Inclined Showers at the Pierre Auger Observatory

Energy spectrum

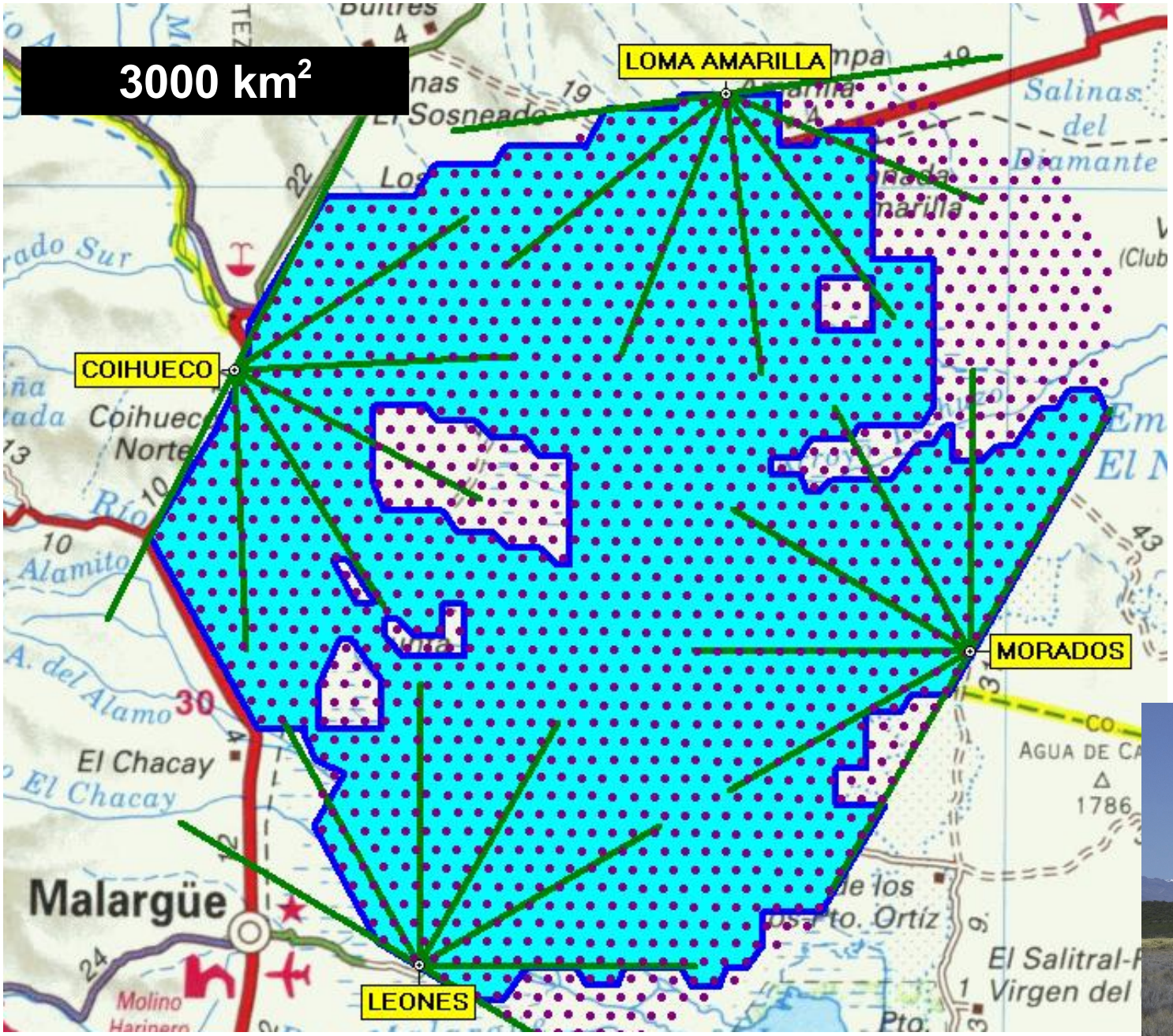
Neutrino Limit

Pedro Facal San Luis

Departamento de Física de Partículas,
Universidad de Santiago de Compostela

for the Auger Collaboration

Pierre Auger Observatory



FD

4 Fluorescence buildings, 6 telescopes each

SD

Water Cherenkov Tanks

1600 Projected

1438 Deployed

1364 Taking Data

85% Completed

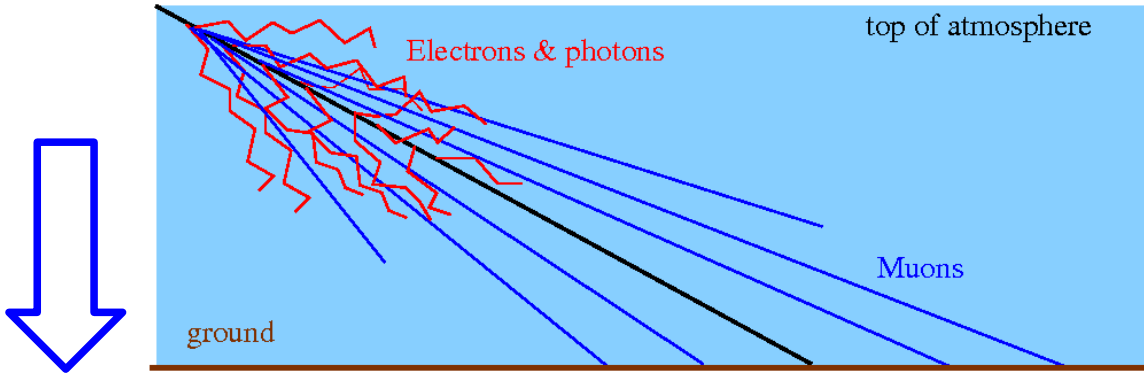
HYBRID DETECTOR

Pierre Auger Observatory:

Surface Detector water Cherenkov tanks, enhanced sensitivity to muons

Inclined showers (θ>60°):

At ground, mainly composed of muons



Inclined showers at the Pierre Auger Observatory

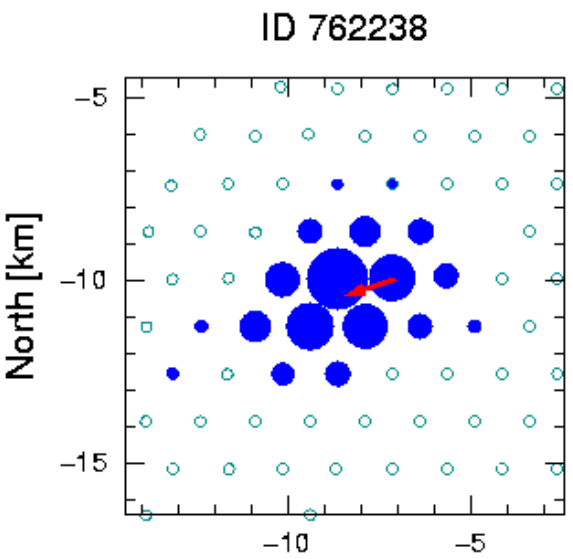
- Enhanced **exposure** and sky coverage.
- Muon measurements at ground relevant in mass composition and hadronic model studies.
- **Neutrino detection is possible through inclined showers.**

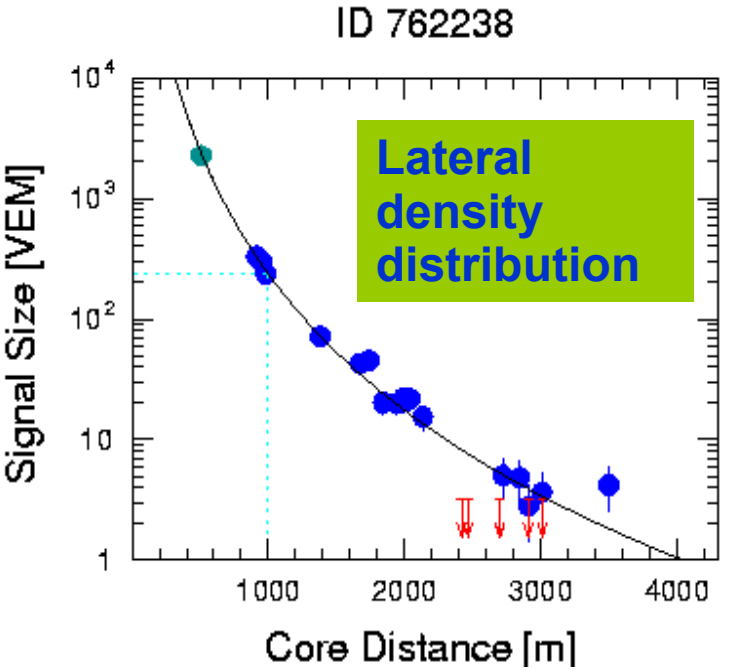
Ground plane

Shower plane

Moderately inclined event

θ = 48°



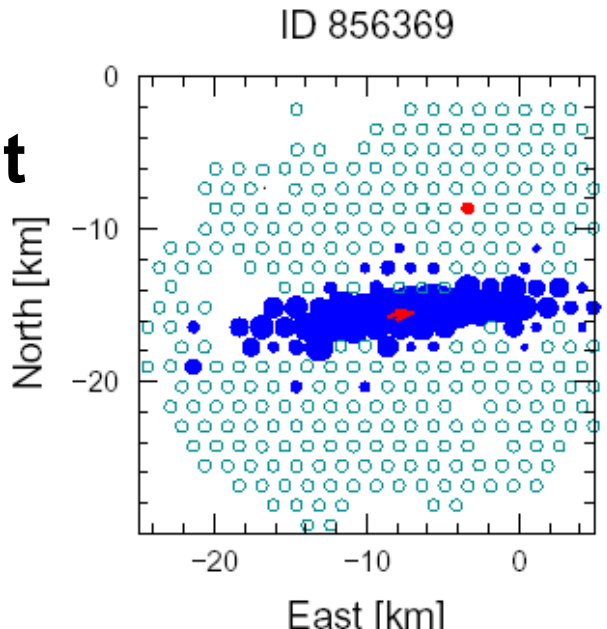


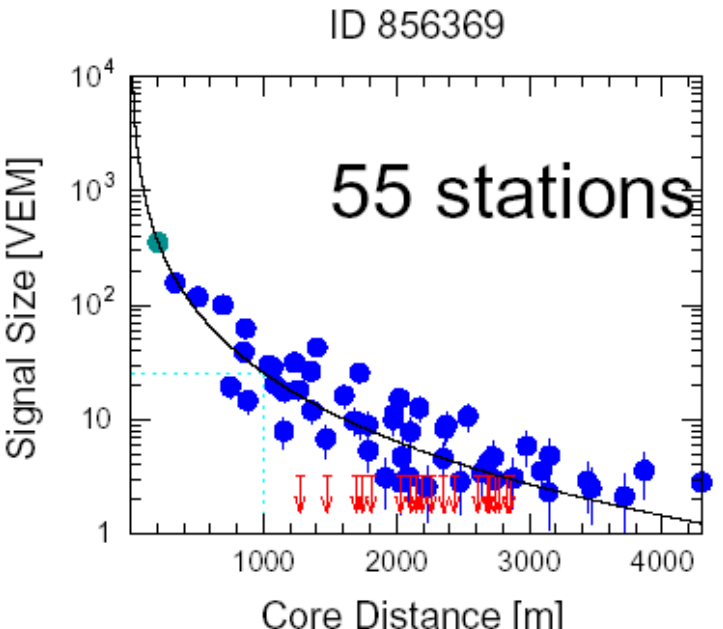
Geometry

Muon deflection in geomagnetic field

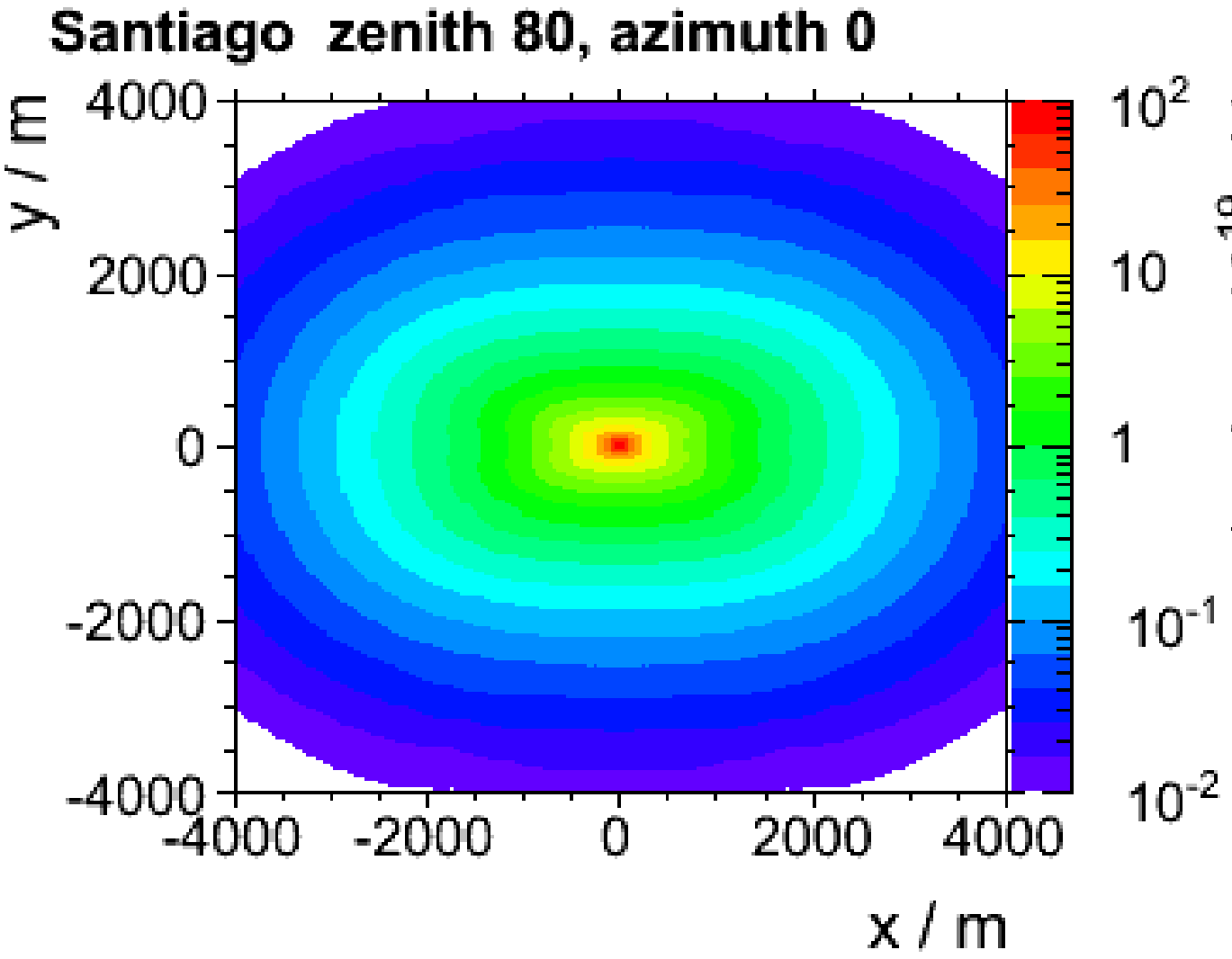
Highly inclined event

θ = 79°





Use MUON MAPS: 2-dim distributions of muons at ground



Maps for 10^{19} eV protons

Different zenith and azimuth

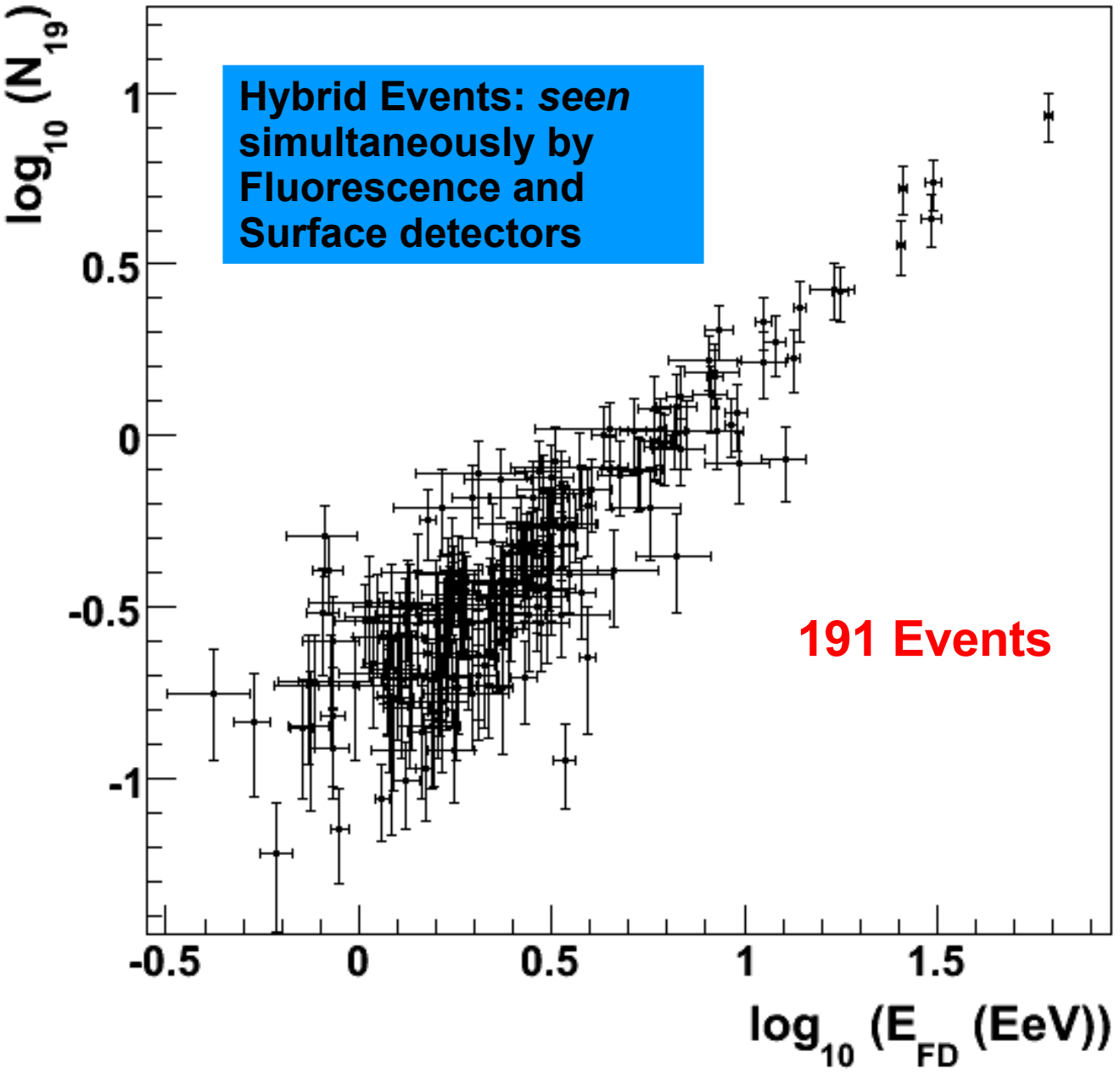
AIRES + QJSJET

The shape of the map is MASS and MODEL independent

Electromagnetic signal: parametrized from simulations

Muon map normalization fitted to data => N_{19}

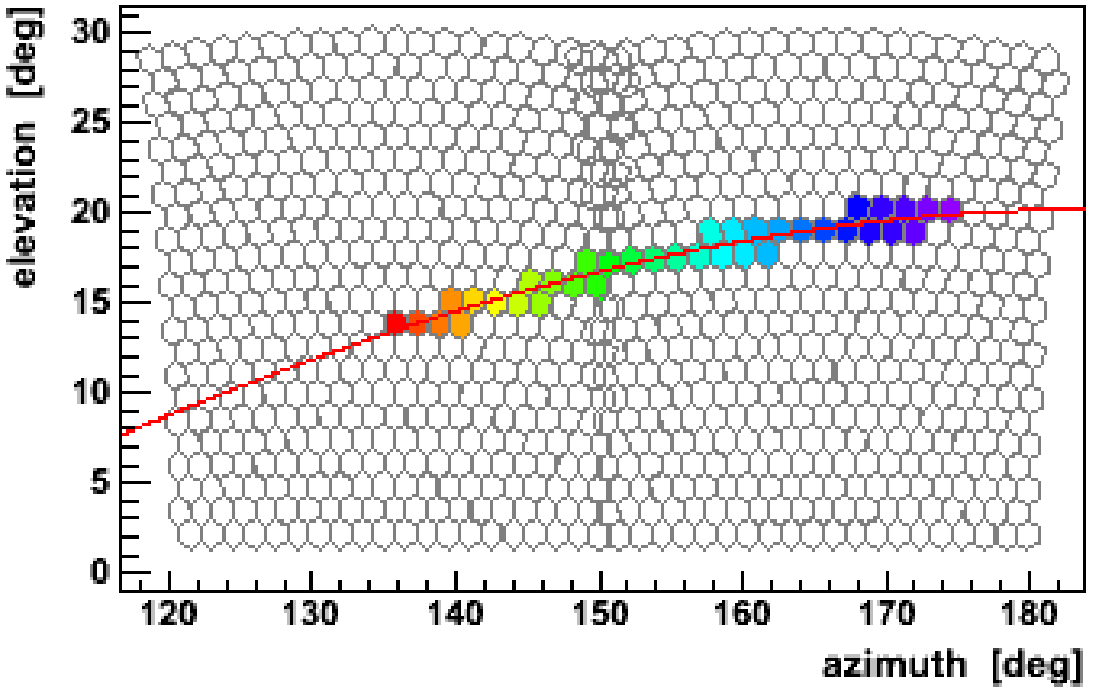
Inclined Hybrid Events



- E_{FD} near-calorimetric energy measurement by the fluorescence detector
- Event selection: quality cuts on FD events
- No hybrid events above 75°
- Good correlation between the energy and N_{19}
- FD energy systematic uncertainty 22%

Used to calibrate the spectrum

Hybrid Event: FD Reconstruction

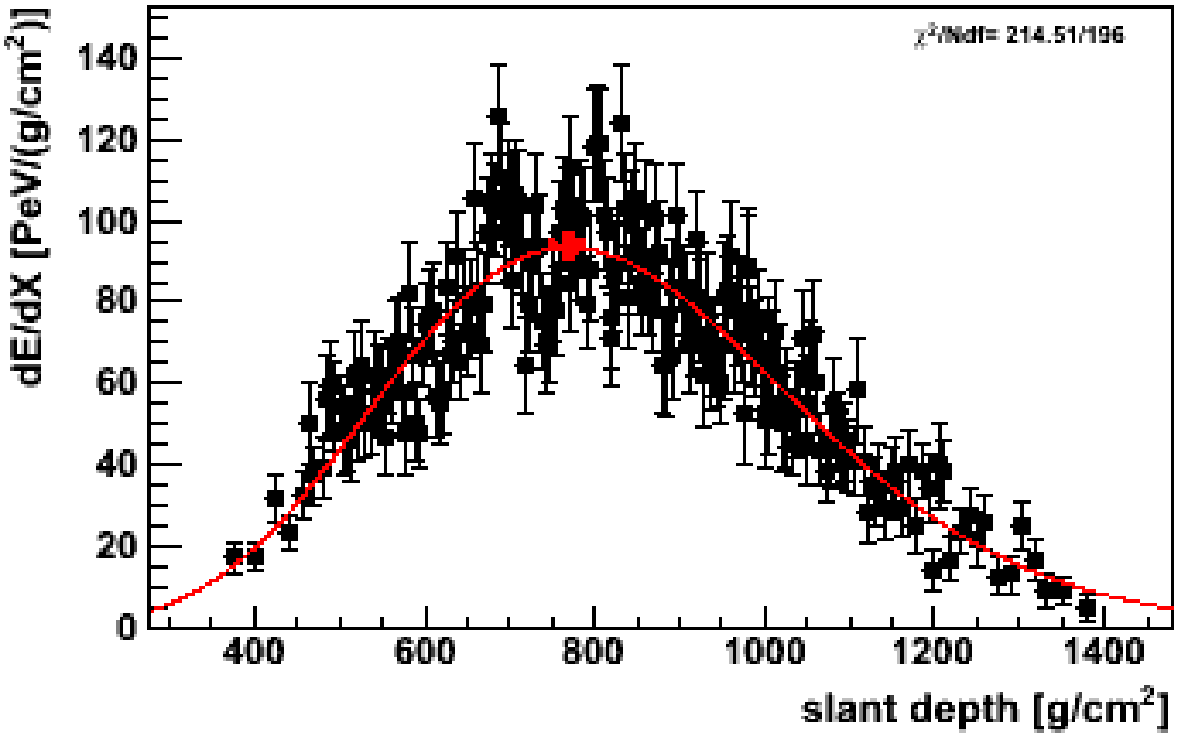


Camera track

First -> Last

Longitudinal profile

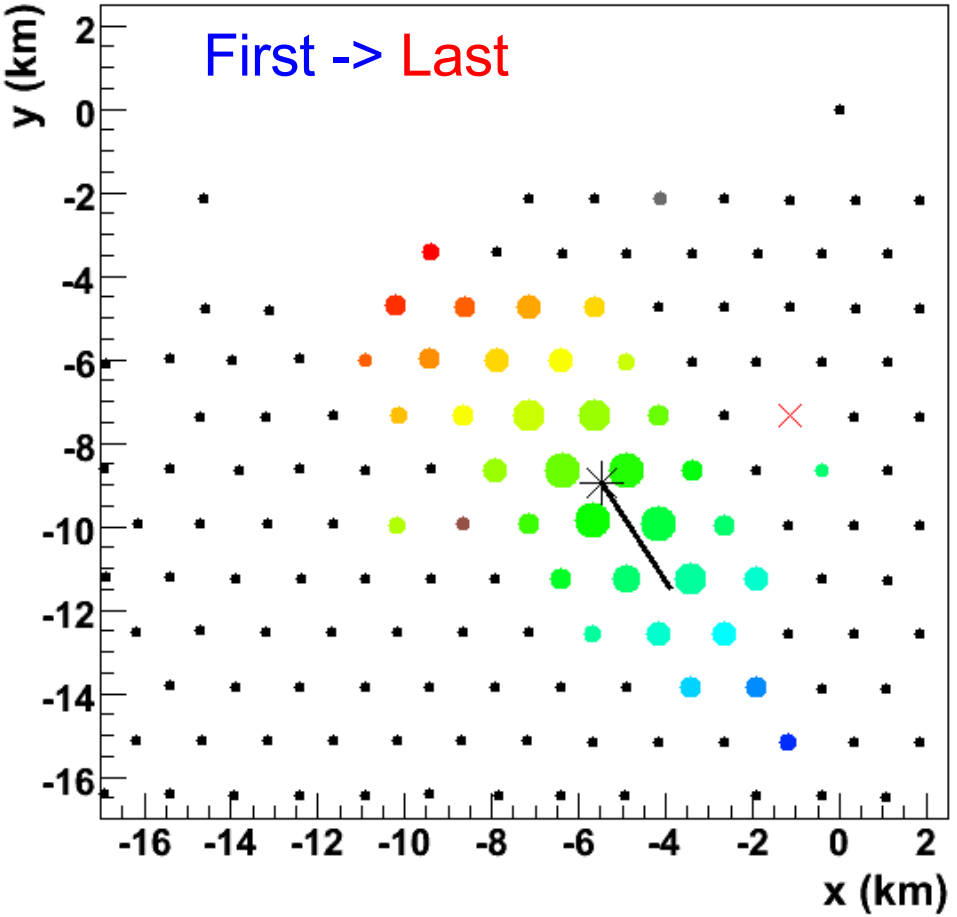
Fitted Gaisser-Hillas



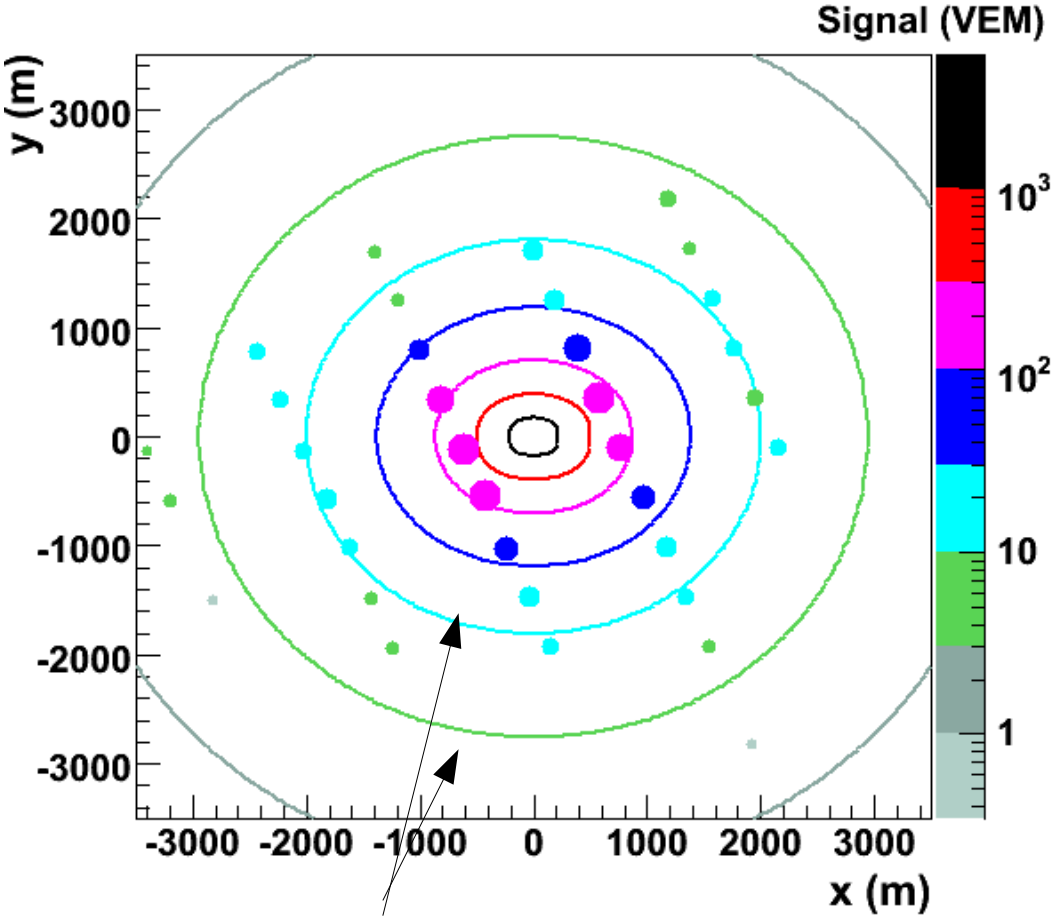
$E_{FD} = 6.1 \cdot 10^{19}$ eV

Hybrid Event: SD Reconstruction

Time at ground



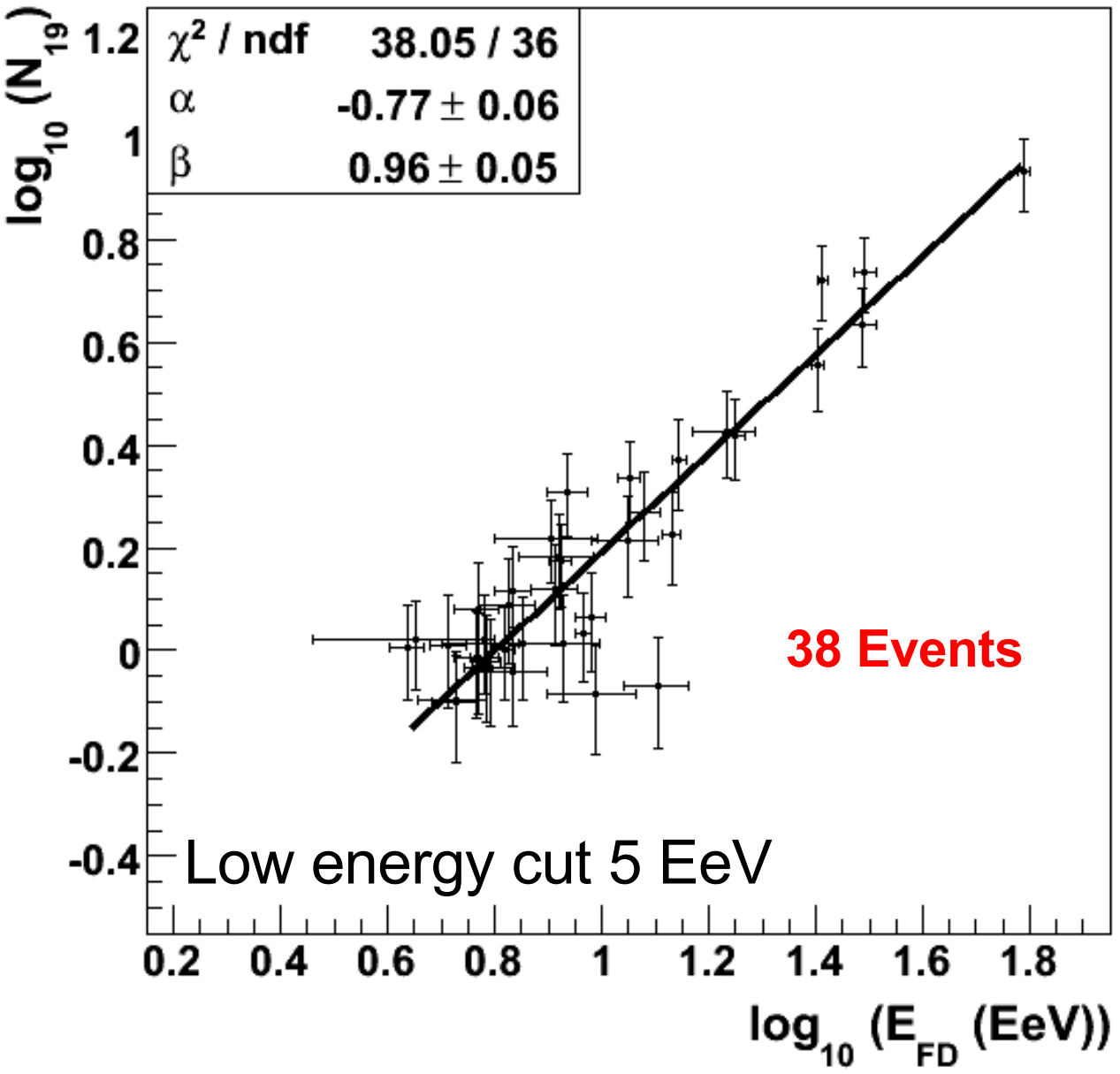
Signals on shower plane



Signal levels from the muon map

$N_{19} = 8.5 \Rightarrow E_{cal} = 5.9 \cdot 10^{19}$ eV

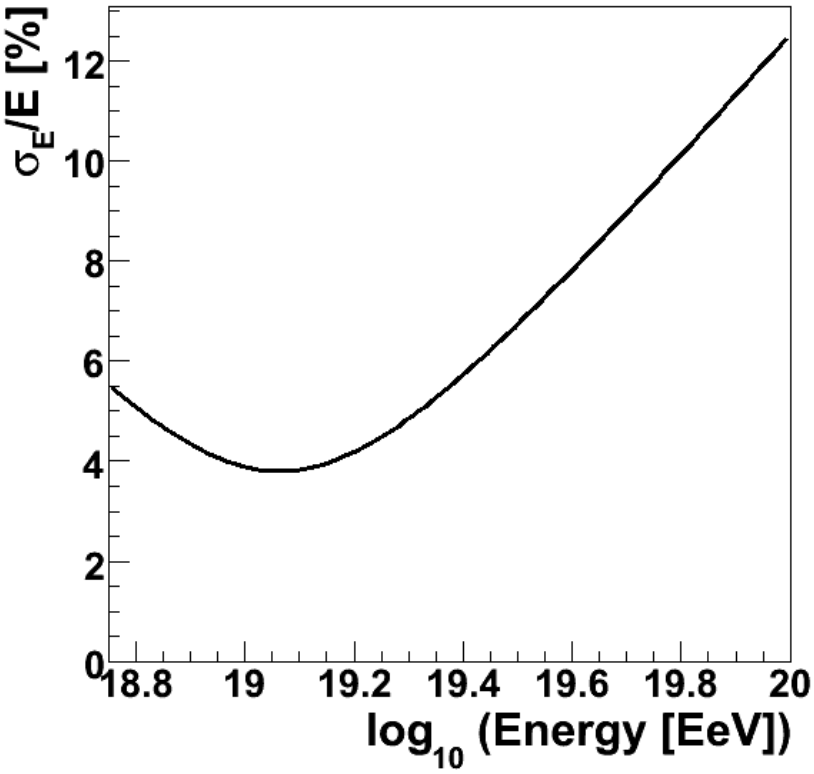
Calibration



$$E = 10^{-\alpha/\beta}(N_{19})^{1/\beta}$$

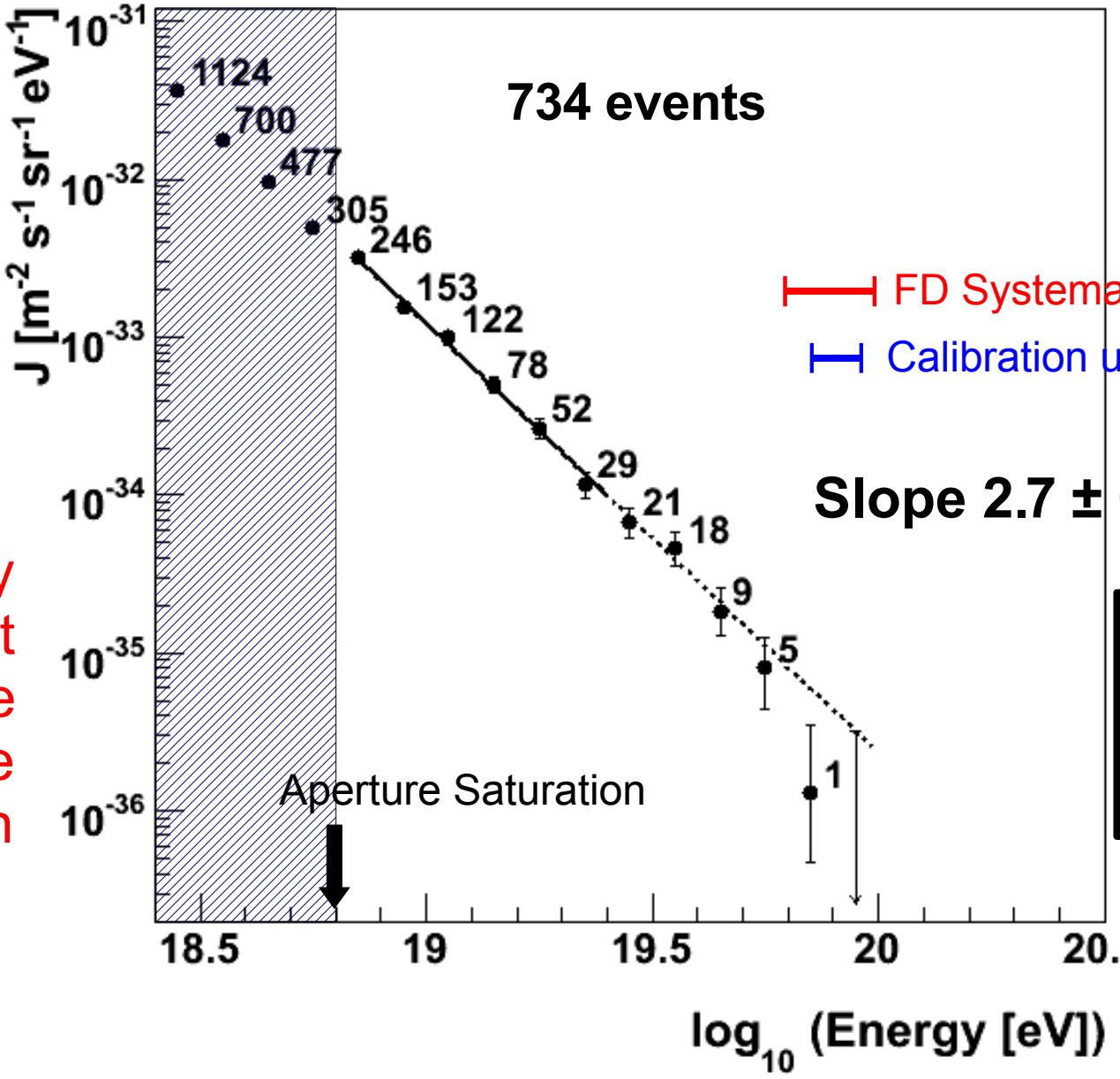
$E\ (N_{19}=1) = 8.0 \pm 0.3$ EeV

Energy Uncertainty



Energy scale determined from Fluorescence data

UHECR spectrum using inclined events



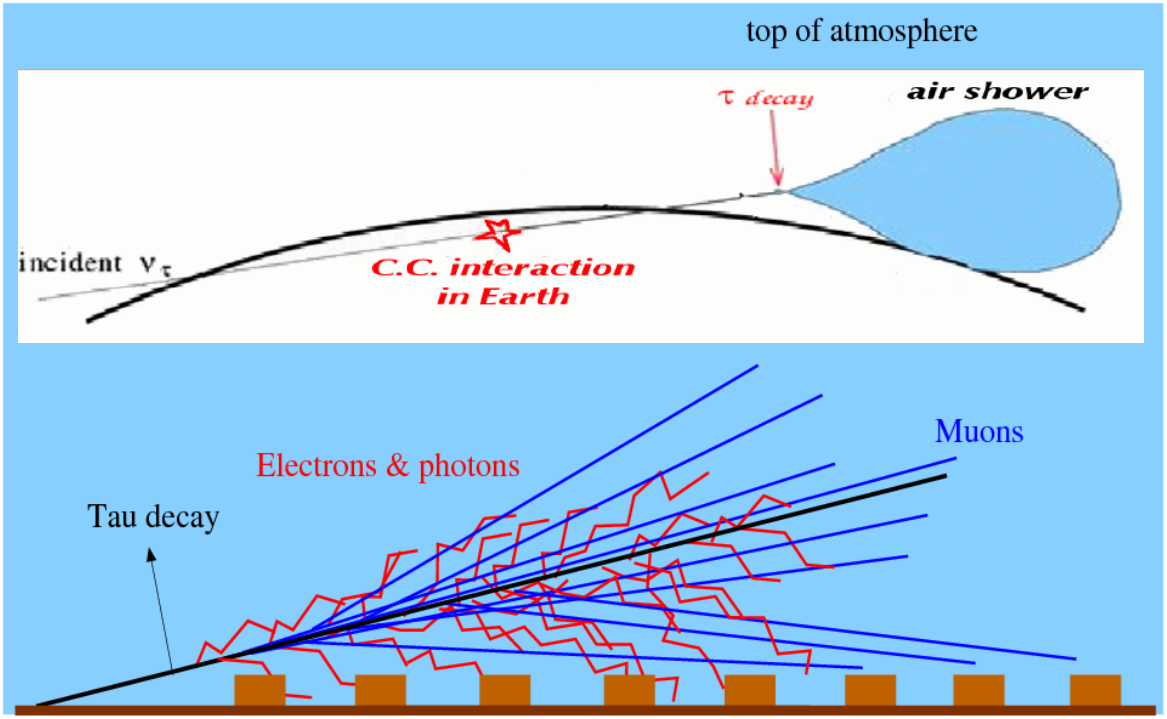
Energy independent aperture above saturation

60° < θ < 80°

Jan 2004 – Feb 2007

Exposure 1510 km^2 yr sr (29% of θ<60°)

Neutrino identification @ Auger

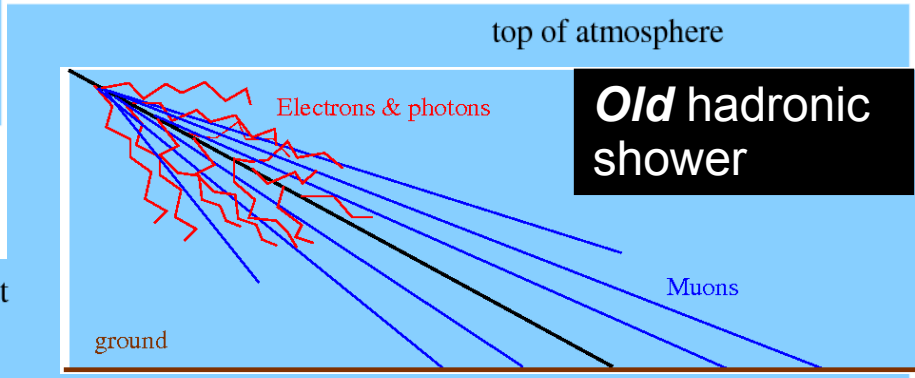


Earth skimming ν_τ

L_{int} (ν) ~ 500 km (θ>95, Earth opaque)

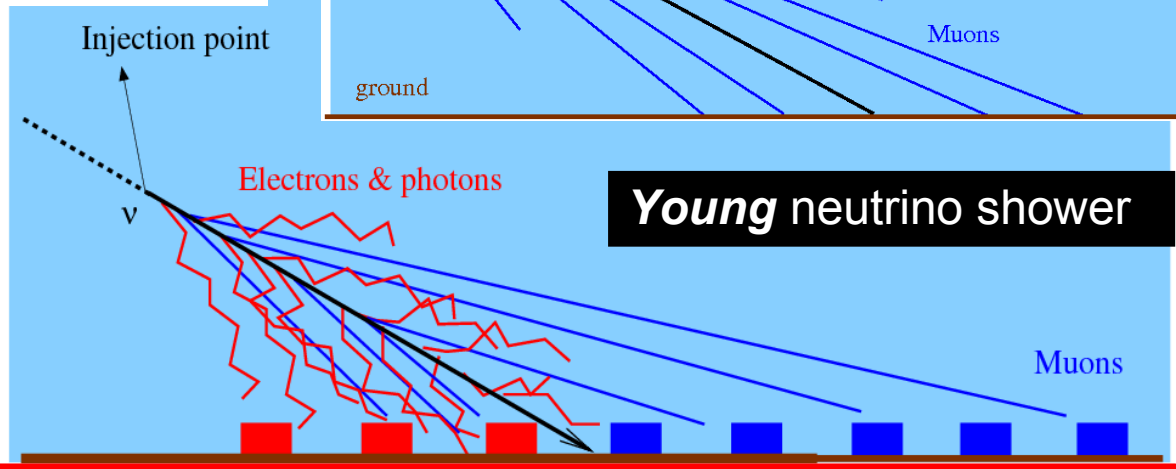
L_{Eloss} (τ) ~ 10 km (e, much smaller)

L_{decay} (τ) ~ 50 km (μ, much larger)
(1 EeV)



Old hadronic shower

Down-going ν



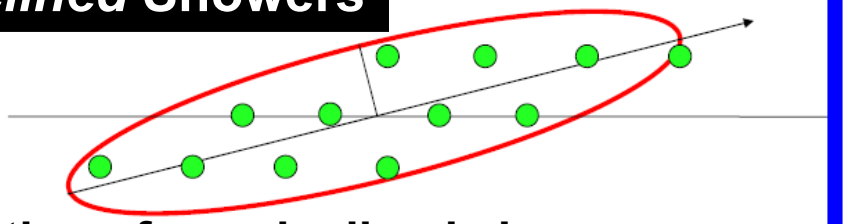
Young neutrino shower

Both: inclined showers with significant em content

Earth skimming neutrinos

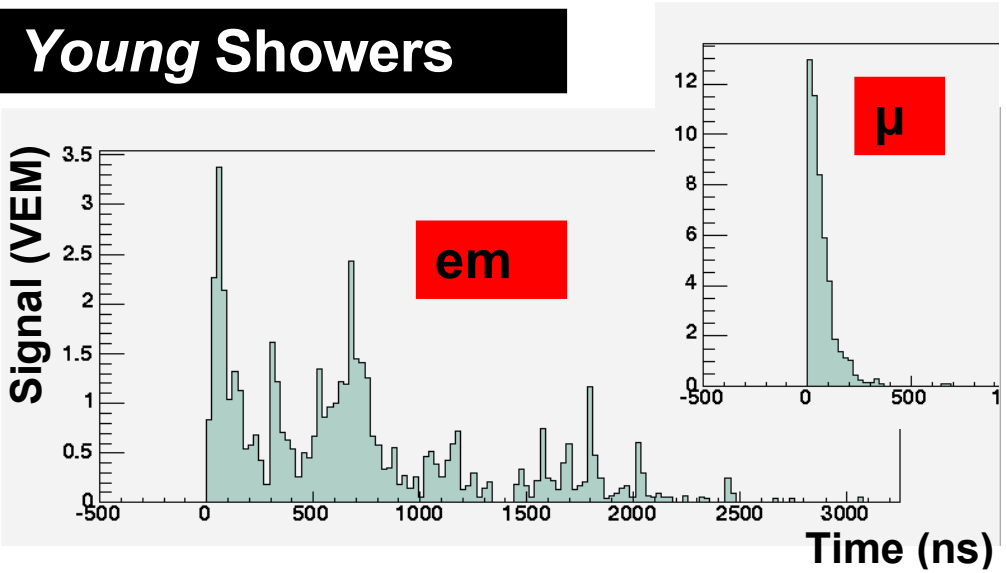
Identification

Very Inclined Showers



Selection of very inclined showers through time and space compatibility of the footprint

Young Showers



Select events where most tanks have FADC traces characteristic of electromagnetic showers

No candidate (80% identification efficiency)

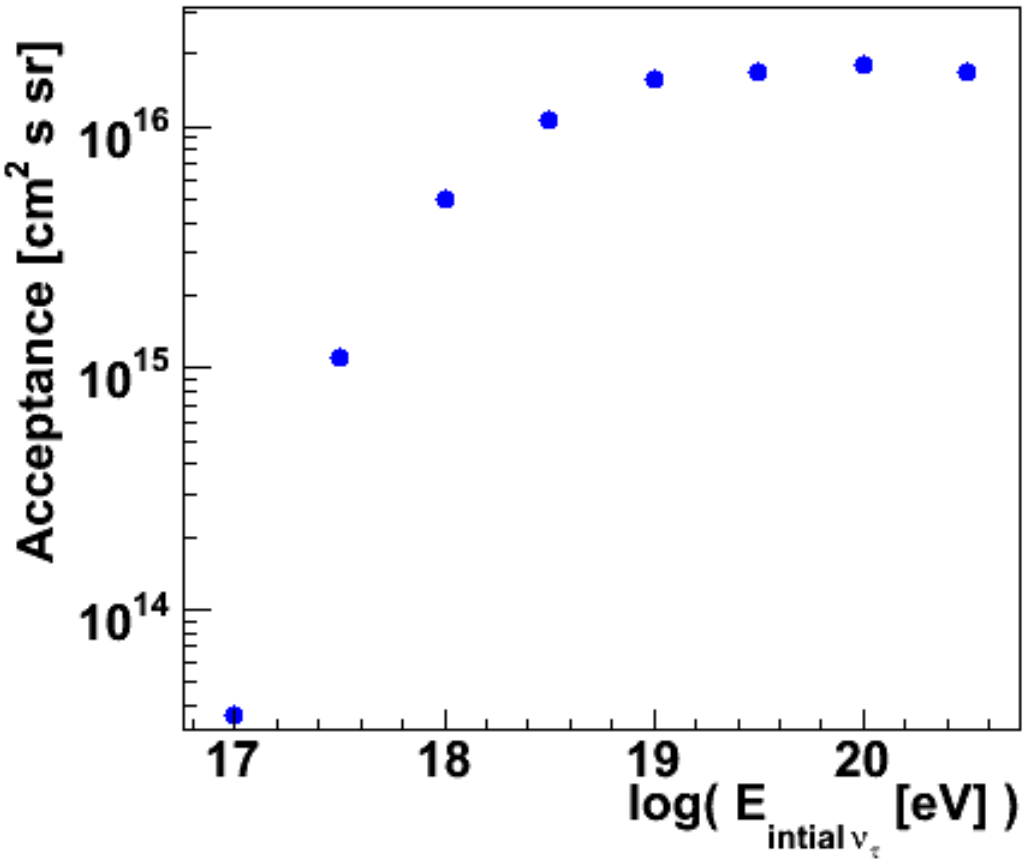
Acceptance

Conversion $\nu_\tau \rightarrow \tau$:

- Neutrino cross section
- Tau energy losses
- Tau decay

Acceptance for τ showers:

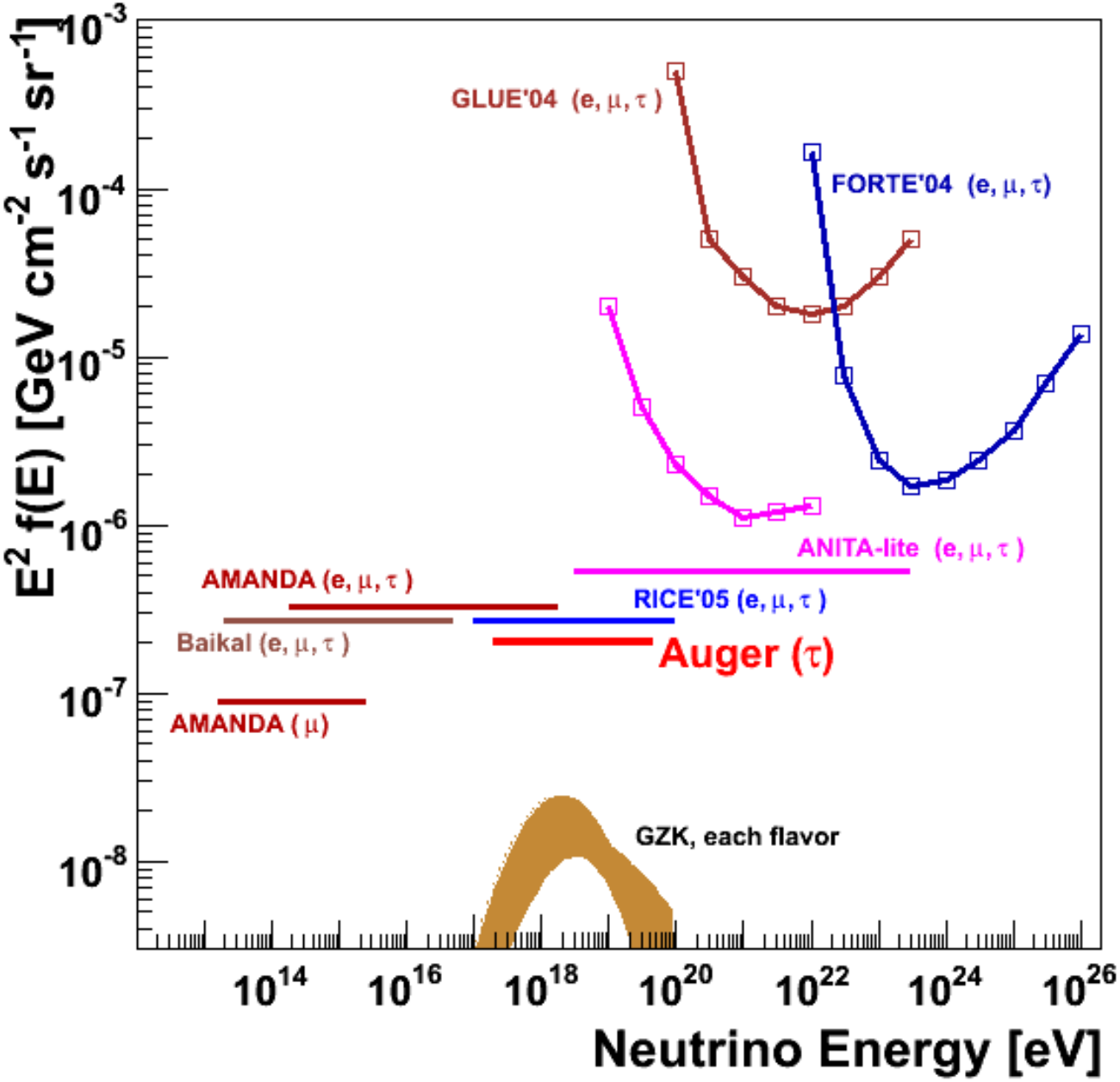
- Depends on energy and geometry
- Growing detector



Earth Skimming Tau Neutrino Flux Limit

Jan 04 – Dec 06

90% CL



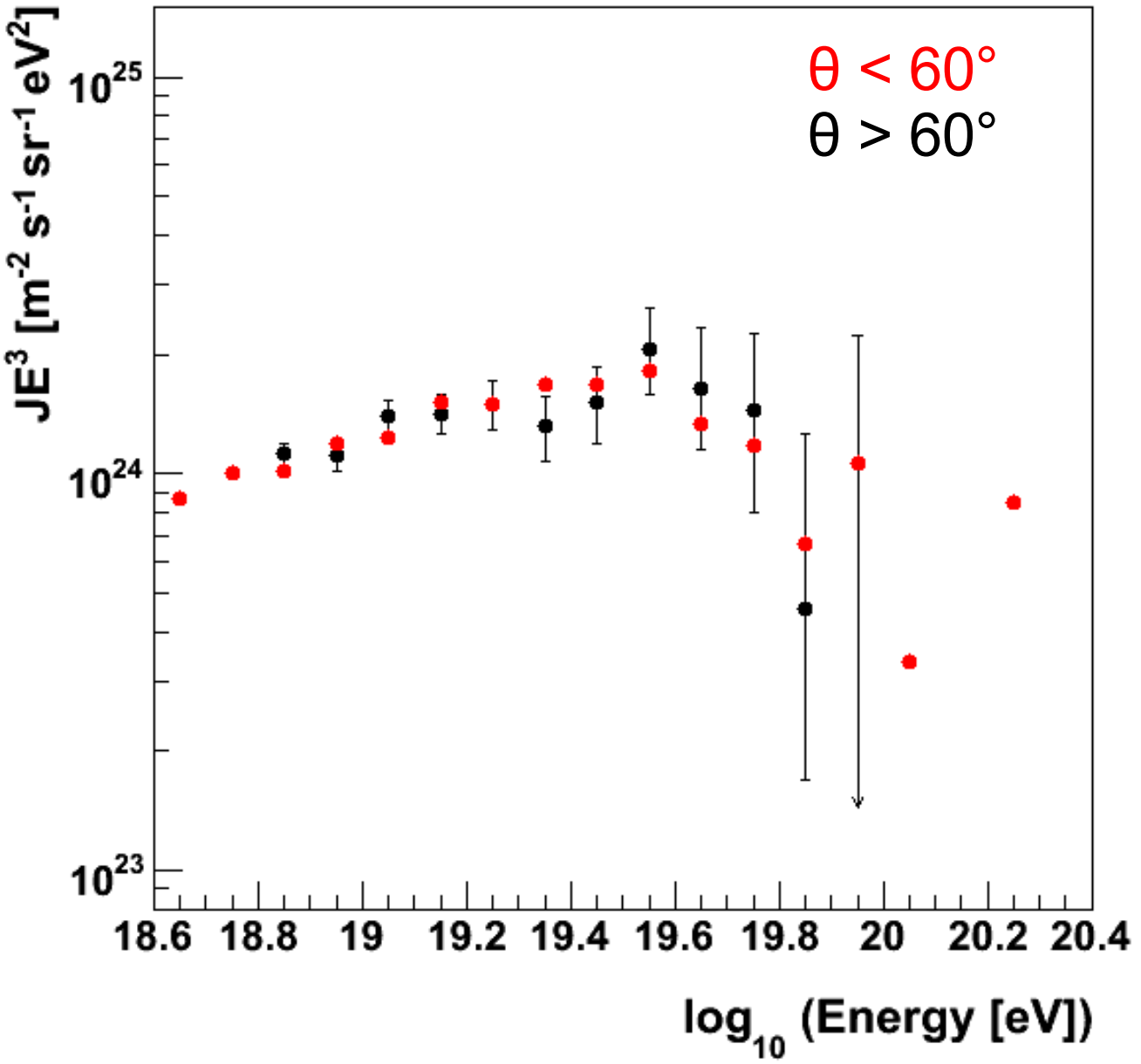
$$\frac{dN_{\nu_\tau}}{dE} = f_0 E^{-2}$$

Conservative: worst-case for systematic uncertainties in the acceptance

Outlook

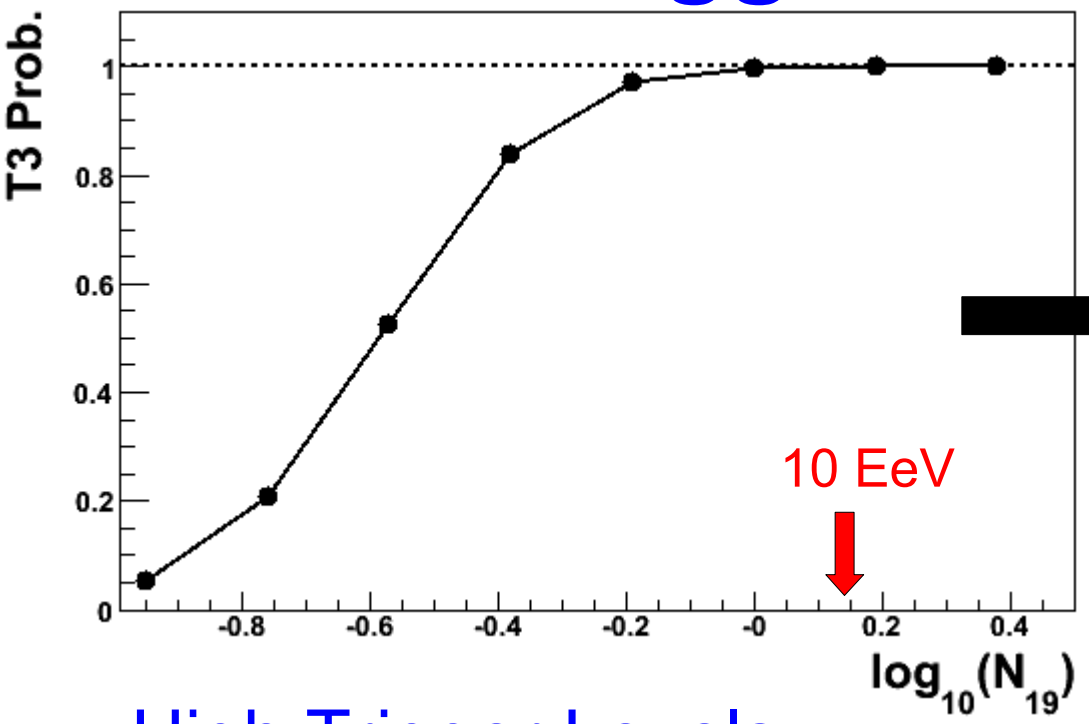
- Inclined events can be used to extend Auger Observatory aperture by a 30% at the highest energies.
- The analysis, based on muon maps and FD energy calibration, leads to consistent results.
- Implications for composition or hadronic models presently under study but limited by statistics.
- Very inclined showers used for neutrinos searches.
- Spectra dependent limit to tau neutrinos of $E^2 dN/dE\ 2 \cdot 10^{-7}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$
- GZK neutrinos will be tested in 10 years.
- Down-going neutrino channel still to be fully exploited.

Comparison with θ < 60° spectrum



Good agreement

Trigger & Aperture



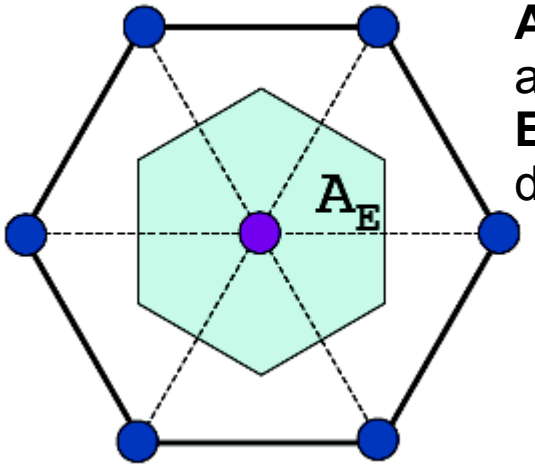
Trigger probability as calculated with the muon maps.

Trigger saturates at $N_{19} = 1$

High Trigger Levels

- T4: selection of physical events.
- Quality trigger (T5): station near to the core surrounded by 6 working stations.

Basic aperture cell

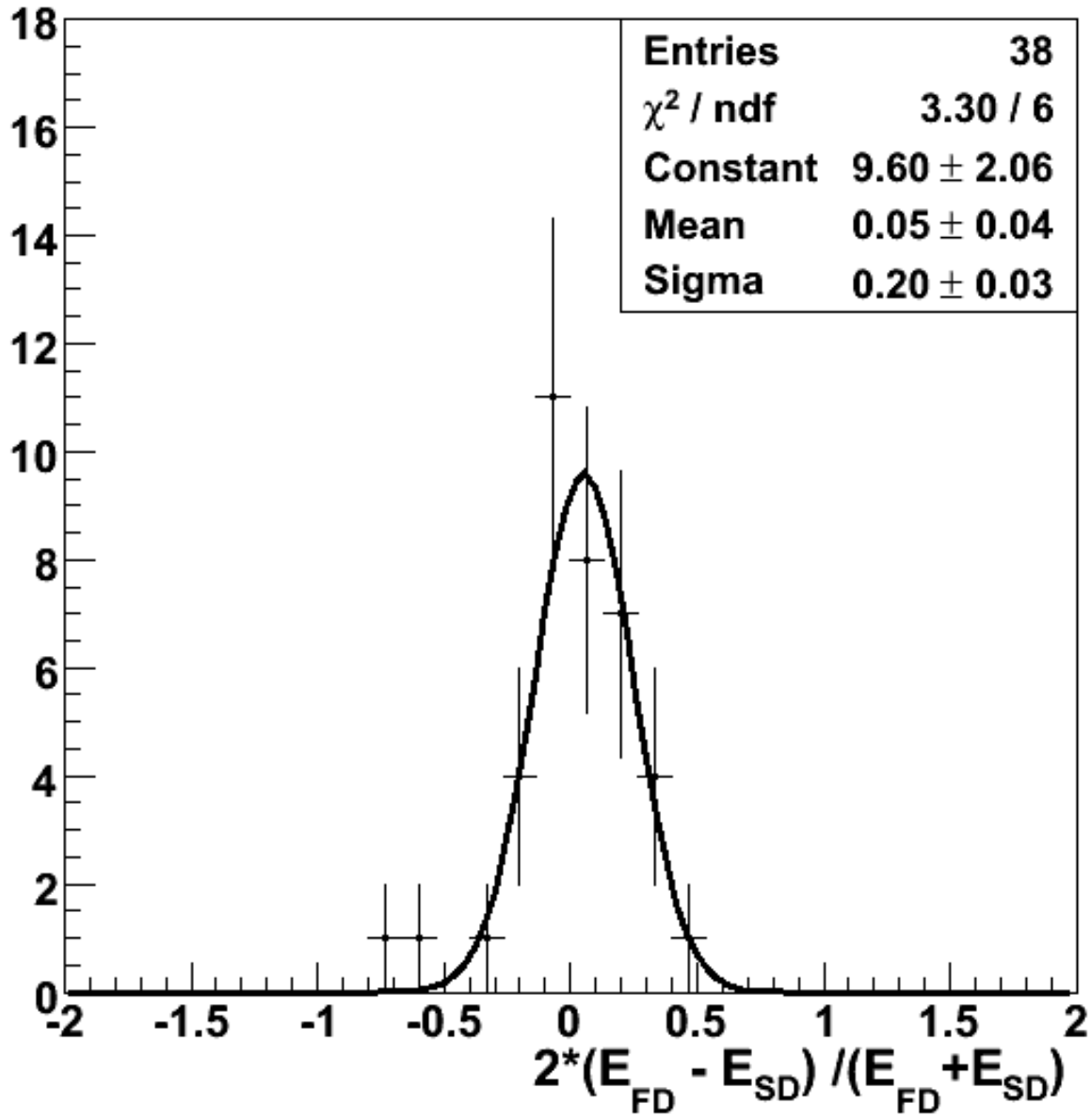


Aperture -> count active cells
Exposure -> integrate detector configurations

1.95 km²

Energy independent aperture above $N_{19} = 1$

Energy resolution from hybrid events



N_{19} uncertainties:

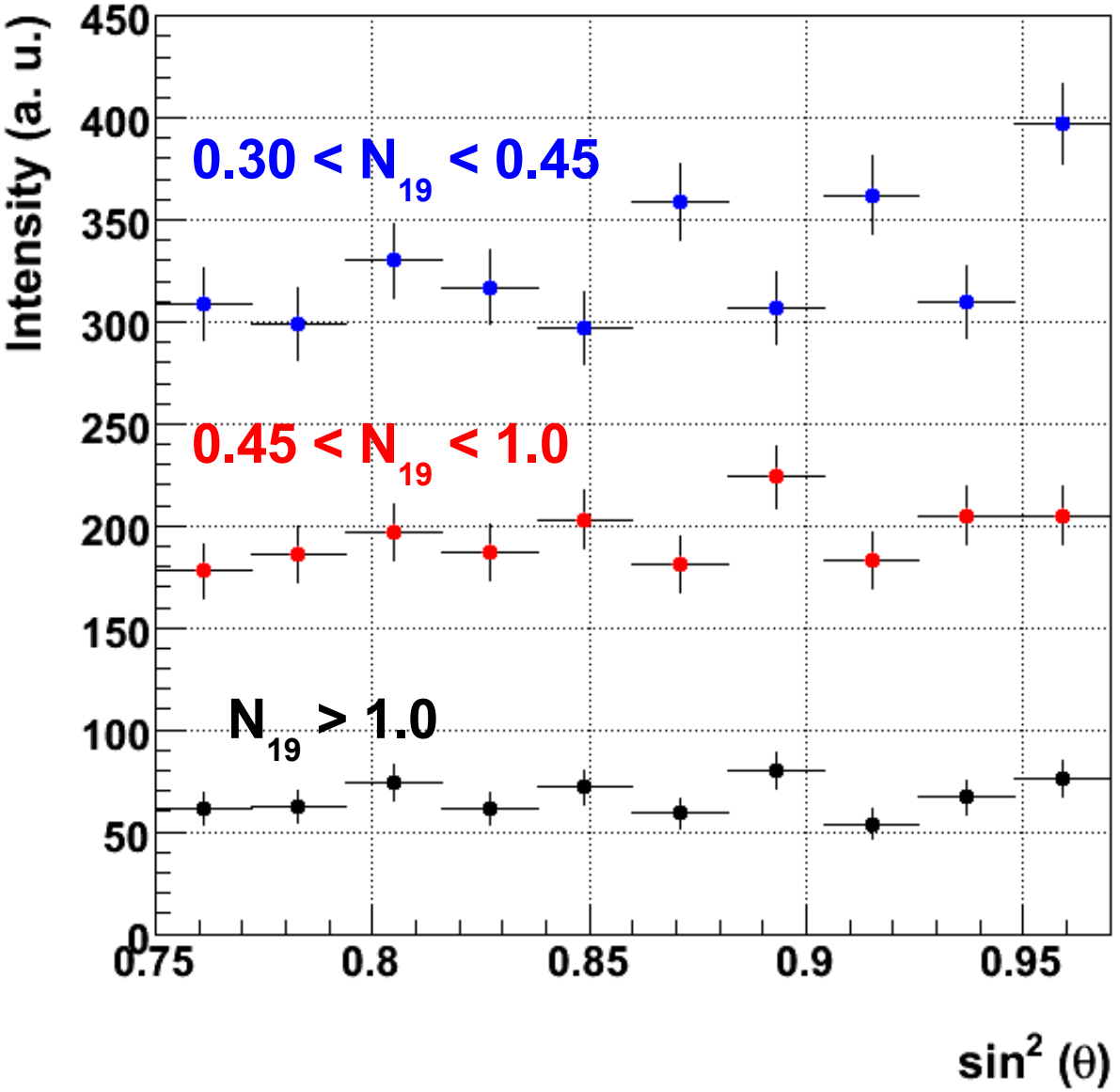
- Statistical ~10%
- Fluctuations 5% - 15%
- Systematics [Preliminary]

Propagation of geometric uncertainty 12% @ 80° [Max]

Uncertainty on the em correction 7% @ 60° [Max]

$(\Delta E/E)_{FD} \sim 10\% \Rightarrow (\Delta E/E)_{N19} \sim 18\%$

$\sin^2\theta$ distribution



Attenuation implicit in the muon maps

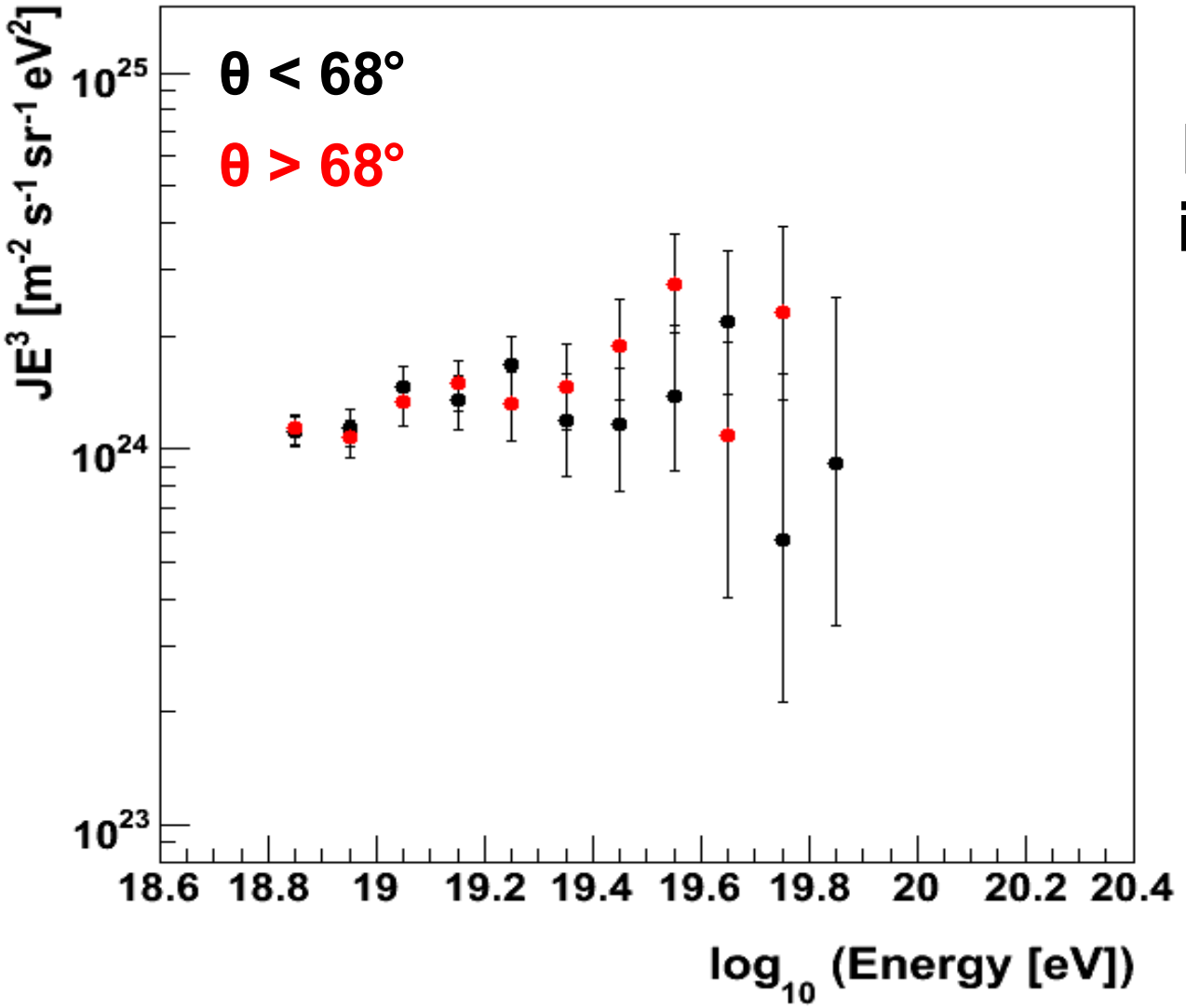
$\sin^2$ distribution flat if:

1. Detector is saturated

2. The attenuation in the maps is correct

Distribution flattens as we reach saturation

Cross-check: electromagnetic correction

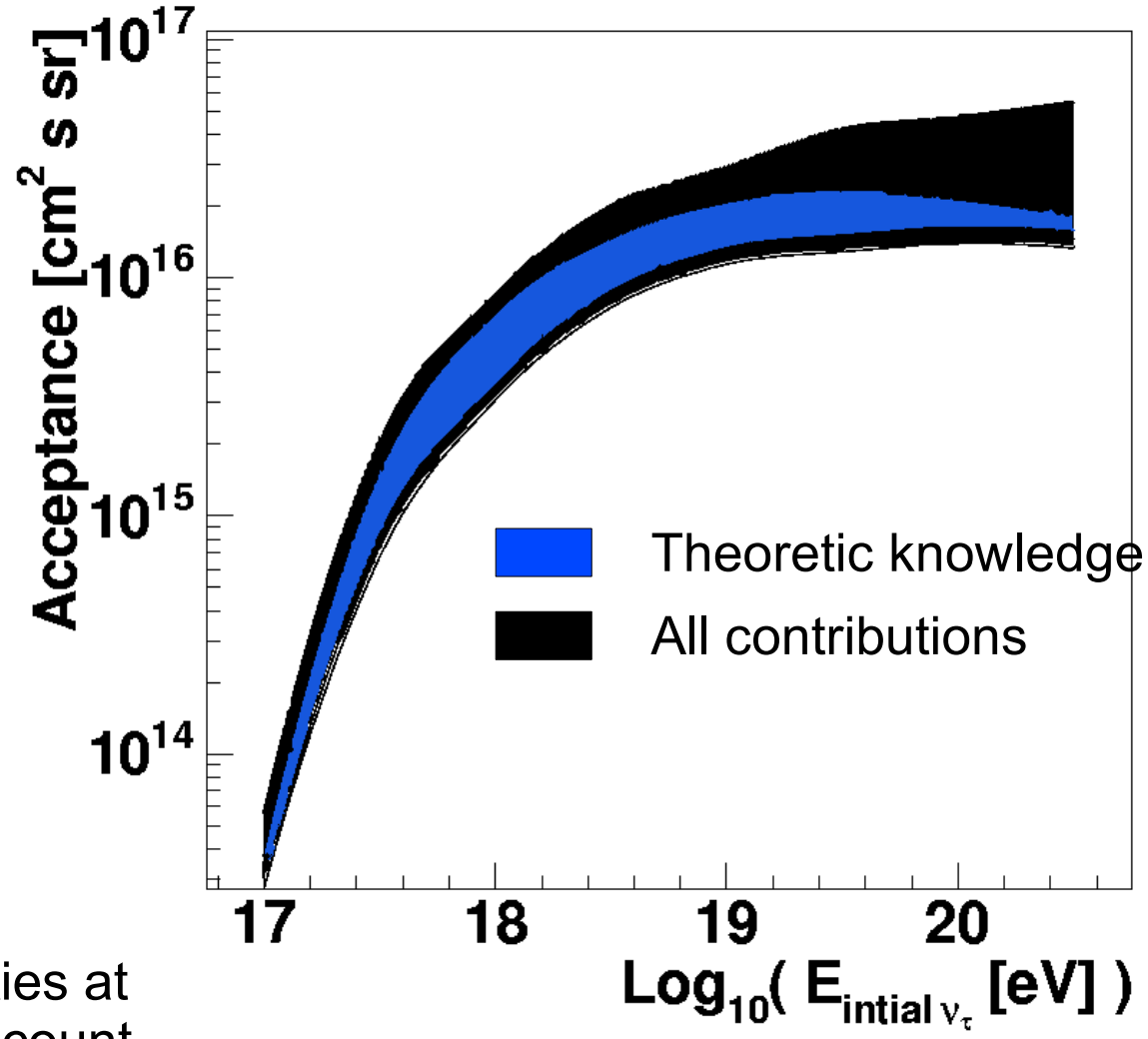


EM correction more important below 68°

The two spectra agree within the statistics

EARTH SKIMMING ACCEPTANCE SYSTEMATICS

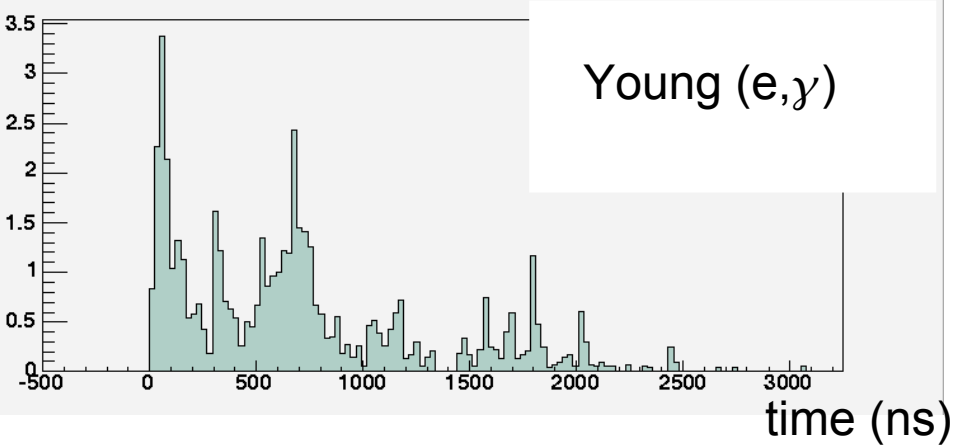
Source	Uncertainty
MC Simulations	
Interactions in Earth	±5%
Extensive Air Shower	+20%, -5%
Pierre Auger Observatory	
Acceptance	±2%
Topography	+18%
Theoretic knowledge	
Tau Polarisation	+17%, -10%
Cross Section	+5, -9%
Energy Losses	+25%, -10%
Total	-132%, -45%

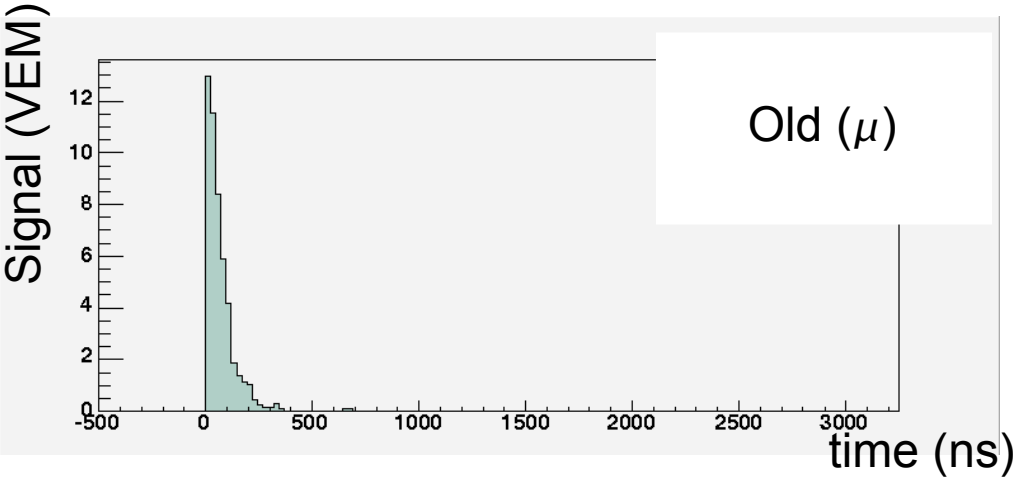


Parton Distribution Function uncertainties at low x and high Q^2 are not taken into account

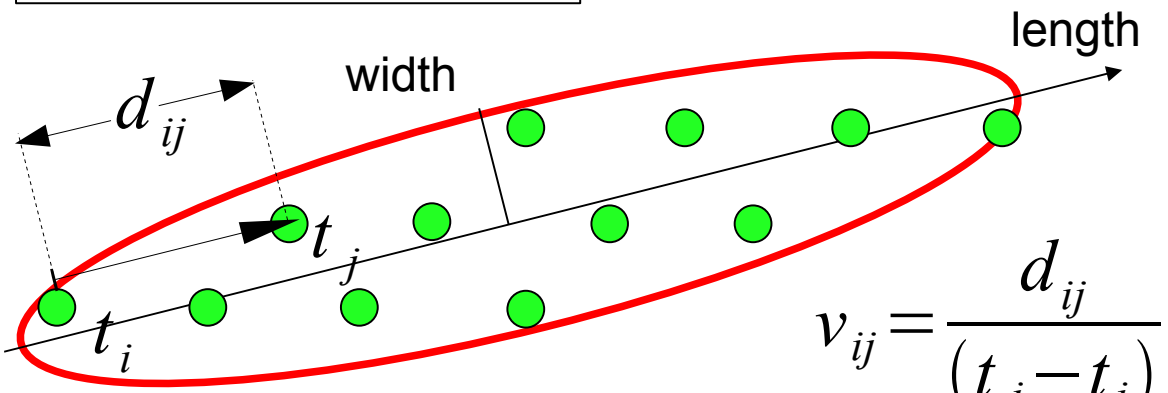
Worst/Best combination of scenarios leads to a factor ~3 difference for the flux limit

Young Showers





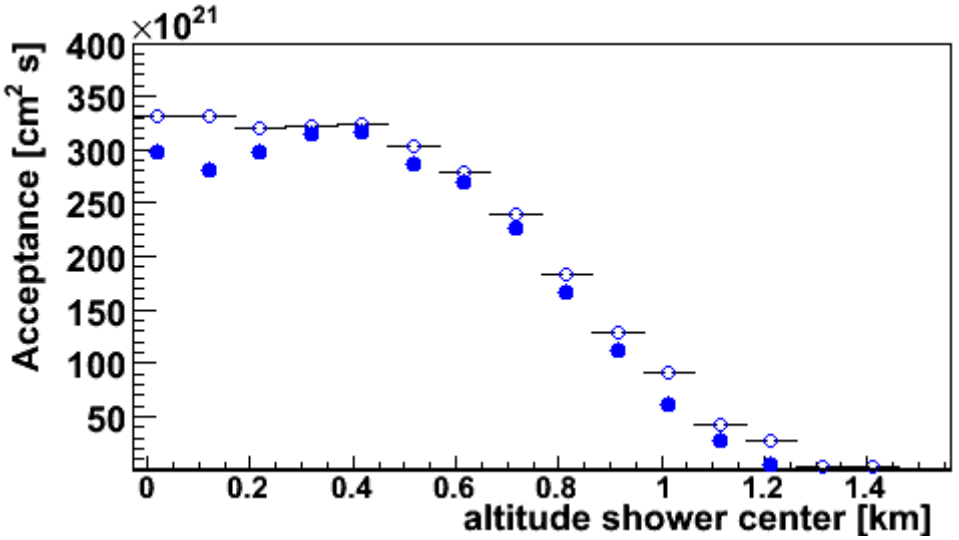
Inclined Showers



$$v_{ij} = \frac{d_{ij}}{(t_j - t_i)}$$

length/width > 5
<v> ∈ (0.29,0.31) m/ns
RMS(v) < 0.08 m/ns

$$Acc_\tau(E_\tau, dh_c)$$



$$\int dh_c \frac{d^2 N}{dE_\tau dh_c} Acc_\tau(E_\tau, dh_c)$$