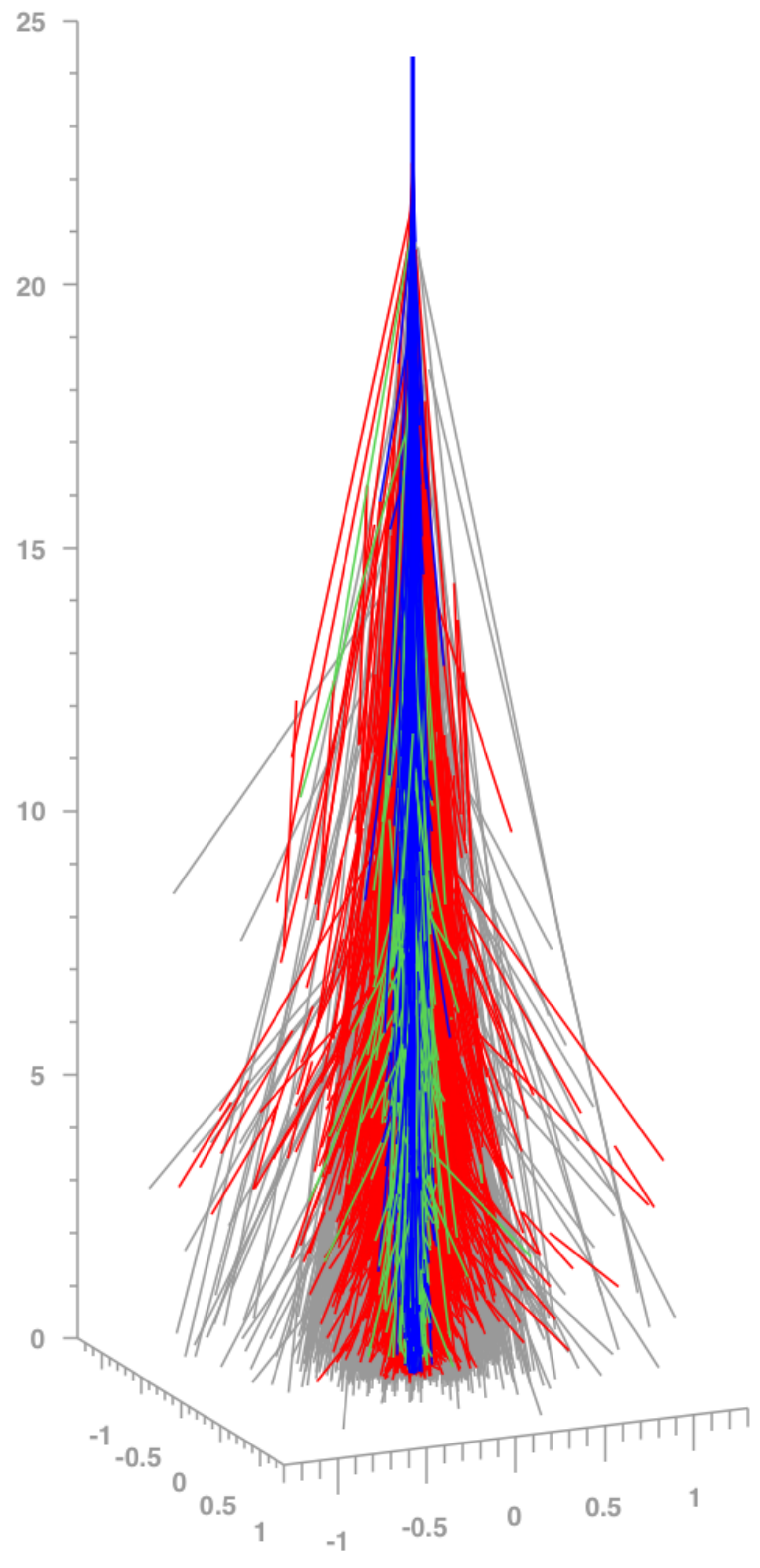
Neutron Production in Extensive Air Showers

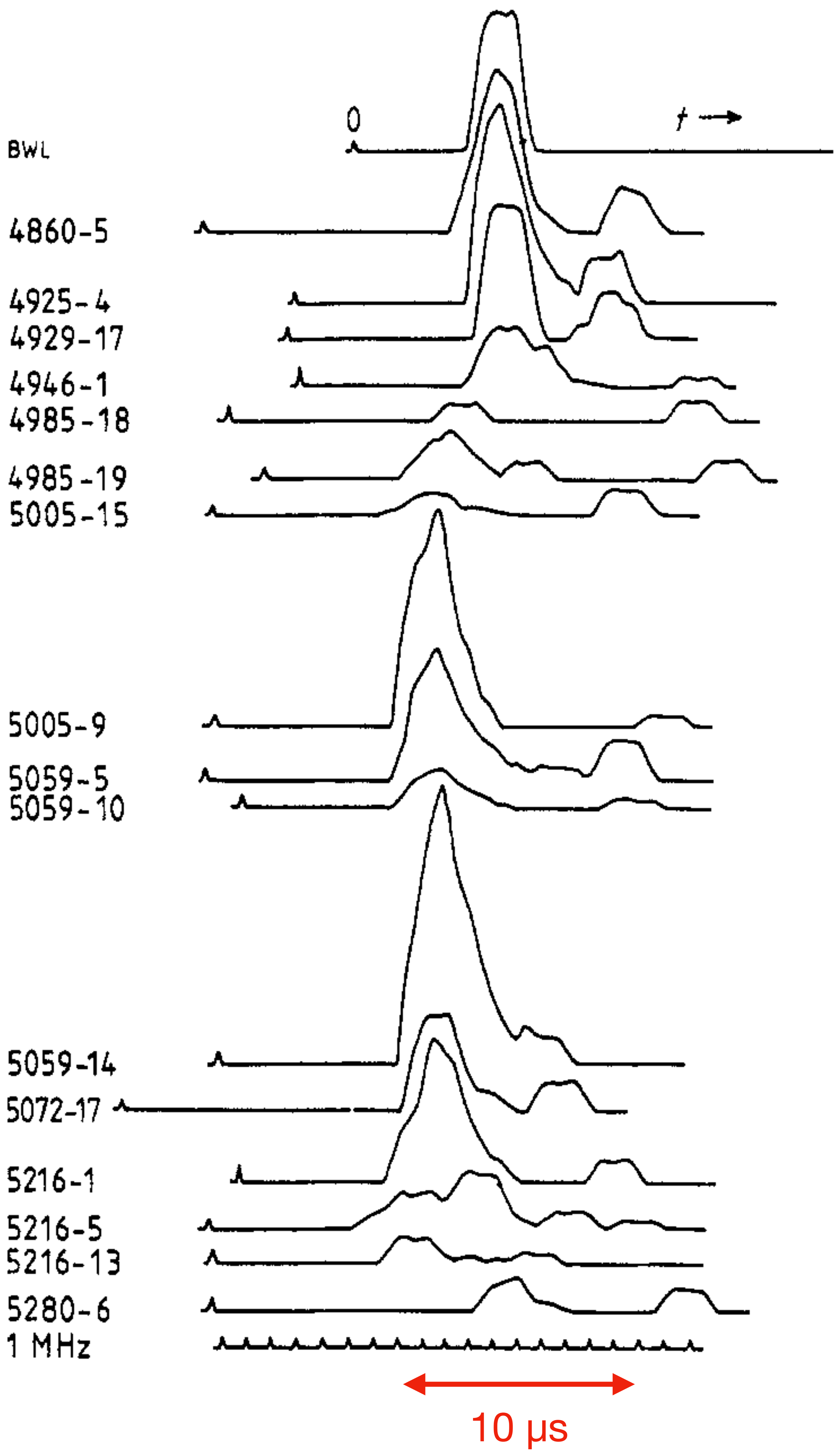
(based on Schimassek et al. 2406.11702)



R. Engel, A. Ferrari, M. Roth, M. Schimassek, D. Schmidt, and D. Veberič

Karlsruhe Institute of Technology

Motivation (i)



Vulcano Ranch (1962-63)

J. Linsley
(J. Phys. G: Nucl. Phys. 10 (1984) L191)

- Sub-luminal pulses with a delay of at least 3μs
- Sometimes several pulses observed
- Typically 1 km from core, high-energy showers
- Greisen: **neutrons** as sub-luminal particles

Note by A.M. Hillas (1982)

scattered particles. The most likely cause of the pulses seems therefore to be heavily-ionizing protons generated by neutrons of 30 - 200 MeV which have performed a random walk from the central region of the shower. The neutrons are non-relativistic and suffer large-angle scattering by interactions with nuclei. (Non-relativistic muons do not deposit enough energy in a scintillator before stopping, and are not scattered so much in the last kilometre or so.) Large numbers of sub-GeV neutrons and protons are produced as recoils from the interactions of hadrons with nuclei (and also to a non-negligible extent from interactions of photons with nuclei). The number of such nucleons should be nearly proportional to shower primary energy, but if the pulses are due to individual particles, one would not expect smaller showers to show the subluminal particles as smaller-amplitude pulses, but rather to show the same large pulses though much less often. Water-Cerenkov detectors are not expected to detect these particles to any appreciable extent.

Today: Extensive literature on dedicated neutron measurements (e.g. Stenkin and others)

Motivation (ii)

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ELEMENTARY PARTICLES AND FIELDS
Experiment

Overview on EAS Neutrons: Recording and Simulations

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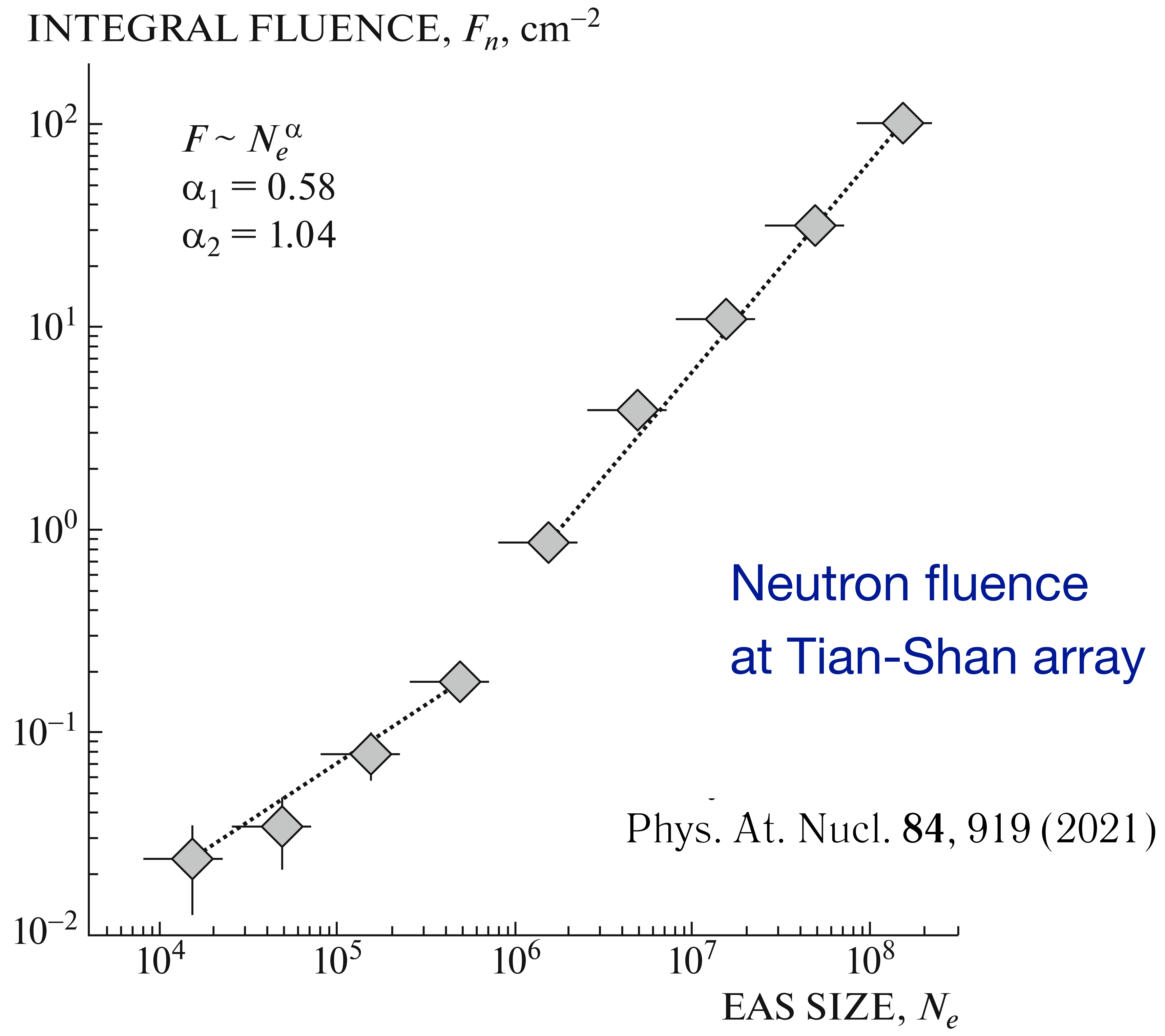
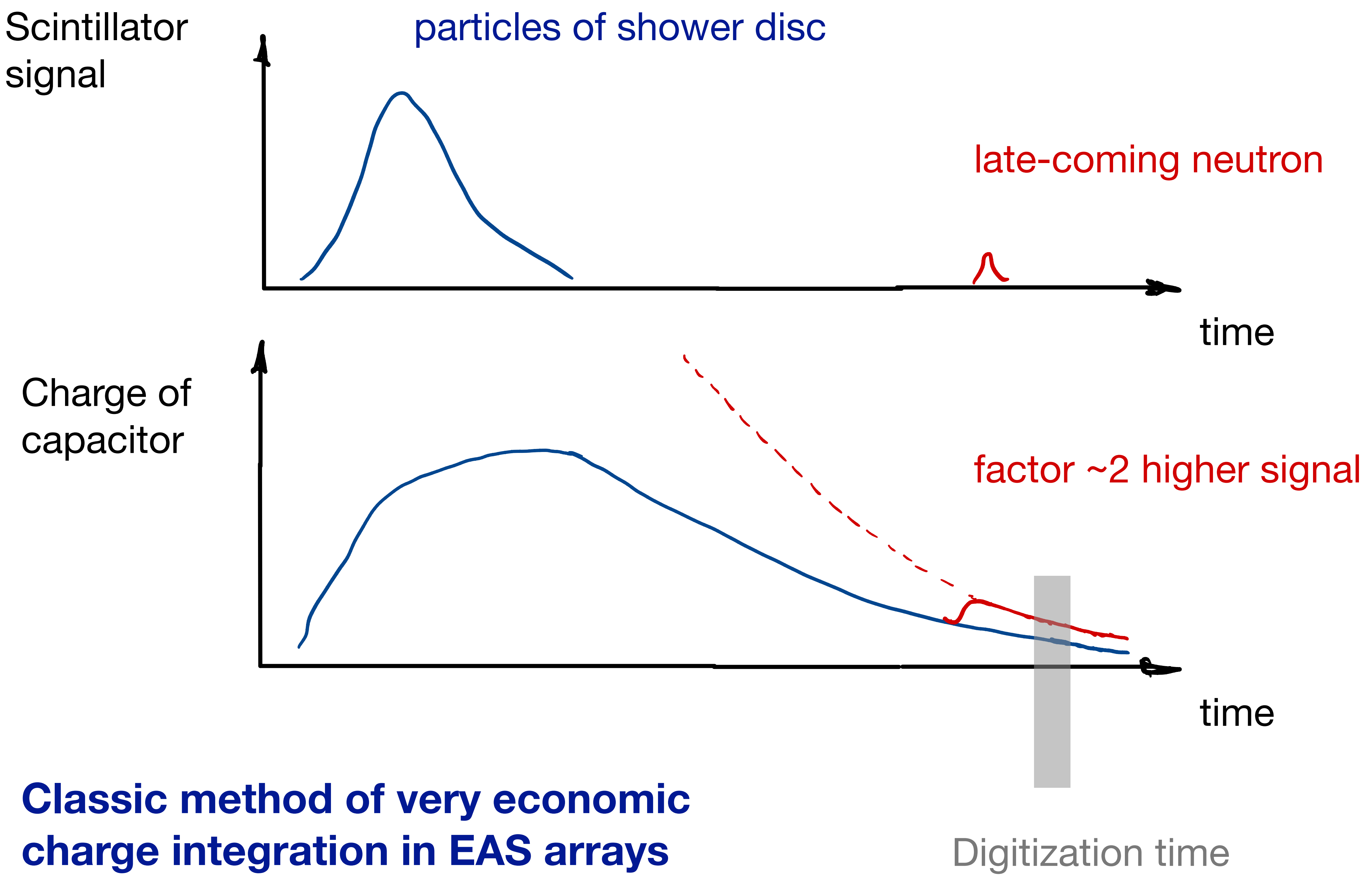
Received August 3, 2023; revised August 3, 2023; accepted August 3, 2023



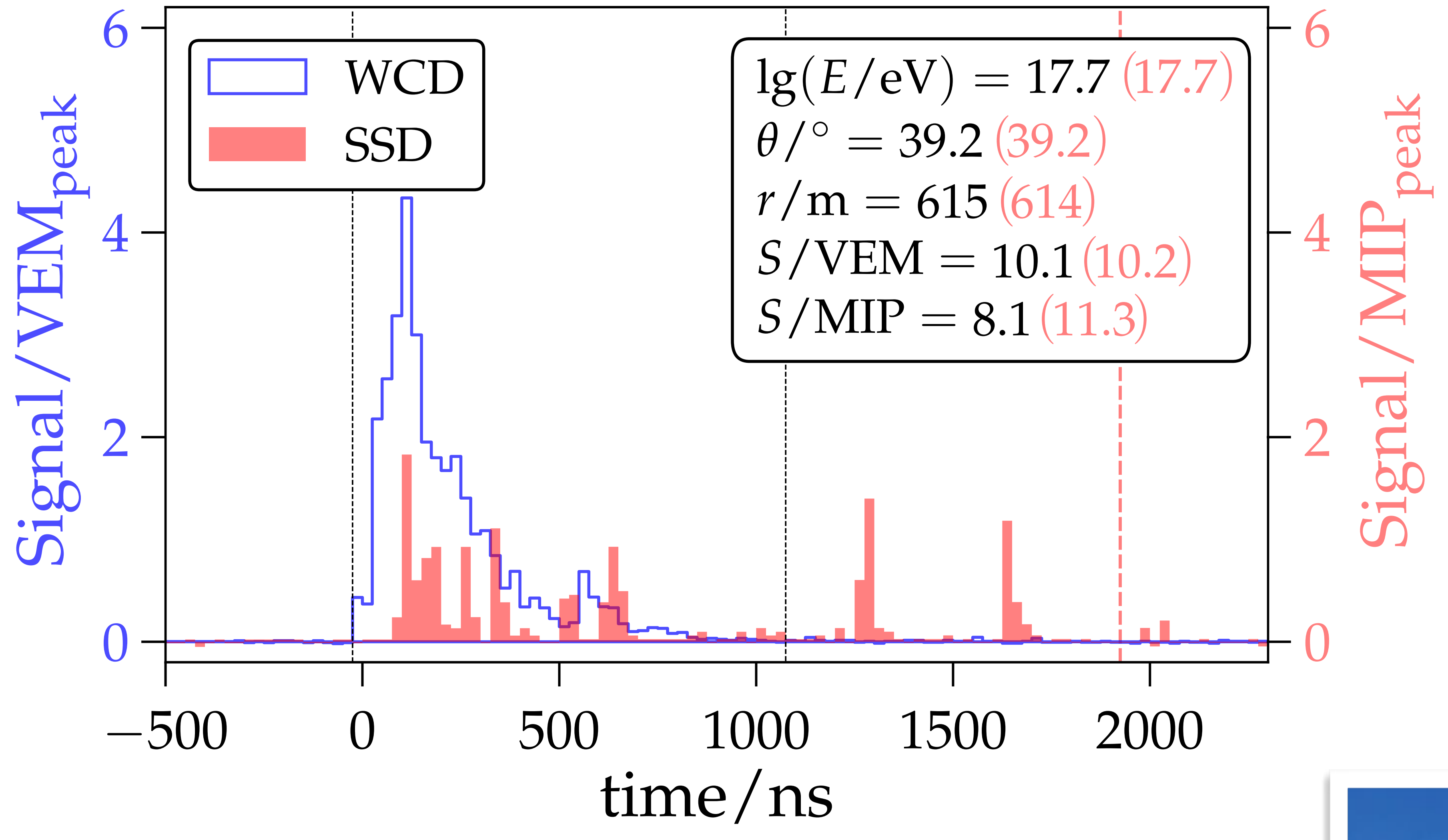
Possible impact depending on measurement principle

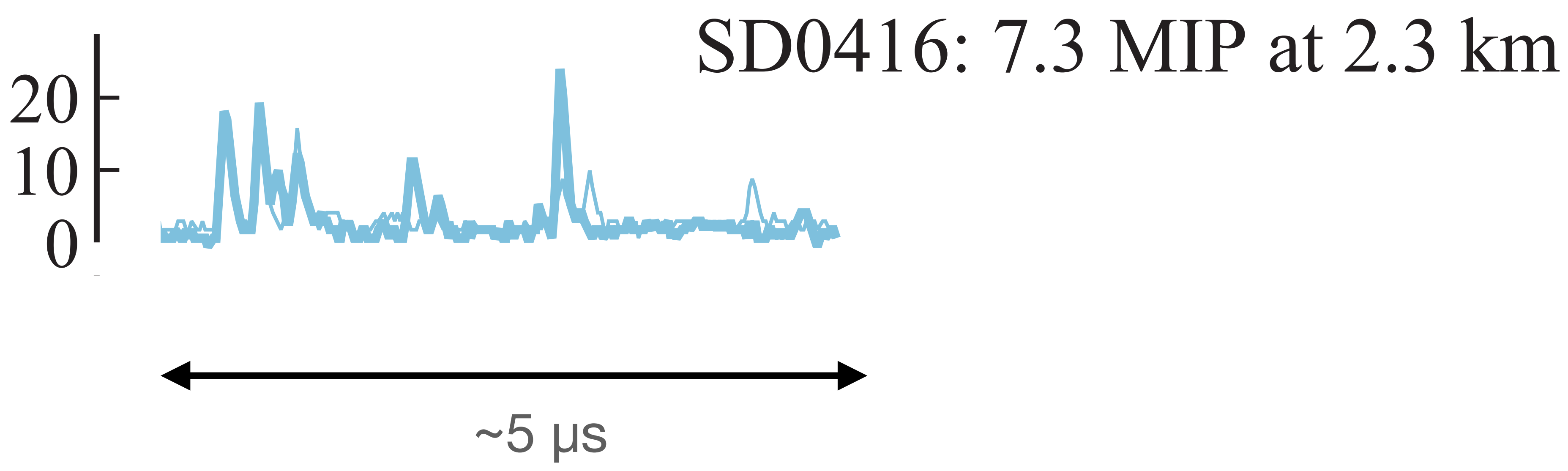


Classic method of very economic charge integration in EAS arrays

(Drescher & Farrar, Astropart Physics 24 (2005) 372)

Motivation (ii)





Scintillators in Auger Observatory

D. Schmidt, Pierre Auger Collaboration (ICRC 2021)

- Late signals seen in scintillators (SSD)
- Late pulses have no coincident signal in water-Cherenkov detectors (WCD)

Scintillators in Telescope Array

TA Collaboration (Amaterasu event, Science 2024)

- Two layers of scintillators, steel plate
- Late signals seen in scintillators
- Late pulses in only one of the two scintillator layers?

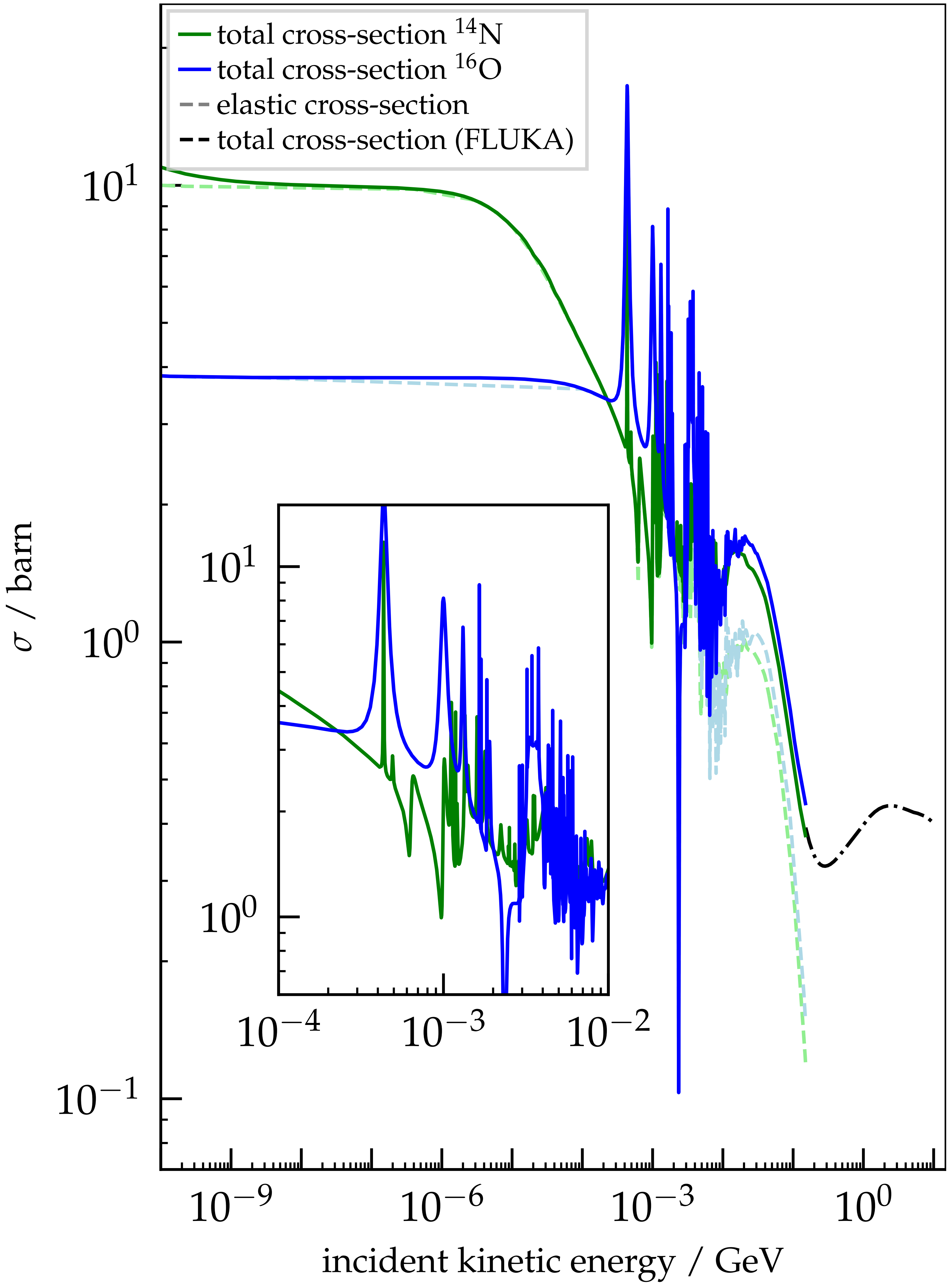
Neutrons in the cascade Monte Carlo code FLUKA

Simulation of neutrons in FLUKA

- FLUKA: neutrons below 20 MeV **low-energy neutrons**
- Neutron interactions at higher energy are handled by FLUKA nuclear models
- Transport and interactions of neutrons with energies below 20 MeV are handled by a dedicated library (matrix-transfer calculation)

Why are **low-energy neutrons** special?

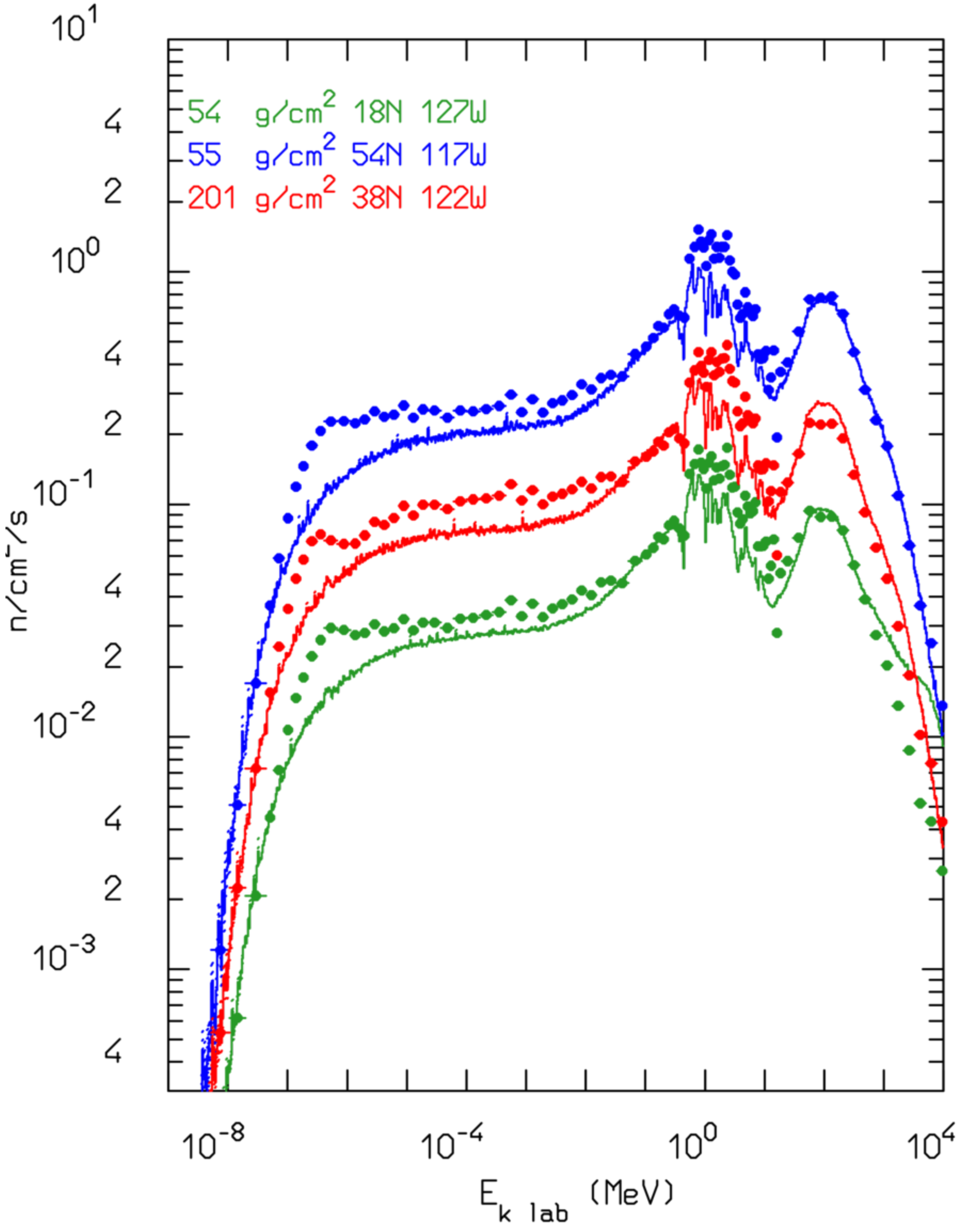
- No charge and ~ ∞ lifetime ➔ can (only) undergo nuclear interactions even at very low energies, e.g. meV
- Cross sections (σ) are complex and structure rich ➔ cannot be calculated by models ➔ we rely (like all codes) on evaluated data files
- Even at "thermal" energies neutrons can still generate several MeV's of γ's and/or charged particles through capture



(A. Ferrari, P.R. Sala, A. Fasso, J. Ranft, FLUKA: A multi-particle transport code, CERN-2005-010)

www.fluka.org

Benchmarking FLUKA with cosmic-ray neutron data

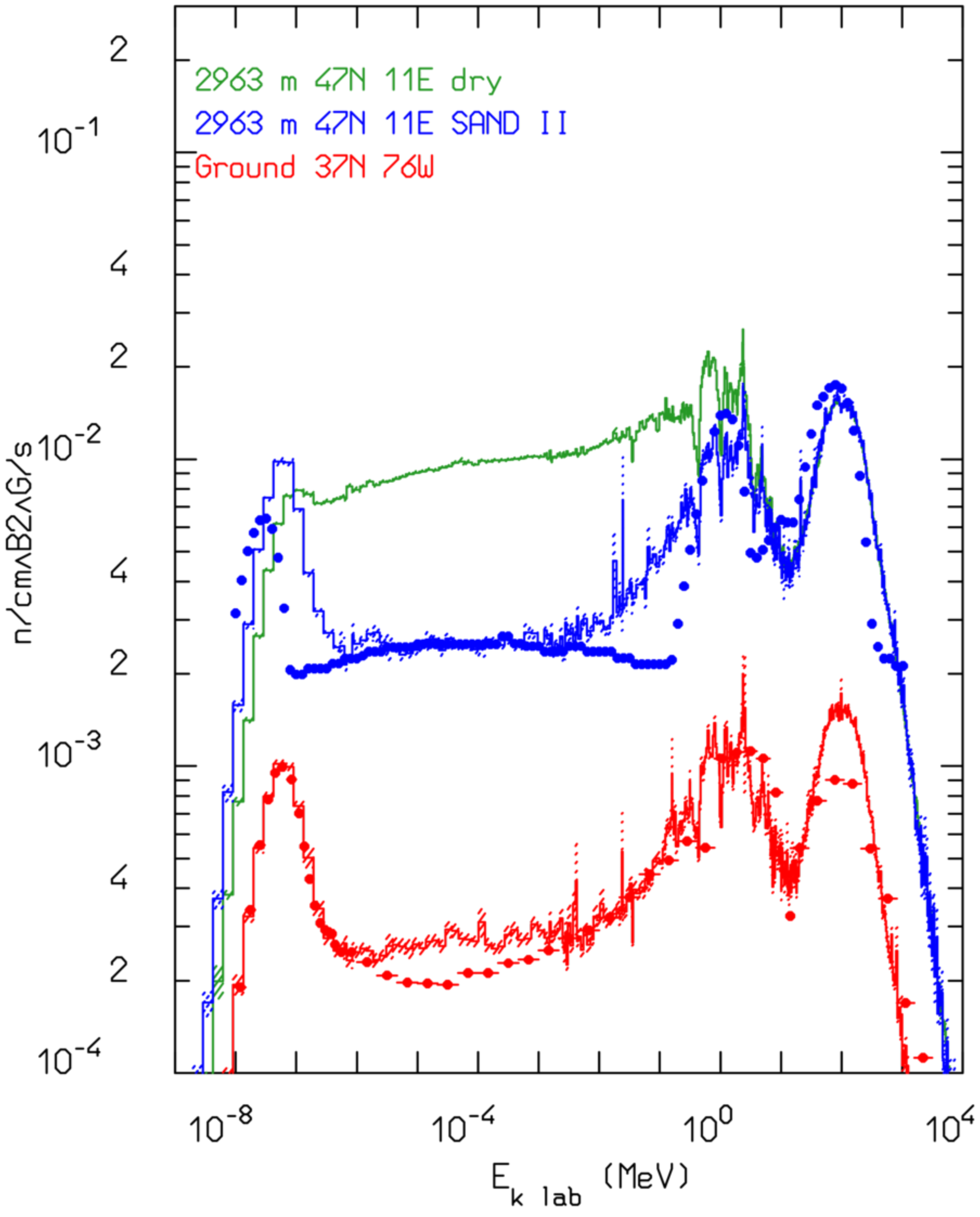


Left: neutron energy spectrum from air plane measurements at different depths

Right: neutron energy spectrum measured at Zugspitze (2963 m)

- **Green:** for a dry environment
- **Blue:** for an environment representative of the exp. conditions)
- **Red:** at ground level

Exp. data are actually unfolded spectra from multi-sphere Bonner spectrometers



Comparison of expectations for muons and neutrons

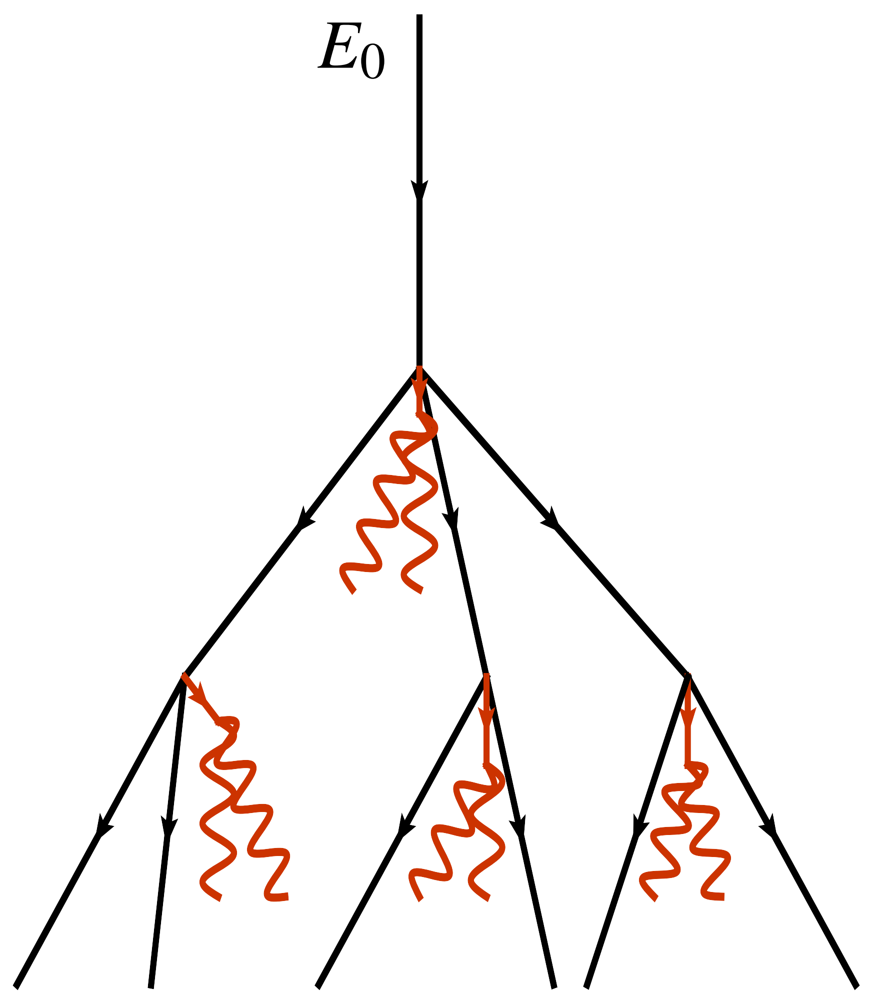
Multiplicity of charged pions

$$N_{\pi^\pm,1} = n_{\mathrm{ch}}$$

$$N_{\pi^\pm,2} = (n_{\mathrm{ch}})^2$$

⋮

$$N_{\pi^\pm,k} = (n_{\mathrm{ch}})^k$$



$$\beta = \frac{\ln n_{\mathrm{ch}}}{\ln n_{\mathrm{tot}}} \sim 0.9$$

(Matthews, APP22, 2005)

(Superposition model)

$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^\beta$$

$$N_\mu^A \sim A^{1-\beta} N_\mu \sim 1.4\, N_\mu$$

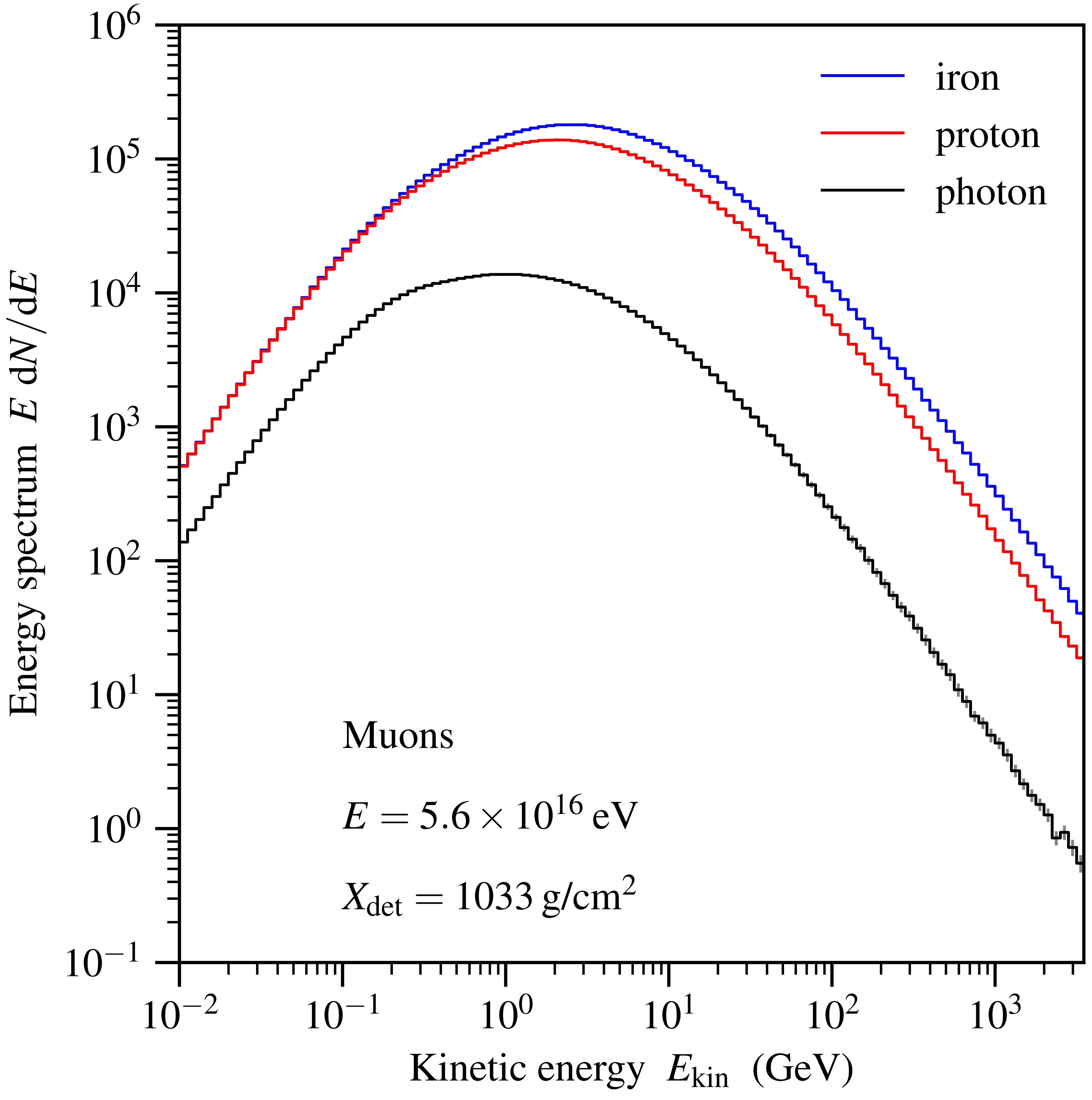
Muons

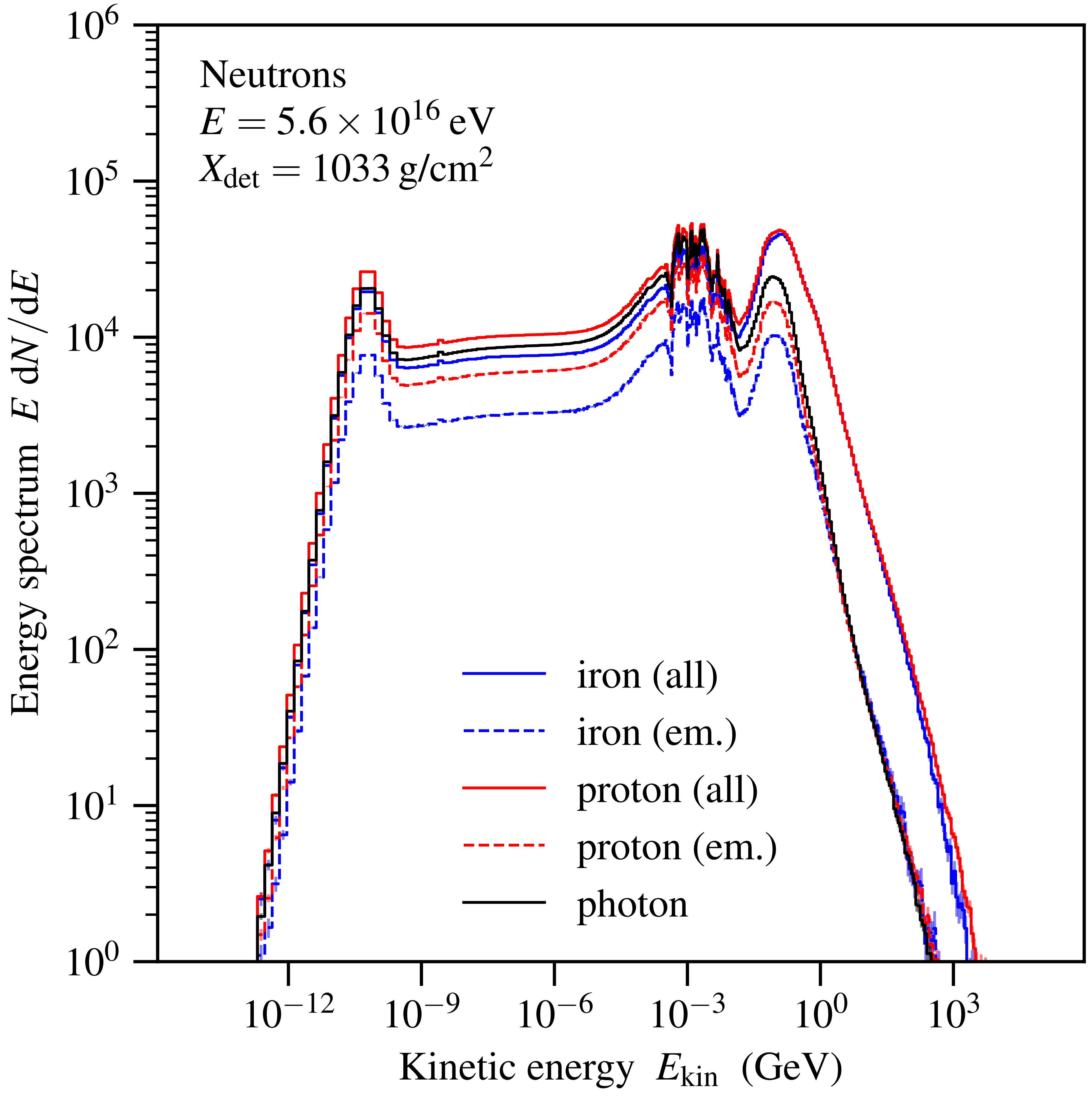
- Mainly produced in hadronic interactions through decay of charged pions and kaons
- Small energy loss, large attenuation length (~1000 g/cm^2)
- Directional information approx. preserved
- Arrive early at ground (less multiple scattering than em. particles)

Neutrons

- High energy: mainly produced in hadronic interactions, baryon-antibaryon pair production
- Low-energy: photo-dissociation of air nuclei
- Energy loss due to elastic scattering, attenuation length (~100 - 150 g/cm^2)
- Directional information lost, wide lateral distribution
- Bulk of neutrons arrives late with very long time delay (neutron cloud / thunder)

Air shower results: primary particle dependence

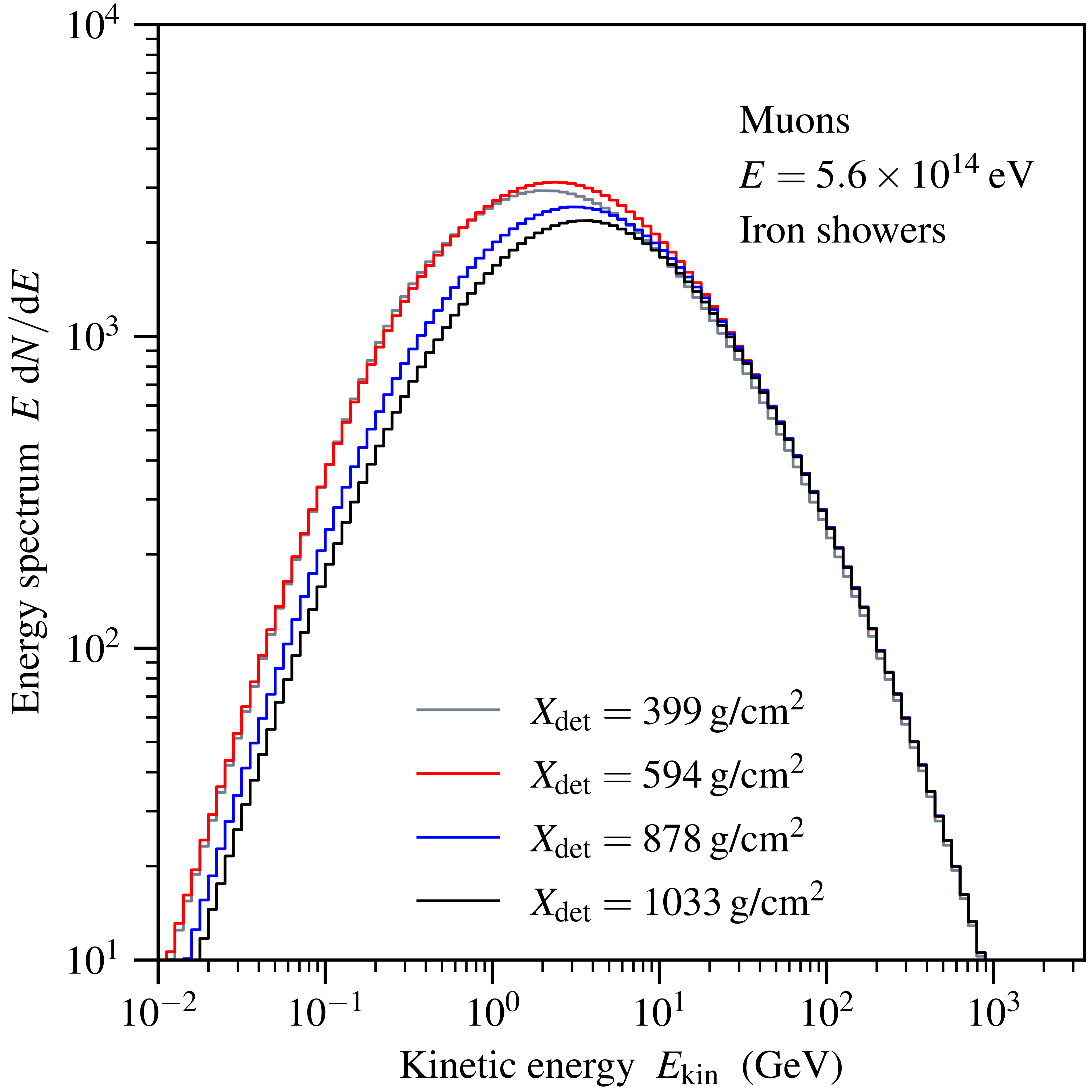


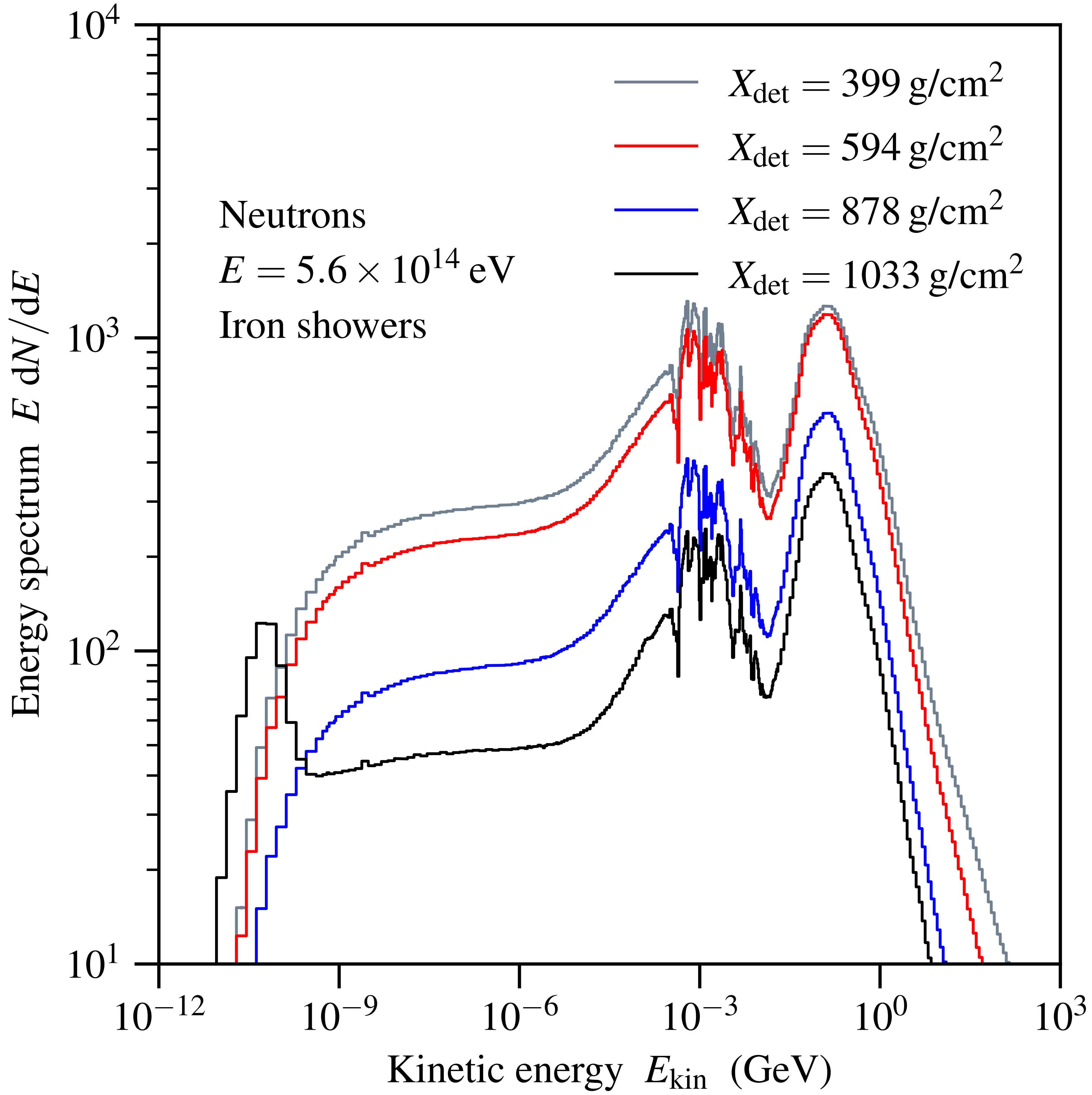


Muons: expected difference between primaries reproduced

Neutrons: high-energy part surprisingly similar for hadron primaries, low-energy part dominated by attenuation

Air shower results: depth evolution (attenuation)



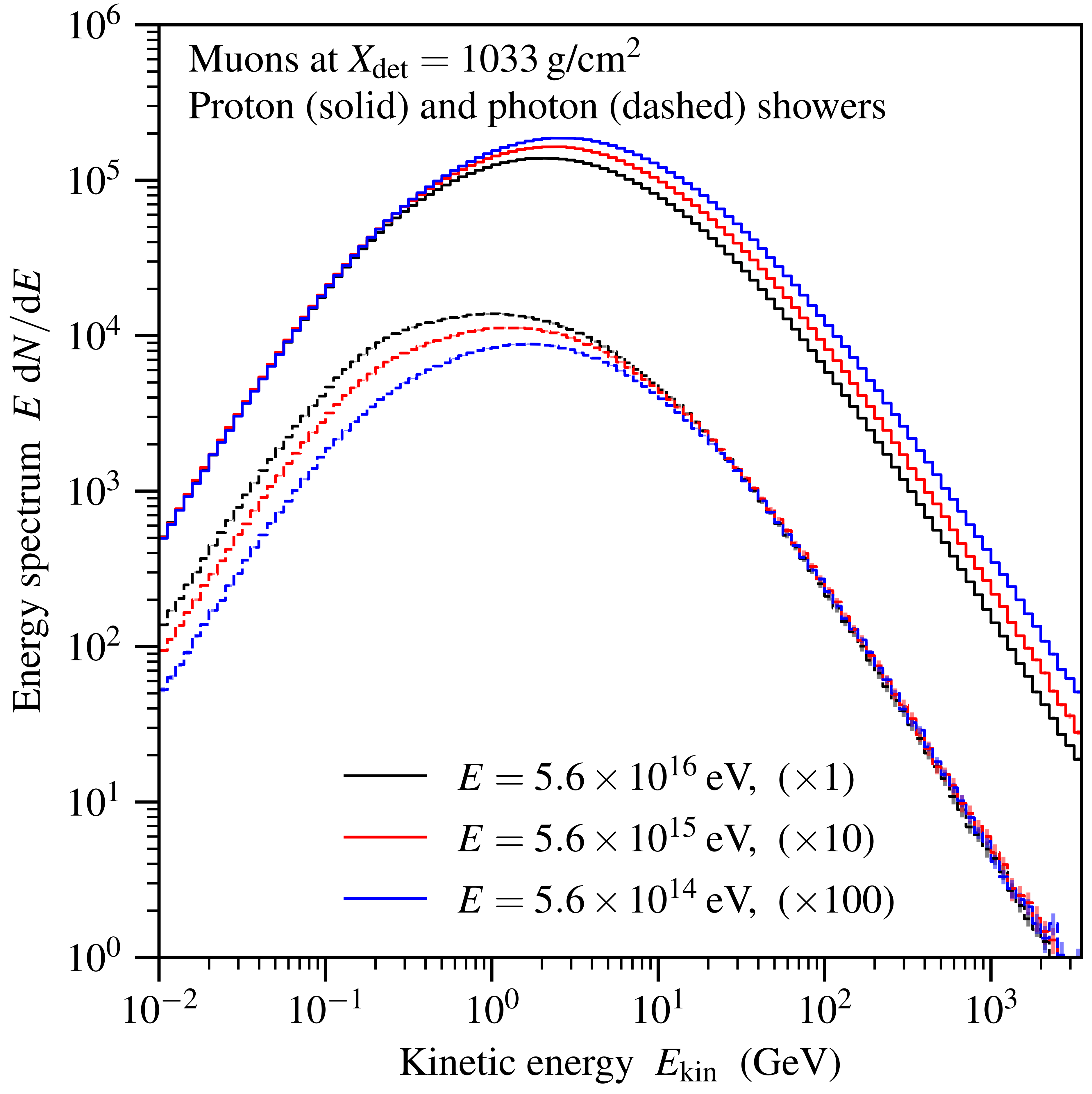


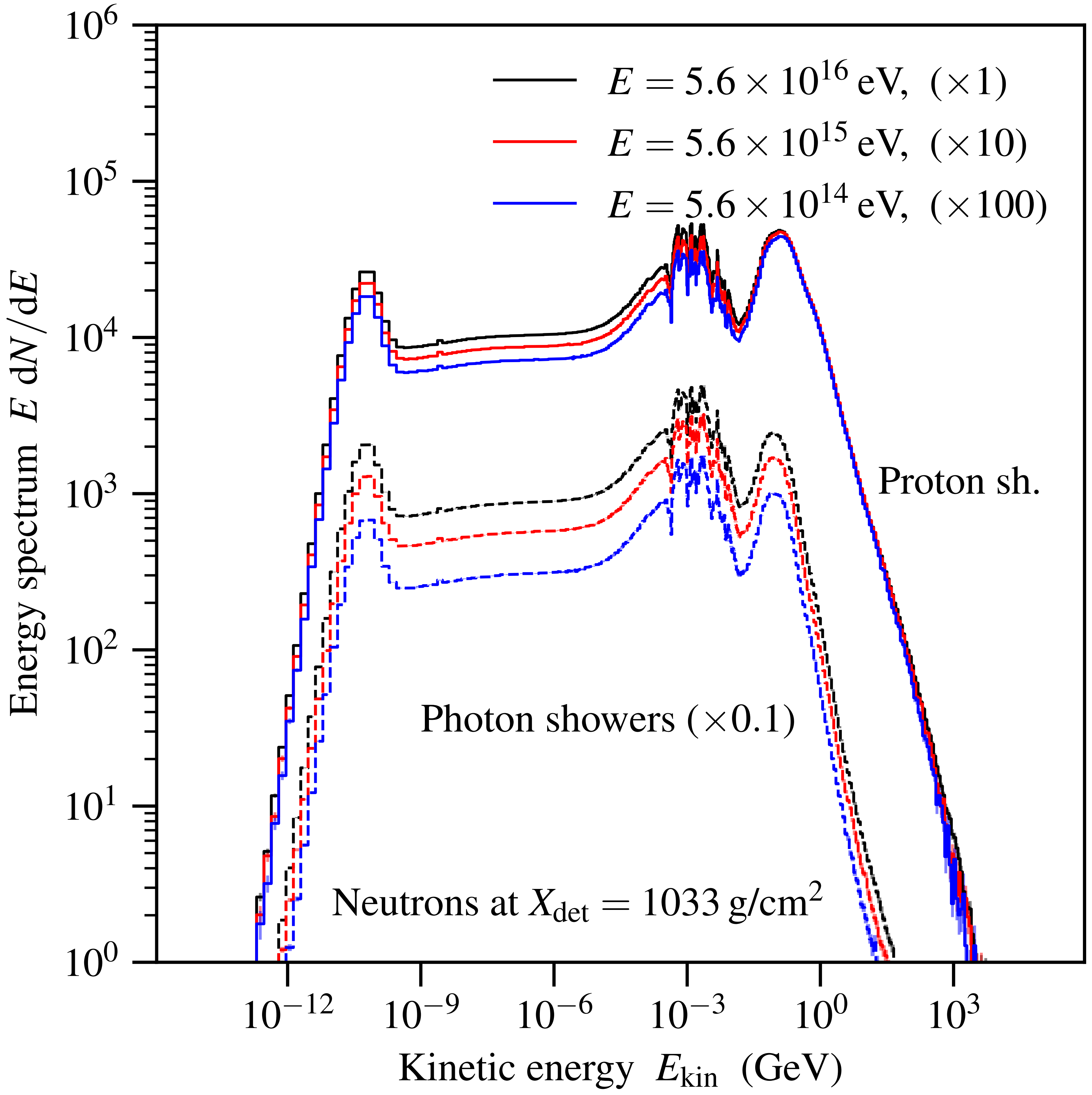
Muons: attenuation negligible in depth range,
low-energy part dominated by muon decay

Neutrons: significant depth-dependent attenuation

$$X_{\rm att,n} \sim 80 \ldots 200\, {\rm g/cm^2}$$

Air shower results: energy dependence



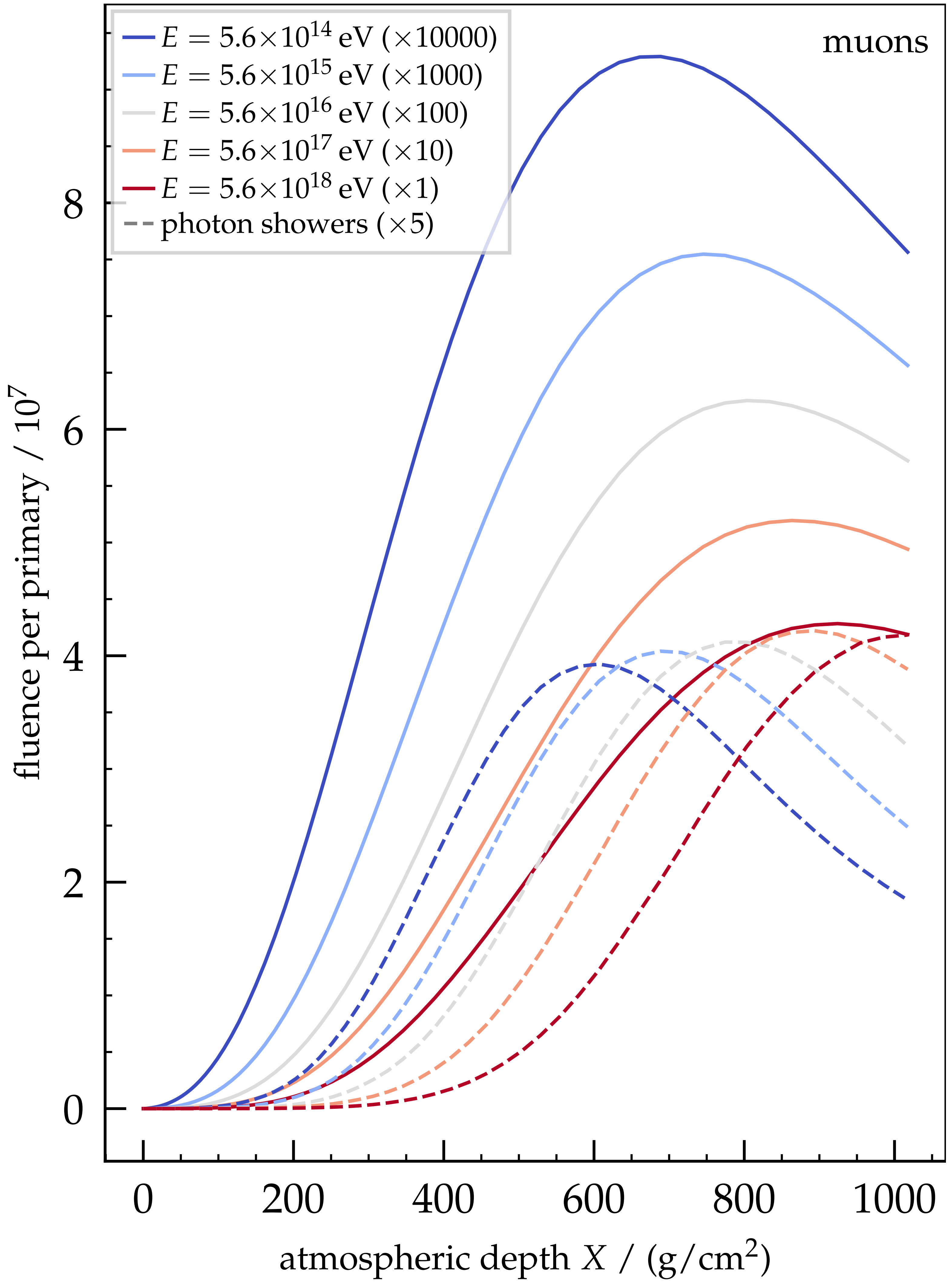


Muons: expected energy scaling for high-energy part

$$N_\mu \sim (E_{\rm had})^{0.9} \qquad N_\mu \sim E_\gamma$$

Neutrons: high-energy part seems to scale linearly with energy for hadron primaries but not for photons

Air shower results: energy dependence

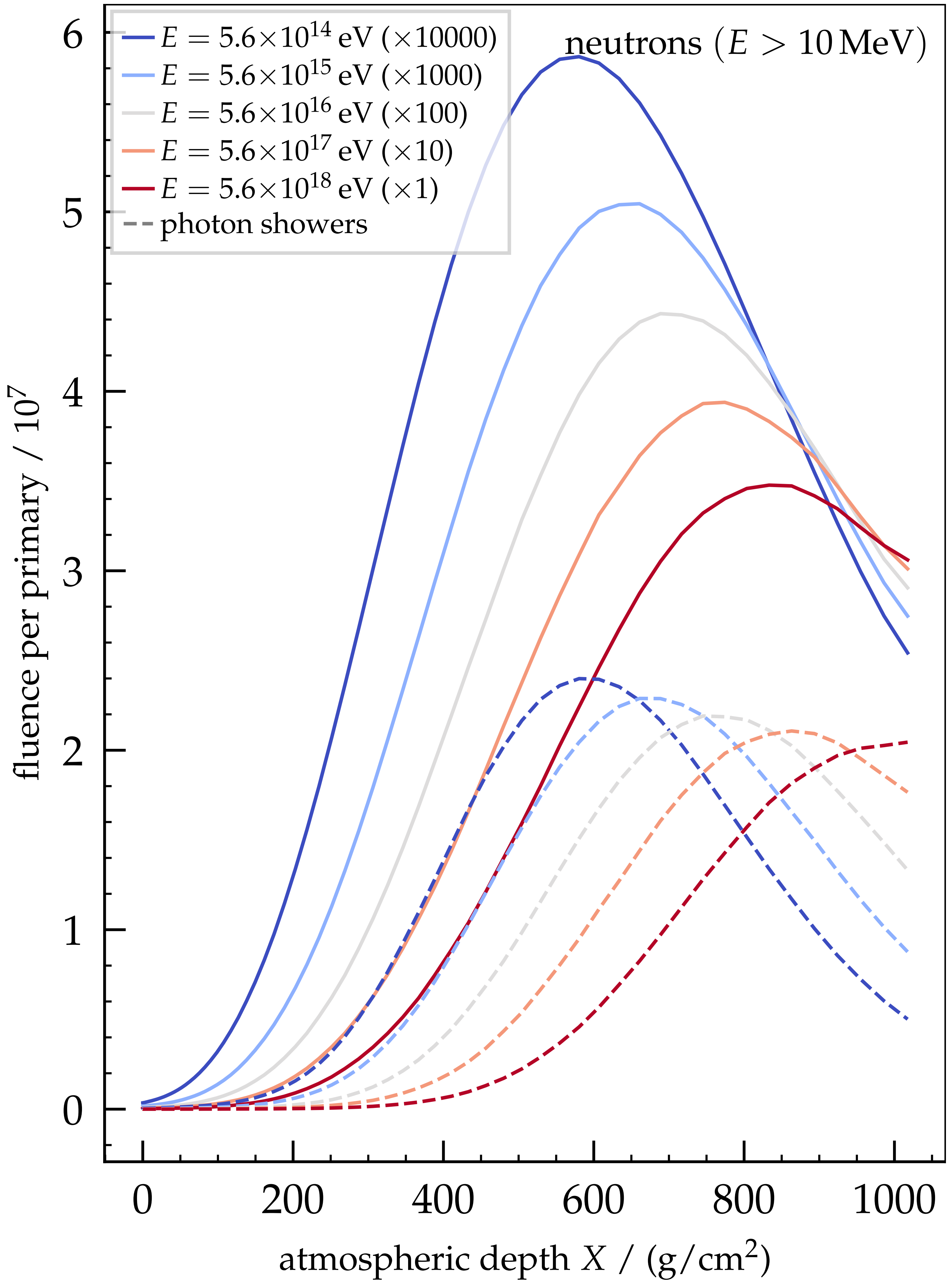


Proton showers

$$N_{\mu,\max} \sim E^{0.9}$$

Photon showers

$$N_{\mu,\max} \sim E$$



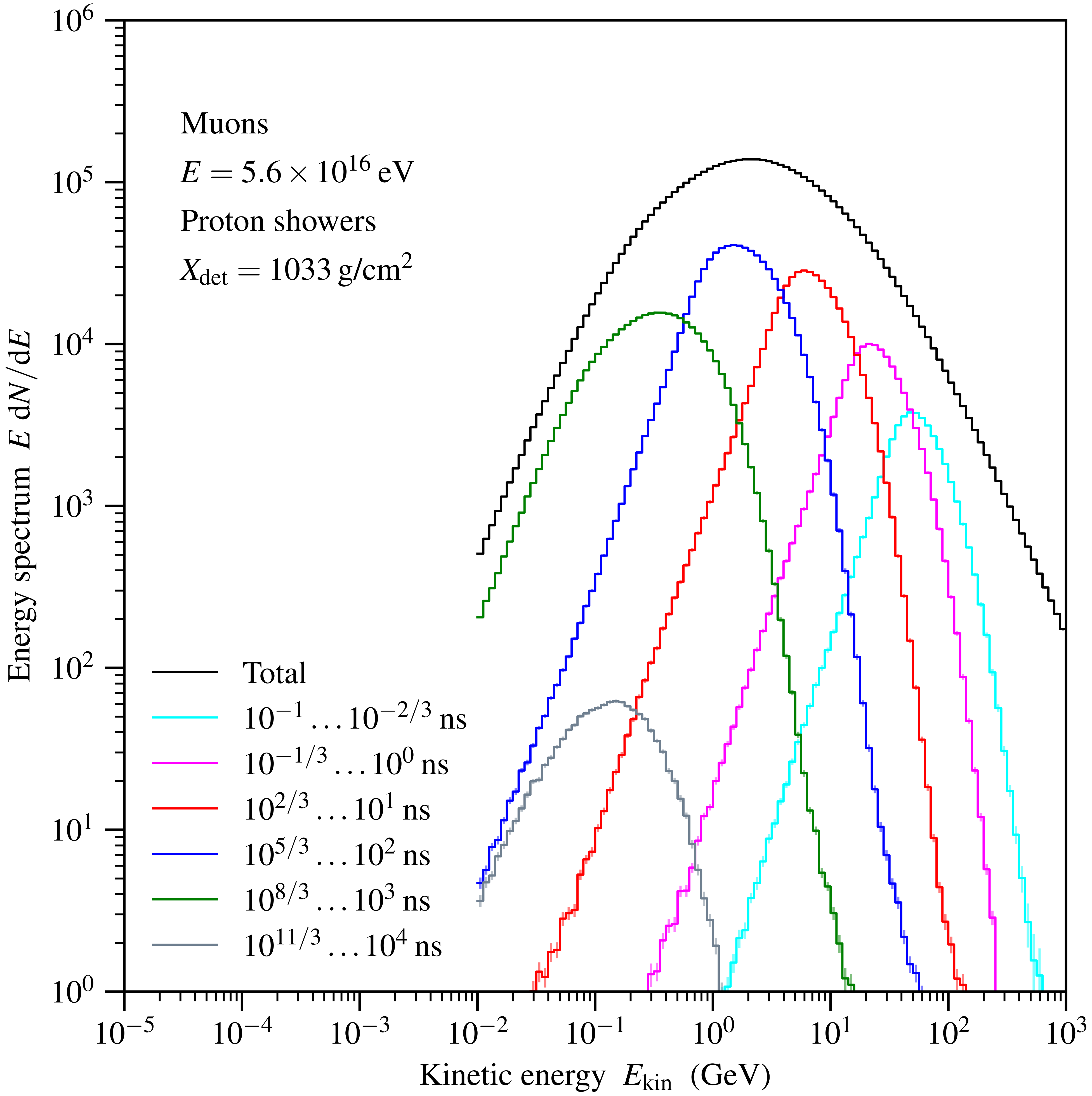
Proton showers

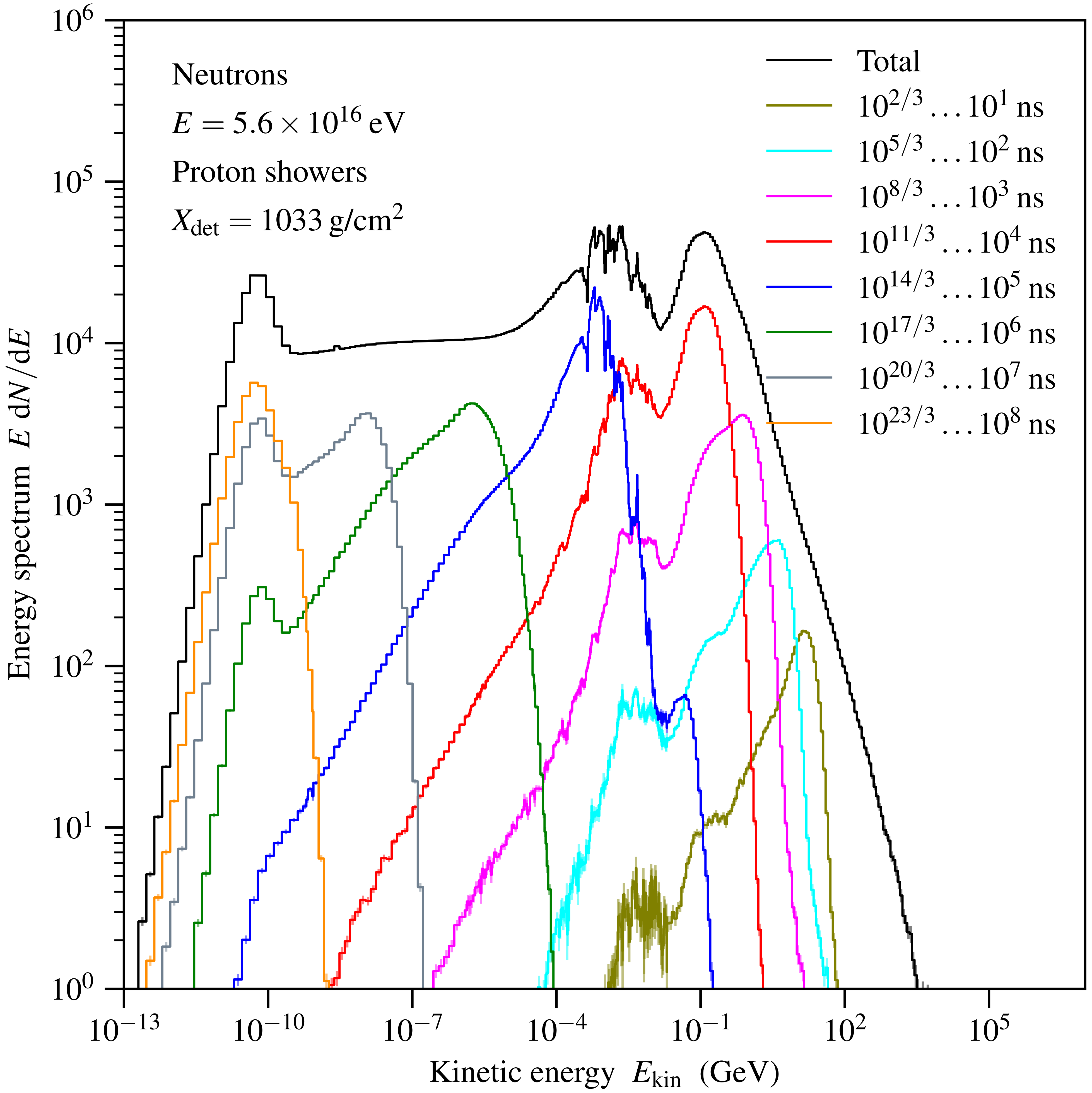
$$N_{n,\max} \sim E^{0.95}$$

Photon showers

$$N_{n,\max} \sim E$$

Air shower results: time delay distribution

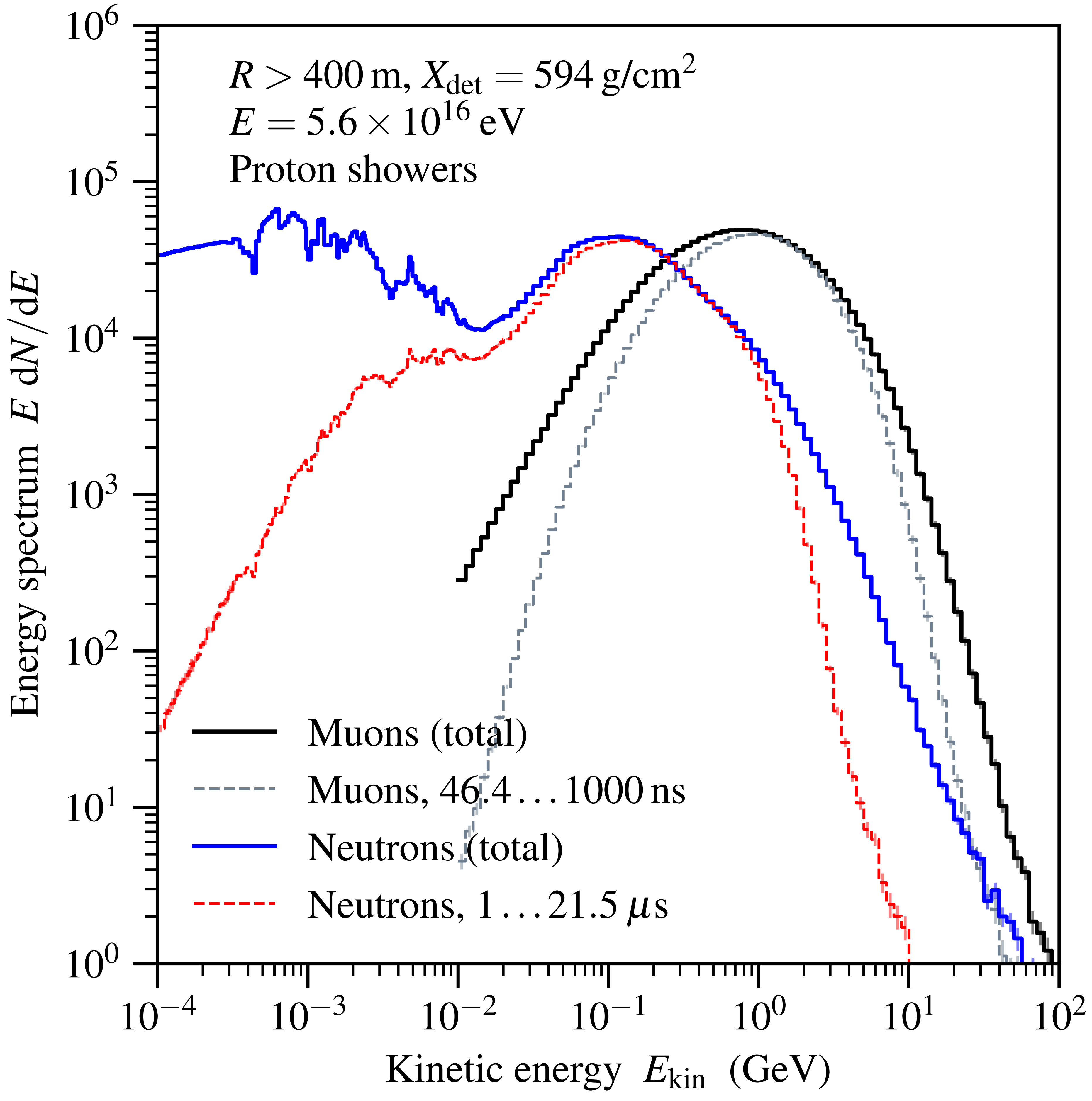




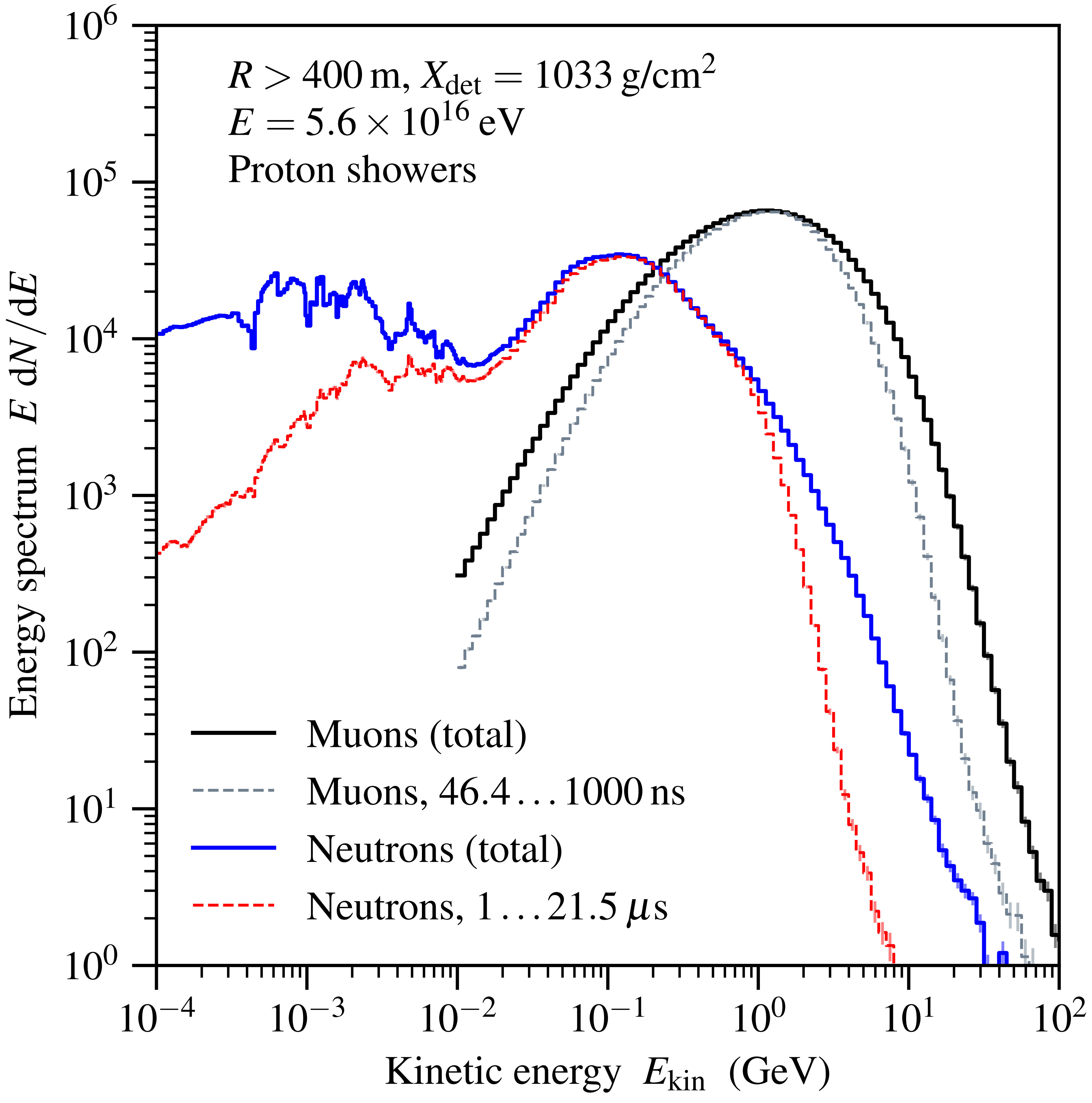
Muons: time delay of bulk of particles: 1 - 500 ns

Neutrons: time delay of high-energy particles: 1 - 20 μs, slow (thermal) neutrons up to 100 ms

Air shower results: muons vs. neutrons at large distance



Close to shower maximum: neutrons as abundant as muons



Past shower maximum: neutrons much less abundant than muons

Summary *(see 2406.11702 for details)*

Neutrons

- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators

Scaling observations

- Production ~50% hadronic, ~50% electromagnetic. dissociation
- Hadronic production scales similar to muons
- Electomag. production scales linearly with energy
- Attenuation (neutron removal) length 80 … 200 g/cm^2
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 … 20 μs (E_{kin} > 20 MeV)
- Thermal neutrons up to ~ 100 ms

First very rough estimate of detection probabilities (%)

Neutron Energy (MeV)	Scintillator Threshold (100 e-keV)	Water Threshold ($^1/_{300}$ VEM)	Water Threshold ($^1/_{100}$ VEM)
0.0001	2.3×10^{-2}	13.7	$<10^{-3}$
0.001	1.0×10^{-2}	13.7	$<10^{-3}$
0.01	4.2×10^{-3}	13.7	$<10^{-3}$
0.1	1.3×10^{-3}	15.0	$<10^{-3}$
0.5	$<10^{-3}$	18.5	$<10^{-3}$
0.7	4.65	20.1	$<10^{-3}$
1	14.7	16.9	$<10^{-3}$
2	17.1	25.1	$<10^{-3}$
3	15.5	28.0	$<10^{-3}$
5	12.4	29.0	4×10^{-3}
10	9.78	41.3	11.1
20	7.67	49.2	19.1
30	6.46	53.2	22.8
50	4.47	58.6	30.3
100	2.87	61.8	37.5
200	2.30	63.9	44.4
500	2.31	75.3	52.3
1000	2.55	83.2	79.7

Note by Michael Hillas on neutrons

Note provided by Alan Watson
(Haverah Park array, unpublished)

"Sub-luminal" particles in air showers

(1) Qualitative deductions

These pulses, discovered in scintillators by John Linsley, are delayed after the shower front by a time $T > r/c$, r being the distance from the shower axis. They are not very uncommon in scintillators at 1 - 2 km from the axis in showers above 10^{19} eV, but have not been noticed in much smaller showers. The pulses were sharp (compared with normal shower pulses), and had sizes around 2 to 5 times that produced by a standard muon — say 30 to 80 MeV deposited in the scintillator. More than one such signal could be detected in some showers — sometimes more than one in a single scintillator, well spread out in time.

The sharpness of the pulses suggests that each one is due to a single particle, from a population well spread out in time, rather than being due to a narrow shell of particles, the sharpness of which would be hard to account for so far from the axis. The pulse size would then call for somewhat slow heavily-ionizing particles (such as 30-100 MeV protons, possibly knocked on by 50 - 100 MeV neutrons), and the long delay also calls for slow and highly scattered particles. The most likely cause of the pulses seems therefore to be heavily-ionizing protons generated by neutrons of 30 - 200 MeV which have performed a random walk from the central region of the shower. The neutrons are non-relativistic and suffer large-angle scattering by interactions with nuclei. (Non-relativistic muons do not deposit enough energy in a scintillator before stopping, and are not scattered so much in the last kilometre or so.) Large numbers of sub-GeV neutrons and protons are produced as recoils from the interactions of hadrons with nuclei (and also to a non-negligible extent from interactions of photons with nuclei). The number of such nucleons should be nearly proportional to shower primary energy, but if the pulses are due to individual particles, one would not expect smaller showers to show the subluminal particles as smaller-amplitude pulses, but rather to show the same large pulses though much less often. Water-Cerenkov detectors are not expected to detect these particles to any appreciable extent.

Volcano Ranch:
scintillators of 9 cm thickness

Monte-Carlo simulations are being carried out to check the numbers of non-relativistic nucleons expected in this energy range at around 1.5 km from the shower axis, and the typical time delays to be expected. The details of nucleon production and scattering in intra-nuclear cascades are complex, and it is necessary to check that the simulation reproduces this to a reasonable extent, as the amount of scattering and energy loss must have a large influence on the numbers and delays of particles at very large distances. Initial results with a much simplified treatment (which may be inaccurate) indicate that at least half of the neutrons above 30 MeV are "sub-luminal", and a considerable proportion of the protons, and the detection probability in a scintillator at the distance mentioned would become high at a shower size of a little above 10^{19} eV. The tail of the muon time distribution probably ends at about $\frac{1}{2}r/c$.

A. M. Hillas

28th October 1982.