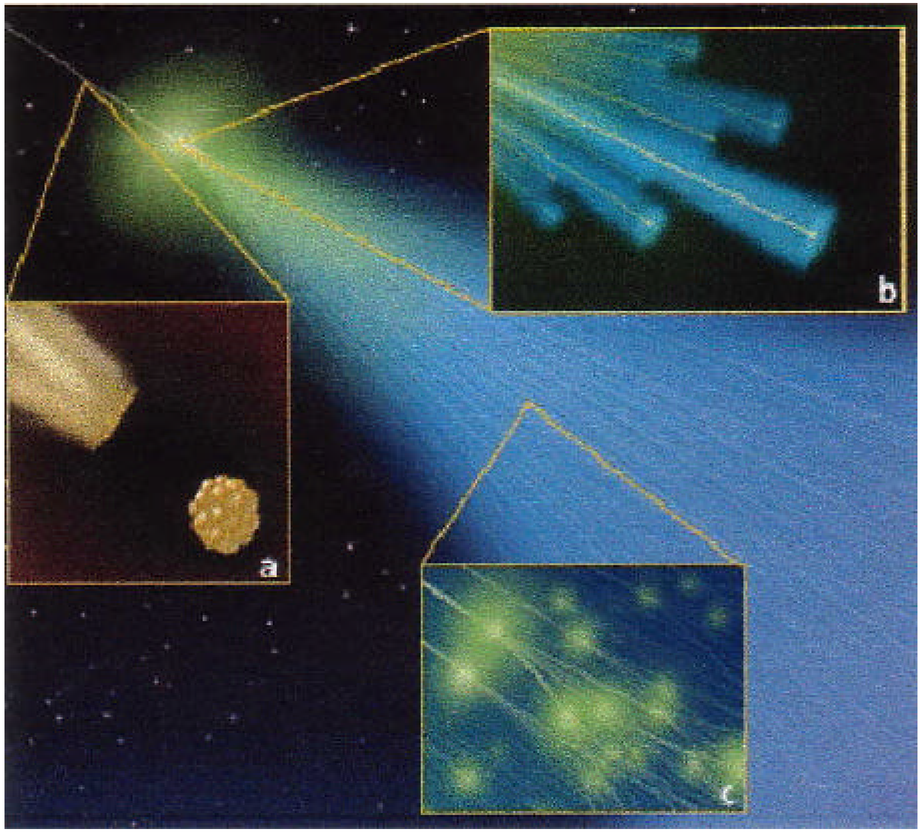
ISAPP 2003

Observations of Cosmic Rays

- Air Shower Detection Techniques

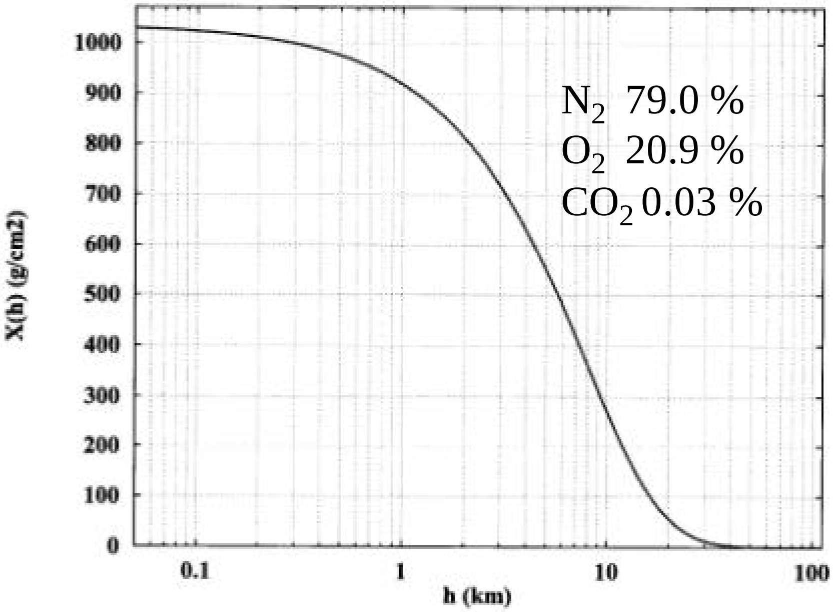
Extensive Air Shower Detection



The primary cosmic ray particle collides with air nucleus leading to a cascade of secondary particles

Detector media: Earth’s atmosphere !

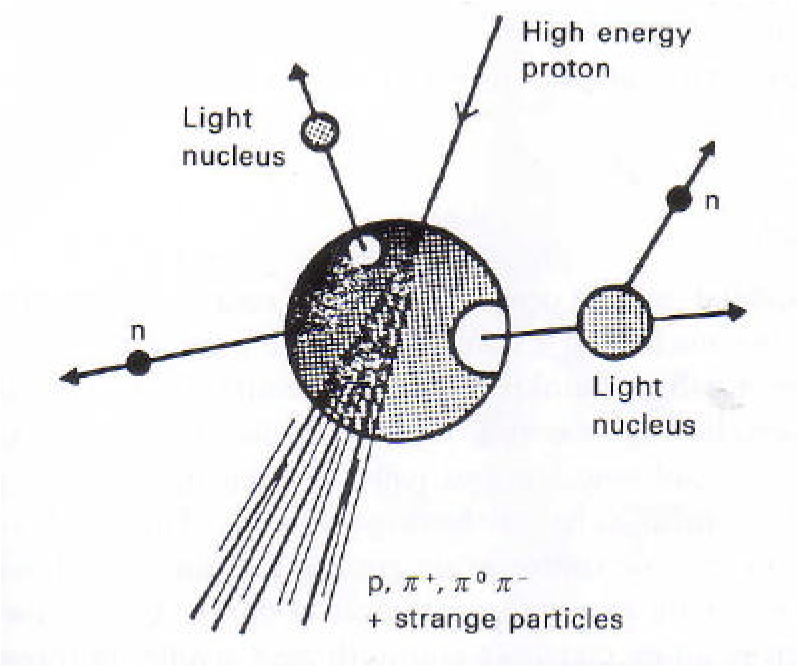
Air pressure as a function of heigth



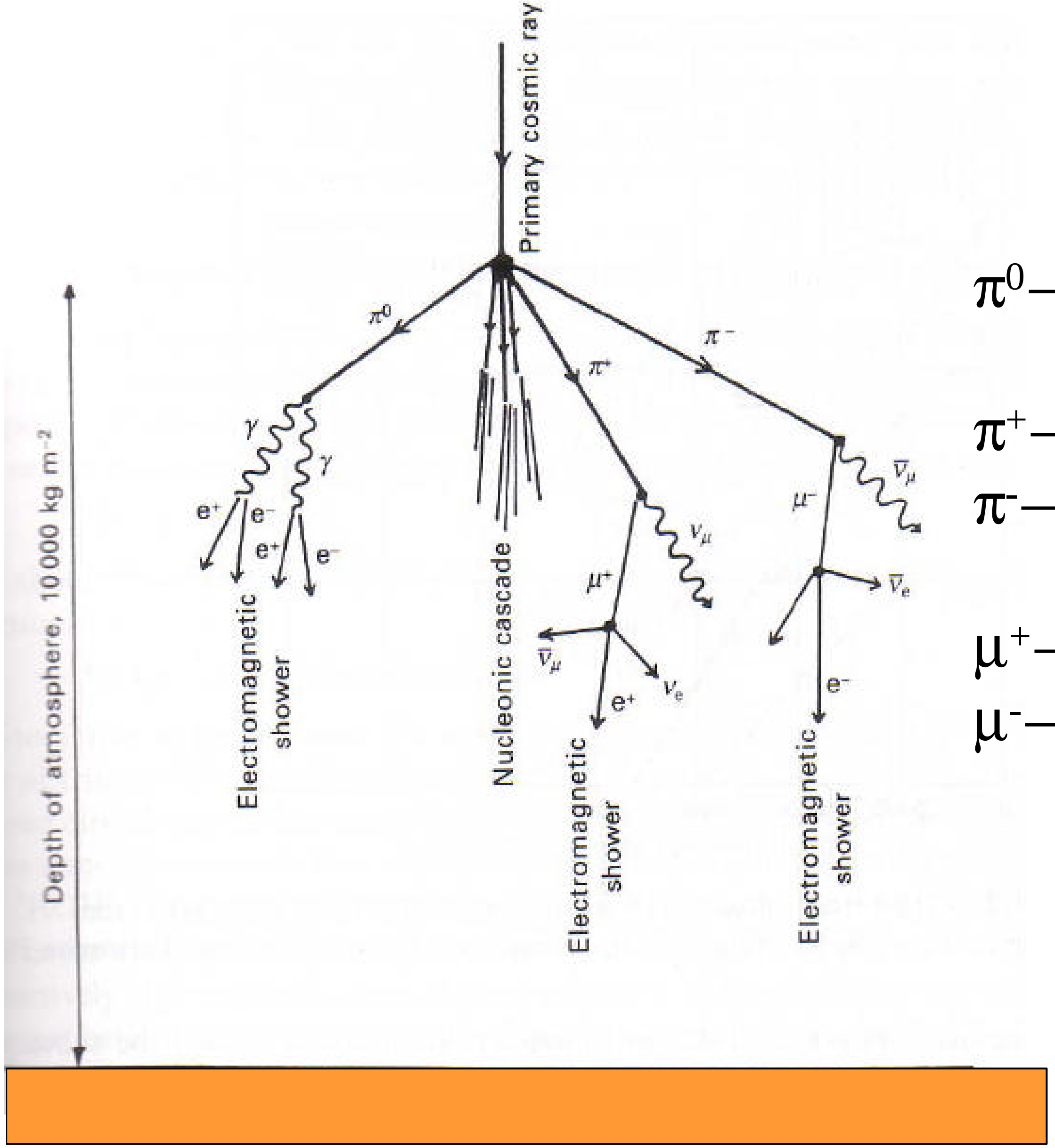
N_2 79.0 %
O_2 20.9 %
CO_2 0.03 %

Interactions of High Energy Protons with Matter

- Proton interacts with an individual nucleon in a nucleus
- Pions, π^+, π^-, and π^0 are produced together with some strange particles
- In the laboratory frame all products are very forward focused
- The pion density is some measure of the energy of the primary particle
- The remaining nucleus is left in a very highly excited, unstable state and several nuclear fragments can evaporate from the nucleus : **spallation** fragments
- The mean free path of the proton in the atmosphere is about 800 kg m^{-2} (depth of the atmosphere is 10 000 kg m^{-2})



Main Features of Hadronic Showers



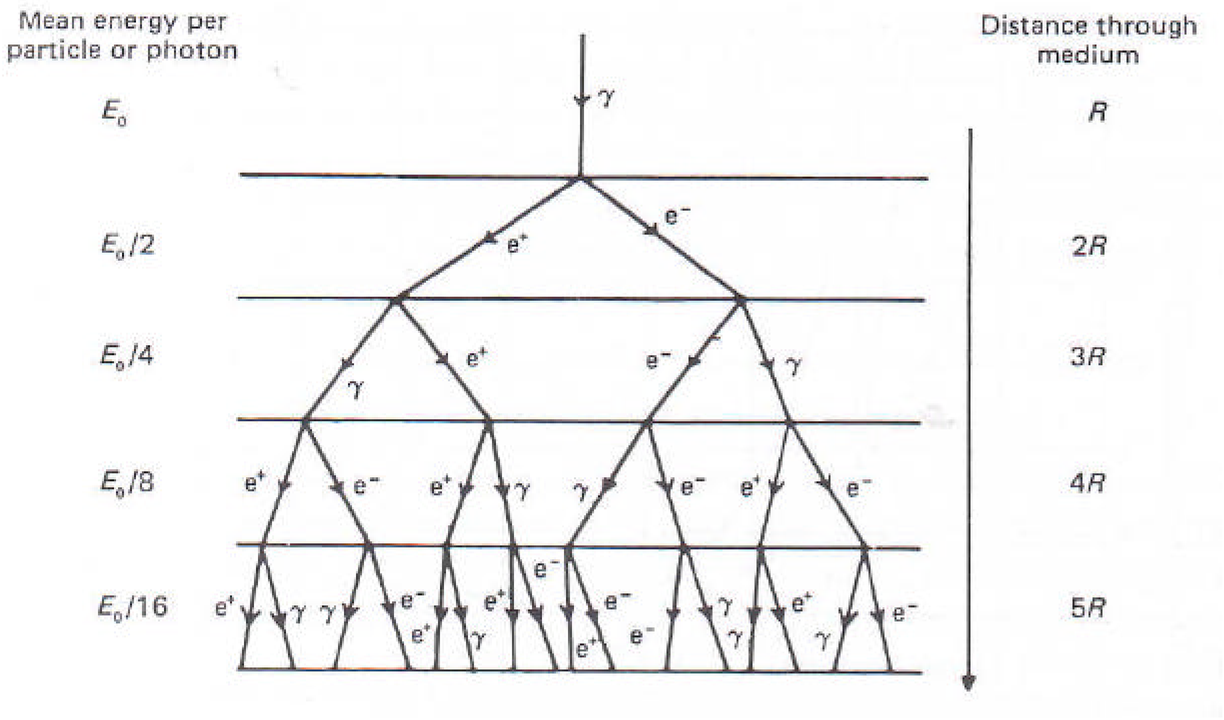
$\pi^0 \rightarrow 2\gamma$ $\quad$ $1.78\ 10^{-16}$ s

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\quad$ $2.551\ 10^{-8}$ s
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ $\quad$ $2.2001\ 10^{-6}$ s
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Interactions of High Energy Photons with Matter and EM Showers

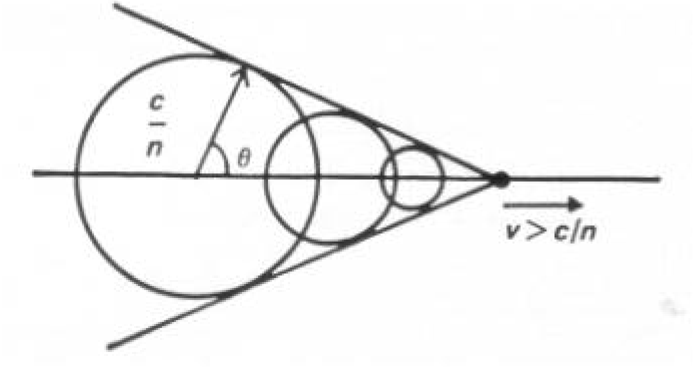
Main processes: photoelectric absorption, Compton scattering and electron-positron pair production
At high energy (above a few MeV pair production become dominant)



- ✓The initial growth is exponential
- ✓The maximum number of particles is proportional to E_0
- ✓Rapid attenuation of electron flux beyond maximum
- ✓Hadronic interactions of very high energy gammas can develop a hadronic shower

Cherenkov Radiation

Particle moves through medium at a constant velocity which is greater than the velocity of light in that medium



A shock wave is created behind the particle resulting in a energy loss

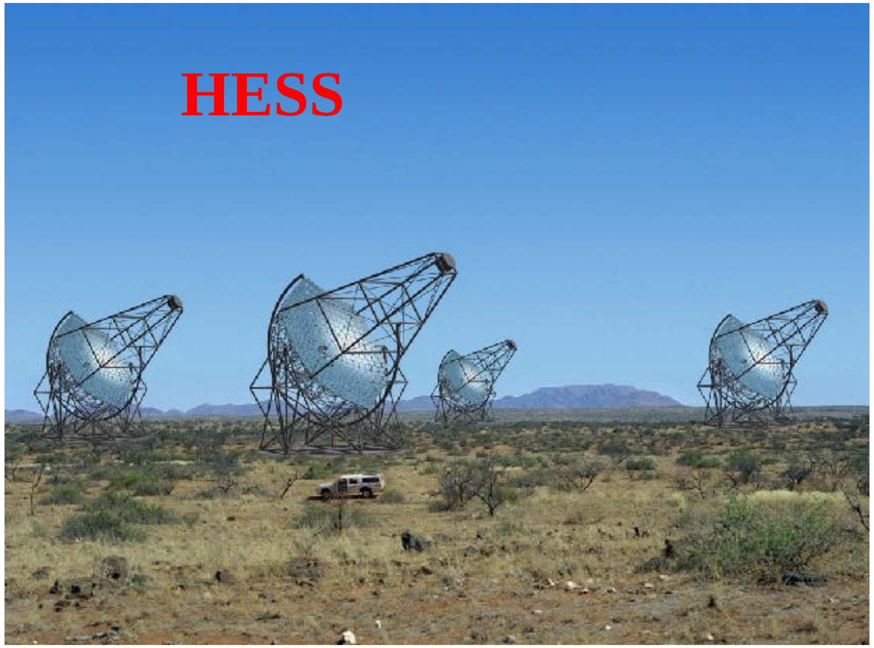
✓Cherenkov wavelength around 400 nm

✓Cherenkov light can be used to detect high-energy gamma rays when they enter on top of the atmosphere (gamma astronomie)

✓Or to detect high energy particles or photons (Cherenkov water tanks)

Cherenkov Light in the Atmosphere

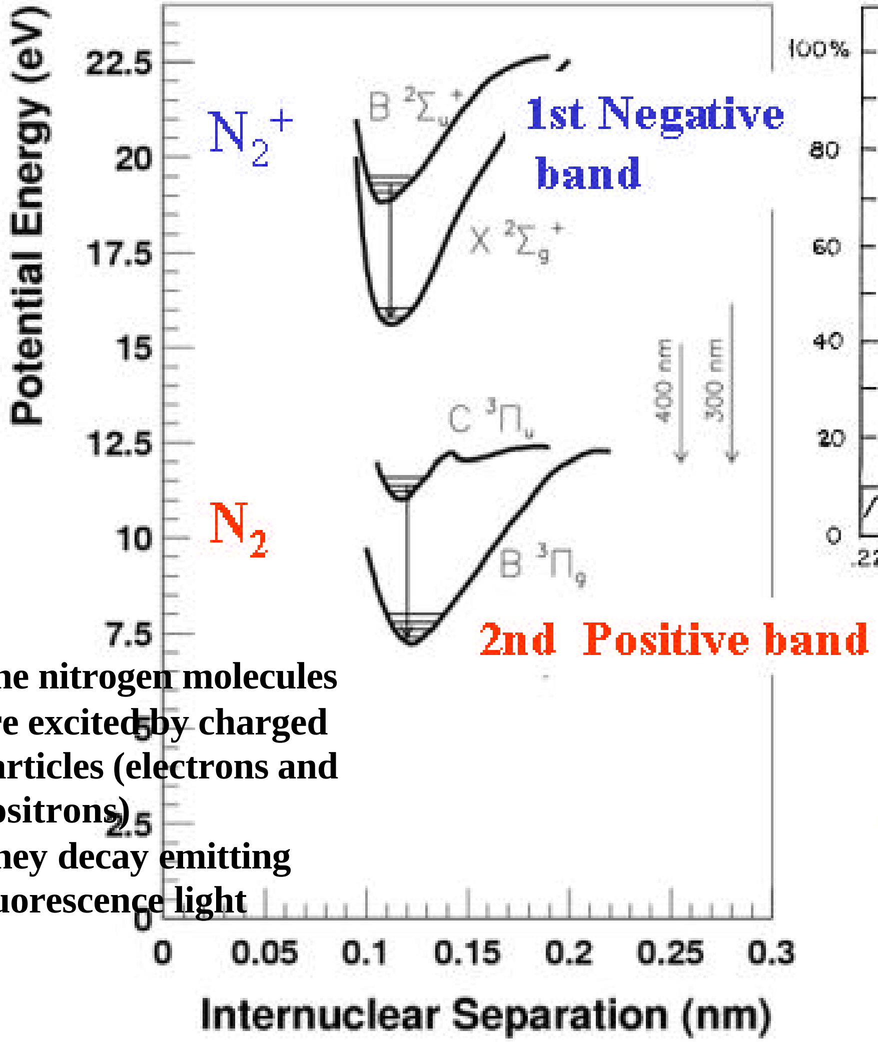
- ✓Atmosphere is transparent to light between 300 and 600 nm, Most Cherenkov light reached ground
- ✓Cherenkov photons are strongly beamed
- ✓Cherenkov photon yield initiated by cosmic ray primaries (hadrons) is significantly smaller than for yield initiated by gamma rays
- ✓Imaging technique for gamma hadron discrimination !



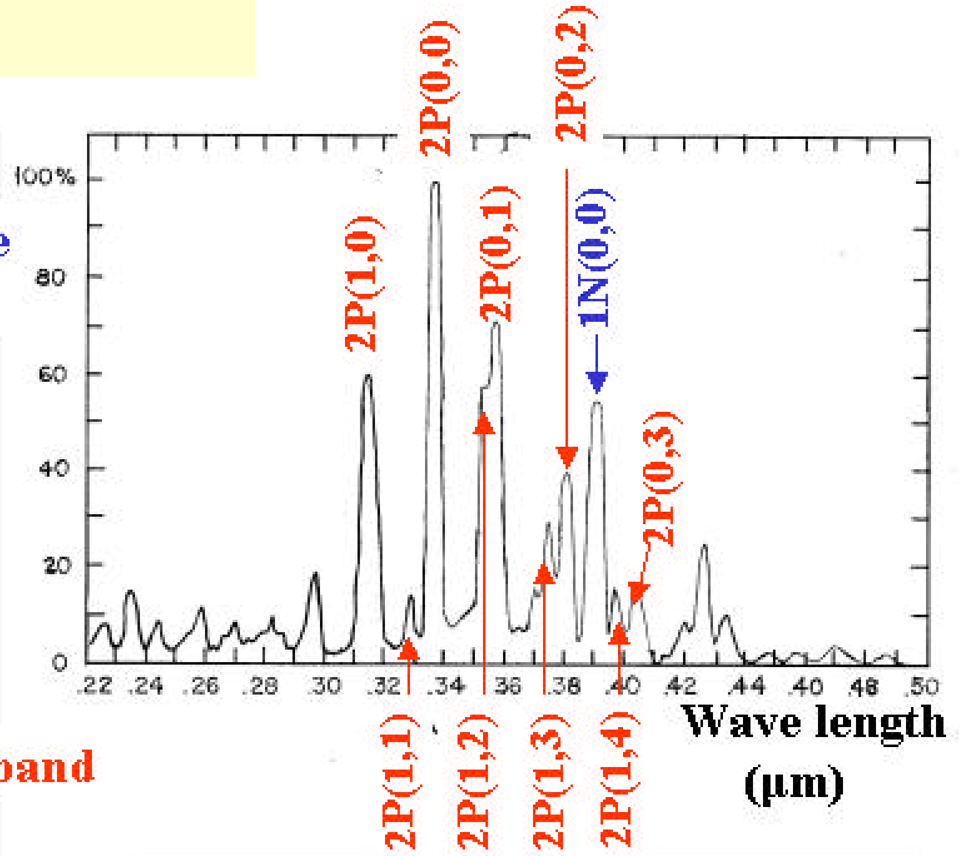
Atmospheric Cherenkov Telescopes to detect gamma rays !

Fluorescence Light

Potential energy of Nitrogen molecule and Nitrogen molecular ion



The nitrogen molecules are excited by charged particles (electrons and positrons)
They decay emitting fluorescence light

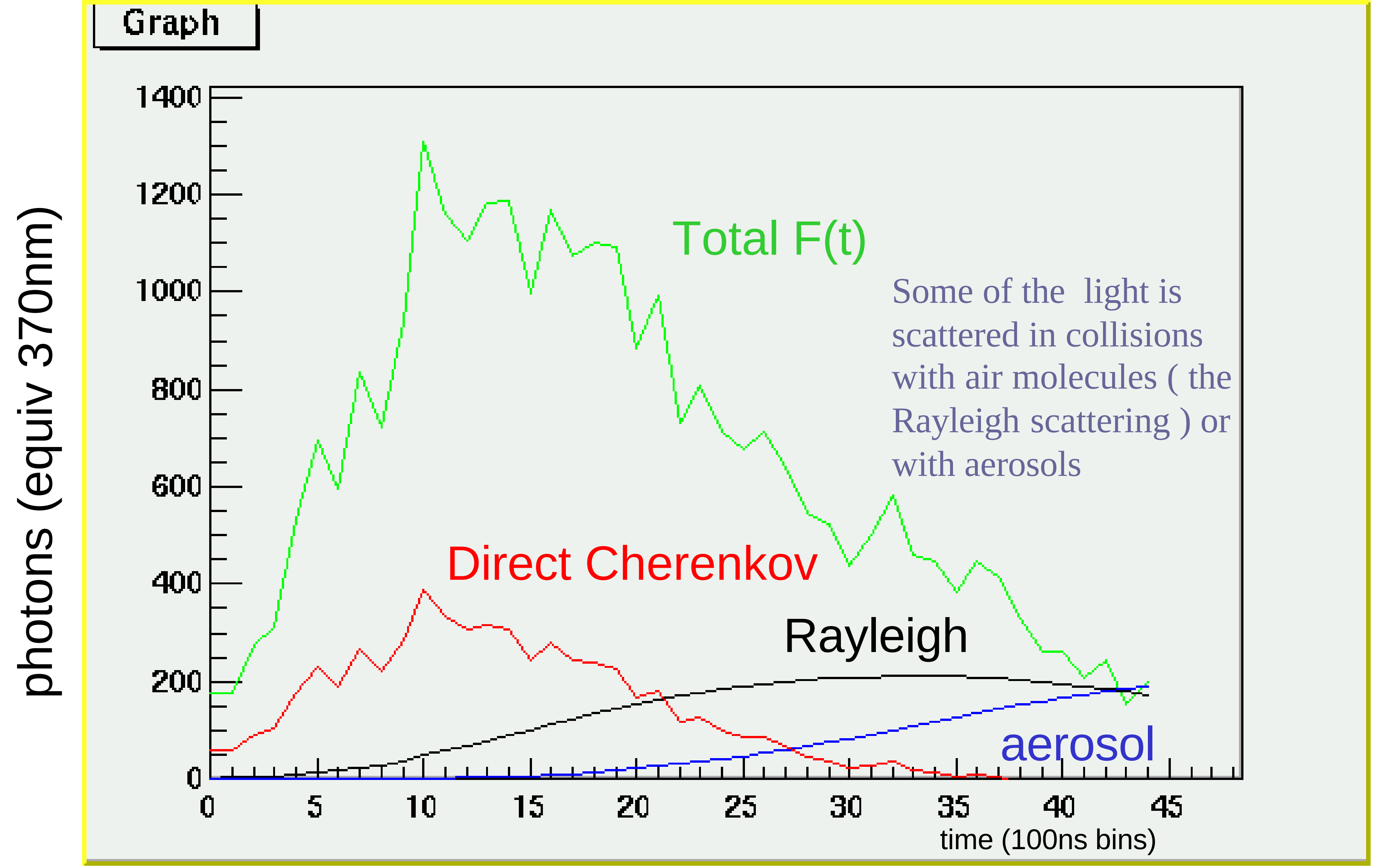


Fluorescence spectrum in air

Bunner(1964)： charged particles stopping in the air

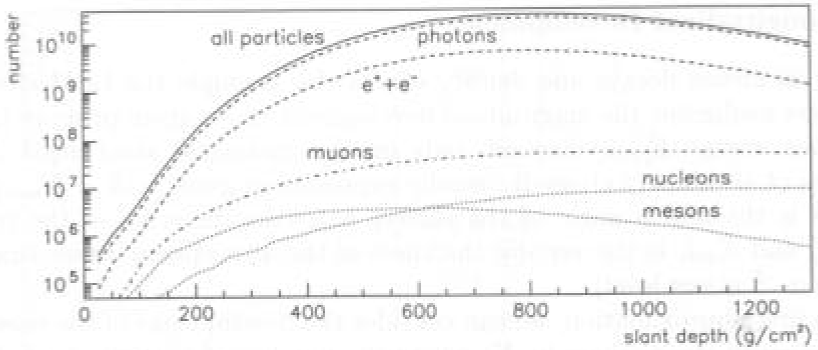
Kakimoto et al.(1996) : electrons (1.4MeV – 1000MeV)

Contamination of the Fluorescence Light

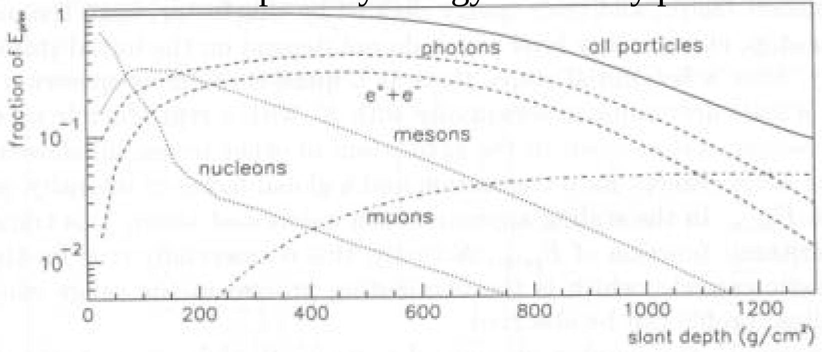


Some of the light is scattered in collisions with air molecules (the Rayleigh scattering) or with aerosols

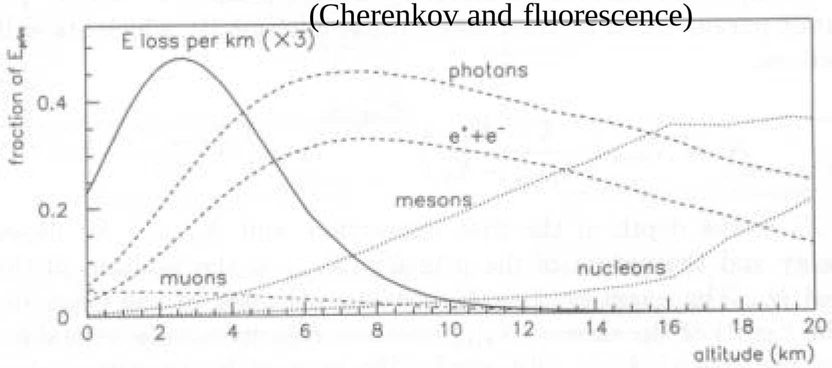
Longitudinal Development of the Shower



Fraction of primary energy carried by particles



(Cherenkov and fluorescence)



Shower induced by a proton at 10 EeV at θ = 40°

The longitudinal development depends on the cumulated slant depth X (thickness of air already crossed): $X = X_{vert}/\cos\theta$

Steps where the number of particles is multiplied by a constant factor and their energy is divided by the same factor (scaling approximation)

The number of charged particles (mainly e^+ et e^-) may be parametrized by Gaisser-Hillas function:

$$N_e = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{70}} \exp\left(\frac{X_{max} - X}{70}\right)$$

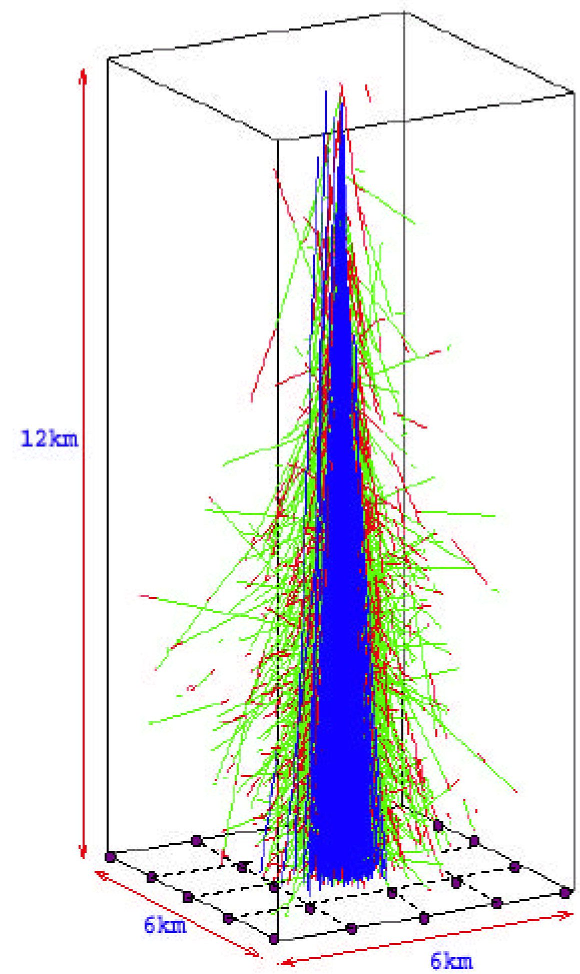
X_0 is the depth of the first interaction,
X_{max} is the position of maximum of N_e,
X-X_{max} indicates the « age » of the shower

If the primary particle is a photon or electron, the descent in energy is slower than for proton/nucleus induces showers: Xmax is larger

Primary identification !

Atmosphere as a Calorimeter

A 10 EeV Extensive Air Shower (EAS)



100 billion particles at sea level

photons, electrons (99%), muons (1%)

• Ground Array stations

The hadronic cascade (except a few nucleons) ends up with the decay of charged pions into muons at intermediate altitudes
The electromagnetic cascade goes down to energies below 1 MeV before stopping by ionisation. This is not achieved at ground level

The energy loss of the shower along the cascade is essentially deposited through low energy charged particles, only a few percent of initial energy goes into neutrinos which are mainly produced in meson and muon decays

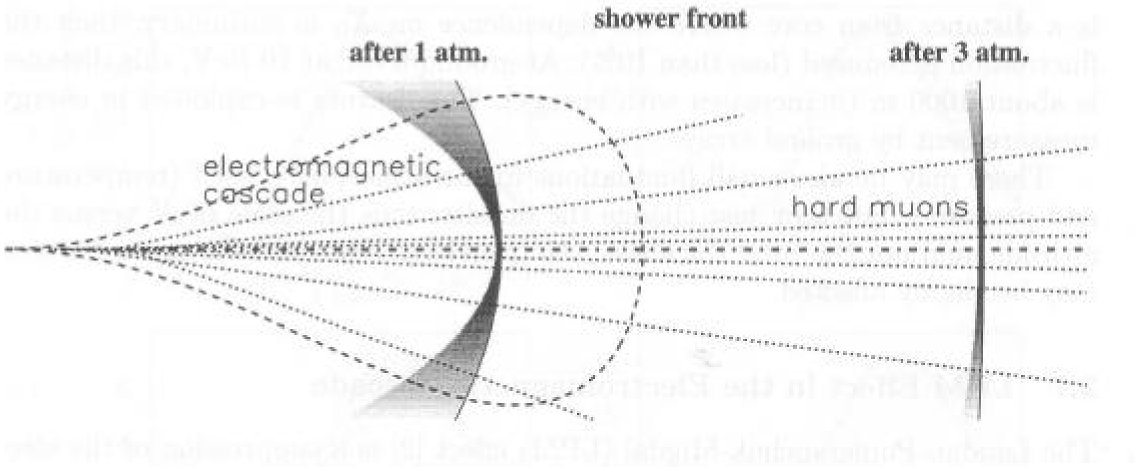
Atmosphere behaves as a giant calorimeter with good linearity !

Typical energies at ground level:
γ, e, (99%) μ (1%)

γ et e : Energy about a few MeV

μ : Energy about a few GeV

Space-Time Structure of the Shower



✓The nucleons survive down to lowest energies. However, this component is almost negligible

✓The muons and surviving pions are generally highly relativistic and very forward focused

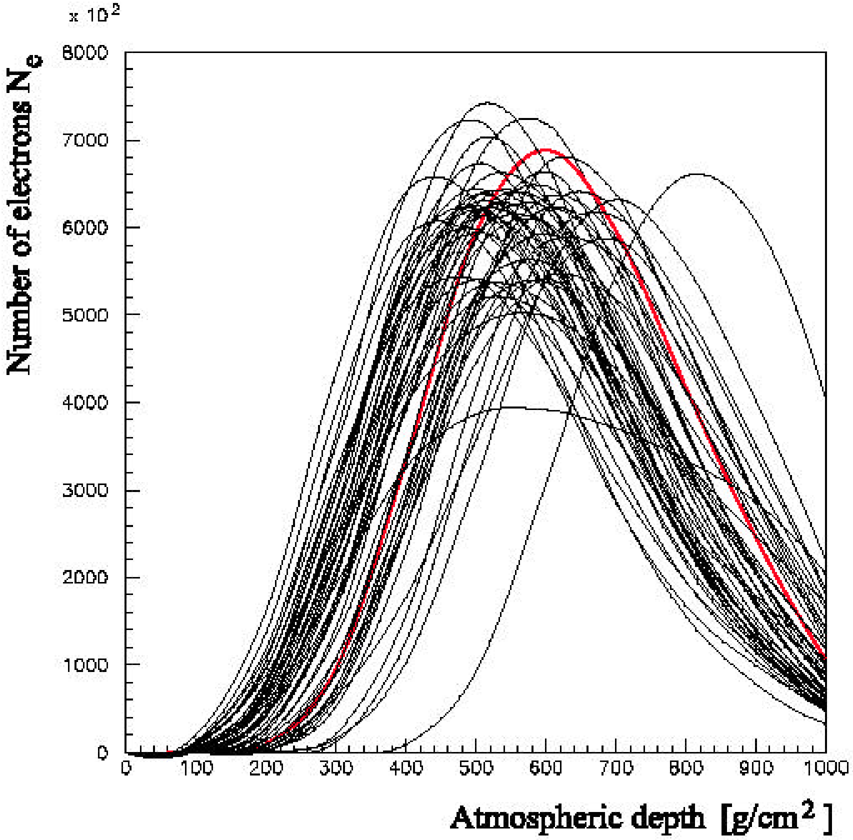
✓Electromagnetic component is a result of a diffusive process and has a larger spread

✓The shower halo is a cone, a delay of 1 µs corresponding to a longitudinal distance of 300 m

✓The muons are mostly concentrated in the front part of the shower cone

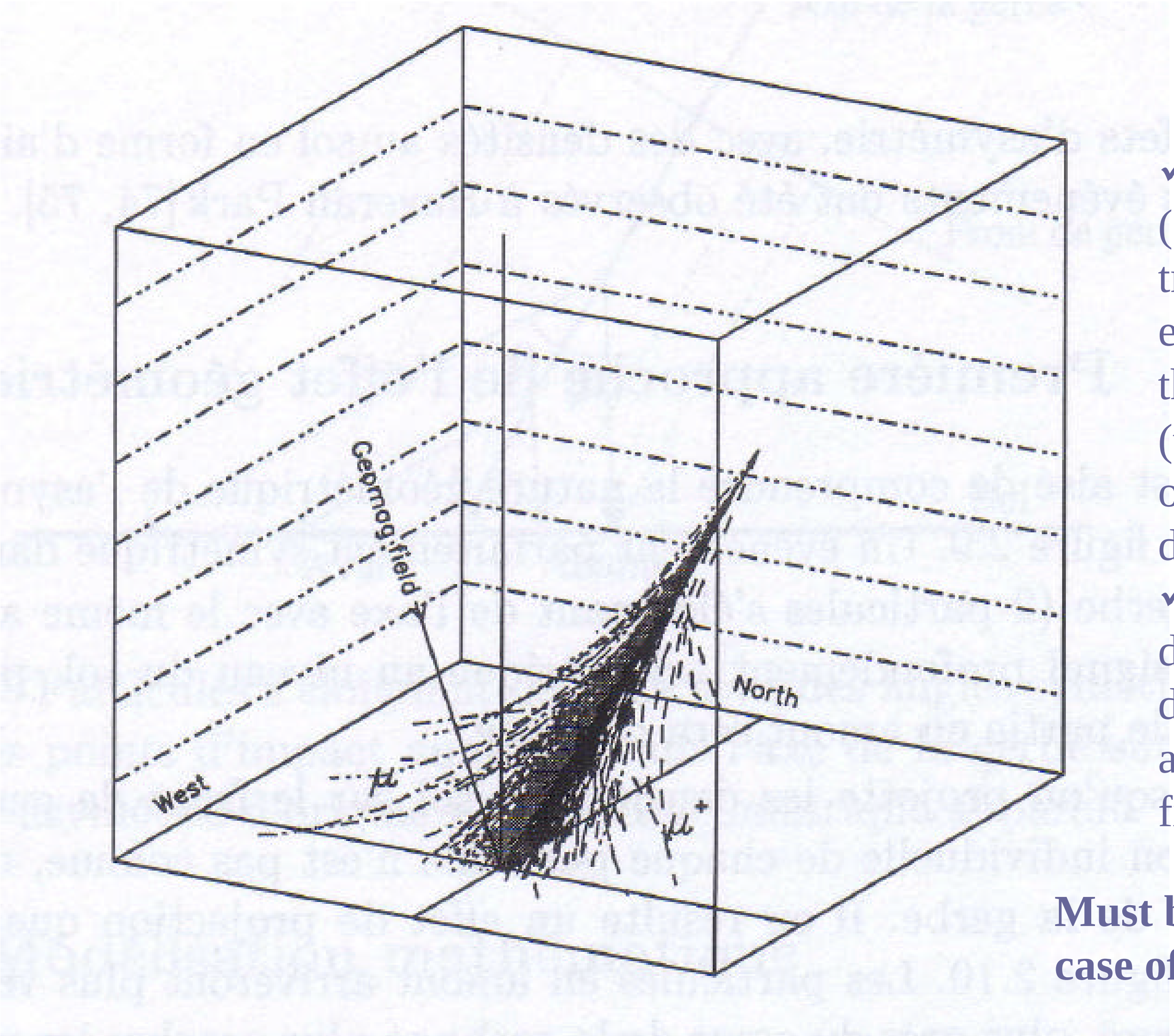
Fluctuations

Fluctuations originate mainly from the very first steps, and especially from the position X_0



The position Xmax has a fluctuation of a few 10 g cm^{-2}
The distribution of the ground particles (lateral distribution) depends on X and is also affected by the X_0 fluctuations

Effect of the Earth’s Magnetic Field



✓At large primary angles (> 60°), the distance traveled by muons is large enough to be affected by the Earth’s magnetic field (typically 50 μT): A muon of 50 GeV traveling 10 km deviates about 200 m.

✓Electromagnetic cascade develops on shorter distances and is not affected by the magnetic field.

Must be taken into account in the case of horizontal showers !

Photons: LPM Effect and Geomagnetic Field

Landau-Pomeranchuk-Migdal

- LPM effect reduces bremsstrahlung and pair production cross sections above photon energy:

$$E_{LPM} \sim \frac{X_0}{1\mathrm{m}} 10^{16}\,\mathrm{eV} \sim 3\times 10^{18}\,\mathrm{eV}\ \text{ in air}$$

⇒ very slow shower development (very large X_{max})
easy to discriminate from p,A

- Pair production on geomagnetic field will occur almost surely for $E\gamma > 10^{20}$eV if photon ⊥ B but not if // B.

Shower Simulations

To simulate atmospheric showers at high energies two programs currently used: **Aires and Corsika**

Selection algorithm, thinning

A shower with primary energy of 10^{21} eV is composed of about 10^{14} particles in the atmosphere ! → All particles cannot be followed in the simulation.

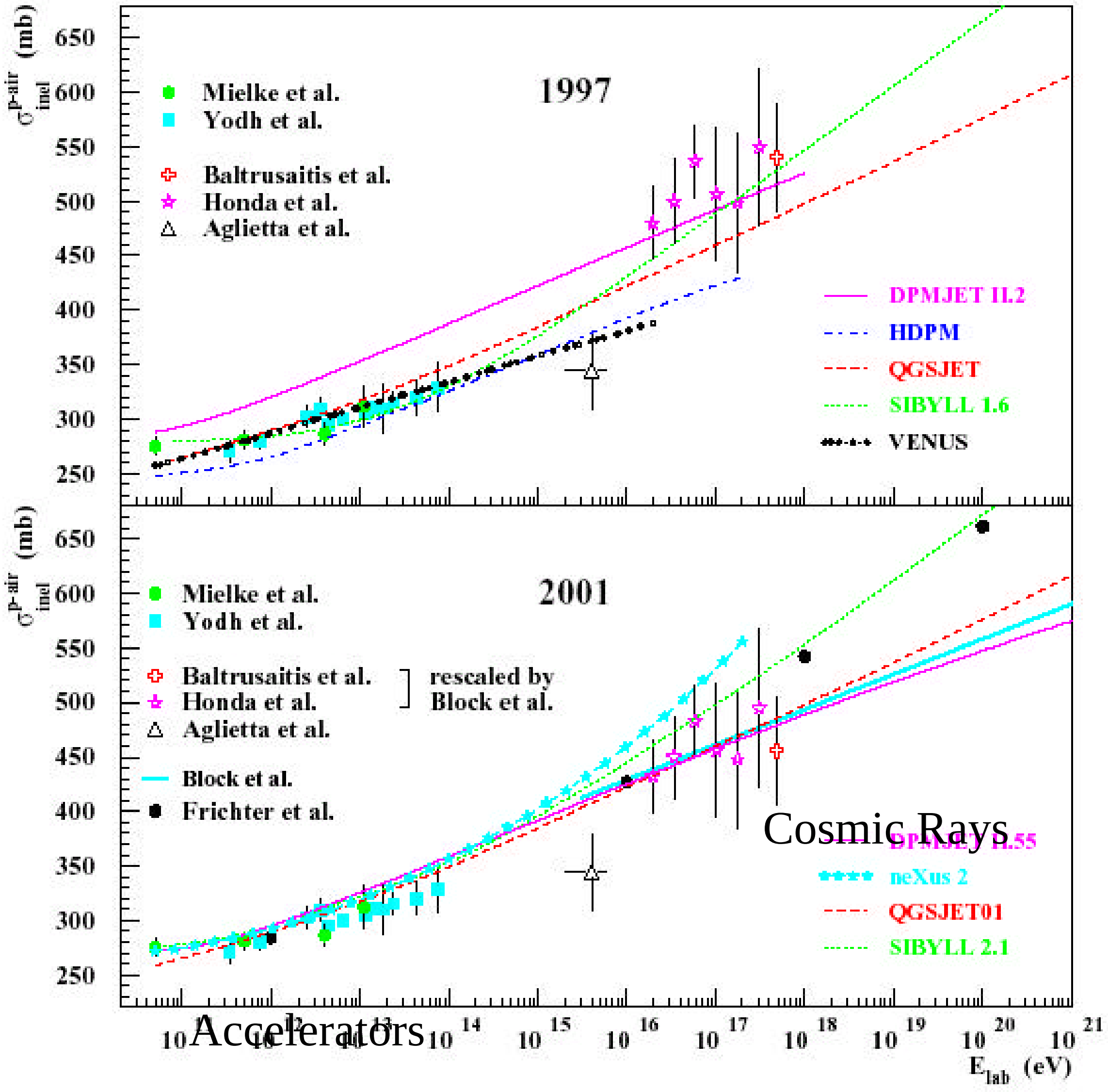
Above certain energy (selection energy) all particles are followed

Below the selection energy, only one particle is followed.

Each secondary particle has a selection probability proportional to its energy

The selected secondary particle will have an energy with a weight equal to the primary energy divided by its energy

Hadronic Interaction Models



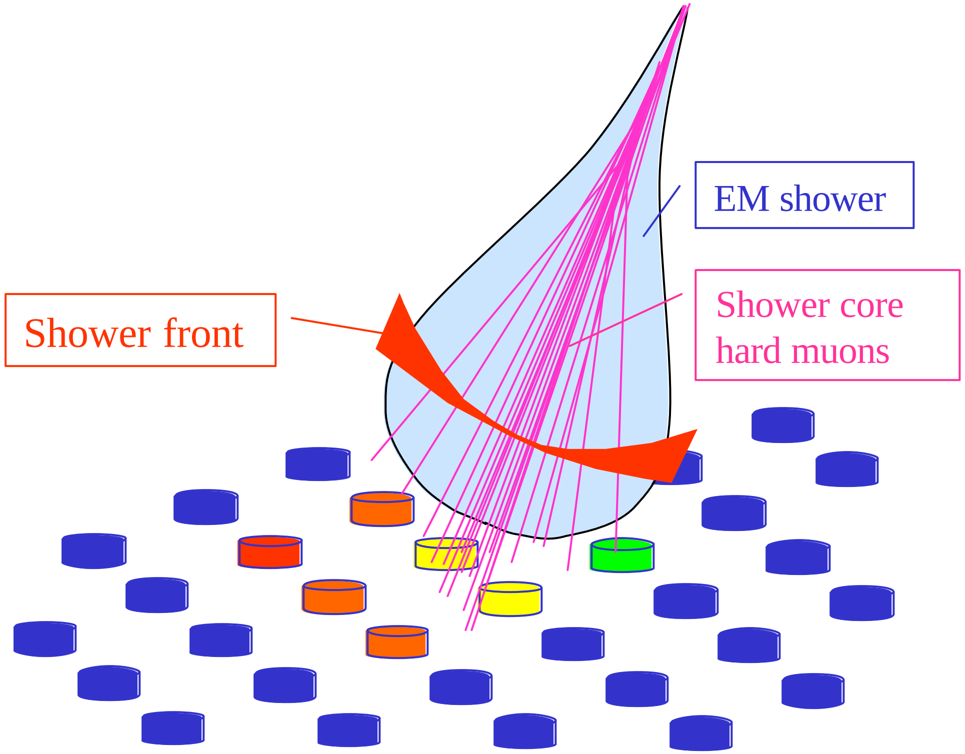
Typically two models used for high energy showers: SIBYLL and QGSJet

Extrapolations required for high energy showers !

Shower Observation Techniques

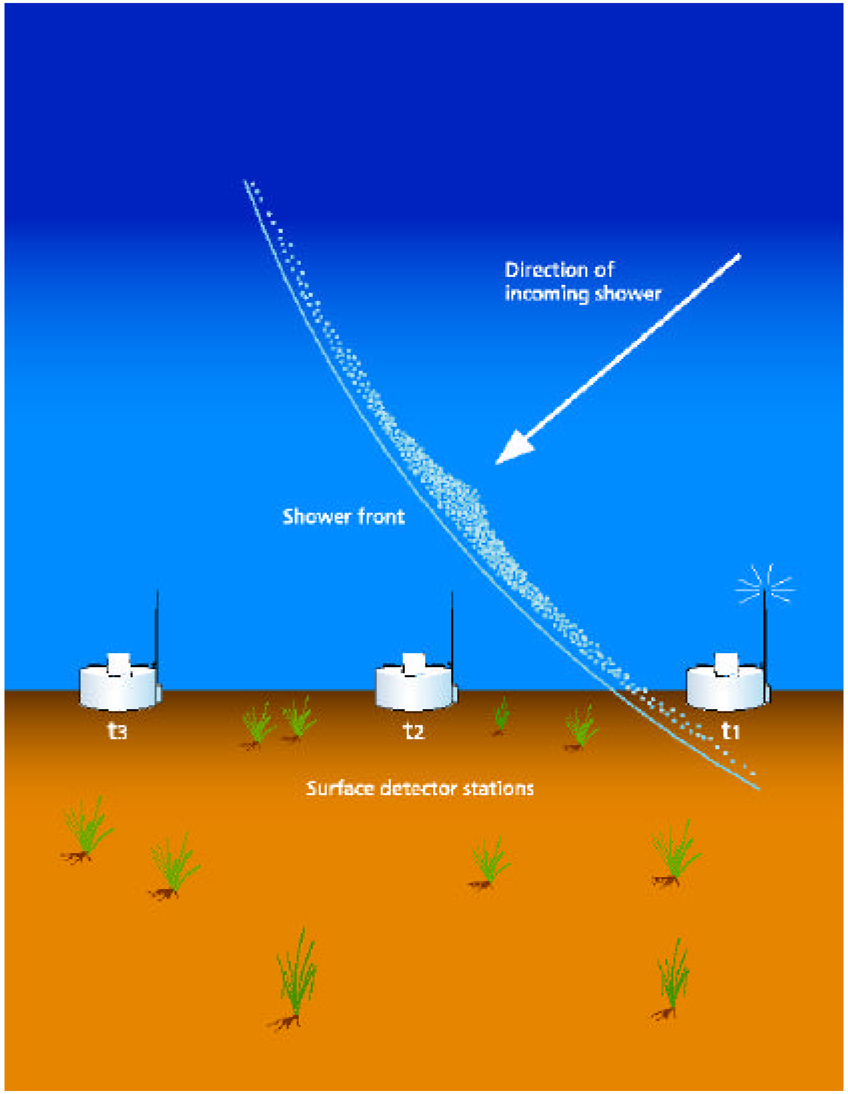
- Detection of ground particles : hadron primaries, high energy gamma rays
- Detection of fluorescence light : hadron primaries, high energy gamma rays
- Detection of Cherenkov light : gamma rays (10^{10} eV to 10^{14} eV)

Shower Observation Techniques: Detection of Ground Particles

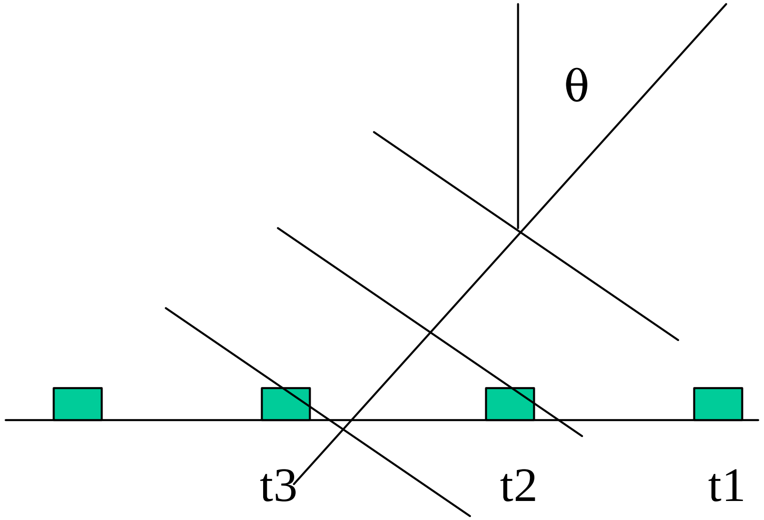


Use lateral density and time distribution together with muon/EM identification

Reconstruction of Primary Angle

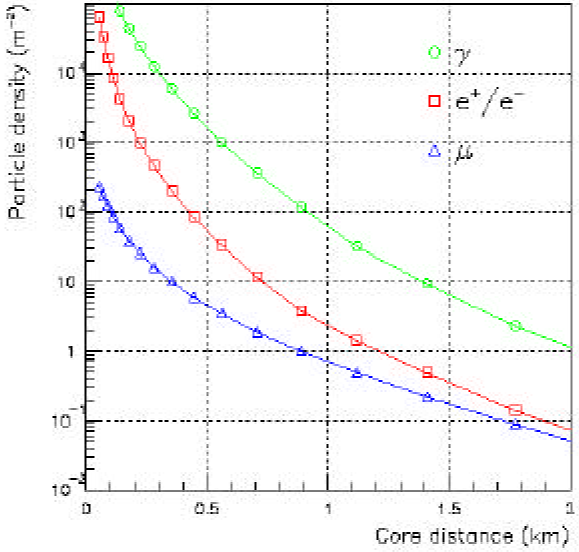


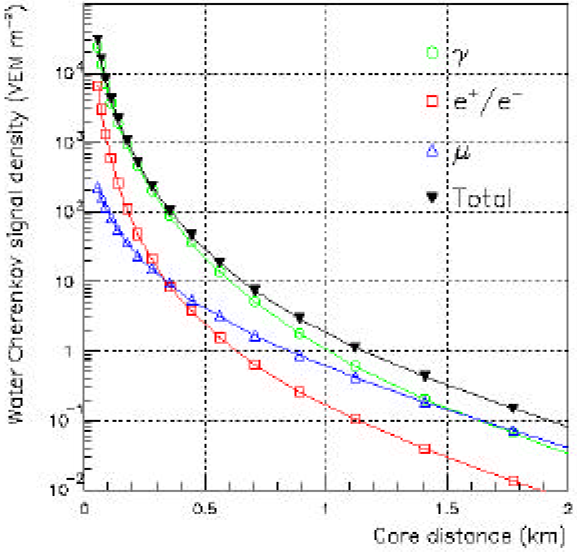
Primary angle obtained from arrival time of the shower front
$C\Delta t = d\cos(\theta)$, d is the distance between detectors projected to the shower axis

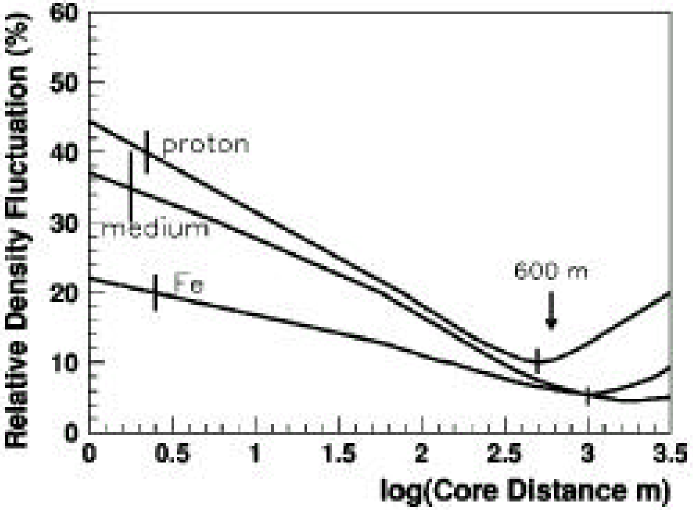


Lateral Energy Density Distributions

Lateral distributions of energy deposited vs core distance:







Lateral distributions

- Quasi-proportional to E_{prim}

  $$E_{PRIM} = \alpha \times \rho(600)^{(1+\varepsilon)}$$

- For several events: fluctuations in the 600m to 1000m range < 15%

Primary Composition

For a Nucleus: - E = A×E/A i.e. superposition of lower E showers,
- Interaction higher up in the atmosphere,

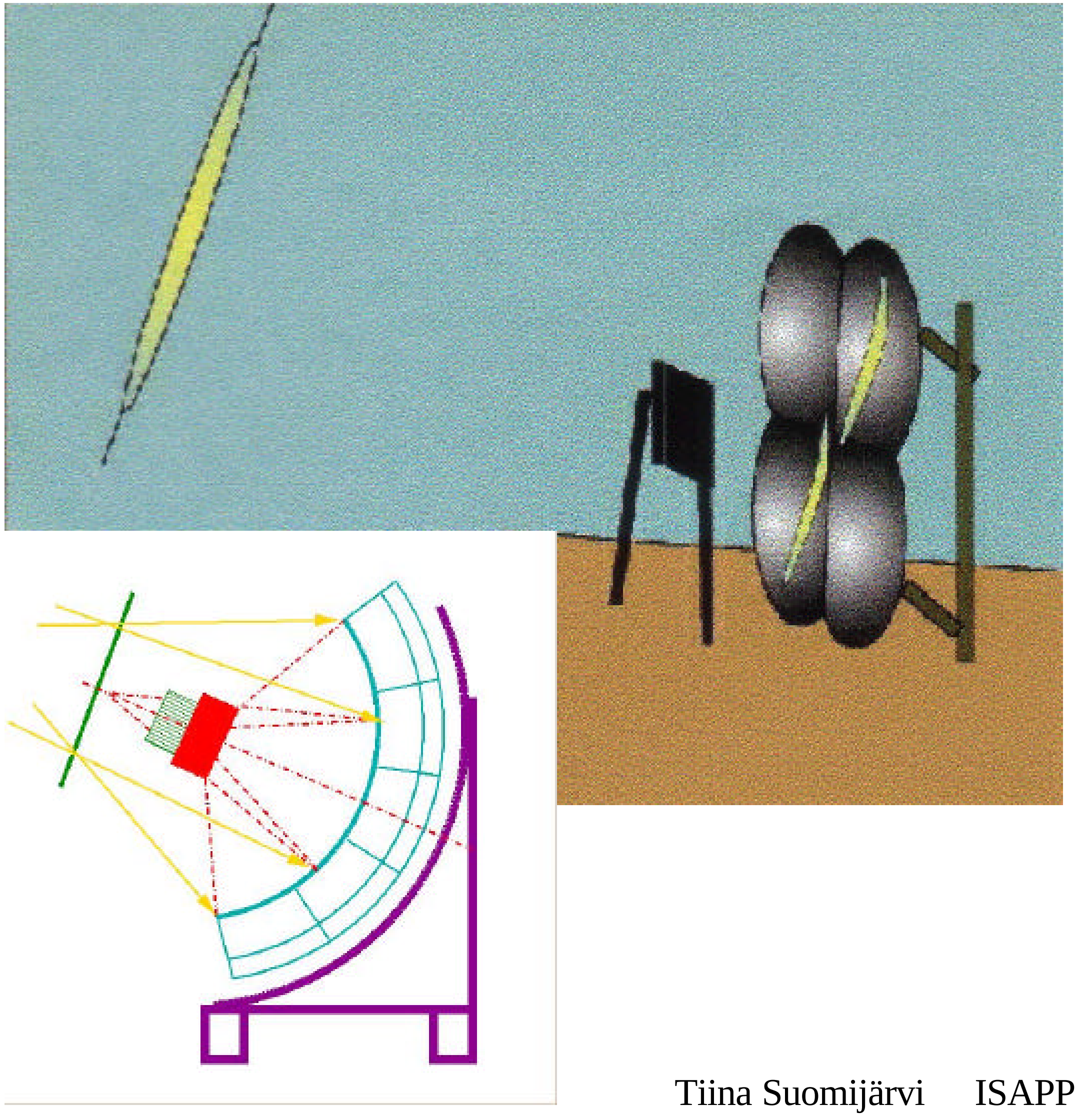
$\Rightarrow$ less cascade steps before reaching $\varepsilon_\pi \Rightarrow$ more μ's.

$\Rightarrow$ less EM energy.

$\Rightarrow$ Muon rise time (10% to 50%) is smaller

Gamma primaries separated from hadron primaries
Statistical separation of protons and heavy hadrons (Fe)

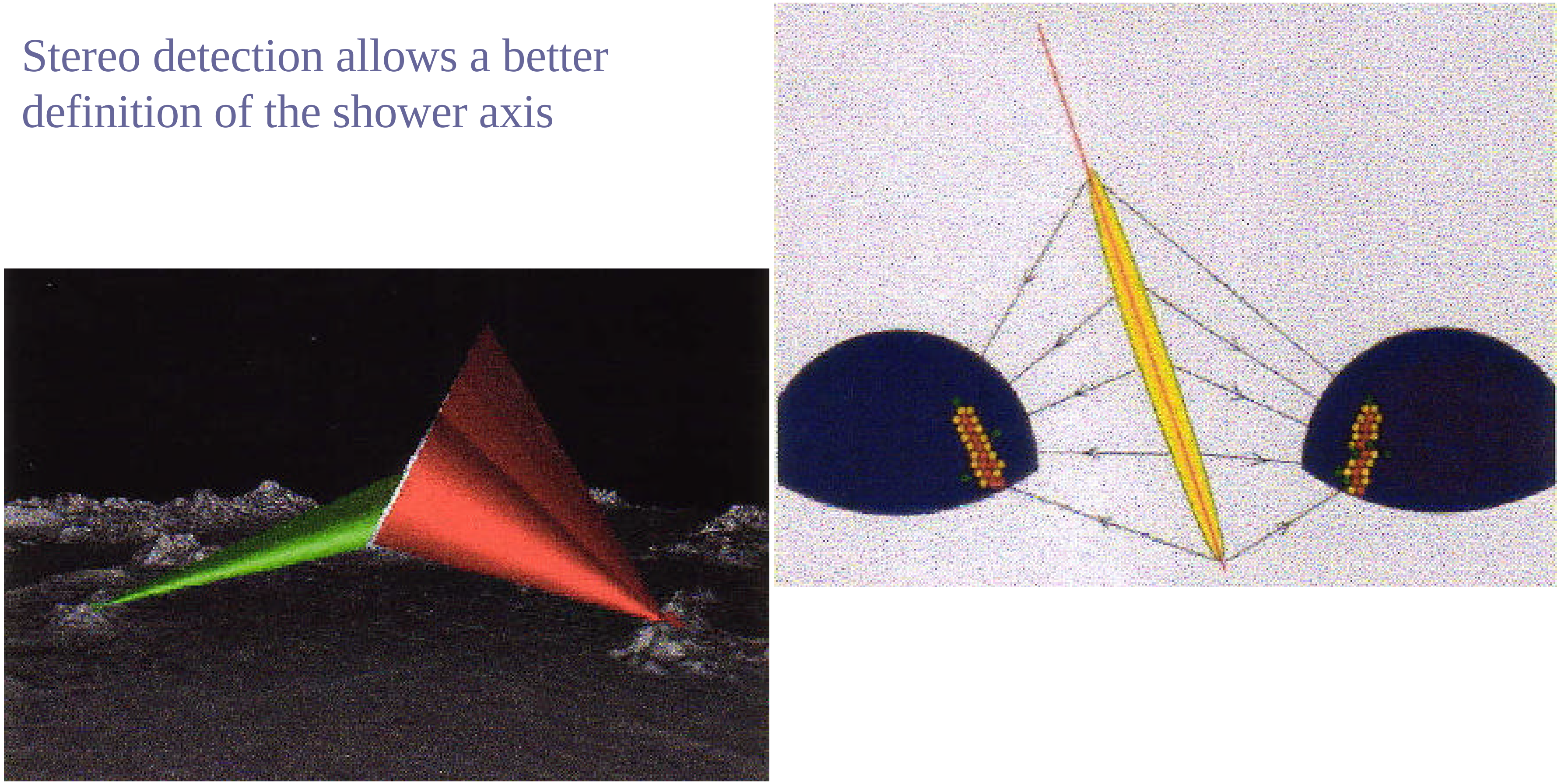
Shower Observation Techniques: Measurement of Fluorescence Light



- ✓The particle shower leaves a faint glow in its trail: like a 100 W, ultra-violet lightbulb moving at the speed of light
- ✓This flash light lasts only a few millionths of a second
- ✓This faint glow can be seen by extremely fast, sensitive electronic cameras on clear, moonless nights

Stereo Detection

Stereo detection allows a better definition of the shower axis

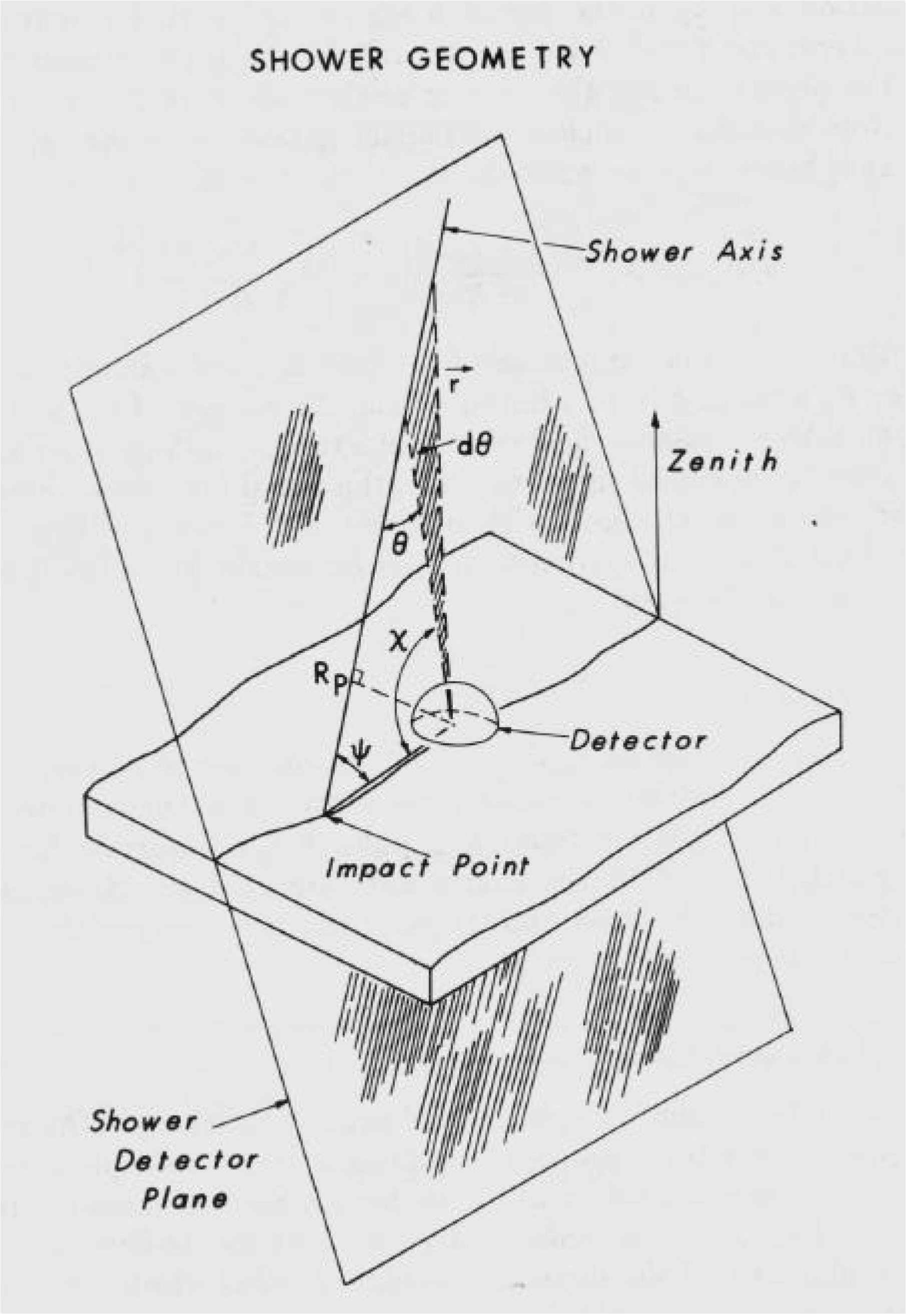


Shower Geometry

- Monocular detectors: time fit

$$t_i = t_o + \frac{R_p}{c}\tan\left(\frac{\pi-\psi-\chi_i}{2}\right)$$

- determine ψ, R_p and t_o
- Need long tracks
- Stereo detection and hybrid detection allow to better define the shower geometry



Primary Energy

EM shower energy is ~90% of E_{prim}

Compensate for atmospheric attenuation and Cherenkov contribution.

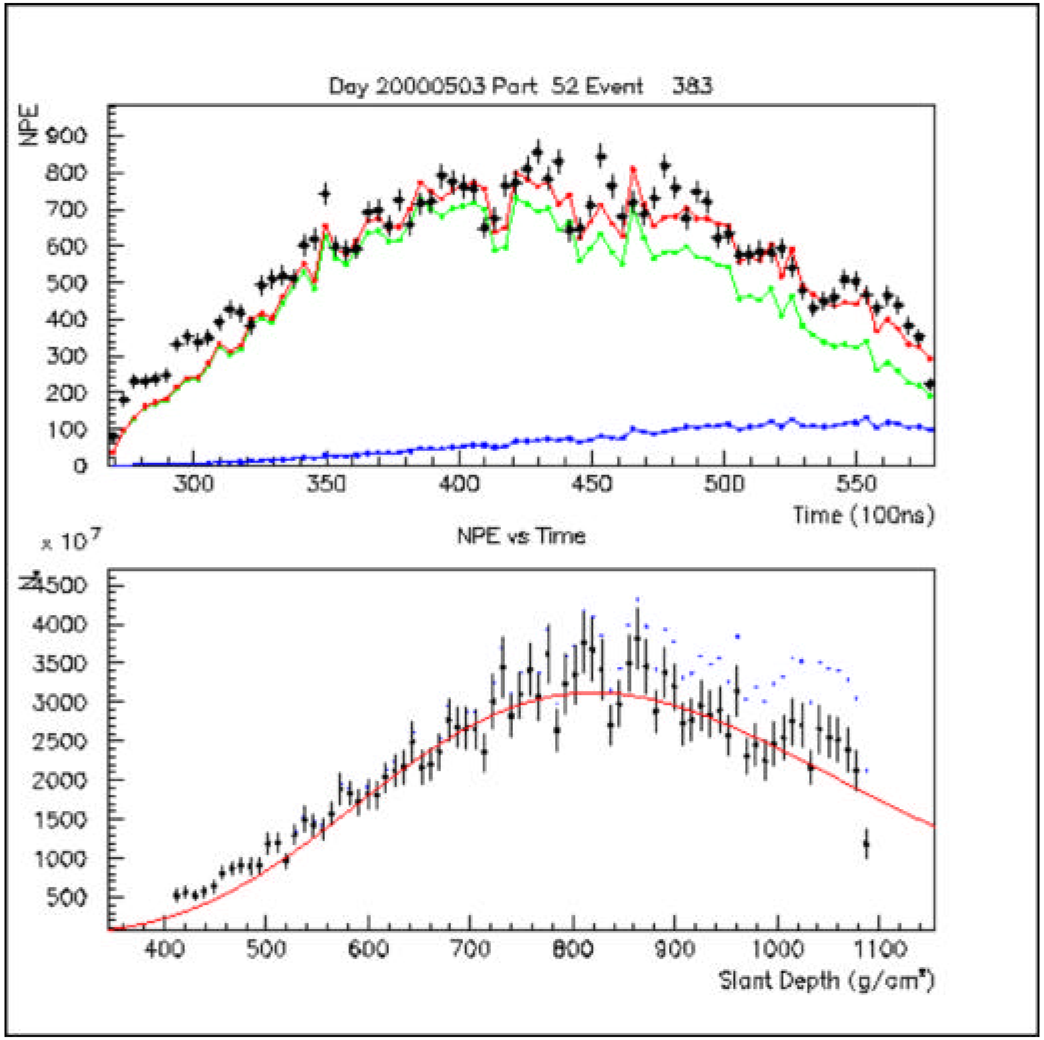
PMT light yield after corrections $\propto N_e \propto E_{EM} \propto E_{prim}$.

The measurement of atmospheric attenuation important !

Cherenkov Correction

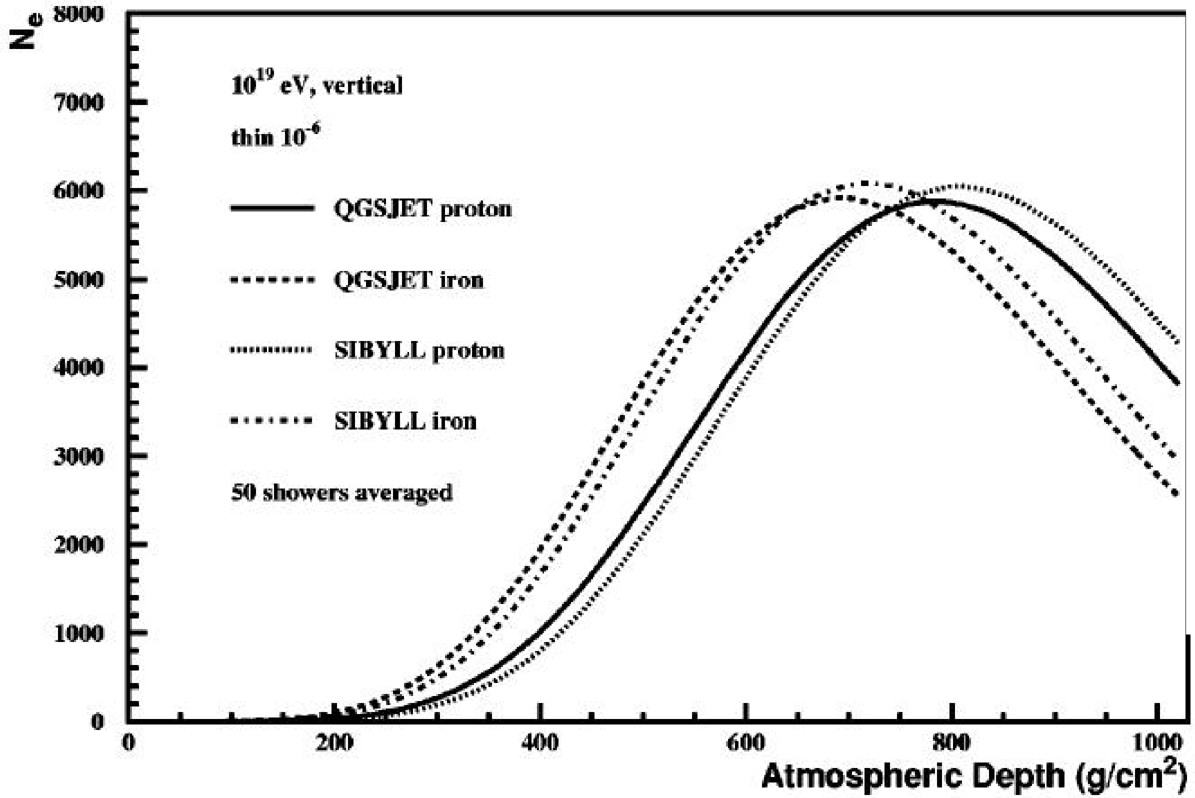
- Observed NPE (points) together with predicted NPE from final GH fit: green-fluorescence, blue-Cerenkov, red-total

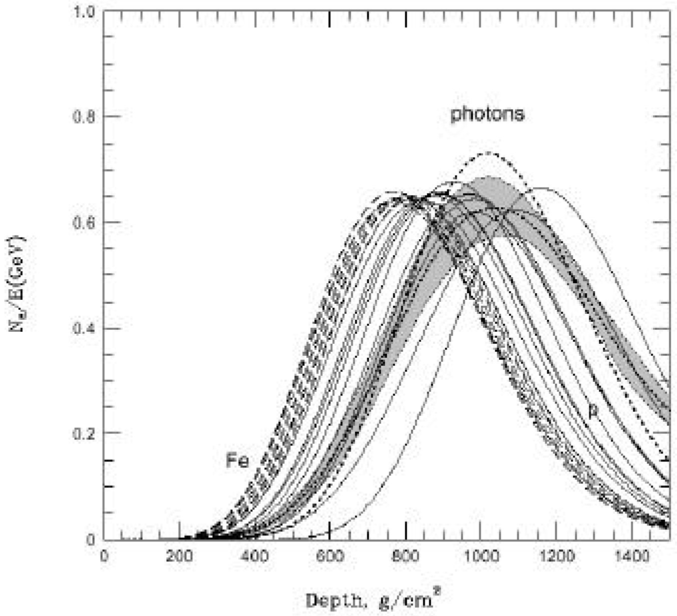
- Shower size initially (blue) and after Cerenkov correction (black) along with GH fit



Primary Composition

Xmax is smaller for heavy particles





- ✓ p and Fe separated by ~ 100g/cm^2
- ✓ Large fluctuations → statistical discrimination, not event by event.