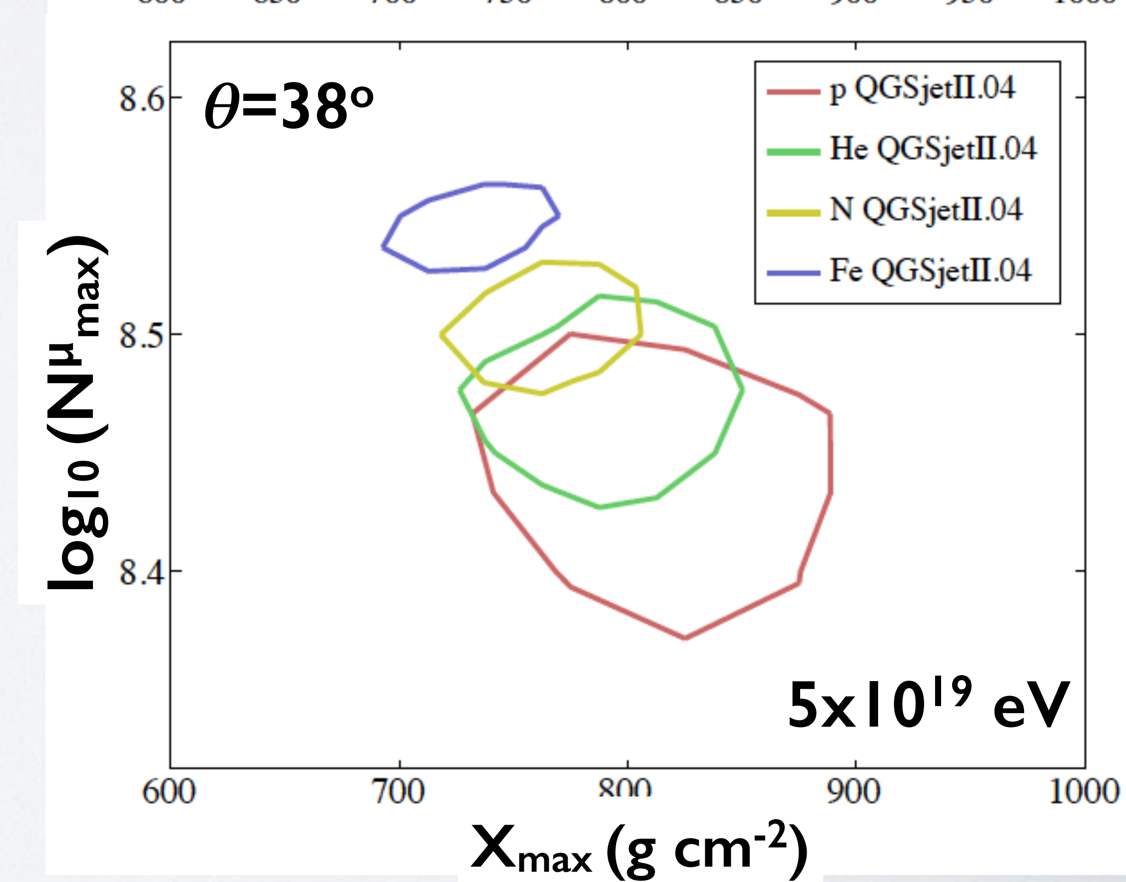
- GZK cut off or sources out of steam?
- Is there a proton fraction (~ 10%) at the highest energies?
- Proton astronomy?
- Anisotropy studies based on event-by-event mass estimation
- Are there ultra-high energy photons and neutrinos?
- Search for new physics: LIV, extra dimensions, …
- Study fundamental interactions at the scale of ~100 TeV

PLANNED DETECTOR UPGRADE TO OPEN A NEW FLOURISHING ERA OF UHECR MEASUREMENTS

IMPORTANCE OF ENHANCED MUON DETECTION

- Composition mostly based on optical observation of Xmax
    - 15% duty cycle
- Surface detector offers 100% duty cycle ➠ Better mass discrimination capabilities by



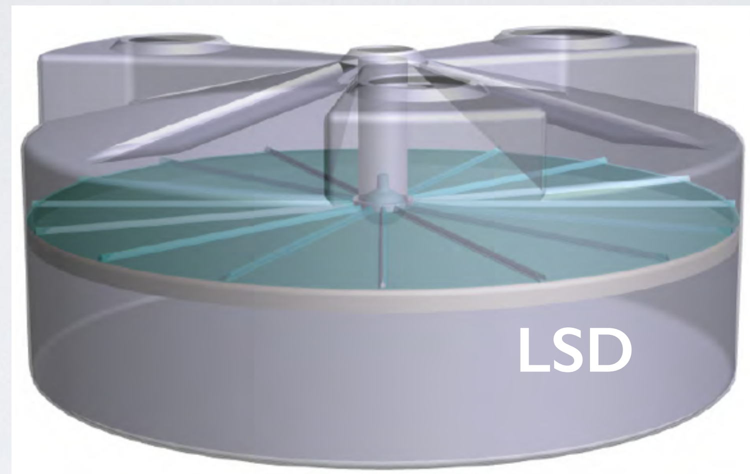


Improving separation of electromagnetic and muonic shower components!

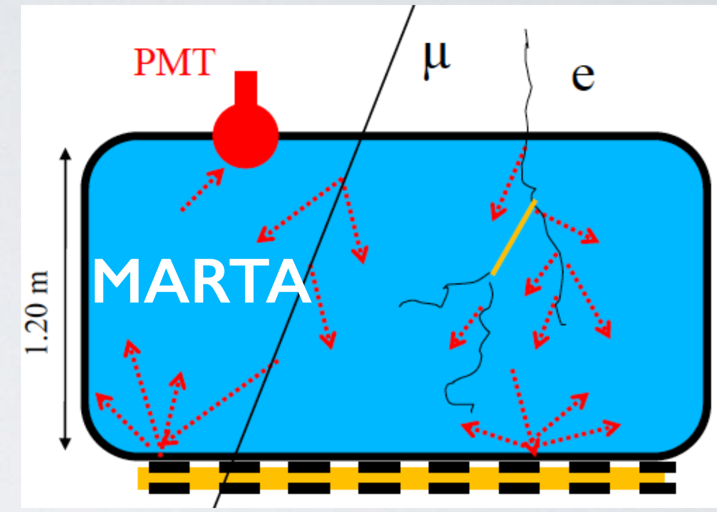
DETECTOR UPGRADE PLANS

- Take data until 2023
- It will triple our present statistics
- Improved electronics
  - Enlarged dynamic range & faster sampling
- **Enhanced muon detection capabilities**

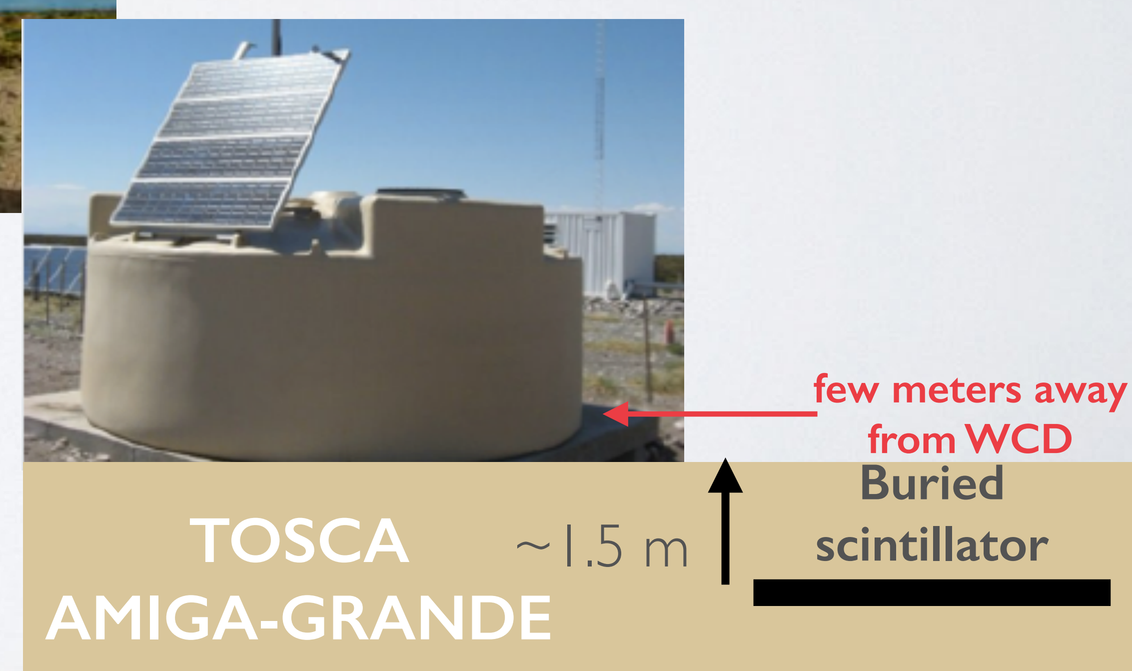
Layered Water Cherenkov Detector



RPC (under the WCD)



Scintillators



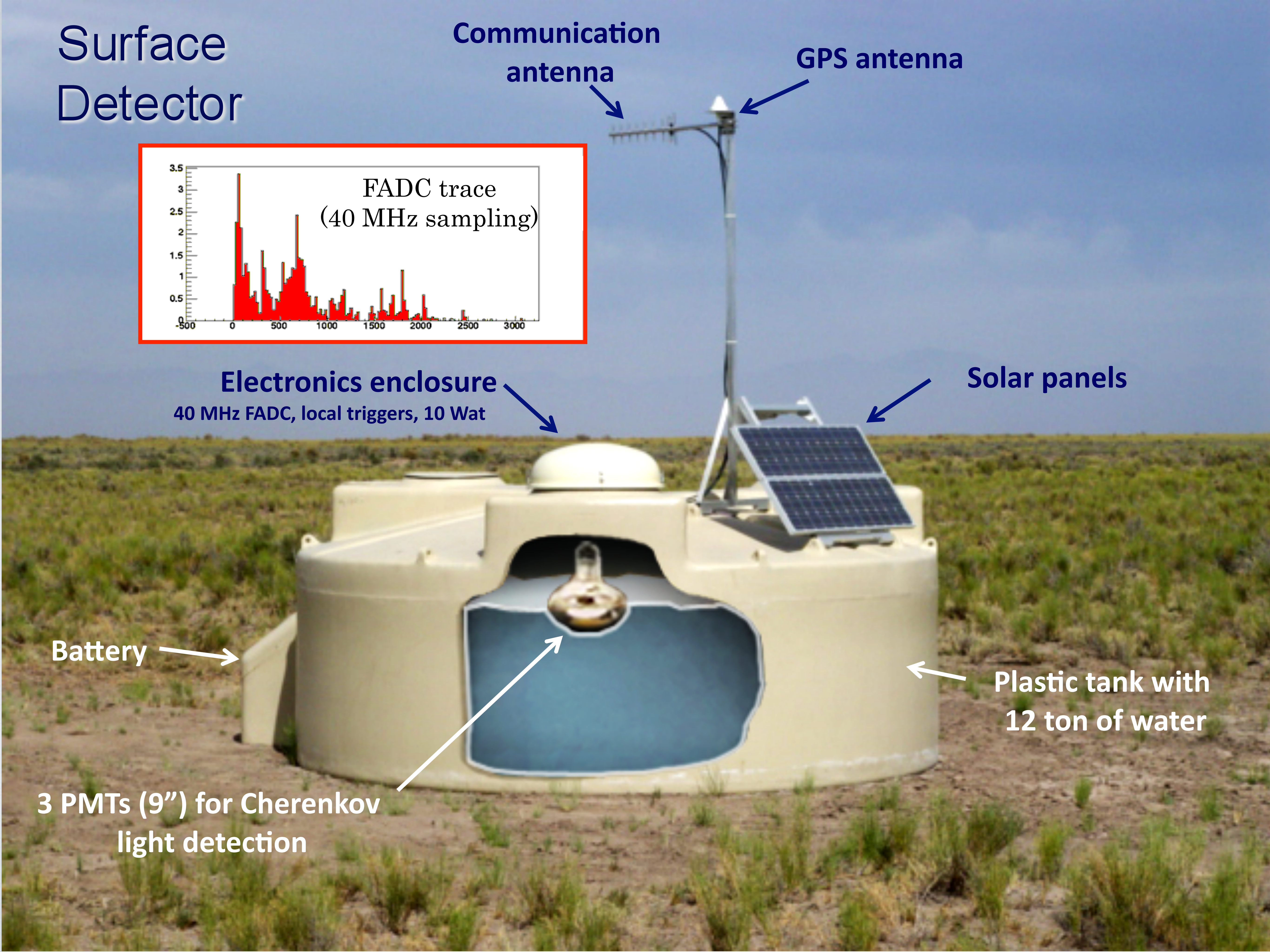
SUMMARY

- The Pierre Auger Observatory has provided copious data of unprecedented quality and size.

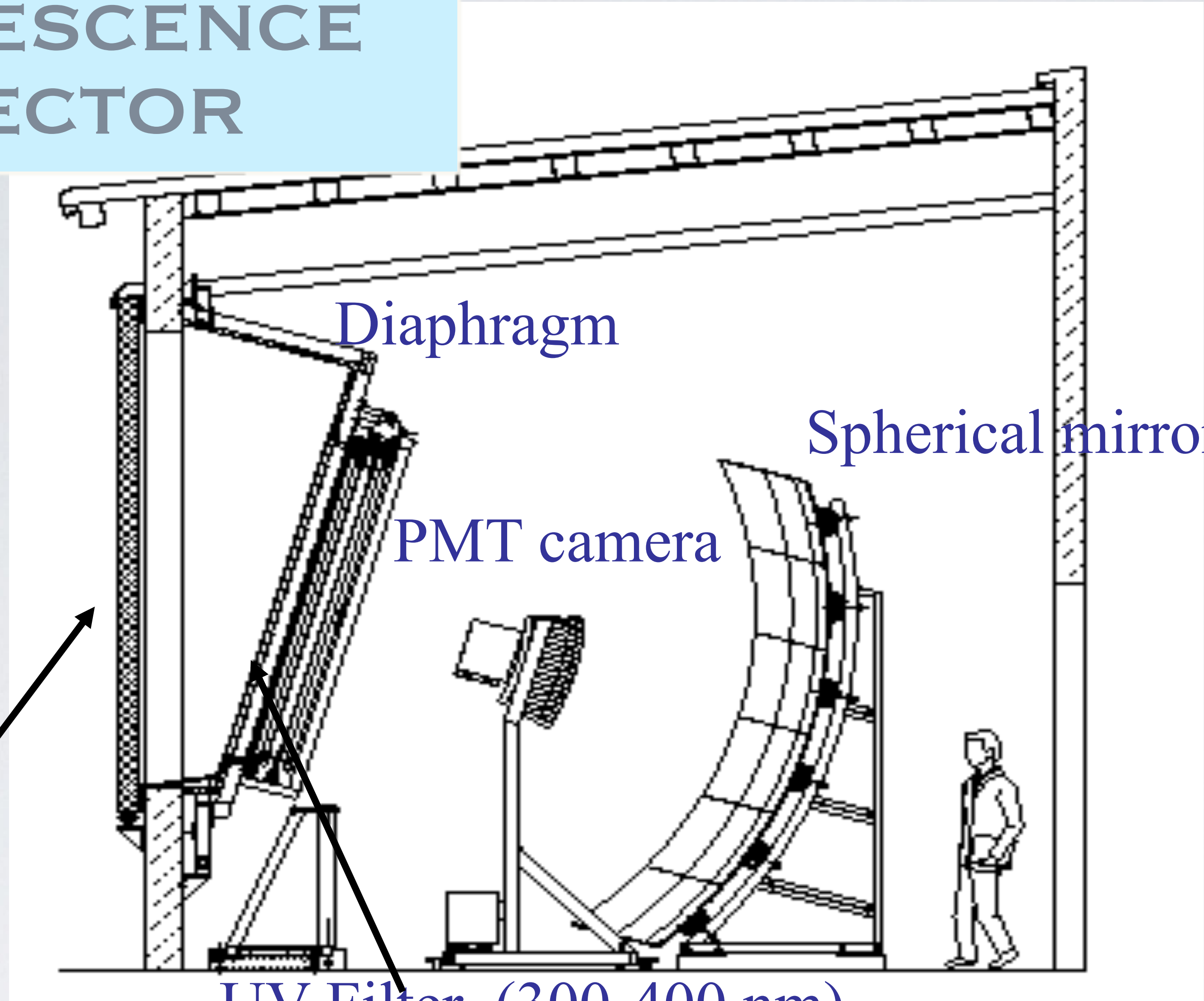
- Intensive campaign to improve detector capabilities: seeking definitive answers to open key questions.

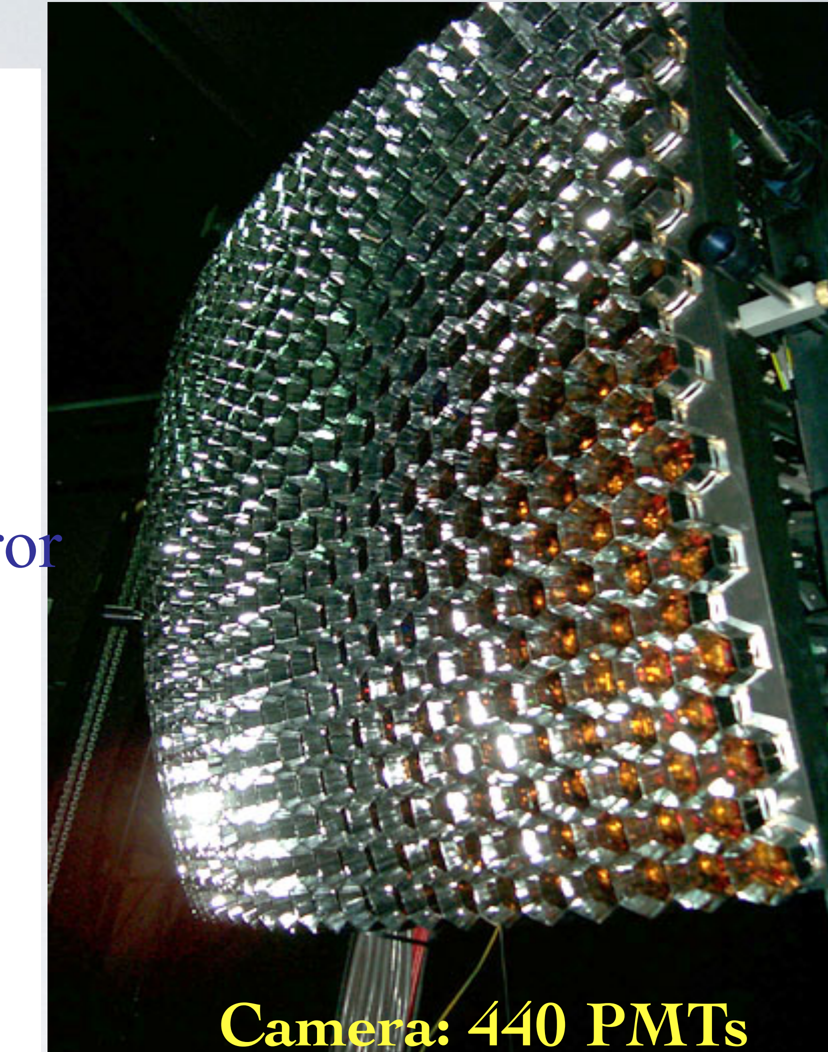
- Setting ground for a next-generation UHECR experiment (ten times bigger in size?).

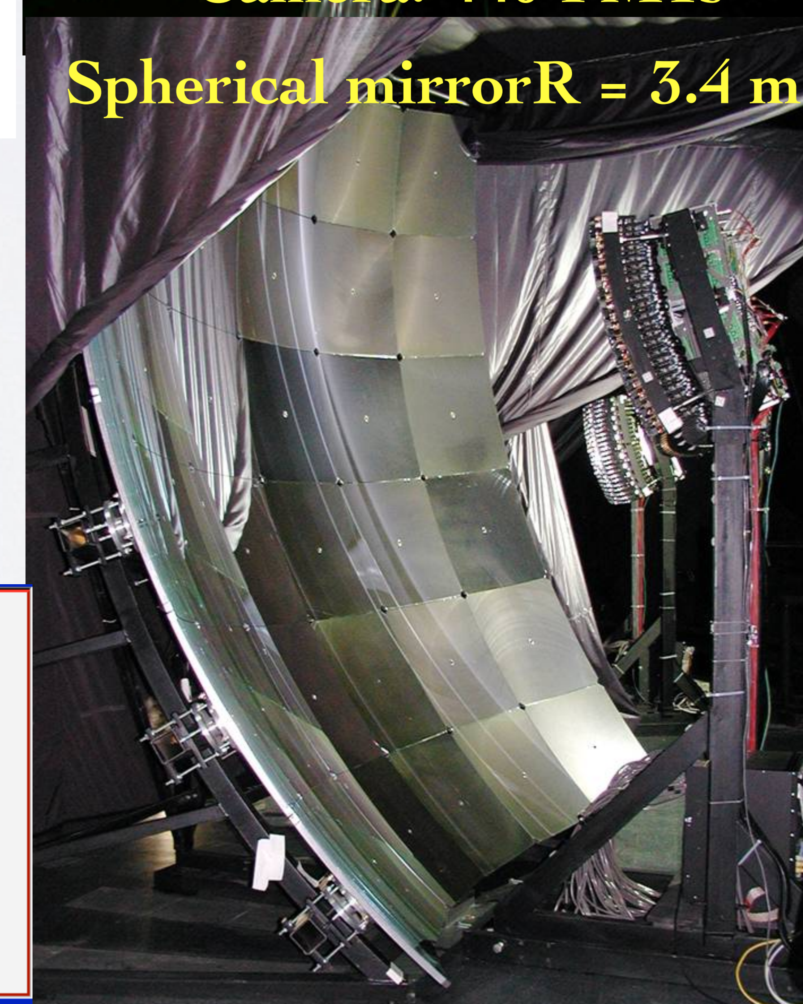
BACK-UP


Surface Detector
Communication antenna
GPS antenna
FADC trace
(40 MHz sampling)
3.5
3
2.5
2
1.5
1
0.5
0
-500
0
500
1000
1500
2000
2500
3000
Electronics enclosure
40 MHz FADC, local triggers, 10 Wat
Solar panels
Battery
Plastic tank with
12 ton of water
3 PMTs (9”) for Cherenkov
light detection

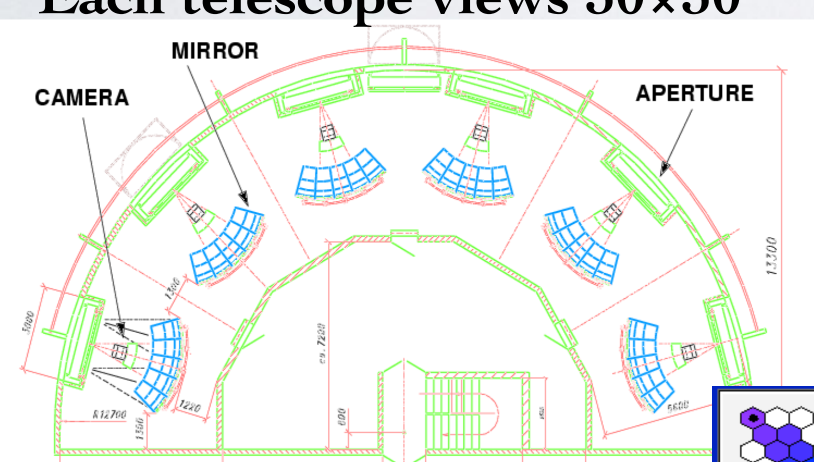
Fluorescence Detector



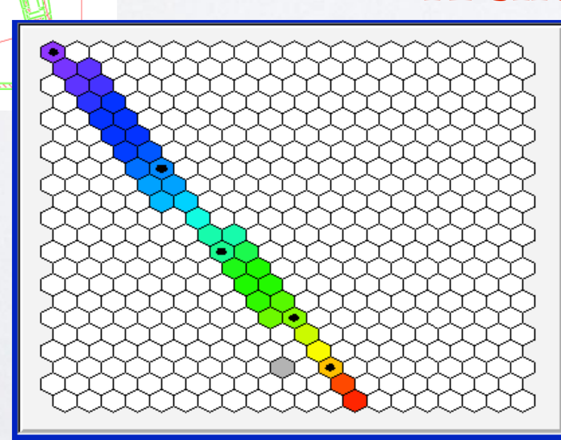


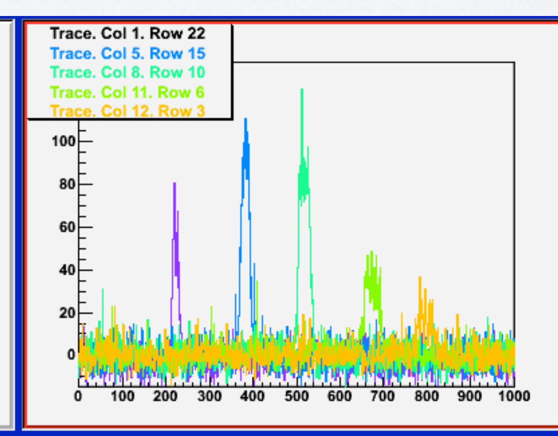


Each telescope views 30×30°

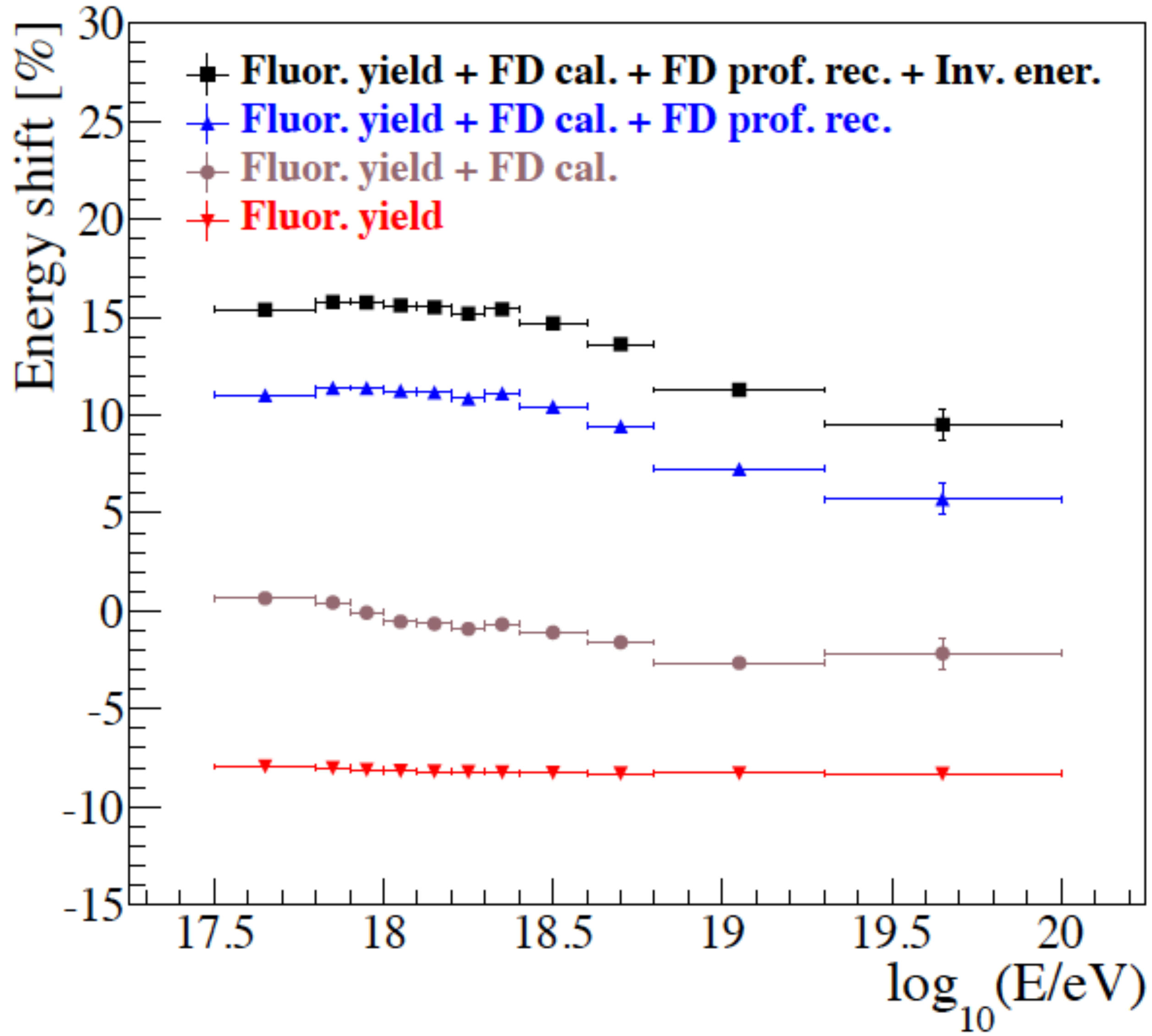


A shower event



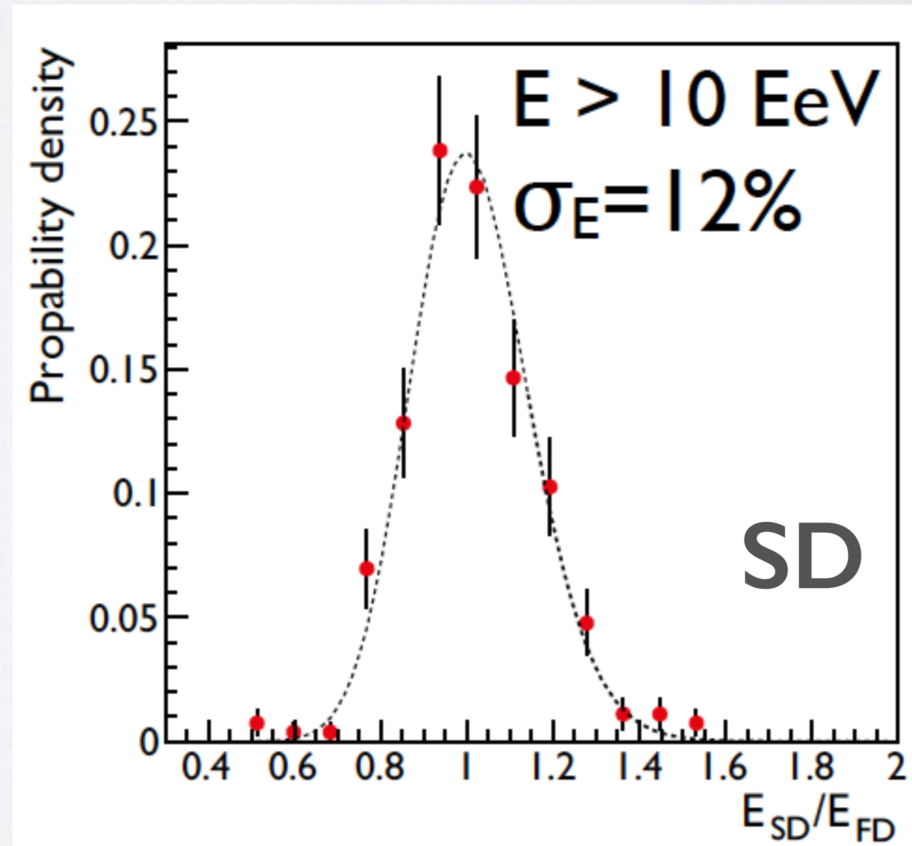


CHANGE IN FD ENERGIES



Total change between 16% ÷ 10%

Aerosol optical depth	3% ÷ 6%
Horizontal uniformity of aerosols	1%
Atmosphere variability	1%
Nightly relative calibration	3%
Statistical error of the profile fit	5% ÷ 3%
Uncertainty in shower geometry	1.5%
Invis. Energy (shower-to-shower fluc.)	1.5%
Total FD energy resolution	7% ÷ 8%



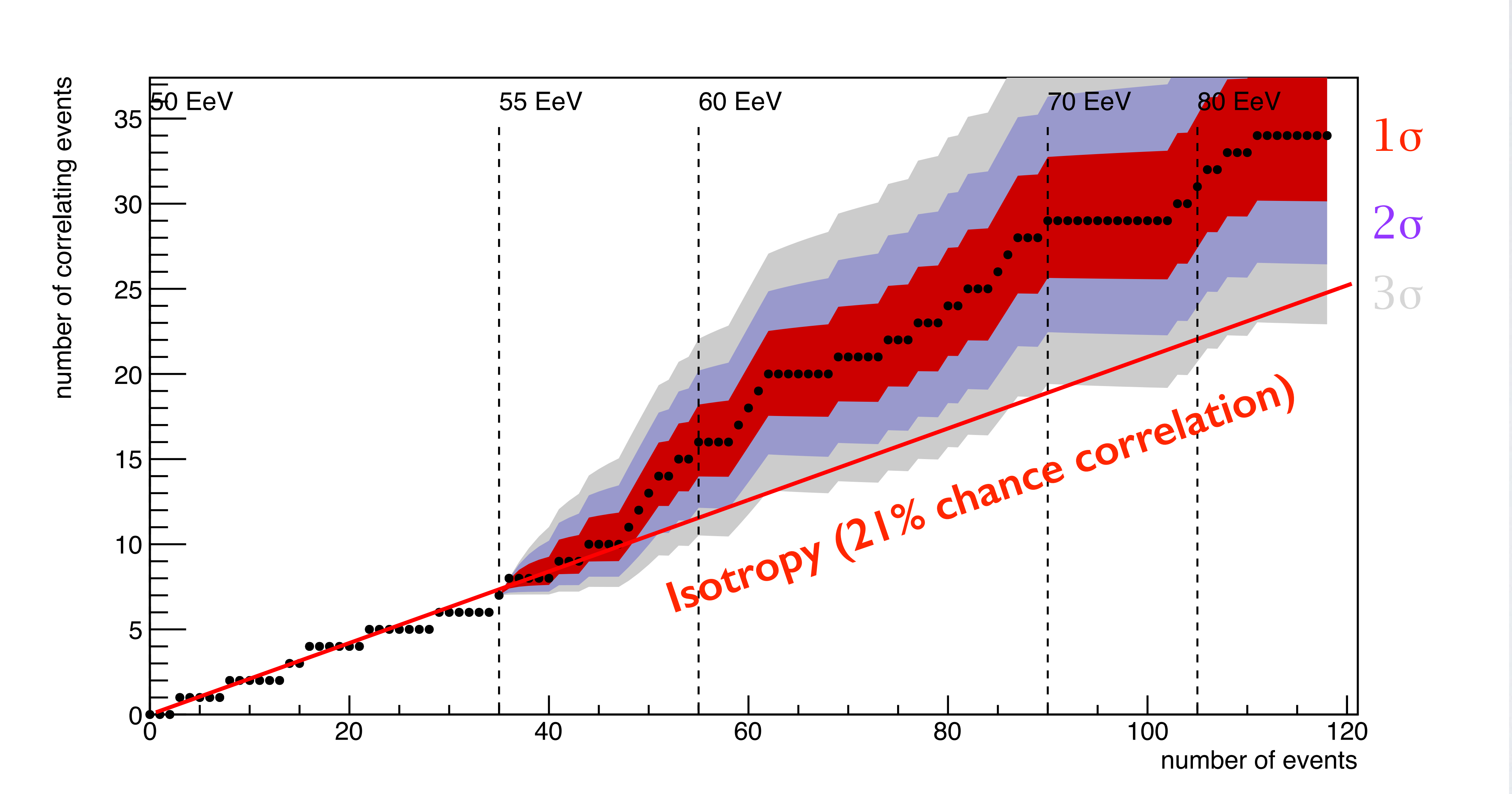
SYSTEMATIC UNCERTAINTY OF ENERGY SCALE

Absolute fluorescence yield	3.4%	
Fluores. spectrum and quenching param.	1.1%	
Sub total (Fluorescence Yield)	**3.6%**	**14%**
Aerosol optical depth	3% ÷ 6%	
Aerosol phase function	1%	
Wavelength dependence of aerosol scattering	0.5%	
Atmospheric density profile	1%	
Sub total (Atmosphere)	**3.4% ÷ 6.2%**	**5% ÷ 8%**
Absolute FD calibration	9%	
Nightly relative calibration	2%	
Optical efficiency	3.5%	
Sub total (FD calibration)	**9.9%**	**9.5%**
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.)	**6.5% ÷ 5.6%**	**10%**
Invisible energy	**3% ÷ 1.5%**	**4%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**	
Stability of the energy scale	**5%**	
TOTAL	**14%**	**22%**

RED: NEW

BLACK: OLD

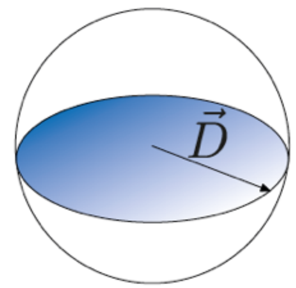
CORRELATION WITH AGNS OF VCV CATALOG

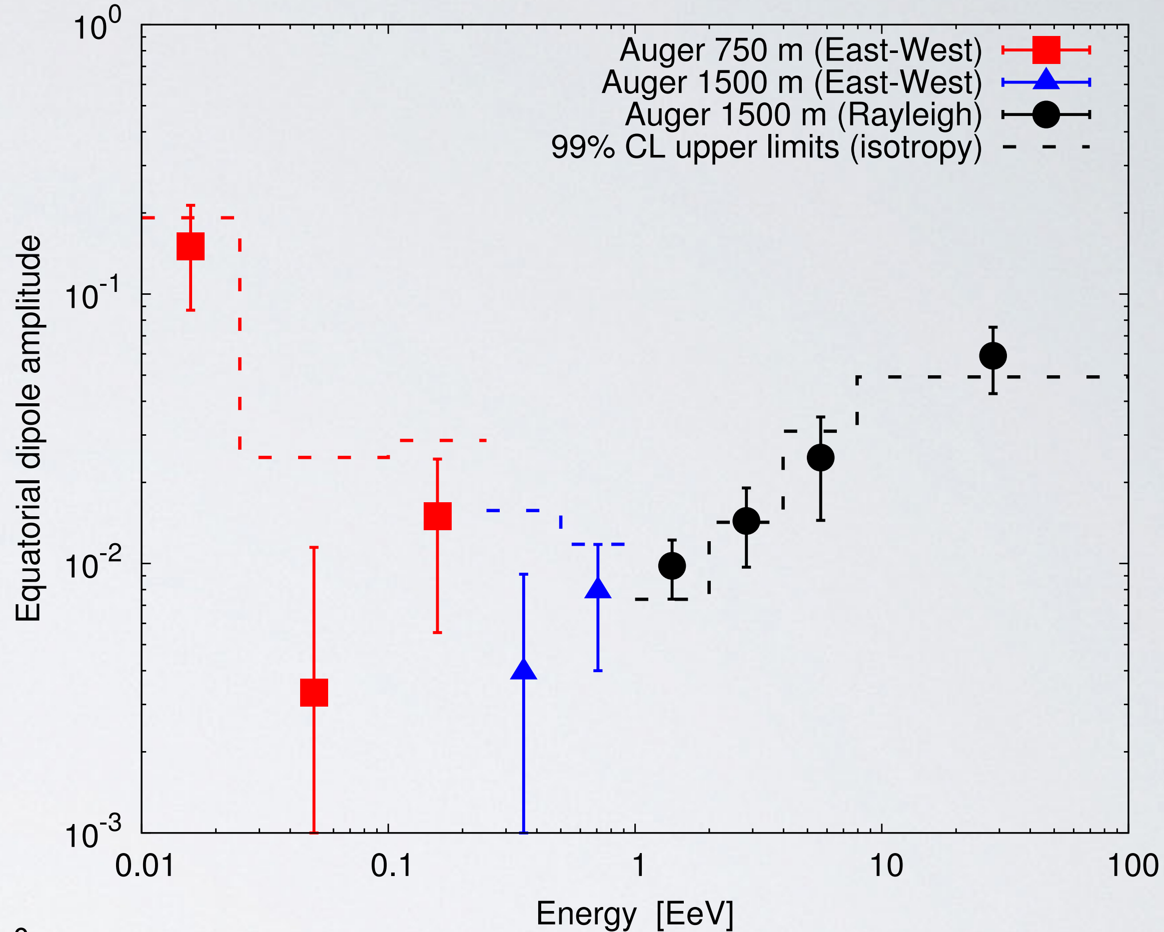


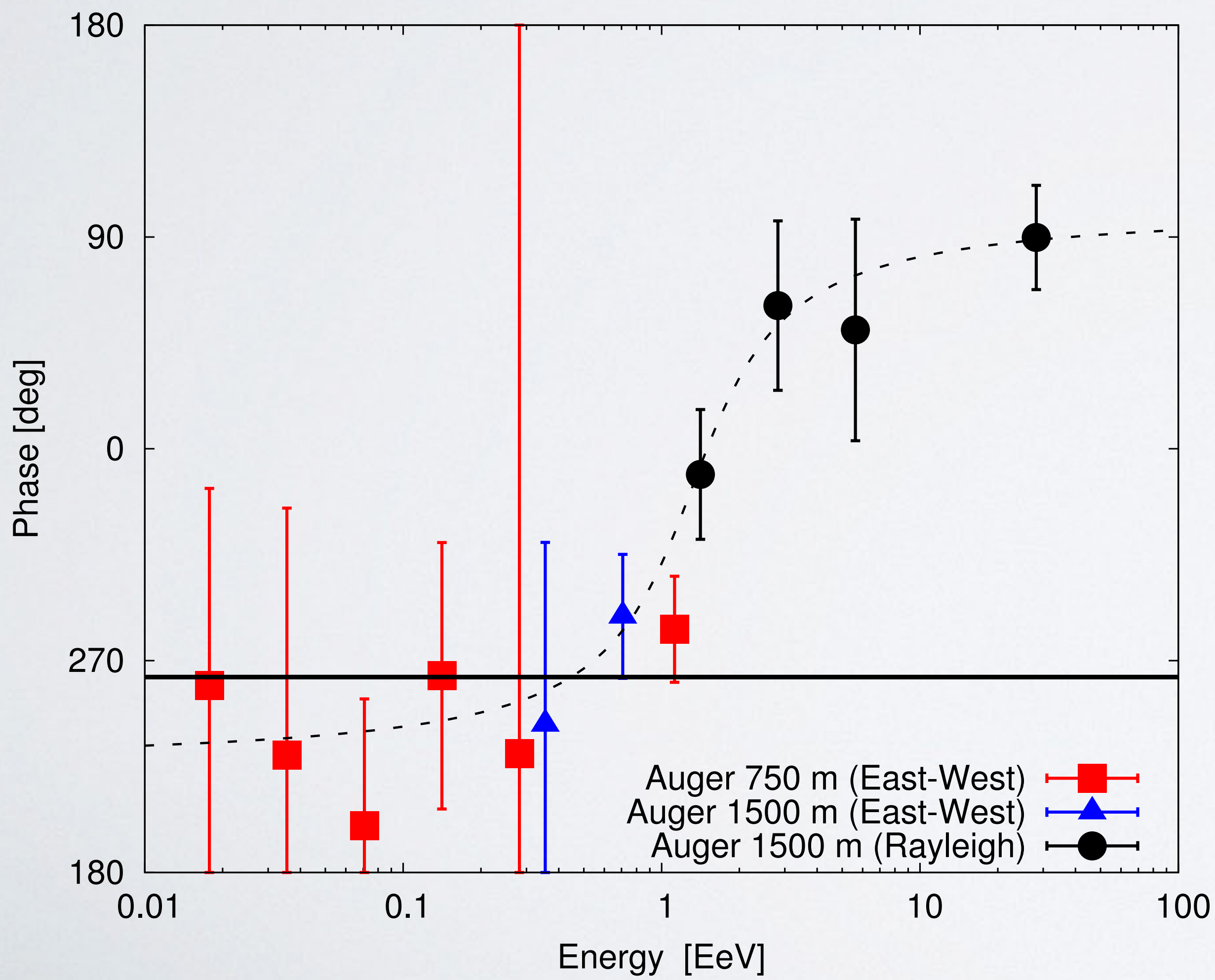
LARGE SCALE ANISOTROPY

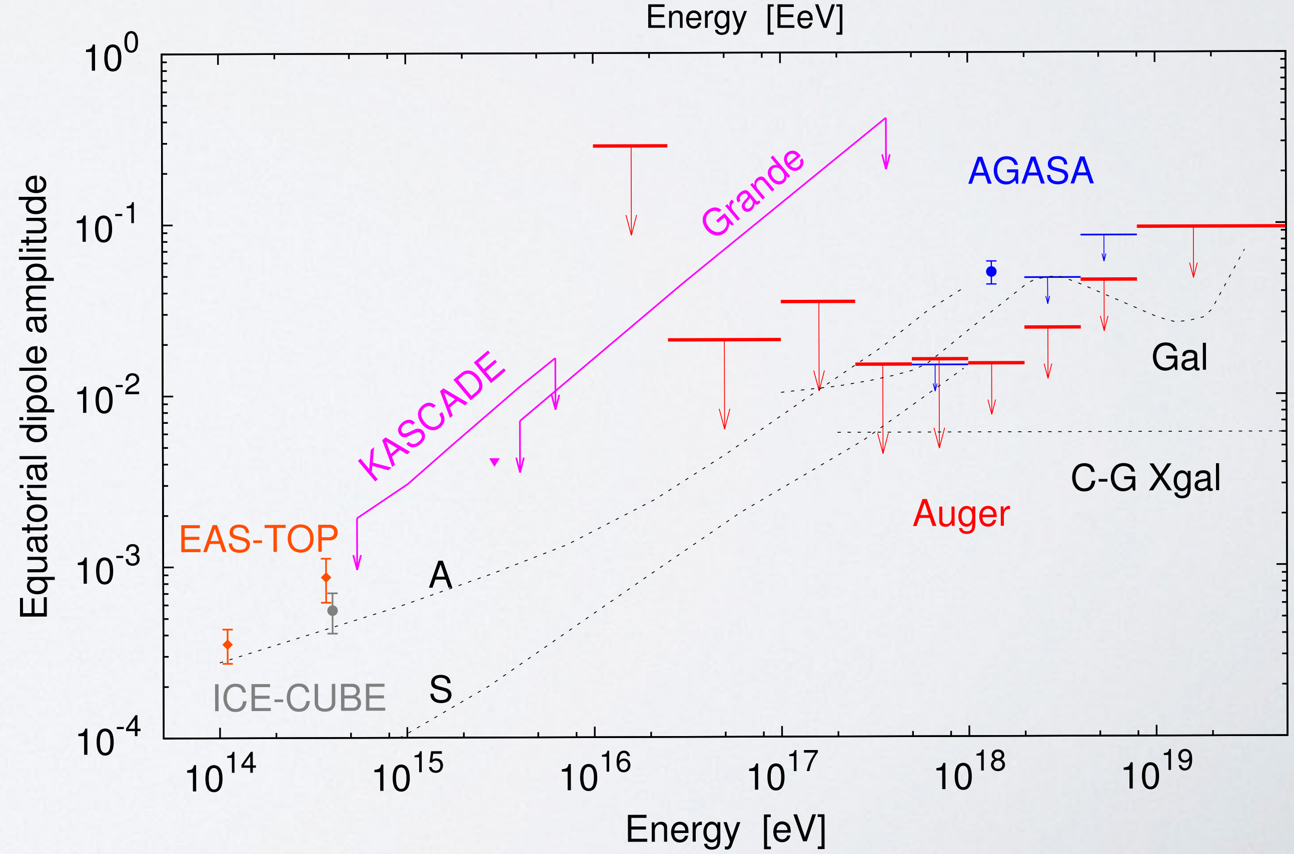
First harmonic

Amplitude and phase of first harmonic in right ascension: dipole $\vec{D}$



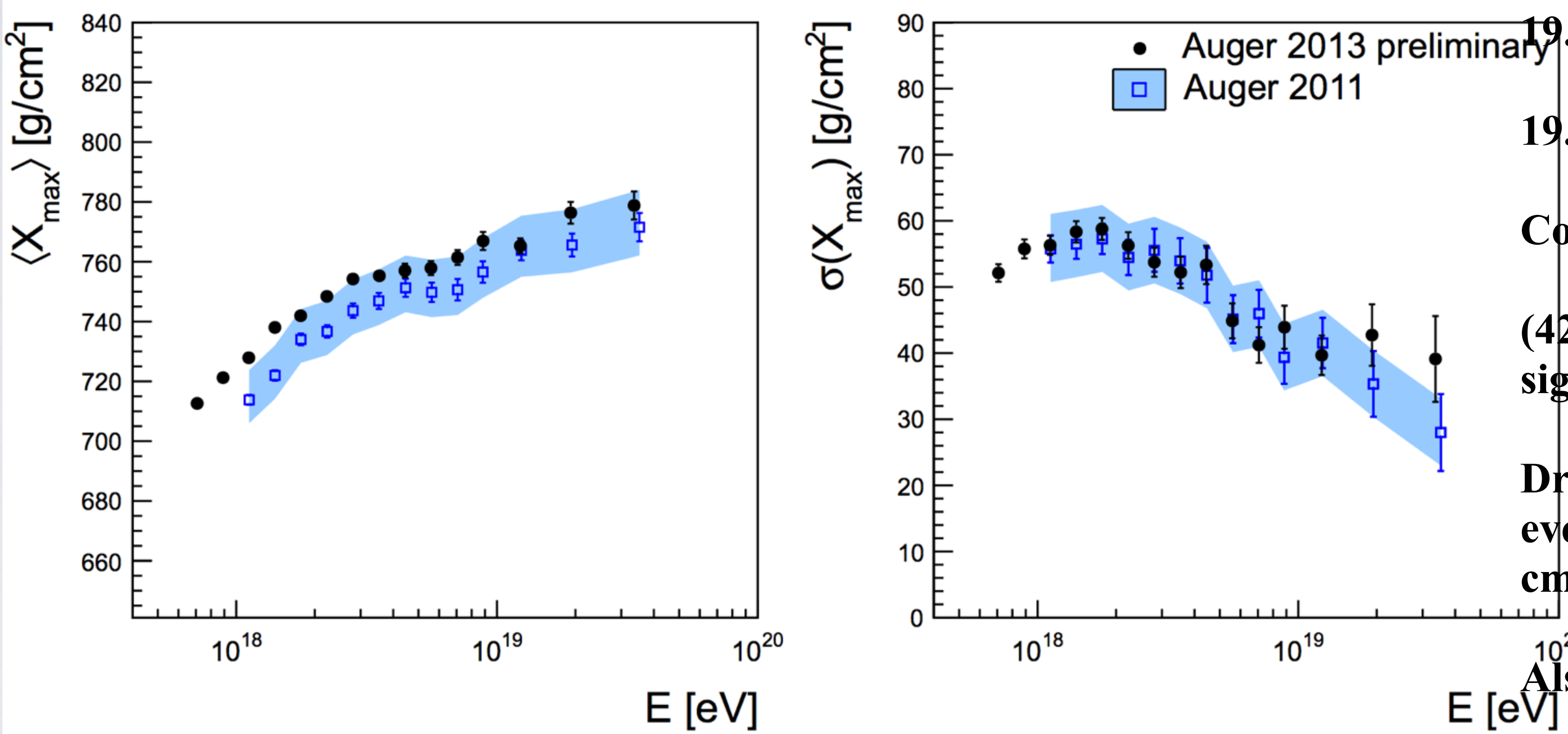






Comparison to previous Results

new reconstruction and calibration



log E	X_{max}
19.2 – 19.4	42.9 ± 5.1 g cm^{-2}
19.2 – 19.3	40.4 ± 6.3 g cm^{-2}
19.3 – 19.4	46.9 ± 7.0 g cm^{-2}

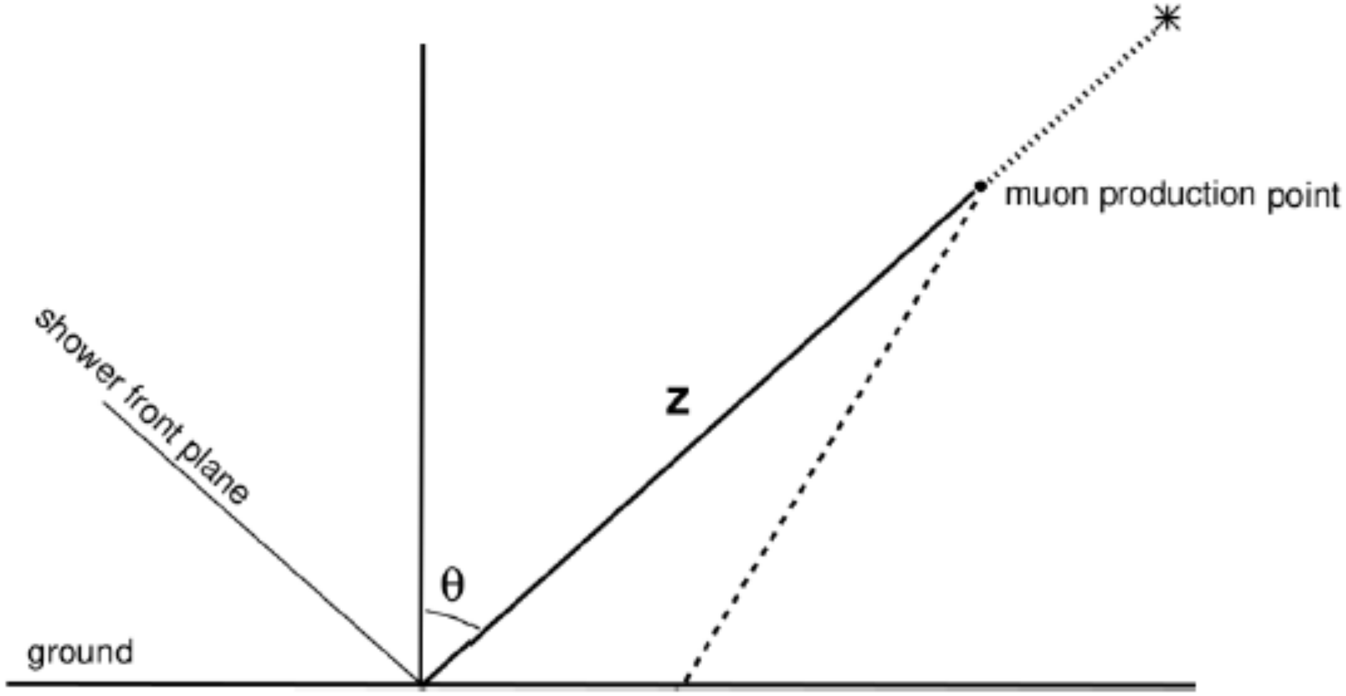
Corresponding Pull:-

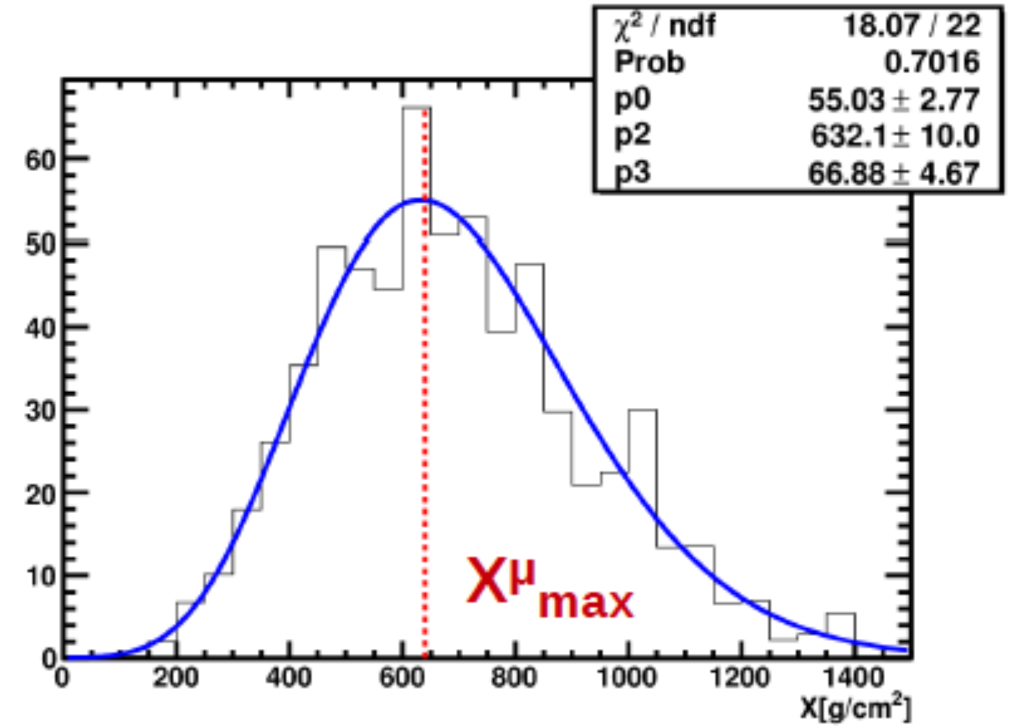
$(42.9 - 28.9)/\sqrt{(4.5^2 + 5.1^2)} = 2.1$ sigma

Drawing 71 events (2010) from 194 events (2013) give RMS < 28.9 g cm^{-2} at 3.1%

Also there is a trials factor

MPD in a nutshell





- Muons travel along straight lines close to the speed of light

Arrival time, *t* → *Kinematics* → **Production distance, *z*** → *Atmosphere* → **Production depth, *X***

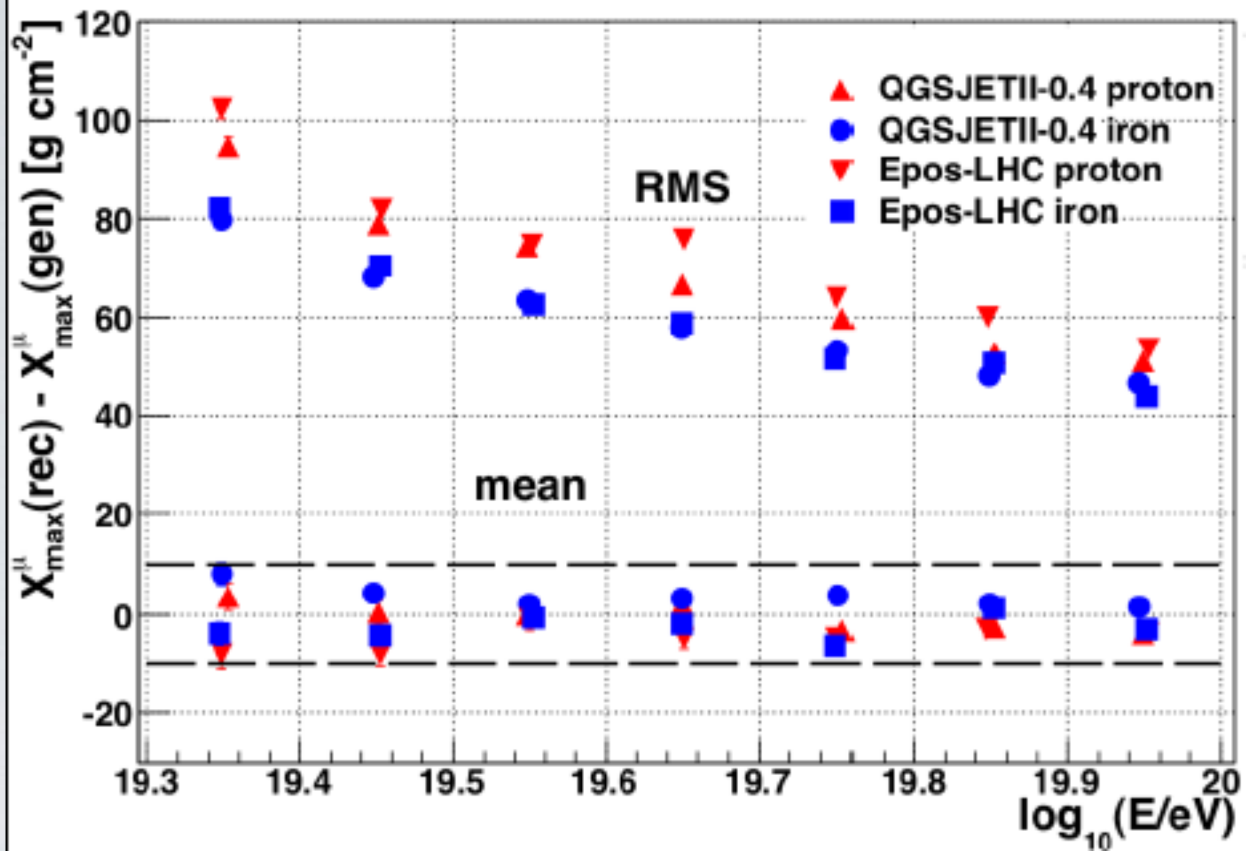
- The distribution of produced muons vs depth is the MPD

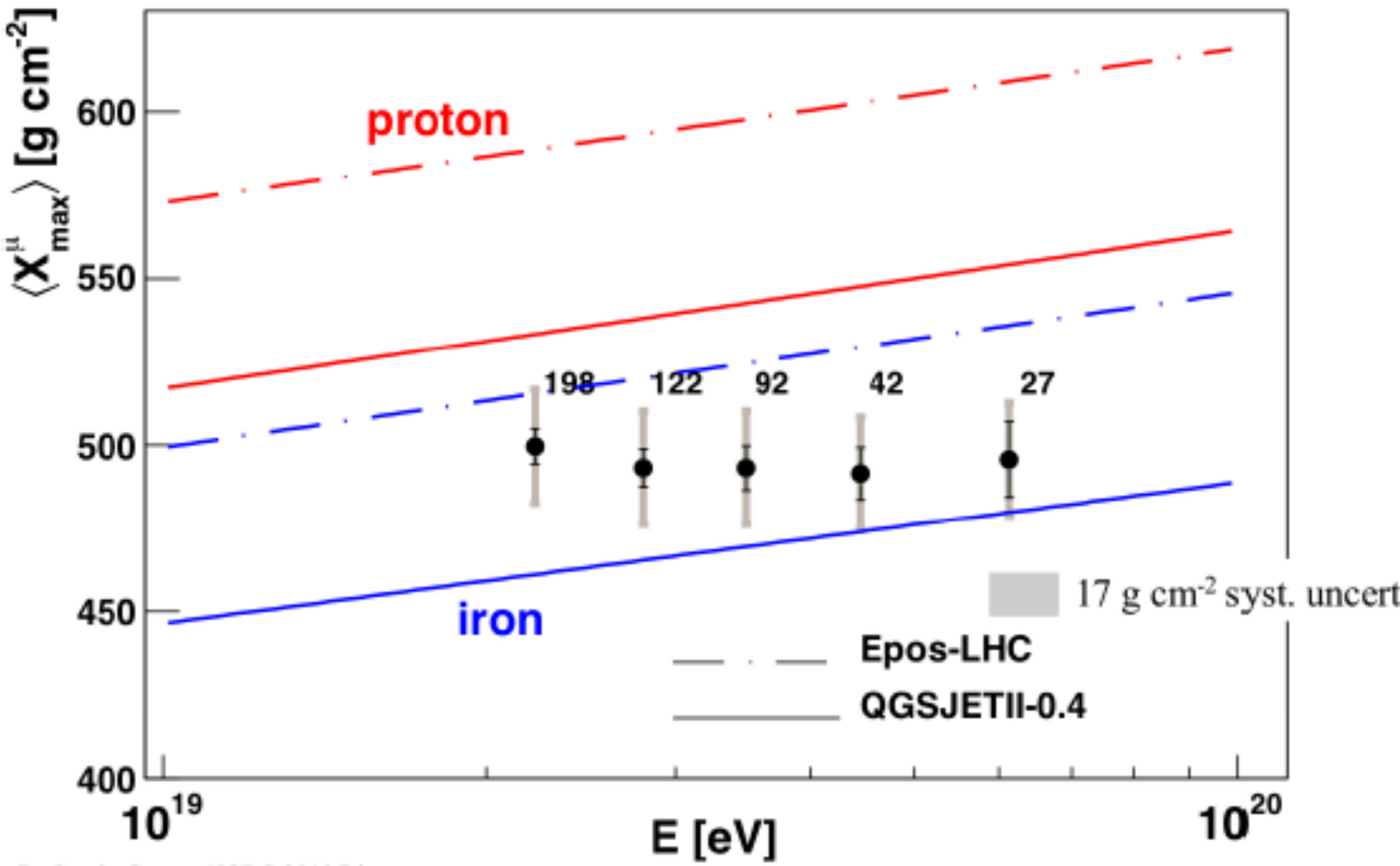
$$dN^{\mu}/dX^{\mu} \equiv MPD \xrightarrow{\text{Maximum}} X^{\mu}_{max}$$

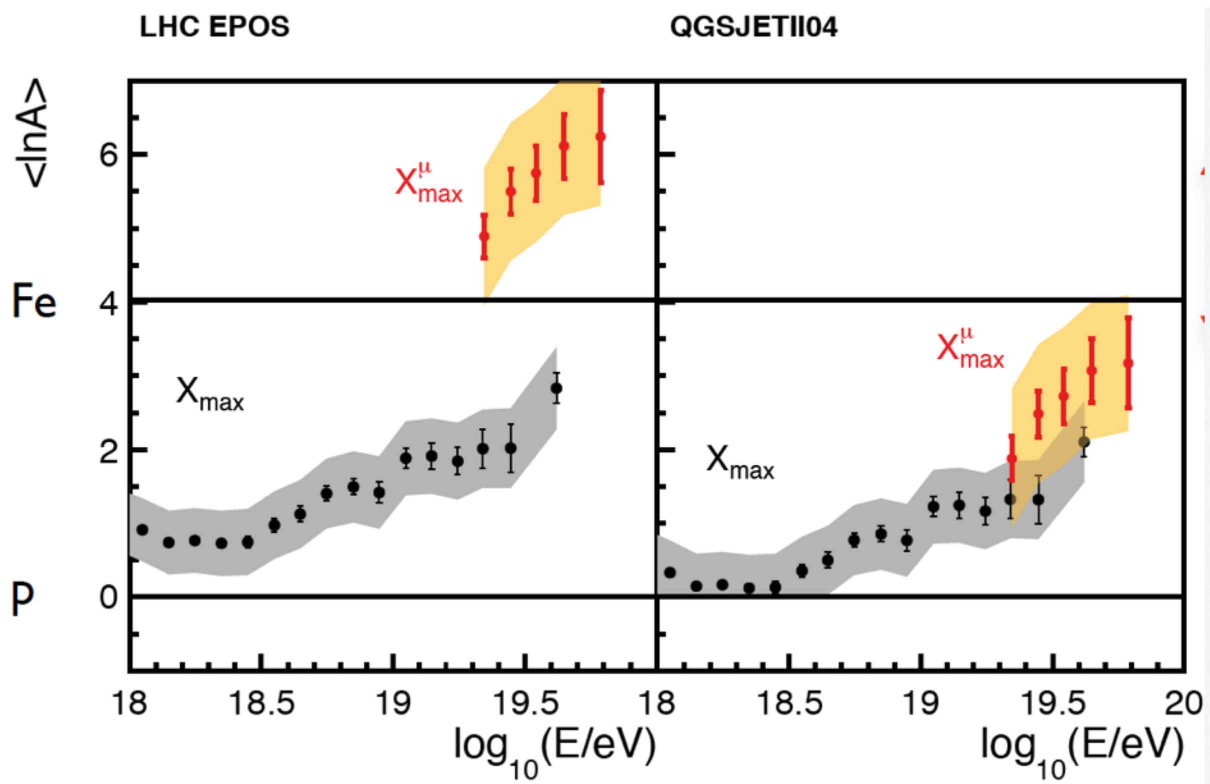
[55º,65º] ~~EM~~

X^{μ}_{max} results

Auger 2013 preliminary

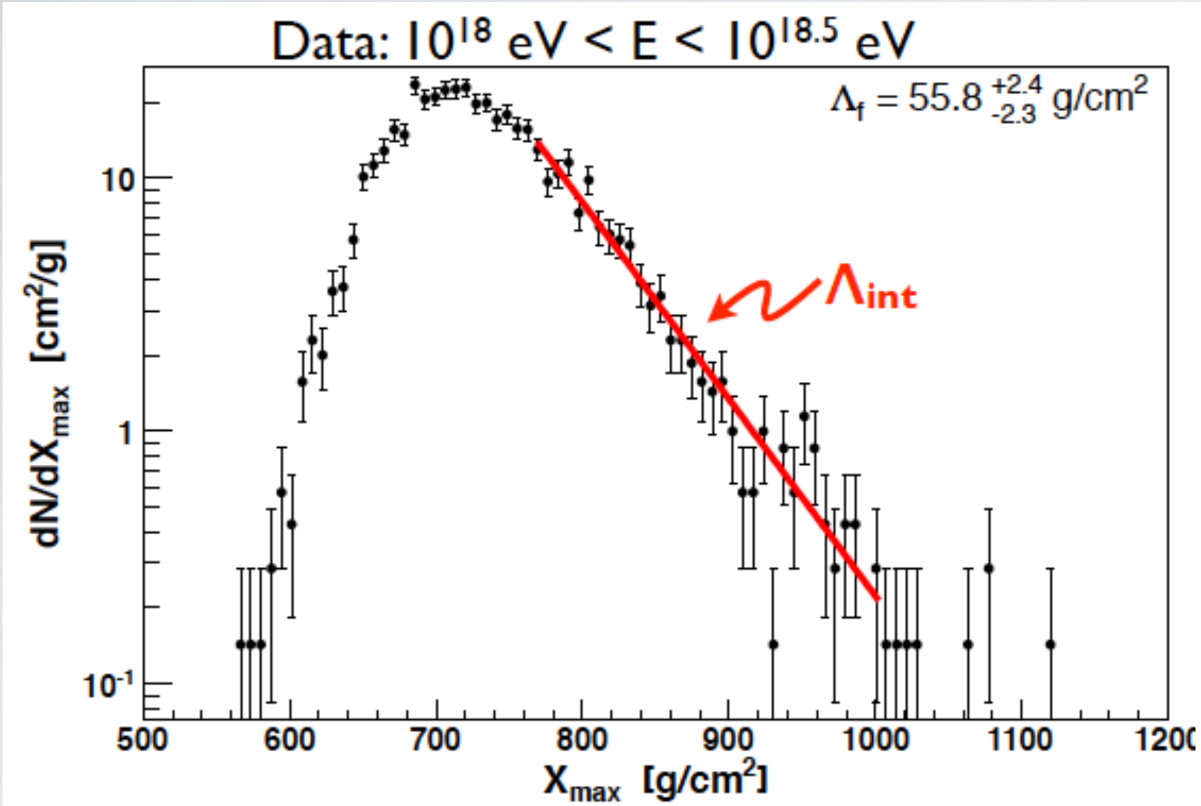


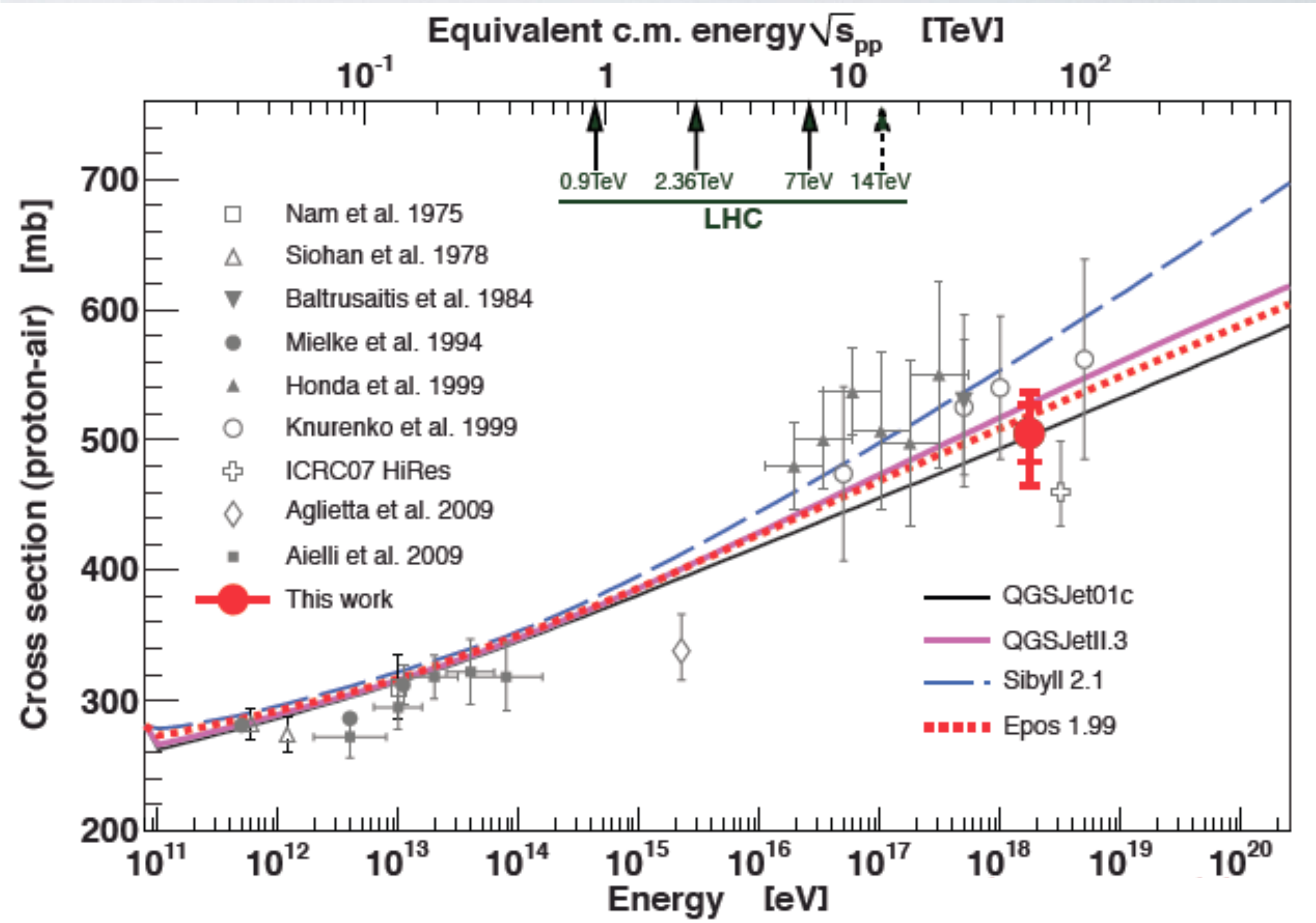




Additional constraints to hadronic interaction models!

CROSS SECTION MEASUREMENT





$$\sigma_{p-Air} = \frac{\langle m_{Air} \rangle}{\lambda_{int}}$$

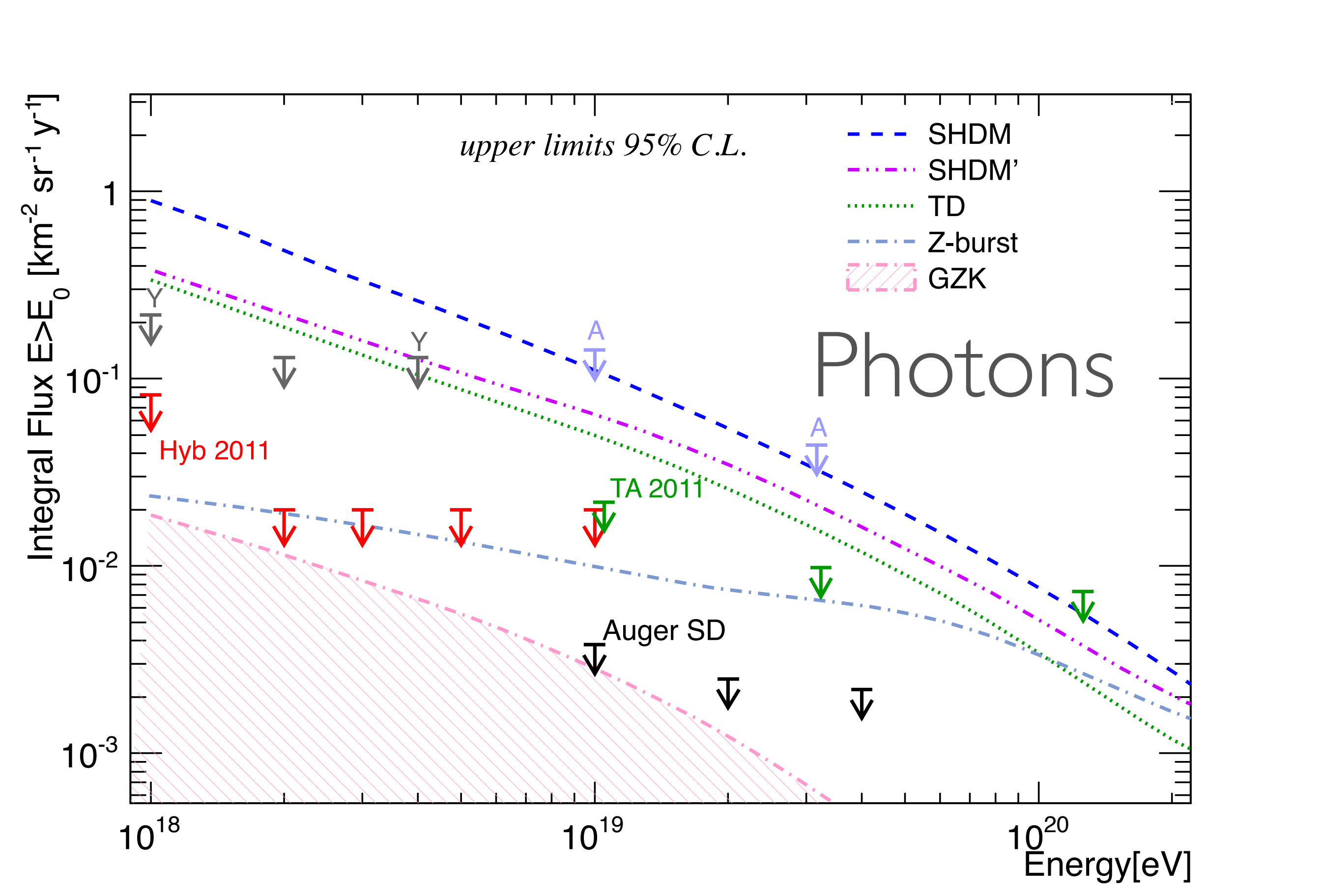
In practice: $\sigma_{p\text{-}Air}$ by tuning models to describe Λ seen in data

$$\sigma_{p\text{-}Air} = (505 \pm 22_{stat} (^{+26}_{-34})_{sys}) \text{ mb}$$

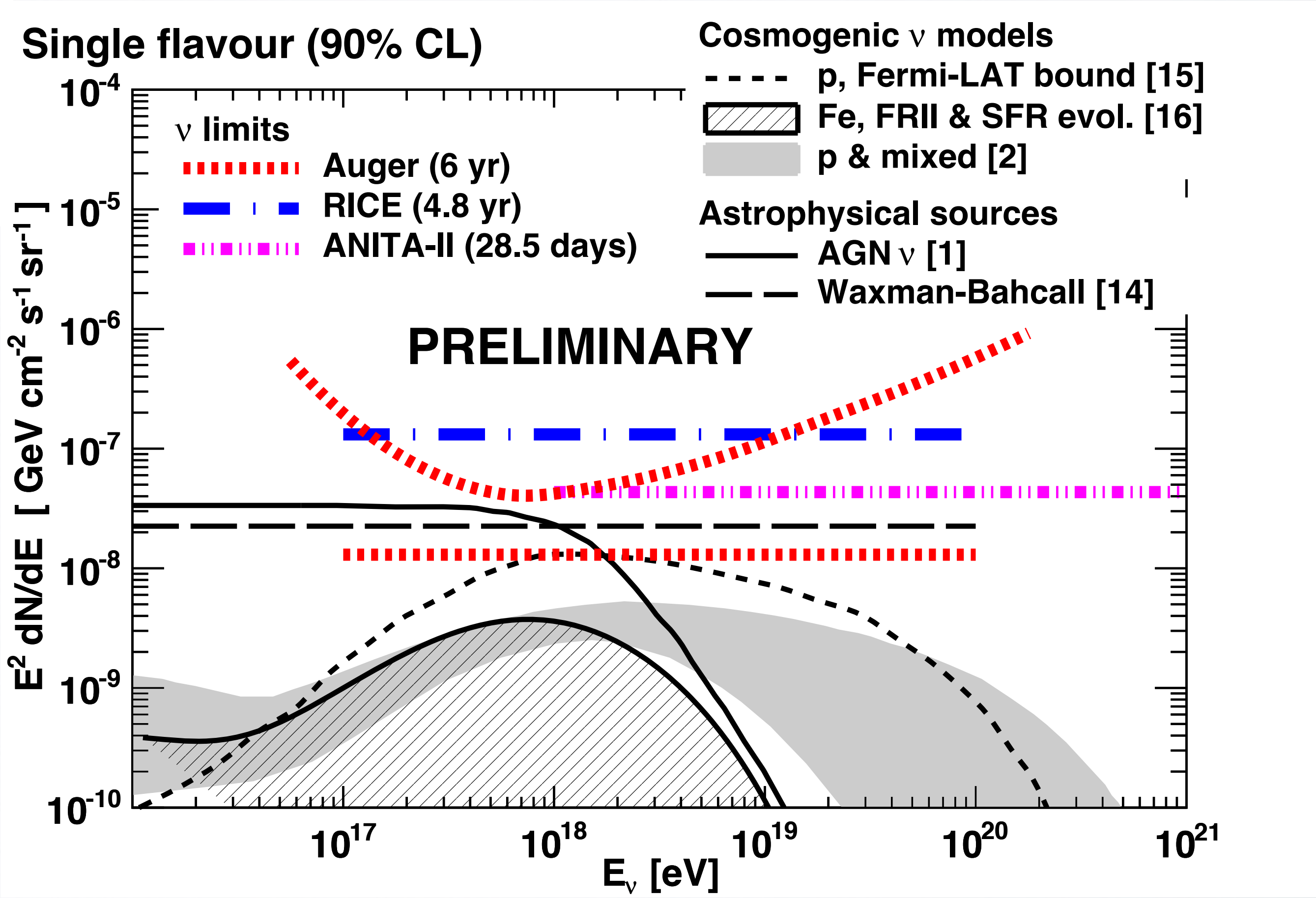
Contaminations assumed for systematics:

< 25% He < 0.5% γ

PHOTONS & NEUTRINOS



Neutrinos



Summary

AUGER provides a wealth of high quality data

Ankle range

Suppression range