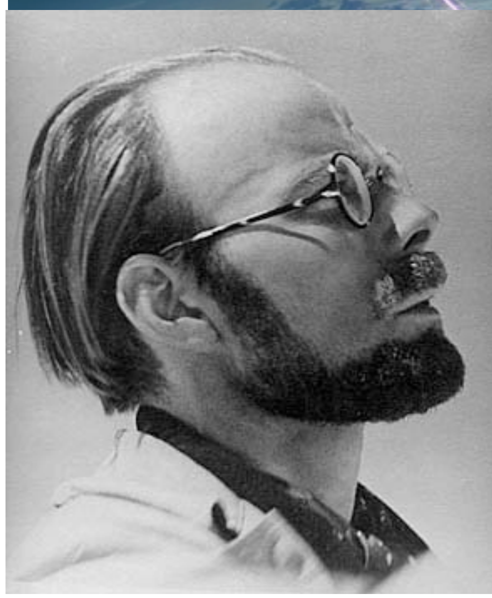

Recent Results from the Pierre Auger Observatory

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for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

23rd Rencontres de Blois Particle Physics and Cosmology
30 May 2012

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Outline

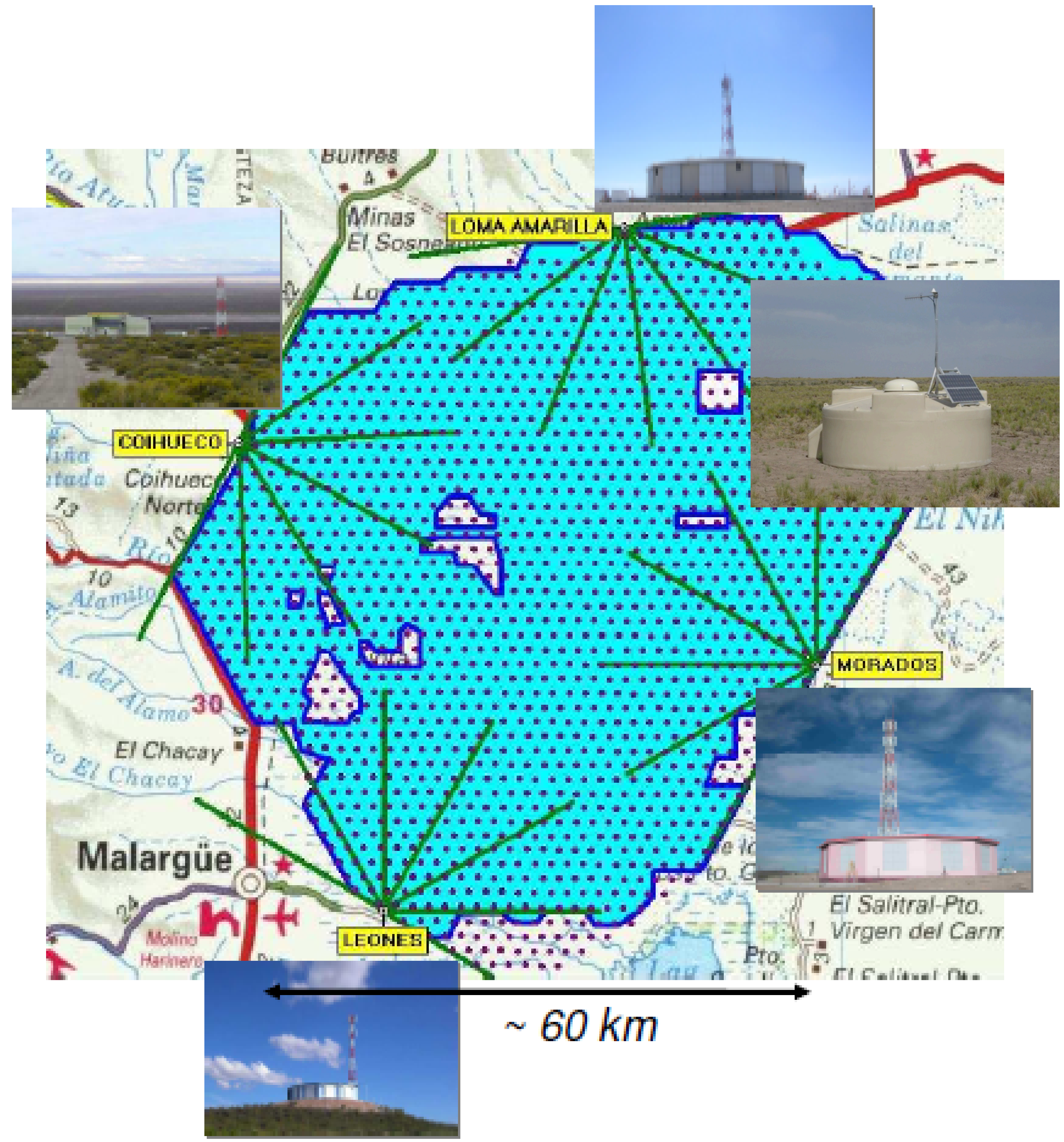
- The Pierre Auger Observatory
- Energy Spectrum
- Mass Composition
- Cross Section
- Test of hadronic interaction models
- Photons and Neutrinos search
- Anisotropy search

The Pierre Auger Observatory

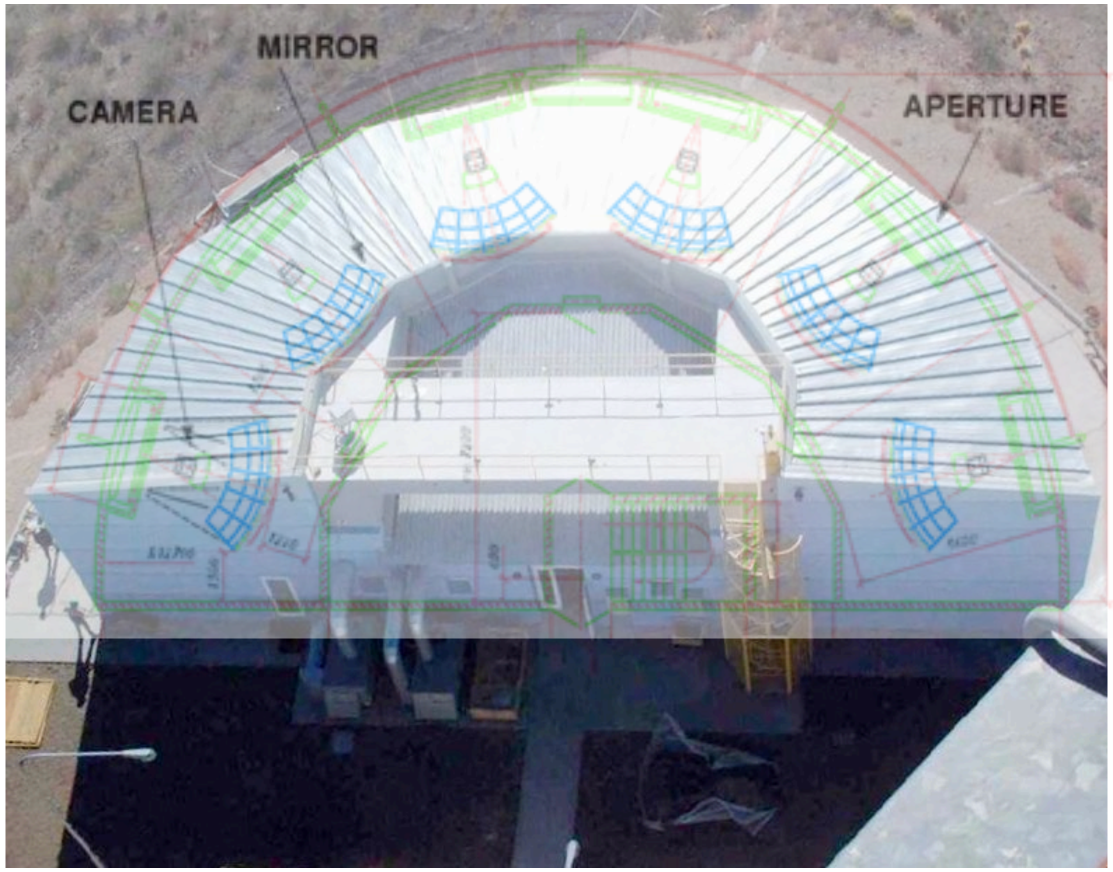
Located in Argentina, province of Mendoza, Malargue

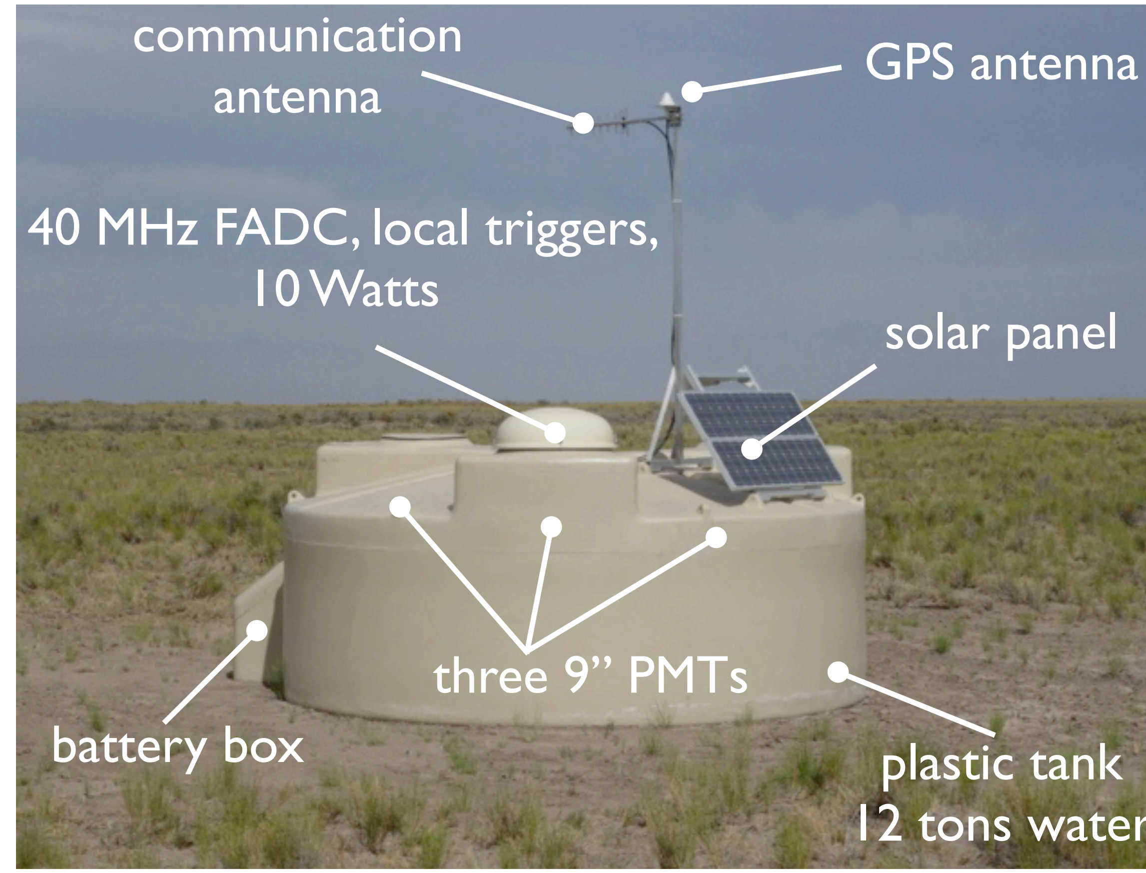
Total area 3000 km^2

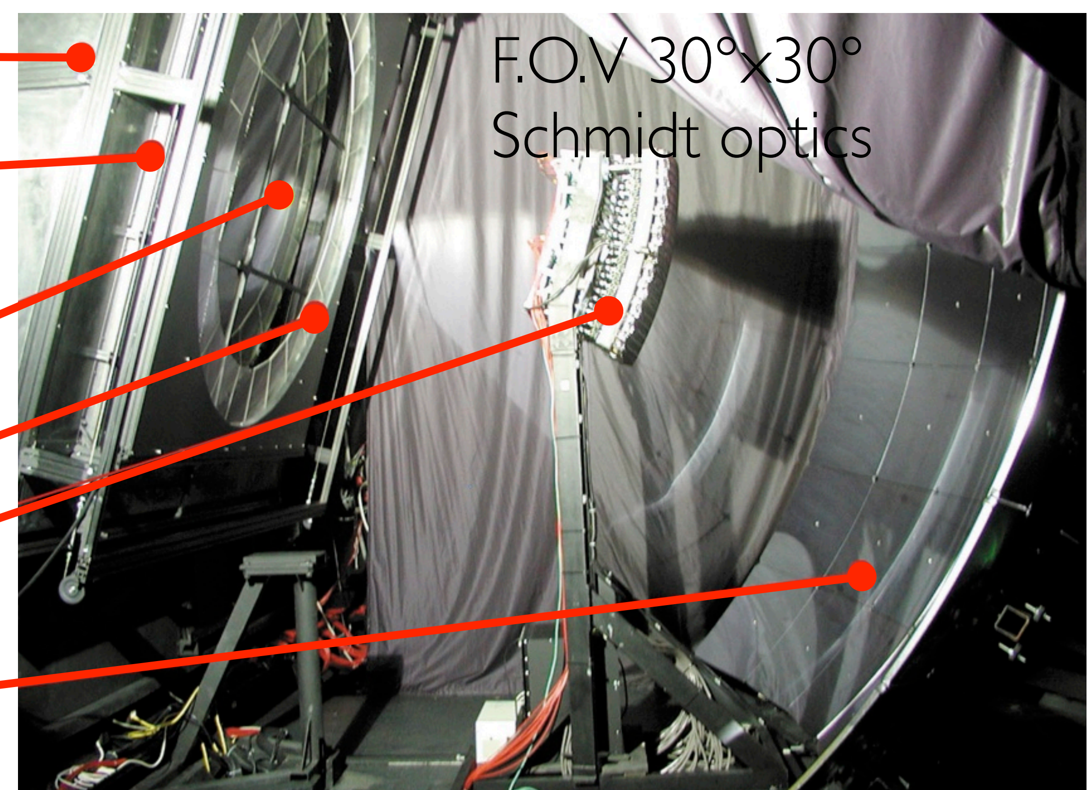
- Surface Detector array (SD)
  - ❖ water Cherenkov detectors
  - ❖ 1660 in 1.5 km grid
  - ❖ 61 in 0.75 km grid (infill low energies ~3 x 10^{17}eV)
  - ❖100% duty cycle
- Fluorescence Detector (FD)
  - ❖ 4 Fluorescence sites + 1 (Heat low energies ~10^{17}eV)
  - ❖ 6 telescopes per site (3 for Heat)
  - ❖ ~14% duty cycle (moonless nights)
- Atmospheric monitoring
  - ❖Lidars
  - ❖CLF
- Muon detectors(AMIGA)
- Radio detectors (Mhz & GHz)



The Pierre Auger Observatory







aperture box

filter

reference point

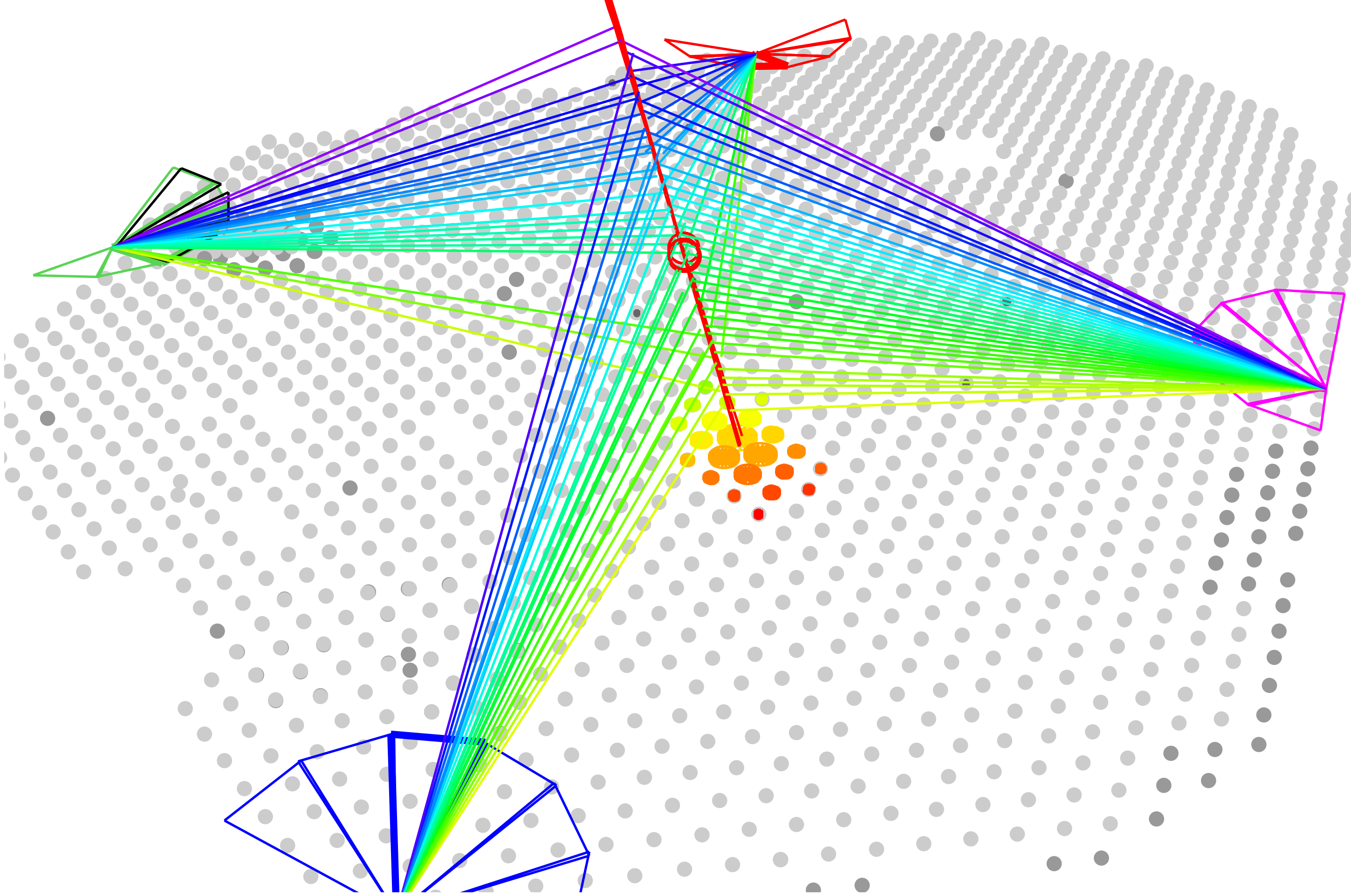
corrector ring

camera 440 PMTs

mirror 11 m^2

The hybrid concept

Real event 201022604036, energy 72 ± 1 EeV, 54 degrees

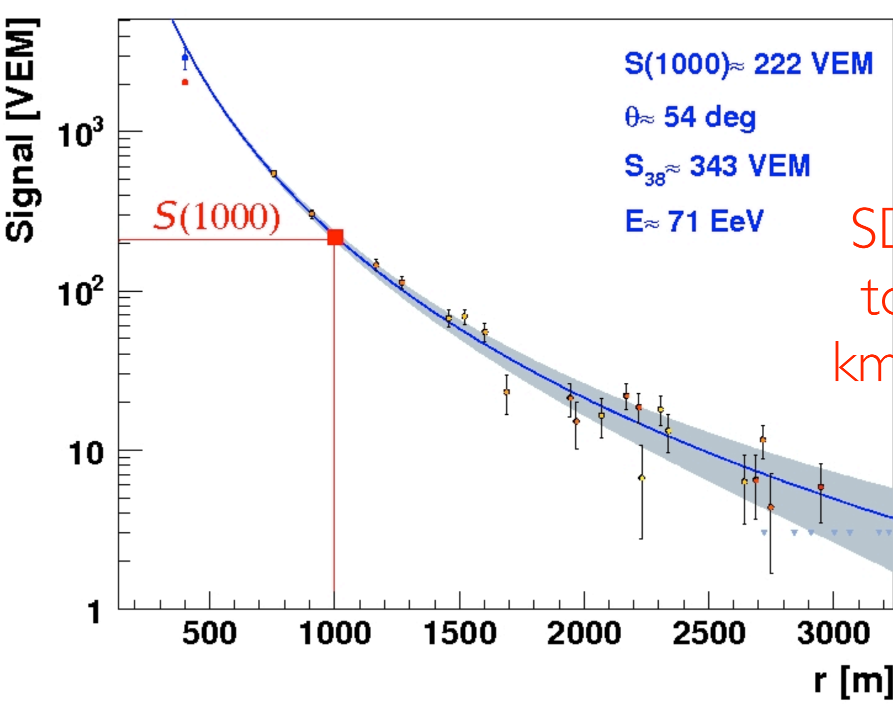


3 events categories:

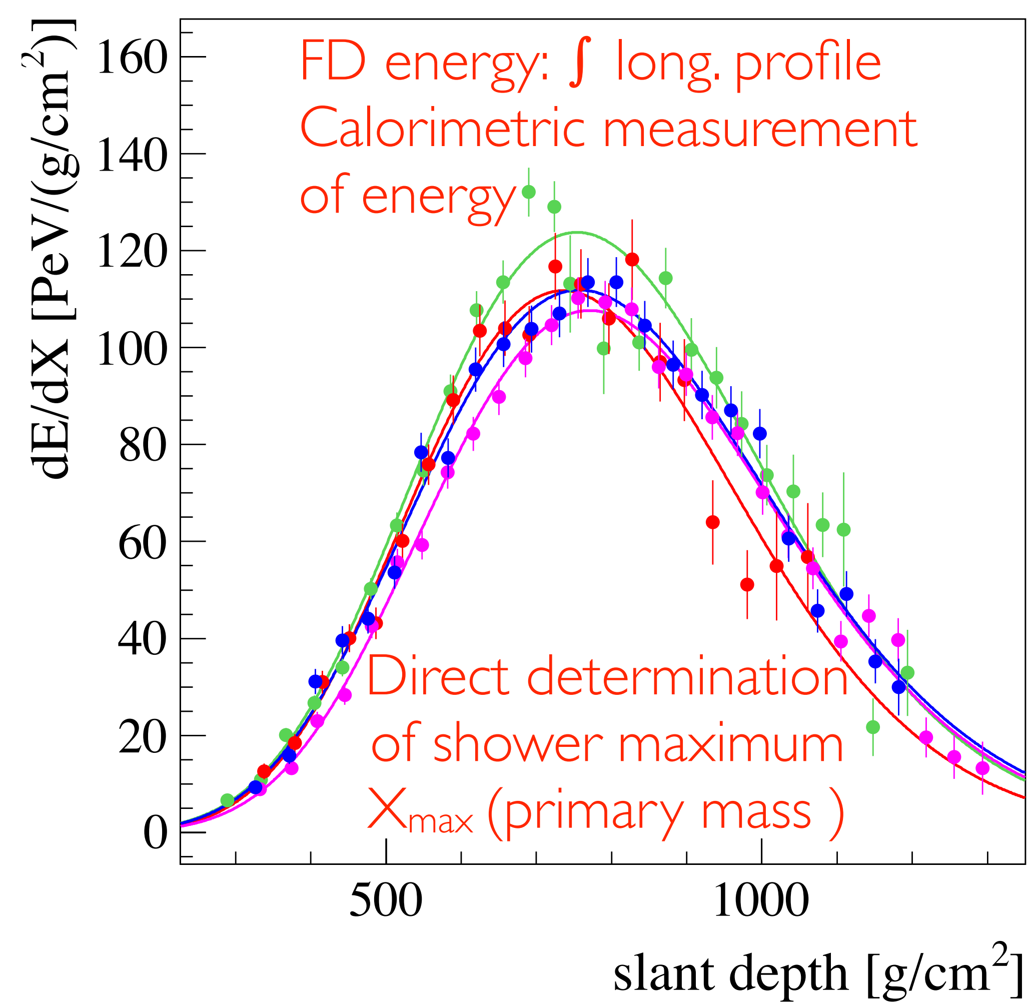
- SD only
- Brass Hybrid (FD + at least one tank)

-> lower the threshold w.r.t SD

- Golden Hybrid (independent SD and FD reconstructions) ->SD Calibration



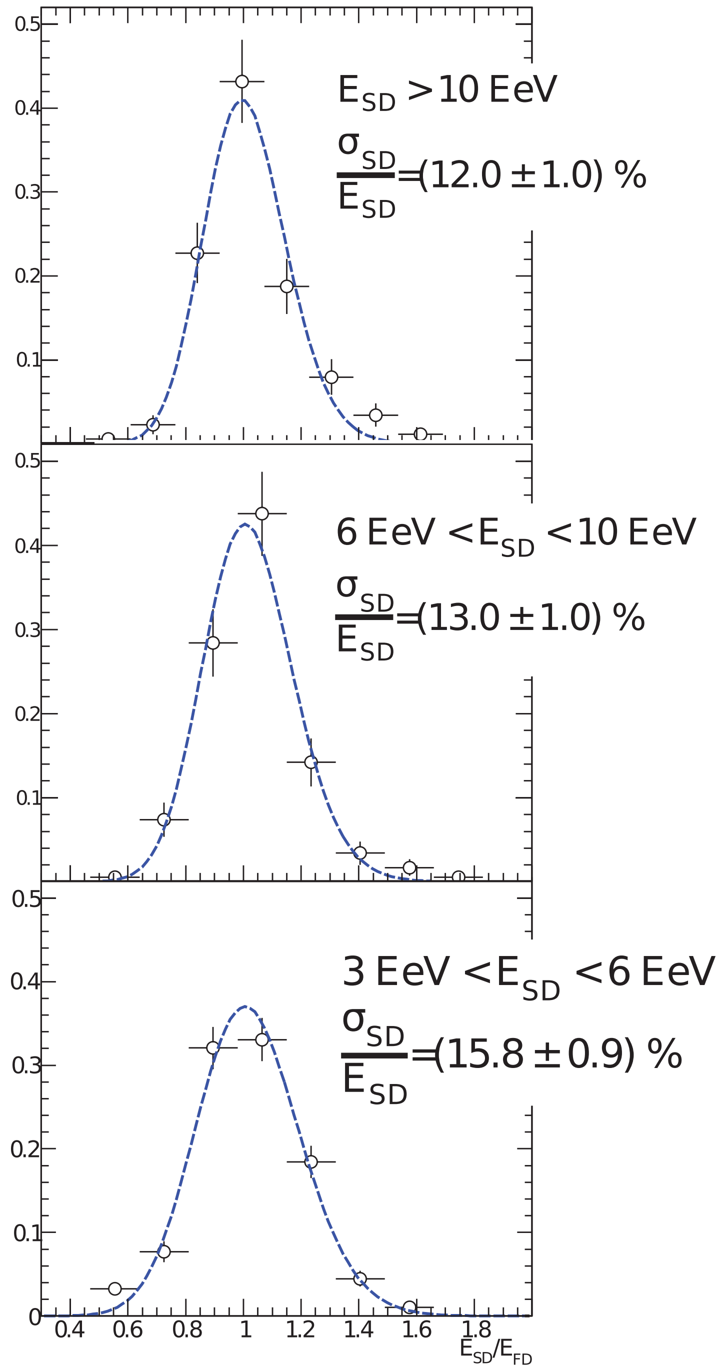
SD energy: proportional to signal measured at 1 km from the shower core



Energy Calibration

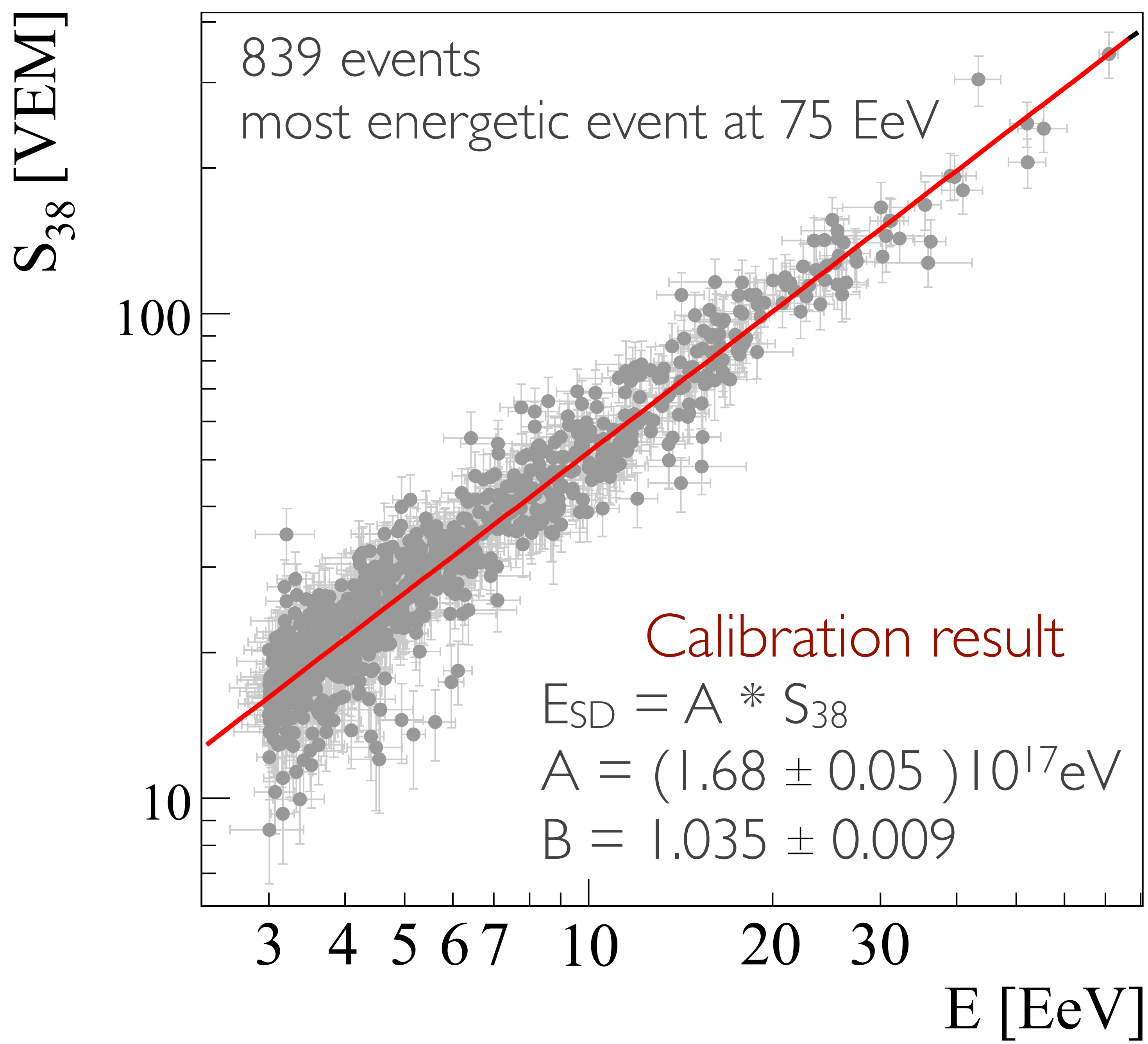
SD Resolution

- ~10% shower to shower fluctuation
- reconstruction uncertainty



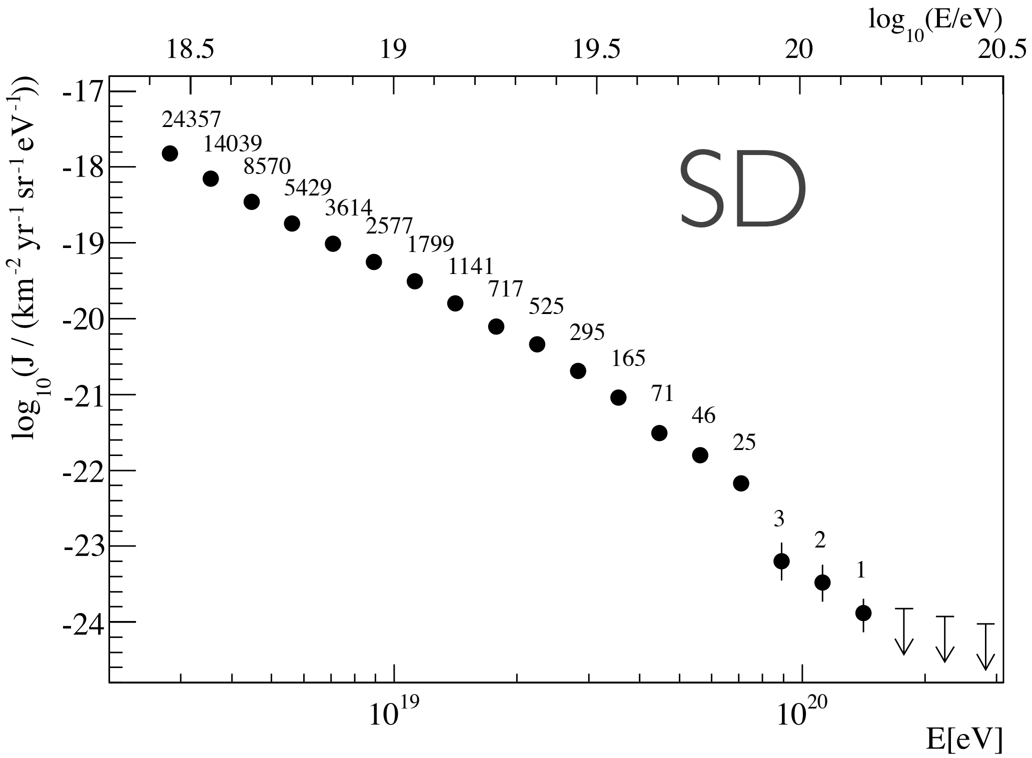
Calibration made using events with independent SD and Hybrid trigger and reconstruction

Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

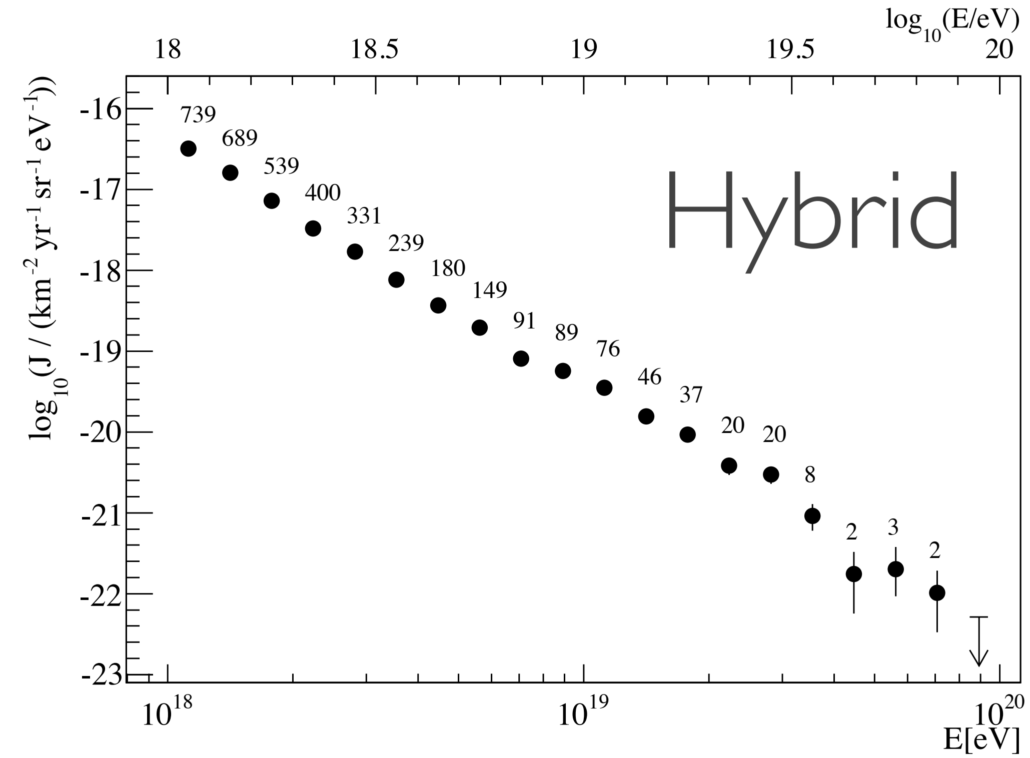


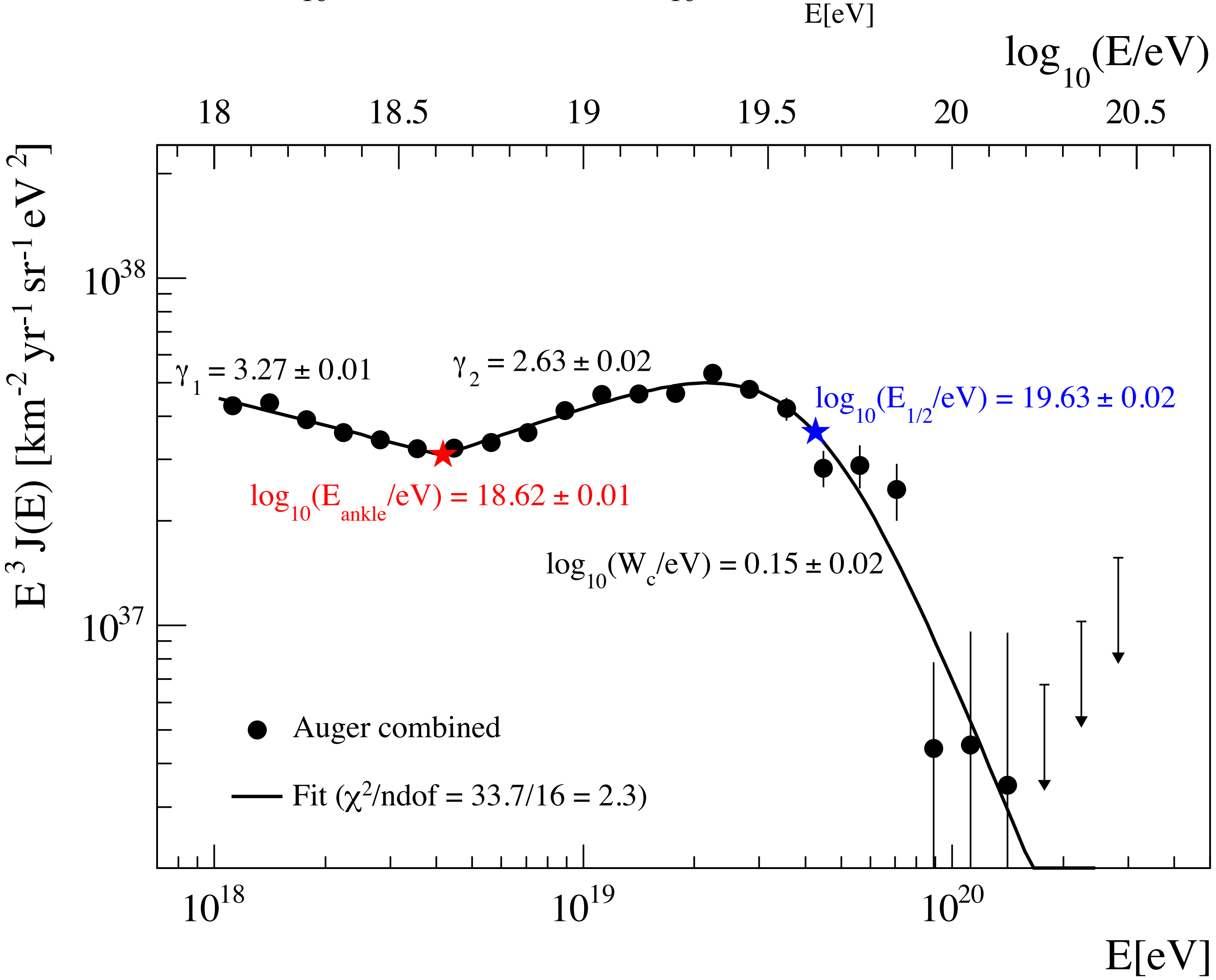
Total uncertainty of FD energy scale : 22% (dominated by fluorescence yield. 14%)

UHECR Flux



Agreement between two spectra better than 1.5%





Combined spectrum results:

- Very precise measurement above 10^{18} eV
- ankle may indicates a change in the acceleration mechanism (origin Gal. to Extra Gal.)
- flux suppression at highest energies found with a significance $>20\sigma$

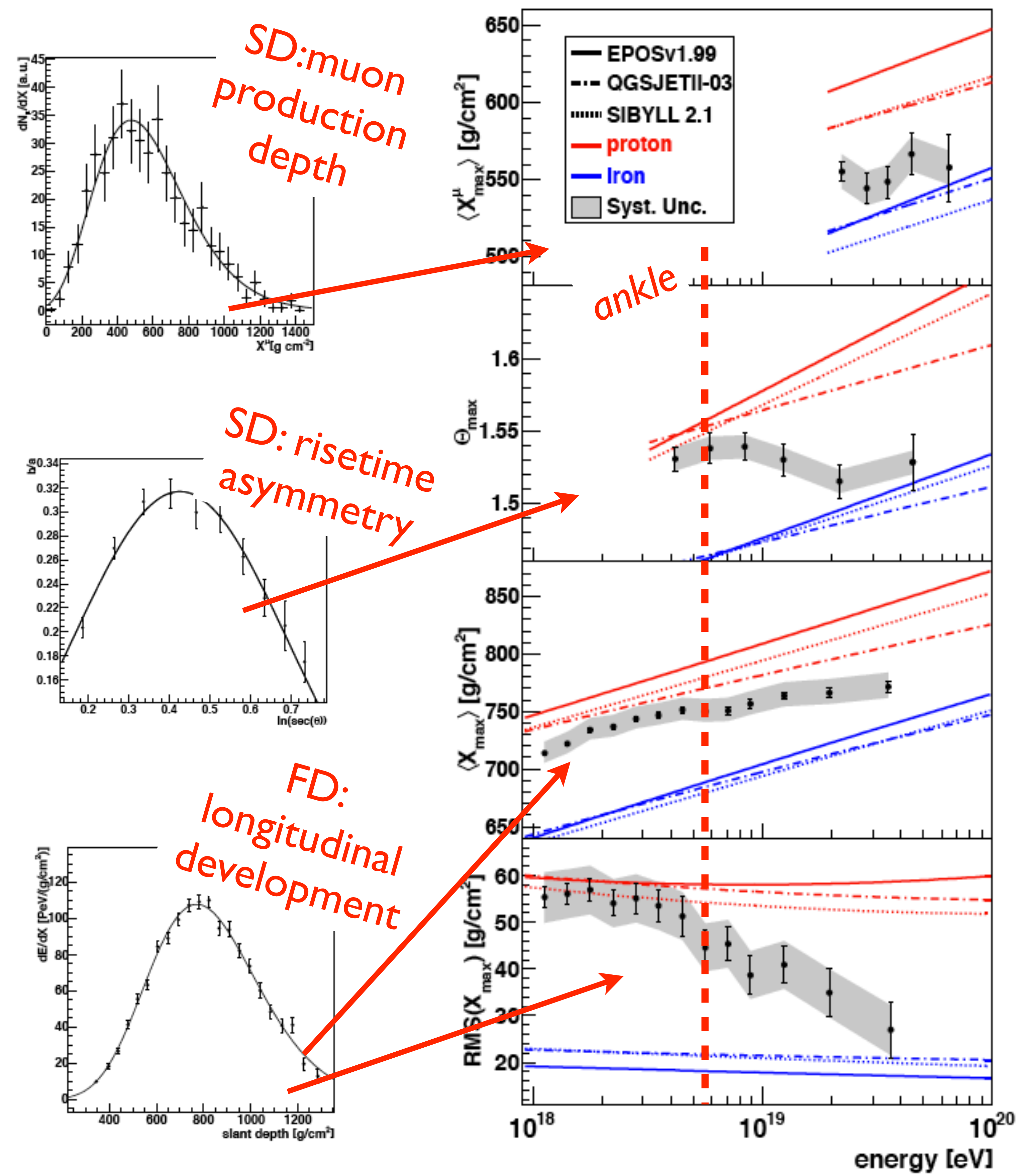
Mass Composition

Why?

- Acceleration mechanisms depend on Z
- Combined analysis with spectrum better discriminate astrophysical scenarios

3 different analysis in Auger

- evolution with energy is similar
- completely independent techniques
- at the highest energies data resemble more the simulations of heavier primaries than pure protons

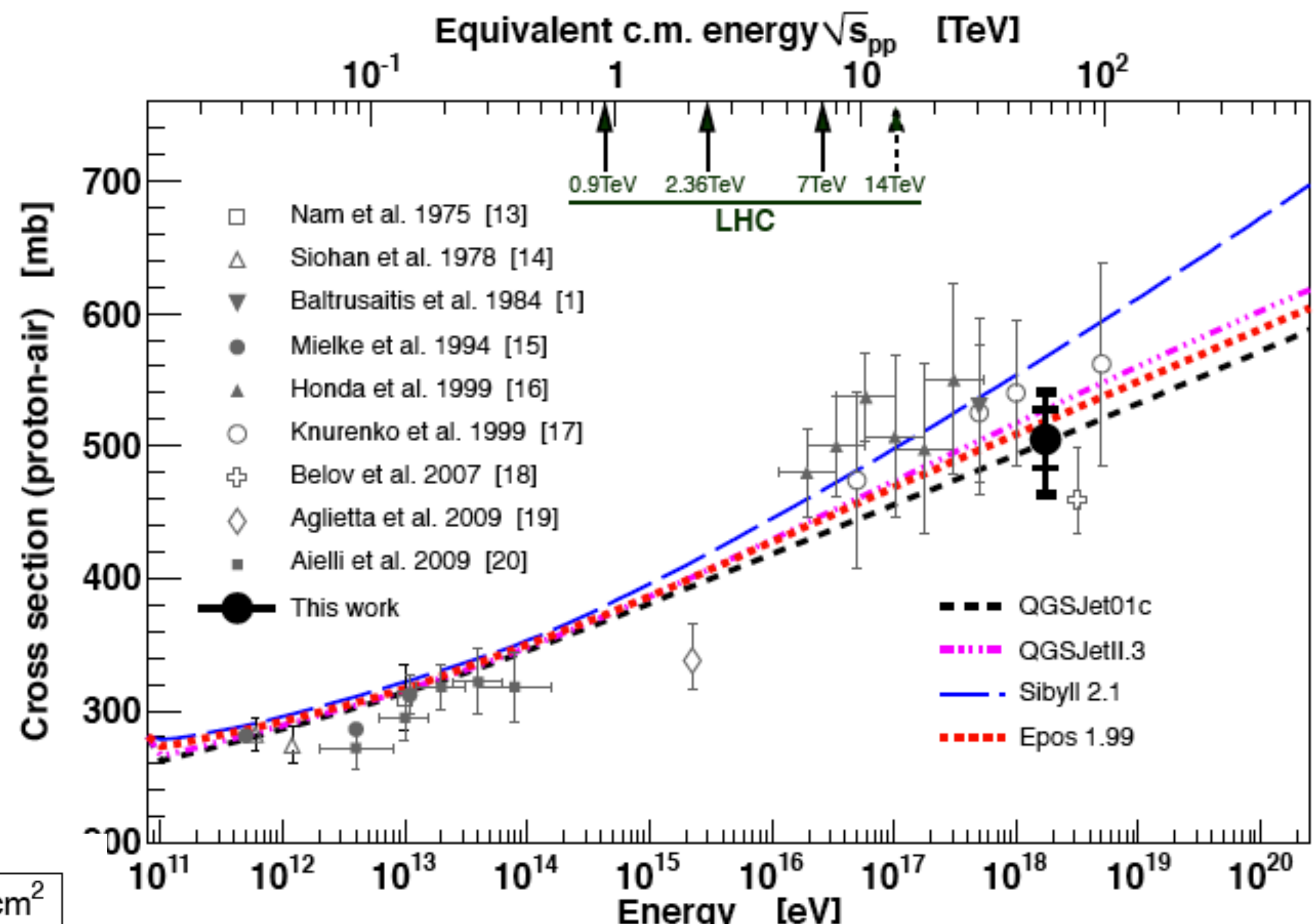


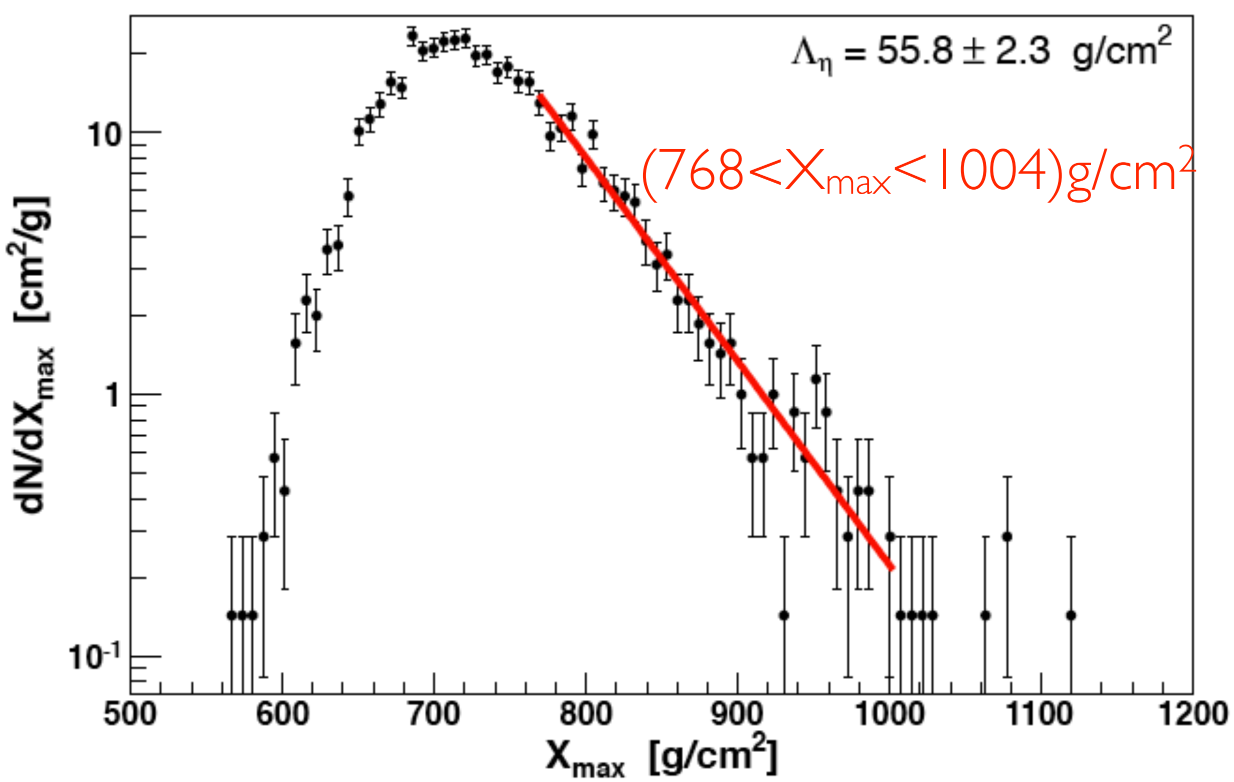
Cross Section at 57 TeV

The tail of shower maximum (X_{max}) distribution is sensitive to proton-air cross section (Ulrich et al. NJP 11 (2009))

As primary observable we define Λ_η via the exponential shape of the X_{max} distribution:

η denotes the fraction of most deeply penetrating air showers used small value enhances the proton fraction, but reduces the sample





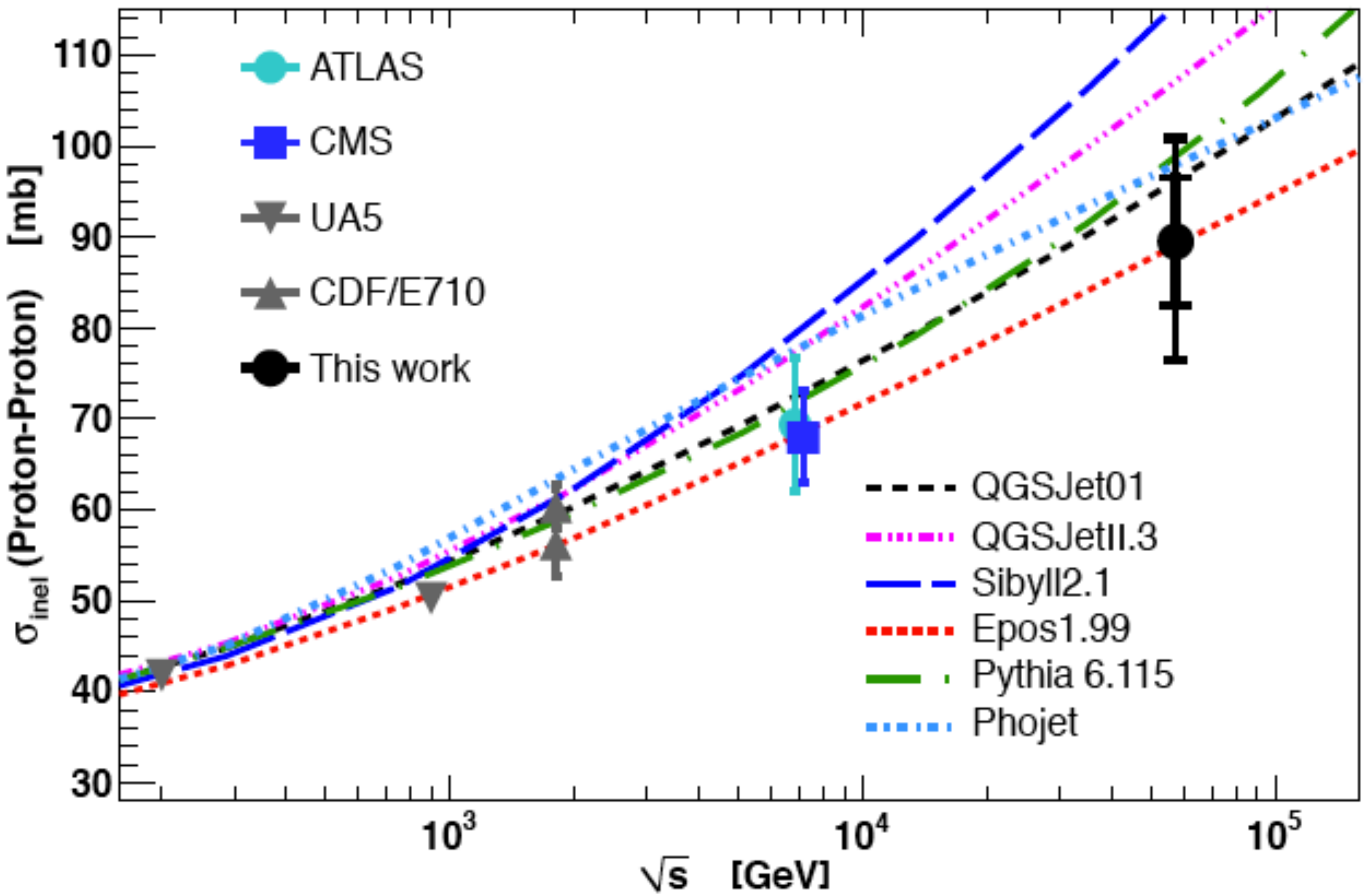
$\sigma_{p\text{-}Air} = (505 \pm 22(\text{stat})\ ^{+28}_{-36}(\text{sys})\ )\text{mb}$

$\eta = 0.2$ means assuming:

- photons < 0.5%
- helium < 25%

Cross Section at 57 TeV

Obtained using the standard Glauber formalism



$$\sigma_{p\text{-}p}^{inel} = (90 \pm 7(stat)\,^{+9}_{-11}\,(sys) \pm 1.5(Glauber)\,)\ mb$$

$$\sigma_{p\text{-}p}^{tot} = (129 \pm 13(stat)^{+17}_{-20}\,(sys) \pm 11(Glauber)\,)\ mb$$

Test of Hadronic interaction models

Information on the nature of the EAS primary particles and cross section depends on models used in the MC simulations.

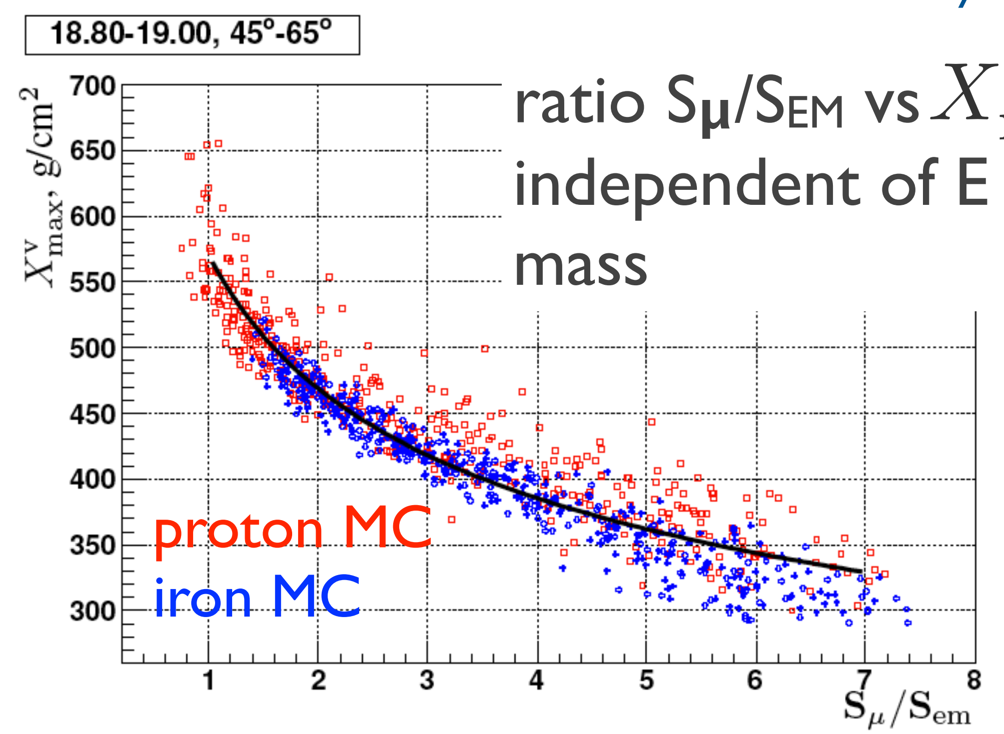
It is very important to validate the models!

Check the muon content relative to models:

$$S_{\mathrm{TOT}} \simeq S_{\mathrm{EM}} + S_{\mu}$$

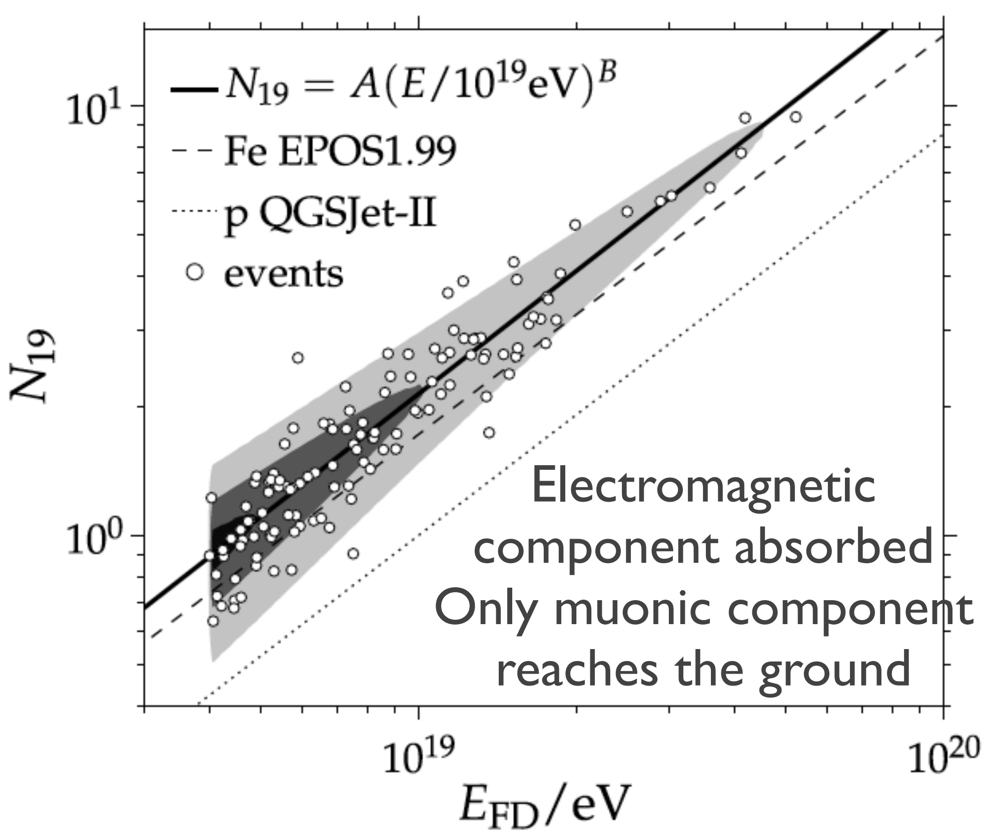
Separation of electromagnetic and muonic components

Shower universality



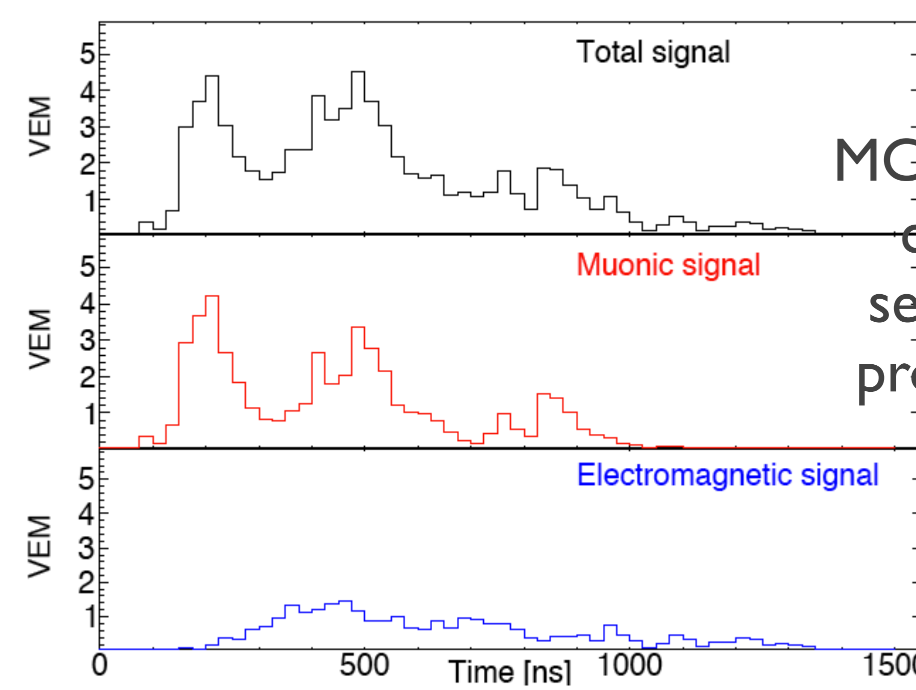
ratio S_{μ}/S_{EM} vs X^{v}_{max} independent of E and mass

Inclined Showers



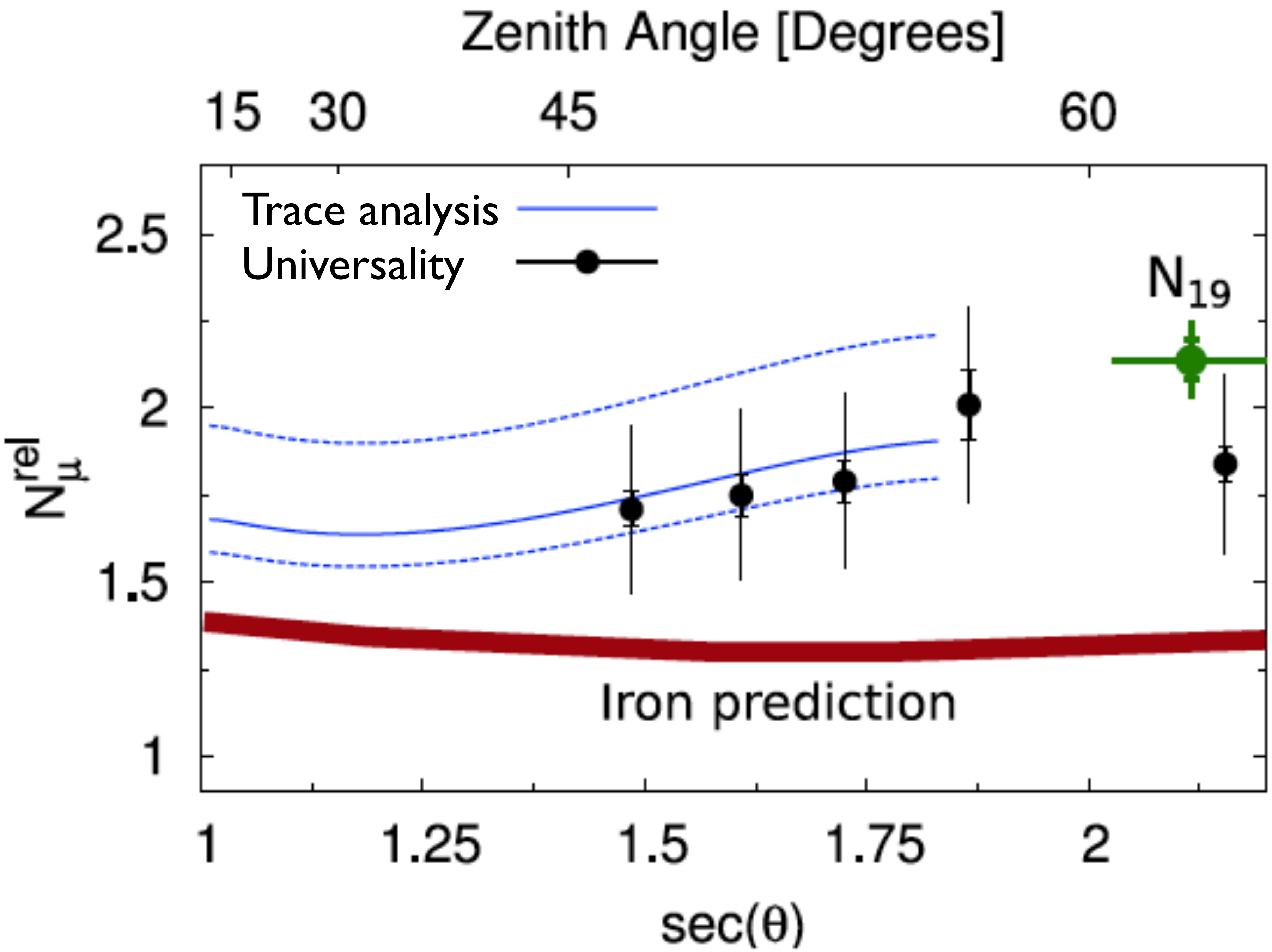
Electromagnetic component absorbed
Only muonic component reaches the ground

Analysis of the SD time trace

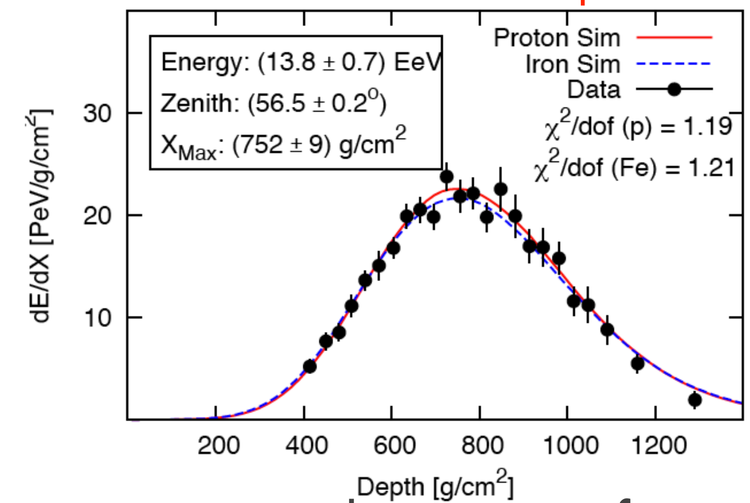


MC: far from the core μs are separated and produce spikes

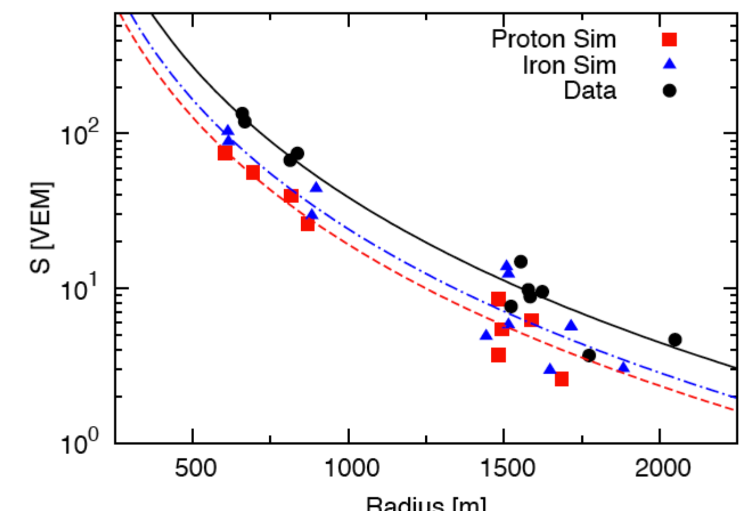
Test of Hadronic interaction models



Data-MC comparison



good agreement for the longitudinal profile



ground signal systematically lower than observed

All the different methods shows that hadronic interaction models underestimate N_μ by a factor 25% - 100% (depending on the model)

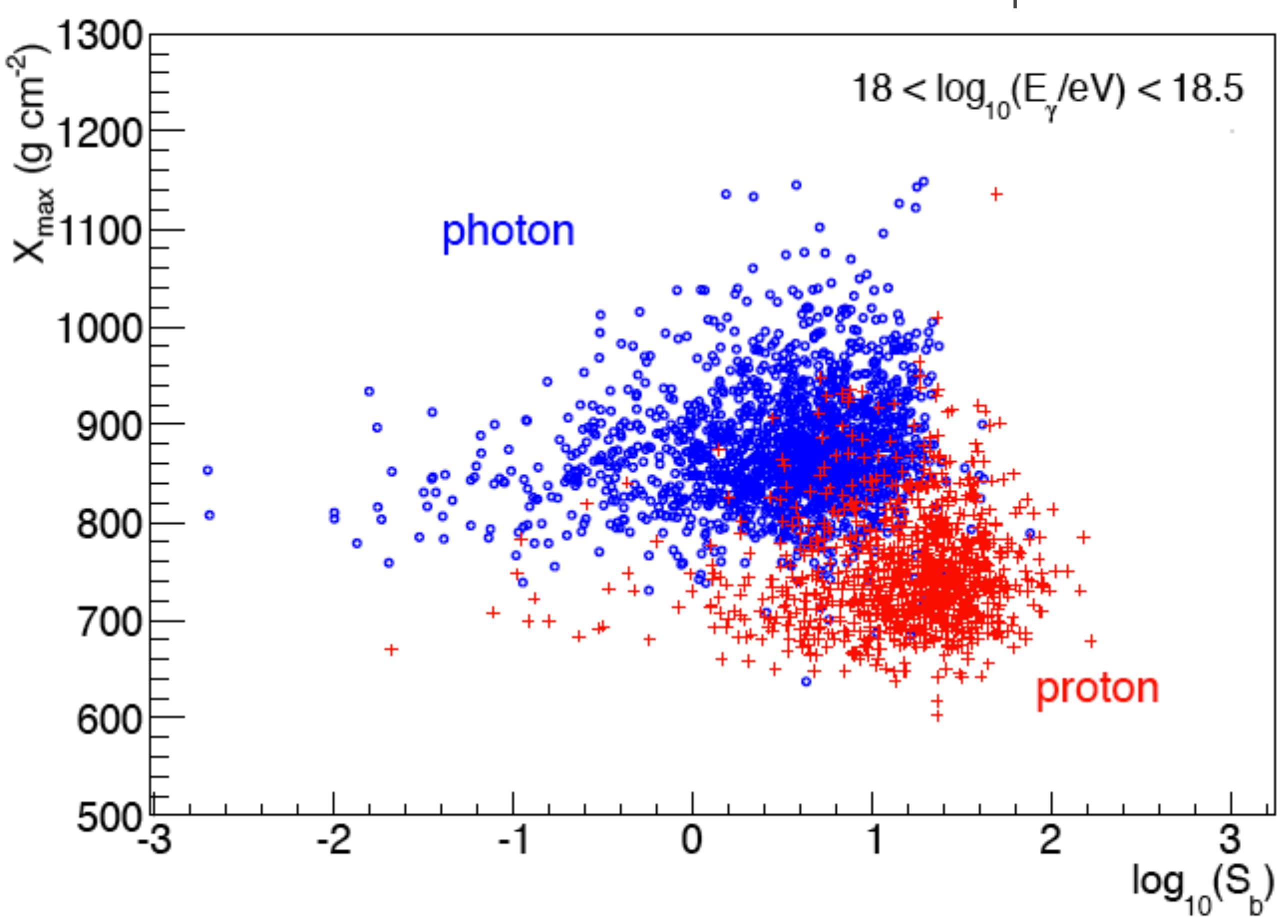
Photon search

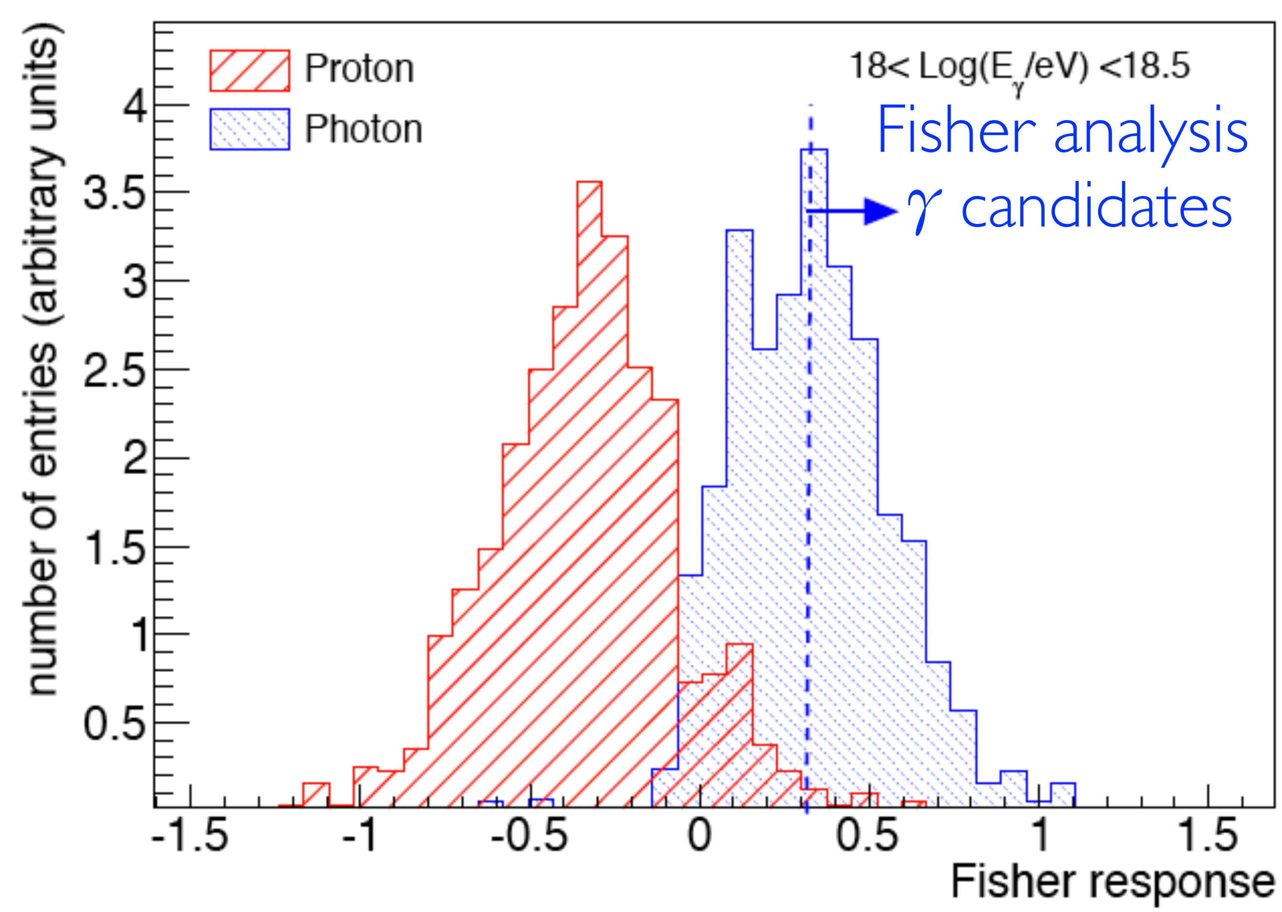
Why searching for photons:
- set limits on top-down mechanisms
- search for GZK photons
- fix the maximum γ fraction in the primary flux

Discrimination parameters:
- development in atmosphere (FD): deeper X_{max}
- shower at ground (SD): larger rise time, small radius of curvature (i.e smaller signal in the tank)

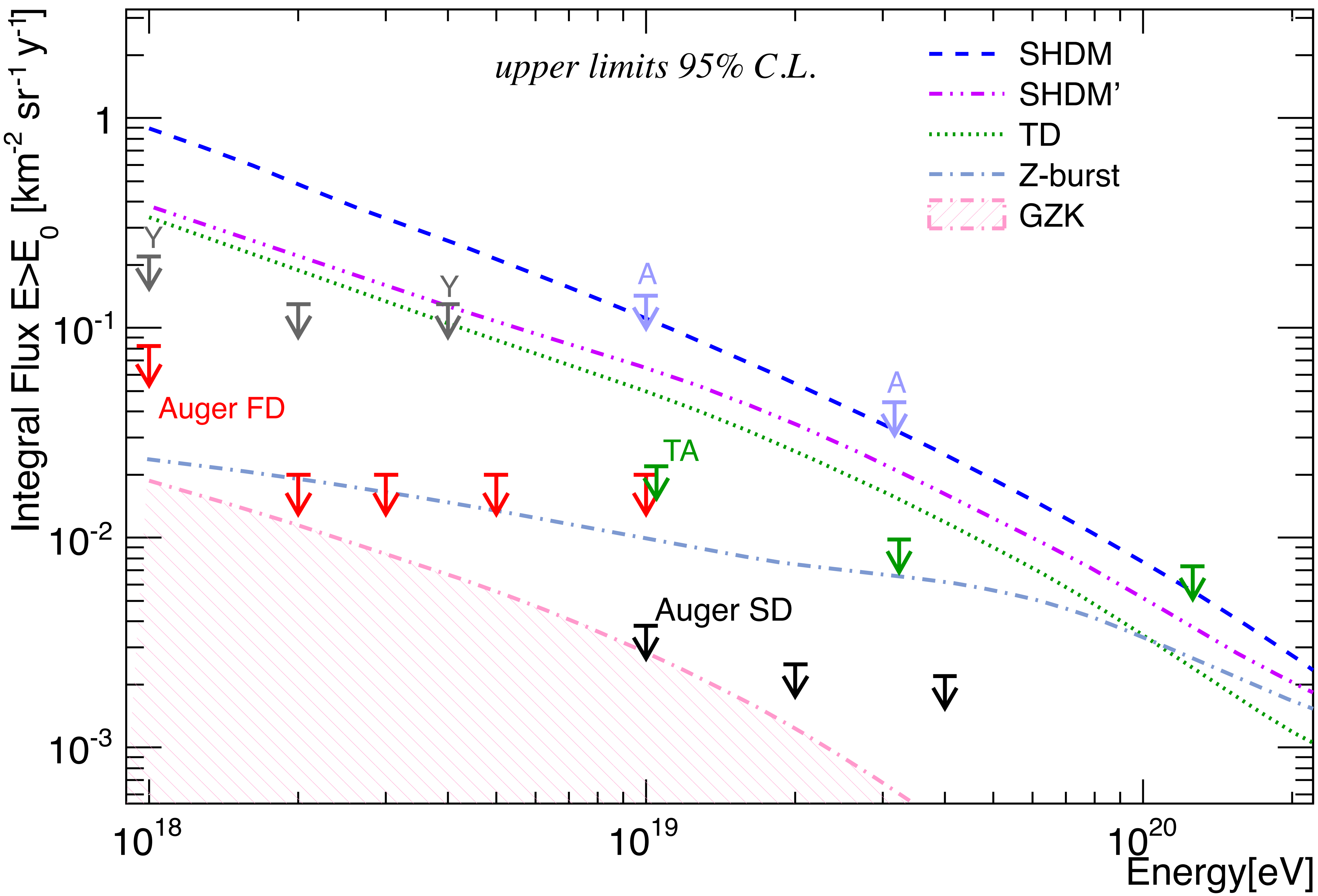
MC simulation have been used to tune the parameters in order to enhance the discrimination power

NB: γ less affected by uncertainties in the hadronic interaction models





Photon search



Exotic model are almost excluded down to 1 EeV

- The contamination from primary photons is negligible when deriving the energy spectrum
- The nuclear primary composition is truly baryonic
- approaching GZK photons

Neutrinos

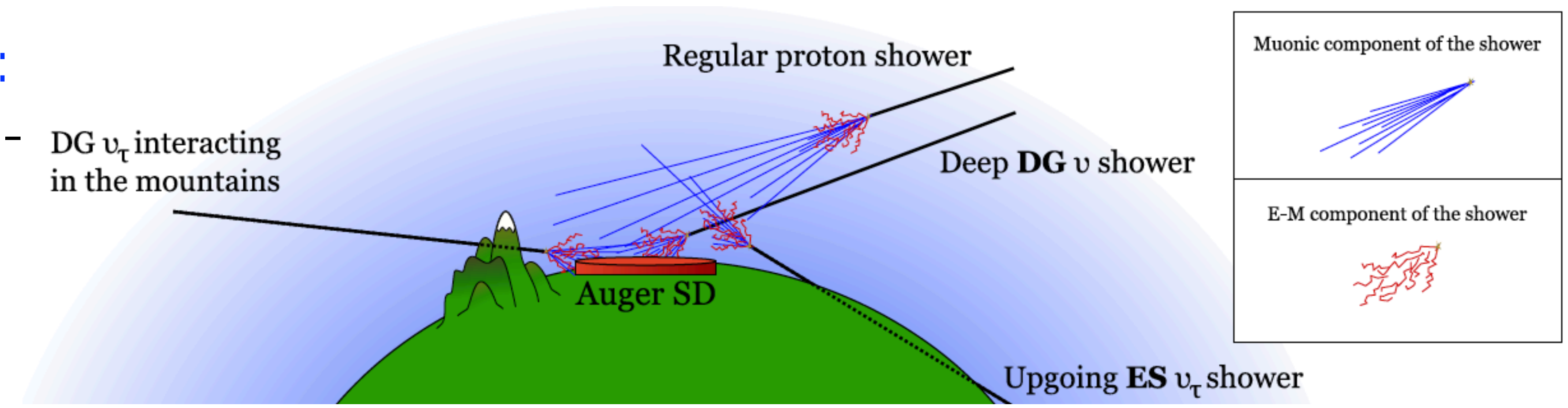
Why?

Neutrinos are produced in the sources:

- from decay of charged pions (bottom-up models)
- from decay of supermassive objects (top-down models)

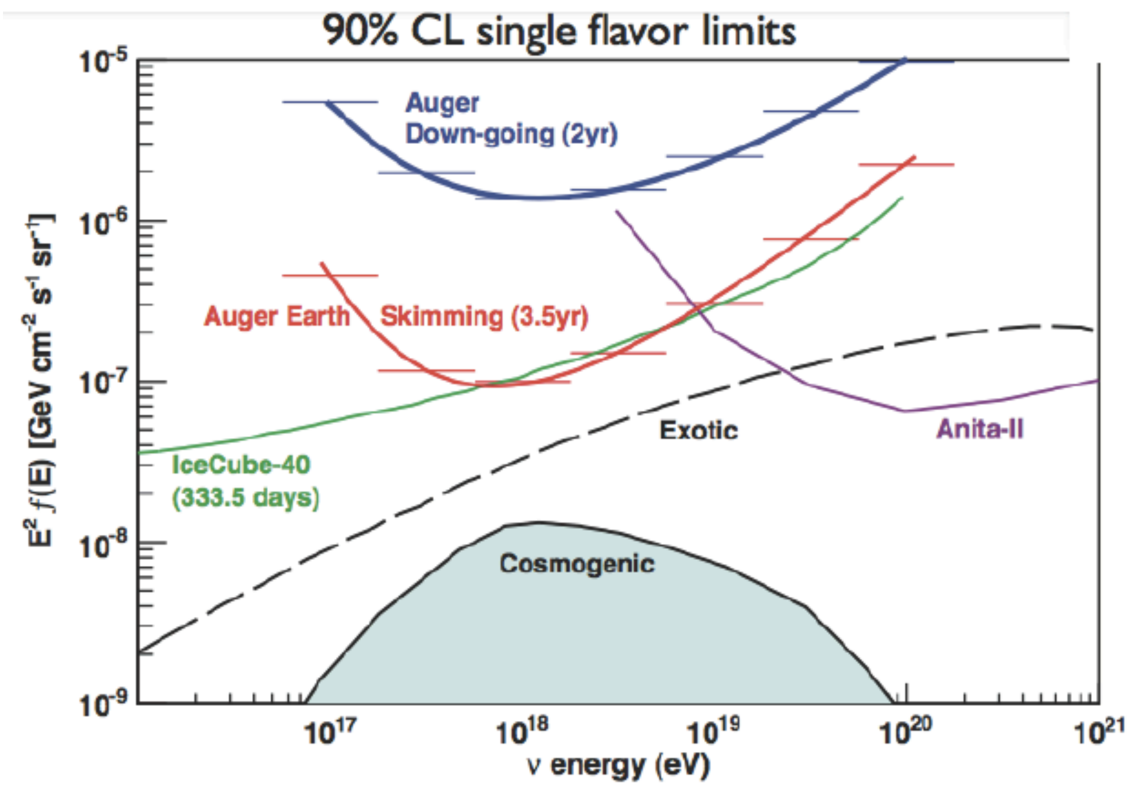
Neutrinos are produced during propagation

- interactions of cosmic rays with CMB (GZK neutrinos)



- up-going Earth skimming showers
- down going neutrino showers

Diffuse neutrino limits

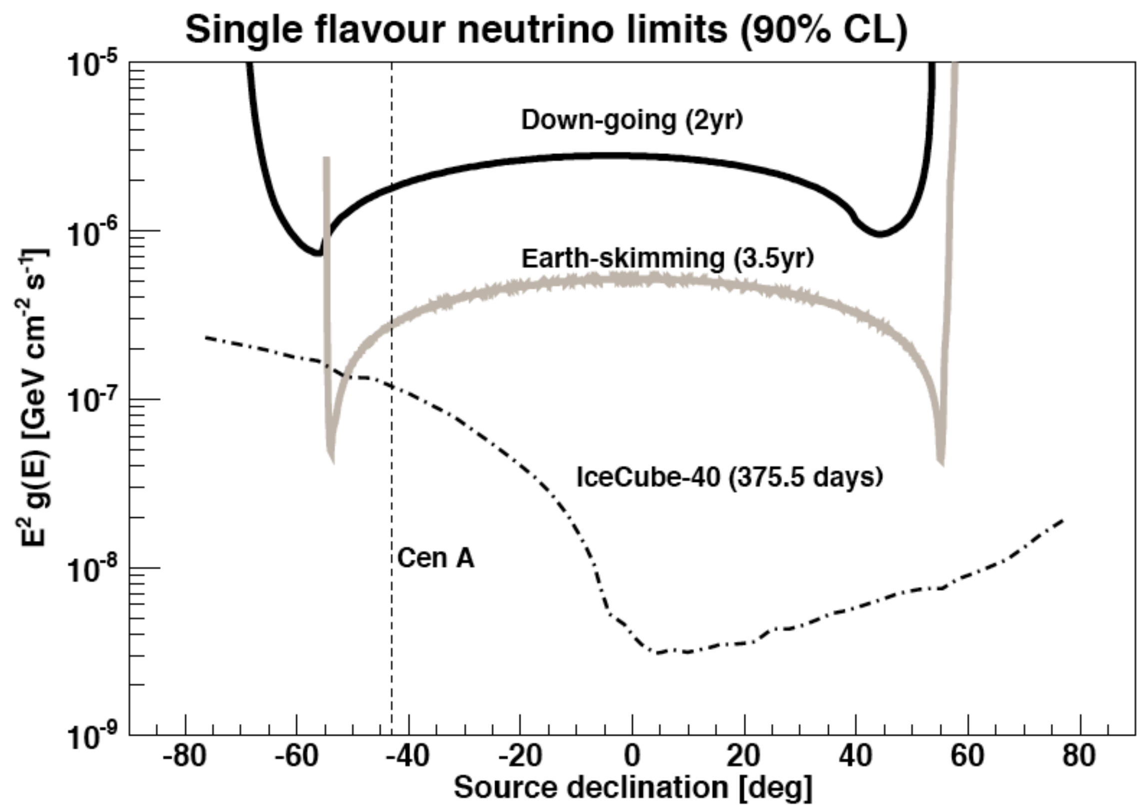


Integral flux limits:

$k < 1.7 \cdot 10^{-7}$ GeV cm2 s^{-1} sr^{-1}

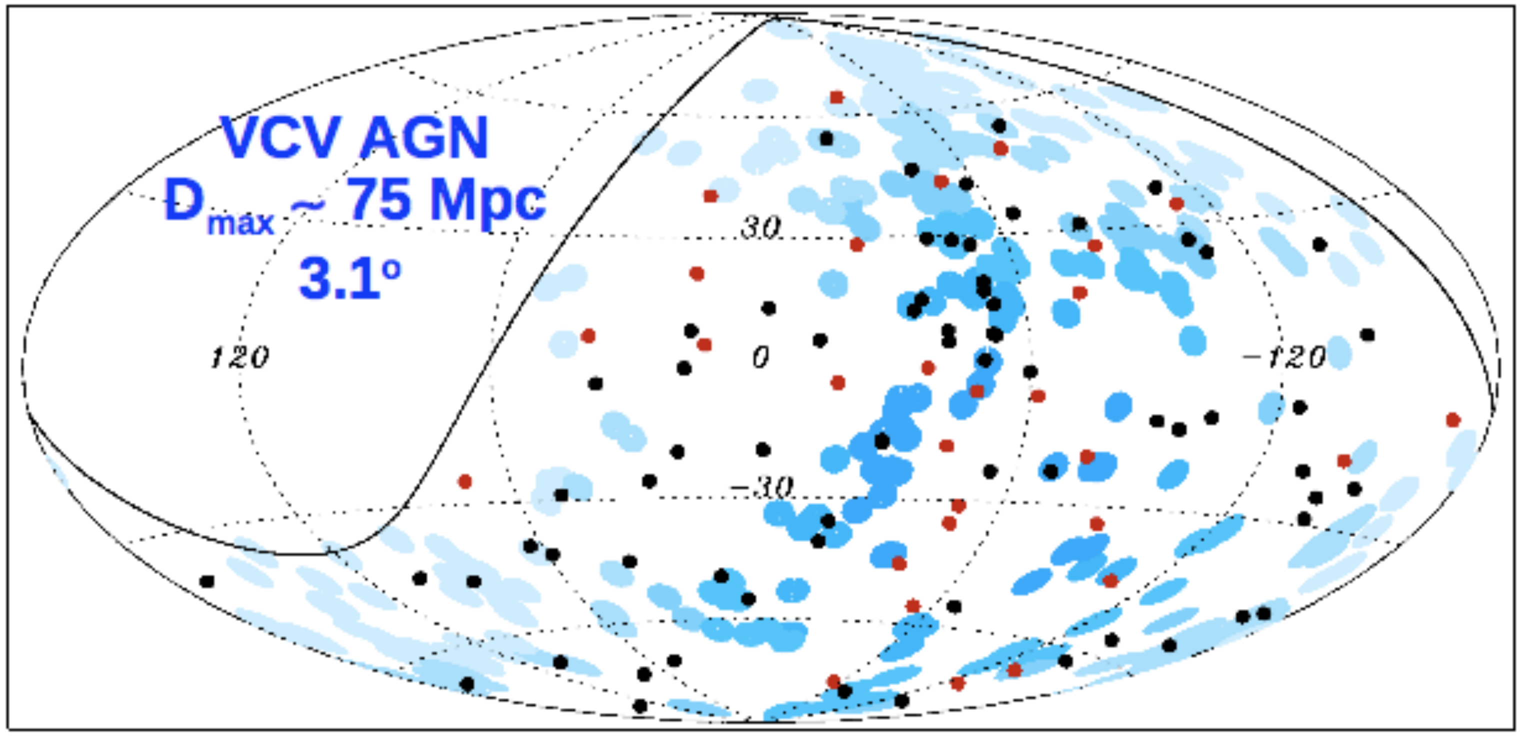
$k < 2.8 \cdot 10^{-8}$ GeV cm2 s^{-1} sr^{-1}

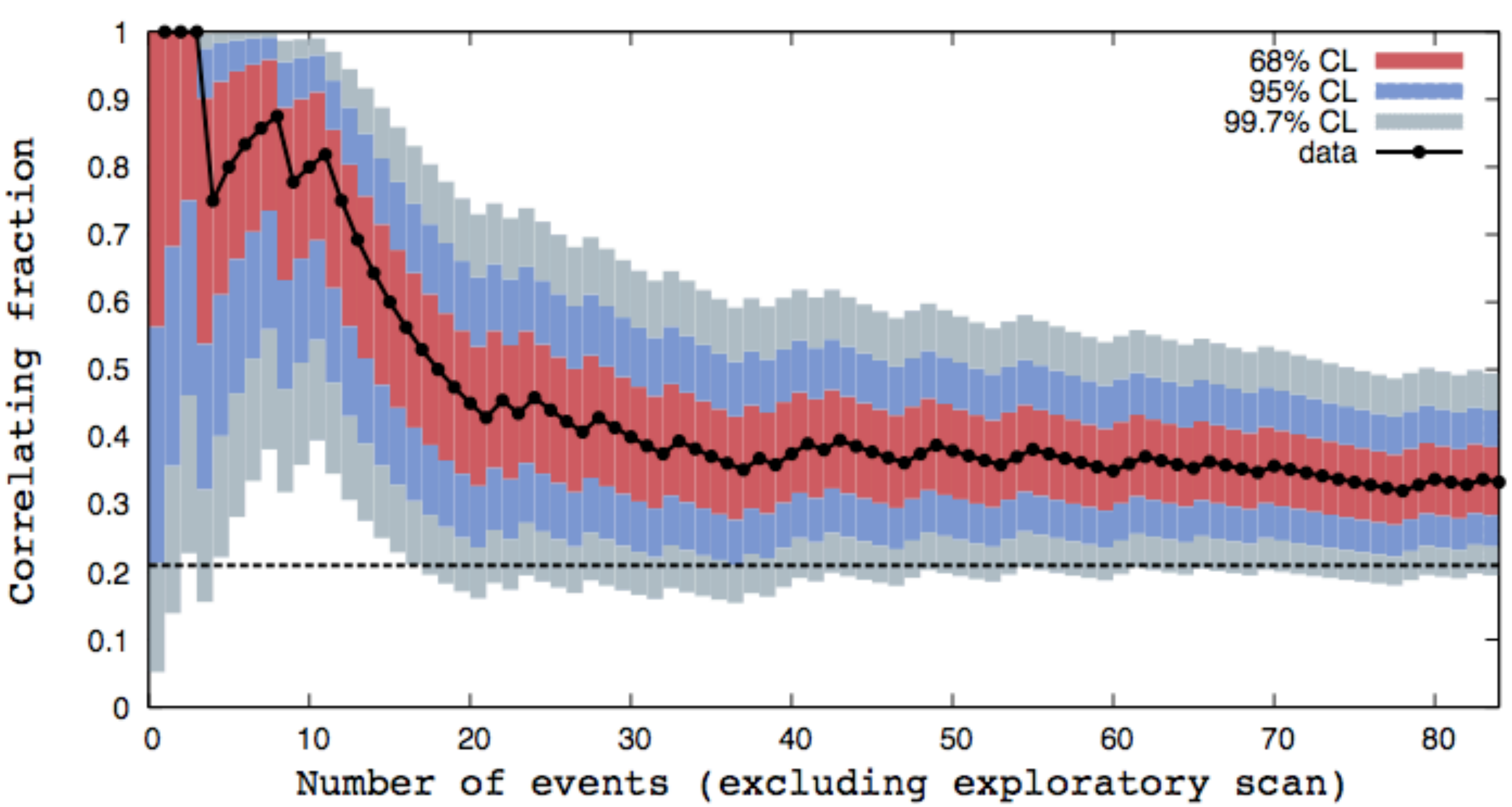
Point source limits



Energy range complementary to IceCube

Anisotropies: Correlation with VCV



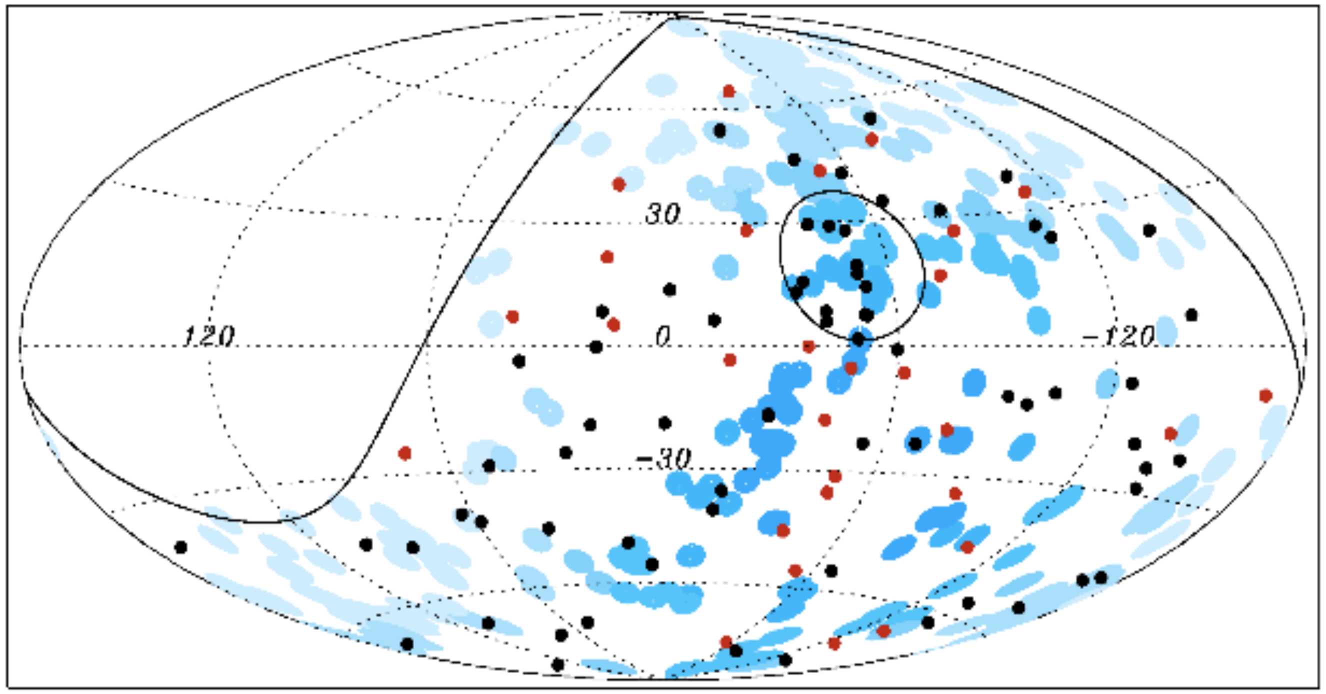


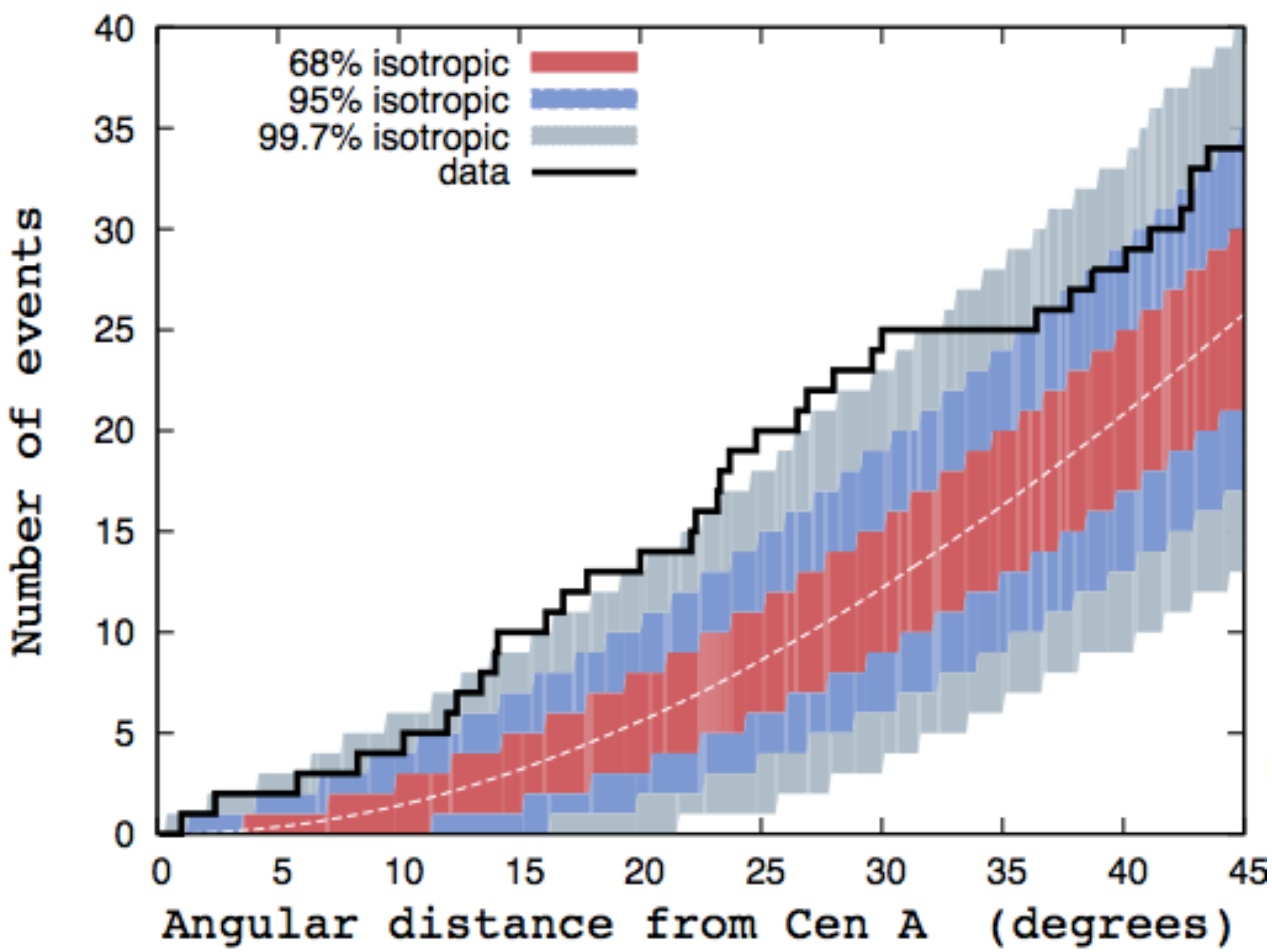
- Correlation of arrival direction with AGN catalog
- E>57 EeV, 3.1°, D_{max} 75 Mpc
- First published November 2007, Science(20/27 evts. correlate, 5.6 expected, P=10^{-5} probability to get this correlation given isotropy)

Update June 2011

- AGN correlation is now weaker than first indicated but is still present
- 28/84 events now correlate,
- 33+/-5% correlation
- P=0.006 (given isotropy)
- Problem: catalogs are not complete

Anisotropies: Correlation with CenA





CenA at 3.8 Mpc

- Overdensity with largest significance
- within 24° from the source
- 19 events against 7.6 expected
- Kolmogorov-Smirnov test : 4% probability to get a larger departure from isotropy for a random isotropic sample of the same size of data

Summary

Energy Spectrum

- observed spectral features : flux suppression at $\sim 10^{19.4}$ eV and ankle at $10^{18.62}$ eV
- energy threshold down to 3×10^{17} eV thanks to AMIGA-Infill, to 10^{17} eV with HEAT

Mass Composition

- hints of changes in composition or in hadronic interactions at high energy
- photons and neutrinos limits approaching GZK.

Hadronic interaction

- models underestimate the muon number by 25-100%
- first measure of the p-Air cross section at 57 TeV (much beyond LHC energies)

Anisotropy search

- Correlation is stabilizing at 33%
- excess of events in the direction of Centaurus A
- large scale anisotropy measured. Exclusion of some model.