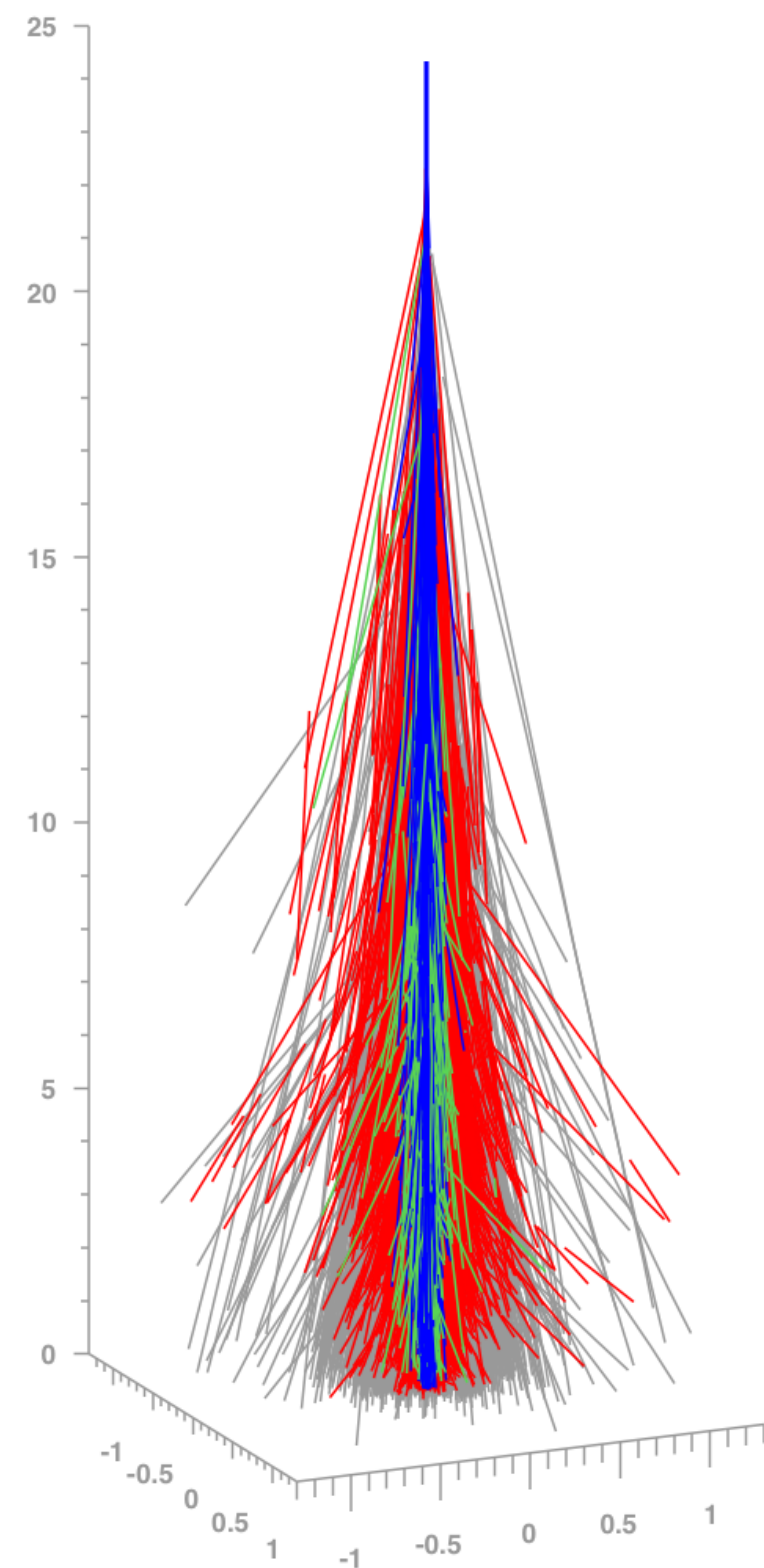


Neutron Production in Extensive Air Showers

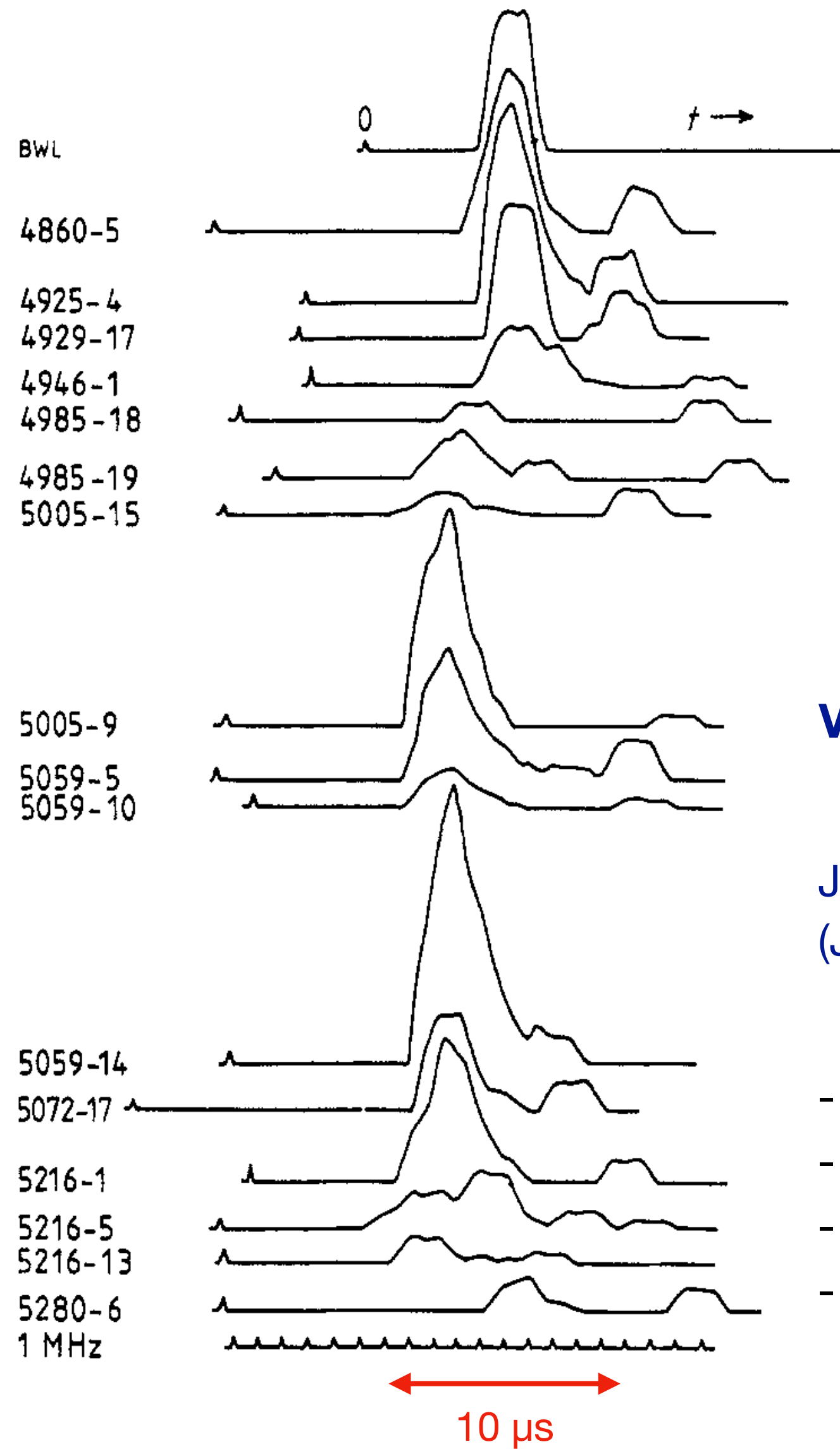
– A Simulation Study –

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

Karlsruhe Institute of Technology



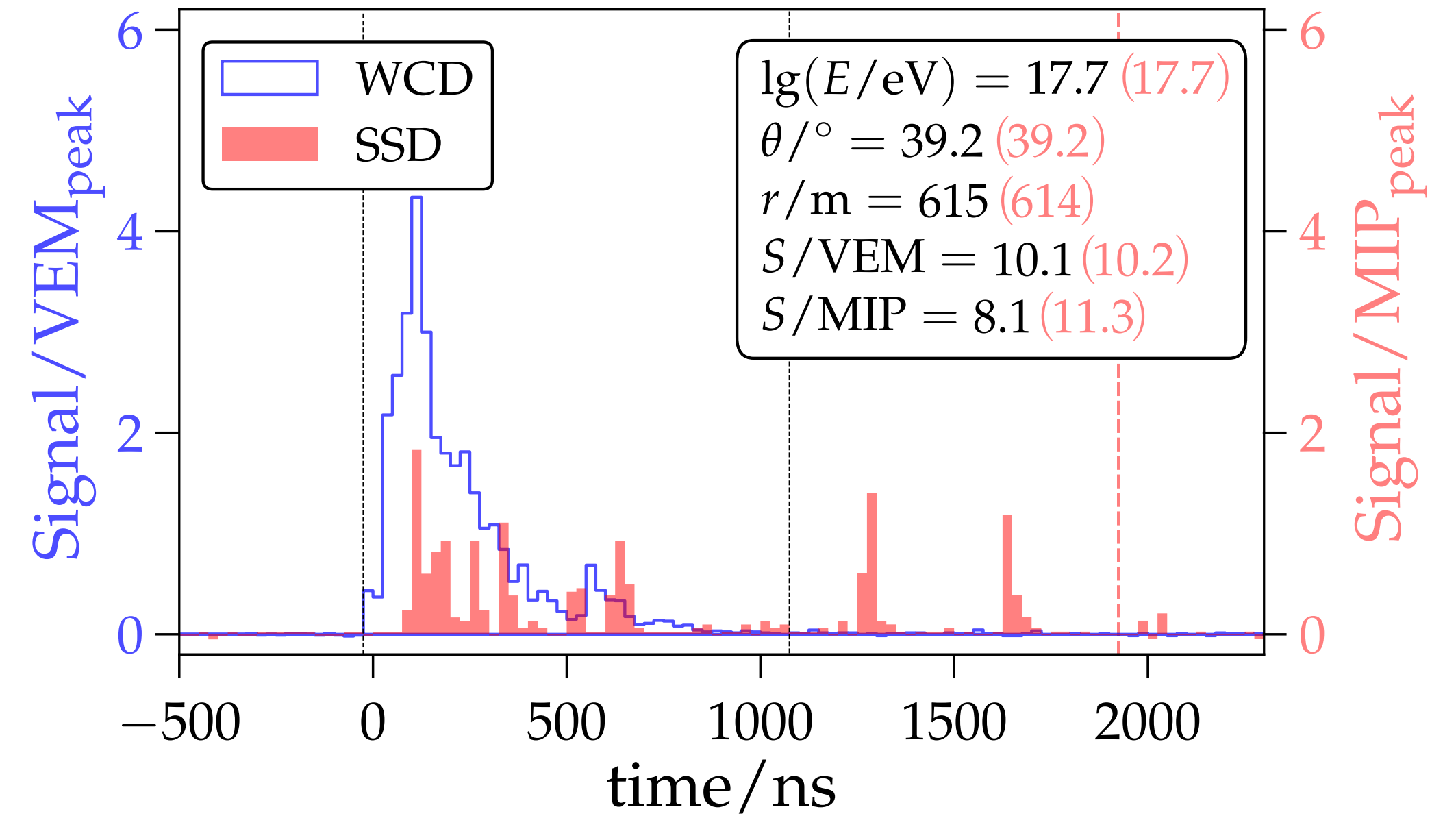
Motivation



Vulcano Ranch (1962-63)

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

- Sub-luminal pulses with a delay of at least $3\mu\text{s}$
- Sometimes several pulses observed
- Typically 1 km from core, high-energy showers
- Greisen: **neutrons** as sub-luminal particles



AugerPrime (2020-21)

D. Schmidt, Pierre Auger Collaboration
(this conference)

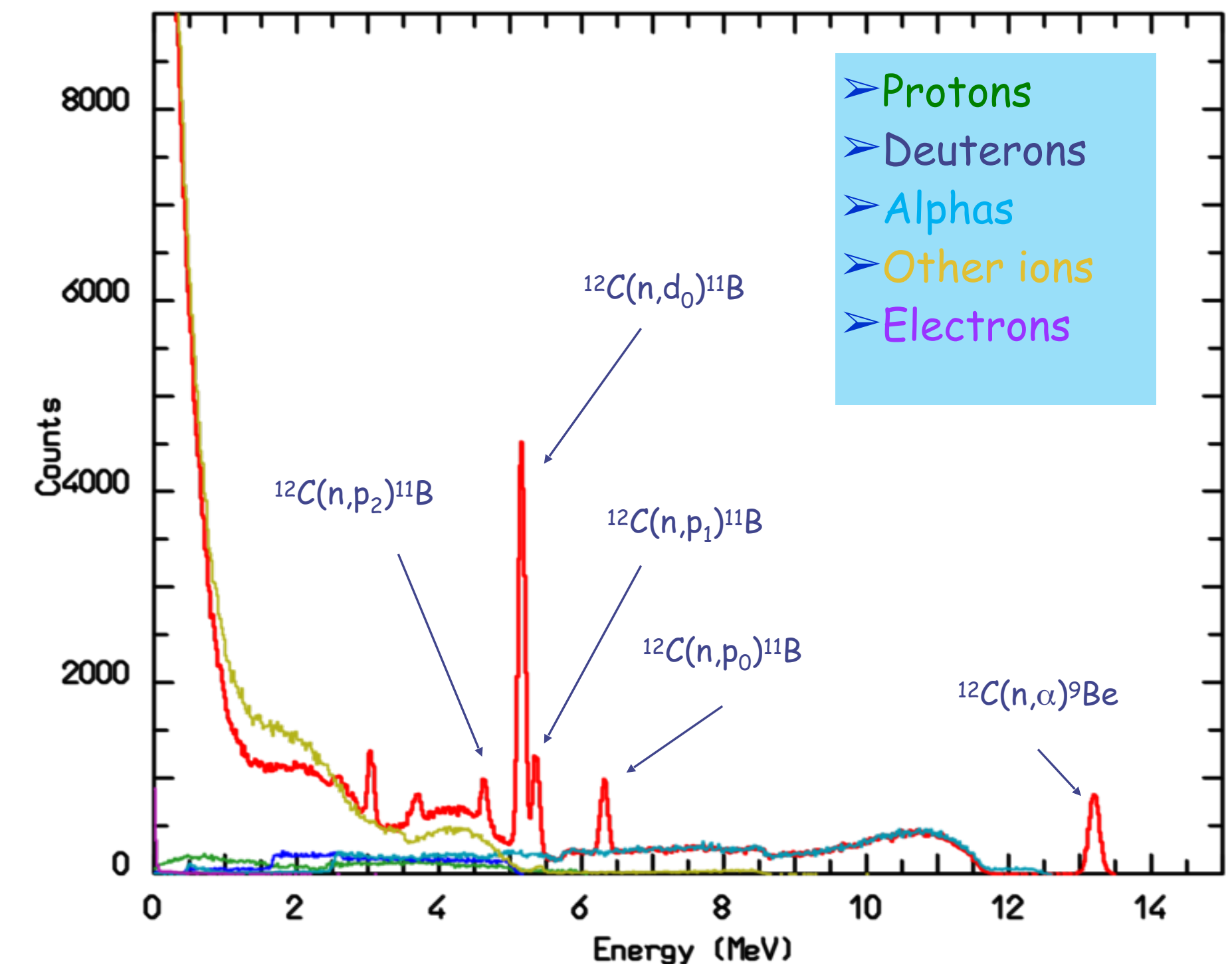
- Late signals seen in scintillators (SSD)
- Late pulses have no coincident signal in water-Cherenkov detectors (WCD)
- Similar height distribution of late pulses?

Neutrons in the cascade Monte Carlo code 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?

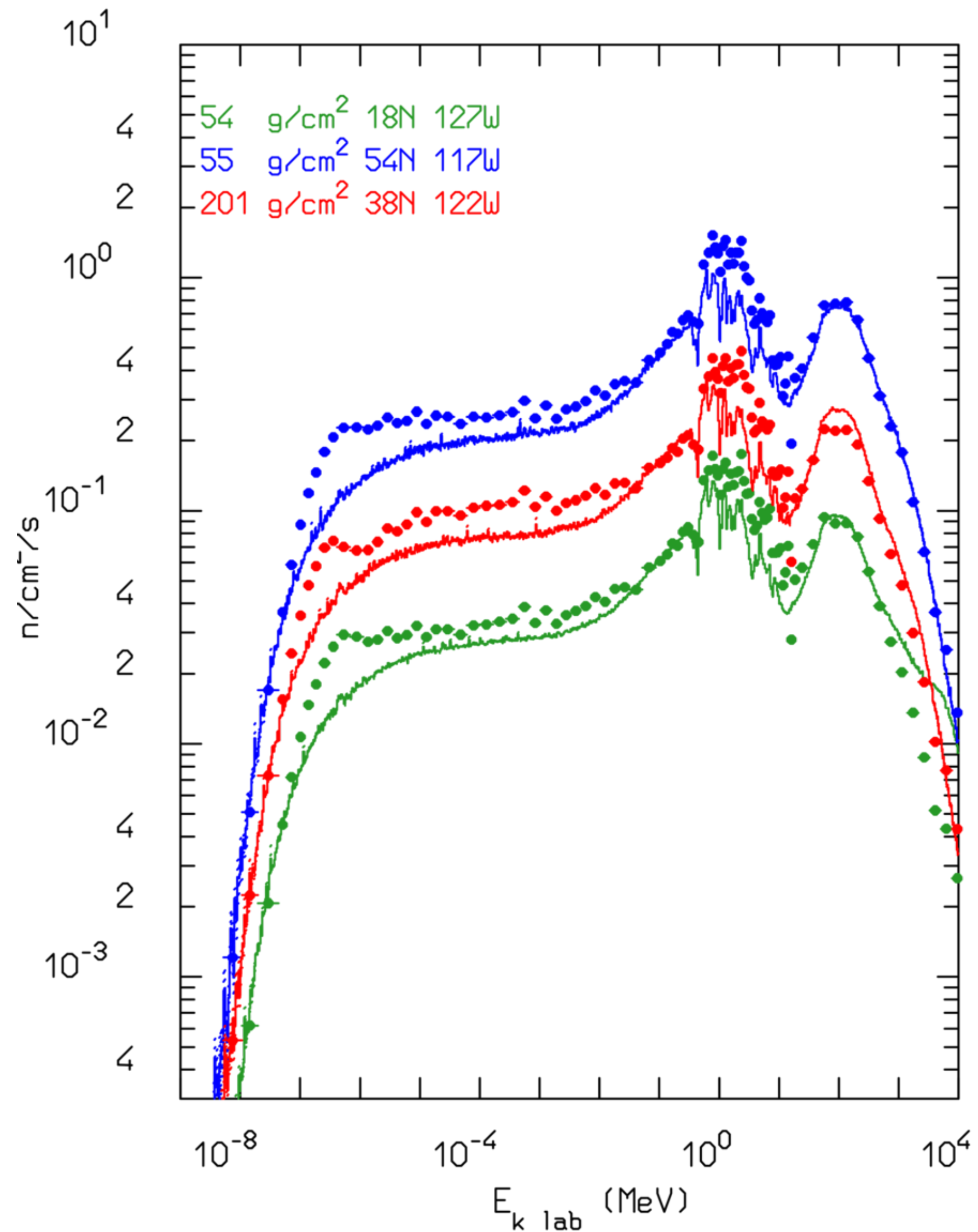
- The neutron has no charge and $\sim \infty$ lifetime \rightarrow can (only) undergo nuclear interactions even at very low energies, e.g. meV
- Neutron cross sections (σ) are complex and structure rich \rightarrow cannot be calculated by models \rightarrow we rely (like all codes) on evaluated data files
- Even at “thermal” energies neutrons can still generate several MeV’s of γ ’s and/or charged particles through capture



Example: deposited energy on a 500 μm thick diamond detector, for 18.91 MeV neutrons

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

Benchmarking FLUKA with cosmic-ray neutron data

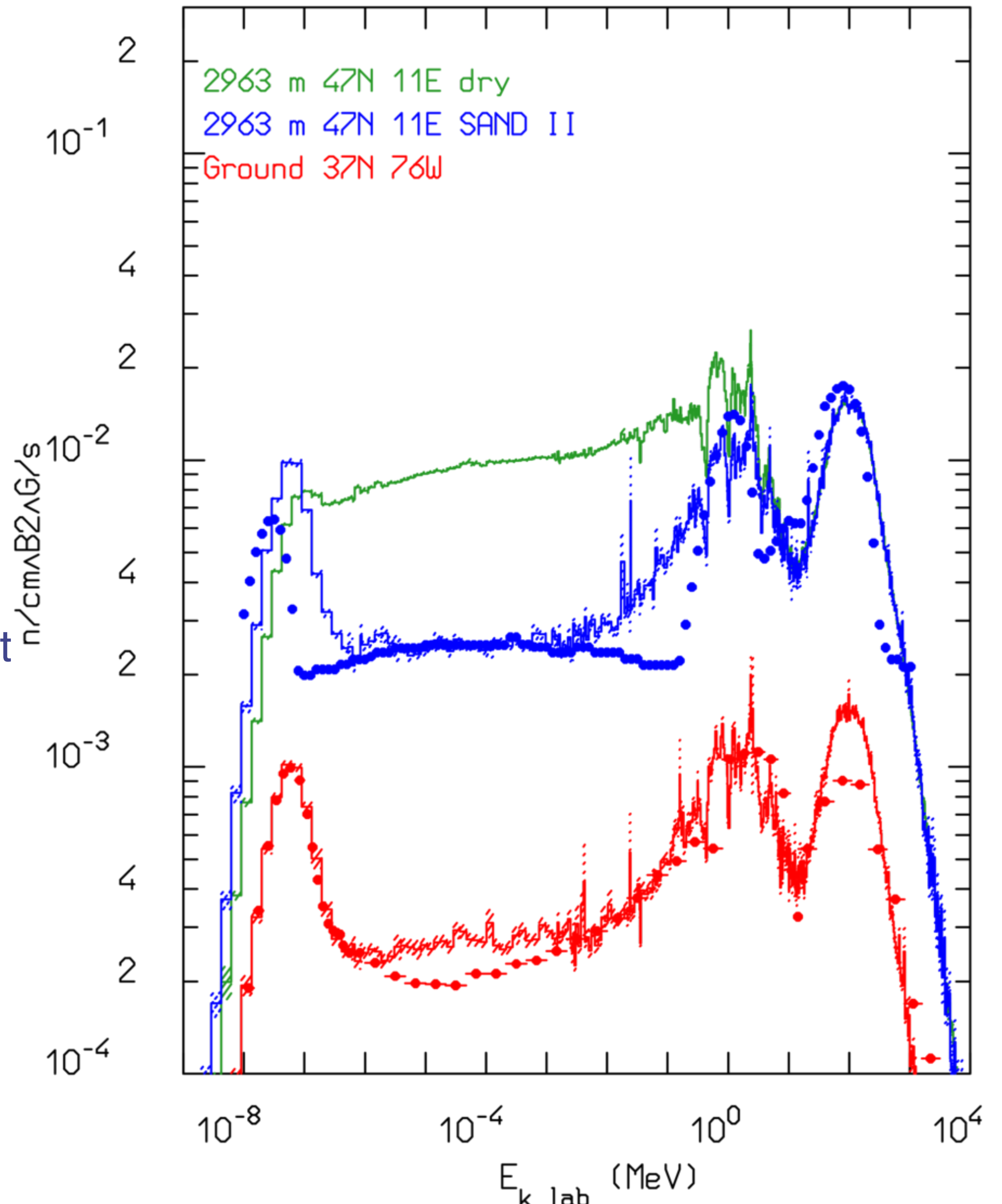


Left: neutron energy spectrum from air plane measurements at different depths

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



Expectations for muons

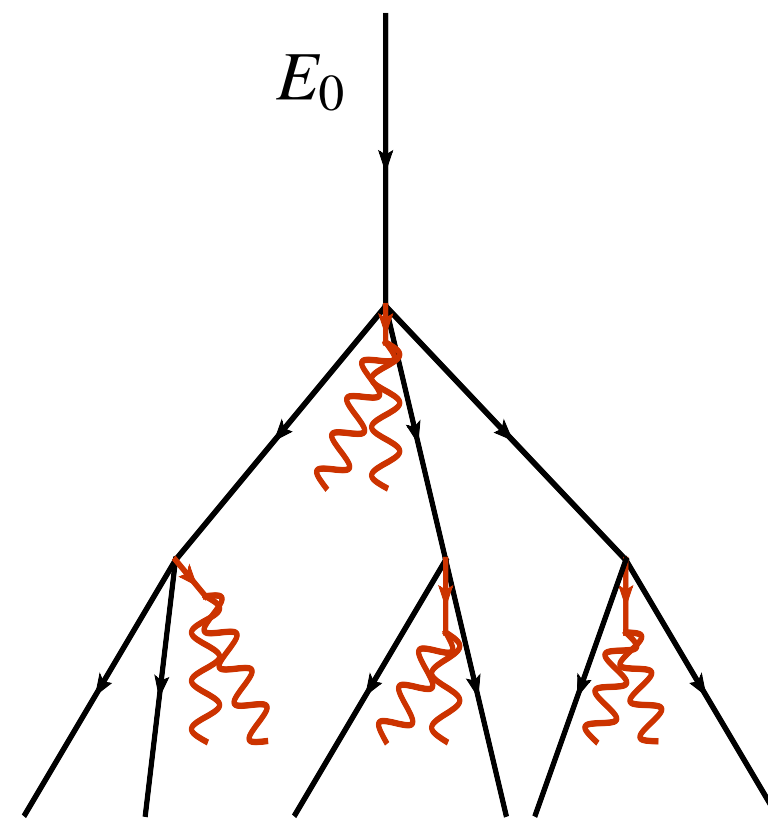
Multiplicity of charged pions

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

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

⋮

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



After k generations ...

$$E_{k_{\text{max}}} = E_{\text{dec}}$$

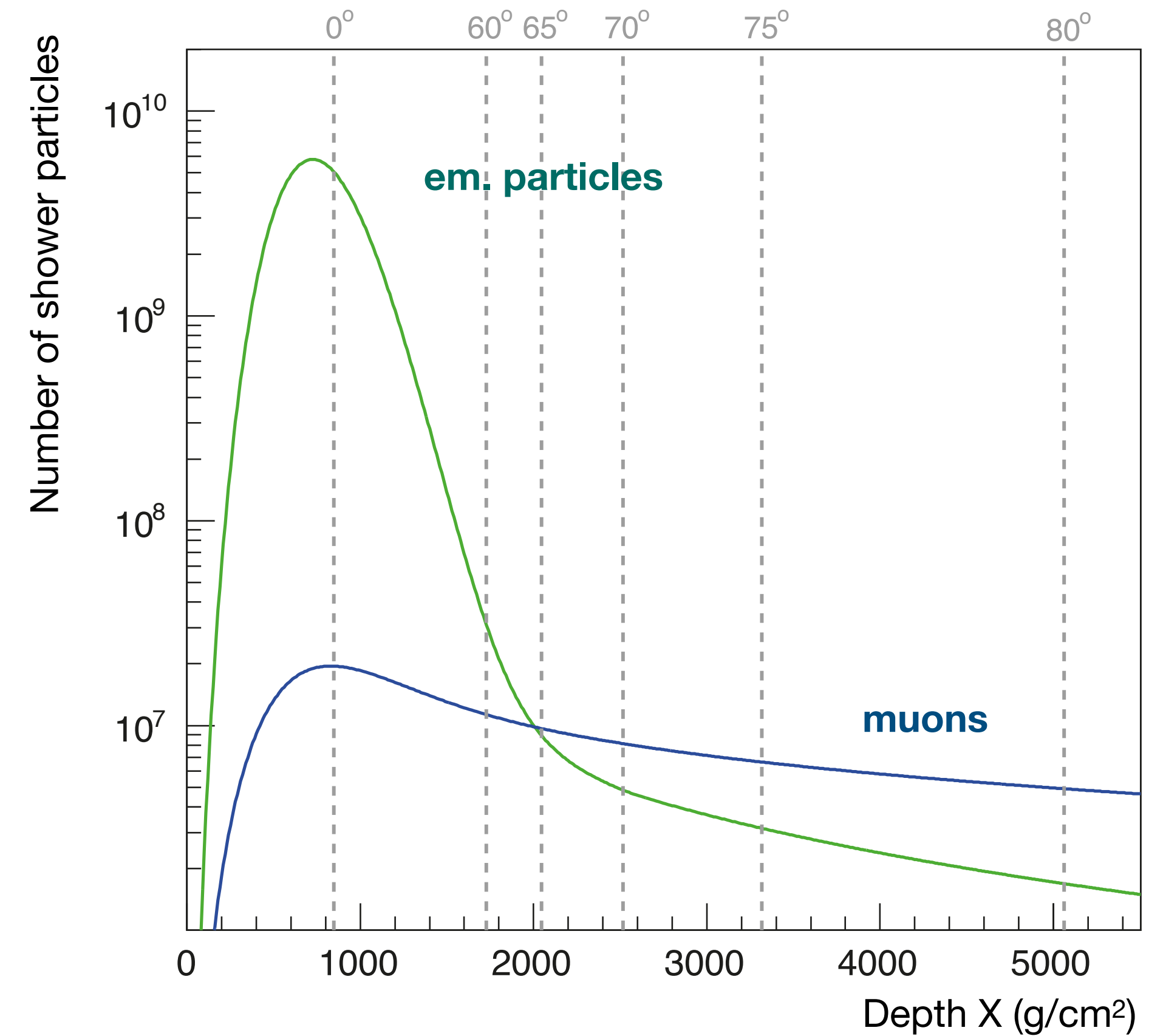
Energy per particle

$$E_1 = \frac{E_0}{n_{\text{tot}}}$$

$$E_2 = \frac{E_0}{(n_{\text{tot}})^2}$$

⋮

$$E_k = \frac{E_0}{(n_{\text{tot}})^k}$$



(Matthews, APP22, 2005)

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

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

$$N_\mu^A = A \left(\frac{E_0}{A E_{\text{dec}}} \right)^\beta = A^{1-\beta} N_\mu$$

Muons

$$X_{\text{att,sim}} \sim 700 \dots 800 \text{ g/cm}^2$$

$$X_{\text{att,KG}} \sim 1250 \text{ g/cm}^2$$

Expectations for neutrons

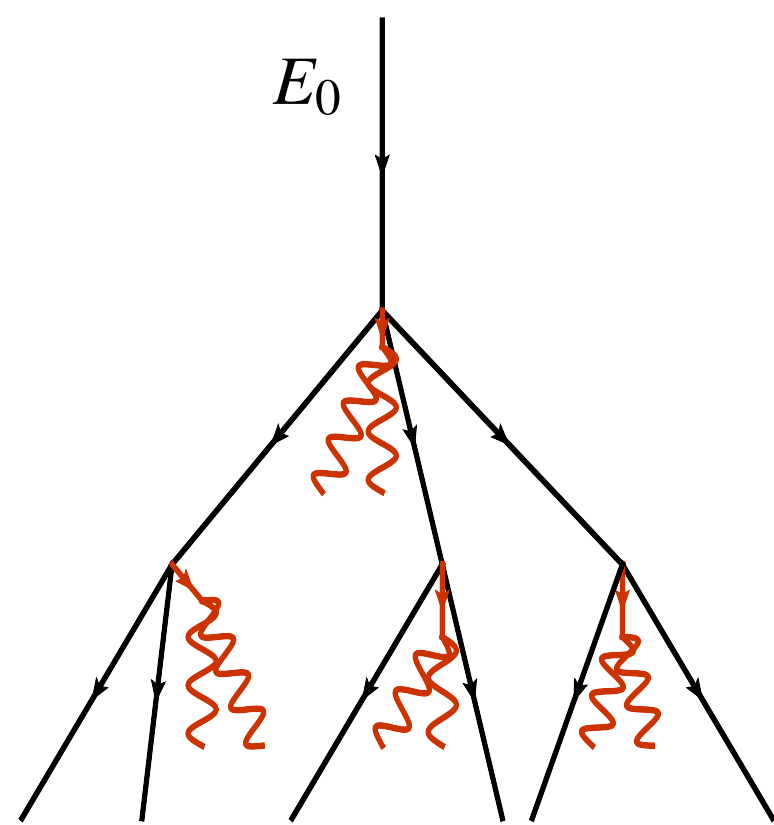
Multiplicity of neutrons

$$N_{n,1} = \epsilon n_{ch}$$

$$N_{n,2} = \epsilon n_{ch} + \epsilon (n_{ch})^2$$

⋮

$$N_{n,k} = \epsilon \sum_{i=1}^k (n_{ch})^i$$



After k generations ...

$$E_{k_{\max}} = E_{\text{dec}}$$

(Mathews, APP22, 2005)

$$N_n \sim \left(\frac{E_0}{E_{\text{dec}}} \right)^\beta$$

Energy per particle

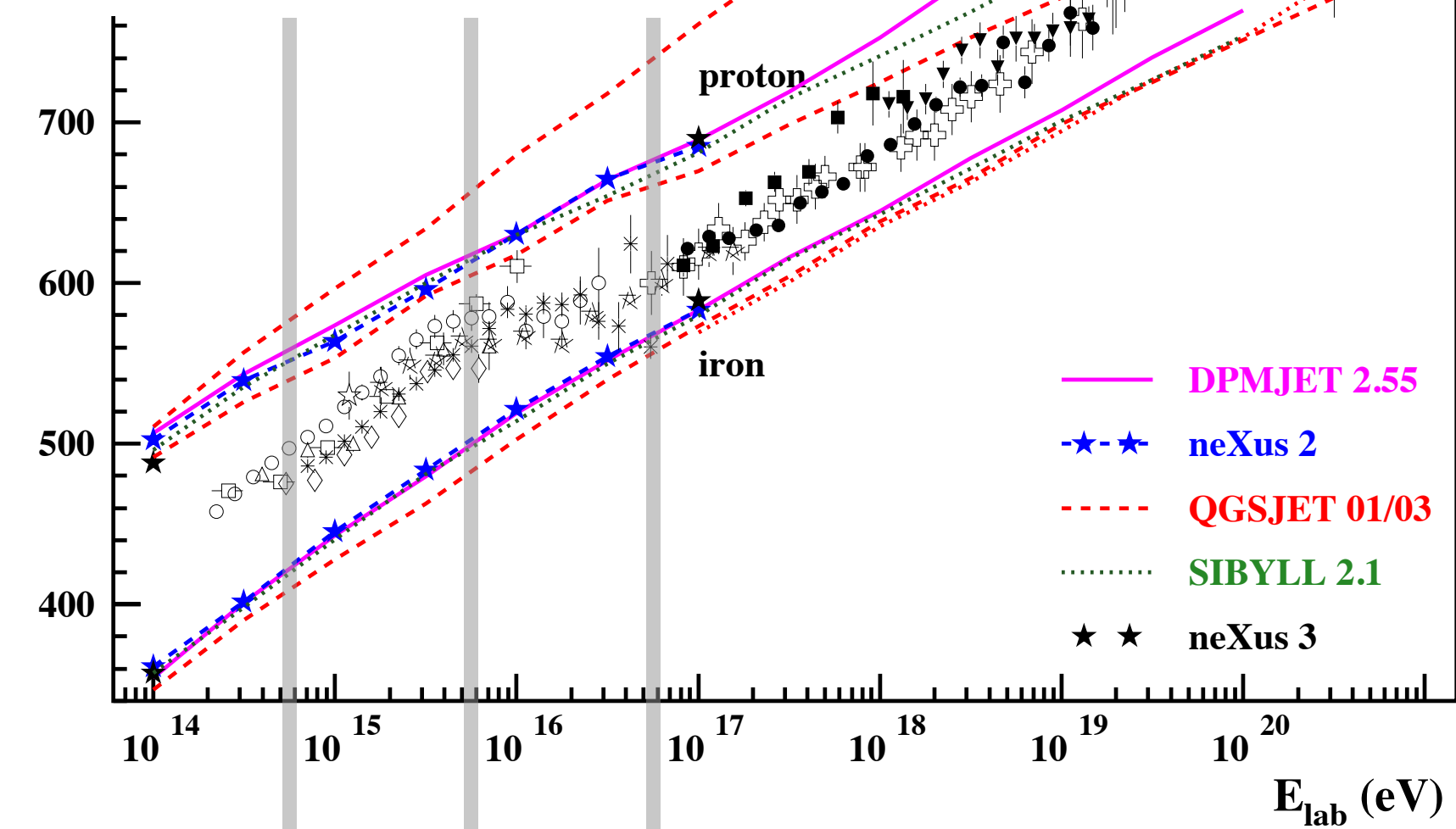
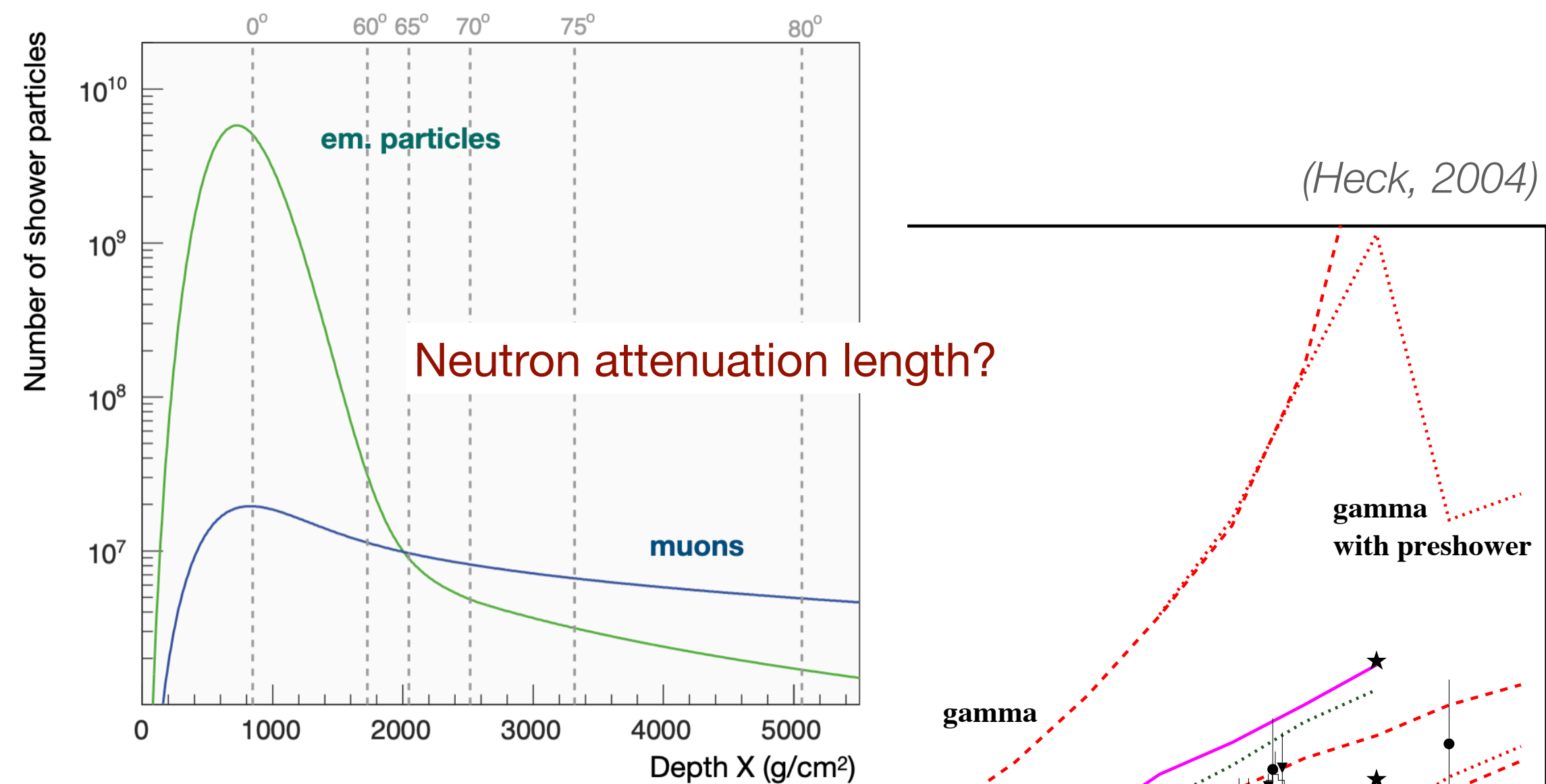
$$E_1 = \frac{E_0}{n_{\text{tot}}}$$

$$E_2 = \frac{E_0}{(n_{\text{tot}})^2}$$

⋮

$$E_k = \frac{E_0}{(n_{\text{tot}})^k}$$

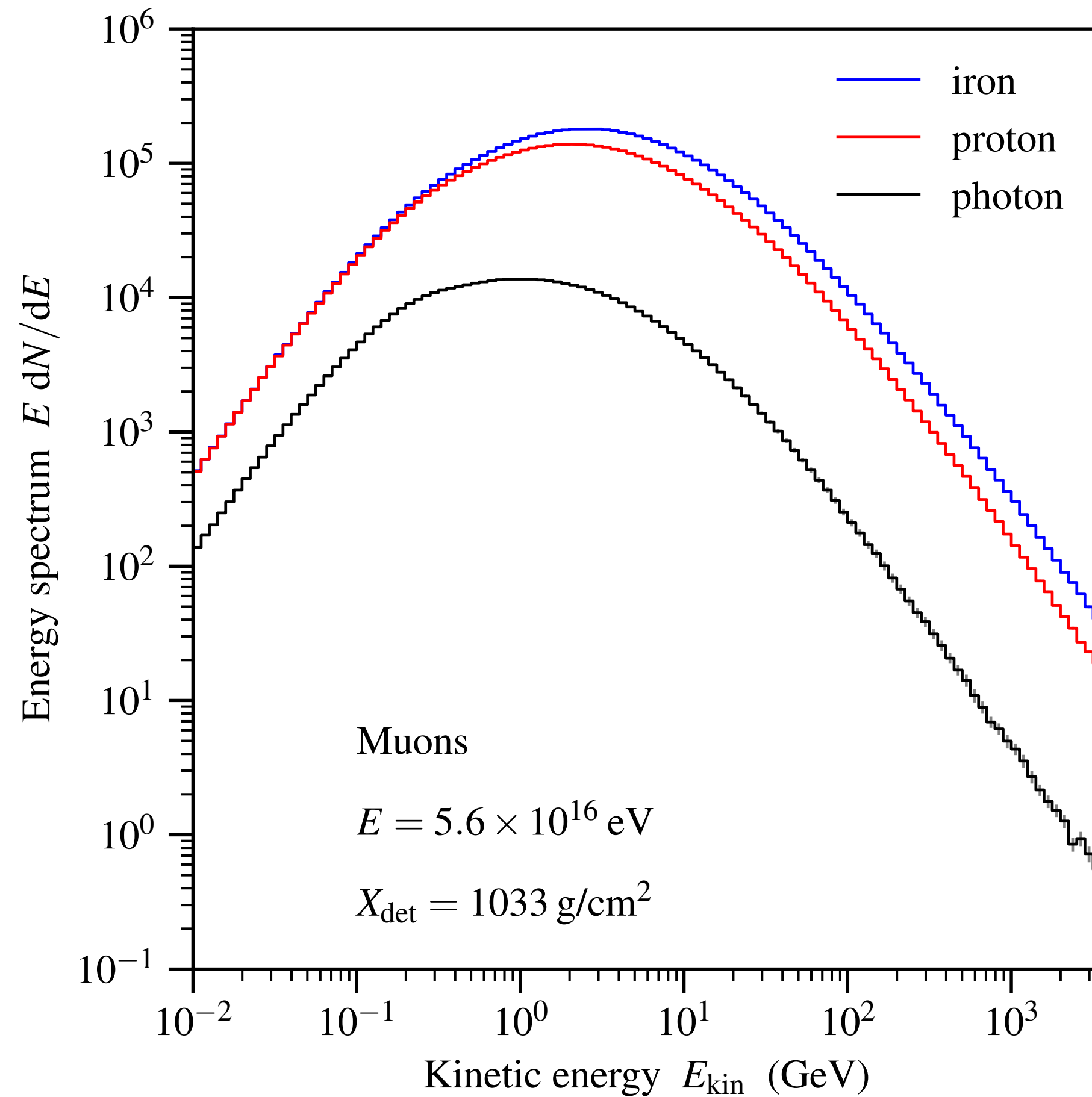
$$N_n^A \sim A^{1-\beta} N_n \sim 1.4 N_n$$



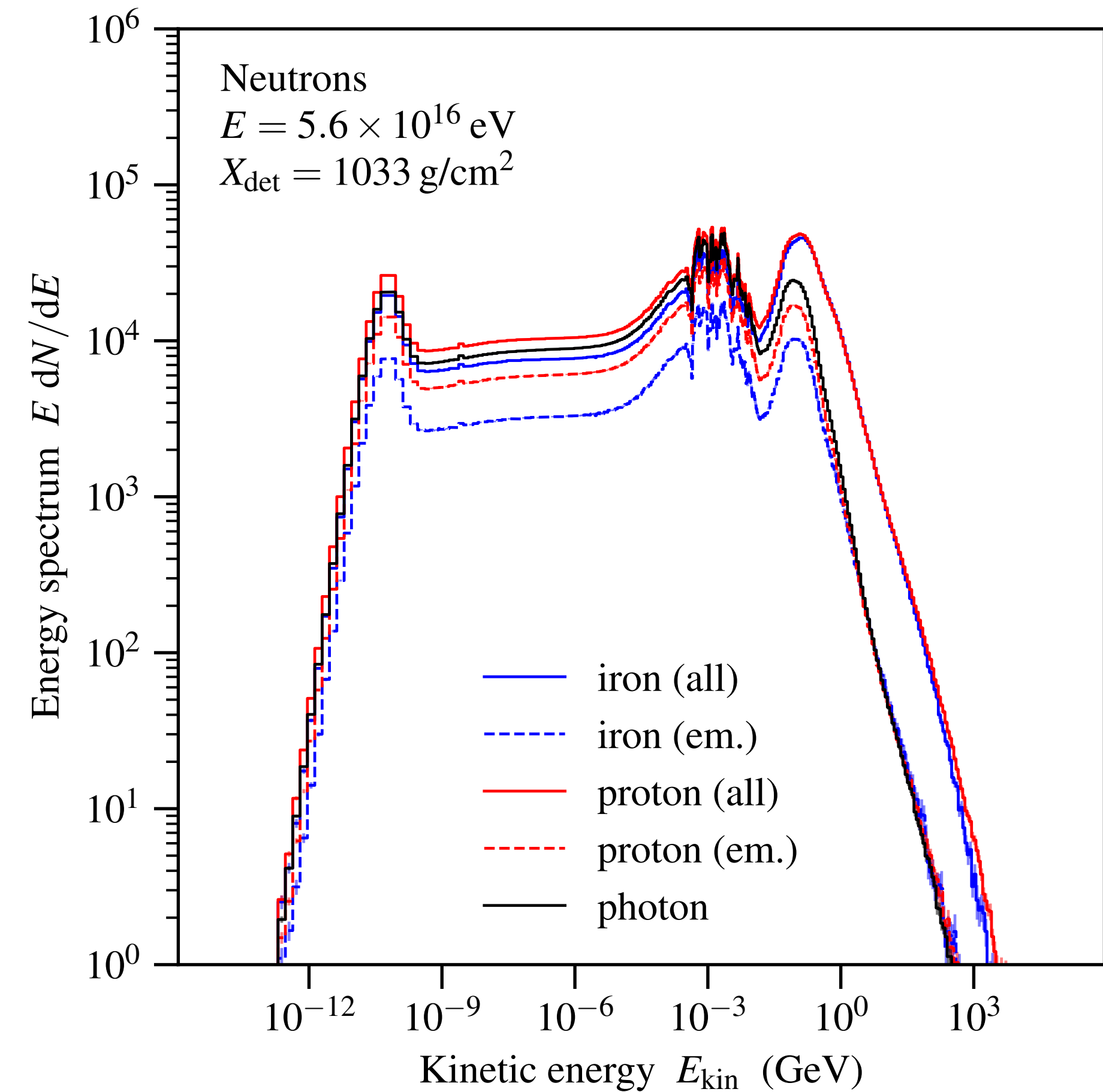
Simulated energies

$$X_{\text{max}}^{\text{p}} - X_{\text{max}}^{\text{Fe}} \sim 100 \dots 120 \text{ g/cm}^2$$

Air shower results: primary particle dependence

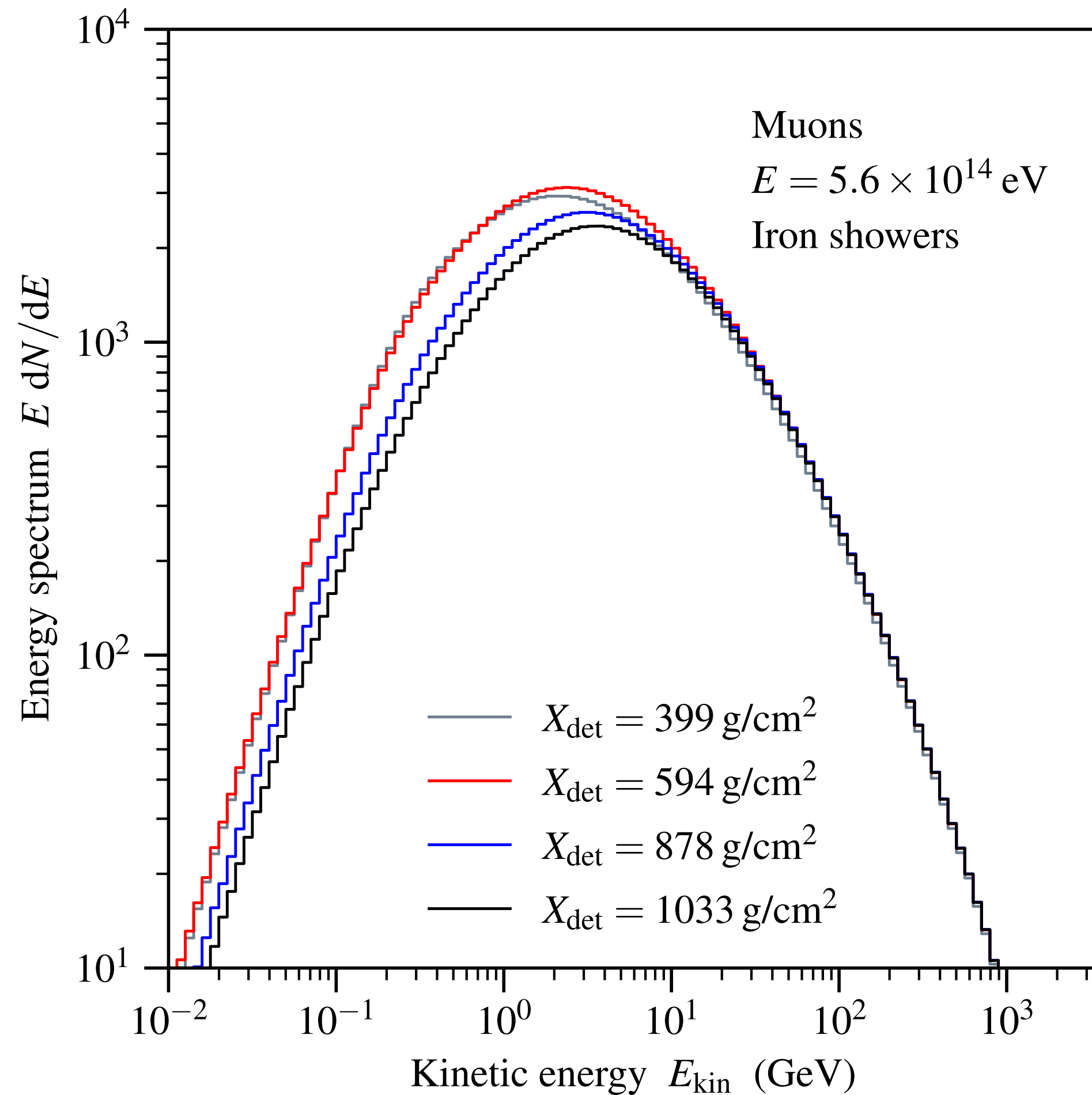


Muons: expected difference between primaries reproduced

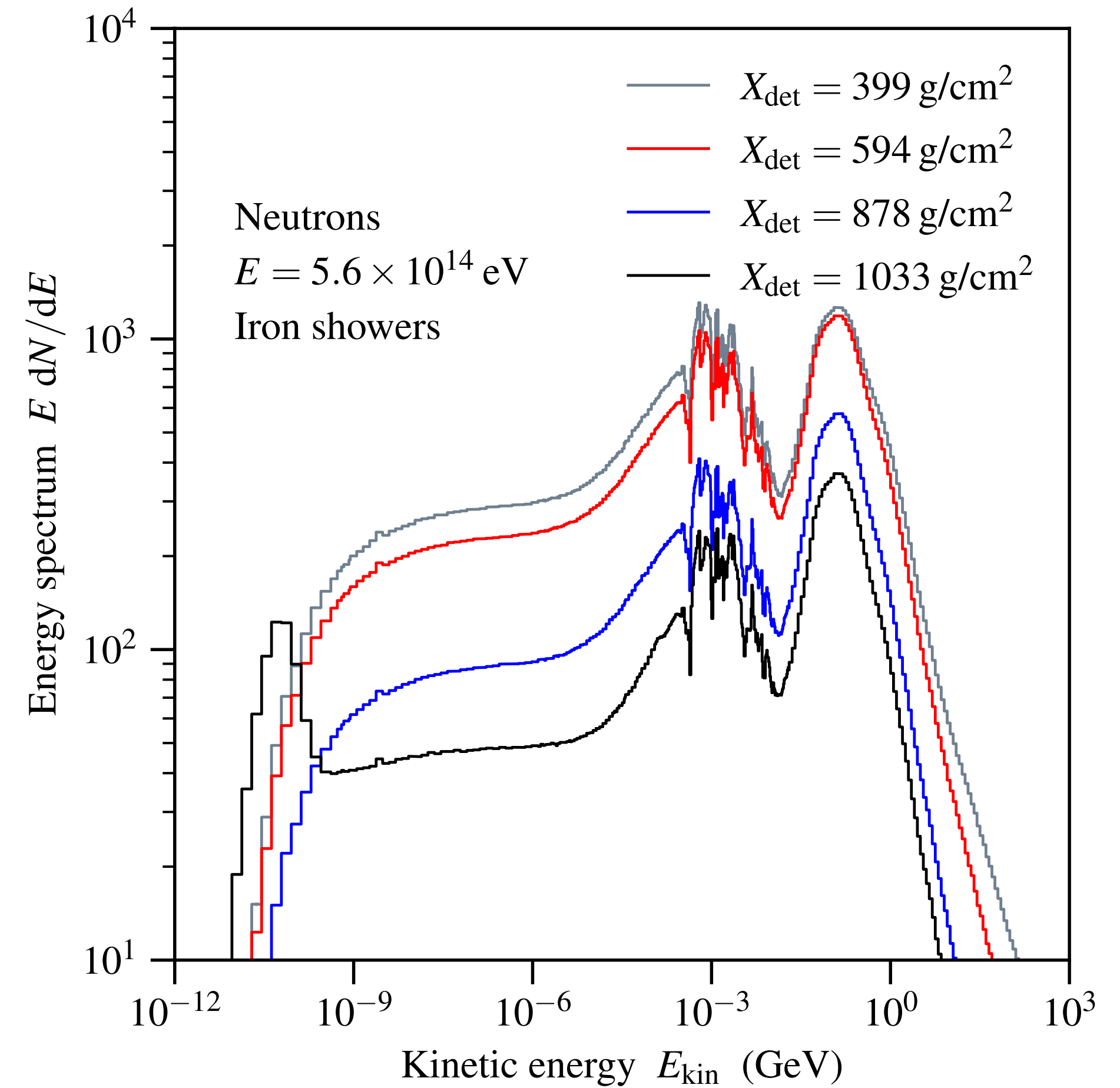


Neutrons: high-energy part surprisingly similar for hadron primaries, low-energy part dominated by attenuation

Air shower results: depth evolution (attenuation)



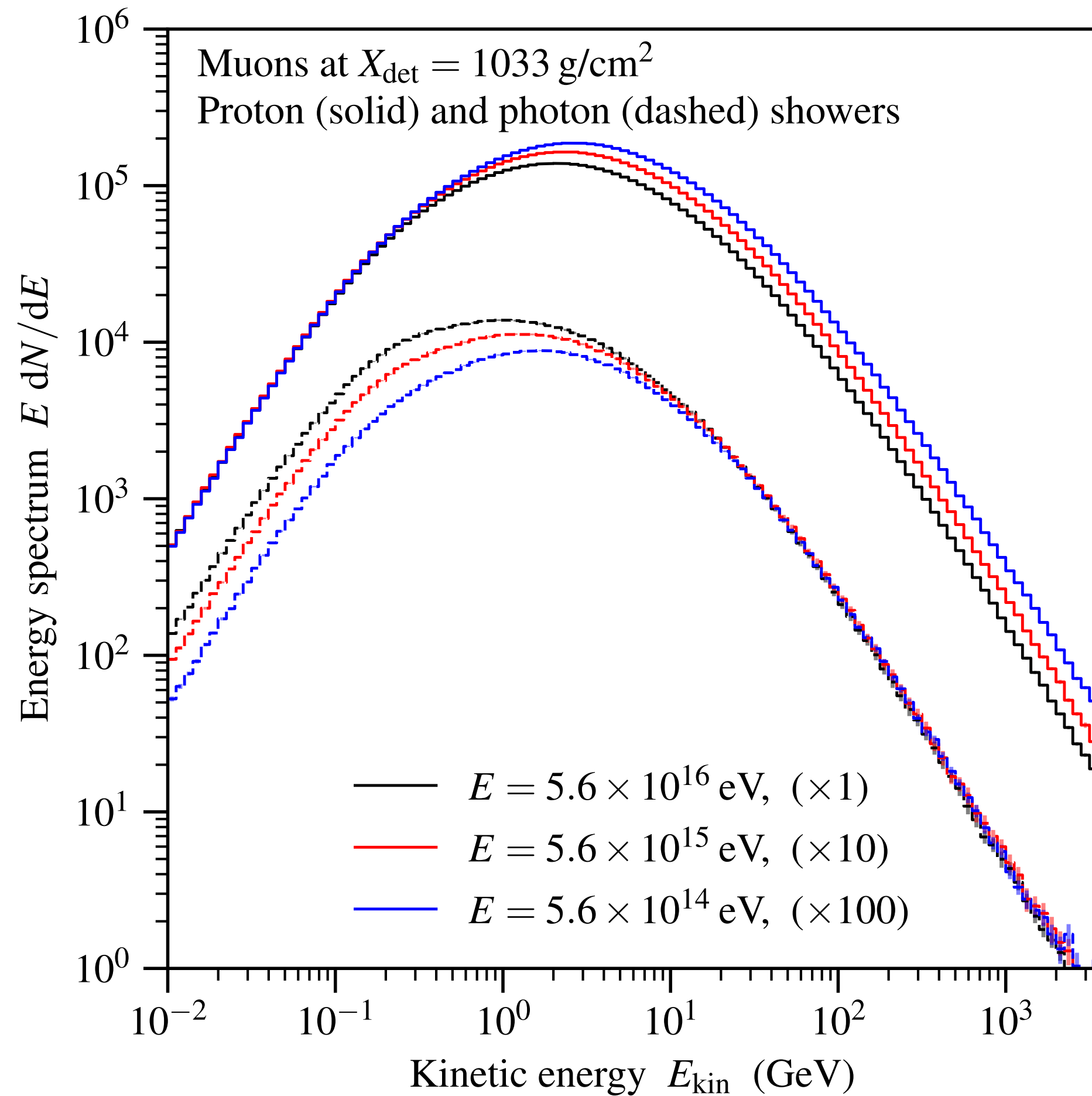
Muons: attenuation negligible in depth range,
 low-energy part dominated by muon decay



Neutrons: significant depth-dependent attenuation

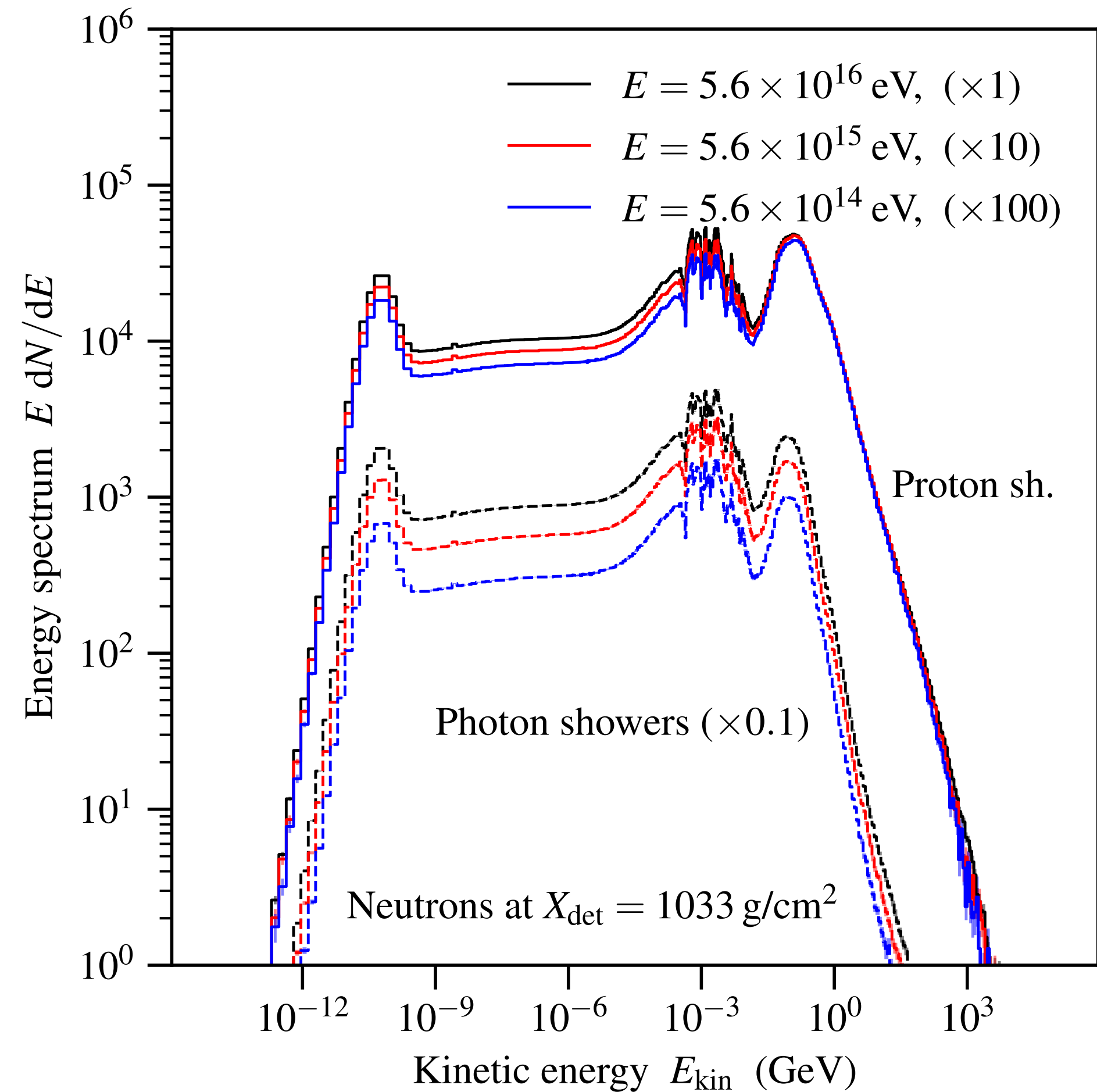
$$X_{\text{att,n}} \sim 200 \dots 80 \text{ g/cm}^2$$

Air shower results: energy dependence



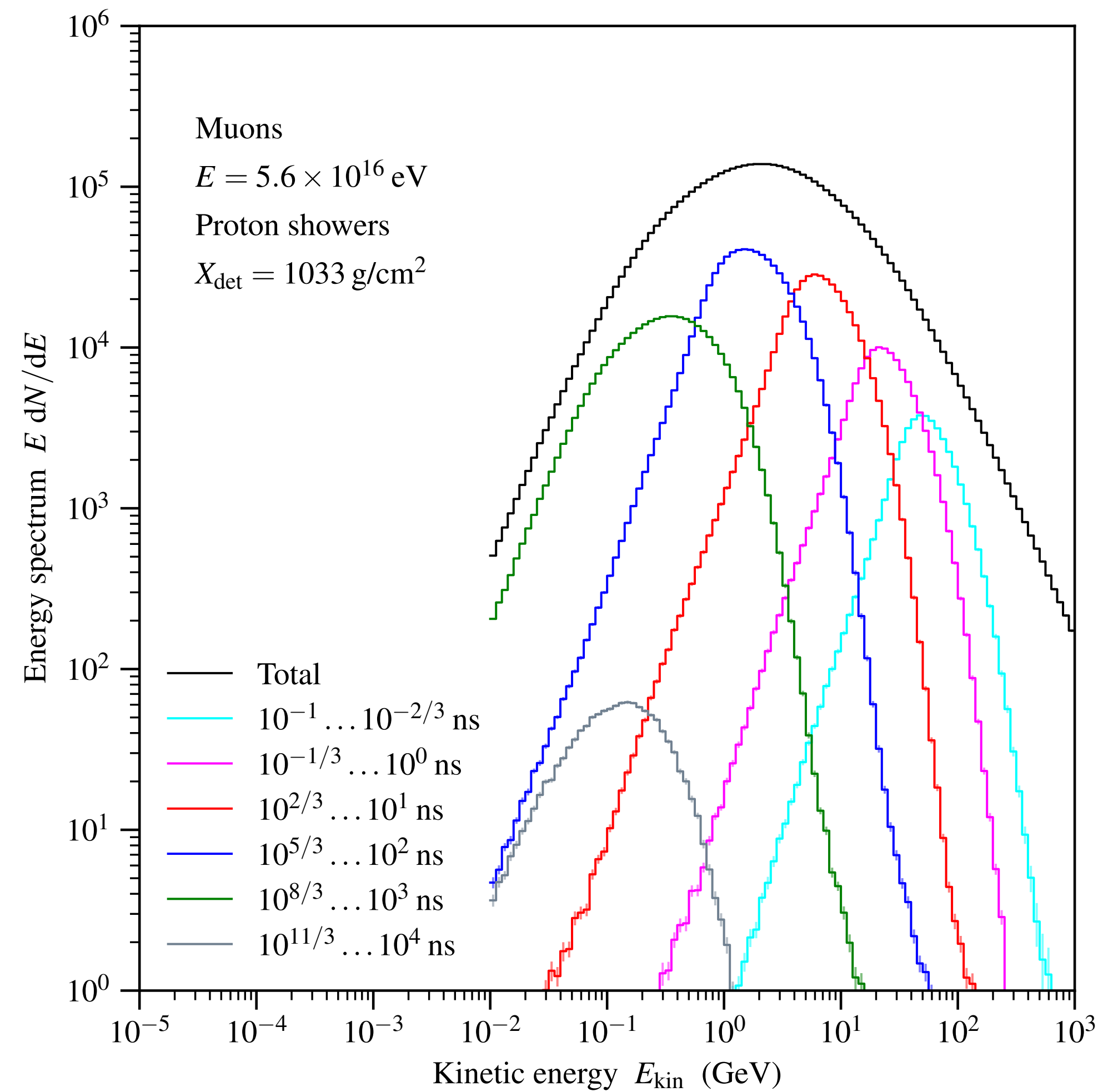
Muons: expected energy scaling for high-energy part

$$N_{\mu} \sim (E_{\text{had}})^{0.9} \quad N_{\mu} \sim E_{\gamma}$$

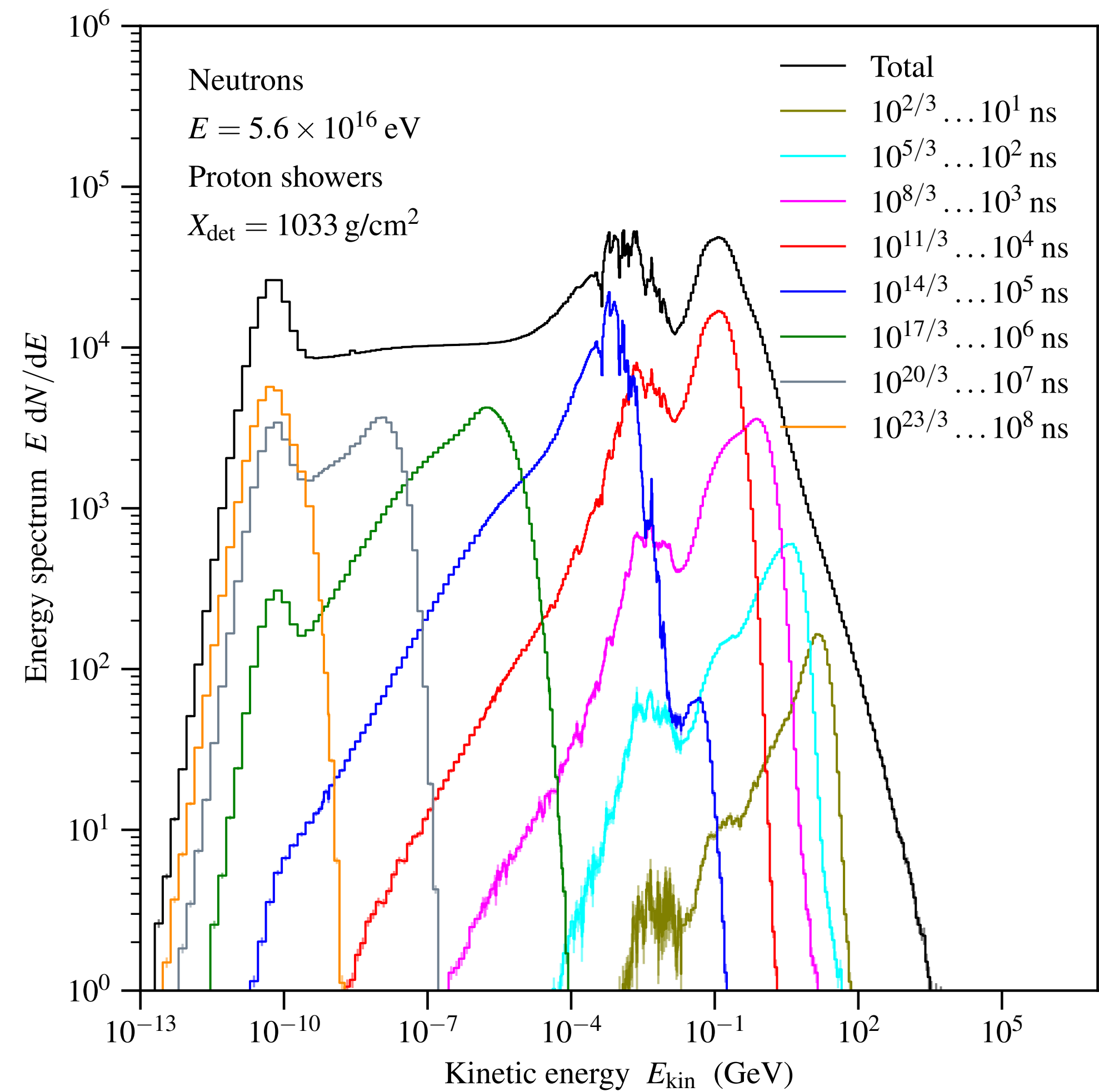


Neutrons: high-energy part seems to scale linearly with energy for hadron primaries but not for photons

Air shower results: time delay distribution

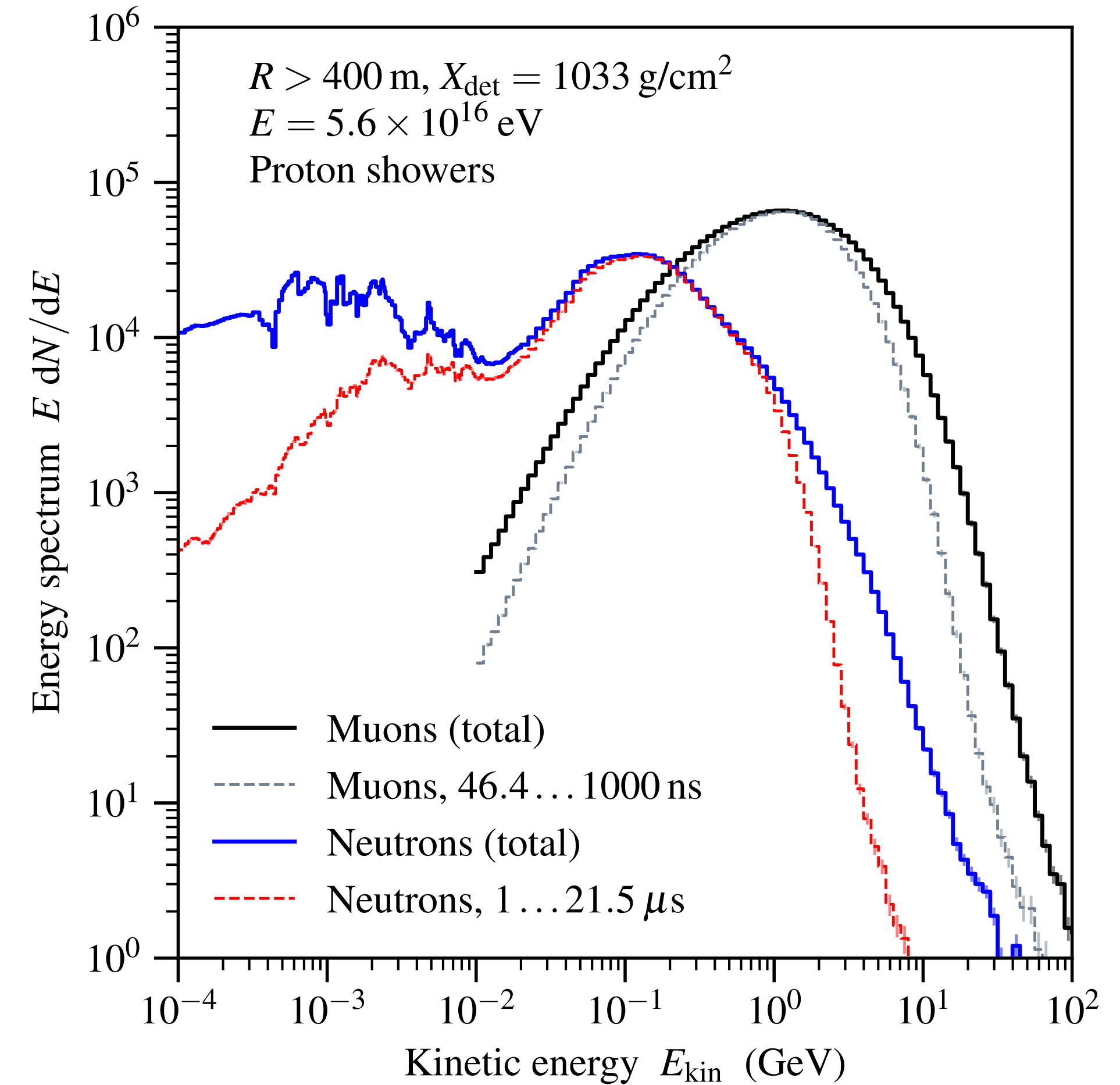
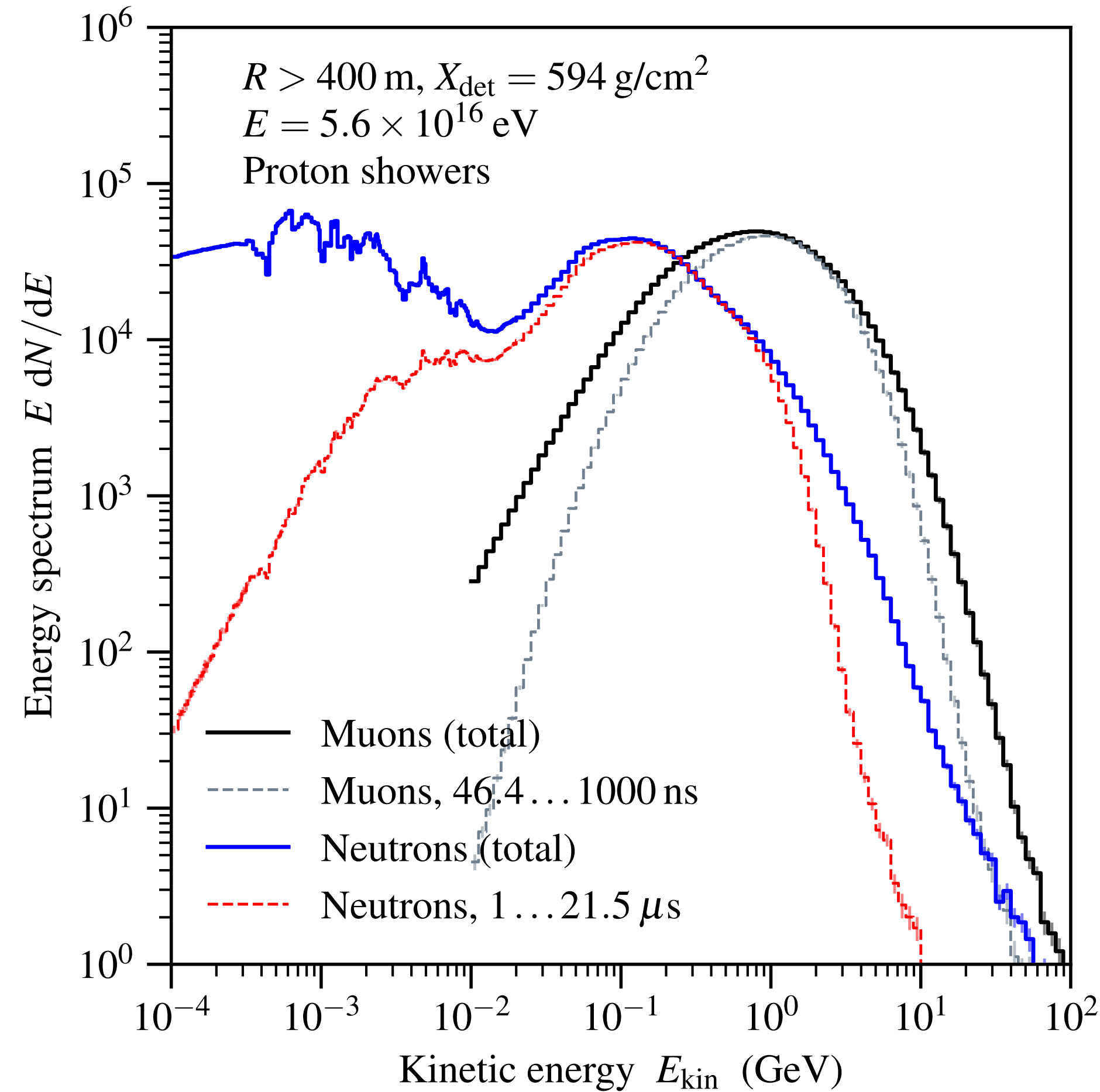


Muons: time delay of bulk of particles: 1 - 500 ns



Neutrons: time delay of high-energy particles: 1 - 20 μ s,
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

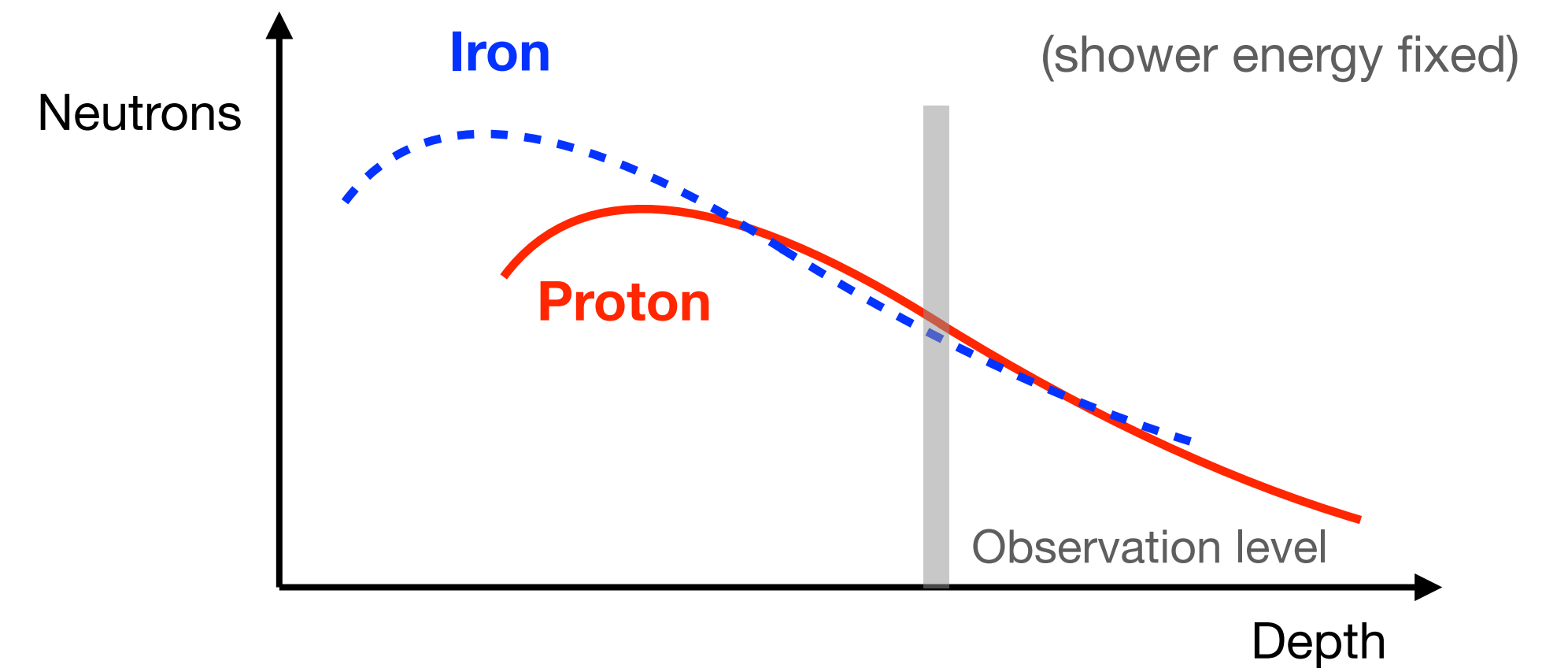
Summary

Neutrons

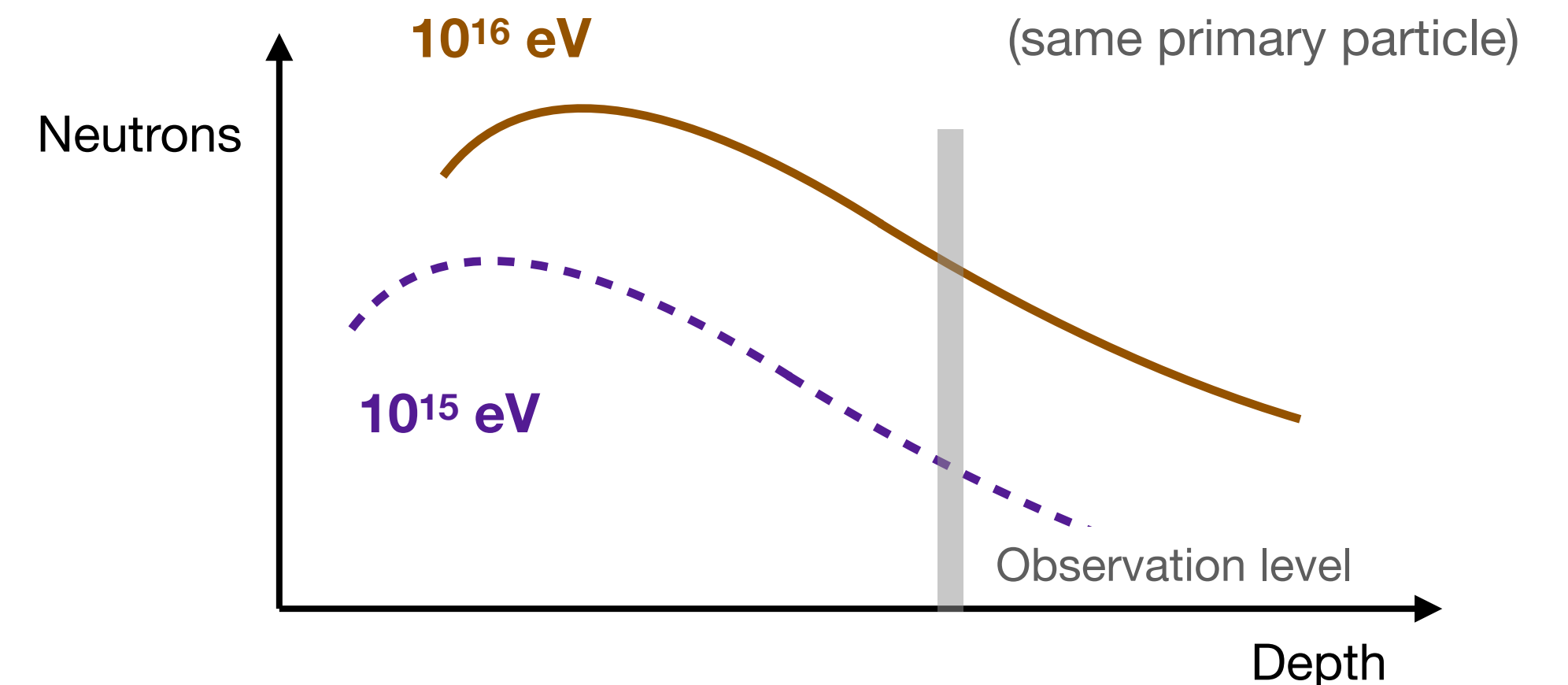
- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators

Scaling observations

- Energy scaling of production similar to muons
- Primary dependence of production like muons
- Attenuation (neutron removal) length 80 ... 200 g/cm²
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 ... 20 μs ($E_{\text{kin}} > 20$ MeV)
- Thermal neutrons up to ~ 100 ms



Reduced composition sensitivity?



Scaling faster than $\sim E^{0.9}$

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.

Note by Michael Hillas on neutrons

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