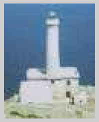


Cosmic Rays at Extreme Energies
The Pierre Auger Observatory

Ezio Menichetti

Dip. di Fisica Sperimentale, Universita' di Torino
INFN, Sez. di Torino

Lecture 2

EAS Detectors

Long history, dating back to the '60s

Volcano Ranch (USA) – Sampling
Haverah Park (UK) – Sampling
SUGAR (Australia) - Sampling
Yakutsk (Russia) - Sampling
Fly's Eye (USA) – Fluorescence

AGASA
HiRes

AGASA
*A*keno *G*iant *A*ir *S*hower *A*rray

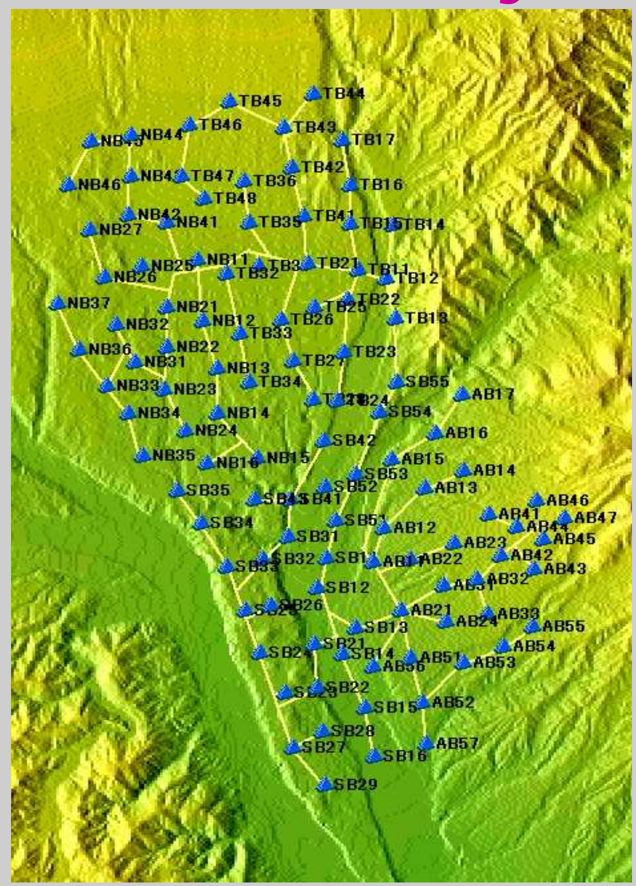
111 scintillators + 27 muon det.
Akeno, Japan

11 Super-GZK events

Small Scale Clustering

Constraints on Composition:

→ protons at UHEs.
(“Classical” analysis based on N_e vs N_μ)



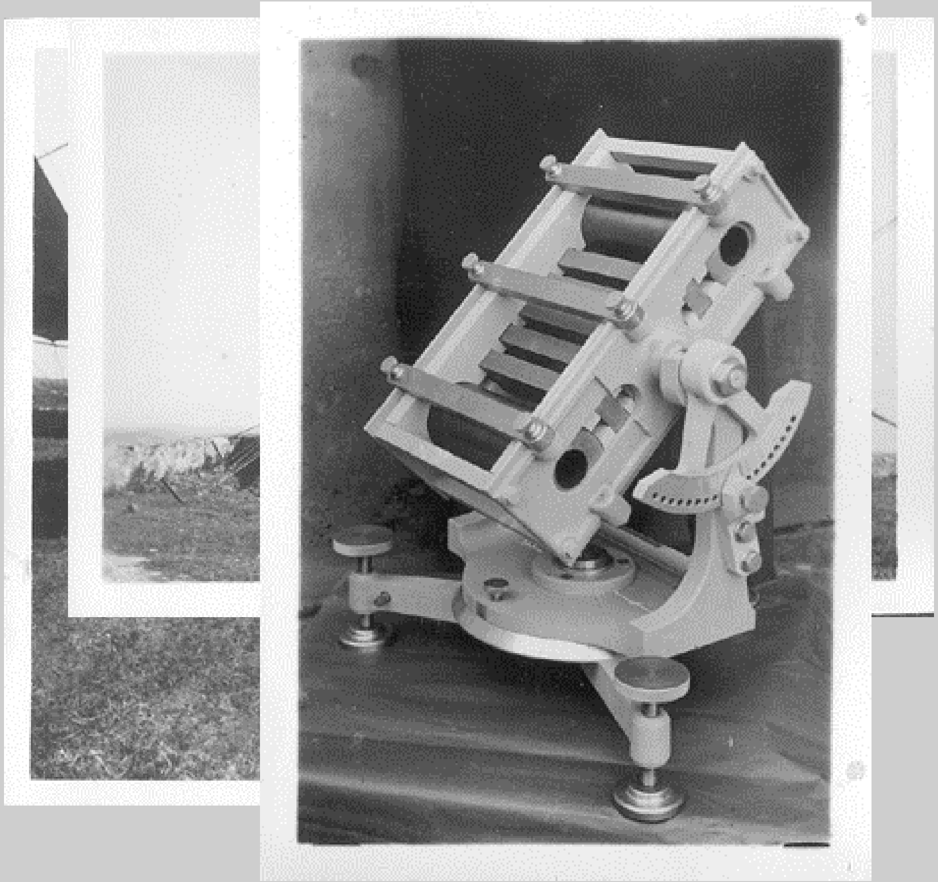
HiRes - *Hi*gh *Res*olution Fly's Eye

Pioneers of FluorescenceTechnique

Air fluorescence detectors
HiRes 1 - 21 mirrors
HiRes 2 - 42 mirrors
Dugway, Utah, USA

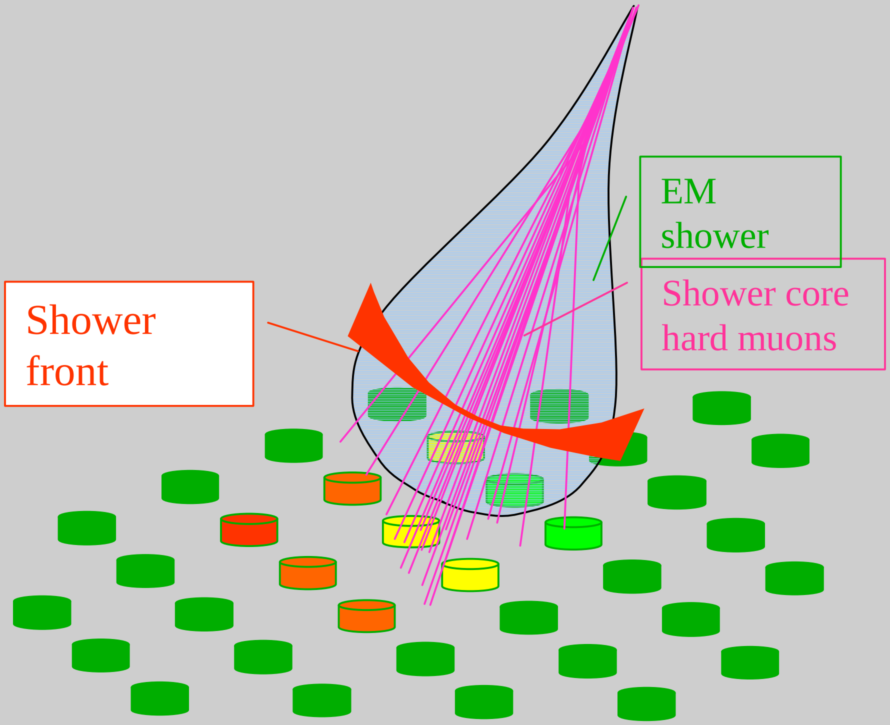
No Super-GZK flux
No Small Scale Clustering
Composition Change

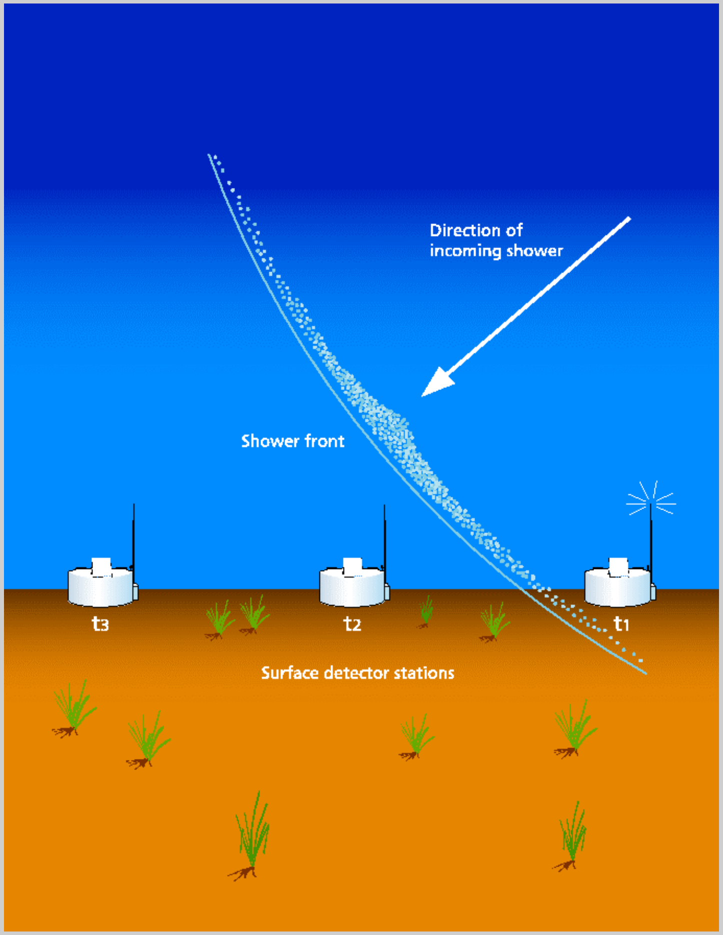
EAS – Early History



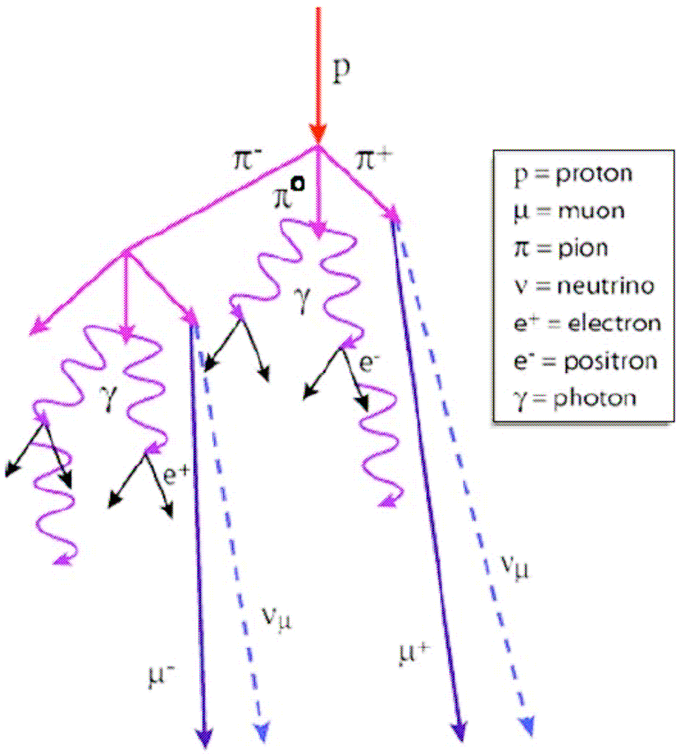
Ground Array

EAS sampled at ground
by a number of detector stations





Particle Composition

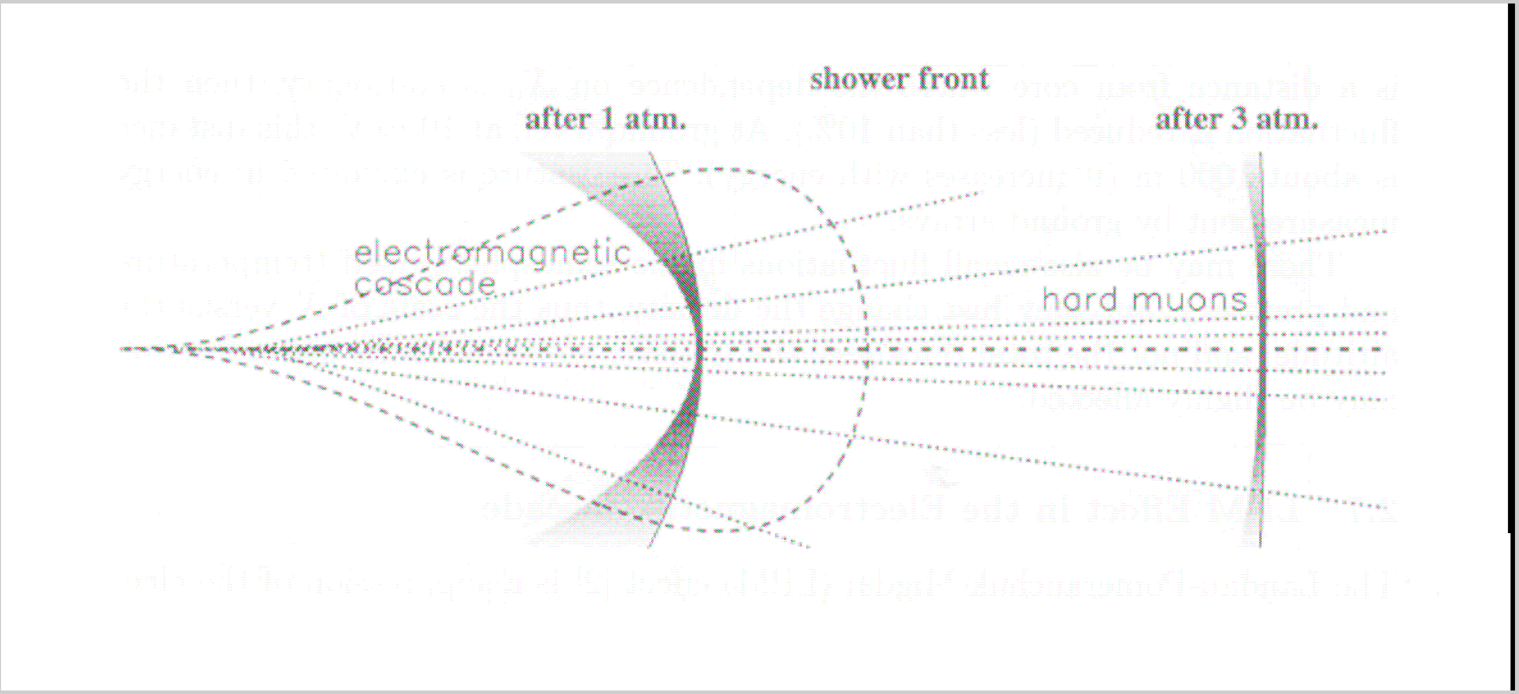


$$\pi^0 \rightarrow 2\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Shower Development

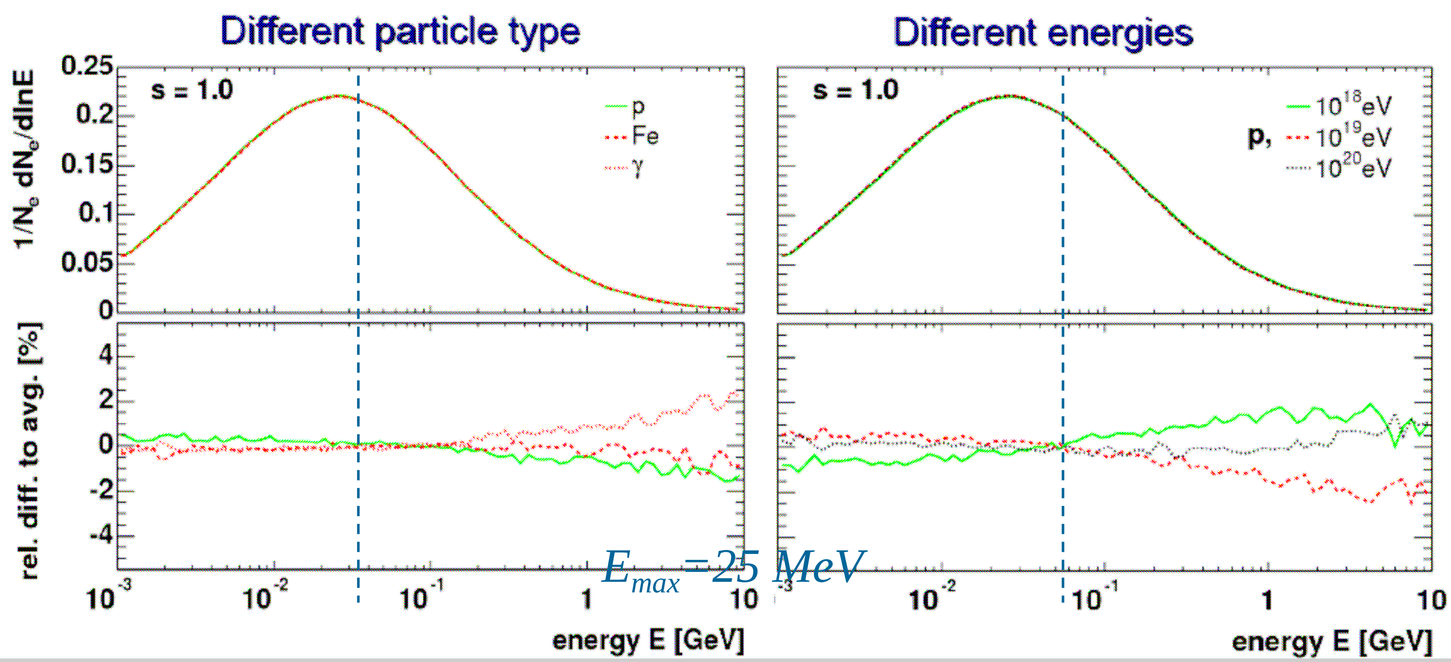


Universality of EM Component

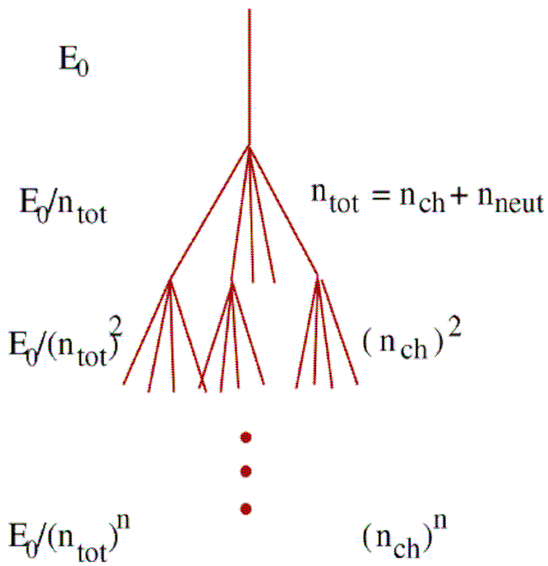
Typical length scale in em. shower X_0 (~37 g/cm^2):

all information of initial energy distribution lost after ~ 2 X_0

CORSIKA simulations: universality for low electron energies



The Muon Component



Primary particle: proton

π^0 decay immediately

Only charged pions initiate new hadronic cascades

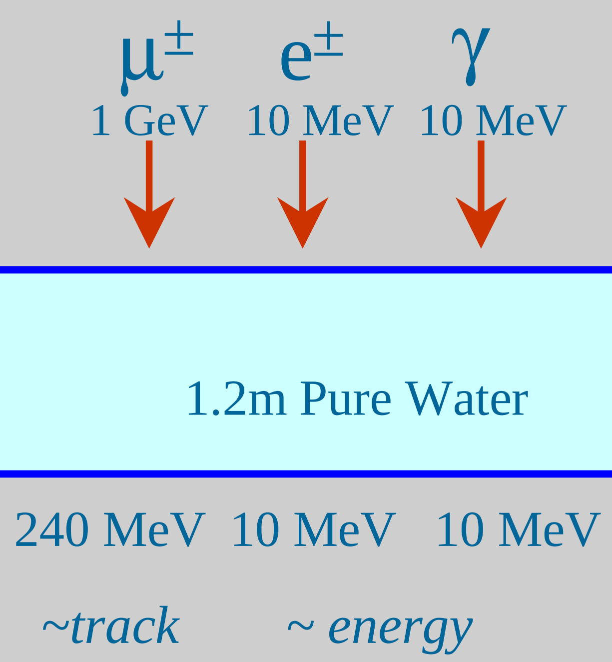
Cascade ends with decay at energy E_{dec}

$$E(X) = E_0/(n_{tot})^n = E_{dec}$$

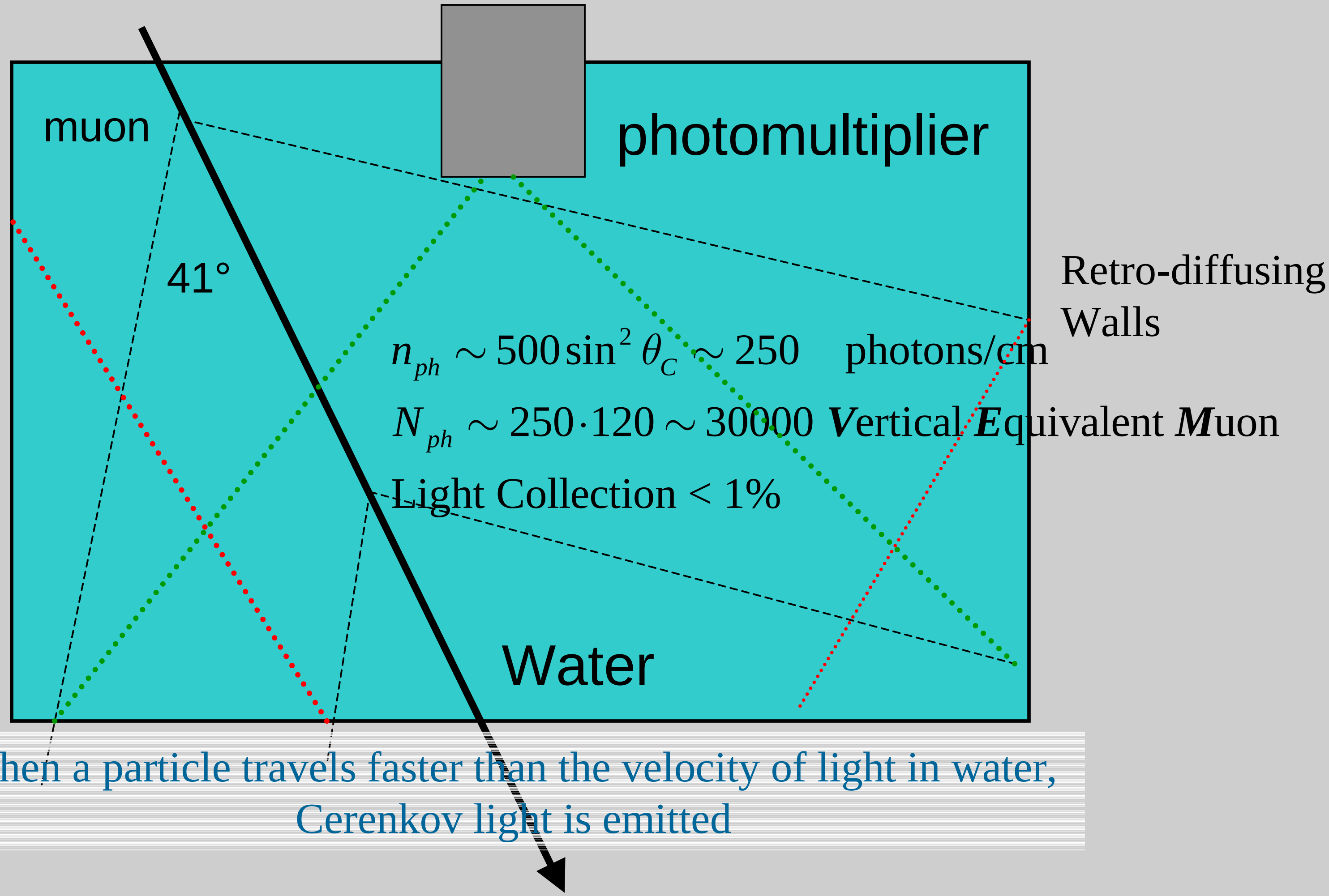
$$N_\mu = (n_{ch})^n$$

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Tank: Signal Components



Tank: Light Emission by Muons



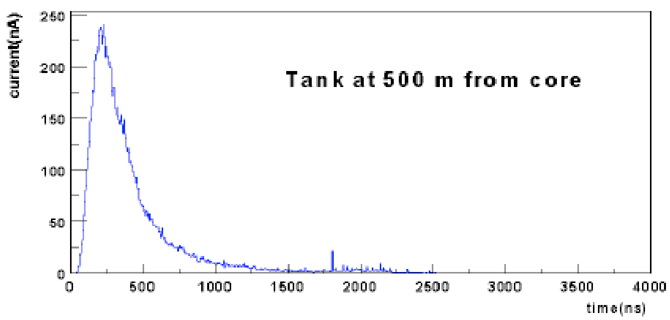
$n_{ph} \sim 500 \sin^2 \theta_C \sim 250$ photons/cm

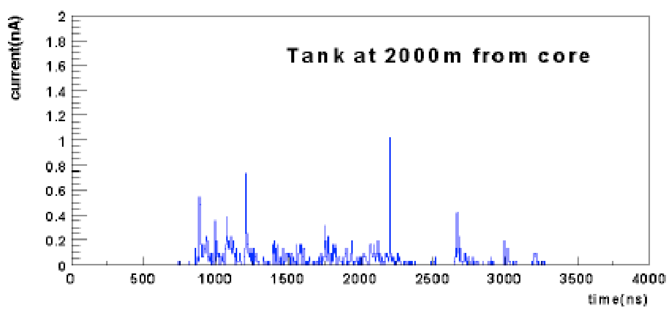
$N_{ph} \sim 250 \cdot 120 \sim 30000$ ***V**ertical **E**quivalent **M**uon*

Light Collection < 1%

When a particle travels faster than the velocity of light in water, Cerenkov light is emitted

Pulse Shape



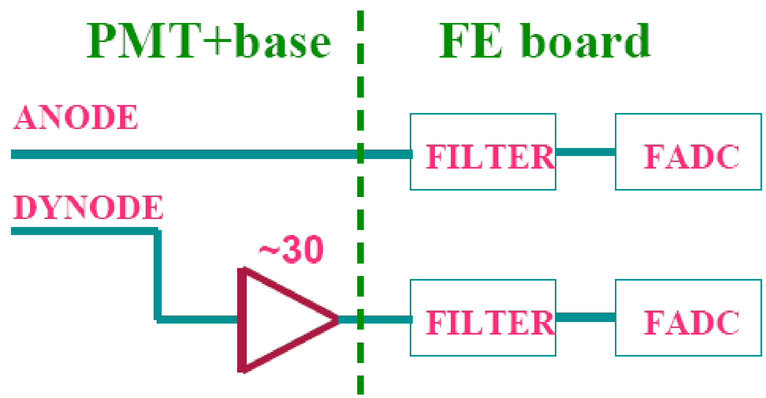


Proton, 5.10^{20} eV, 30°

Signals:

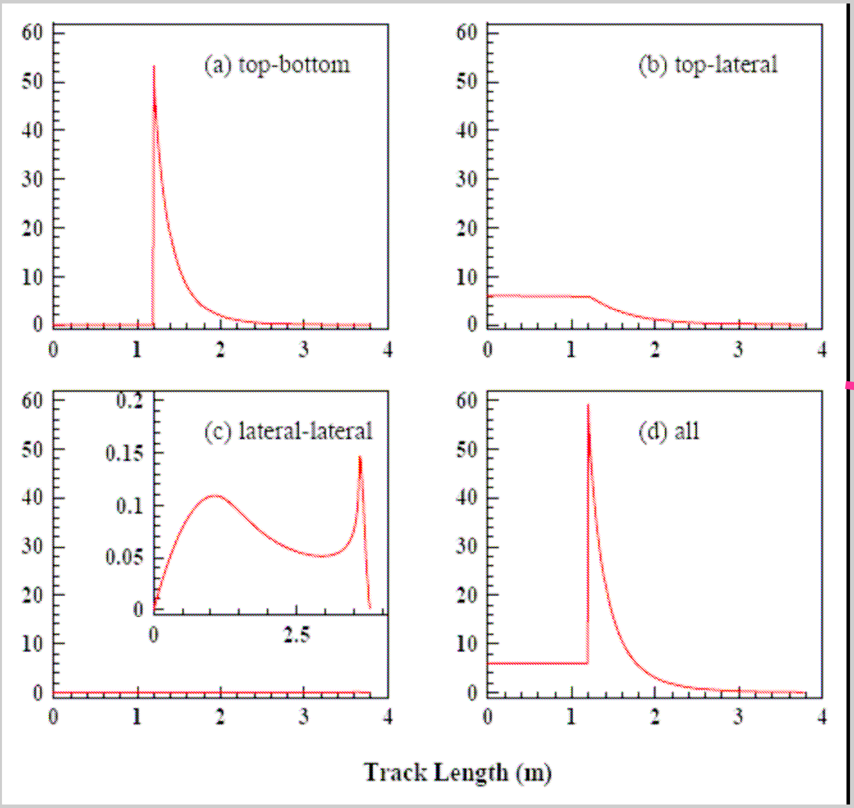
Large dynamic range: 15 bits

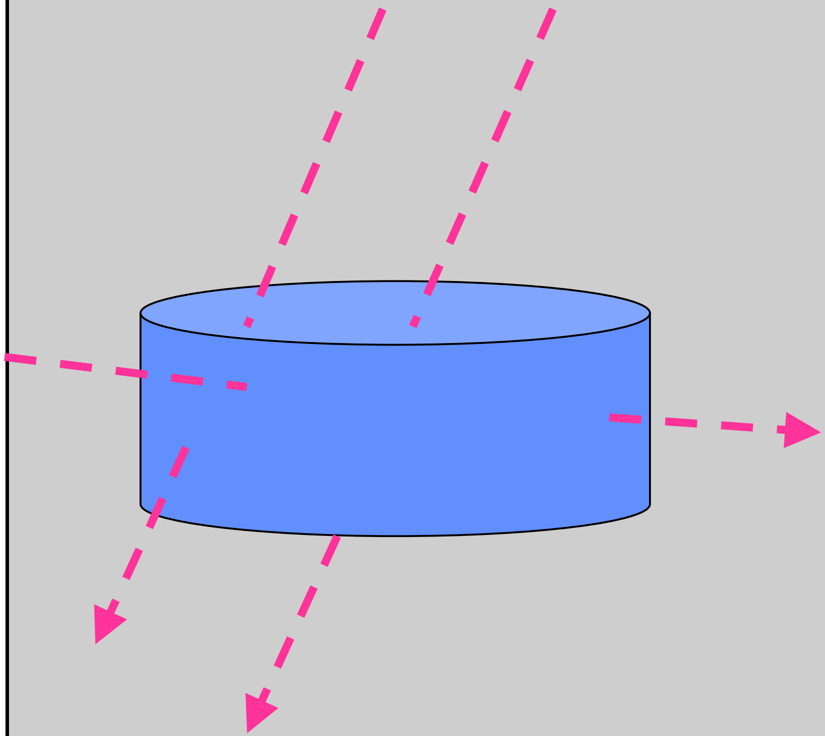
Long duration time: a few μs



40 MHz, 10 bit
Flash ADC

Pulse Height from Muons



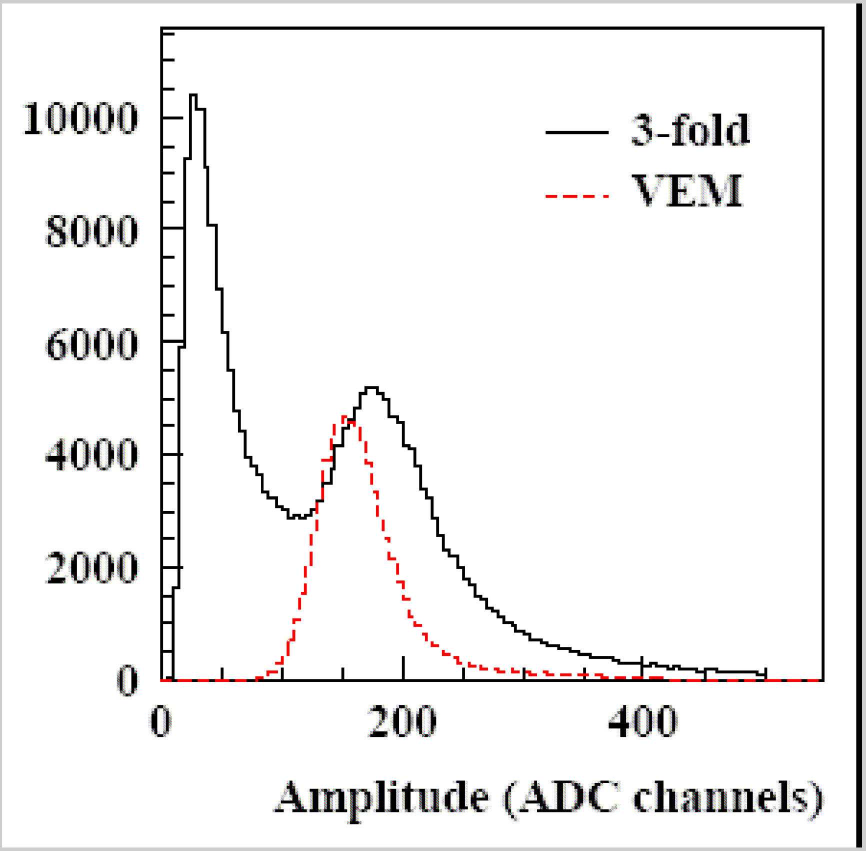


Signal unit ~ 1 VEM ~ 94 ph.e.

Pulse Height for Calibration

Most frequent signals ~ atmospheric muons . .

A/D ratio - sliding average over 3 min of signals > 512



EAS Direction from Timing

B.Rossi, 1953

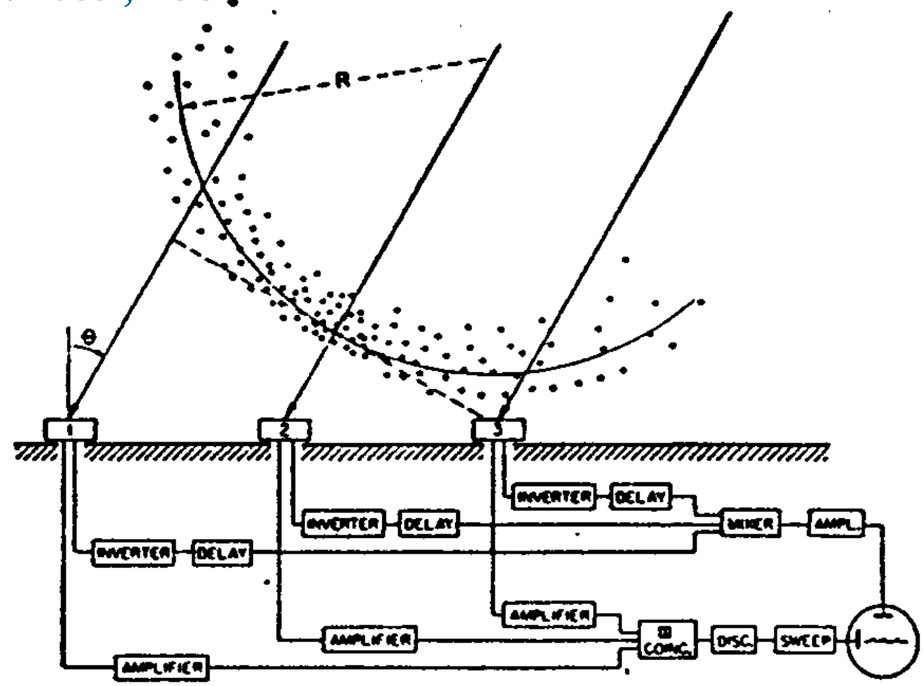
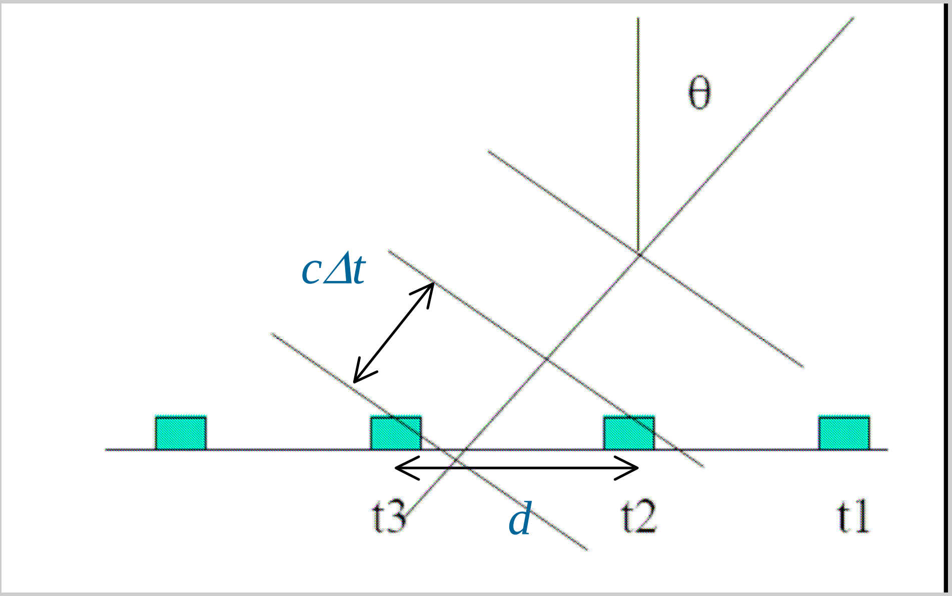


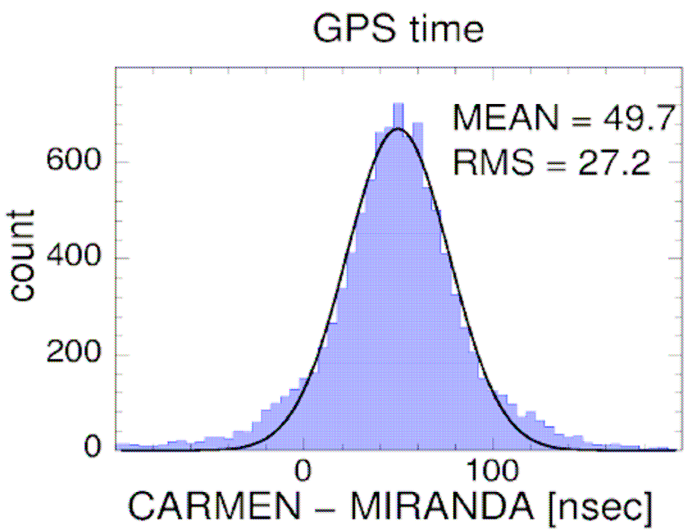
FIG. 2. Block diagram of the apparatus with a schematic representation of an air shower about to strike the counters. The counters are in arrangement II.

Direction from Timing



$$c\Delta t = d \sin\theta$$

Timing



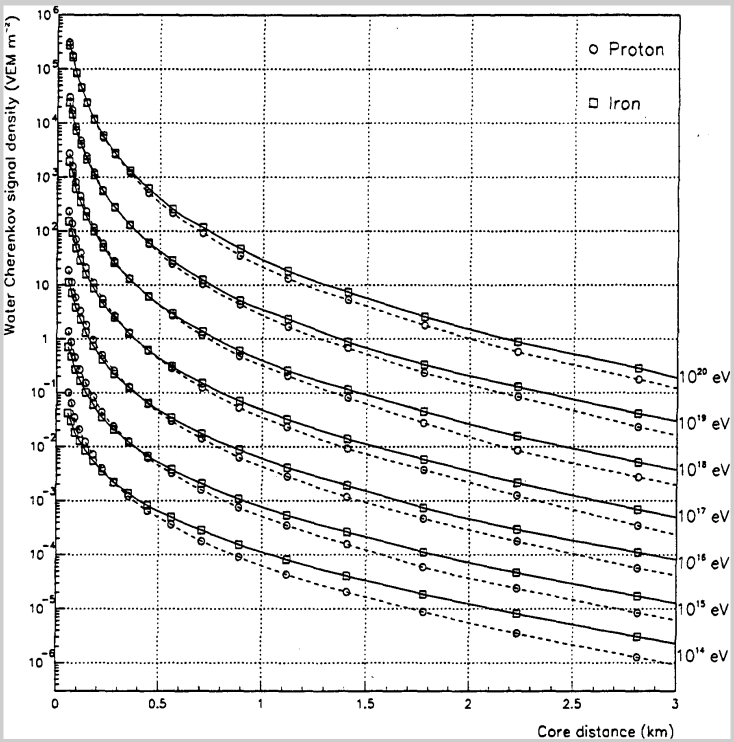
GPS timing precision

Position precision about 1 m
FADC bins 25 ns
GPS intrinsic time resolution 8 ns

Total σ about 10 ns yields angular resolution better than 1°

Ground Array - LDF

Lateral Distribution Function



LDF Parametrization

$$S(r) = S(1000).(r/1000m)^{-\upsilon}$$ Power law

$$S(r) = S(1000).\left(\frac{r}{r_s}\cdot\frac{r_s + r}{r_s + 1000m}\right)^{-\beta}$$ NKG-like (r_s=700m) Nishimura, Kamata, Greisen)

$$S(r) = \begin{cases} k\, r^{-(\eta + r/r_0)} & : r < 800\,\mathrm{m} \\ (\frac{1}{800})^{\delta} k r^{-(\eta + r/r_o) + \delta} & : r \geq 800\,\mathrm{m} \end{cases}$$ HP-like

Haverah Park

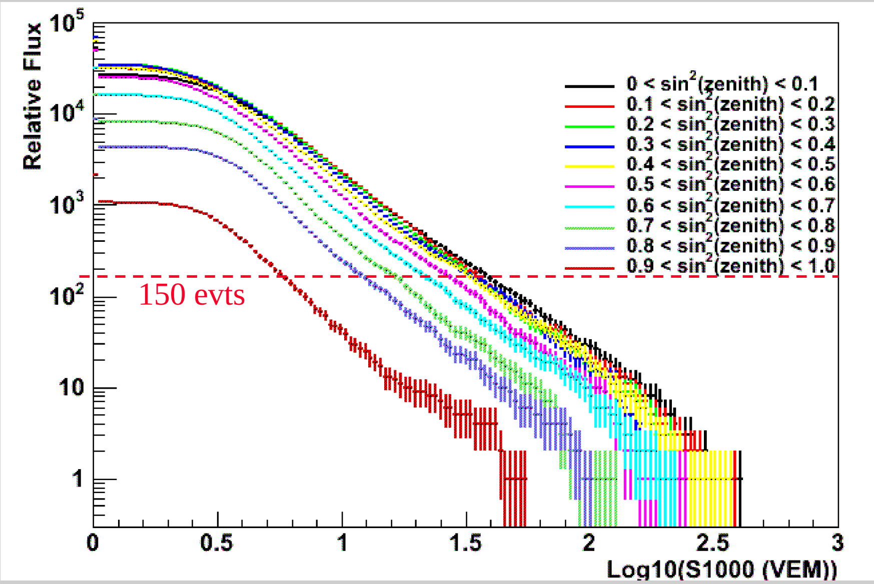
Where υ, β and η are linearly parameterized as function of sec(θ). δ is fixed

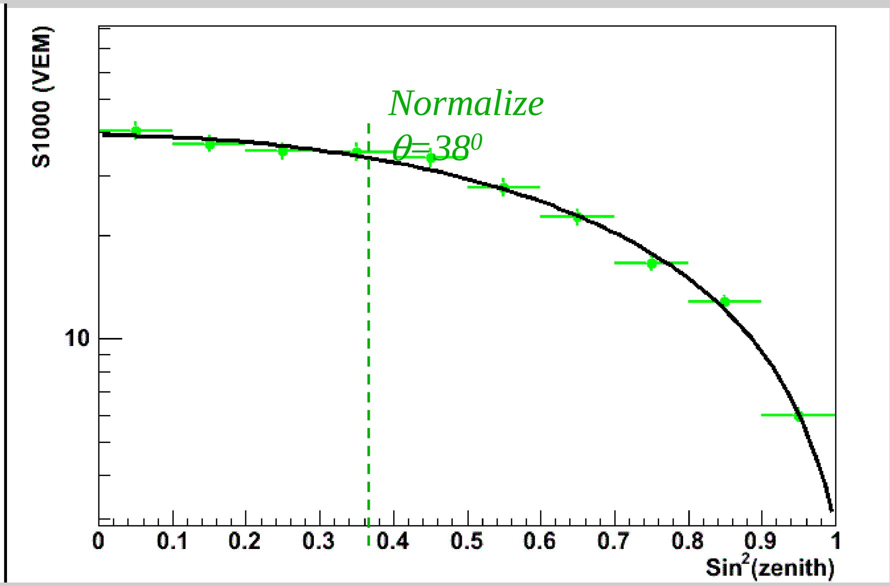
Constant Intensity Cut

Need to unfold the zenith angle dependence of the tank response to any given energy

Assume isotropic flux at high energy: *Expect same flux at all angles at any given E*

→Plot cumulative (i.e. $N(S>S_0)$ *vs.* S_0) pulse height distribution for each θ bin





Relative tank response vs angle

Ground Array - Energy

Measured signal density extrapolated to a reference point

Typ. S(600m) to S(1000m) to minimize fluctuations

Compare to Monte Carlo simulation

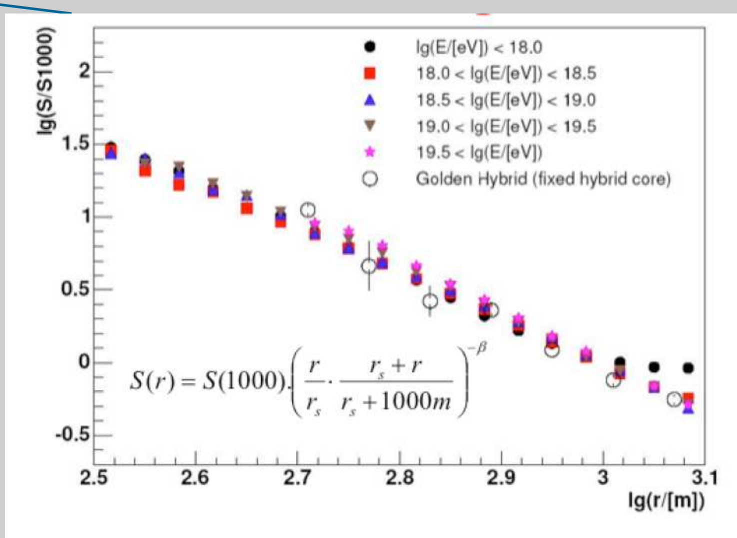
Good linearity with $E_{primary}$

Results somewhat depending on :

Primary interaction (physics)

Composition (p vs. Iron)

E range fixed by detector spacing



Lot of fun for us accelerator physicists!
Get energy from lateral density…

Ground Array - Composition

Several tool available. All in all, looks like a tricky business…

Just as an example: Signal rise time

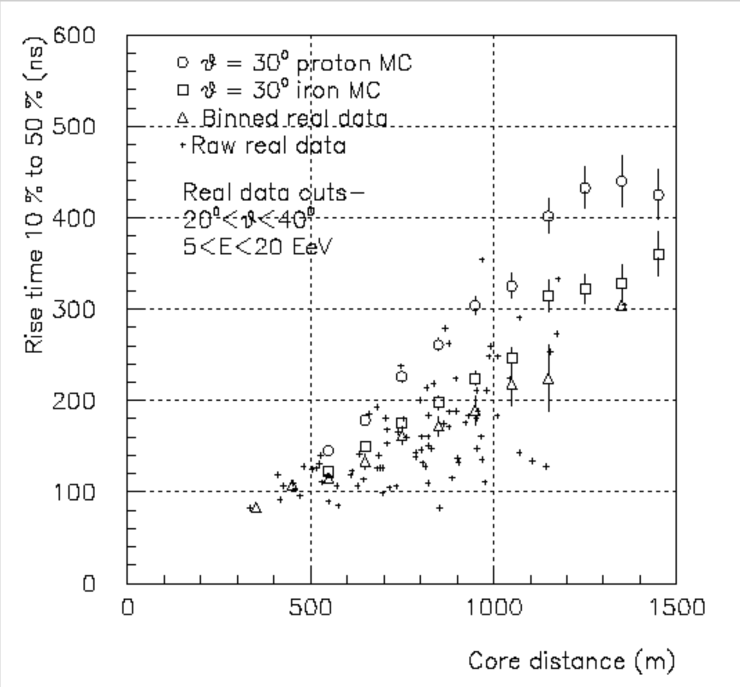
Iron nucleus:

Less cascade steps before reaching ε_π

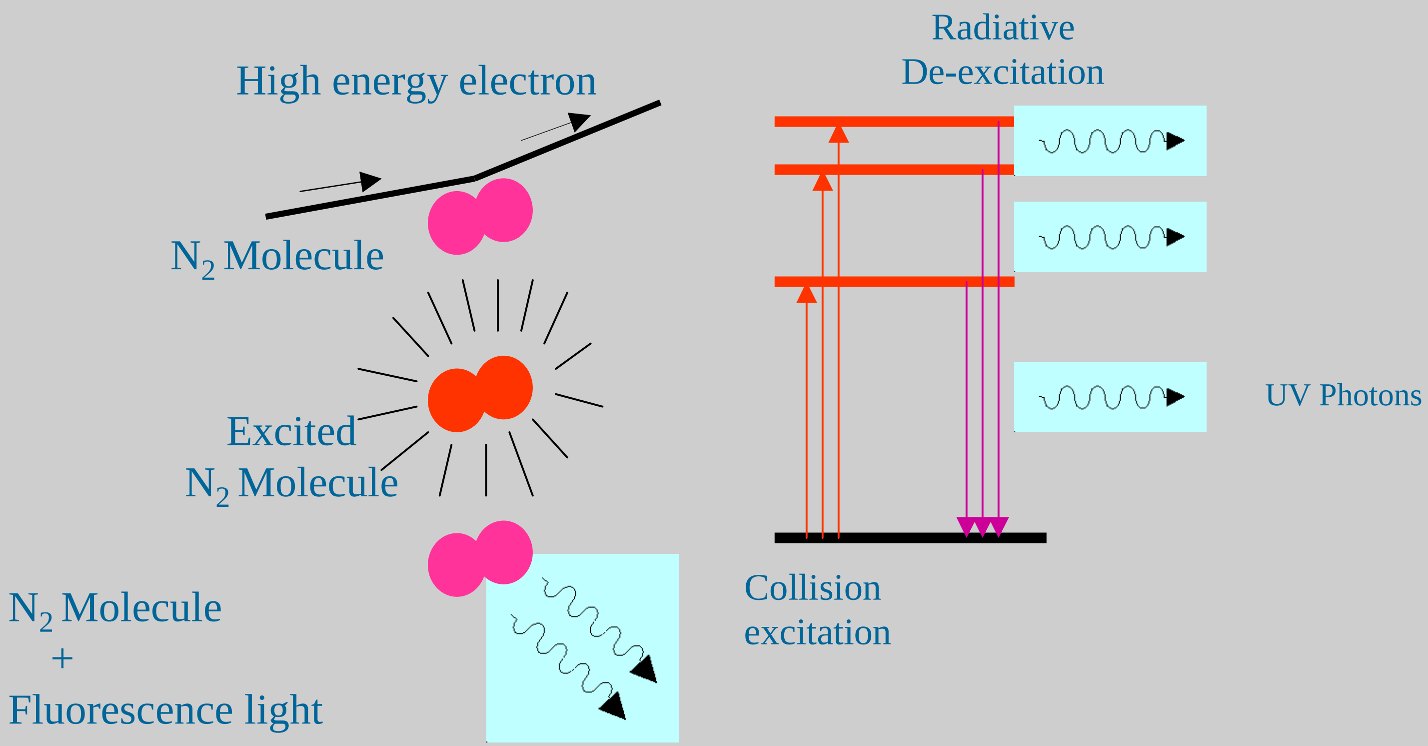
$\Rightarrow$ *More μ's.*

$\Rightarrow$ *Less EM energy*

$\Rightarrow$ *Smaller muon rise time*

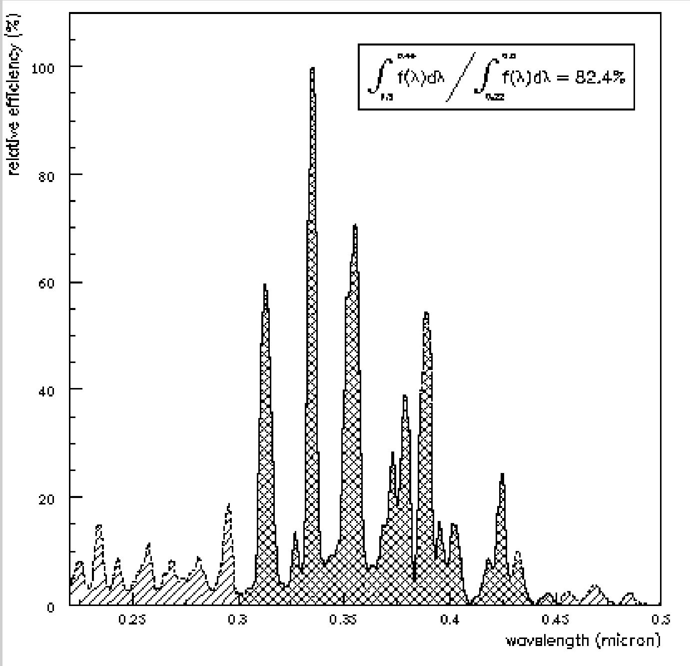


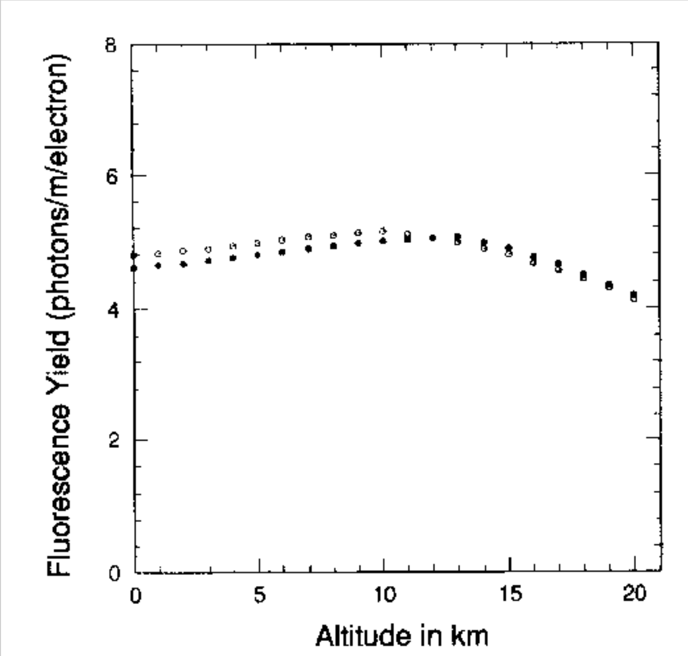
Atmospheric Fluorescence



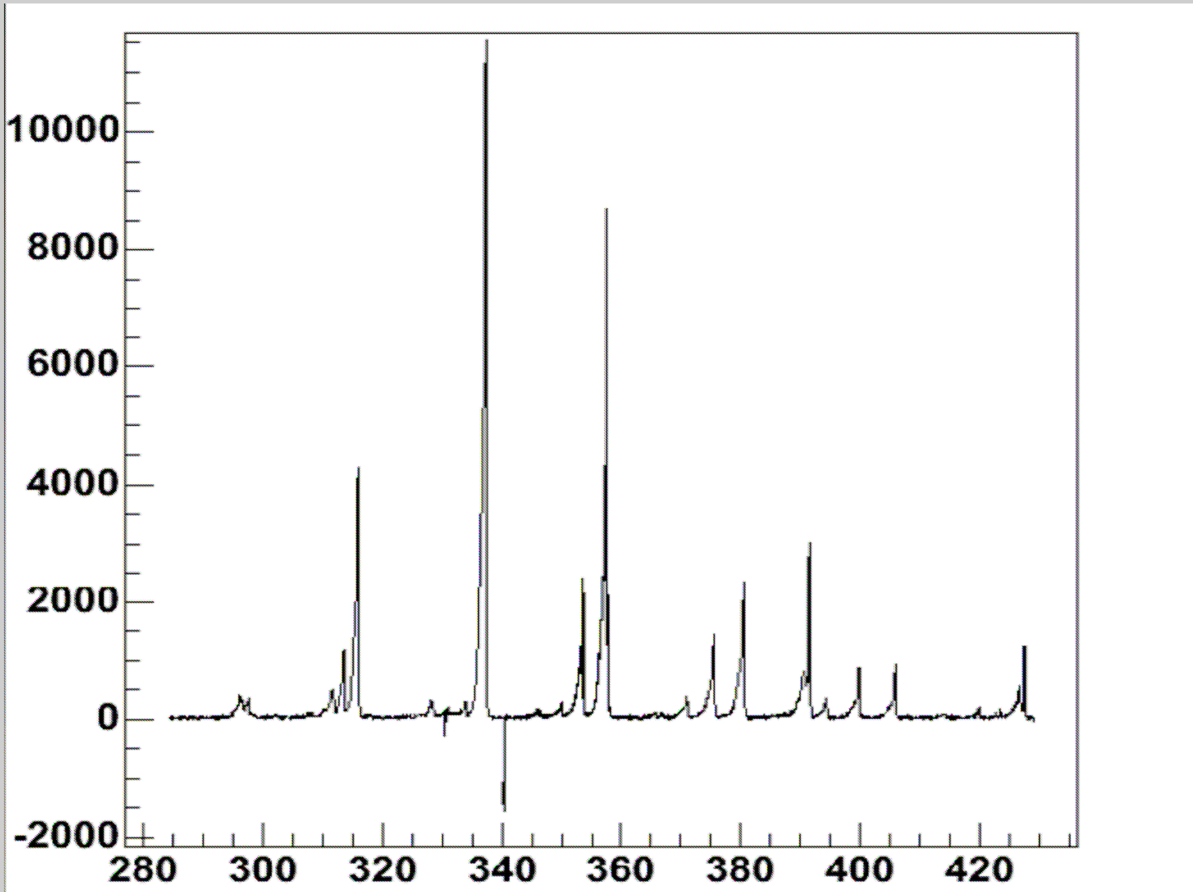
Fluorescence Yield

Atmosphere working as a large scale calorimeter



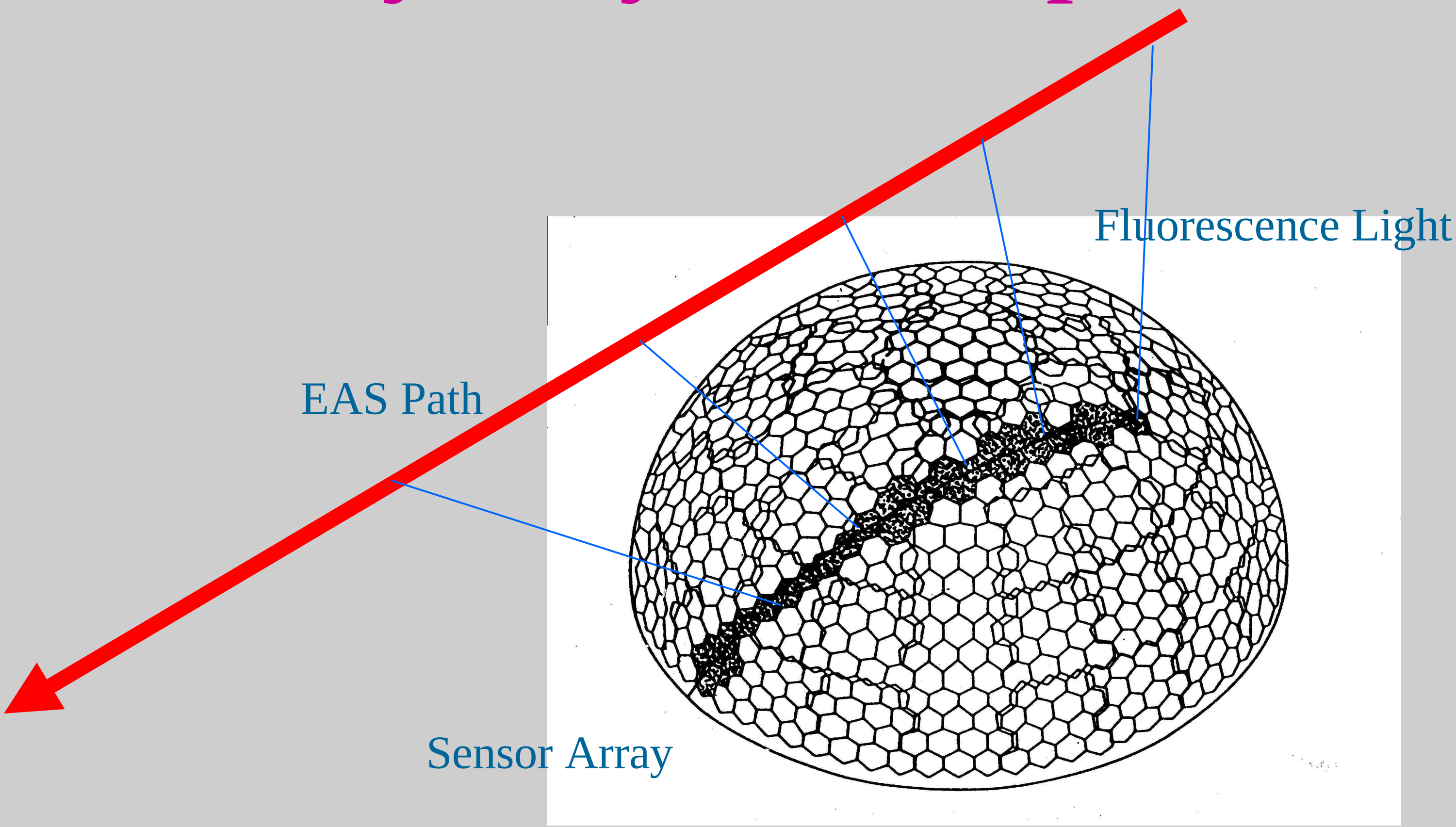


A Recent Measurement



Fluorescence spectrum measured at Argonne laboratory

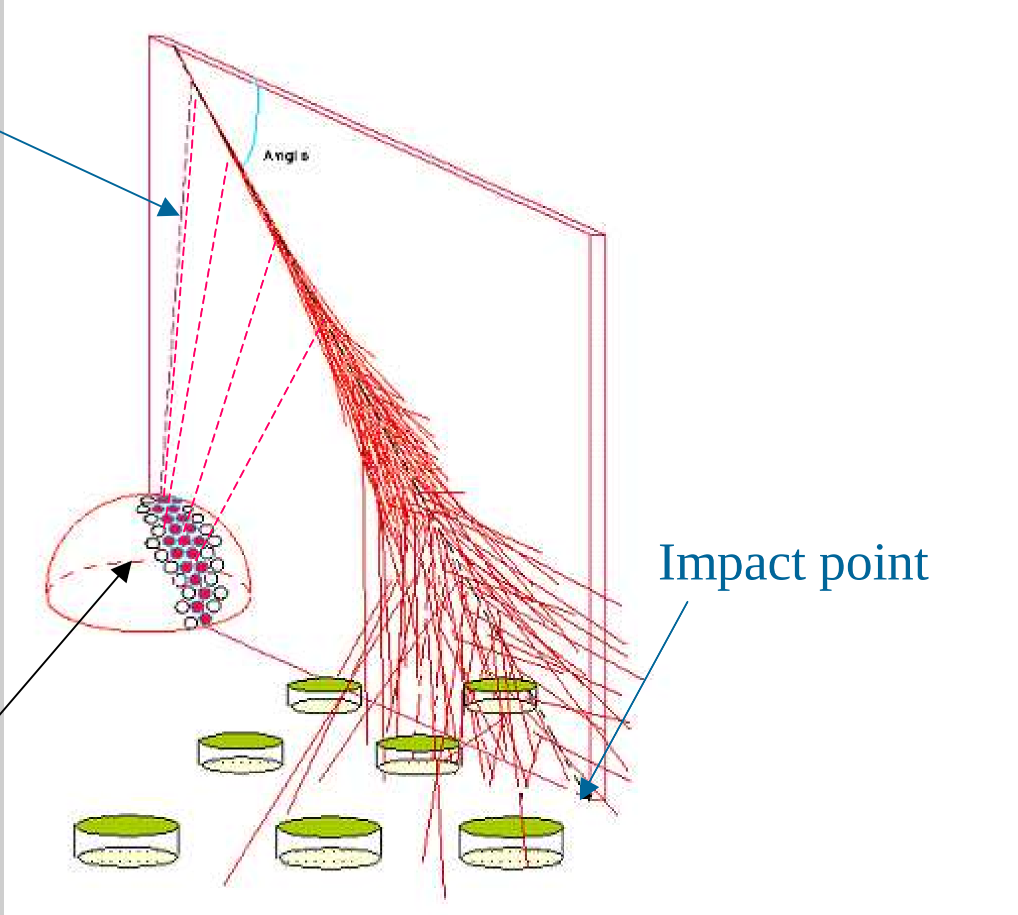
The Fly's Eye Concept



Fluorescence Detector

Shower-detector plane

Each PM seeing one segment of the shower
→ *Sequence of fast pulses by adjacent PMs*



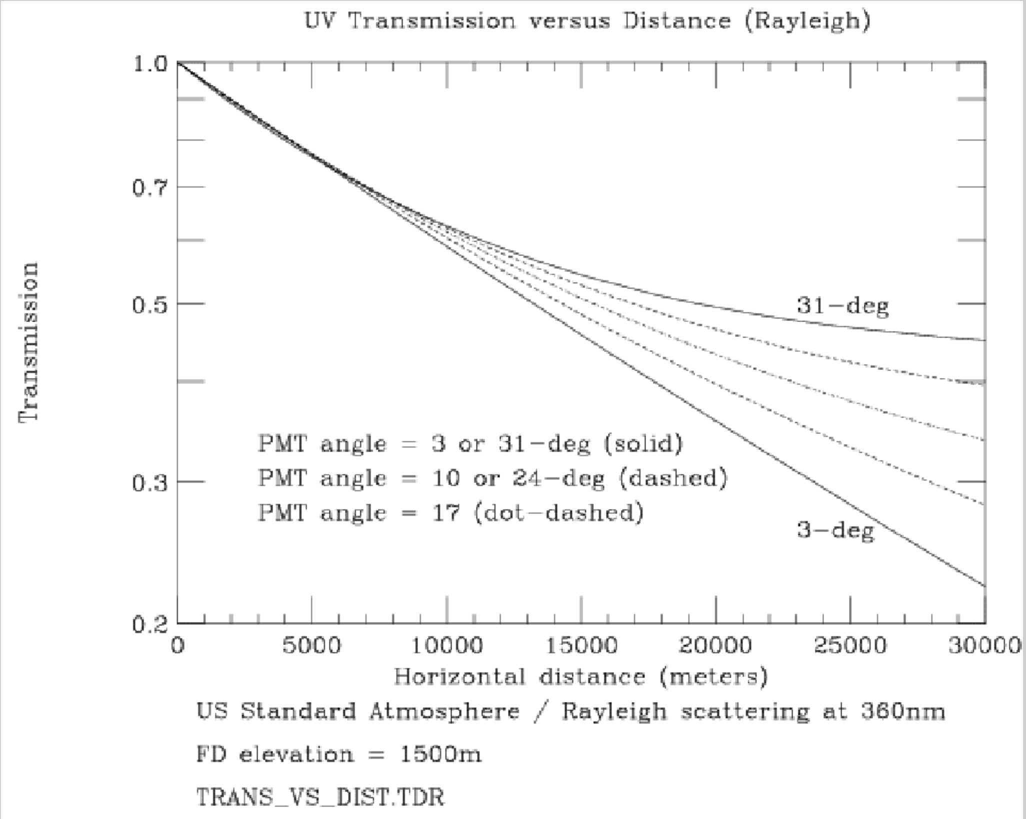
Impact point

Photomultiplier array

Atmospheric Headaches - I

Effect of Molecular (Rayleigh) Scattering

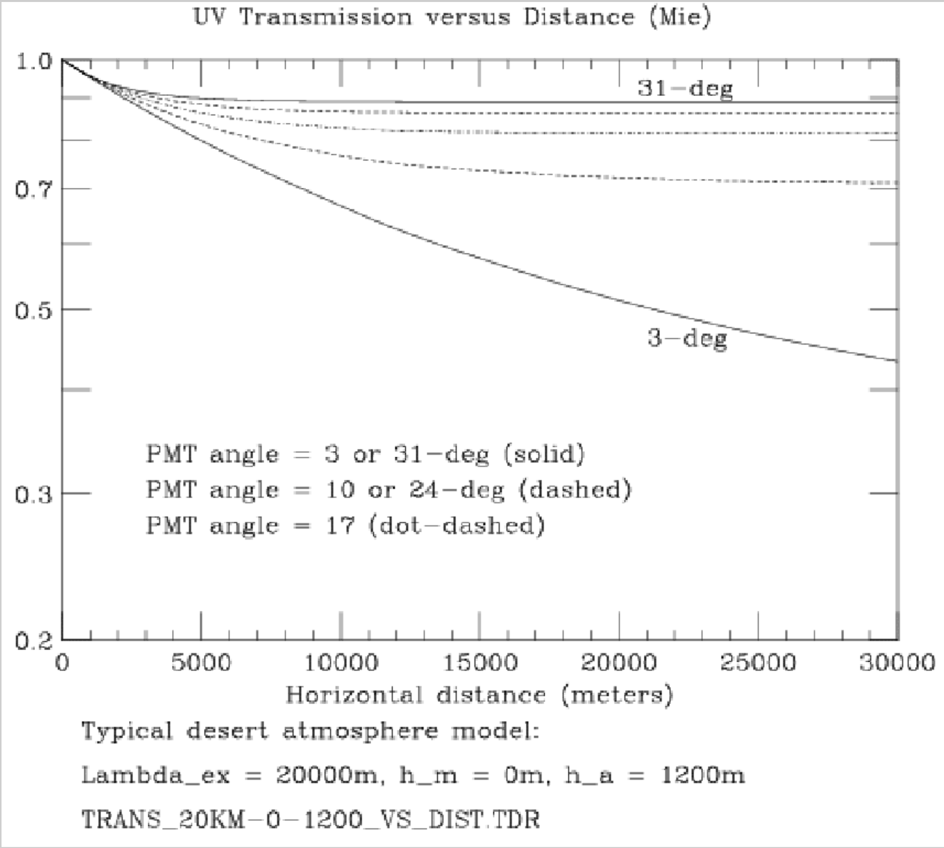
Λ~18km
h~7.5km
τ=h/Λ~0.41



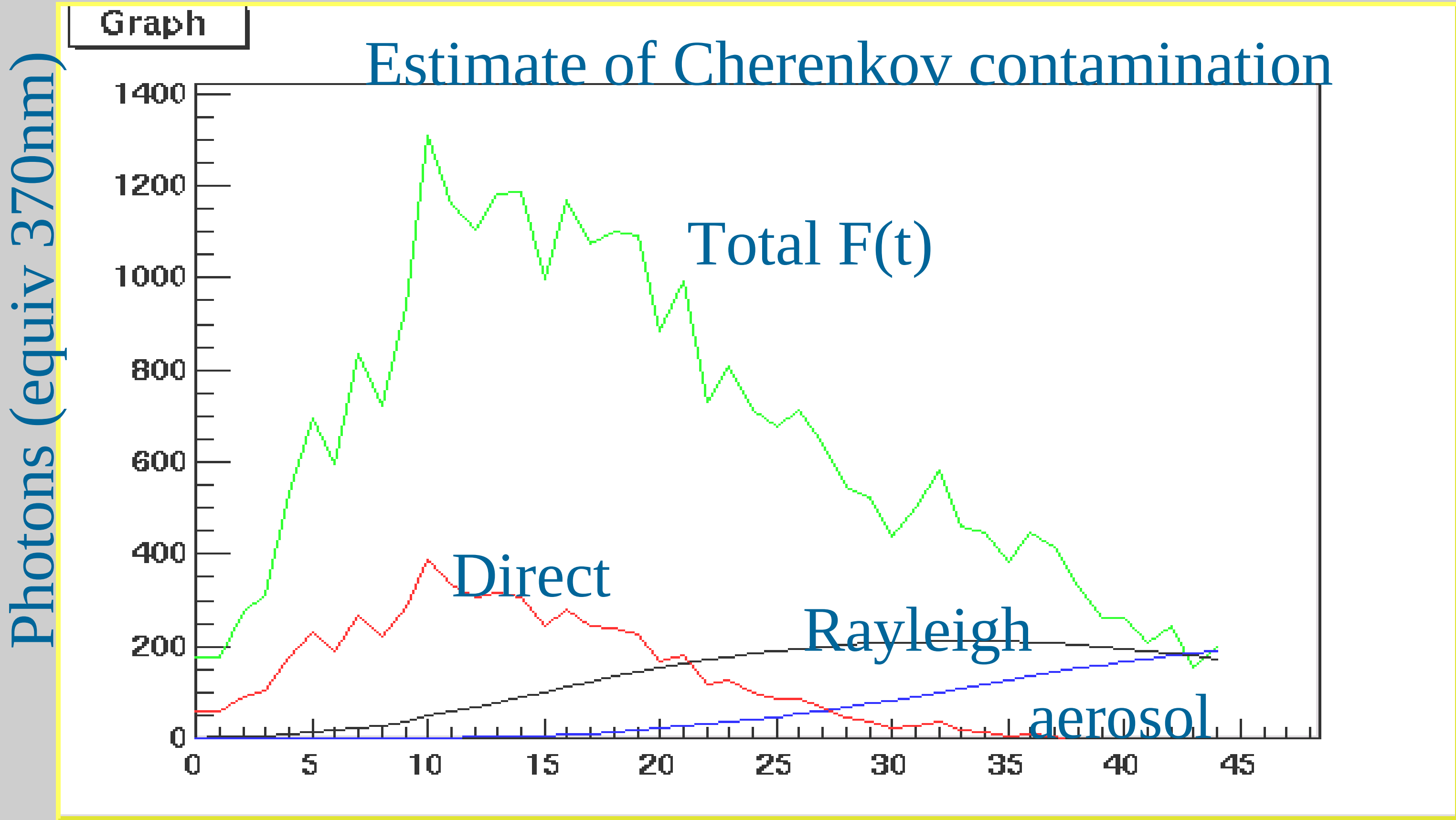
Atmospheric Headaches - II

Effect of Aerosol (Mie) Scattering

Λ~20km
h~1.2km
τ=h/Λ~0.06



Cherenkov Headaches

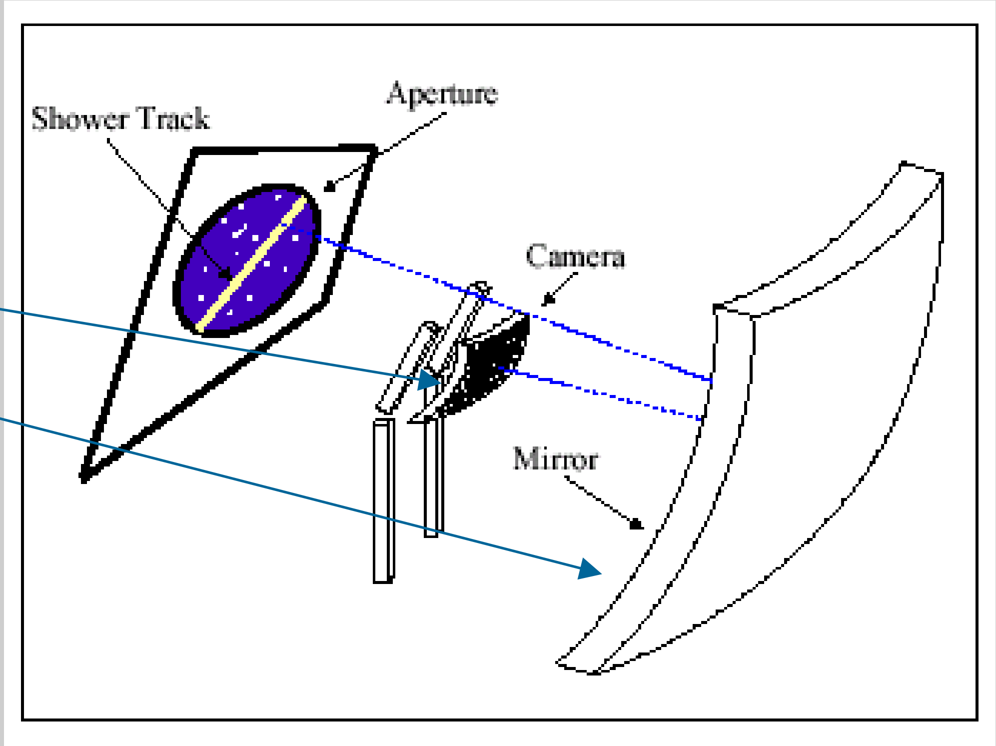


Time (100ns bins)

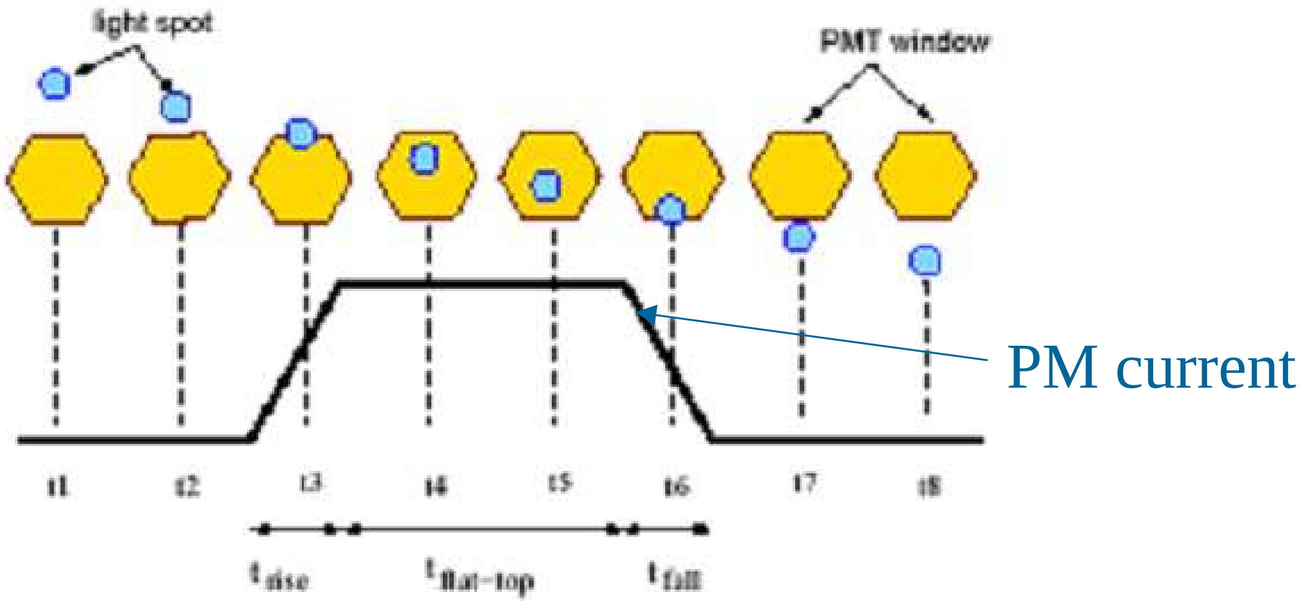
Fluorescence Detector

Practical implementation of light collection (also in Auger)

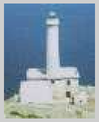
Pixel camera
(Photomultipliers)
Spherical mirror
(Large ~ 10 m^2!)



Fluorescence Detector

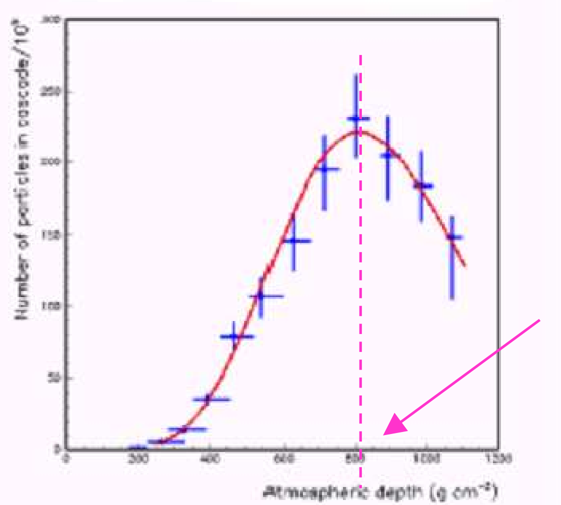


Signal formation:
One PM, sequence of time slices



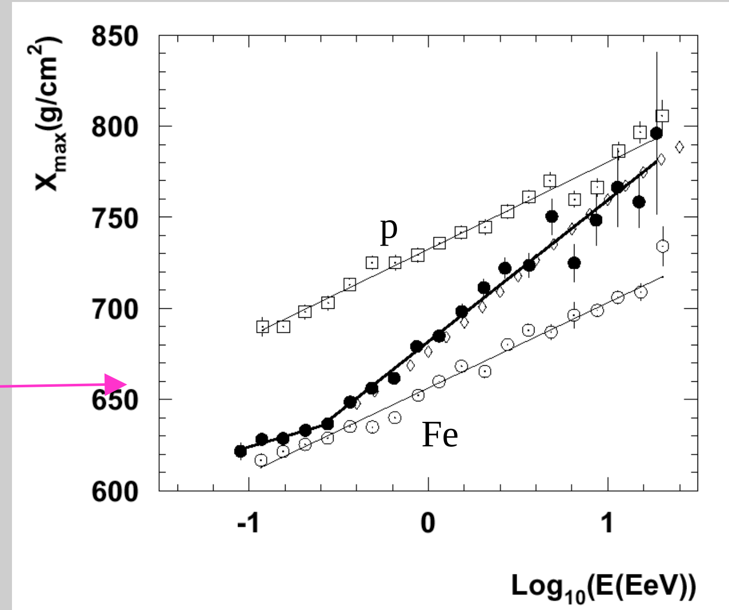
Fluorescence Detector

E=3.2 10^{20} eV (Fly's Eye)



X_{max}

Composition (Fly's Eye)



Unique FD capability: *Longitudinal profile*

Comparison: GA vs. FD

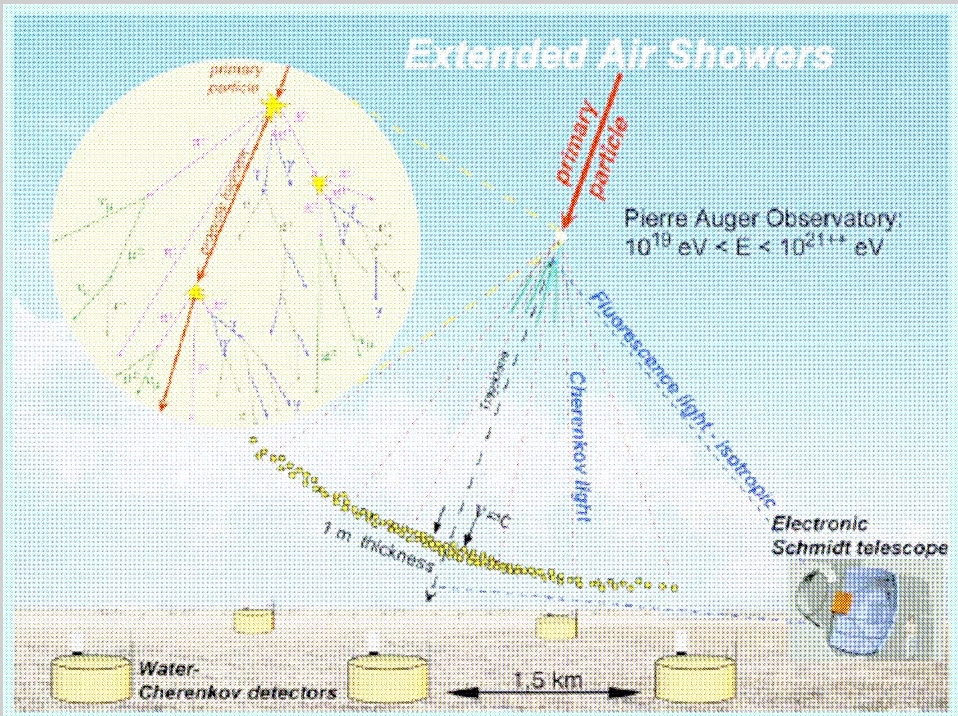
GA

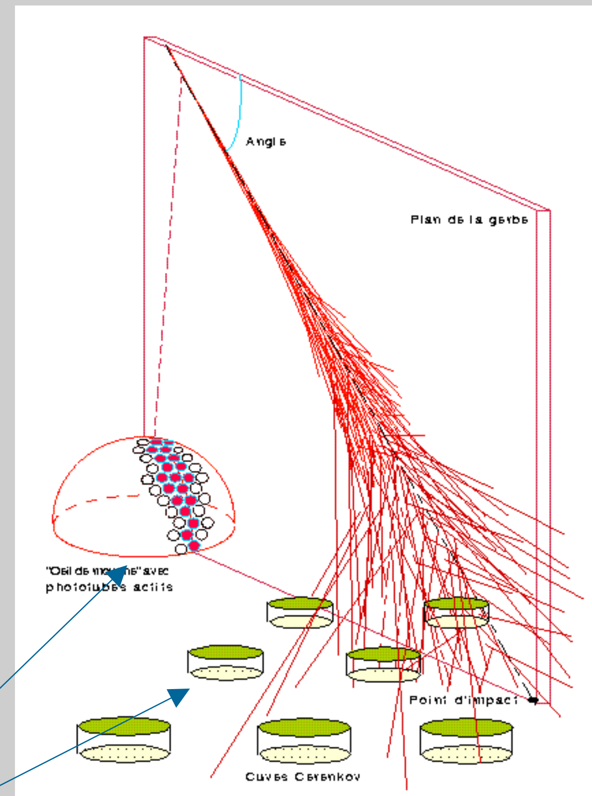
Sampling detector
100% duty cycle
Large number of simple, modular elements
Shower parameters from x-section
Need reliable MCarlo simulation

FD

Integral calorimeter
10% duty cycle
Small number of complex stations
Shower parameters from full shower track
Need good atmospheric monitoring+calibration

The Hybrid Concept





FD: Measuring E_{tot} & Longitudinal Profile
SD: Sampling Lateral Profile at ground