the highest energy cosmic rays

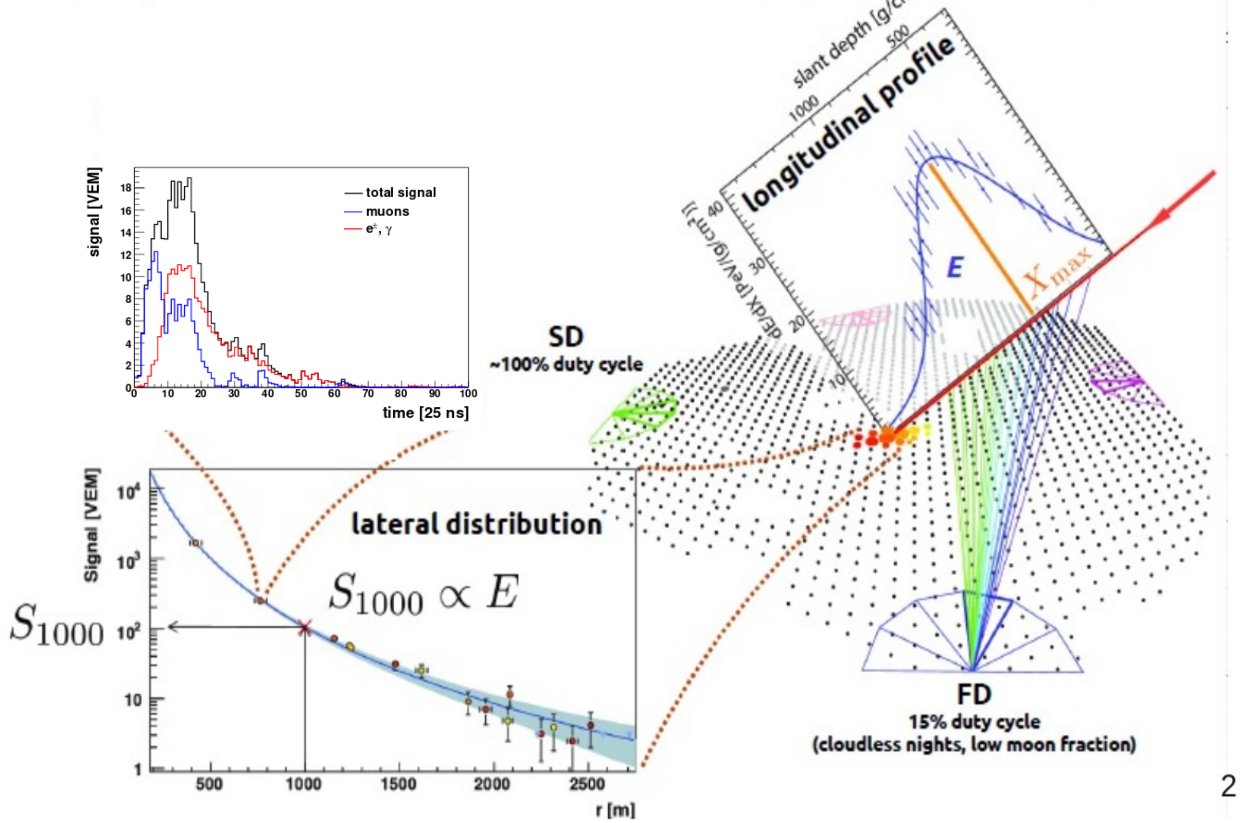
at the Pierre Auger Observatory

Sofia Andringa (LIP) for
the Pierre Auger Collaboration

PASCOS, Manchester, July 2018

Pierre Auger Observatory

sampling lateral distribution EM/MU & imaging the EM component



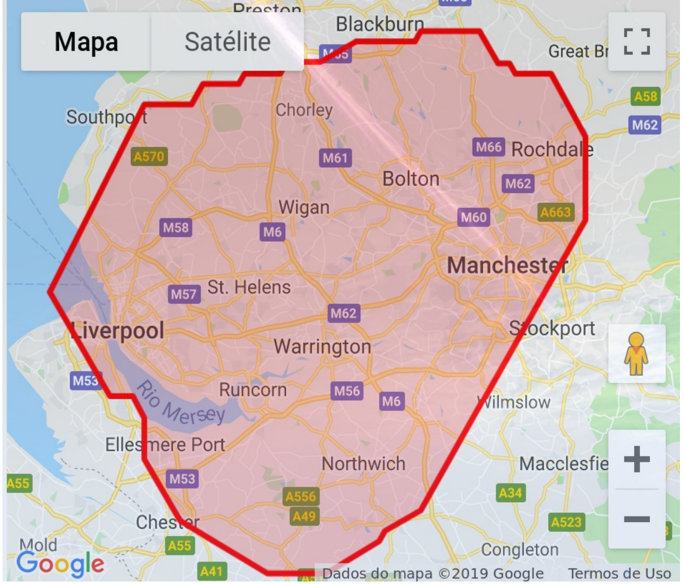
3000 km² array in 1400 m.a.s.l.

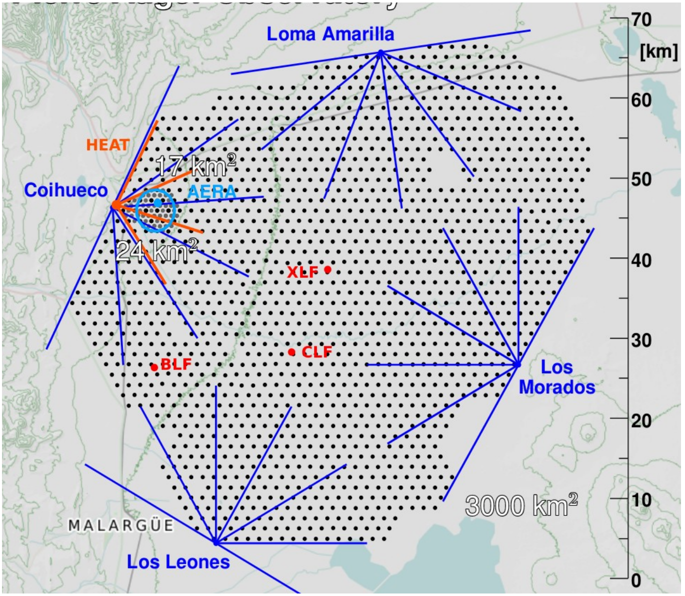
1660 SD stations
(1.5 km + 750 m grids)
~100% duty-cycle

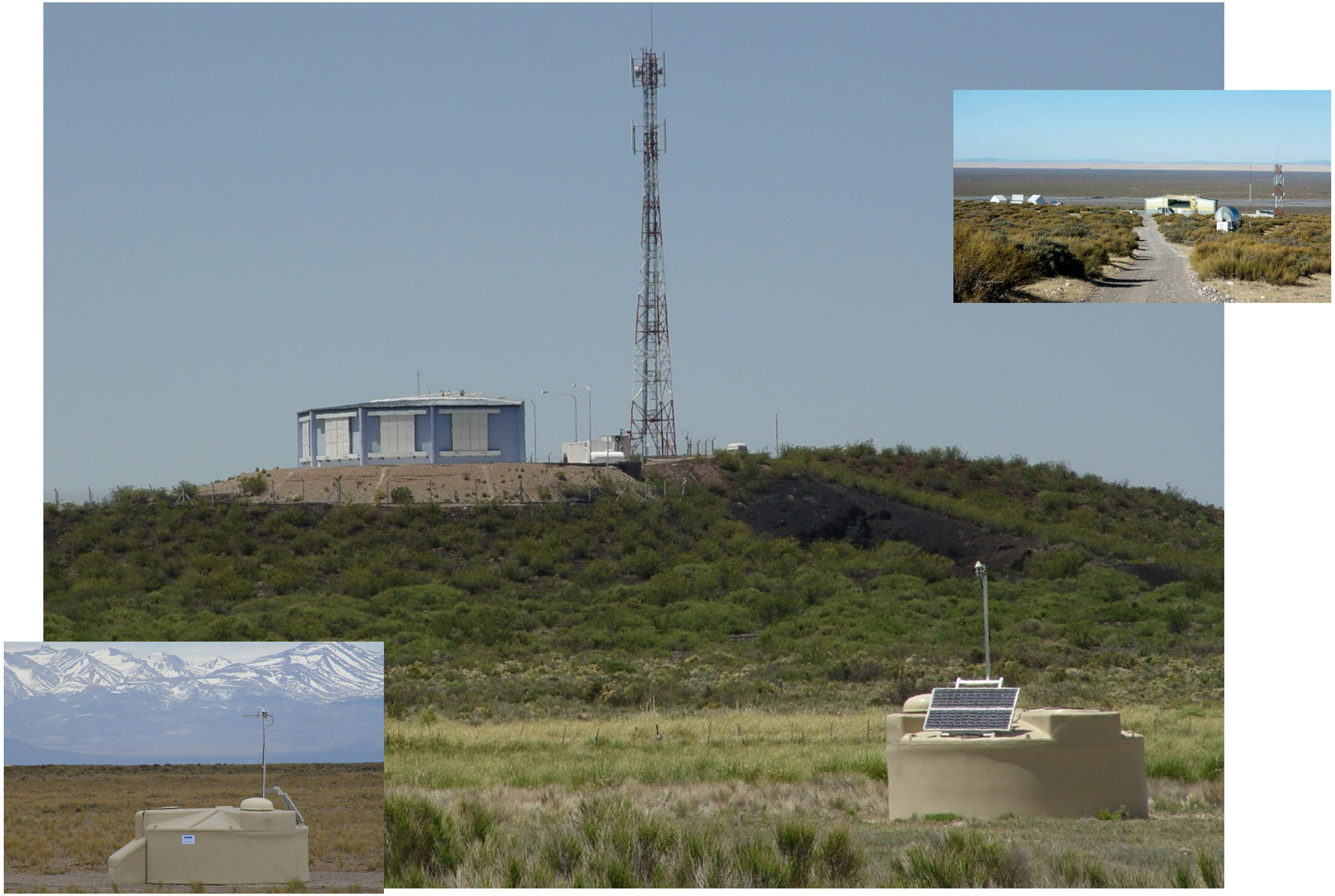
24 + 3 FD telescopes
(direct shower imaging)
~15% duty-cycle

dedicated to log(E/eV) > EeV
+ extension to lower energies

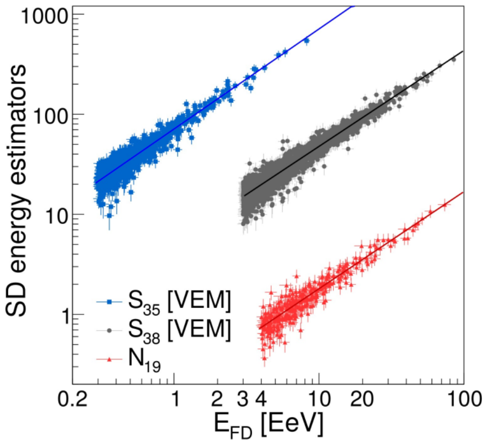
Pierre Auger Observatory







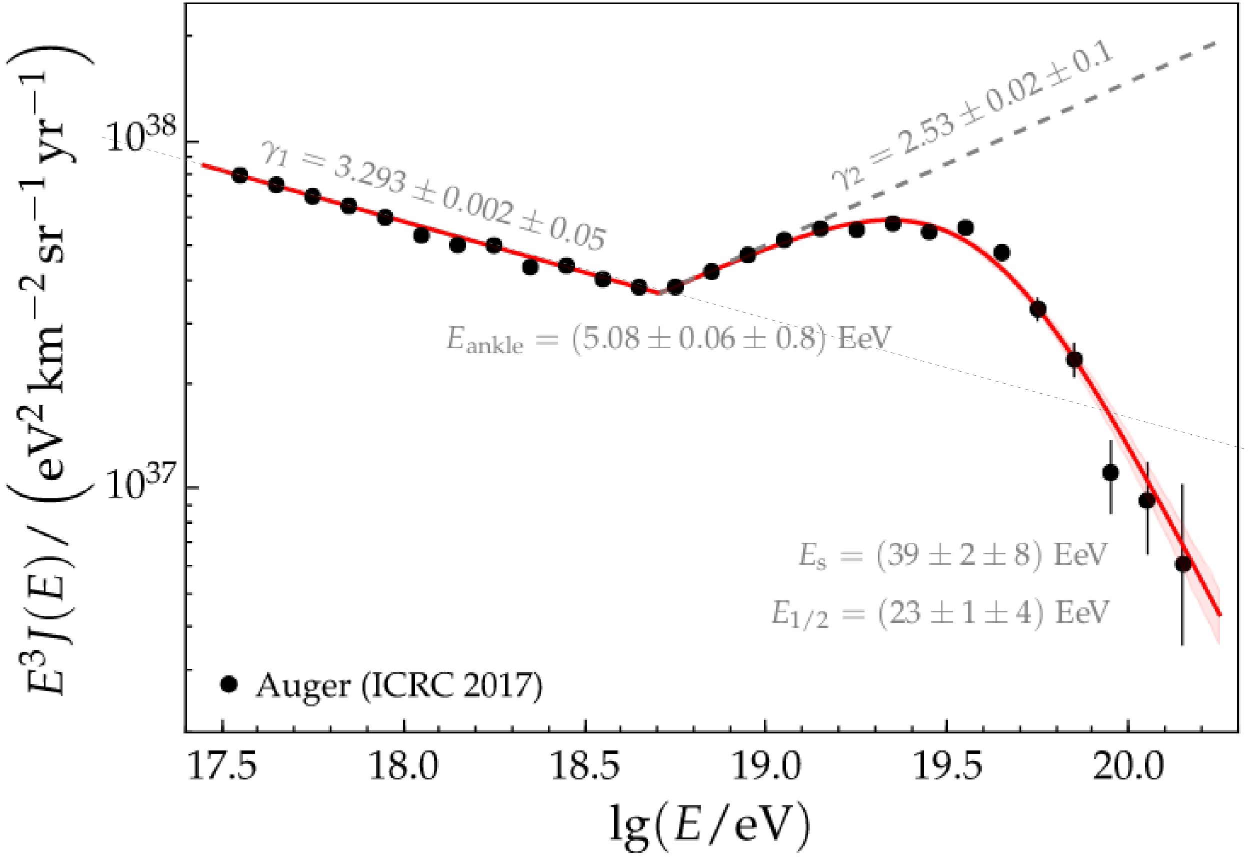
(the end of the) energy spectrum



calibration with FD
calorimetric energy

7% @ FD resolution
13% @ 750 m SD
15% @ 1500 m SD
17% @ inclined SD
+14% systematic unc.

galactic and extragalactic sources (overcoming magnetic field)



limited
power
sources
+
GZK effect:
interaction
with CMB

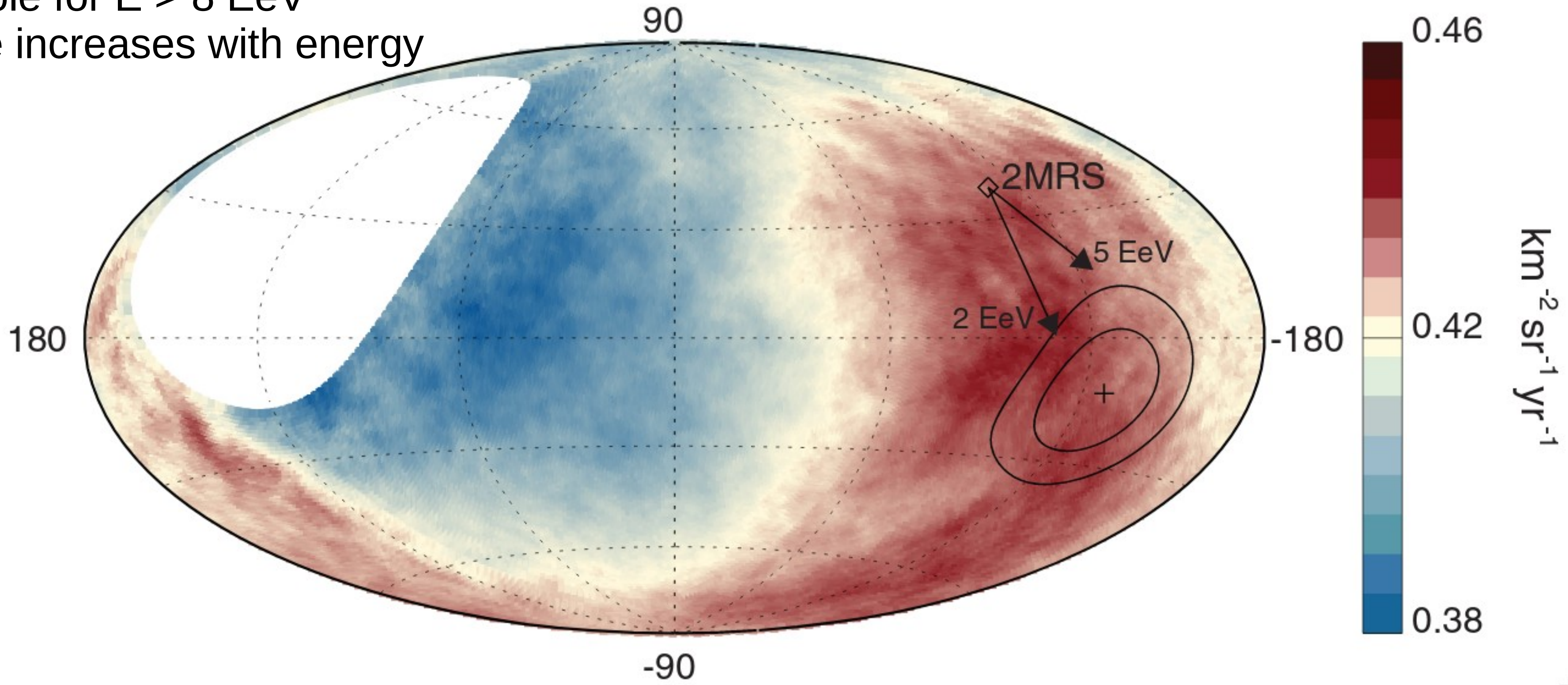
anisotropic high energy sky

large scale anisotropy from **extragalactic cosmic rays**

The Pierre Auger Collaboration,Science357, 1266–1270 (2017)

The Astrophysical Journal,868:4(12pp), 2018 November 20

5.2 σ dipole for E > 8 EeV
amplitude increases with energy



charged and neutral particles

galactic and extragalaction magnetic fields

* only neutrals for coincident detection
* arrival directions smeared by charge

interaction cross-sections

neutrino <<<< gamma << proton < other nuclei

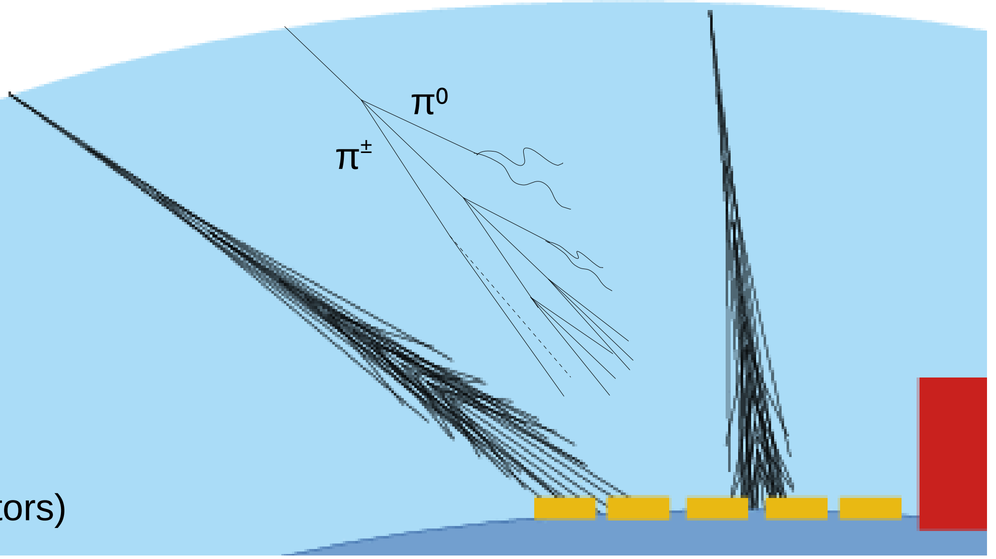
* neutrinos as young inclined showers
  (inclined hadrons have only muons at ground)
* photons as “pure” electromagnetic showers
  (less muons than in hadronic interactions)

electromagetic shower (~90% energy)

* imaged by Fluorescence Detectors (and radio detectors)

muons following hadronic cascade

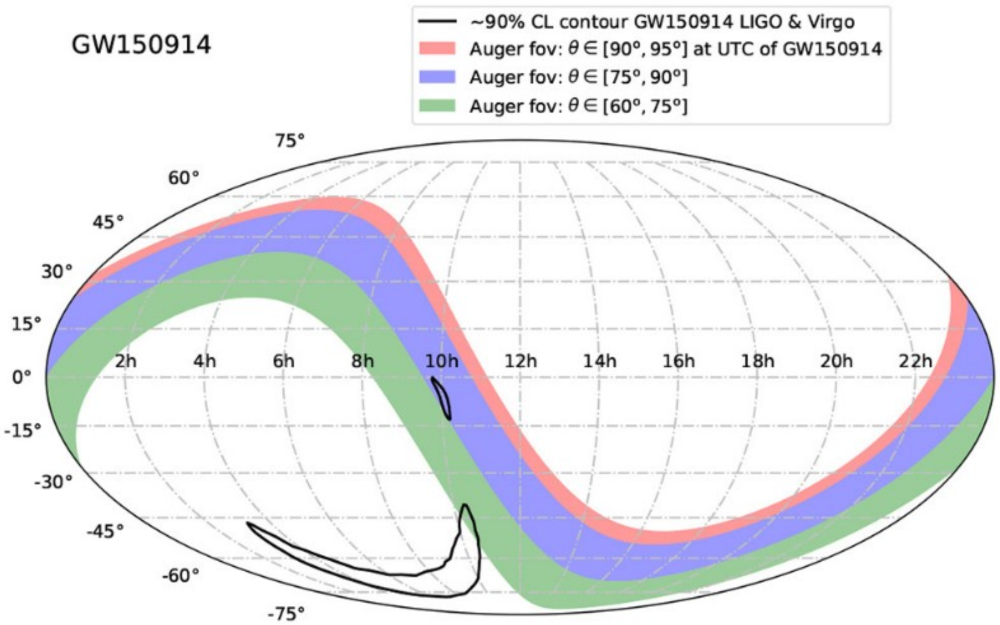
* Water Cherenkov Surface Detectors (and buried scintillators)



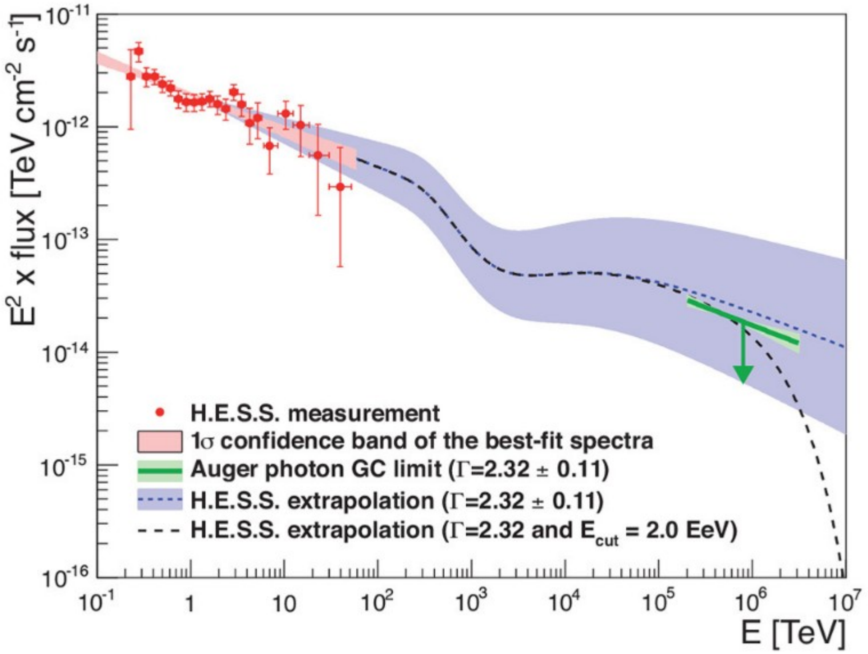
limits on neutrinos and photons

multi-messenger analysis at very high energies

Multi-Messenger Physics: Pierre Auger Observatory
Frontiers in Astronomy and Space Sciences
April 2019 | Volume 6 | Article 24



neutrino exposure at time of single GW event
(also photons would be coincidental in time)



limit on photon flux from the galactic center
(also limit for neutrons from direction maps)

limits on neutrinos and photons

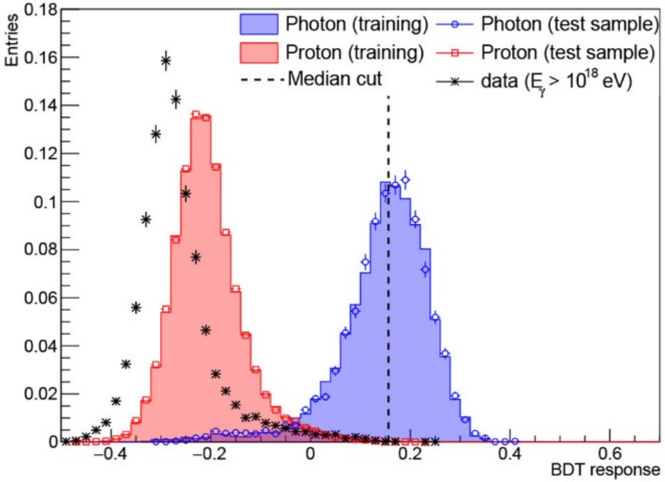
* no neutrino candidates observed yet

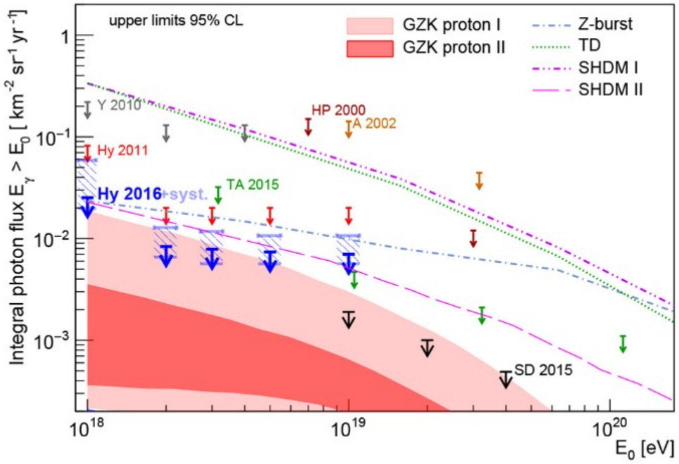
* photons limited to 0.1% (E>1 EeV), 0.85% (E>5 EeV), 2.7% (E>10 EeV) of total flux

    * strong constraints on exotic production models (SHDM, Z-bursts)
    * still above expectations for secondary fluxes

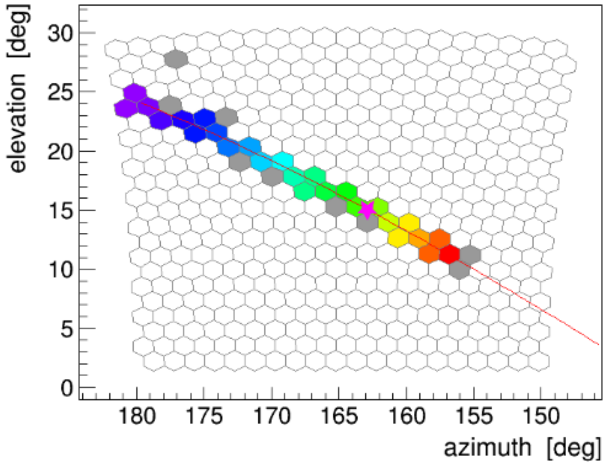
data compatible with nuclear masses higher than protons

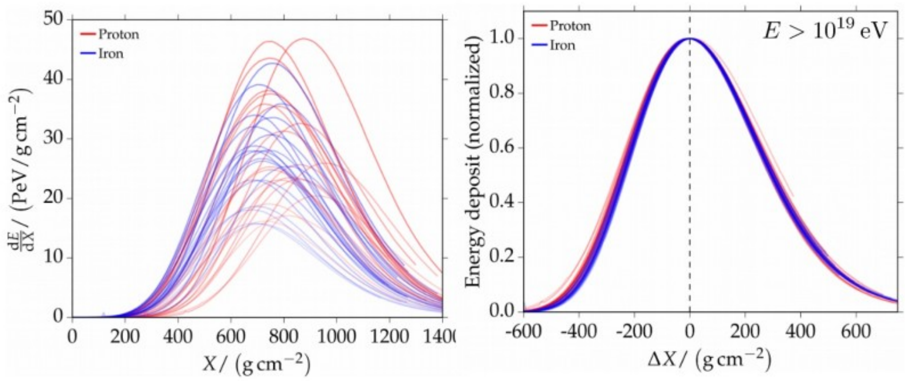
limit exotic shower shapes (for example from magnetic monopoles)



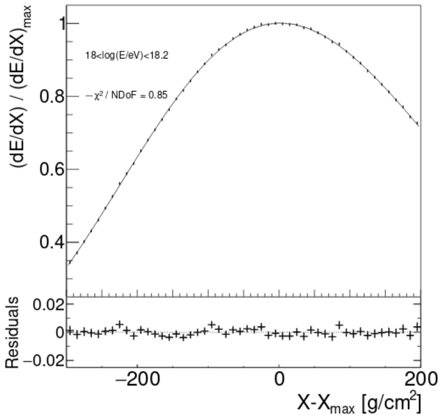


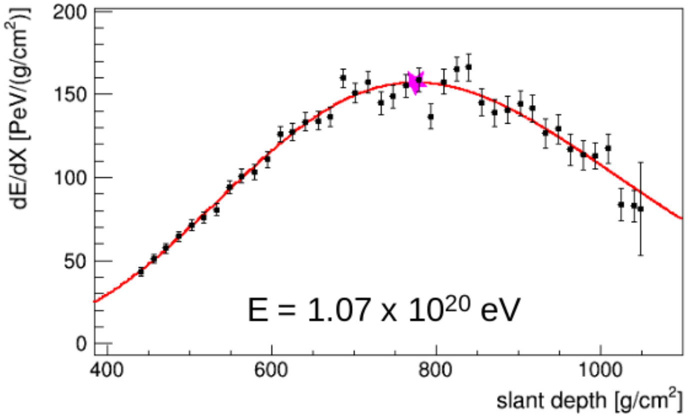
measuring showers in FD





JCAP03(2019)018

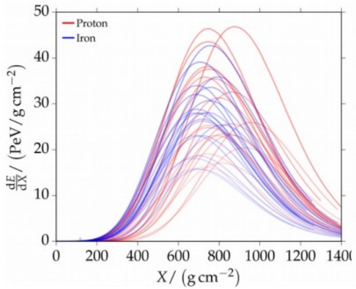


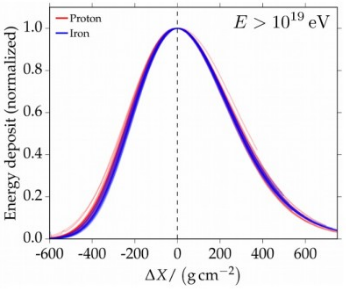


4-parameter GH functional form checked @1% level

* Energy and Xmax are main parameters

Fiducial volume cuts to ensure un-biased Xmax sample
Data-driven corrections for “invisible energy” [arXiv:1901:08040 submited to PRD]

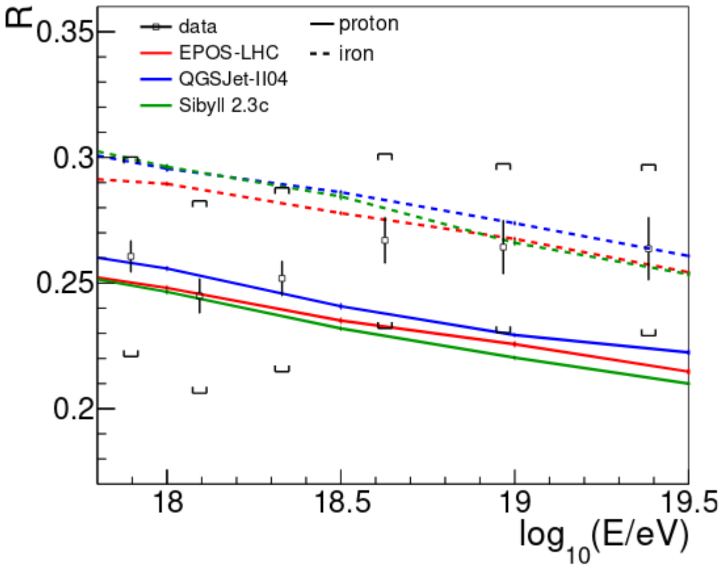


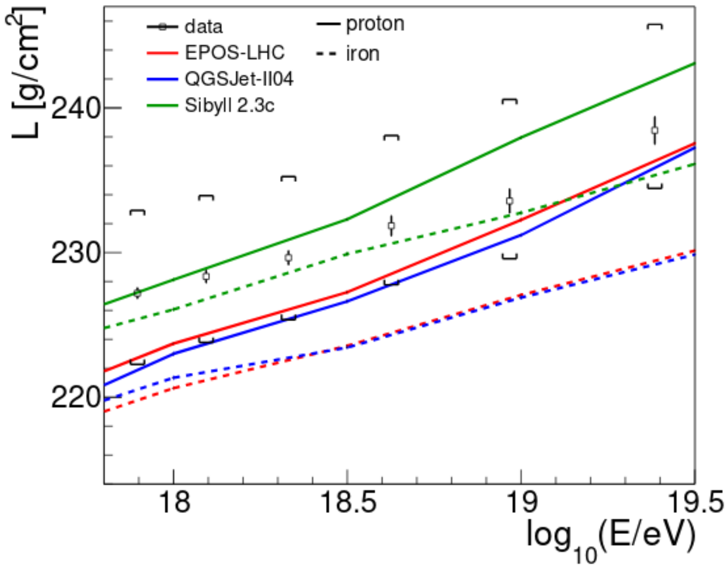


shower development

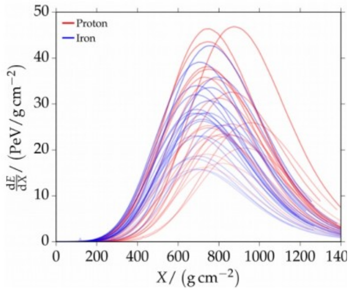
Xmax = X1 (first interaction) + Δ (L,R),
electromagnetic shower longitudinal profiles described by used hadronic models

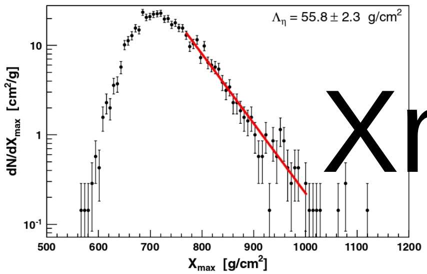
JCAP03(2019)018





main systematics uncertainties in reconstruction are related to atmospheric corrections

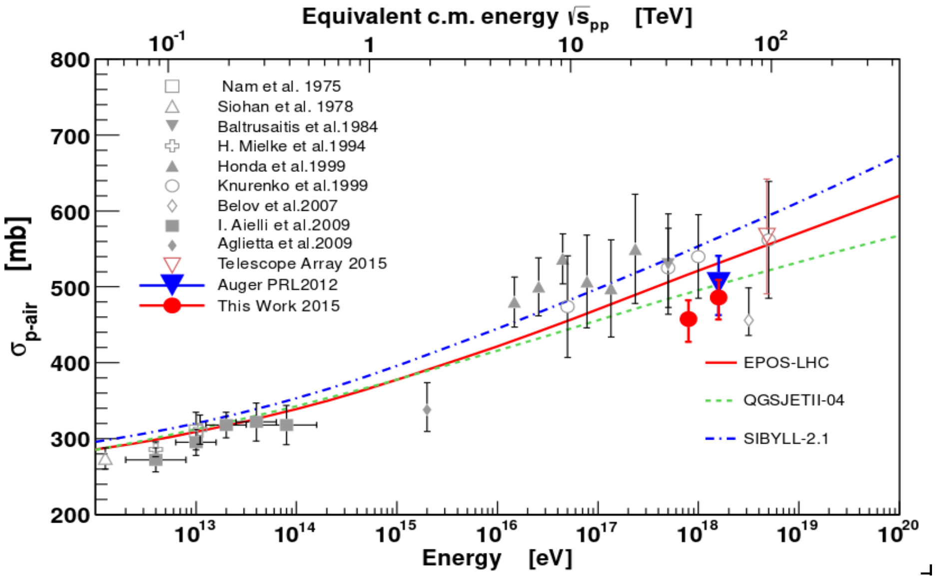




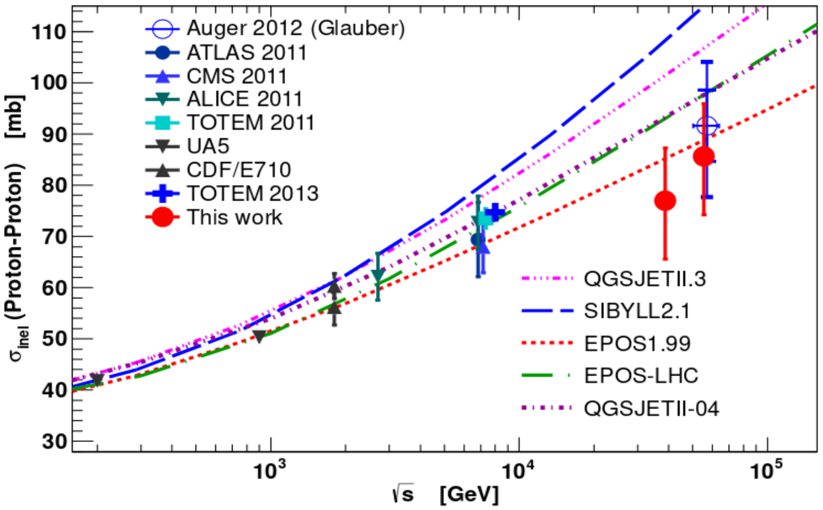
Xmax tail & cross-section

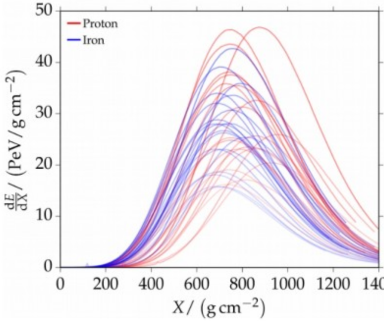
Xmax = X1 (first interaction) + Δ (development),
exponential tail allows to **measure cross-sections, well above the LHC energy**

Rev. Lett. 109, 062002 (2012)

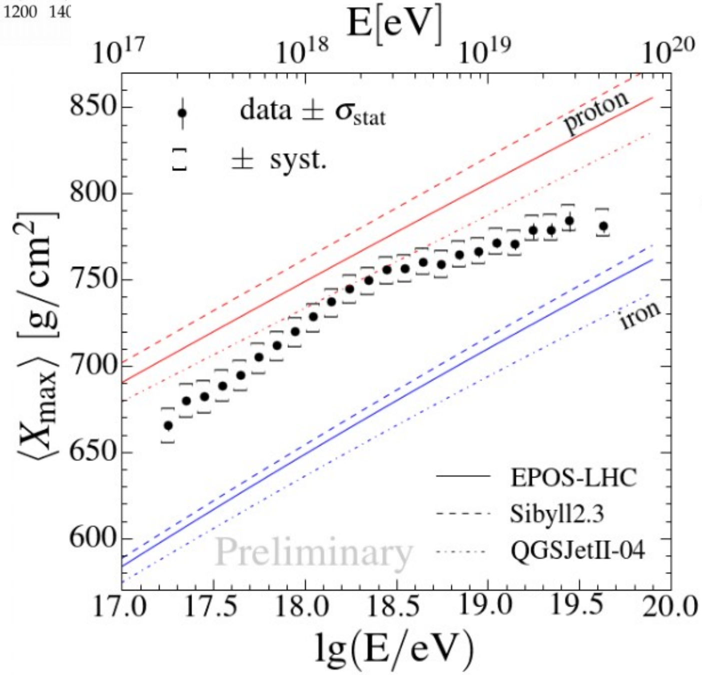


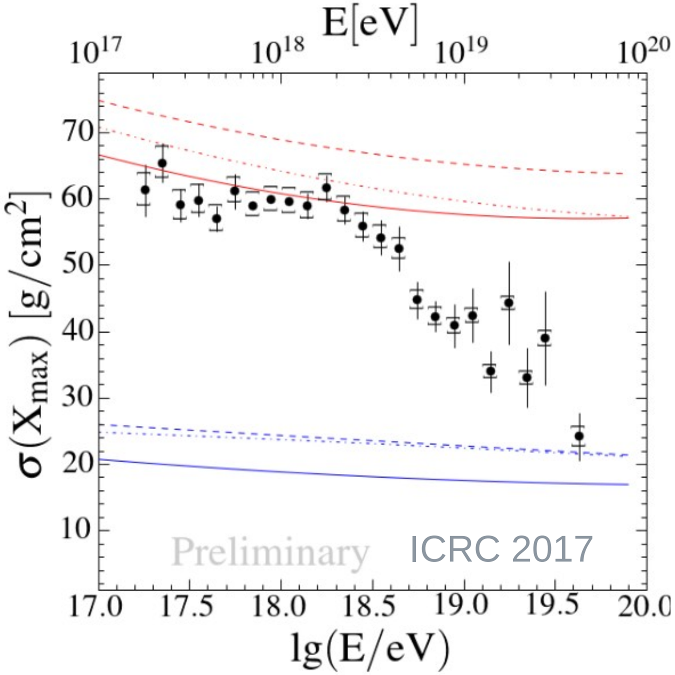
LHC data constrained previous models





Xmax: composition observable



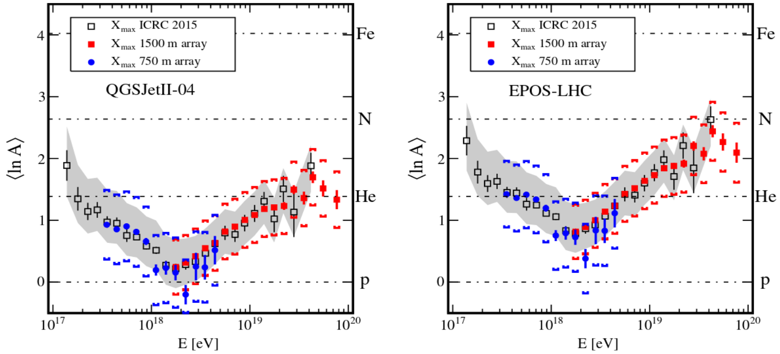


slope break at 2 EeV
spectrum ankle at 5 EeV -> heavy galactic to light extragalactic and back to heavy extragalactic composition

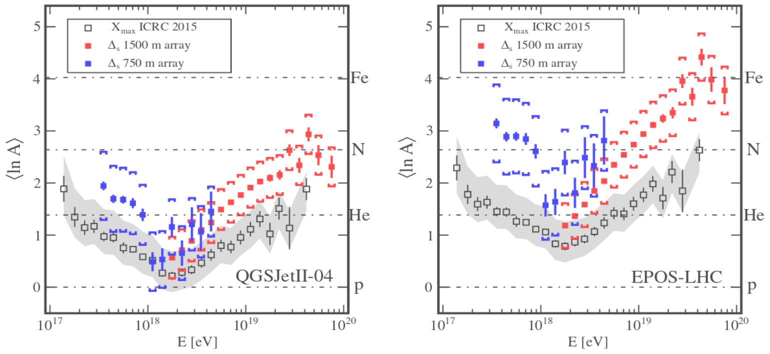
composition at higher energies

SD observable from average signal risetime
directly calibrated with Xmax from FD

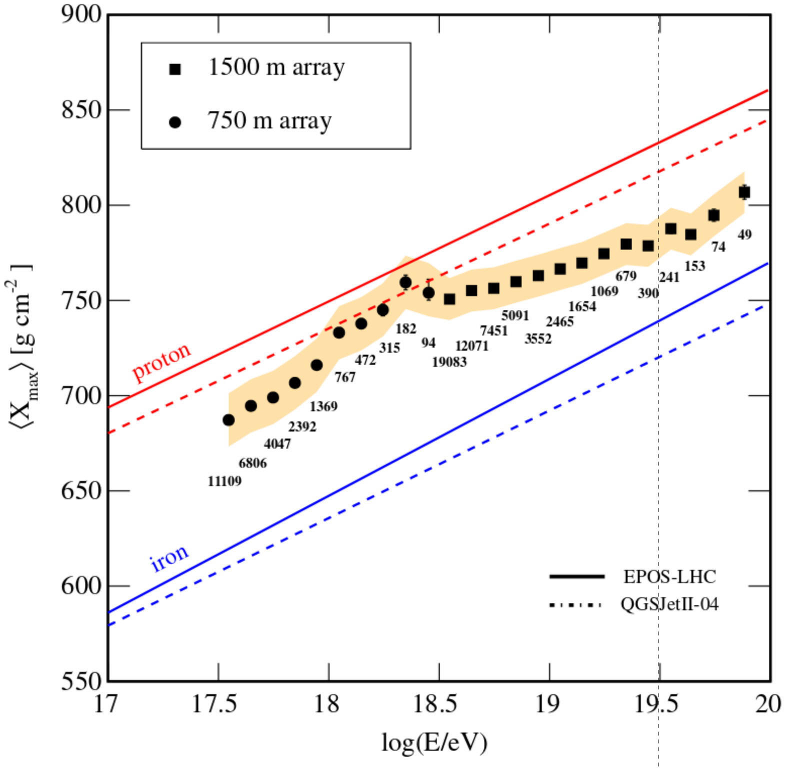
Phys. Rev. D 96, 122003 (2017)



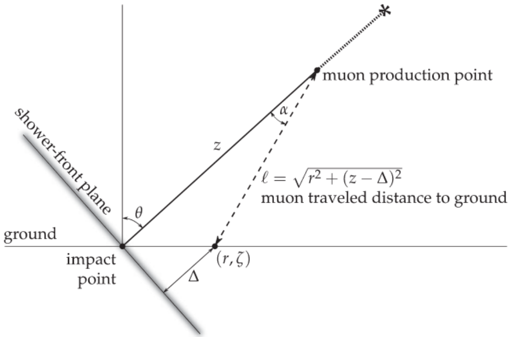
calibrated with
Xmax from FD



taken directly
from models

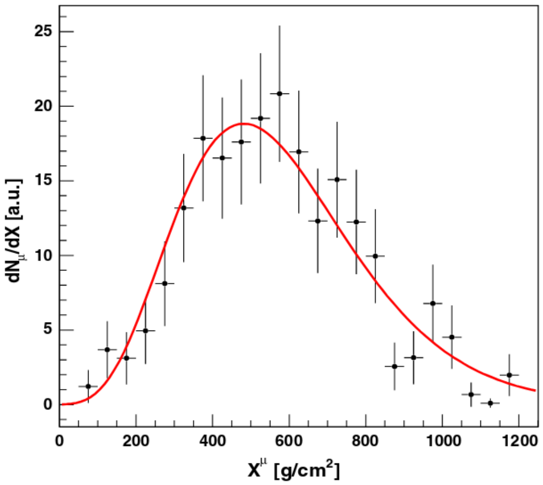


hadronic shower development

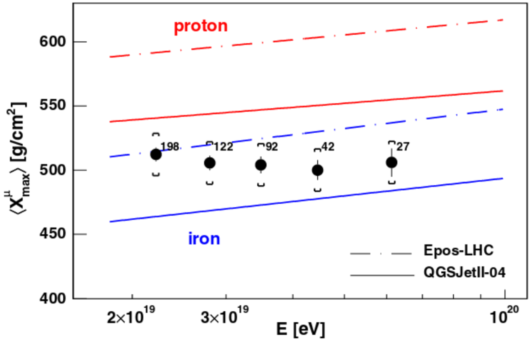


muon production depths can be measured directly from ground signals in high energy inclined events

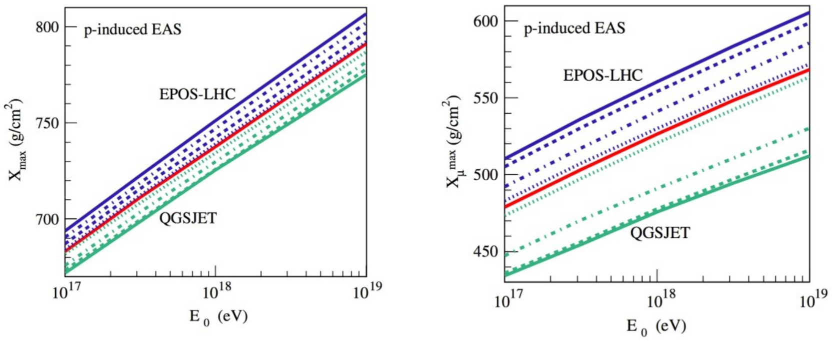
models have large uncertainties on muon production



PRD90,012012 (2014)



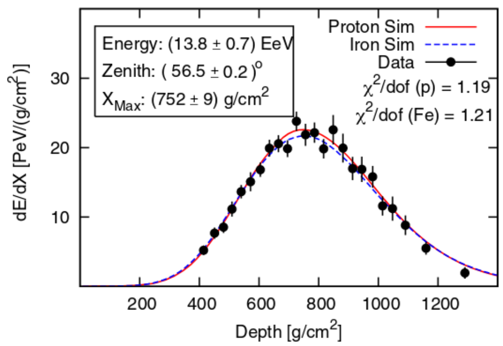
Xmax (em/mu) = X1 + Δ (em/mu)

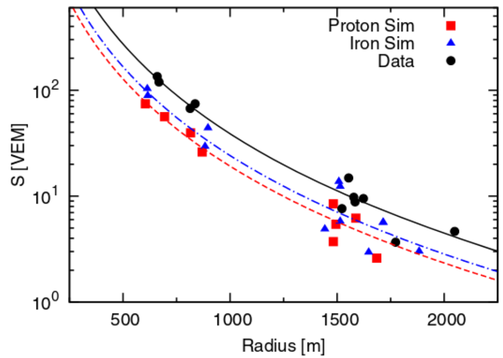


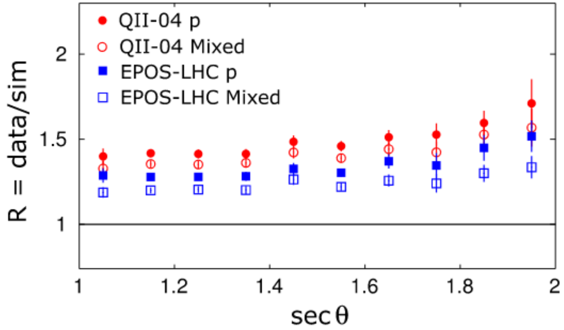
[@S.Ostapchenko, M.Bleicher, PRD93 (2016) 051501]

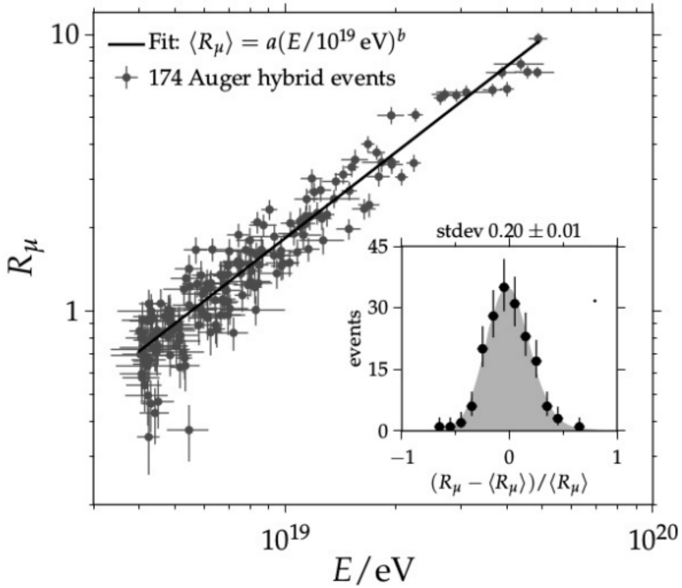
(muon) signal at ground

PRL117,192001 (2016)

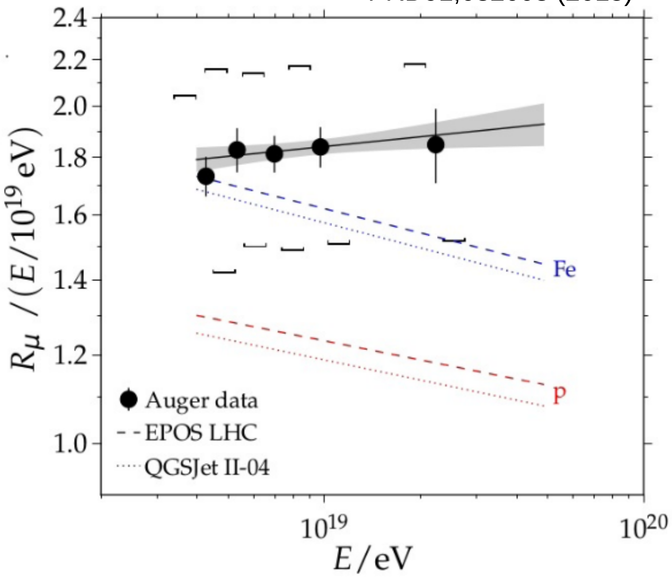








PRD91,032003 (2015)



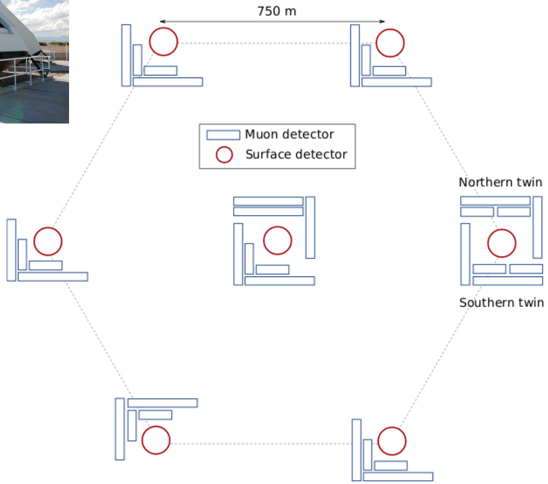
almost pure muons in very inclined (non-neutrino!) events

all hadronic interaction models have a deficit of muons

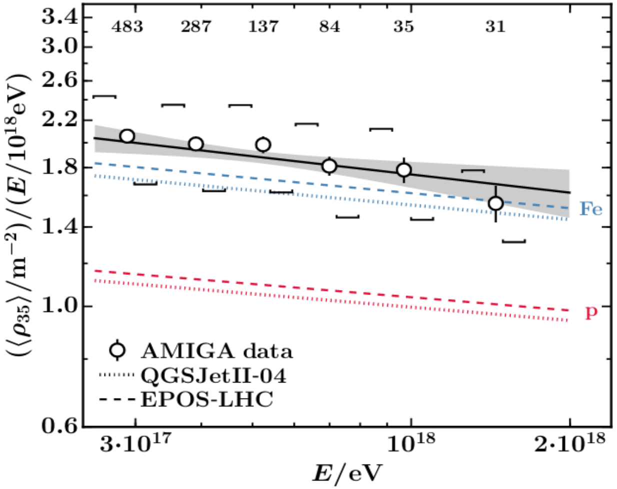
muon deficits also at low energies

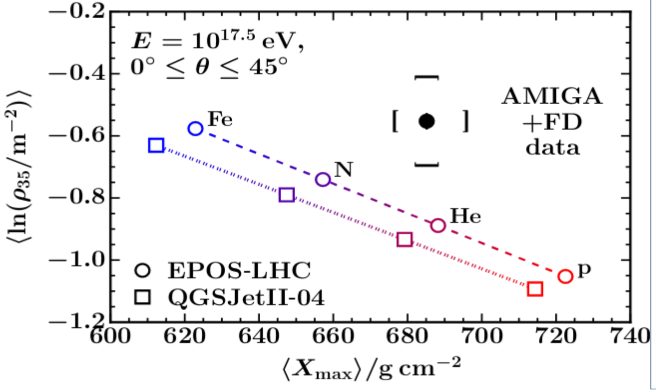
AMIGA:
Auger Muons and Infill
for the Ground Array
(2.3 m deep scintillator)

approaching LHC energy,
together with HEAT

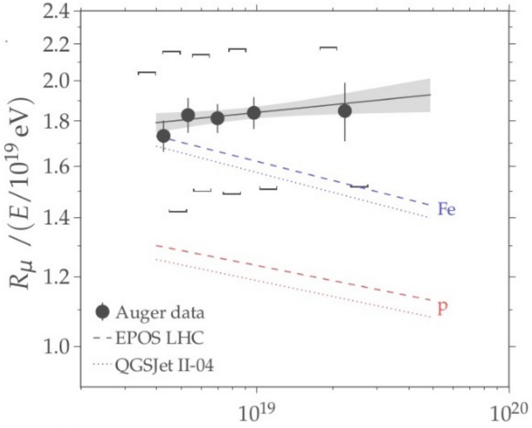


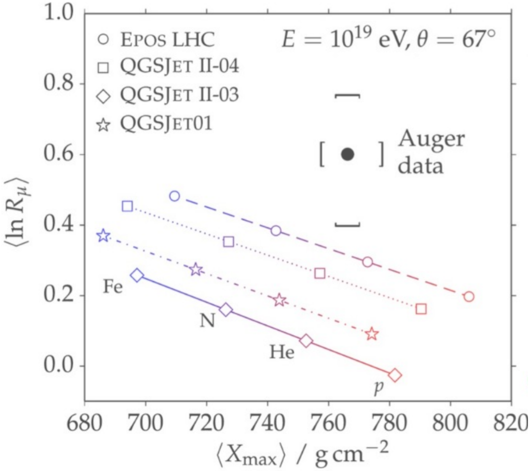
Preliminary - UHECR 2018





high energy inclined showers





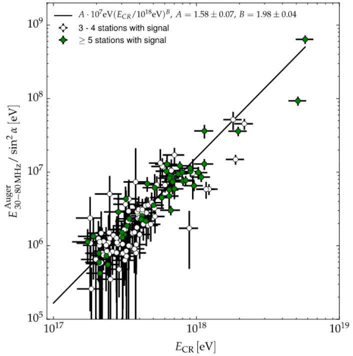
towards Auger Prime

4m² scintillator + radio antenna in each SD station
for **electromagnetic** signal at low and high angles

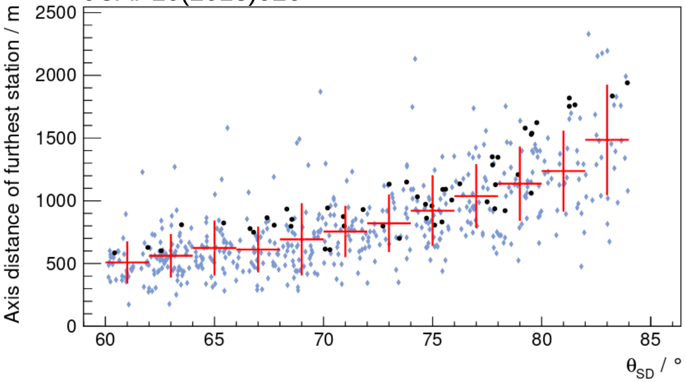
improved WCD and AMIGA counters
for measuring the **muon** signals

extensive R&D on radio detection in the last years

PRL116,241101 (2016)

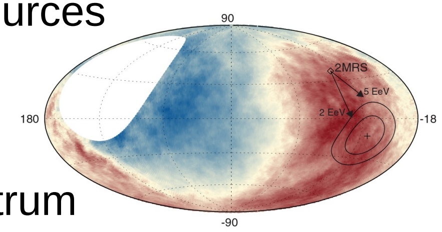


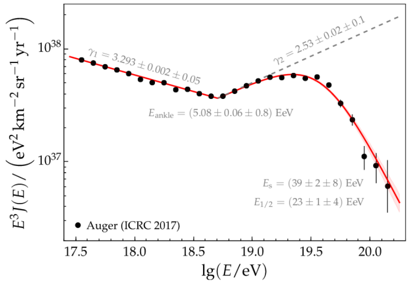
JCAP10(2018)026



summary

Auger detects highest energy particles from extragalactic sources

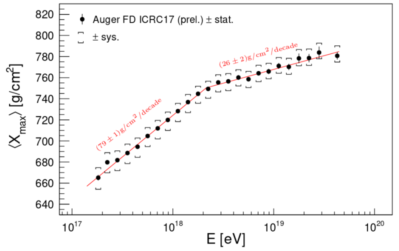




neutral particles for multi-messenger searches

anisotropy seen before the end of the cosmic-ray spectrum

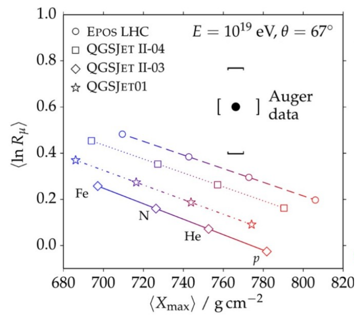
mass / charge increases with energy for galatic and extragalactic sources



Hybrid detection methods are crucial for interpreting results

electromagnetic shower component fully measured and well described

muons more directly probe hadronic interactions, and are not well modeled



Auger Prime will provide measure more details of each shower

new information for both astrophysics & particle physics

engeneering array taking data, full production during 2019