Simulation of Multi-muon Events from EAS at Shallow Depths Underground

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First Arctic Workshop on Cosmic Ray Muons,
Sodankylä, Finland, 24-29 April 1999

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Introduction

Why GEANT?

- a good tracking tool including:
  - energy loss
  - multiple scattering
  - decays
- two hadron packages (tuned at accelerator energies):
  - GHEISHA - optimised below 50 GeV; needs extensive modification at higher energies
  - FLUKA
- muonic interactions simulated up to 10 TeV - useful for cosmic ray studies
  - decay in flight
  - ionisation and δ-ray production
  - multiple scattering
  - bremsstrahlung
  - direct (e^+e^-) pair production
  - nuclear interactions

The Method - I

Started with a study of the hadronic component of EAS:

D.Bourilkov, S.Petrov and H.Vankov, "Low Energy Threshold Calculations of EAS with Primary Energy 10^{13} - 10^{15} eV",
Journal of Physics, **G17**(1991)1925.

GHEISHA below 30 GeV
program ARROW based on accelerator
data/extrapolations for higher energies

The Method - Cross Sections

Total and elastic hadron-nucleon cross sections

Use experimental data for πN, KN, pN, $\bar{\mathrm{p}}$N, nN and $\bar{\mathrm{n}}$N ("Total Cross Sections for Reactions of High Energy Particles", vol. 12a,b, 1987, ed. H.Schopper)

available up to $\mathrm{p_{lab}}$ = 200-400 GeV

extrapolation to higher energies:

use experimental data for $\sigma_{\mathrm{p\bar{p}}}$,
available up to $\sim 10^{15}$ eV

Nuclear cross section:

$$\sigma(\mathrm{A}) = 1.25 \cdot \sigma_{\mathrm{tot}}(\mathrm{proton}) \cdot \mathrm{A}^{\alpha}$$

$$\alpha(\text{particle type, energy})$$

The Method - Multiplicity

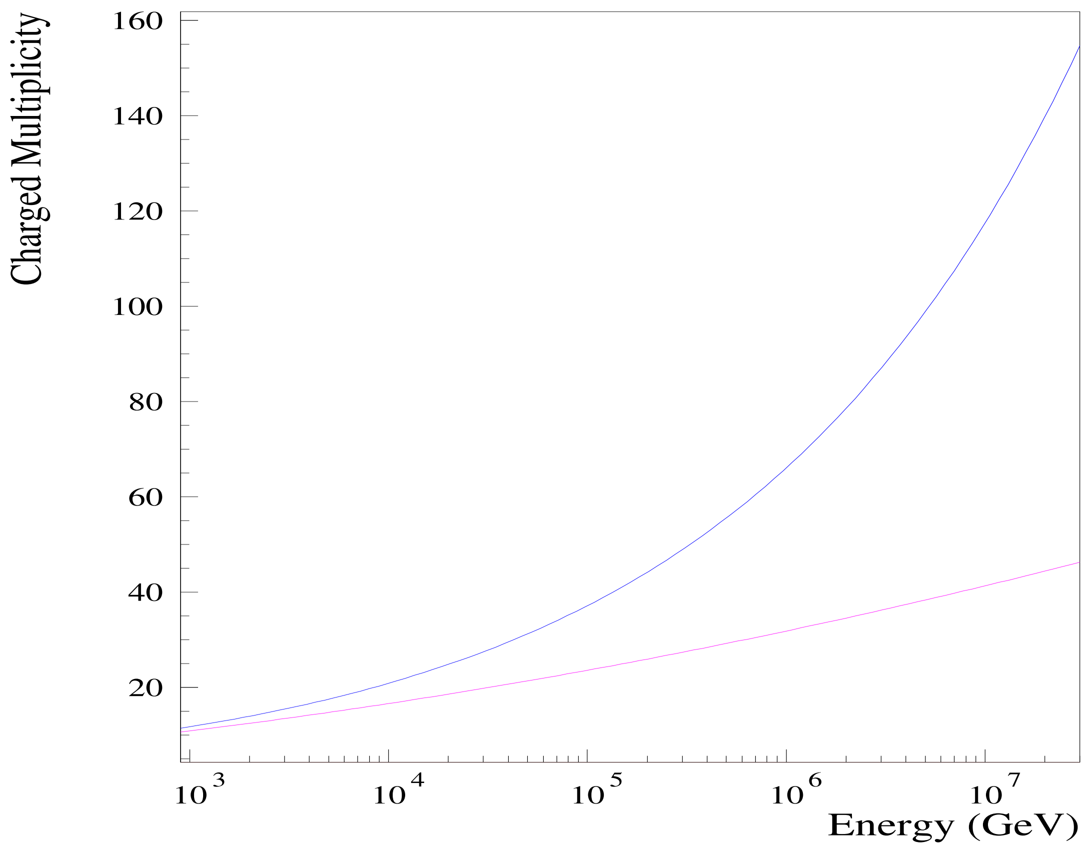
Charged particle multiplicity (with KNO scaling):

from fit to experimental data
(W.Thomé et al., Nucl.Phys., **129**(1977)365.)

$$\bar{\mathrm{N}}_{\mathrm{ch}} = 0.88 + 0.44\ \mathrm{lnS} + 0.118\ (\mathrm{lnS})^2$$

or (to check extremes)

$$\bar{\mathrm{N}}_{\mathrm{ch}} = 2.09\ \mathrm{E}_{\mathrm{lab}}^{1/4}$$



The Method - Generation of secondaries

Greatest influence on the development of the hadronic shower

1. Generate the leading particle

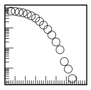
$$(x\frac{d\sigma}{dx})_A = A^{\alpha(x)}(x\frac{d\sigma}{dx})_{A=1} = A^{\alpha(x)}(1-x)^n$$

$$n(\text{particle type} : \pi, K, N)$$

$$\alpha(x) = 0.74 - 0.55\,x + 0.26\,x^2$$

(D.Barton et al., Phys.Rev.,**D27**(1983)2580.)
for p with E=10-1000 TeV - $\bar{x}_{\text{leading}} \sim 0.25-0.30$ (explicit scaling violation)

2. 4-momenta of the other particles are generated using clustering invariant variables (à la GHEISHA)



The Method - Earth's atmosphere

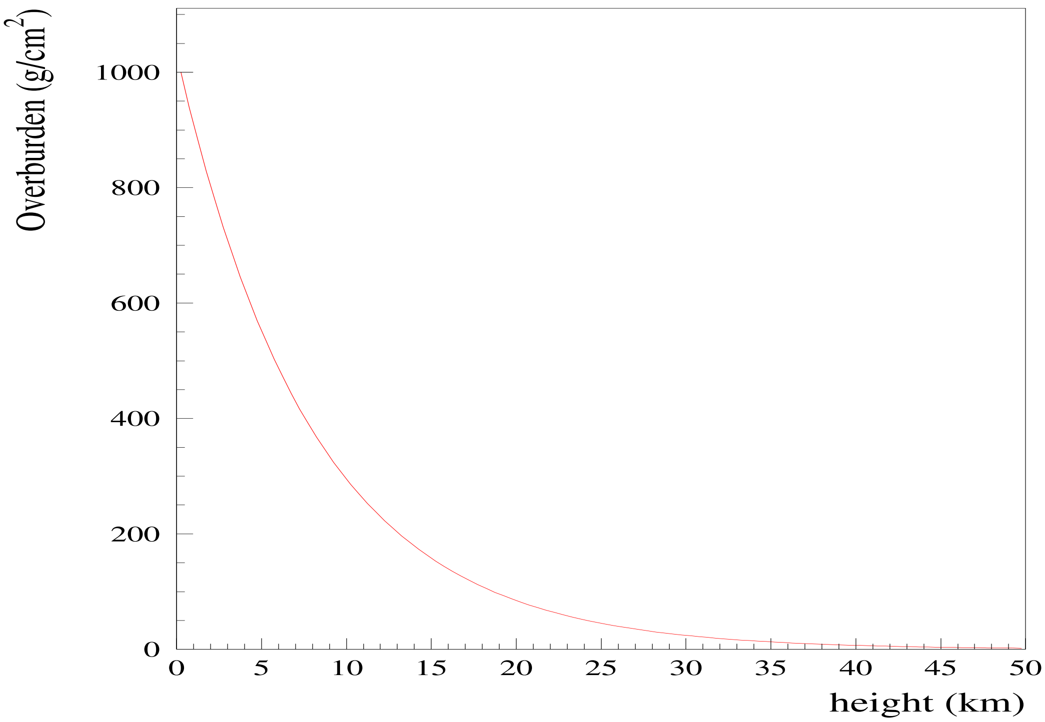
Earth's atmosphere: GEANT defines *only* volumes with constant density

Define a *TUBE* 40 km long, radius = 3 km (for 0^{o})

L3: altitude 420 m - 982 g/cm^2

Divide atmosphere in 30 layers of 32.73 g/cm^2 each

Add a layer of earth (28.75 m thick), the L3 magnet coil and return yoke in the last volume

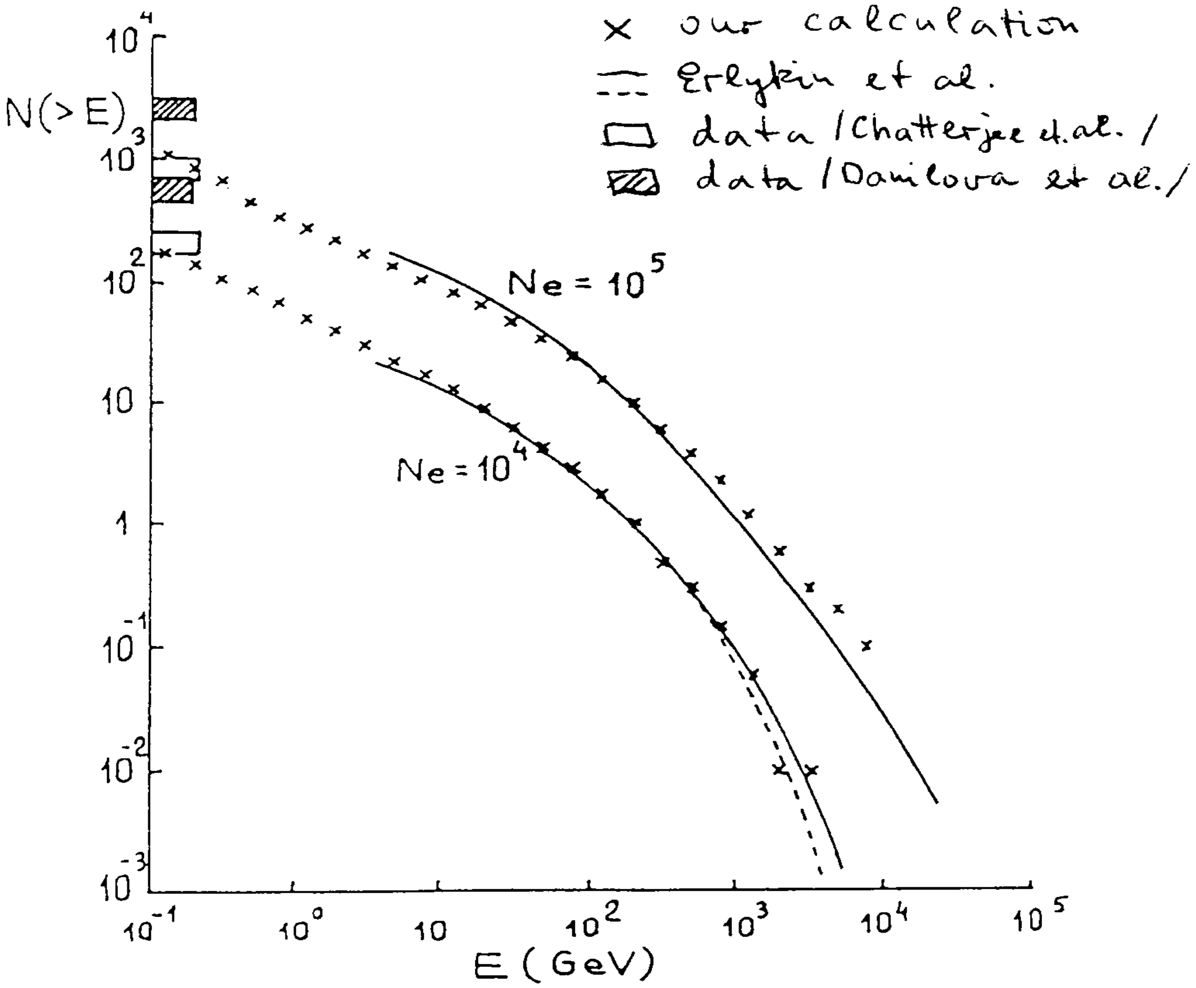


The Hadronic Component of EAS

Calculations with complex composition of the primary nuclei - compared with other calculations and data (mountain level - 690 g/cm^2)

Showers fall at fixed angle $\Theta = 22^{\circ}$

Primary energy chosen to give $N_e = 10^4$ or $N_e = 10^5$ respectively (E_o = 43 or 300 TeV)

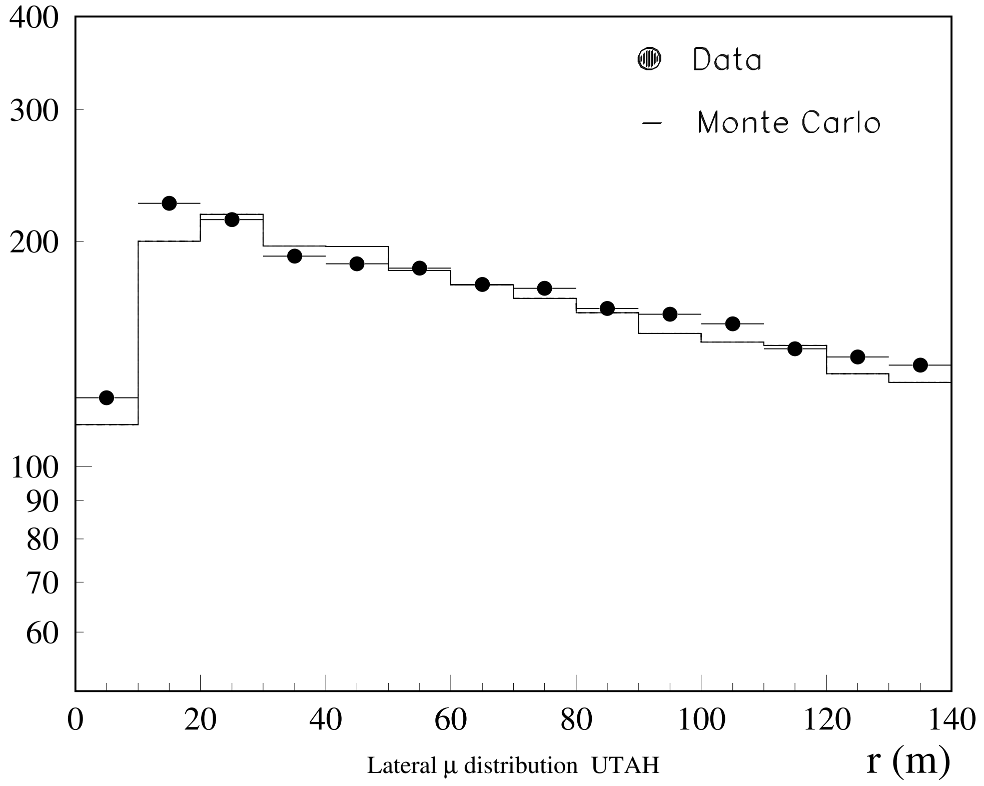


Data from the Utah shower aray - muons in showers with $5.00 < \log_{10}N_e < 5.25$ and within 5^o of vertical (D.Ciampa et al., Phys.Rev., **D42**(1992)3248)

Calculations with complex composition of the primary nuclei (Utah level - 870 g/cm^2)

Showers fall at fixed angle $\Theta = 3^o$

Primary energy (E_o = 500 TeV) chosen to give $\log_{10}N_e \sim 5.11$



Muon Calculations for L3

Vertical showers initiated by protons or iron

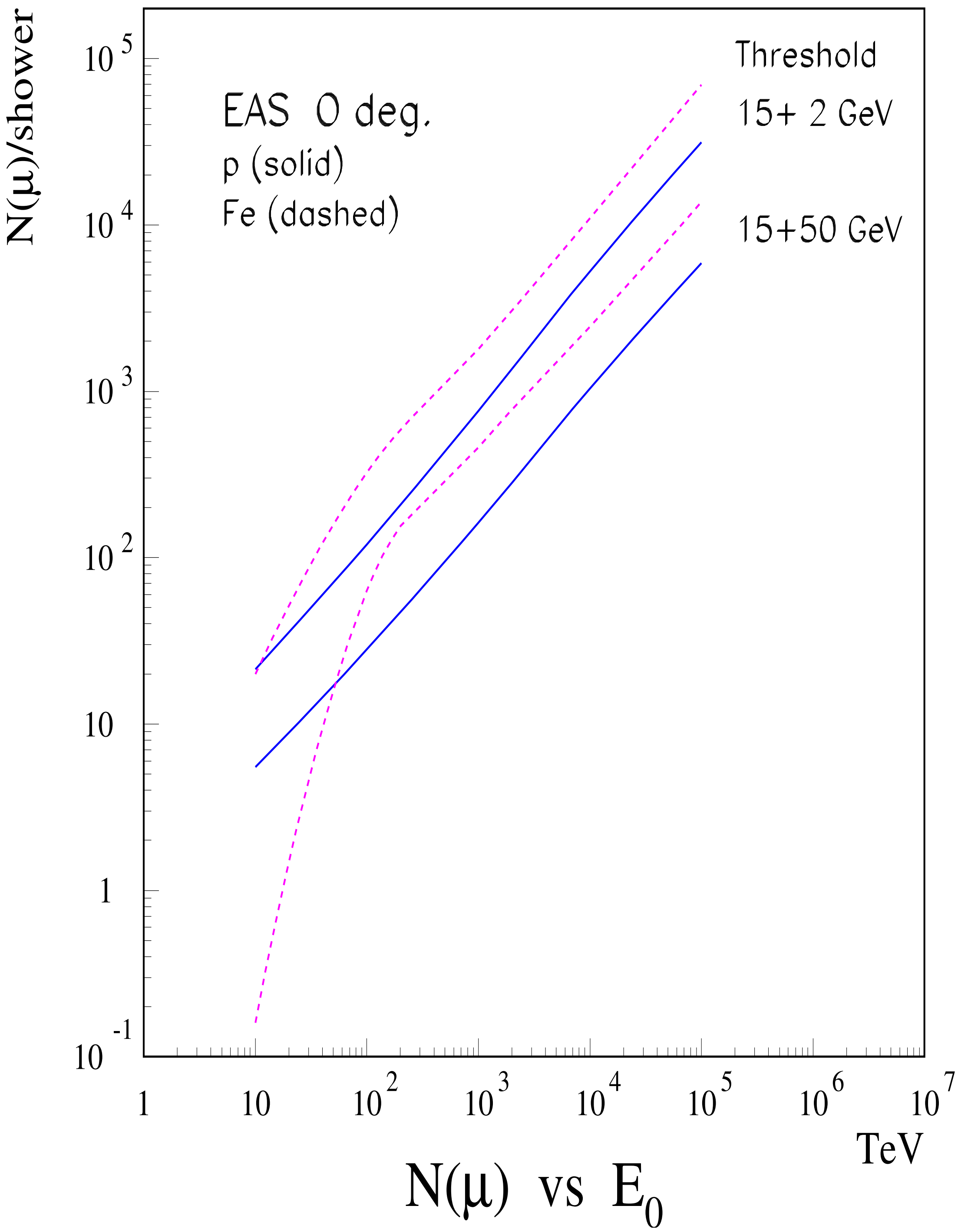
Energy (TeV)	Proton	Iron
	CPU s/shower	
10	4	21
100	52	204
1000	197	876
10000	770	1663
100000	4700	10224

Variation of $\bar{x}_{\text{leading}} \sim 0.25 - 0.30$ changes the muon flux by less than 10 %

Going to extremely high multiplicities changes the muon flux by $\sim$ 20 % for protons at 1 PeV

Number of Muons

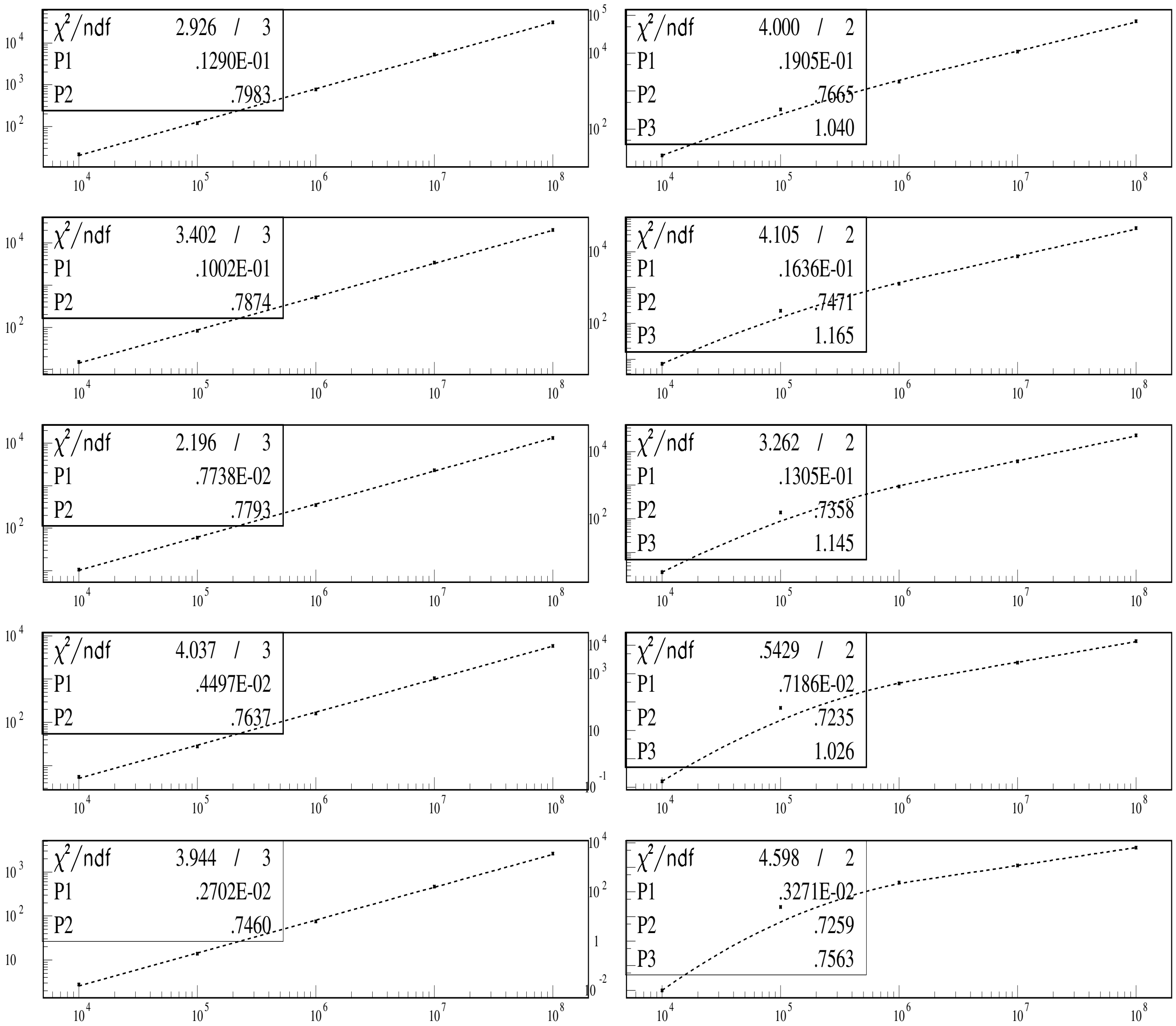
Results for E_0 10, 100 TeV, 1, 10, 100 PeV



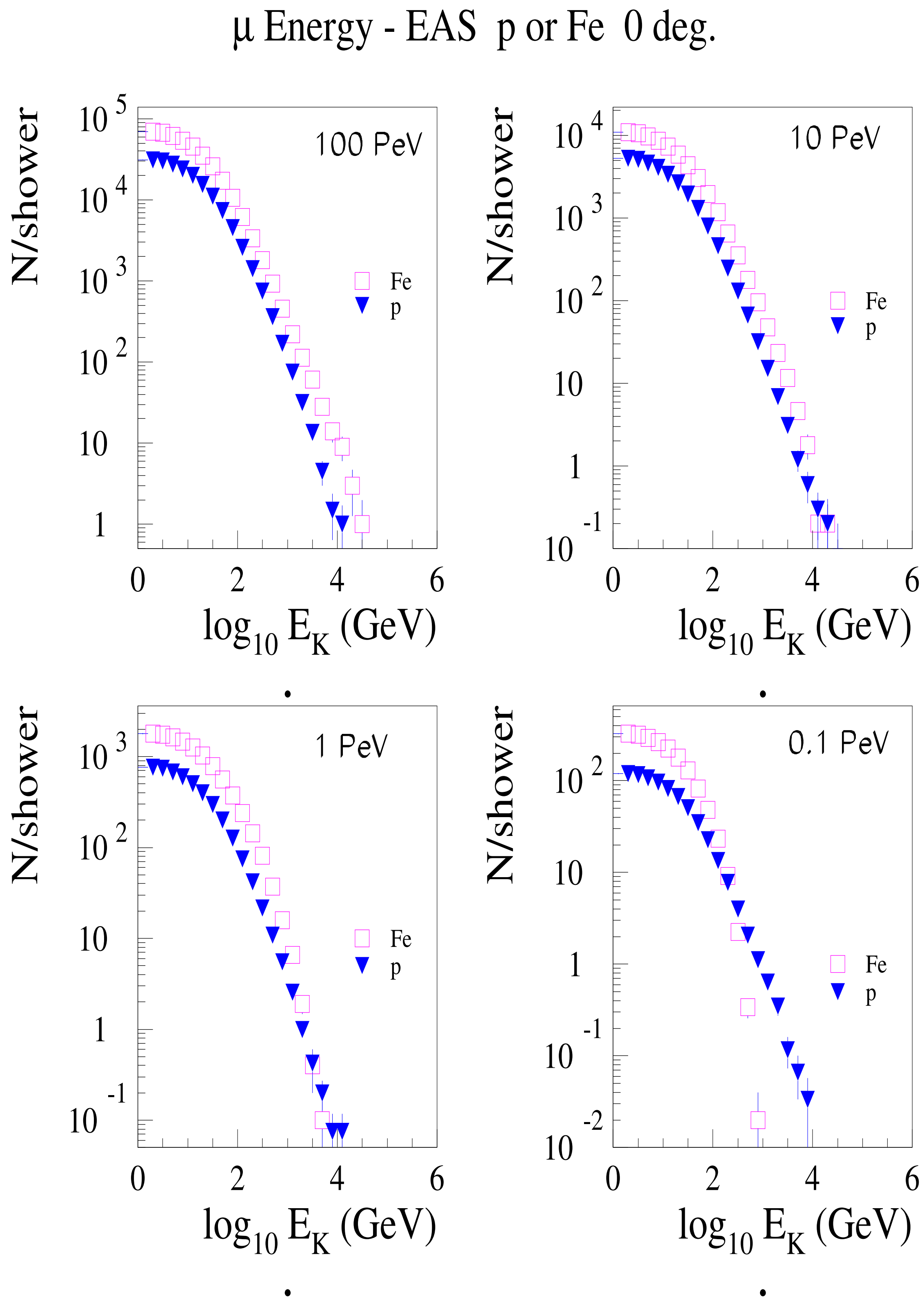
Number of Muons

Fit with

$$N_\mu = A \cdot P_1 \cdot (E/A)^{P_2} \cdot (1 - \frac{P_3 \cdot E_\mu^{thr}}{E/A})^{10}$$



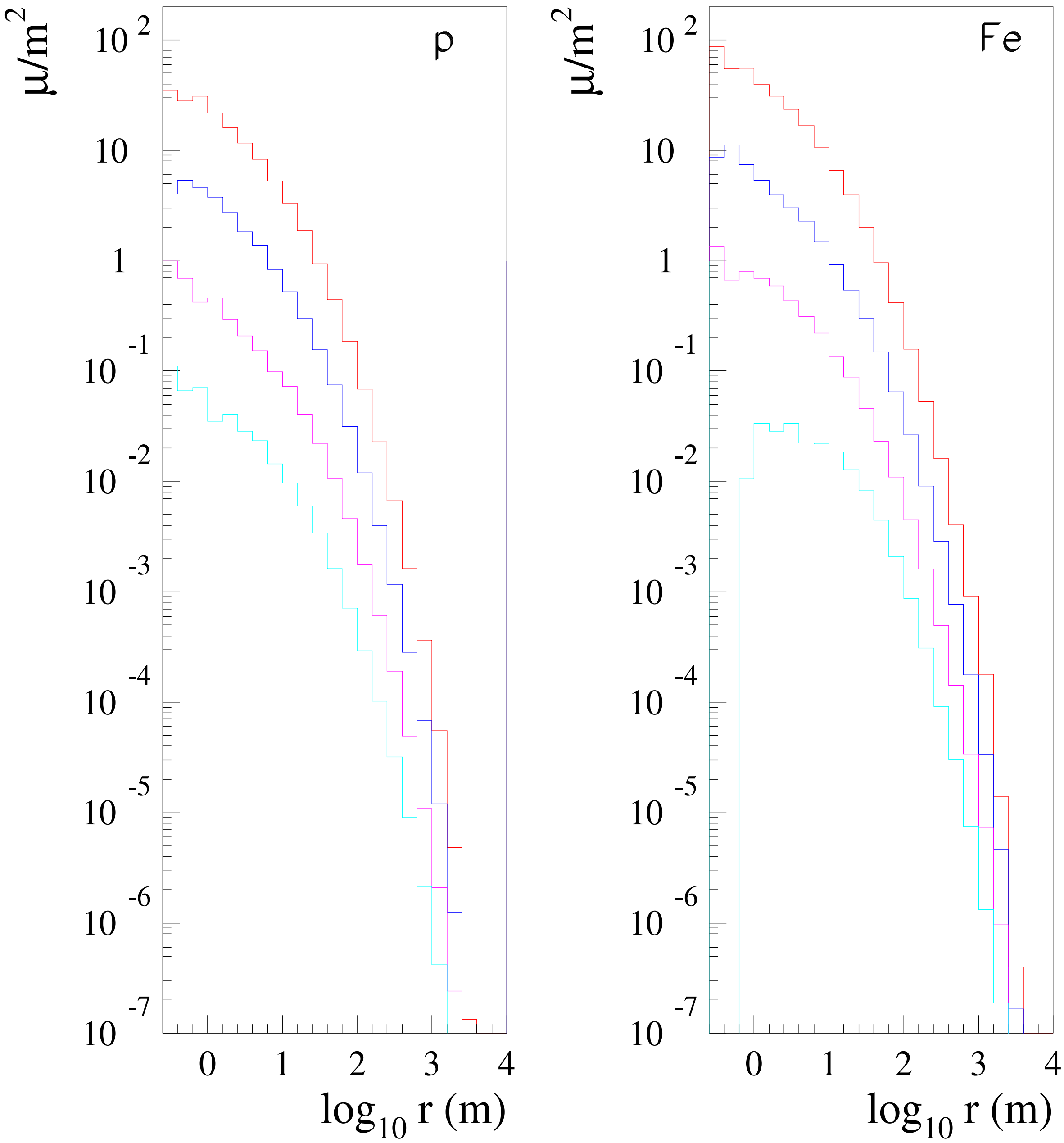
Cumulative Muon Energy Spectrum



Muon Density per m^2

Results for E_0 0.1, 1, 10, 100 PeV

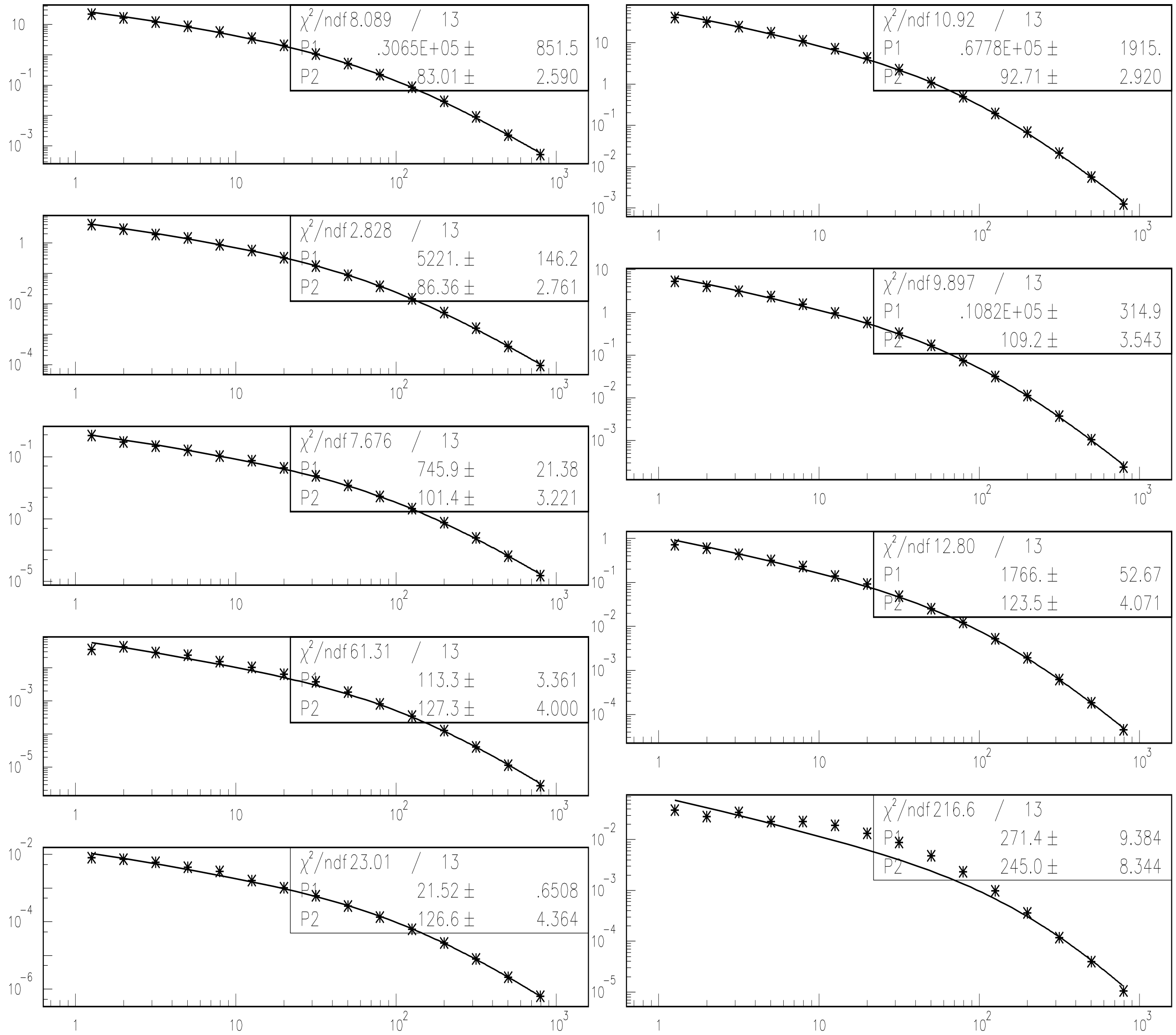
μ Density - EAS p or Fe 0 deg.



Muon Density per m^2

Fit with the Greisen function ($P_1 = N_\mu$, $P_2 = R_0$)

$$\rho_\mu(r) = 0.2575 * P_1 \cdot \left(\frac{1}{P_2}\right)^{1.25} \cdot r^{-0.75} \cdot \left(1 + \frac{r}{P_2}\right)^{-2.5}$$



Fast Monte Carlo

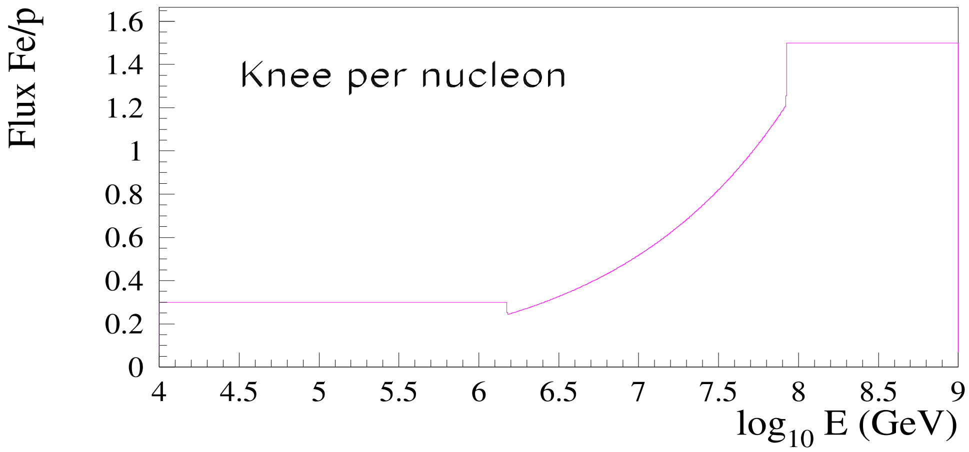
Use fitted parametrizations

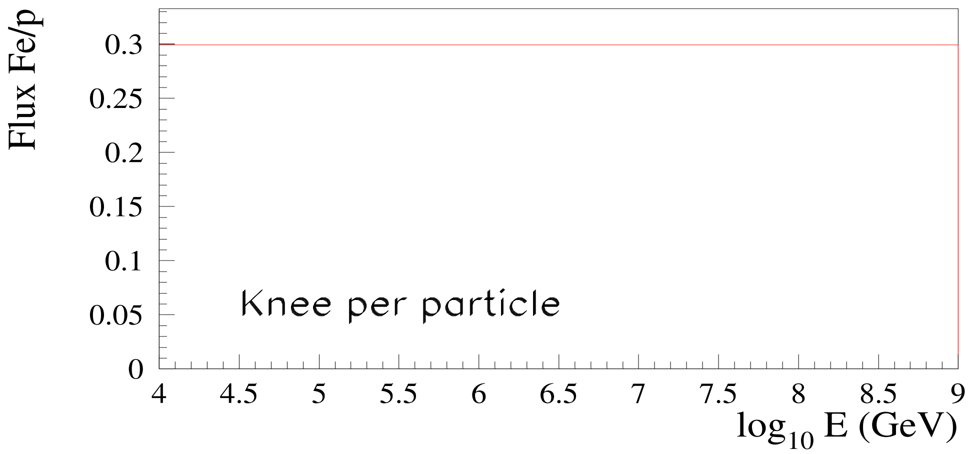
for p or Fe vertical showers within 1 srad

with E_0 from 10 TeV to 1 EeV

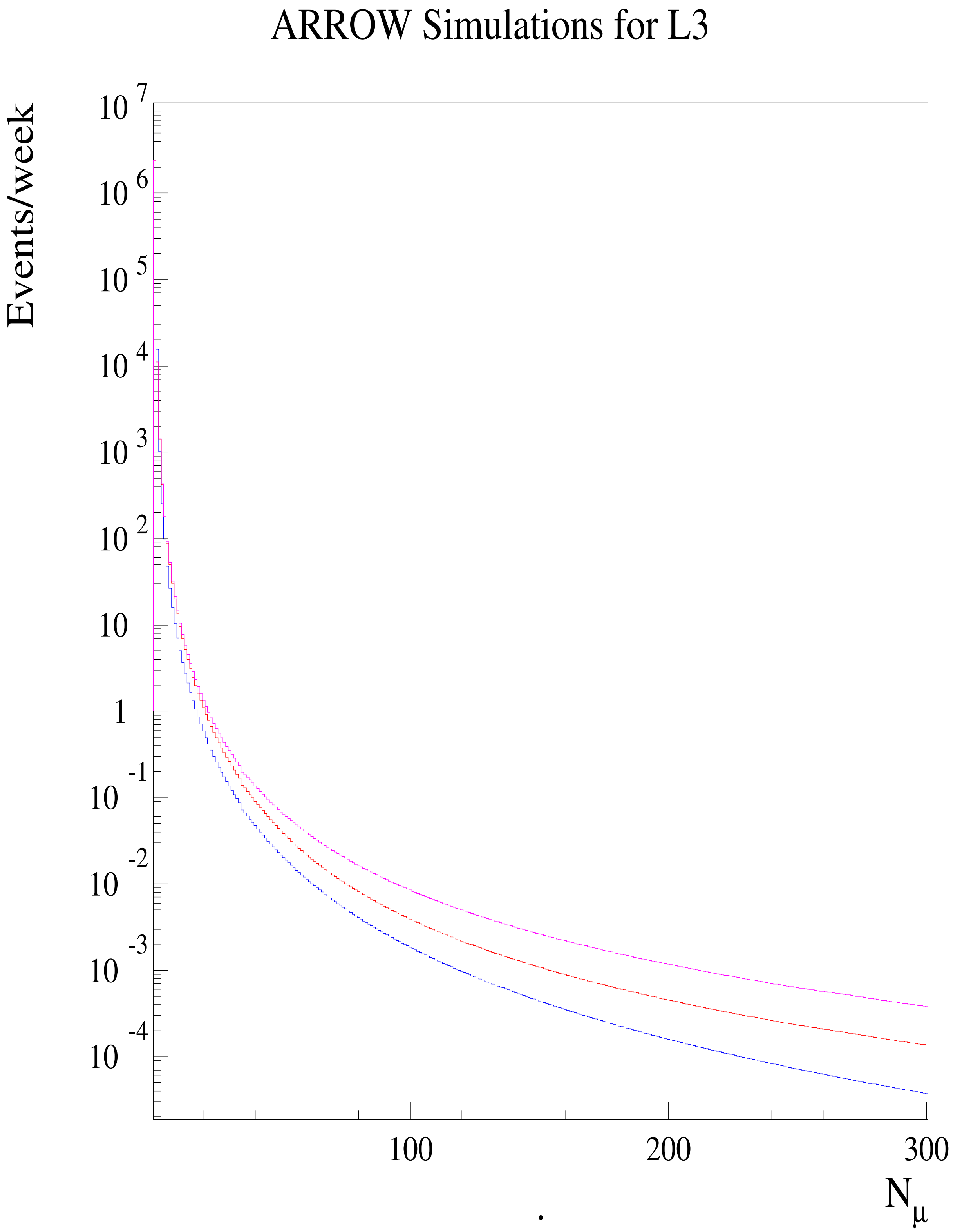
falling up to 1000 m from a

detector with $25\ m^2$

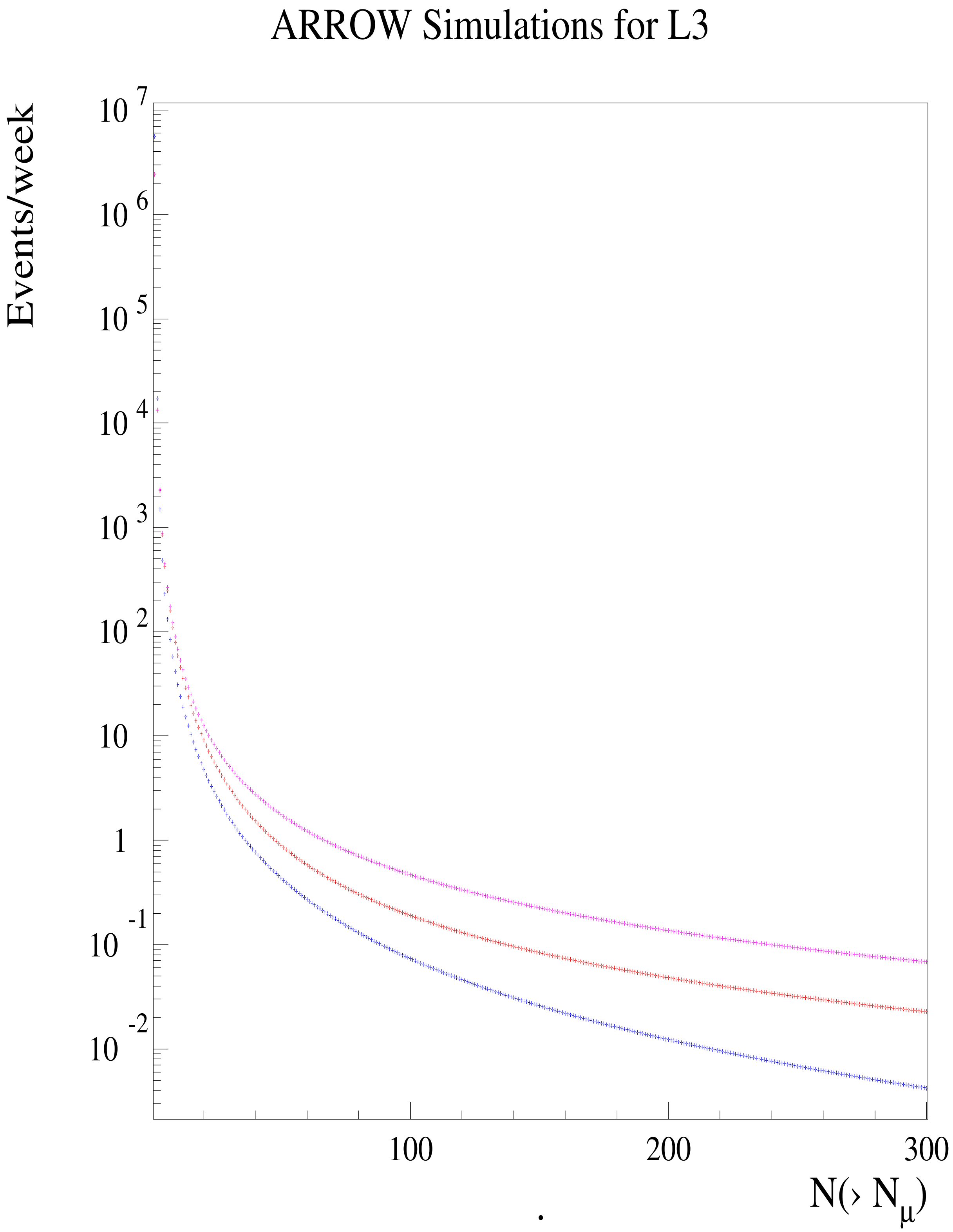




Differential μ Multiplicity



Integral μ Multiplicity



Outlook

- the method works
- basic characteristics of muons at shallow depths underground can be computed in 3d
- dependence on hadronic interaction model :
  - inelasticity
  - multiplicity
- fast MC for μ multiplicity underground
- μ multiplicity is a sensitive tool to study the primary composition around the knee
- prospects: add more nuclei, zenith angles, CPU …

  and compare with real data!