Hadronic interactions of ultra-high energy cosmic rays

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Ultra-high energy cosmic rays

Key questions:

- Where do they come from?
- What are they made of?
- How do their accelerators work?
- Is there a limit to their energy?
- What can they tell us about the fundamental and particle physics?

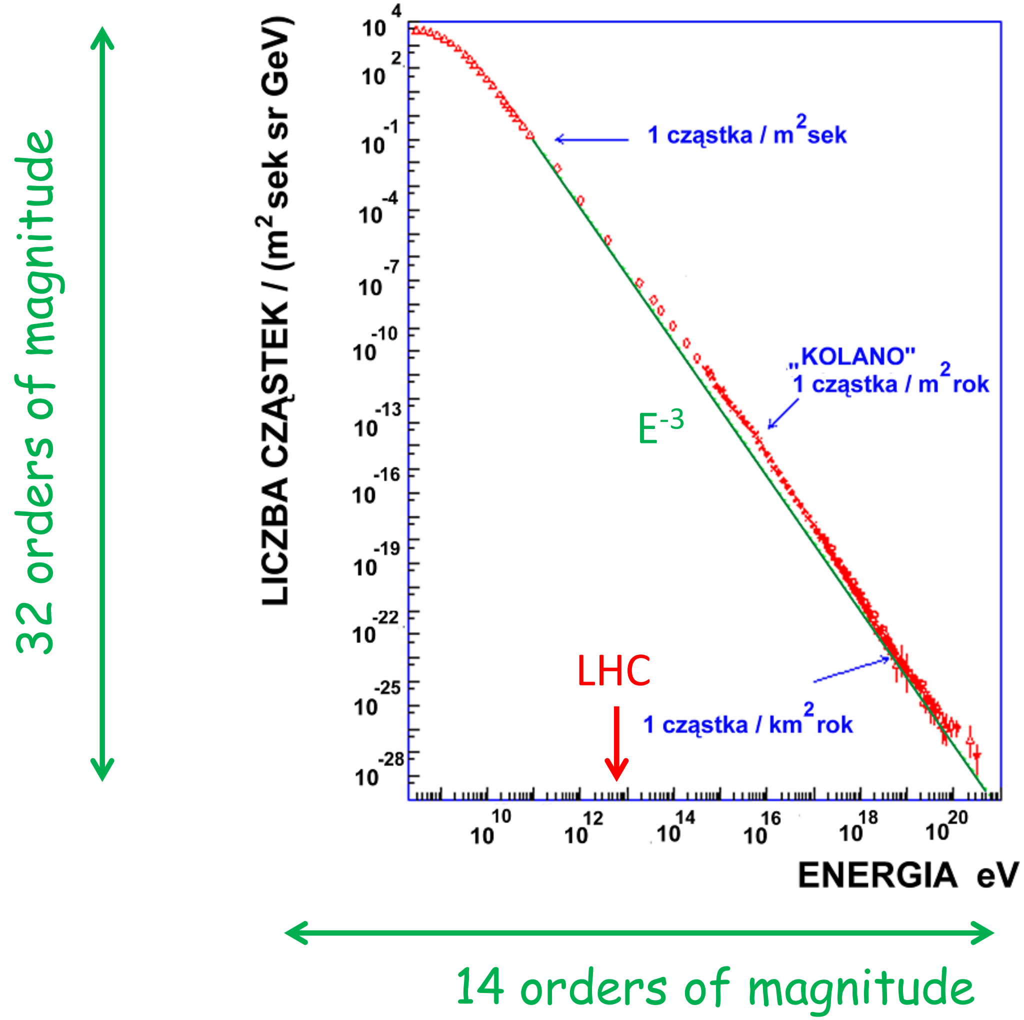
Expect the Greisen-Zatsepin-Kuzmin (GZK) effect

interactions with CMB photons
at $E > \sim 5\times 10^{19}$ eV:

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$n + \pi^{+}$$

$\rightarrow$ reduction of proton energy
$\rightarrow$ spectrum suppression above the threshold

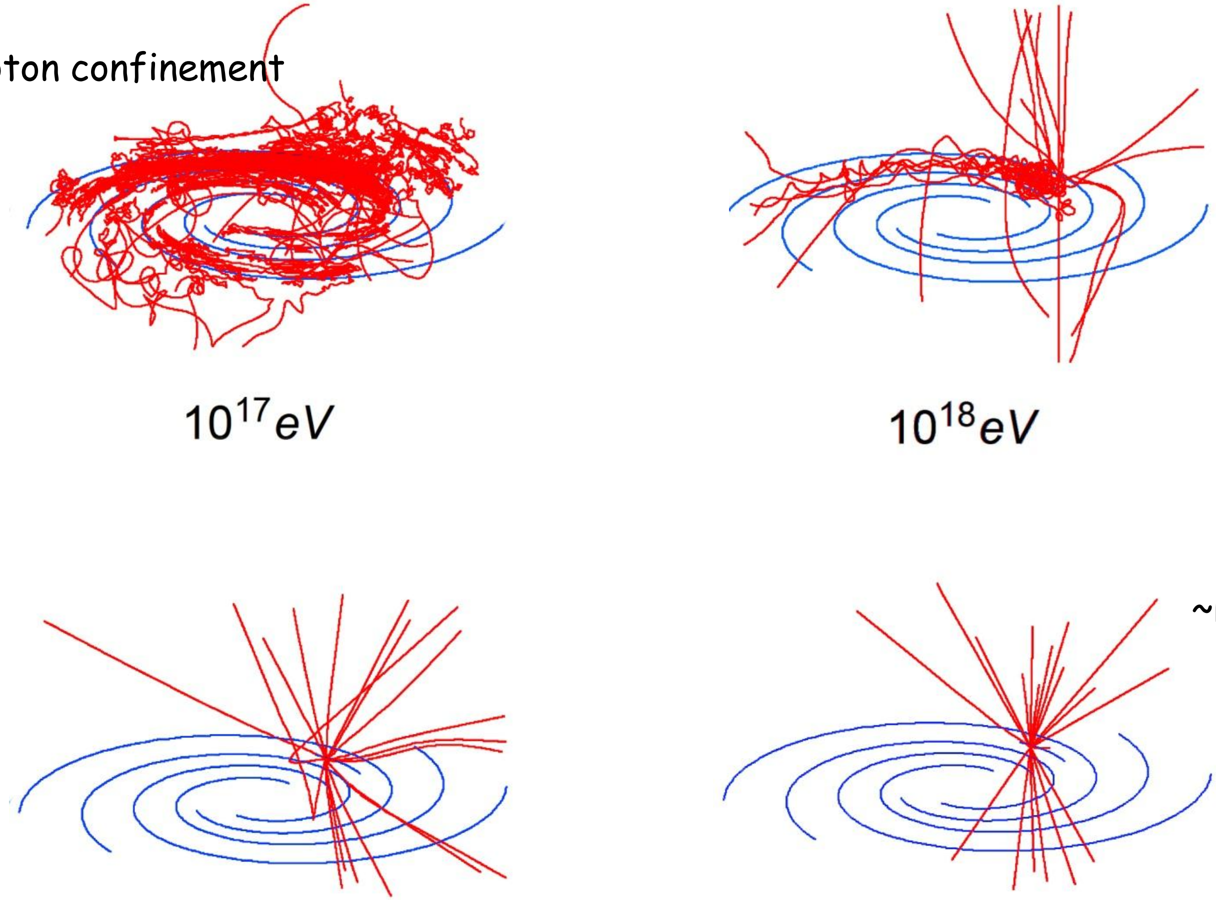
Cosmic ray energy spectrum



10^{20} eV in LHC technology → need accelerator size of Mercury orbit

Cosmic ray propagation in the Galaxy

proton confinement



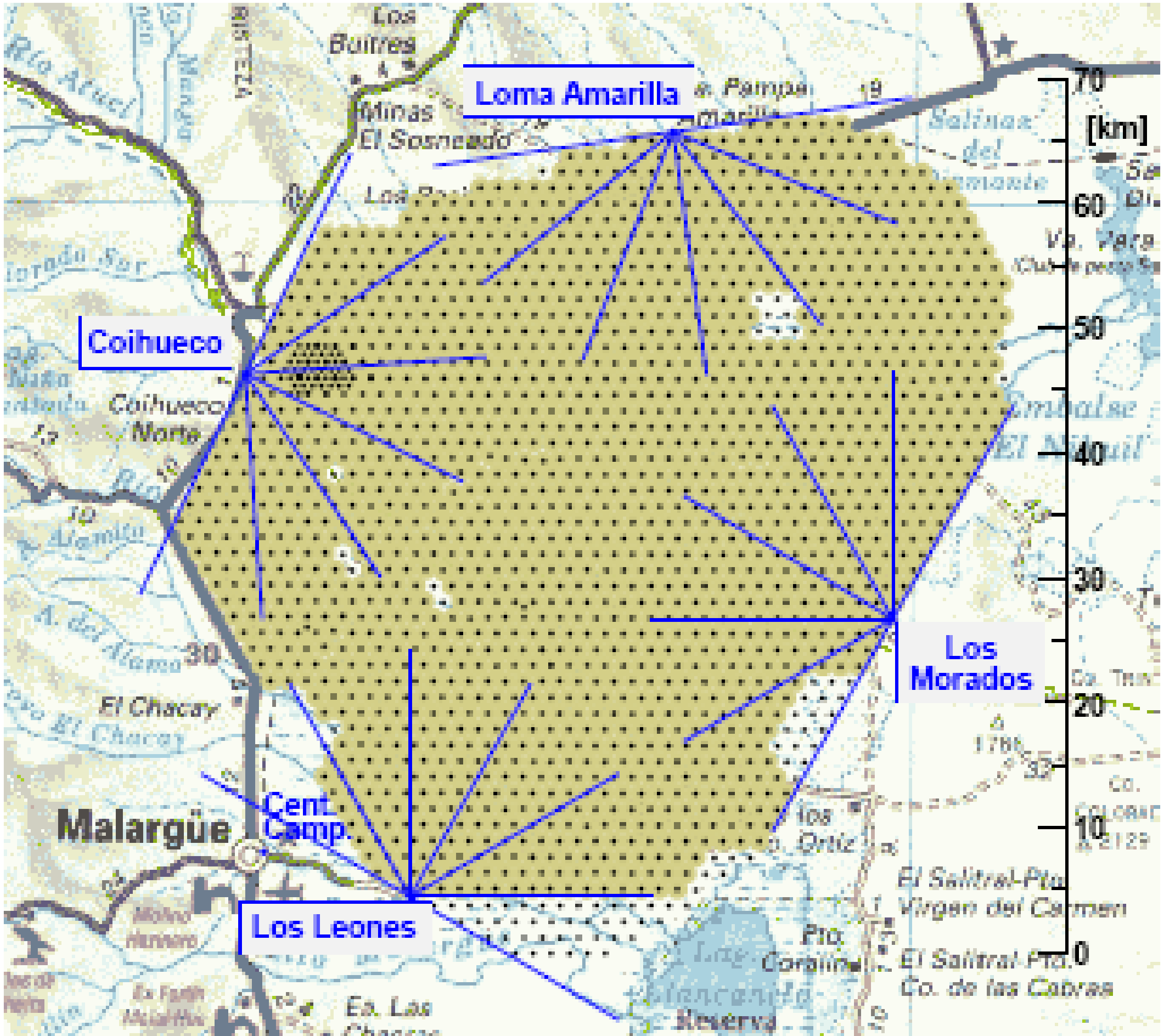
$10^{17} eV$ $10^{18} eV$

~rectilinear motion

$10^{19} eV$ $10^{20} eV$

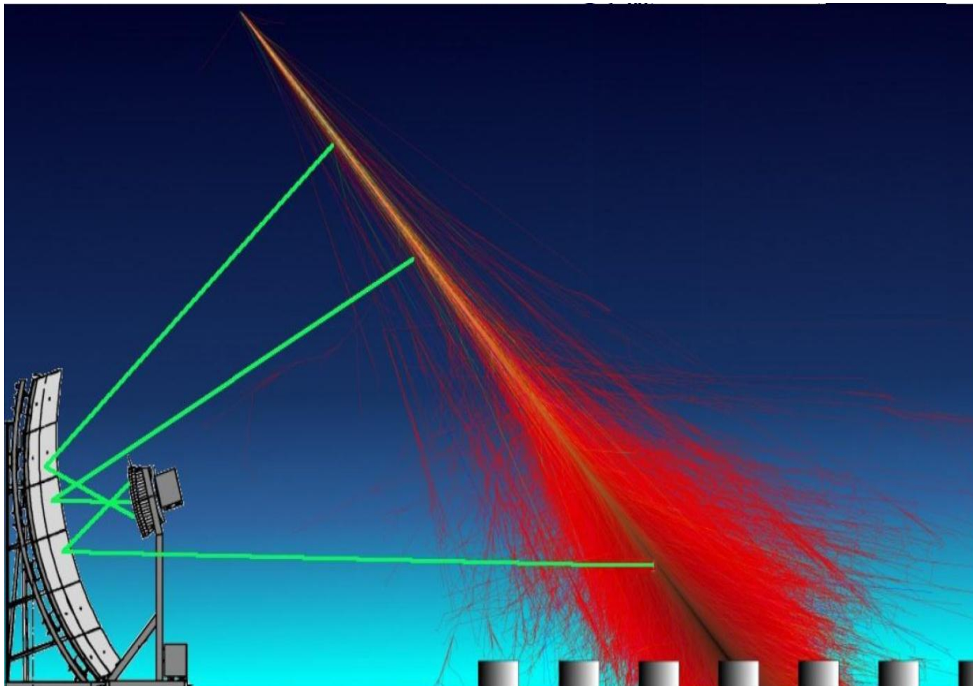
The Pierre Auger Observatory

Located in Mendoza province, Argentina



Surface Detector (SD)
1600 detector stations
1.5 km spacing
3000 km²
100% duty cycle
exposure calculated geometrically

Fluorescence Detector (FD)
27 telescopes
calorimetric energy
duty cycle ~13%
exposure based on MC

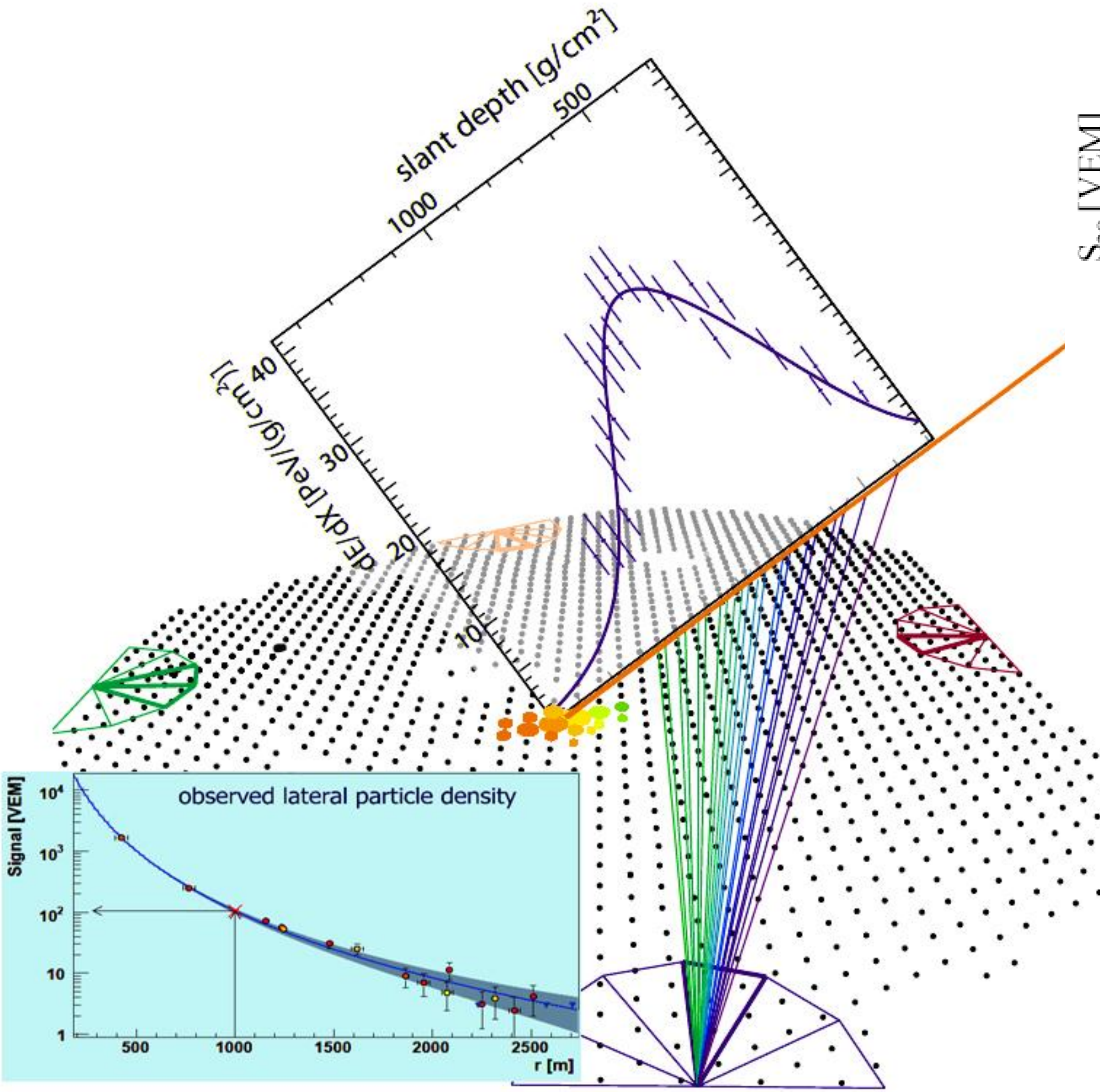


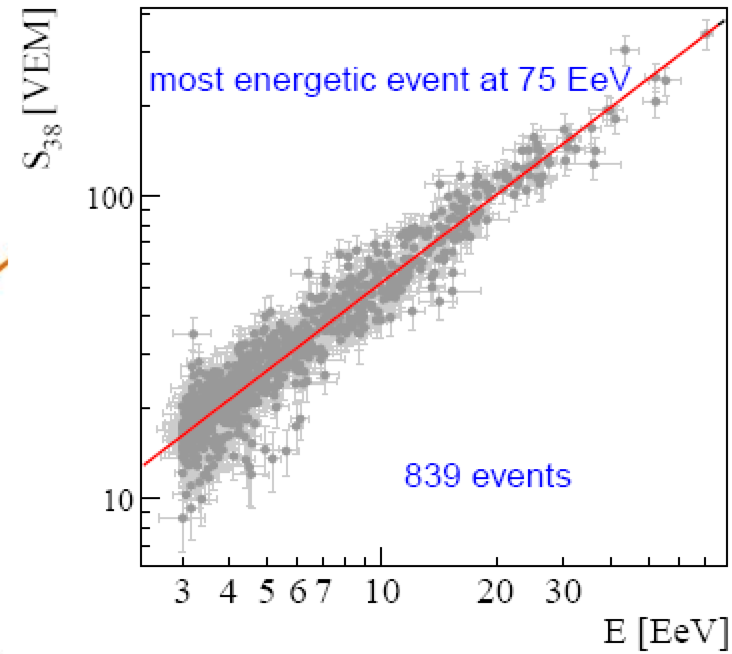
Hybrid detection of extensive air showers

Use simultaneously both FD and SD techniques

Pierre Auger Observatory

Hybrid reconstruction

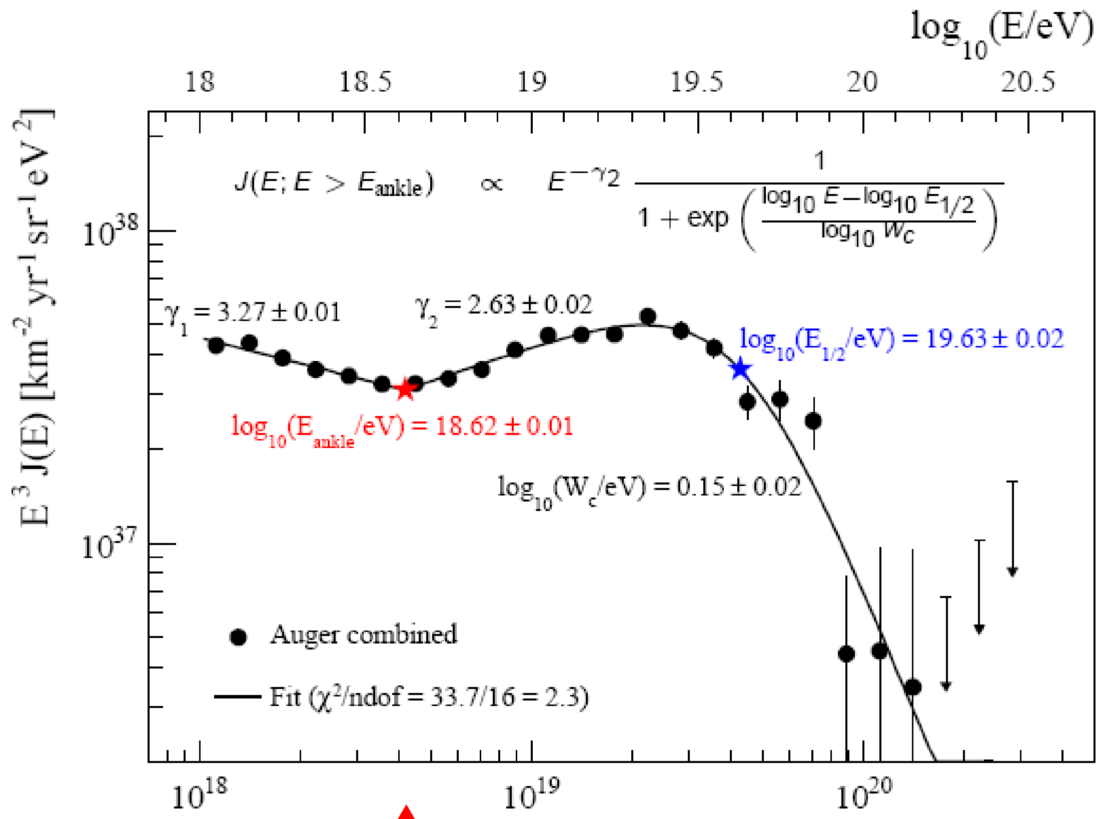




FD-SD energy calibration

Unprecedented accuracy of shower measurements

CR energy spectrum from Auger



E_{ankle} ~ 4 EeV (gal. → Xgal?)

Spectrum suppression:

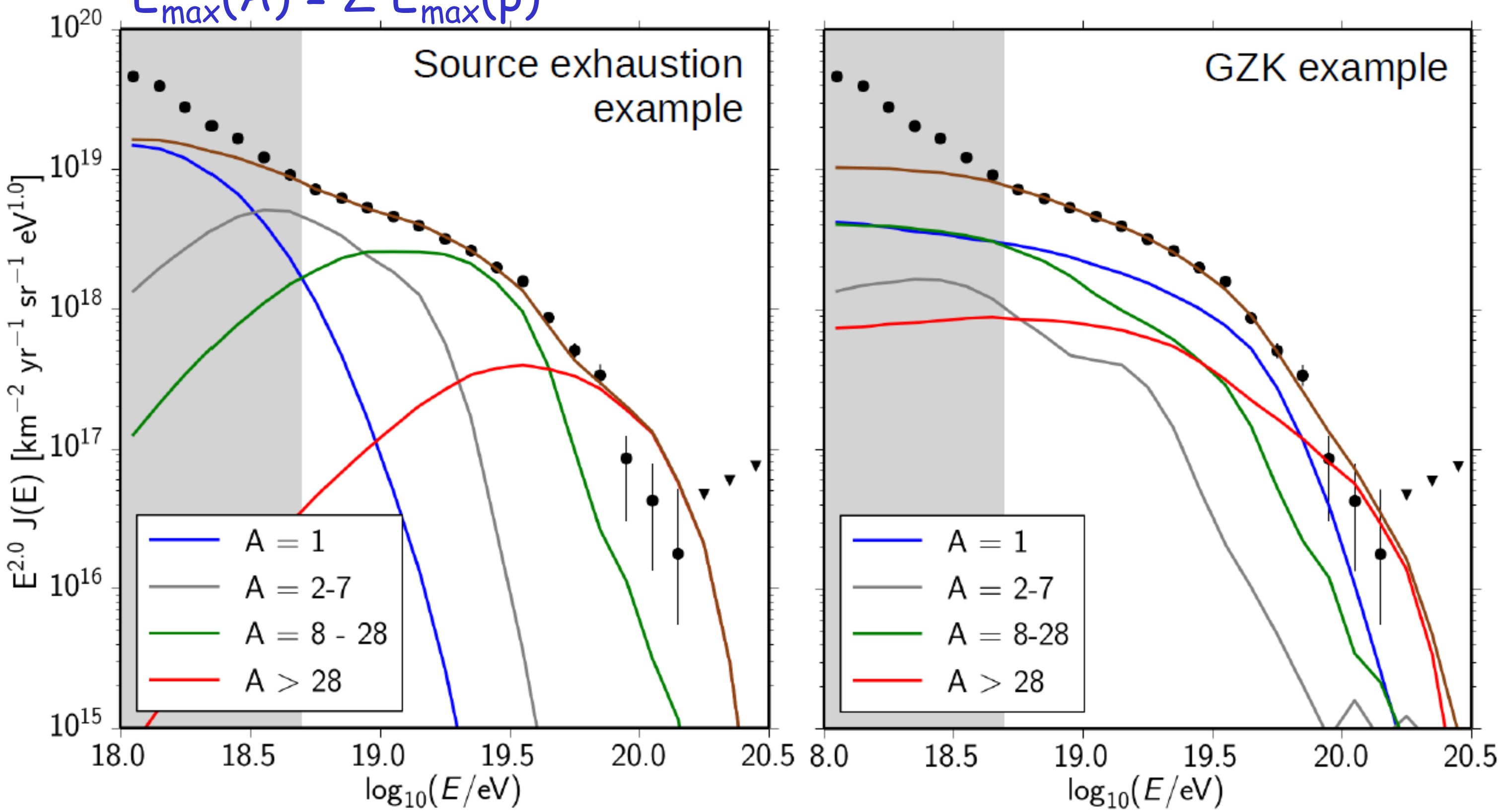
due to the GZK cutoff,
or
maximum
energy of accelerators ?

Composition
measurement is crucial

Interpretation of the spectrum: E_{max} or GZK?

Spectrum fits in different scenarios

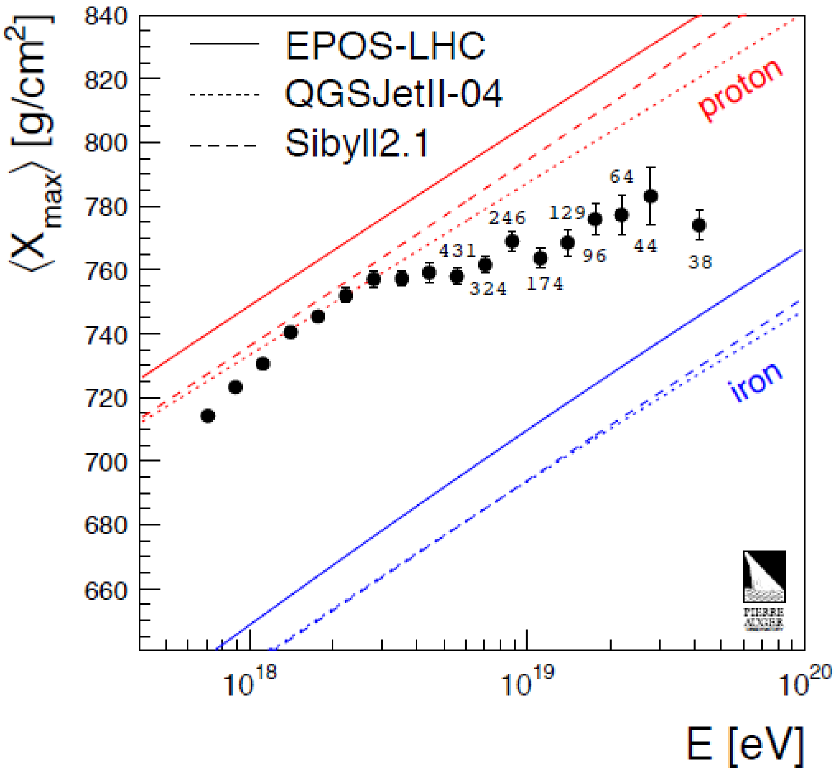
$E_{max}(A) = Z\, E_{max}(p)$

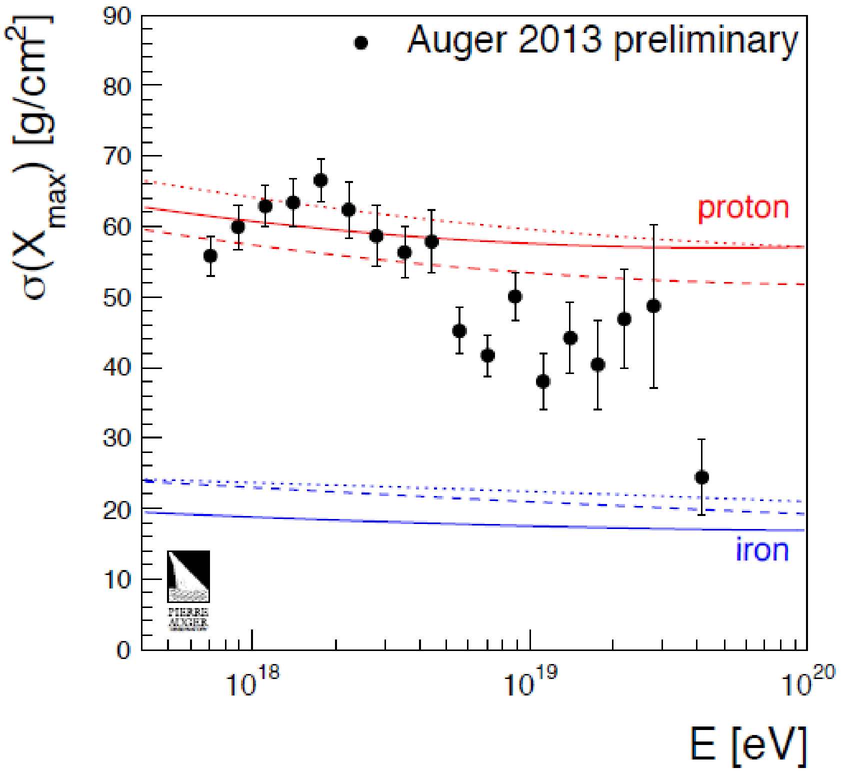


Need for excellent composition measurement to determine the nature of the flux suppression

Mass composition

Depth of shower maximum, X_{max}



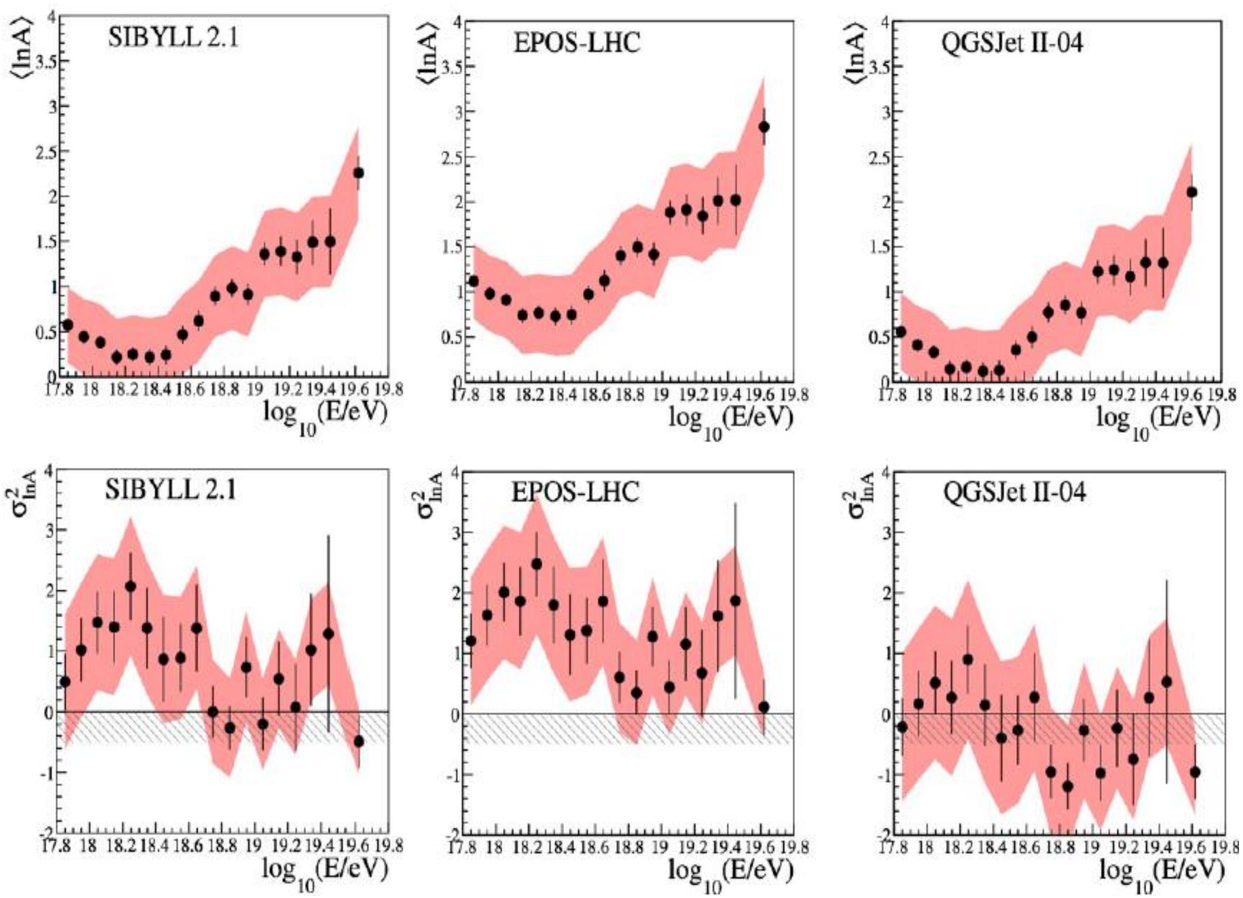


Smooth change from a light/mixed composition to a heavier one ?

Mass composition - from X_{max} to ln *A*

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

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\rm sh}(\langle \ln A \rangle)}{b\, \sigma_p^2 + f_E^2}$$



Average ln *A*

<ln *A*> =4   pure Fe

<ln *A*> ~2   50% Fe 50% p

<ln *A*> =0   pure p

Dispersion of masses (due to source or propagation)

σ^2(ln *A*)=4   50% Fe 50% p

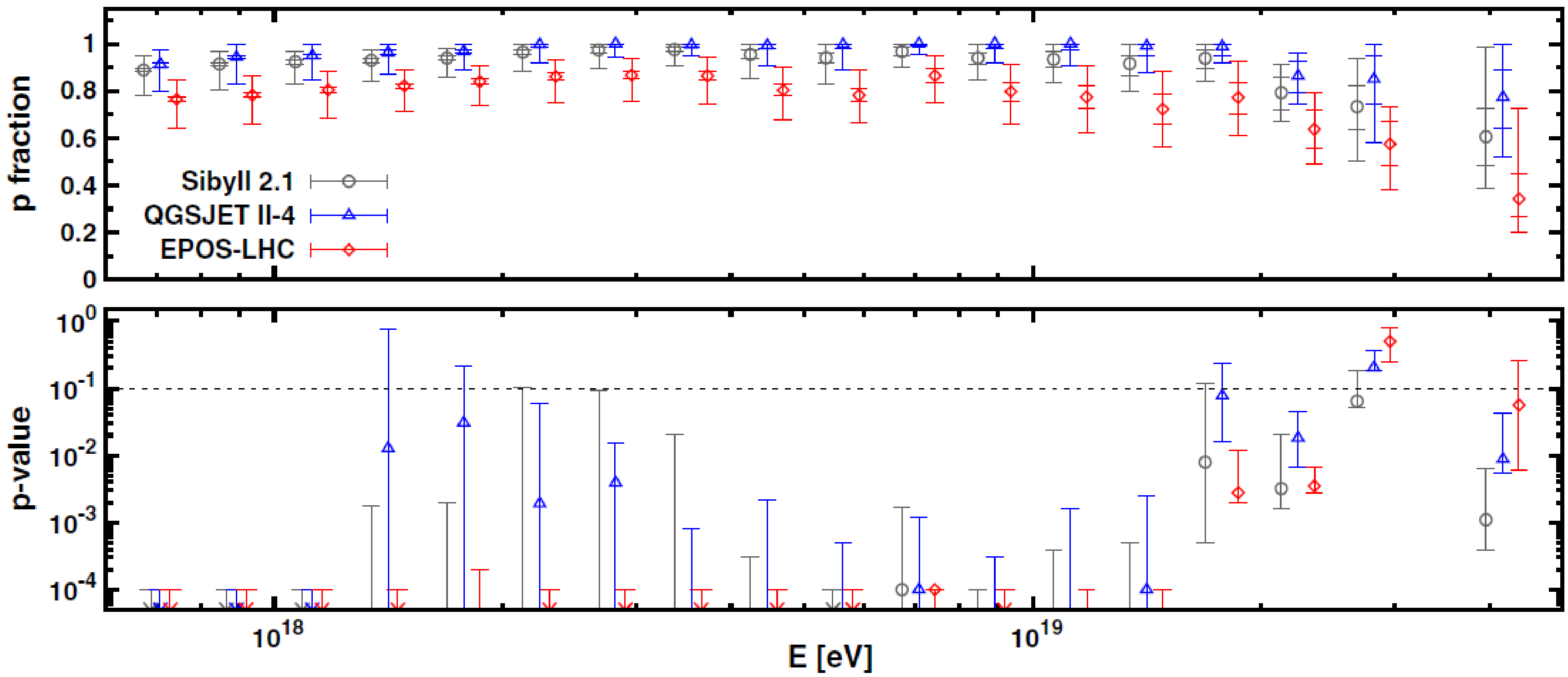
σ^2(ln *A*)=0   pure p or Fe

<ln *A*> has a minimum in the ankle region

The mix must include intermediate nuclei

Mass composition – protons vs Fe

Fitted fraction and quality: p and Fe only

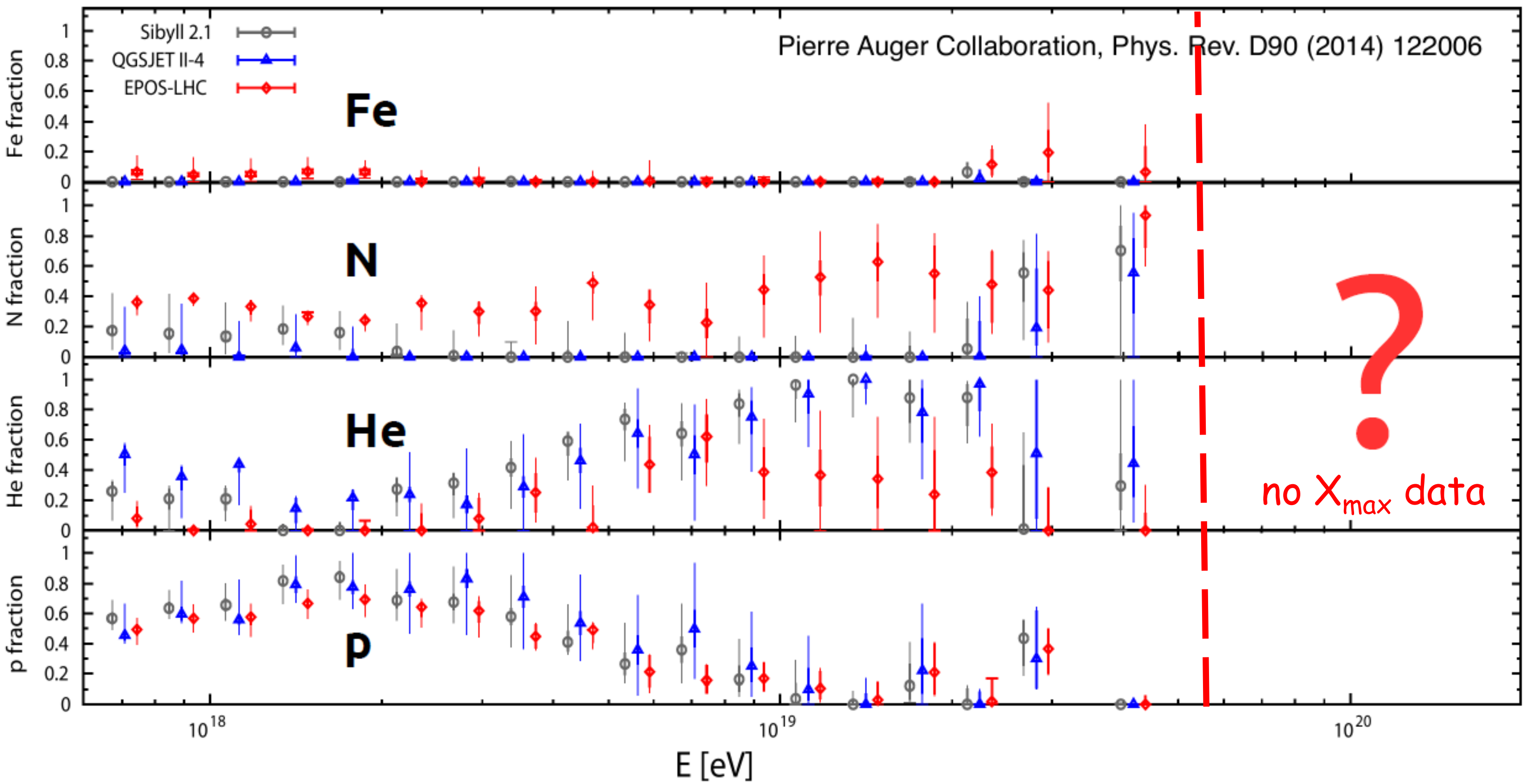


Very poor fit to the data

None of the models can reproduce X_{max} with p and Fe only

Mass composition with intermediate nuclei

Acceptable fit quality with 4 nuclei



Are there protons at E > 5×10^{19} eV? i.e. should one expect pointing to sources?

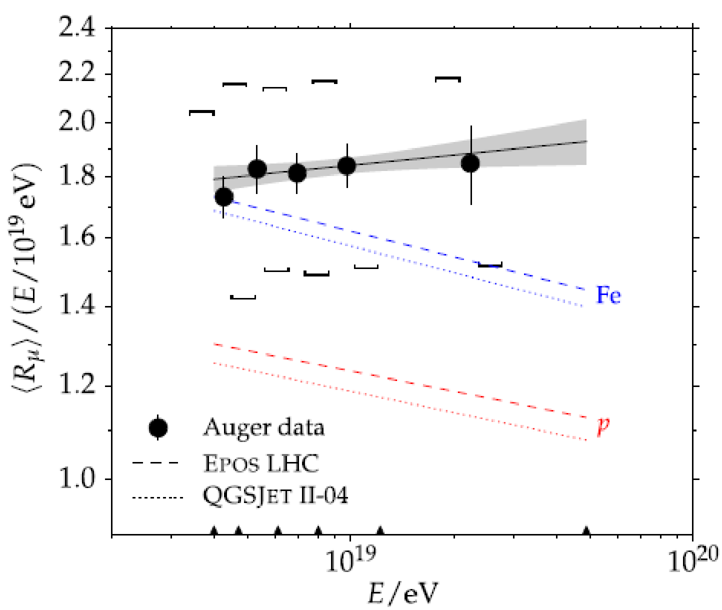
→ use SD data at E>50 EeV, study muon component of showers

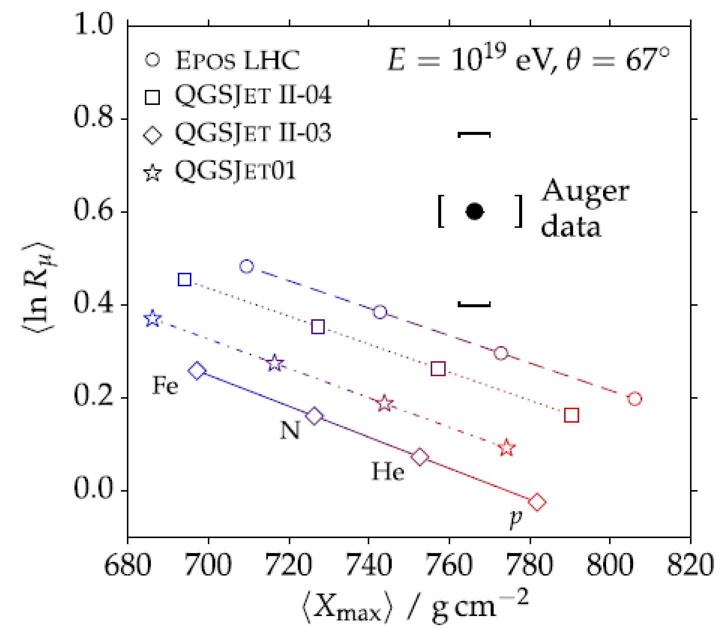
Number of muons in inclined showers

Inclined showers (62°<θ<80°) are muon-dominated at ground

$N_\mu \propto A\,(E/A)^\alpha \quad \alpha \approx 0.9$

muon ratio $R_\mu = N_\mu / N_\mu(10^{19}\ \mathrm{eV})$





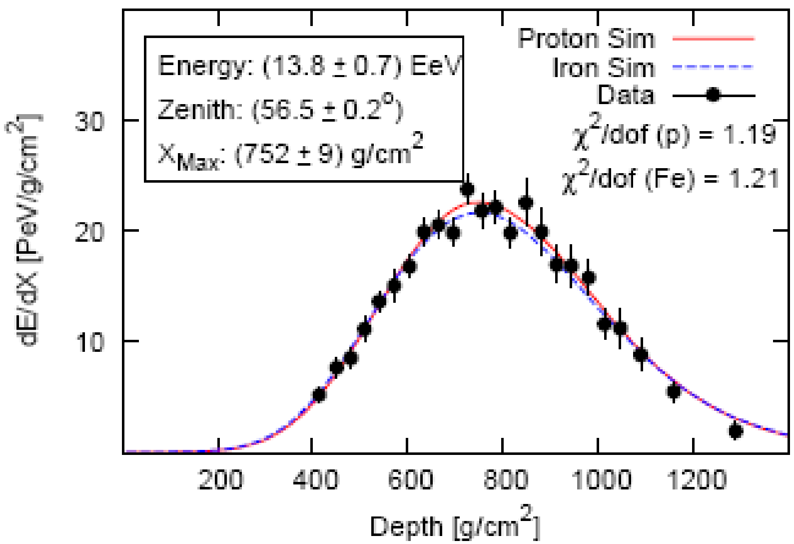
Existing models of HE interactions underestimate the number of muons

PRD 91, 032003 (2015)

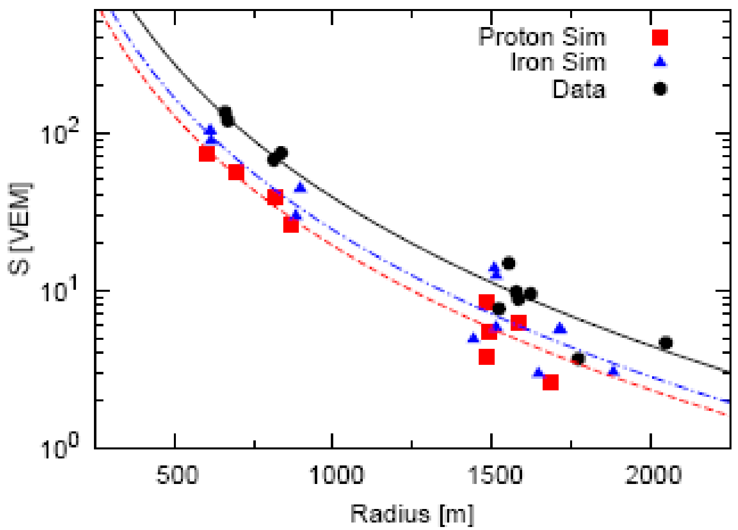
Test of hadronic interaction models

Hybrid events (FD + SD)

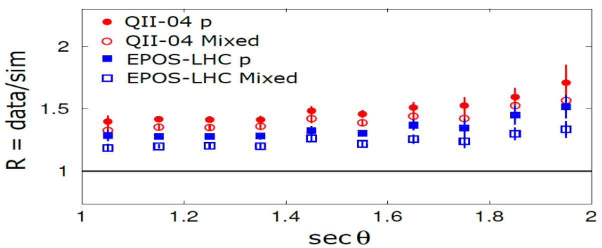
Measured shower and simulated longitudinal FD profile



Same shower and simulated SD signal



R = S(data)/S(sim)



Models underestimate the shower signal

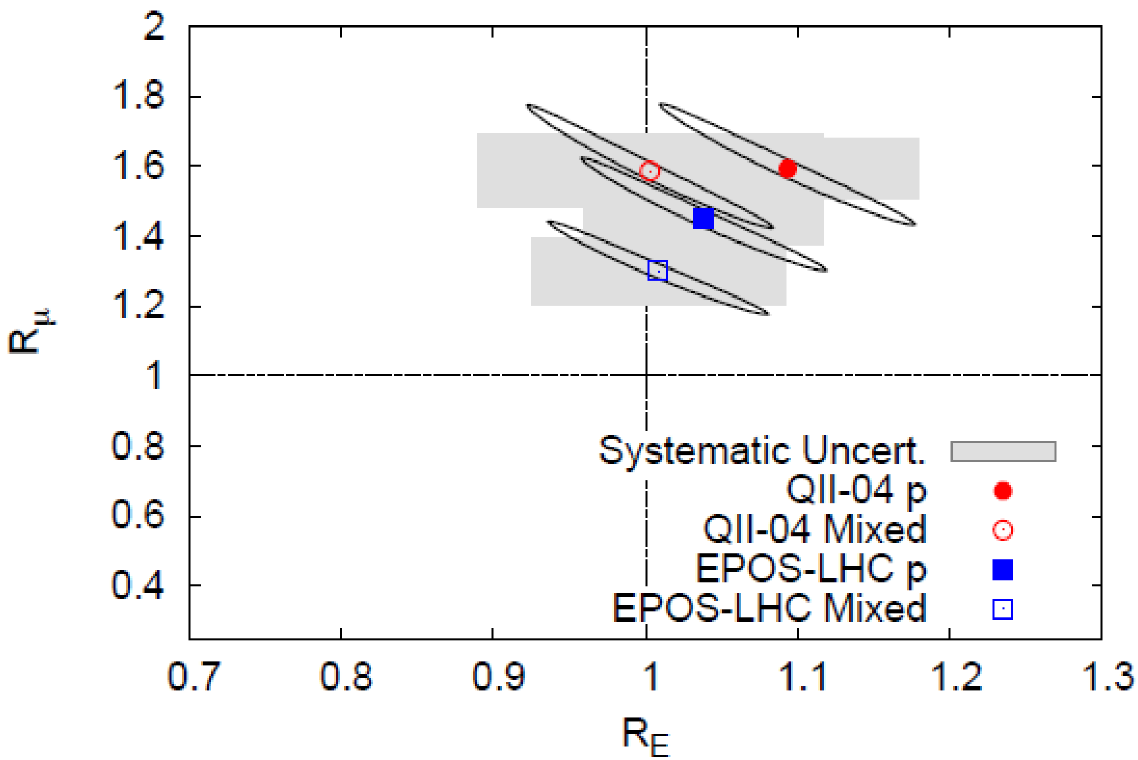
Fitting models to data

Dedicated simulations for each real shower
with rescaling of energy and muon component

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

i = evt
j = primary type

and fitting to data



Muon deficit in simulations: 30-60 %

Energy ~ OK

PRL 117 192001 (2016)

The way forward

Detector duty cycle

Fluorescence Detector (clear, dark nights): <15% → data up to ~ 50 EeV

Surface Detector: 100% → data up to 100 EeV

Use SD observables to study CR composition

- muon production depth
- signal rise time

But the problem is not only statistics:

need to measure precisely the muon component of air showers event-by-event

upgrade the Observatory:

use another detector (along with SD), with different muon response,

to separate muon and EM components of showers

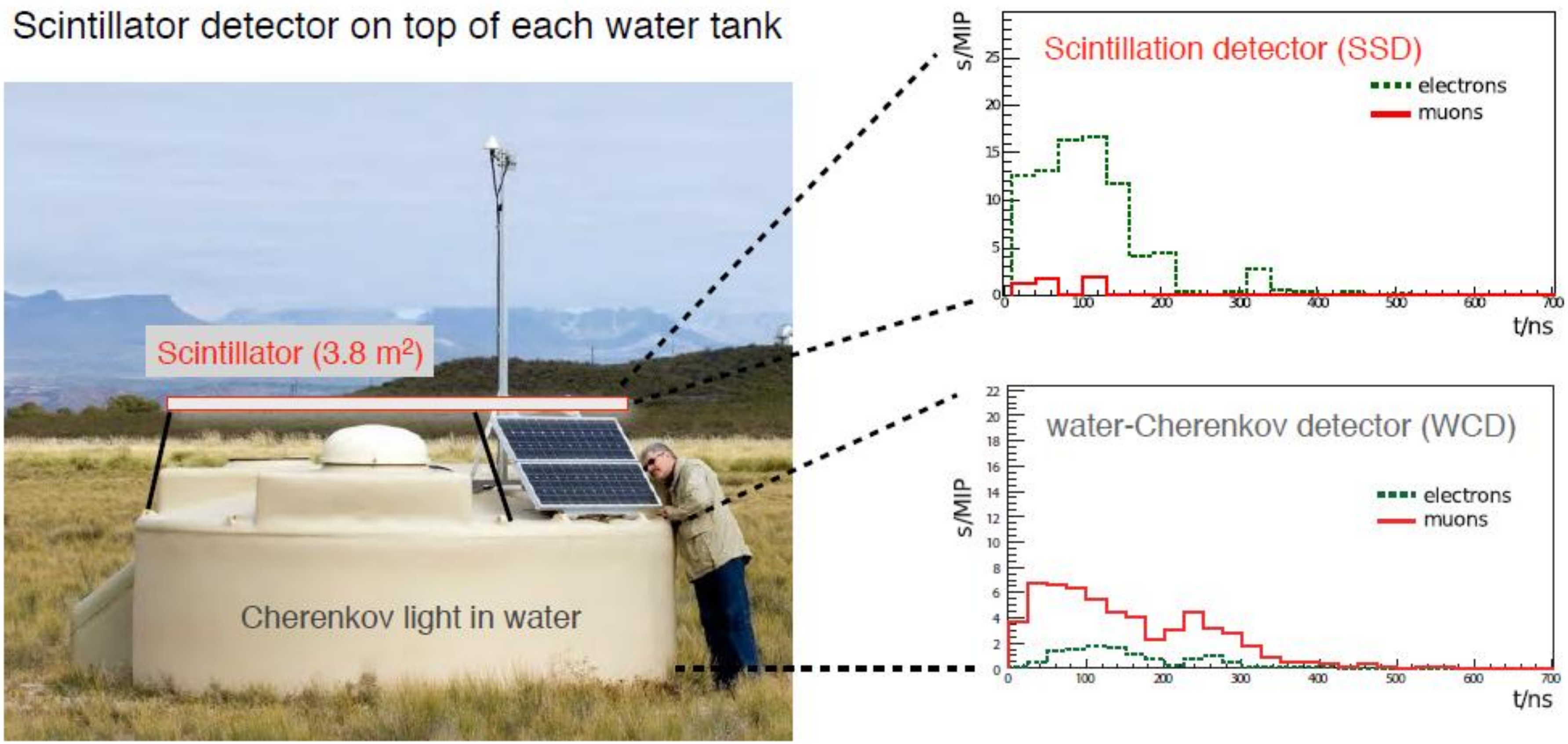
→ scintillator plane (SSD) above water Cherenkov detector

(plus: underground muon detectors

faster electronics

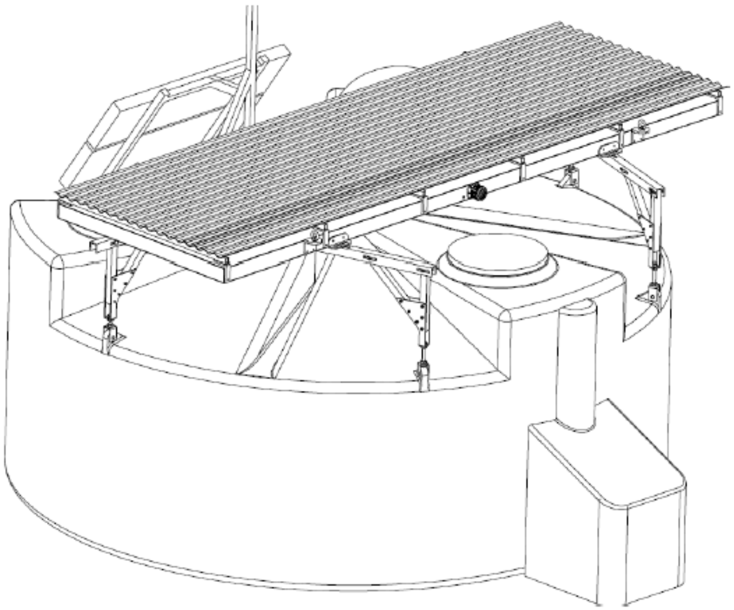
increased hybrid uptime) - AugerPrime

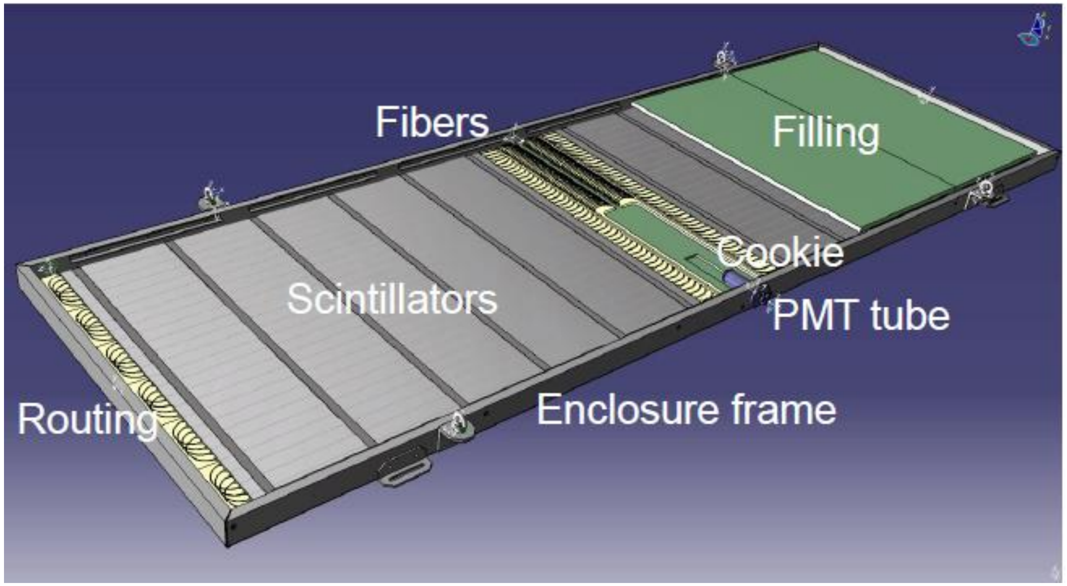
AugerPrime

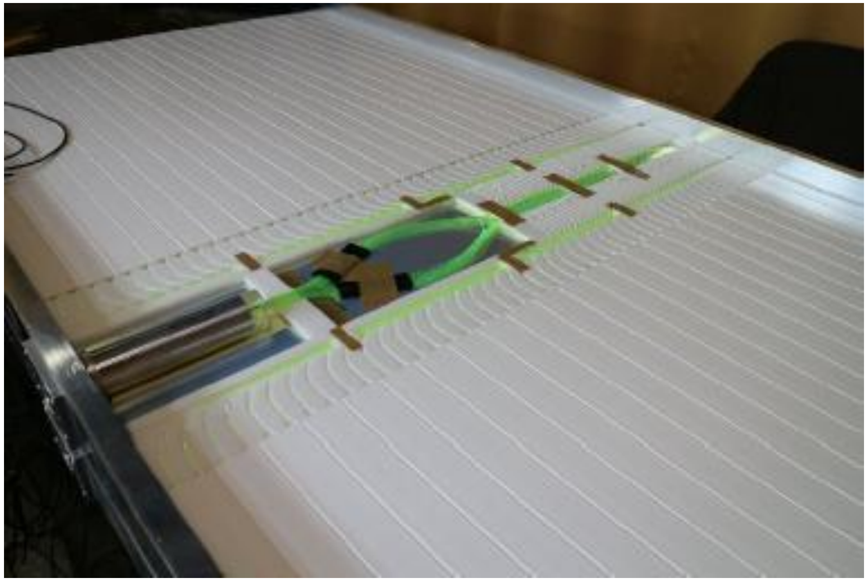


Can measure simultaneously shower energy
and ratio of muon to EM component of shower

Prototype SSD detectors







Summary

Better understanding of hadronic interactions at ultra-high energies is the key to solving main problems in UHE cosmic-ray physics:

Elucidate the origin of the flux suppression, i.e. GZK vs maximum energy

measure composition into the flux suppression region – use Surface Detector for higher statistics

Disentangle composition from interaction properties

air shower physics and hadronic multiparticle production

reliable muon counting in air showers

Search for a flux contribution of protons up to the highest energies, at a level of 10%

proton astronomy up to the highest energies –

composition event-by-event!

→ Need to upgrade detectors of the Pierre Auger Observatory

better EM/muon component separation

better shower modelling …under way!