Kavli Institute
for Cosmological Physics
at The University of Chicago

THE UNIVERSITY OF CHICAGO

Ultra high energy cosmic rays and neutrinos at the Pierre Auger Observatory

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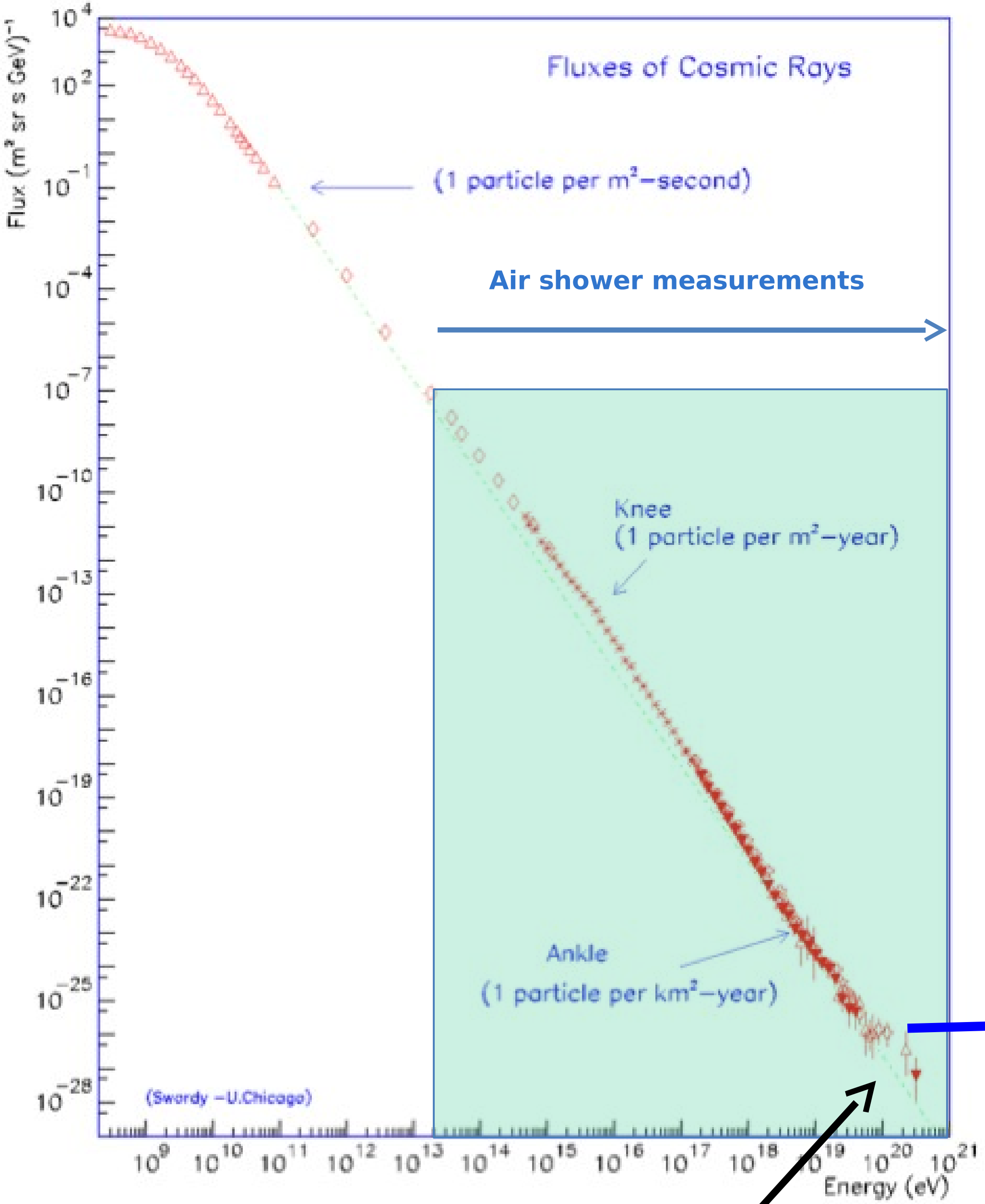
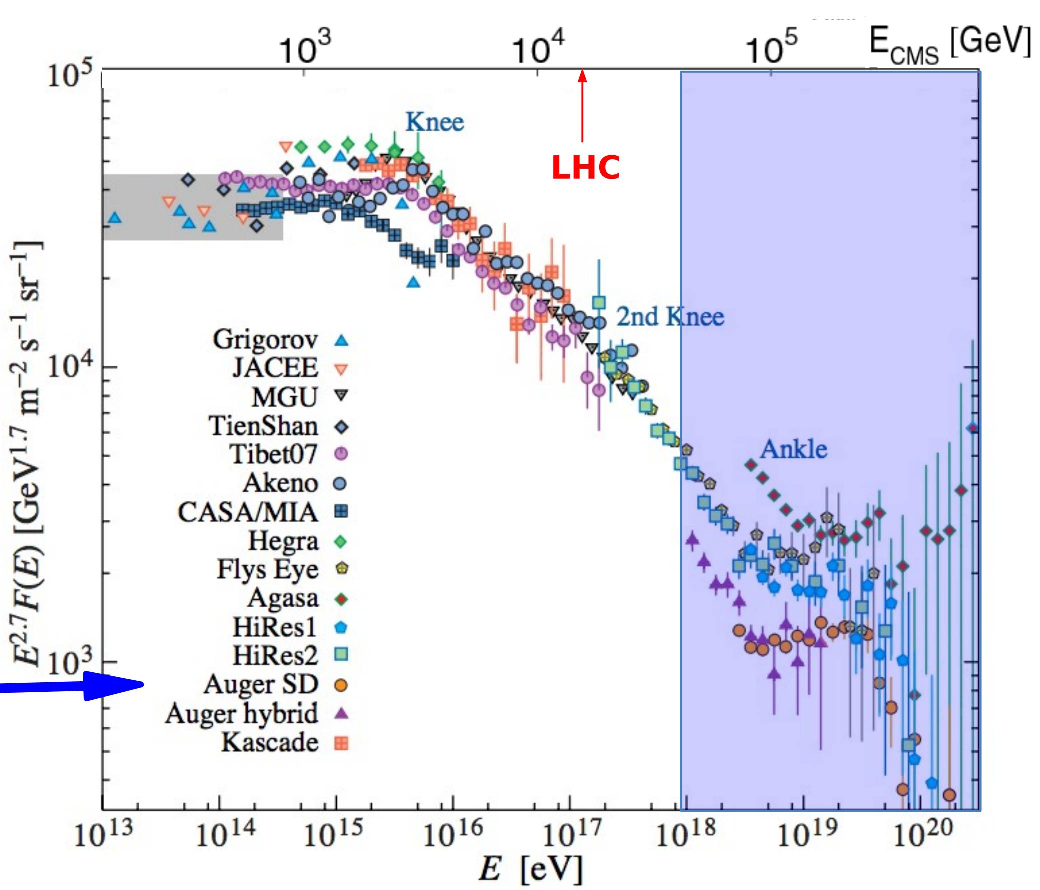
University of Chicago, Enrico Fermi Institute & Kavli Institute for Cosmological Physics

Phenomenology 2013 Symposium, Pittsburgh, May 6-8 2013.

UHECRs

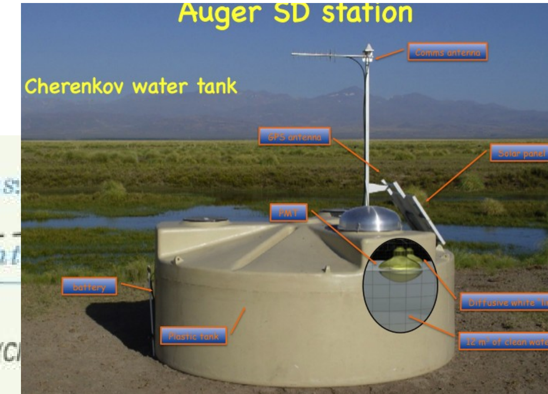




1 particle/km²/century

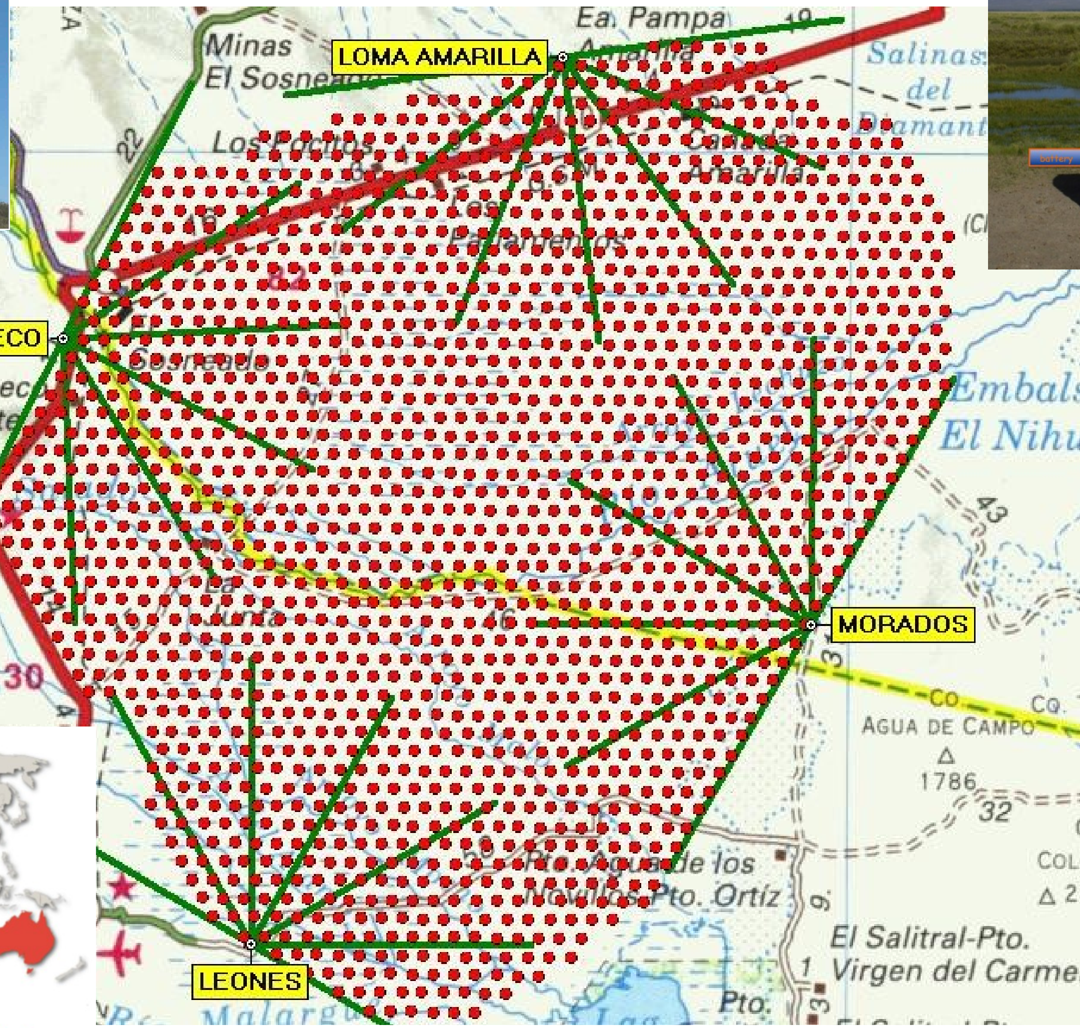
The Pierre Auger Observatory

3000 km^2



Fluorescence Detector

27 telescopes on 4 locations overlooking the array



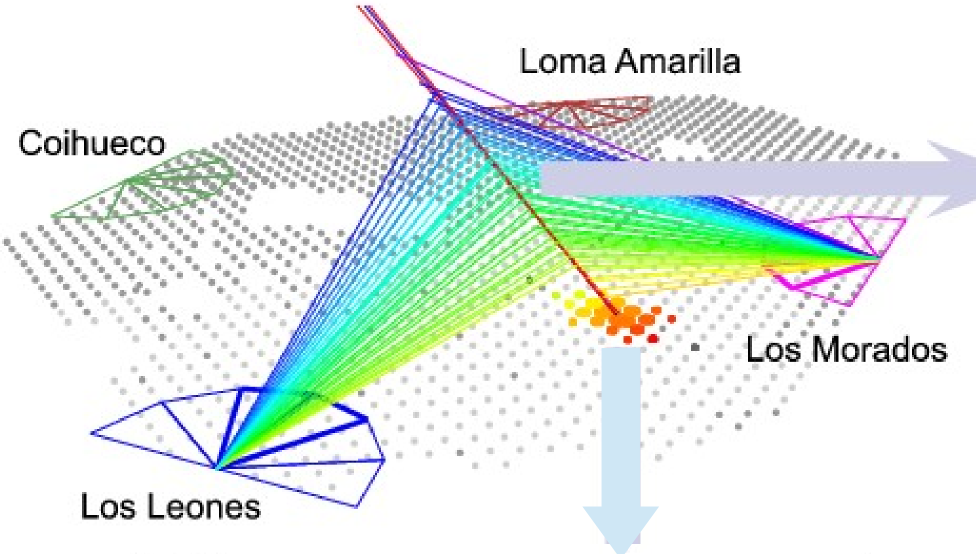
Surface Detector

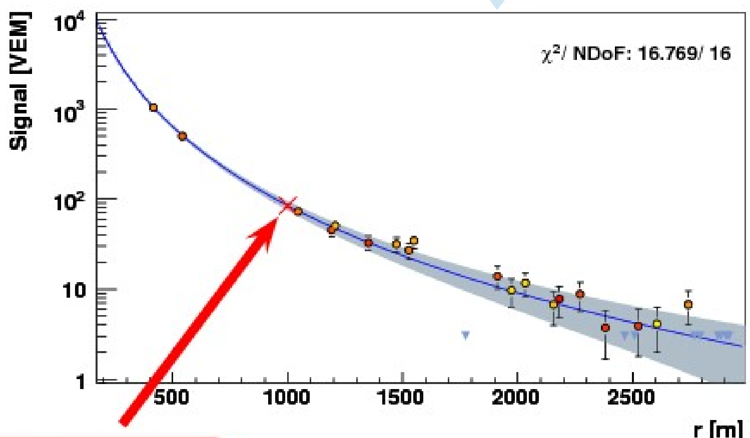
1660 water Cherenkov stations, spacing 1.5 km

17 countries, ~ 500 physicists

Hybrid detector: improve precision and reduce dependence on models

Auger: a hybrid detector





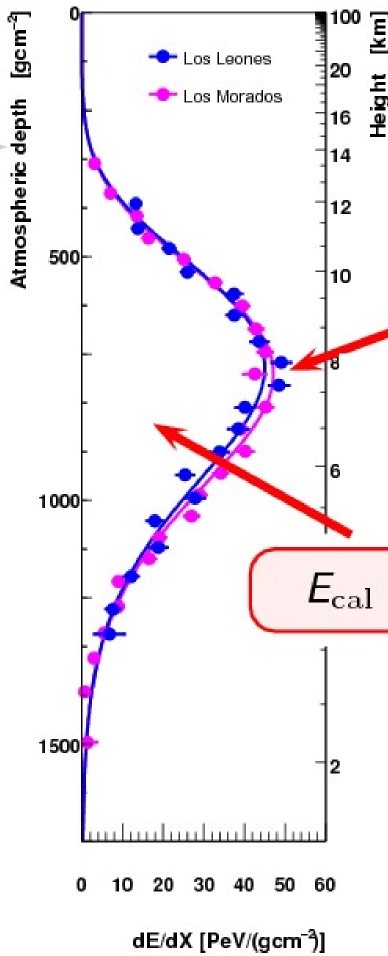
S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$

Surface Detector

Sample shower particles at ground

- 100% duty cycle (good for statistics)
- Energy threshold (full efficiency) 3 EeV
- Geometrical aperture (no MC calculation, no model/mass dependence)



Fluorescence Detector

UV photons (4 ph/particle/m) emitted in the de-excitation of the atmospheric nitrogen

$X_{\max}$

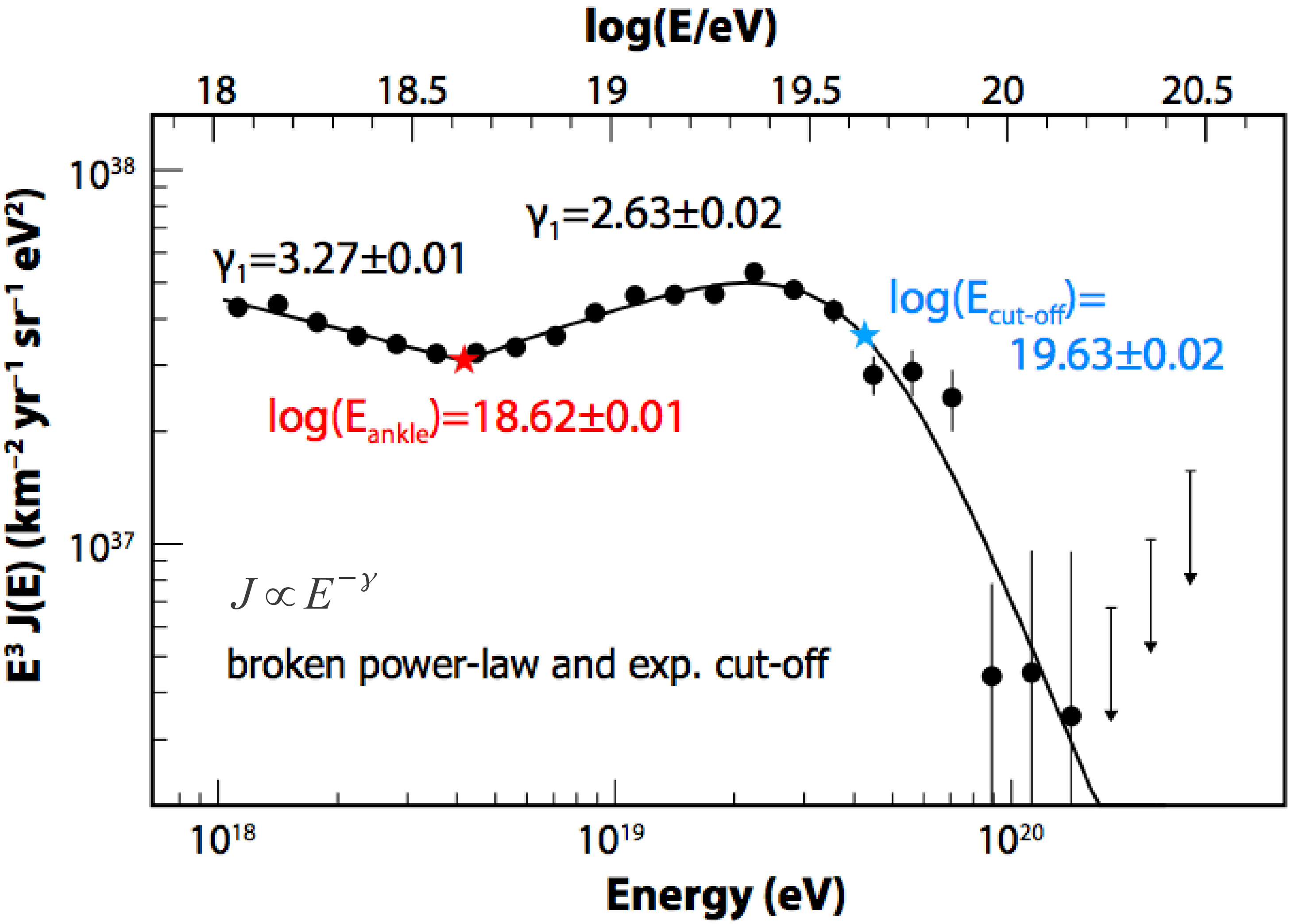
- Direct measurement of X_{max} → mass composition sensitivity

$E_{\text{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

- Calorimetric energy measurement → model independent
- 10% duty cycle (telescope, moonless nights)
- Lower energy threshold

“Golden hybrid” data sample:
- detector cross-calibration, systematics, cross-checks, etc.

Auger Spectrum

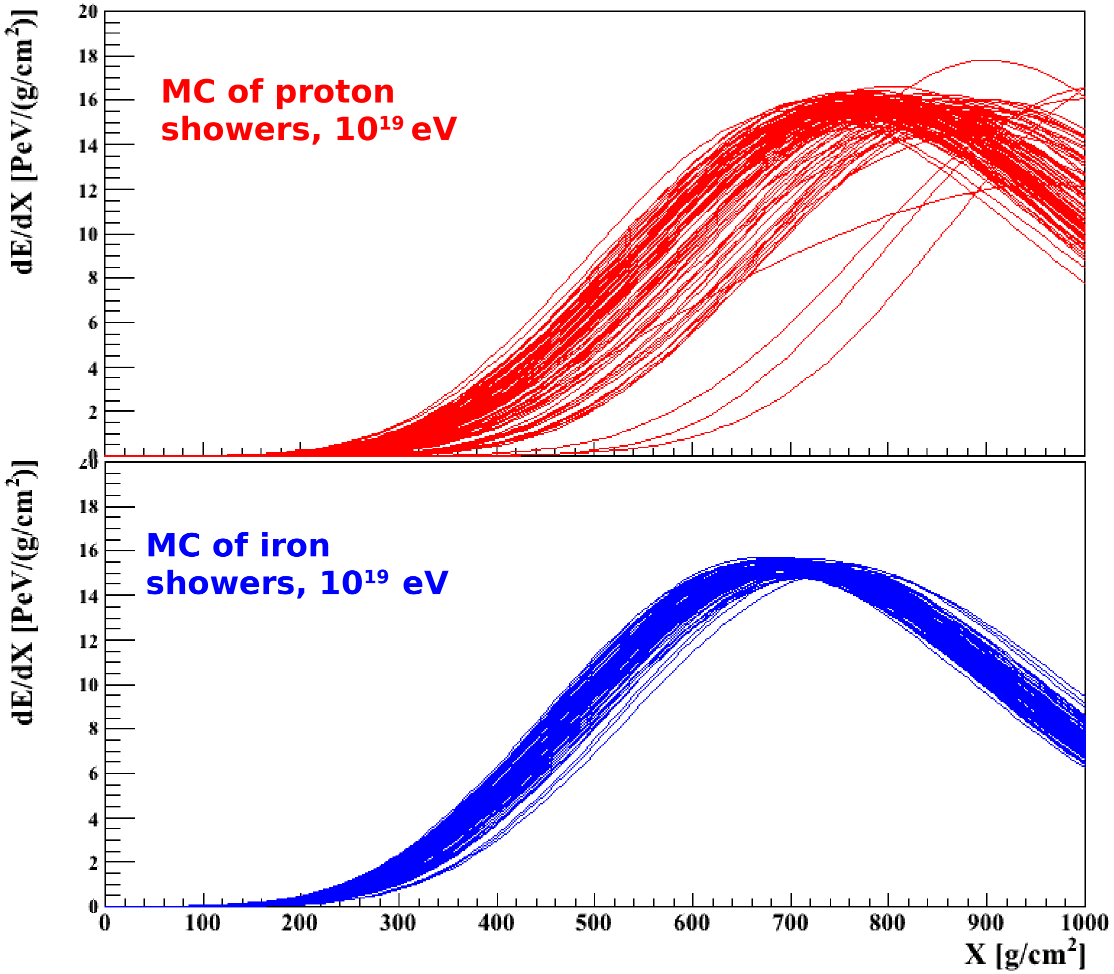


- Flux suppression determined with very high significance. GZK-like, but is it the GZK?

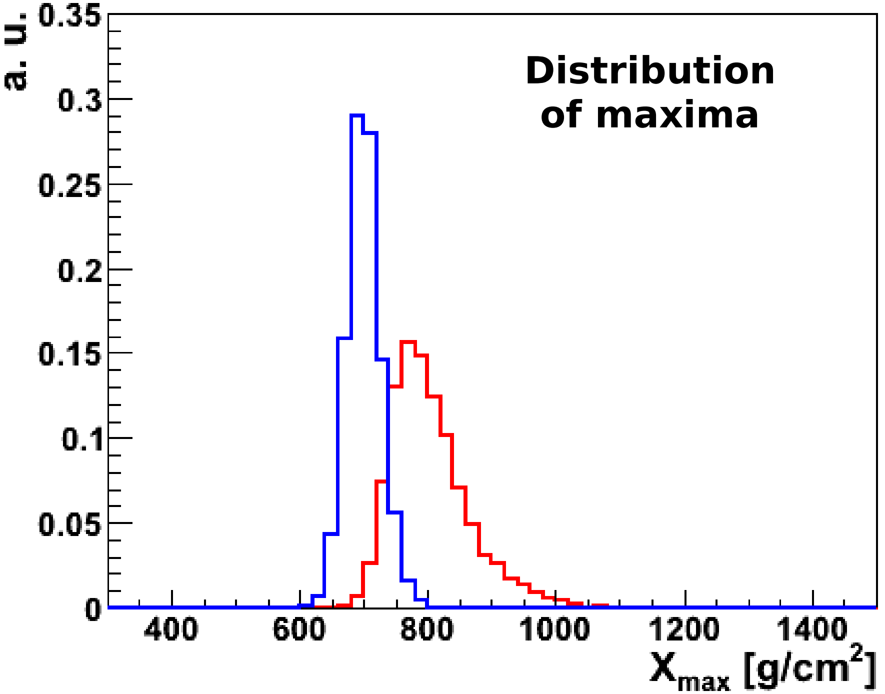
- Systematic uncertainty in the energy: 22%.

I will focus on mass <u>composition & p-Air cross</u> section and <u>neutrinos</u>.

The role of the FD: Longitudinal Profile



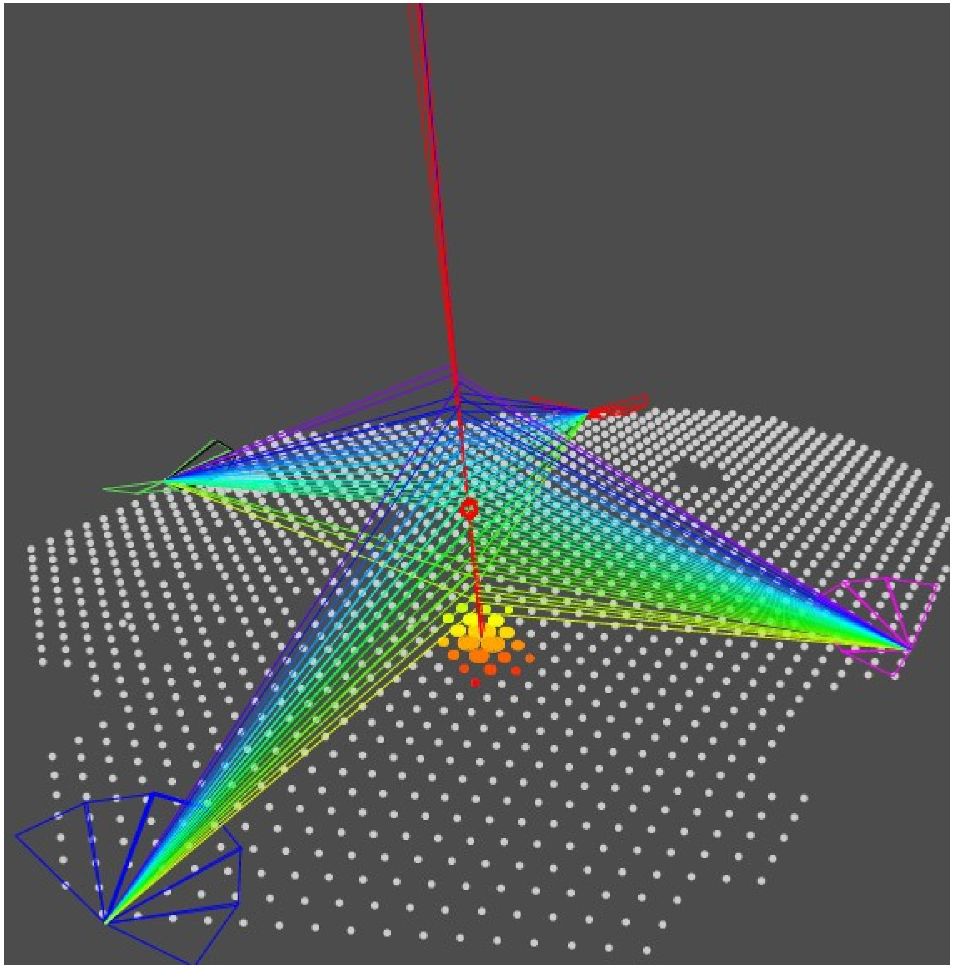
X_{max} reflects mainly the properties of the first interaction.

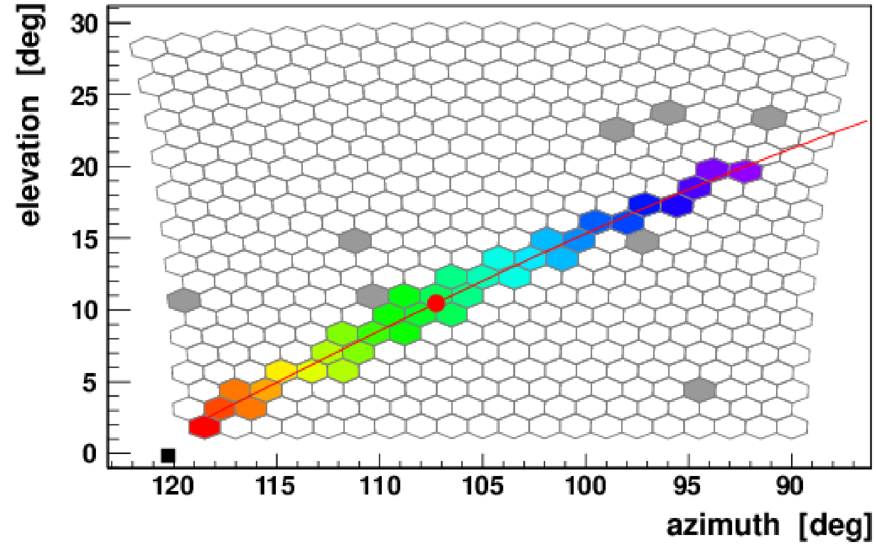


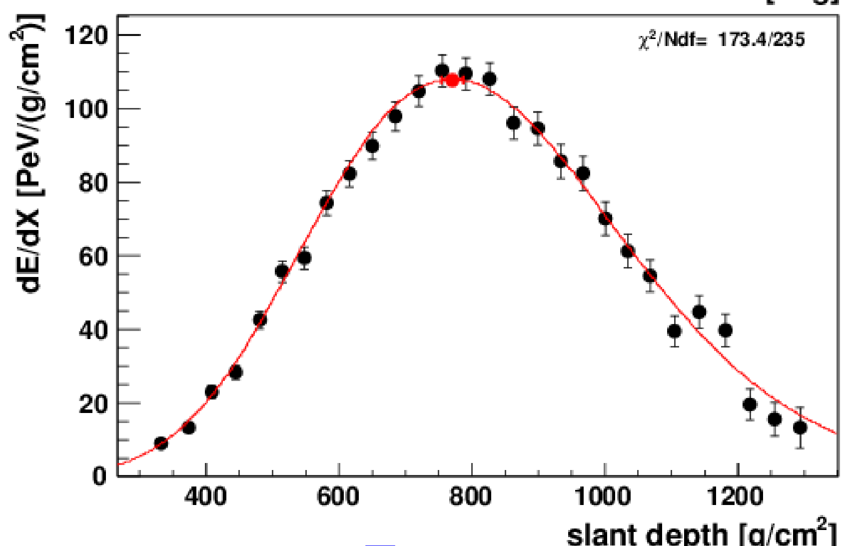
$$\langle X_{max} \rangle = \alpha(\ln E - \langle \ln A \rangle) + \beta$$

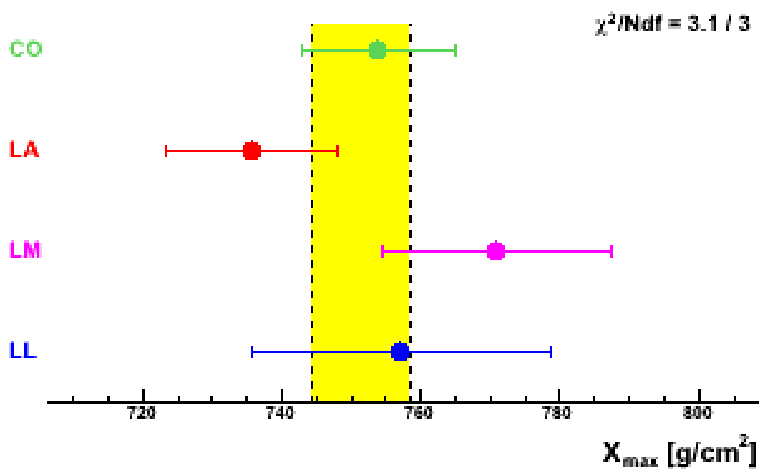
- X_{max} distribution, mean value, RMS and shape are sensitive to the shower primary mass composition
- The tail of the 'deep-shower' part of the distributions reflects the properties of the p-Air interaction (cross section measurement)

Shower development accessible through the FD









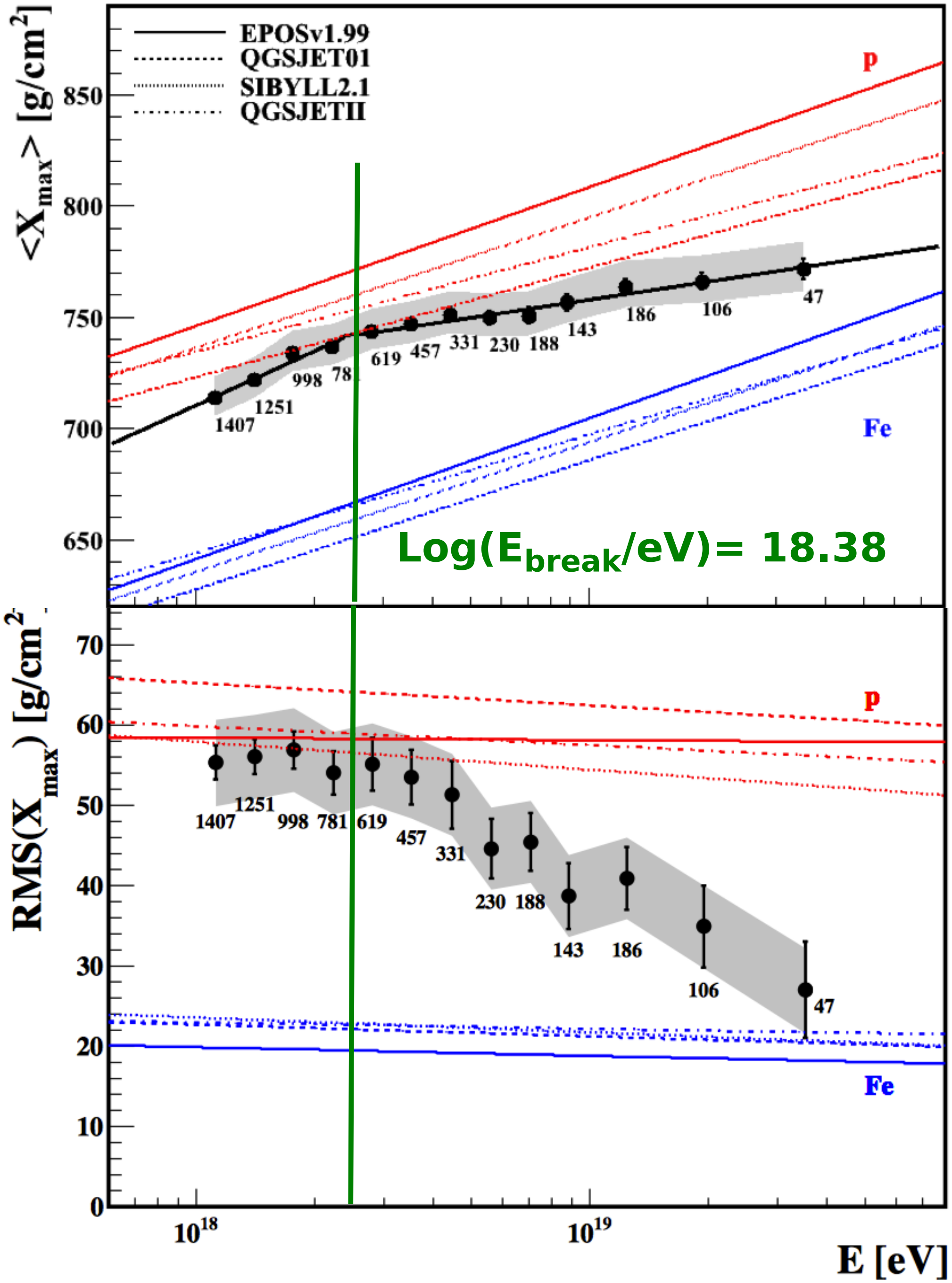
Energy

$E = (7.1 \pm 0.2)\ 10^{19}$ eV

Depth of the maximum

$X_{max} = (752 \pm 7)$ g/cm^2

<Xmax> and RMS from FD



6744 FD events (Jan 2004 – Dec 2010)

Elongation rate $D_{10} = \frac{d\langle X_{max}\rangle}{d\log(E)}$

Low energy	82^{+48}_{-8}	g/cm²/decade
High energy	27^{+3}_{-8}	g/cm²/decade

Data is best described using two different slopes.

At **low E**, consistent with a **significant number of protons**. At **high energies** <Xmax> **increases slowly with energy.**

The RMS becomes increasingly smaller at the joint of the 2 fits, towards the values expected for heavy primaries.

The shape of the distributions (and the RMS) **is heavy-like at high energy**.

Interpretation, especially at high energies, is difficult since it relies on the extrapolation provided by the different hadronic models.

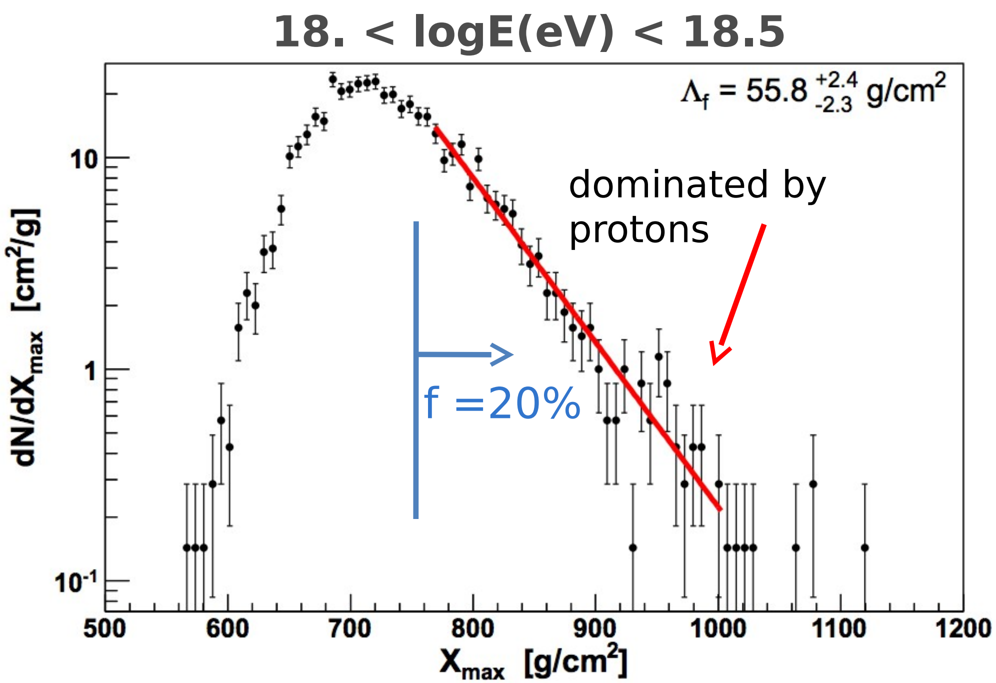
P. Facal, Auger Collaboration, Proc. ICRC11, Beijing.

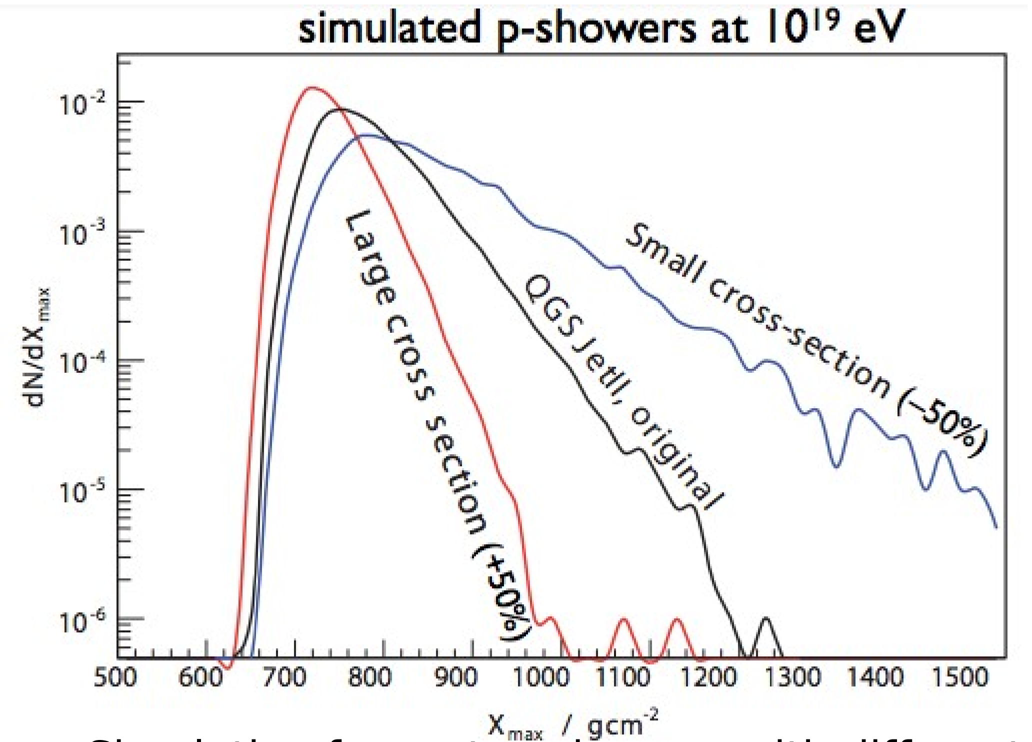
p-air cross section at 57 TeV

The tail of the Xmax distribution is sensitive to the proton-air cross-section

$$\frac{dN}{dX_{\max}} \propto e^{-\frac{X_{max}}{\Lambda_f}}$$

(f and E chosen to enhance the contribution from protons)





Simulation for proton showers with different cross sections: very good sensitivity of tail of distribution

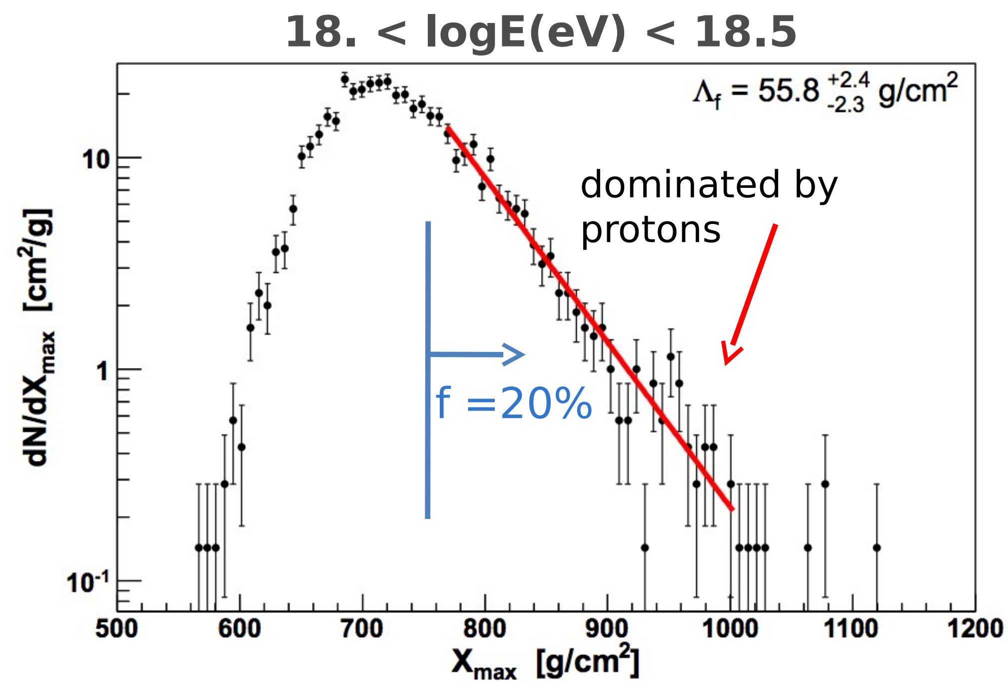
$\Lambda_f \rightarrow \sigma_{p\text{-air}}$

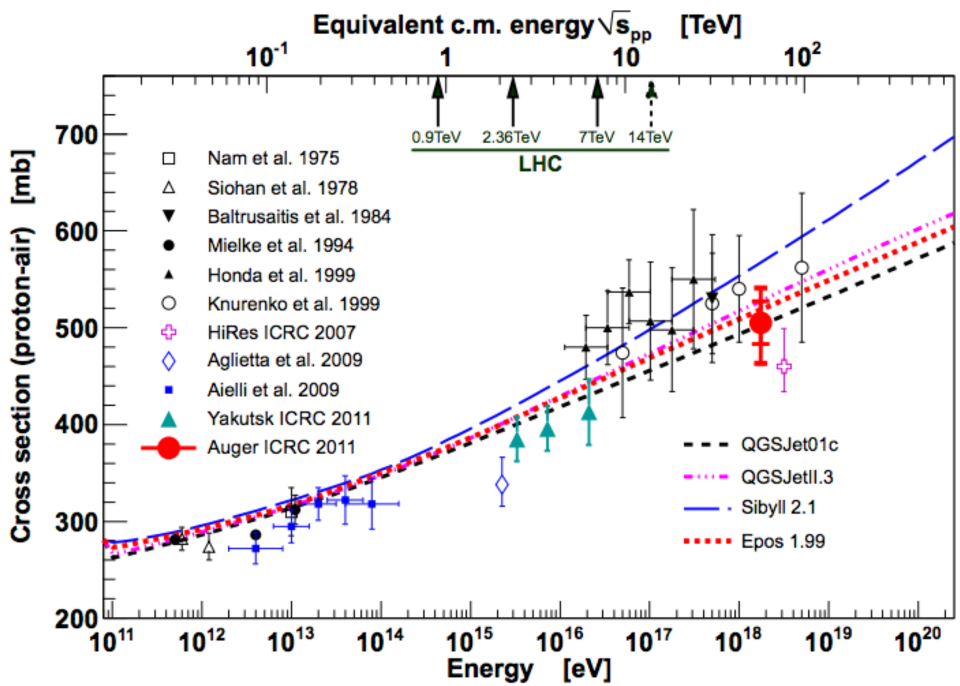
tuning models to describe the tail seen in data.

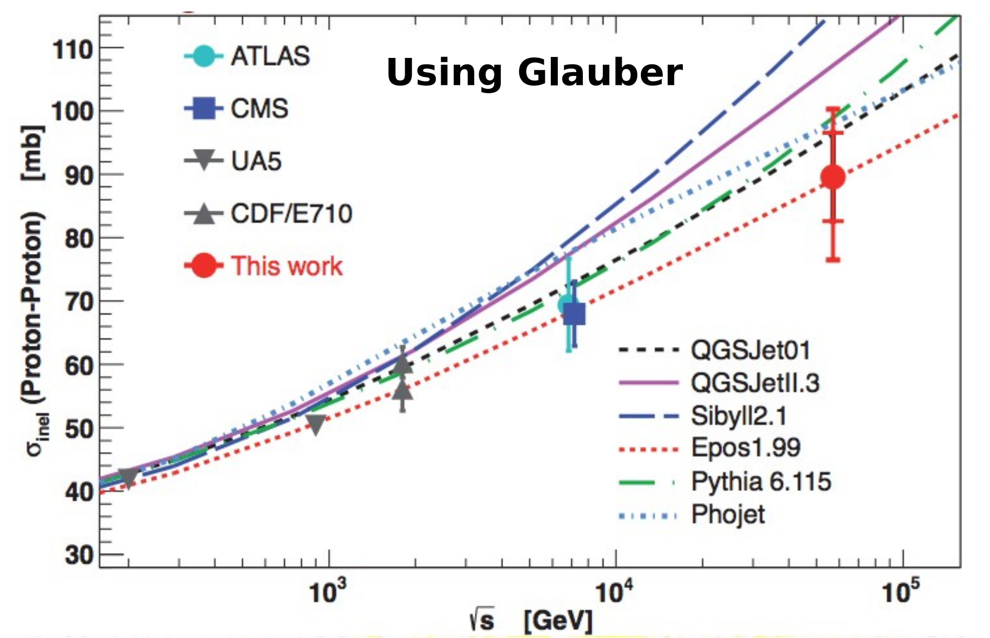
p-air and p-p cross section at 57 TeV

The tail of the Xmax distribution is sensitive to the proton-air cross-section

$$\frac{dN}{dX_{\max}} \propto e^{-\frac{X_{max}}{\Lambda_f}}$$





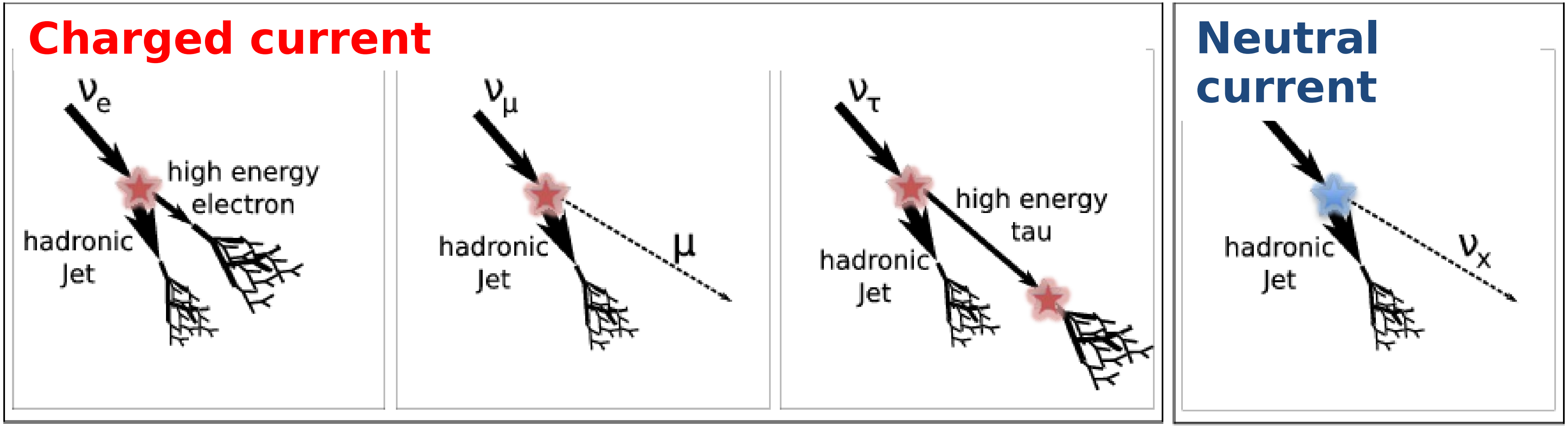


$\sigma_{p\text{-}air} = (505 \pm 22\ (\text{stat})\ ^{+28}_{-36}\ (\text{sys})\ )$ mb

$$\sigma_{pp}^{inel} = \left[90\ \pm 7_{stat}\ \left(^{+9}_{-11}\right)_{sys}\ \pm 1.5_{Glauber}\right]\ \text{mb}$$

$$\sqrt{s_{pp}} = [57\ \pm 6]\ \text{TeV}$$

UHE neutrino-induced showers



Up-Going: Earth-skimming tau neutrinos

↑ τ’stravel large distances in the Earth not losing too much energy before decaying close to the detector

↑ ↓ Sensitivity to ν_τ CC channel

↓ Small solid angle: ≈ 90-95°

↑ Dense mass target (Earth crust)

Down-Going: ν’s interacting deep in the atmosphere

↑ Sensitivity to ALL ν flavours

↑ Sensitivity to ALL weak interaction channels CC & NC

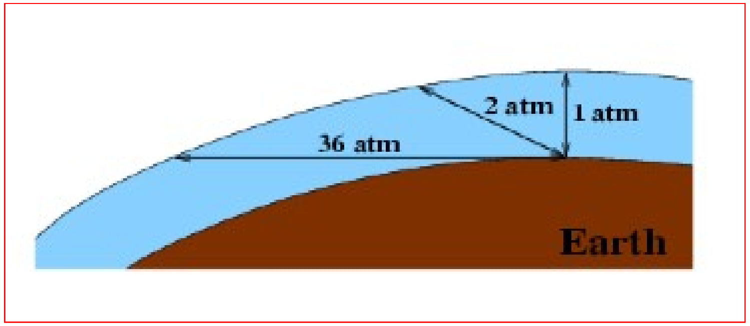
↑ Large solid angle: 60° →≈ 90°

↓ Dilute mass target (air)

Surface Detector Measurement

Identifying neutrino showers with the Auger SD

Look for INCLINED & DEEP showers



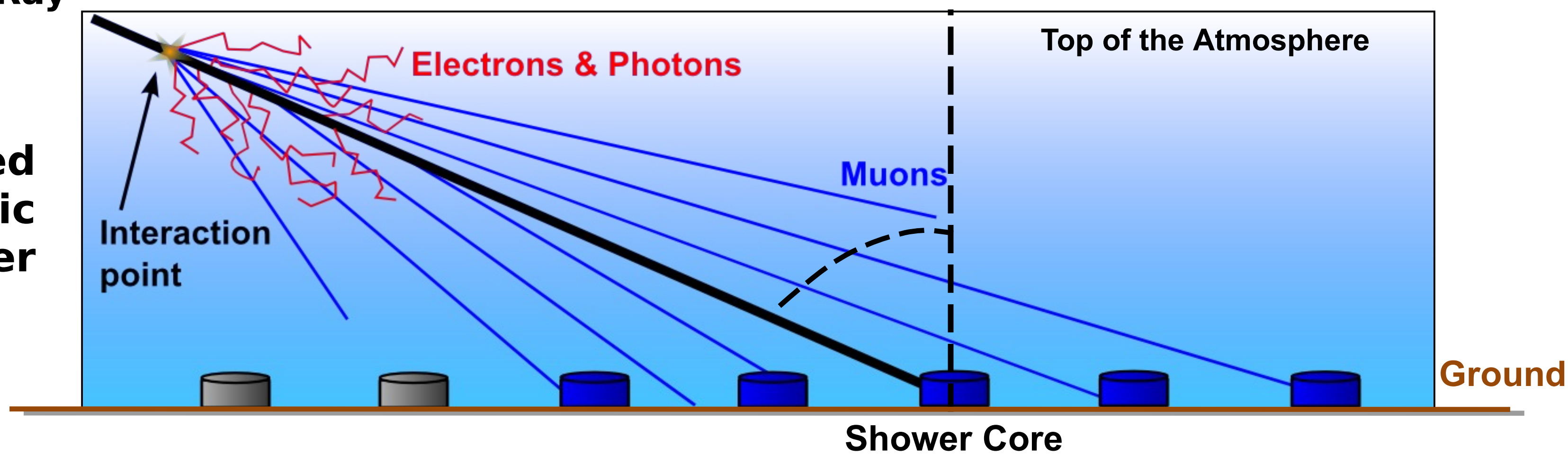
Atmosphere @ Auger site

Vertical ≈ 880 g cm^{-2}

Horizontal ≈ 32000 g cm^{-2}

Primary Cosmic Ray

Regular inclined hadronic shower



OLD shower (develops far from the detector): Electromagnetic (EM) component absorbed in the atmosphere: only muons survive.

Identifying neutrino showers with the Auger SD

Look for INCLINED & DEEP showers

Basis of identification: broad signals in the early region of an inclined shower

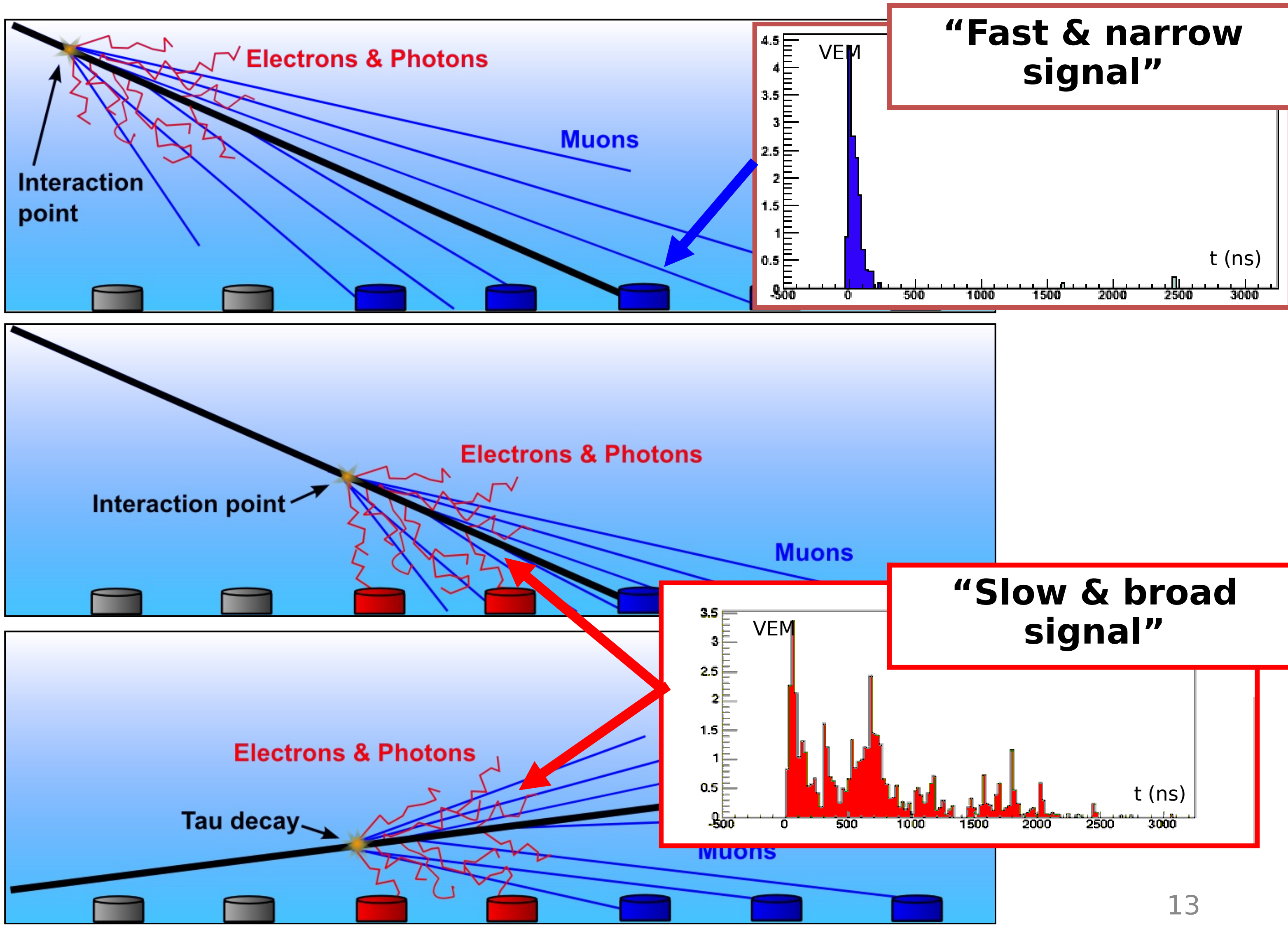
Regular hadronic shower

OLD shower

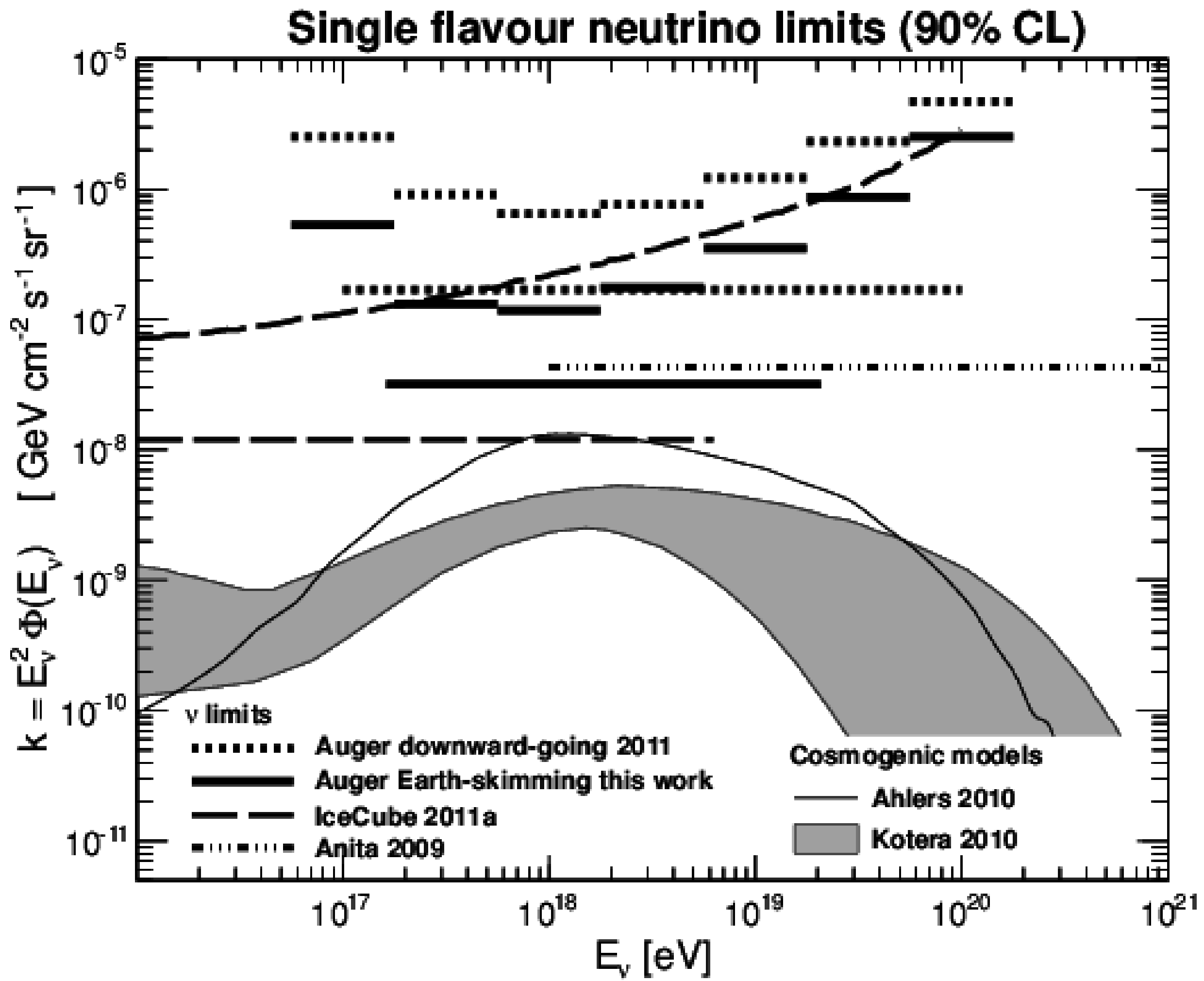
Deep DOWNGOING neutrino shower

YOUNG showers

Deep UPGOING neutrino shower



Auger neutrino limits



Independent limits for up-going and down-going.

Analysis based of Fisher discriminants, with a training data sample (excluded from the limit).

Blind search produces no candidates.

Aperture calculated by MC

Most competitive over 10 EeV

Outlook

The Auger Observatory studies Astrophysics and Particle Physics at the highest energies.

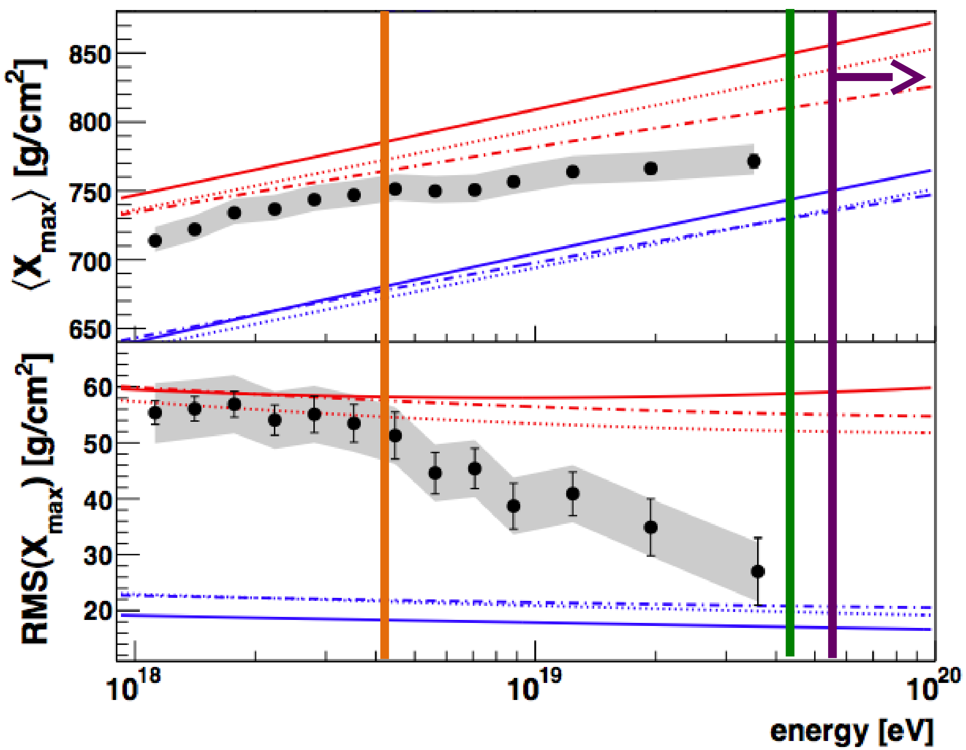
Mas composition: significant number of protons at lower energies, heavier like features at higher energies.

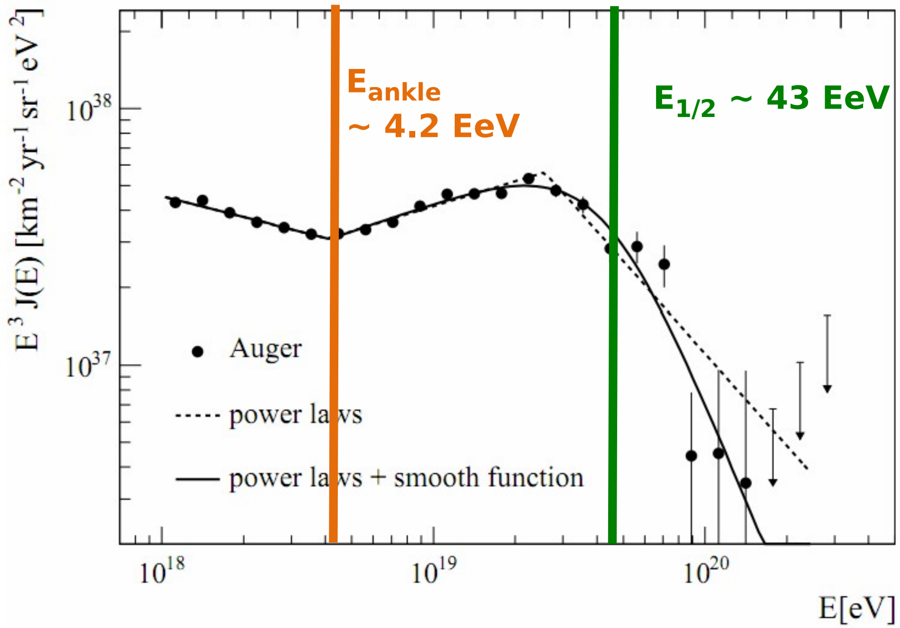
P-Air cross section measurement at 10 EeV, compatible with recent measurements from LCH.

Neutrinos: limit on the flux diffuse flux at the highest energies. Several years of data needed to explore cosmological neutrino models.

Results being updated for the ICRC 13 in Rio (August)

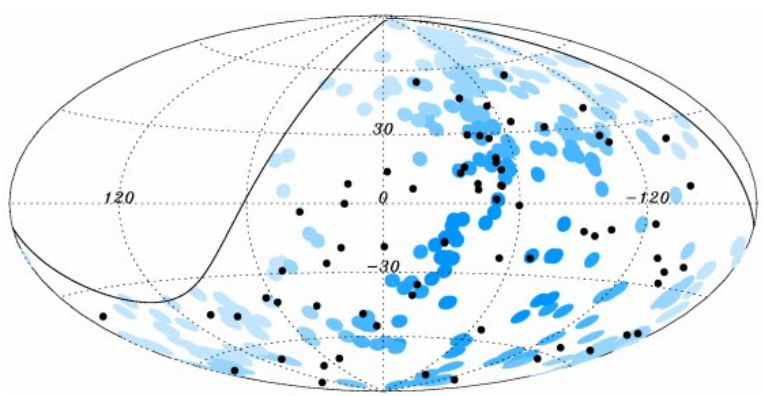
The UHECR 'puzzle'





Flux suppression firmly established

E > 55 EeV



Correlation of arrival directions with nearby matter consistent with protons above 55 EeV.

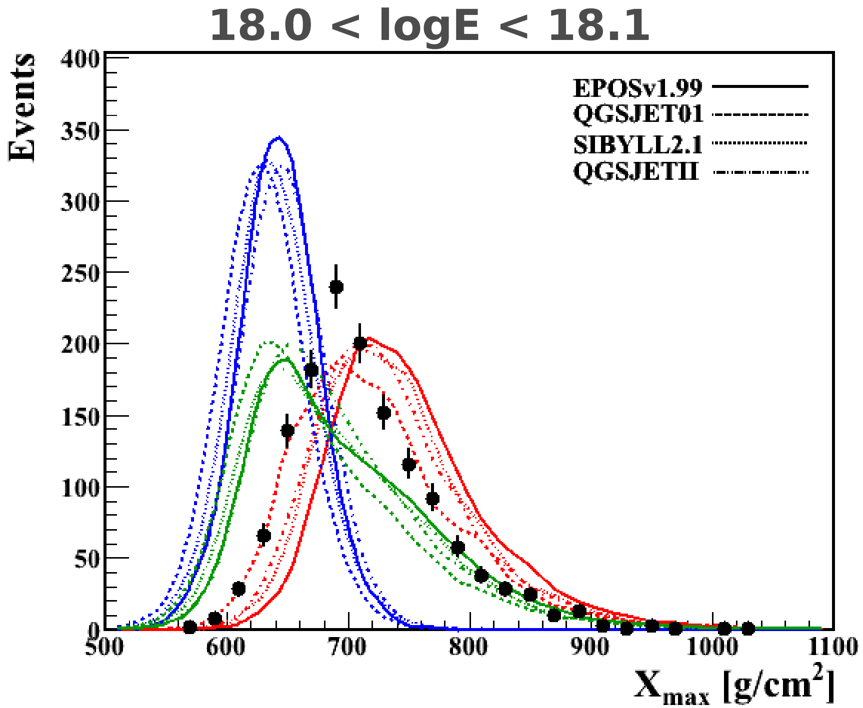
X_{max} would indicate a significant amount of heavy nuclei, but no data at the correlation energies.

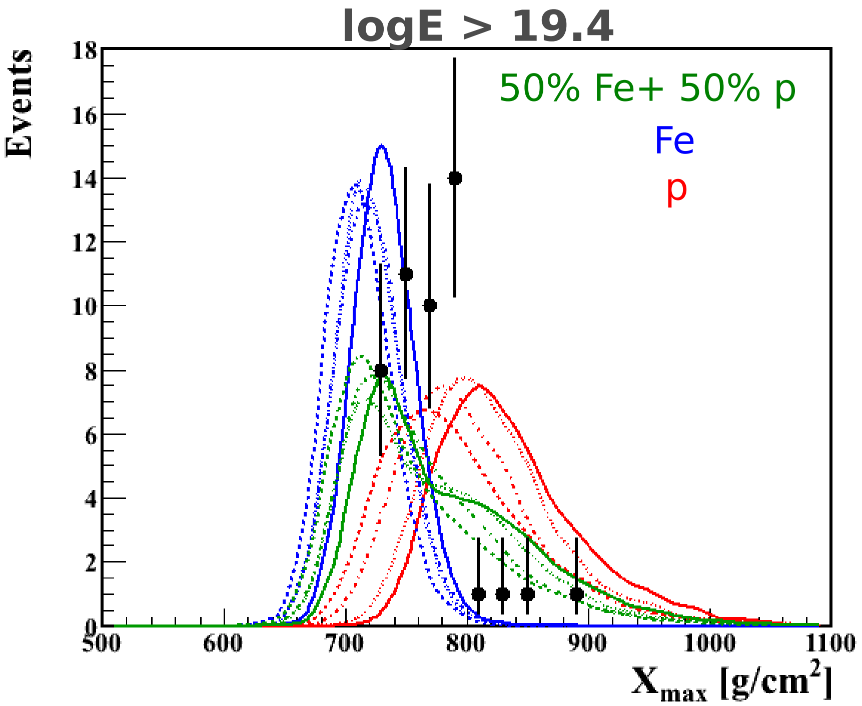
Statistics is limited: only ≈30 events/year with $E > 5.5 \cdot 10^{19}$ eV. No hybrid aperture.

The situation is still quite puzzling ...

Important to develop new detection techniques for large area coverage, 100% duty cycle, X_{max} measurement, low cost

X_{max} distributions





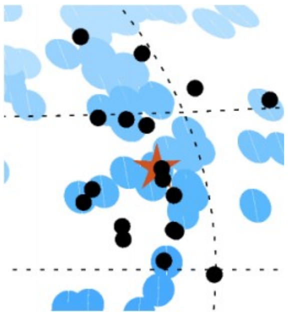
- As **energy increases**: **narrower distributions** and Xmax tail less evident, **more symmetric distributions**.
- For **low energies,** shape compatible with a **significant fraction of protons**.
- The shape of the distributions (and the RMS) **is heavy-like at high energy**.

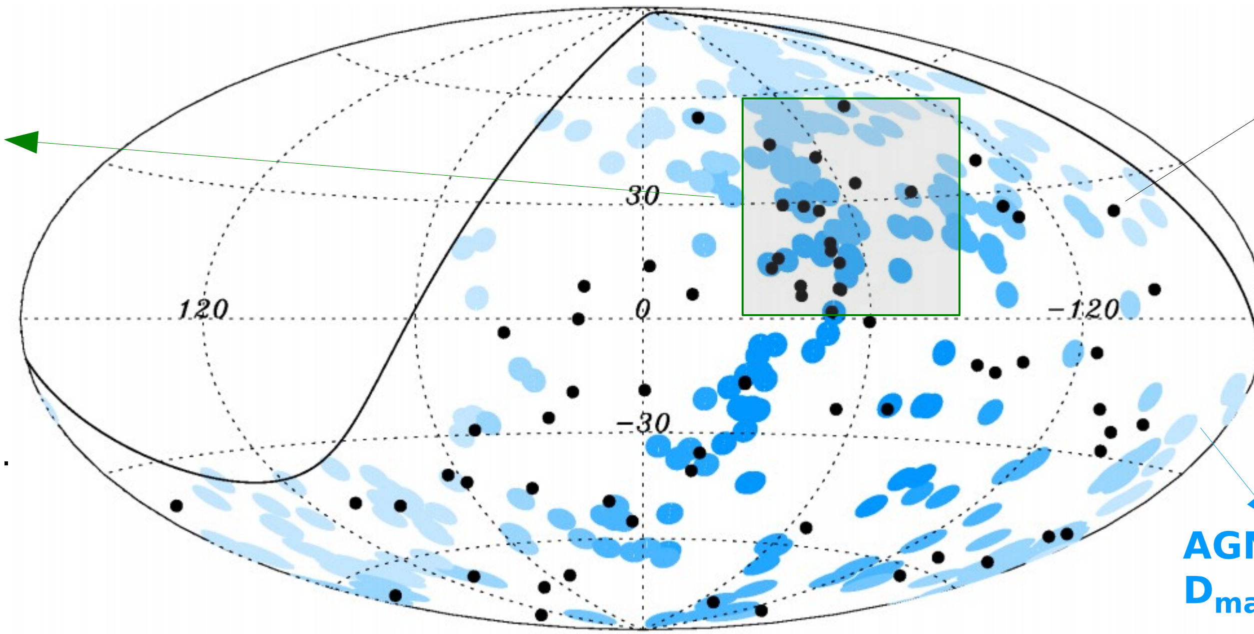
Any interpretation, especially at high energies, is difficult since it would rely on the extrapolation provided by the different hadronic models.

New models including LHC data at 7 TeV coming soon!

Arrival directions: correlation with AGN catalog (VCV)

AGN trace matter content of the Universe

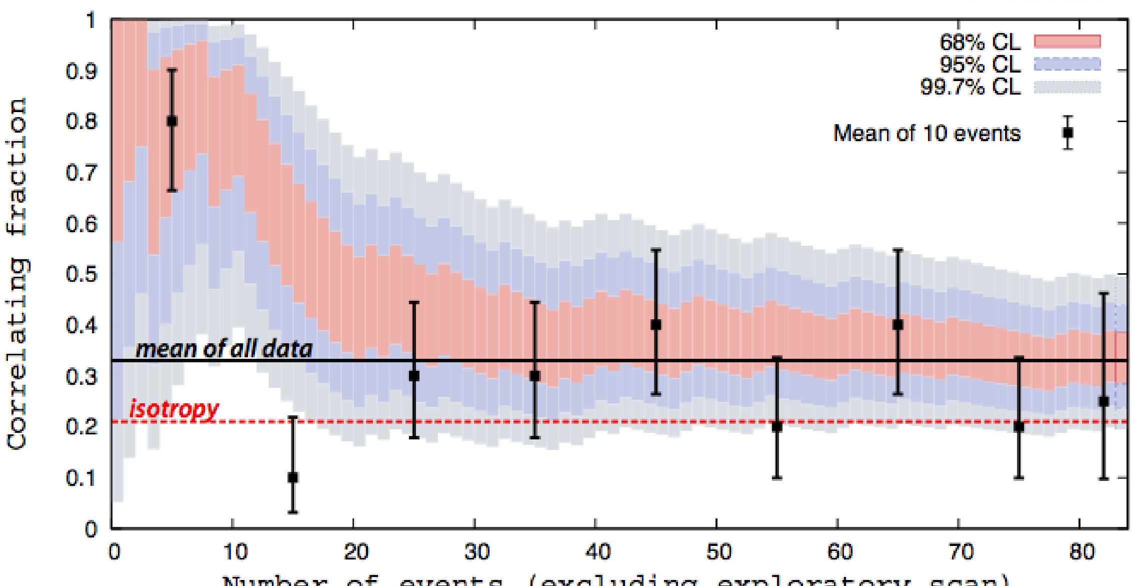




83 events, E_{min}= 56 EeV

A posteri hint of accumulation around Cen-A (closest radio AGN).

AGN Catalog, D_{max}= 75 Mpc, θ = 3.1°



Correlating fraction 33±5%, while expected for isotropic sample 22%

Isotropy rejected at 99% CL

With this degree of correlation several years of new data required for a 5σ significance

Data Sample & Selection

Data Sample: Fluorescence Detector events with signal in at least 1 Surface Detector station from December 2004 to September 2010

Hybrid events: _geometry_ determined with 0.6° uncertainty

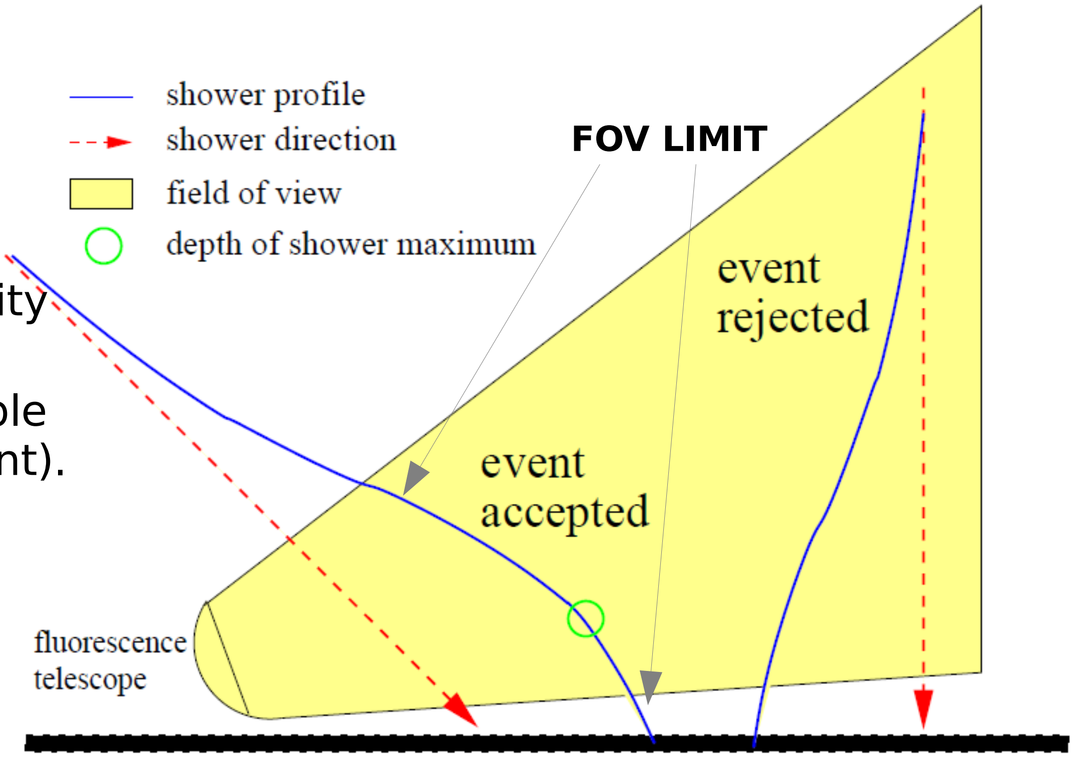
Selection of high quality events:

- Low aerosol content (vert. opt. depth > 0.1) & cloud coverage (<25%).
- χ^2/Ndf < 2.5 for profile fit
- Statistical uncertainty X_{max} < 40 g/cm^2
- Angle between shower and telescope > 20° (avoid high Cherenkov fractions)
- X_{max} observed

15979 events pass this quality selection [E > 10^{18} eV].

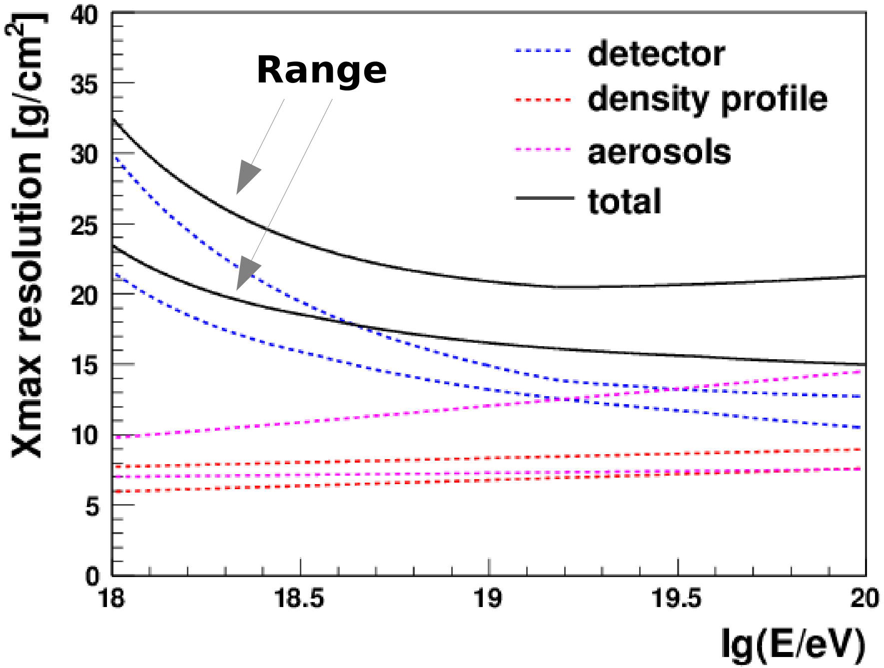
Unbiased selection:

- Select the distance to the SD station, and zenith angle so that the tank trigger probability does not depend on the mass of primary
- Select event geometries that allow to sample the whole X_{max} distribution (from measurement).



6744 events selected

How well do we reconstruct X_{max} ?

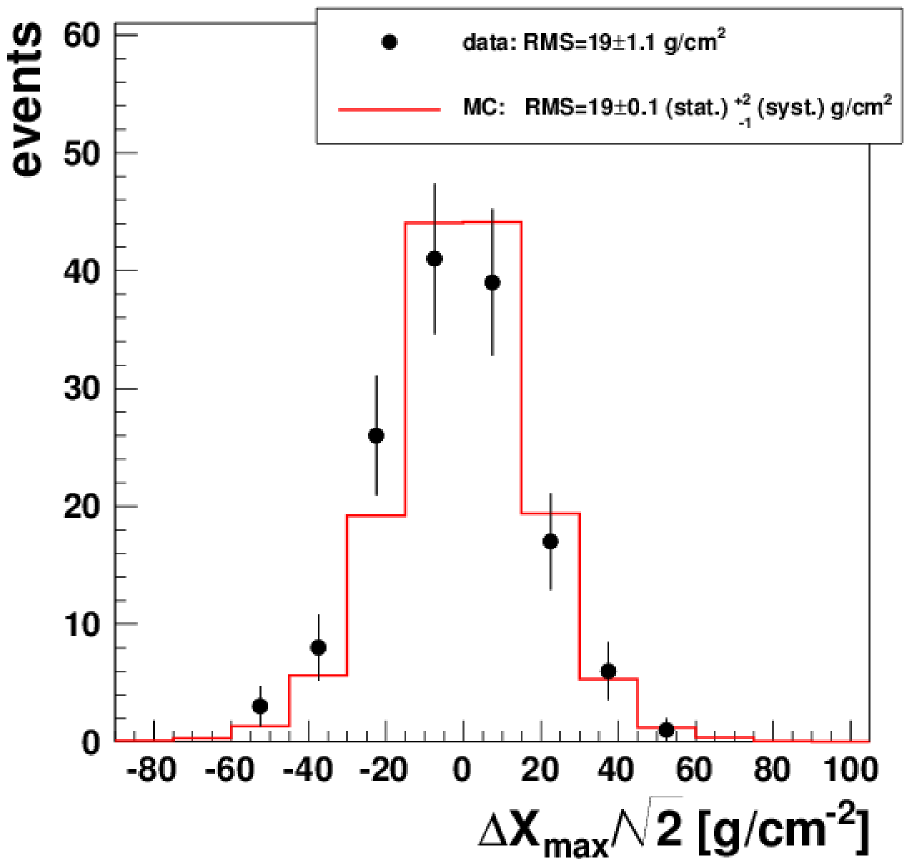


X_{max} resolution from MC ~ 20 g/cm²

Energy dependent: low energy events have less signal and smaller tracks. At high energy, events are farther away and aerosol content uncertainty dominates.

Validated with events observed by more than one FD station

Crucial for RMS(X_{max}) measurement where X_{max} resolution is subtracted



Systematic Uncertainties

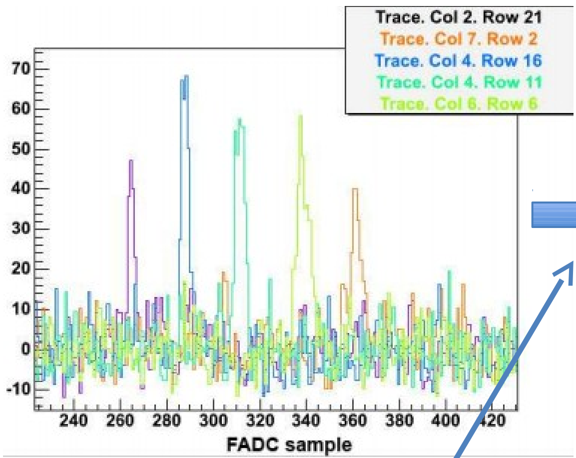
X_{max} → from 10 to 13 g/cm²

RMS(X_{max}) → 5 g/cm²

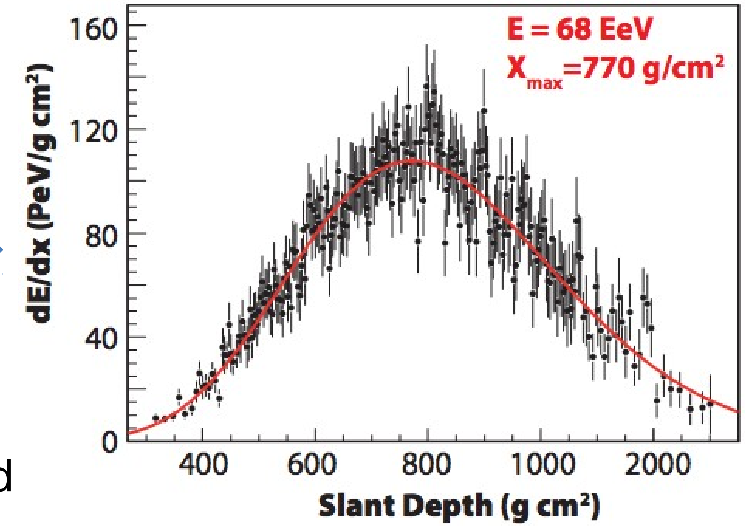
FD Event reconstruction

Geometry reconstruction: timing information from FD and 1 SD station.

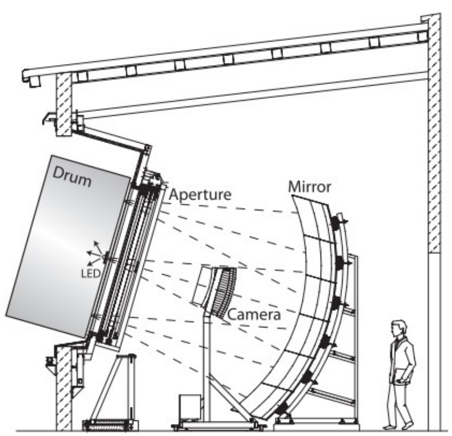
Profile Reconstruction:



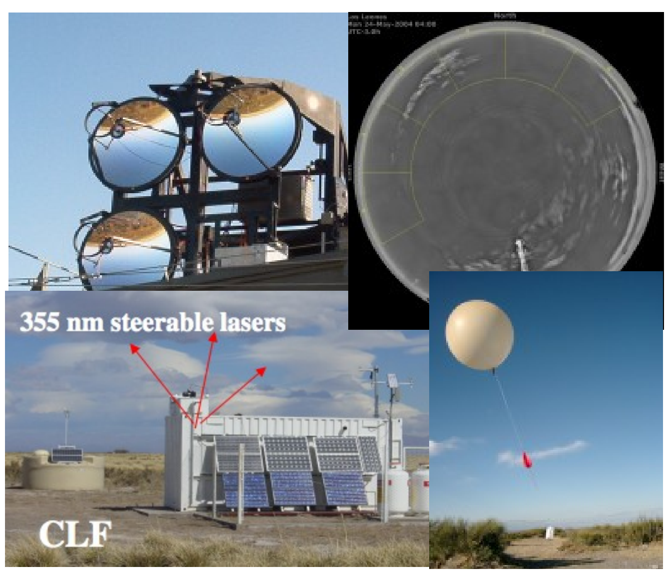
→ Photons at diaphragm → Photons at shower track →



Calibration



Atmospheric monitoring

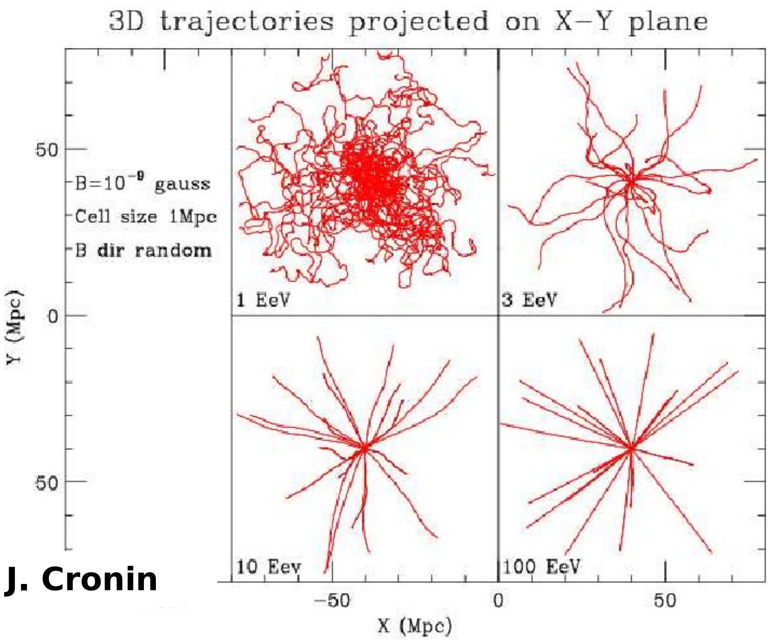


Fluorescence Yield

$$E_{cal} = \int \frac{dE}{dX} dX; \quad E_{FD} = (1 + f_{inv}) E_{cal}$$

Energy systematics:

Fluorescence Yield:	14%
FD absolute calibration:	9.5%
Invisible energy:	4%
Reconstruction:	10%
Atmosphere:	8%
Total:	22%



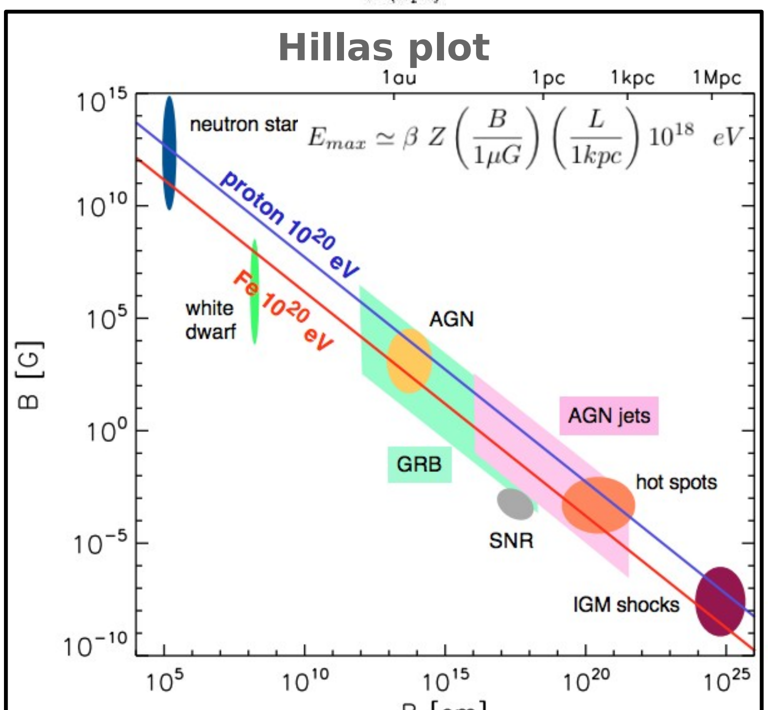
J. Cronin

The Science Case

- GZK effect (interaction with the CMB photons) limits the origin of $5 \cdot 10^{19}$ eV cosmic rays to a distance of ~100 Mpc.

$$p + \gamma_{2.7K} \rightarrow p + \pi^0, \quad \text{for } E_p > 4 \cdot 10^{19} \text{eV}$$

- For protons the deflection expected in the EG magnetic field is small enough that they should trace the source (not true for heavier nuclei.)
- Only a few classes of astronomical objects are know to be powerful enough (in terms of magnetic field and size) to be able to accelerate particles to 10^{20} eV.



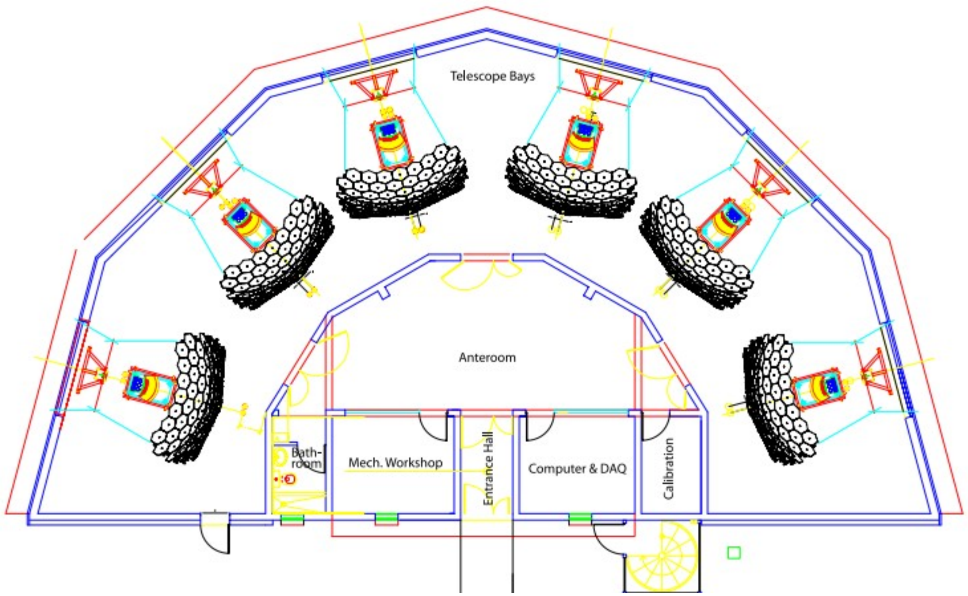
Kotera & Olinto, Annu. Rev. Astron. Astrophys 2010 49

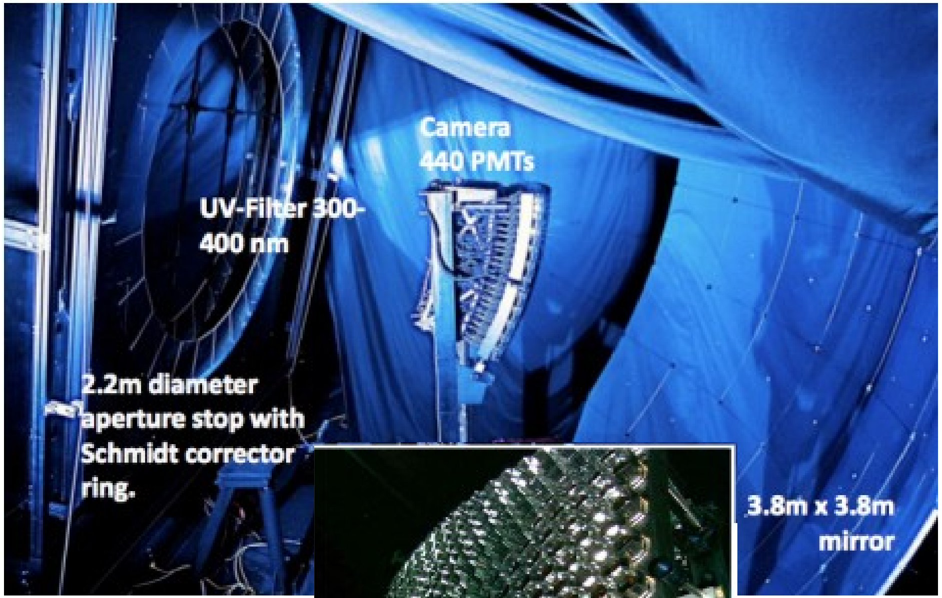
Limited amount of possible sources and good opportunity to trace them (charged particle astronomy!)

Well above available accelerator energies: test of hadronic physics at the highest energies.

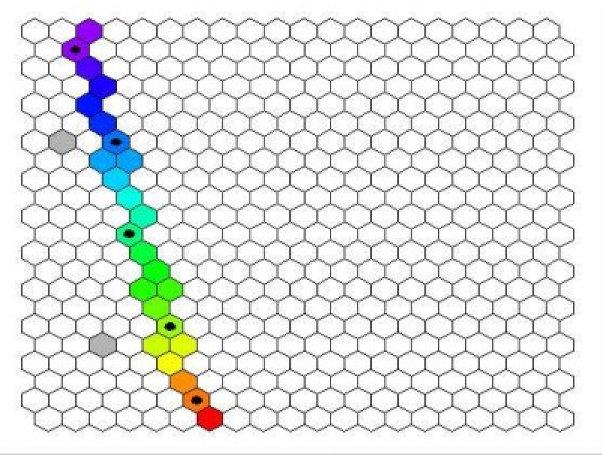
What do we want to measure? Spectrum, arrival directions, mass composition, etc.

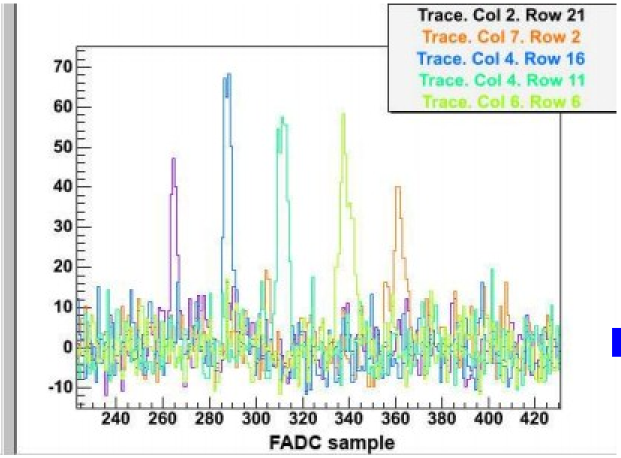
Fluorescence detector

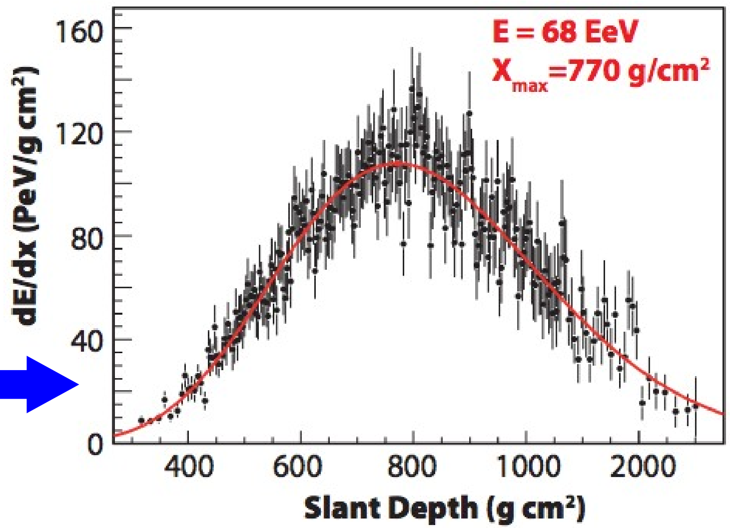




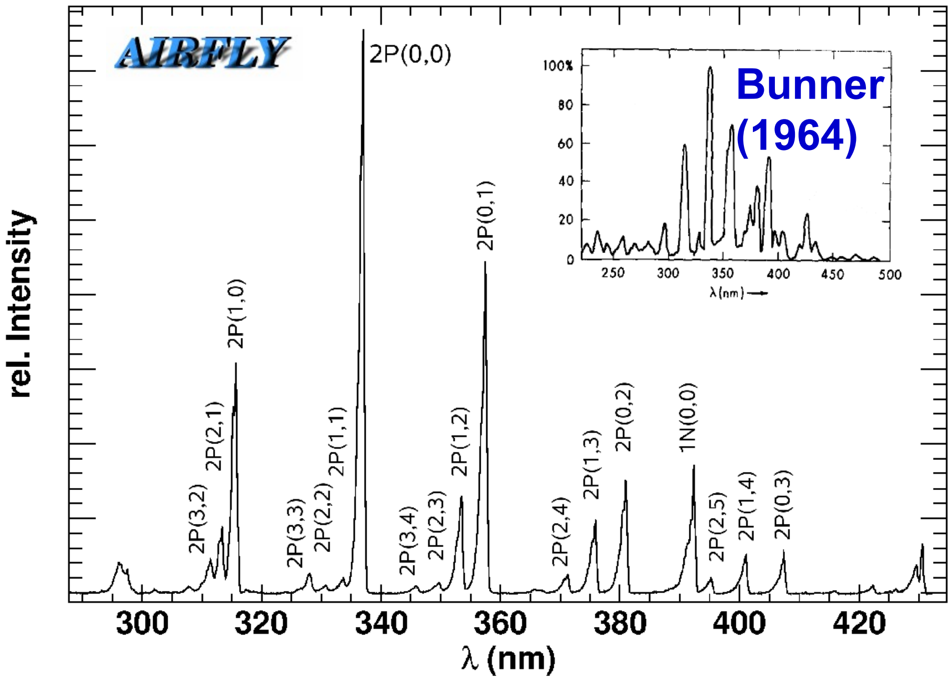
- 6 telescopes per building.
- 30°x30° FoV each
- 300-400 nm UV-filter
- Camera:440 PMT (1.5° pixel FoV)







AIRFLY: measurement of the air fluorescence yield



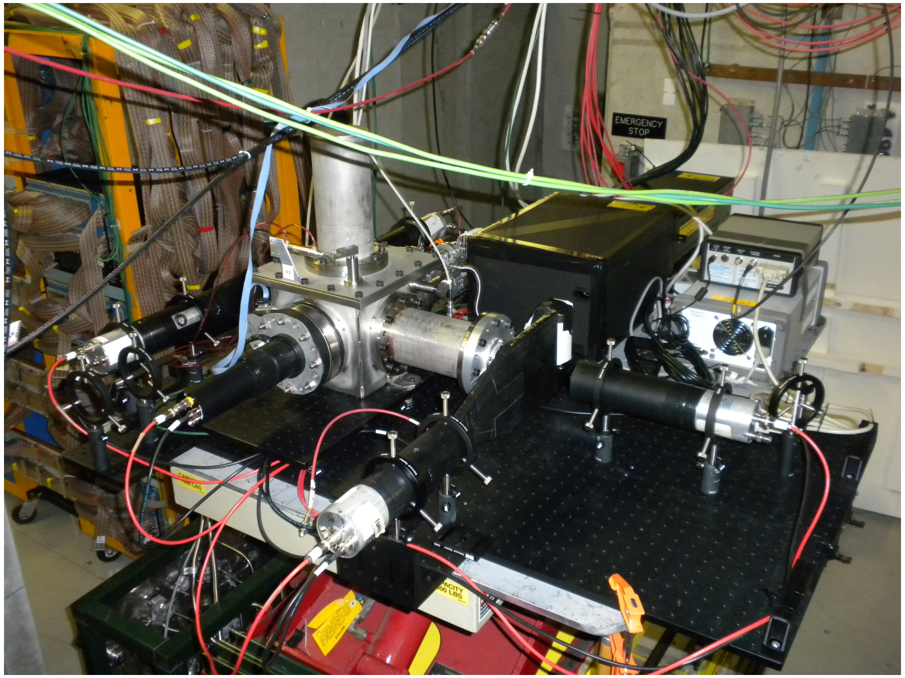
Measured yield dependence with pressure, temperature and humidity for each line (most complete data set)

Absolute measurement at Fermilab

$$Y_{air} = 5.61 \pm 0.06_{stat} \pm 0.21_{syst}\ ph_{337}/MeV$$

Uncertainty better than 4%, with 2 independent absolute calibrations.

P. Facal et al., in Proc. CRIS2010.
M.Ave et al., sub. to NIM, arXiv:1210.6734 [astro-ph.IM].



FD Energy systematics:	
Fluorescence Yield:	14% → 4%
FD absolute calibration:	9.5%
Invisible energy:	4%
Reconstruction:	10%
Atmosphere:	8%
Total:	22%