The decoherence curve - measuring the lateral distribution of muons in cosmic-ray air showers

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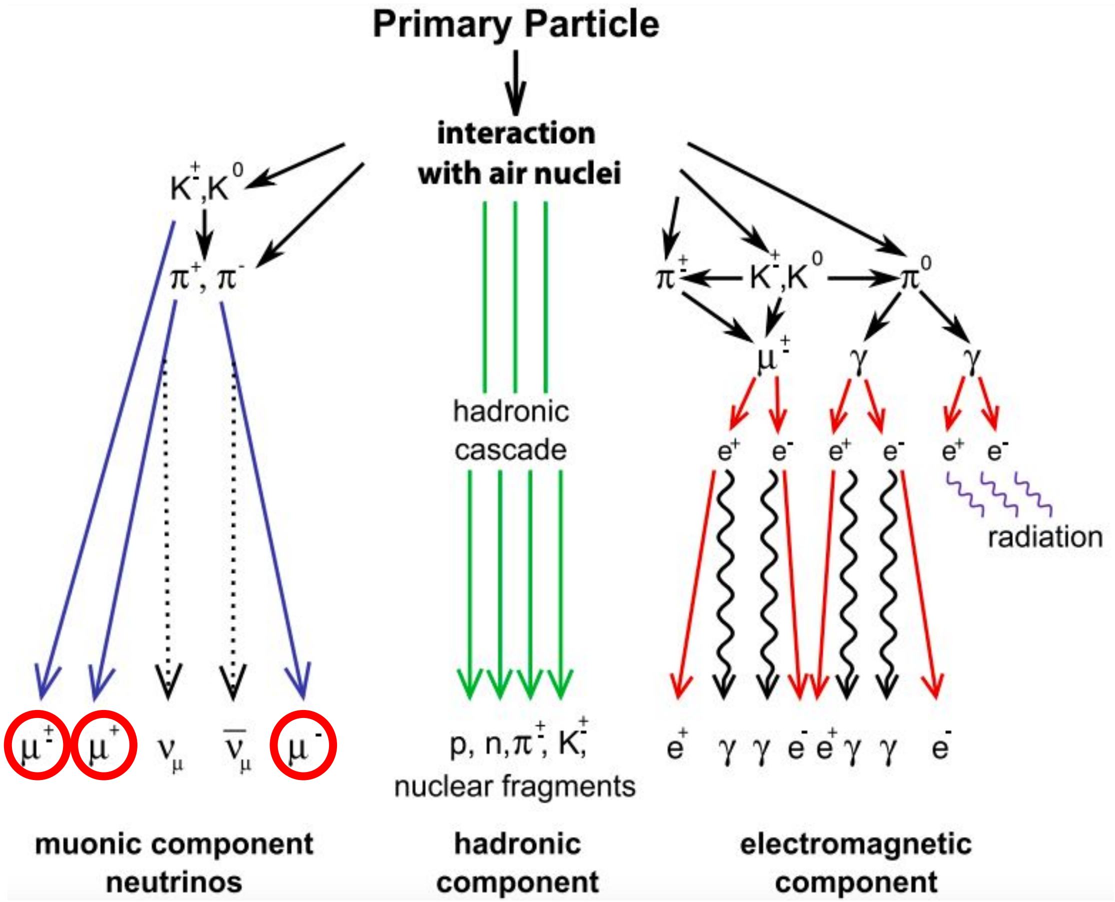
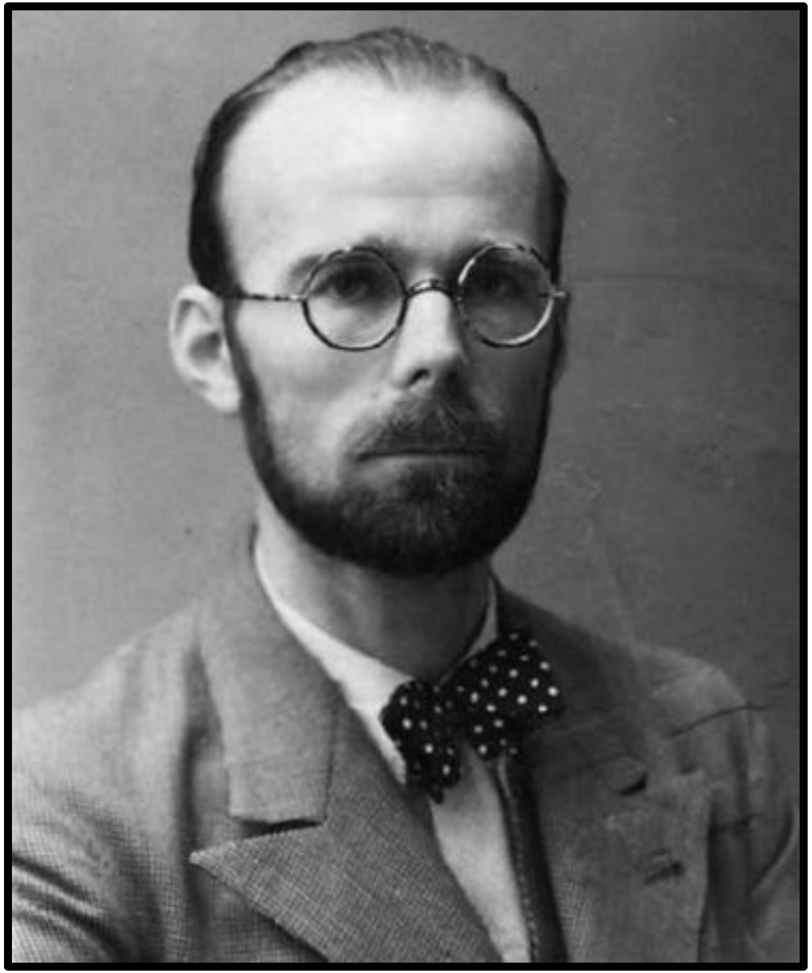
Cosmic-ray muons, μ- and μ+, are created in the upper atmosphere when high-energy cosmic-ray primary particles interact with the nuclei of atmospheric particles, a process that produces pions, π + and π −, which in turn produce muons via their decays

(KASCADE Collaboration, 2018; Lal & Peters, 1967)



- **Pierre Auger**
    - Discovered air showers in 1938
    - Detected coincidences between counters separated by several meters

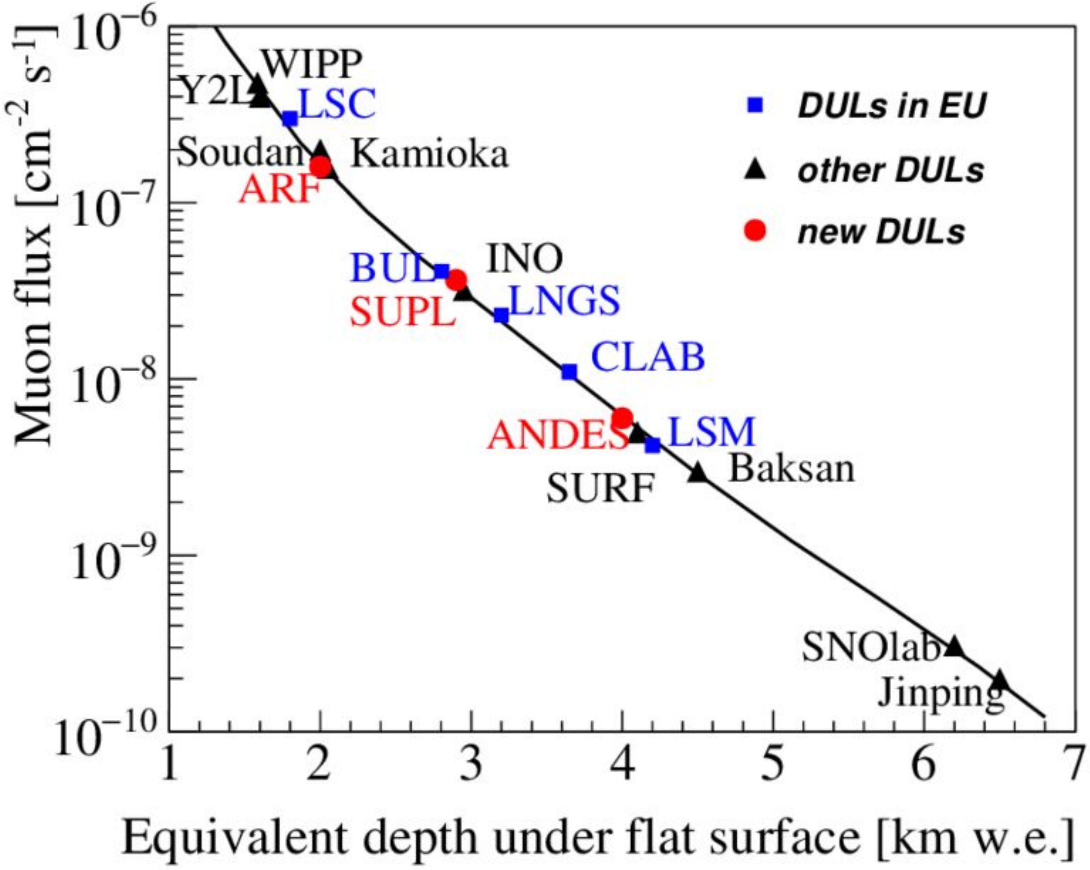
(Auger et al., 1939)



Muons are highly penetrative particles with a large time-dilated lifetime, which allows them to survive long enough to reach sea level and beyond.

Net result is a flux of muons that is easy to detect and use as a tool but is also a problem for low-background experiments.

(Rossi, 1952; Ianni, 2020)



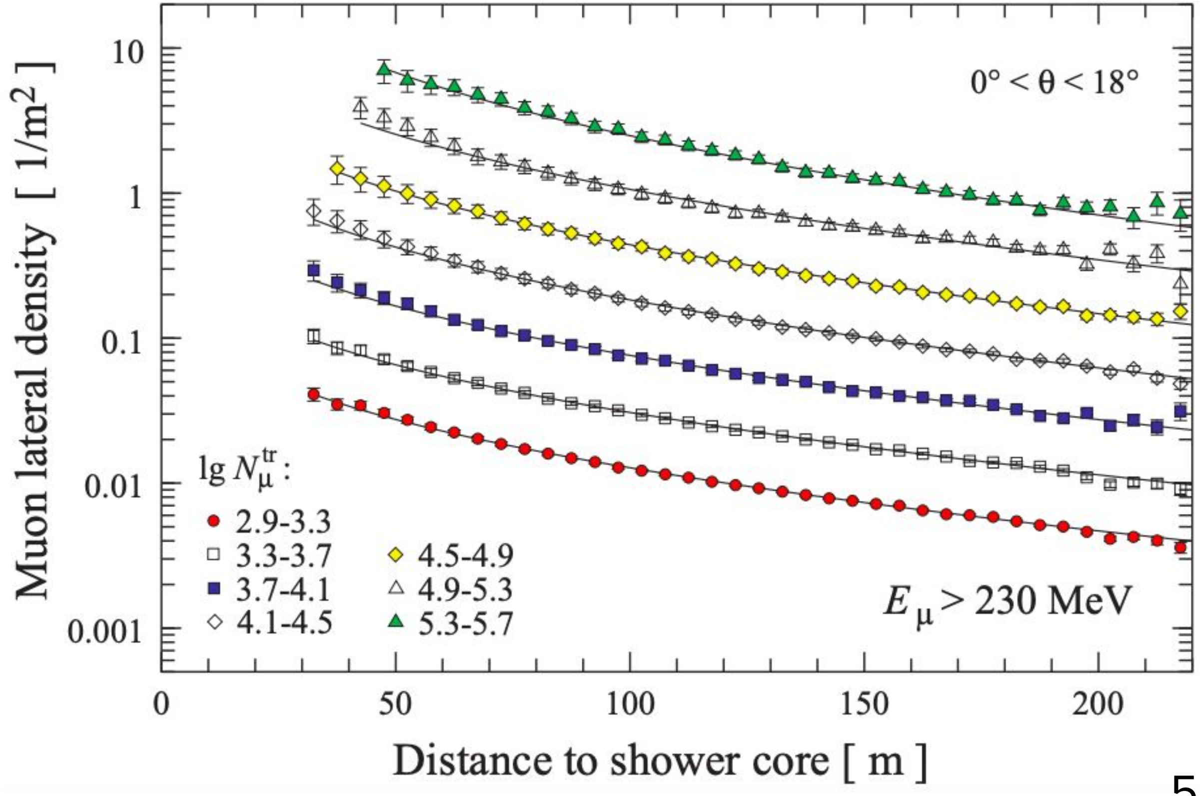
$$\rho_{\mathrm{NKG}}(r, s, N_e) = \frac{N_e}{r_{\mathrm{M}}^2} \frac{\Gamma(4.5 - s)}{2\pi\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{r_{\mathrm{M}}}\right)^{s-2} \left(1 + \frac{r}{r_{\mathrm{M}}}\right)^{s-4.5}$$

Lateral distribution of muons above 230 MeV kinetic energy fitted to NKG

The Nishimura - Kamata - Greisen (NKG) function is a well established mathematical equation used to describe the lateral distribution of charged particles, such as muons. It includes three parameters:

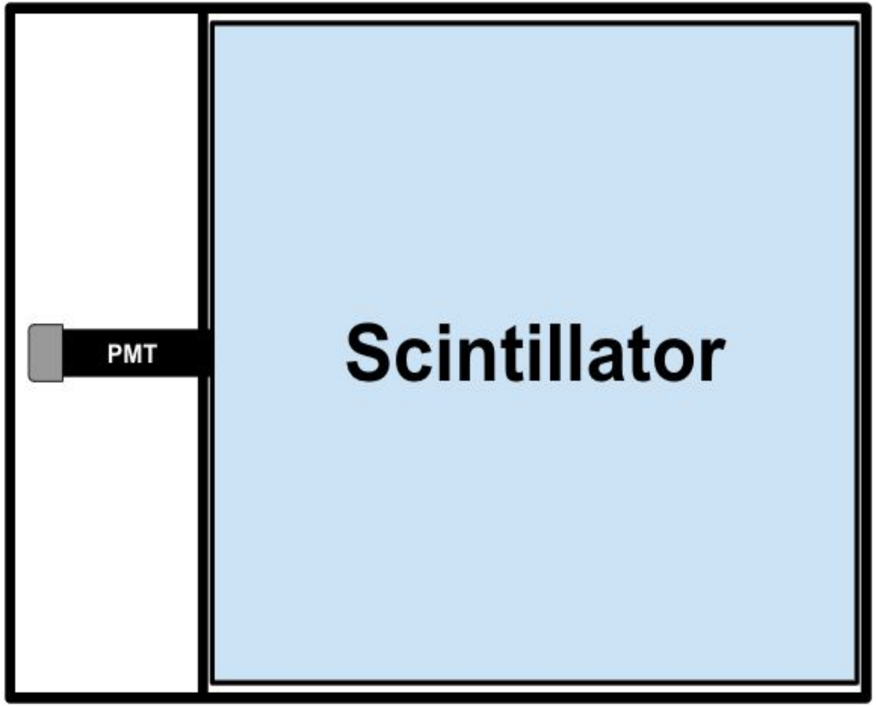
- Age parameter, s (broadening of shower)
- Molière radius, r_m (lateral size)
- Number of particles, N_e

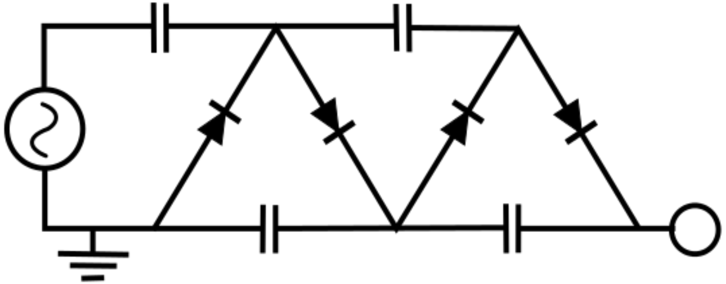
(KASCADE Collaboration, 2001; Kamata & Nishimura, 1958; Greisen, 1960)



- **Scintillation Detectors**
  - Eljen EJ200 Plastic Scintillator
  - Hamamatsu R580 Photomultiplier Tube (PMT)
  - HV Cockcroft-Walton Multiplier

(Leo, 1994)





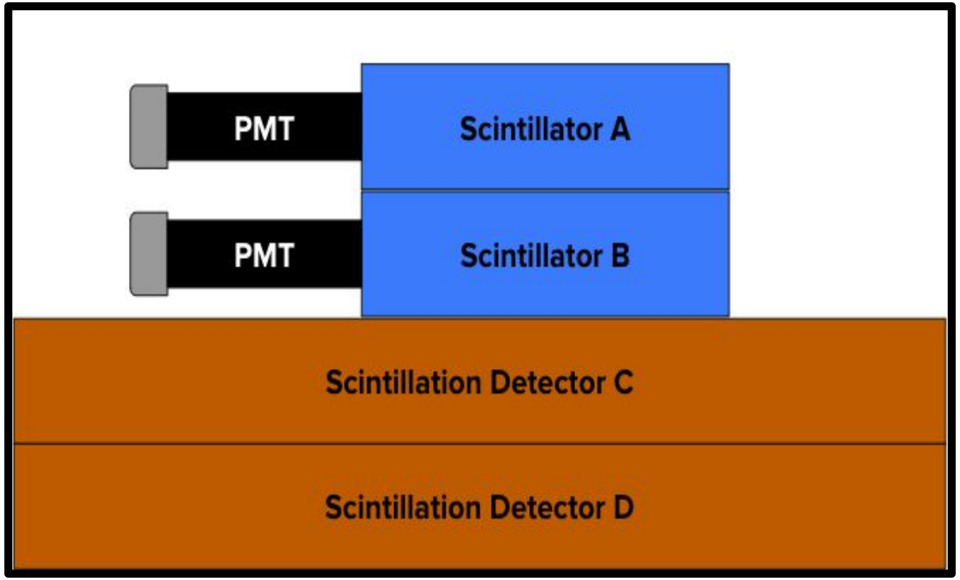
Scintillation detector in the lab

The large square of plastic scintillator is wrapped in Tyvek reflective material and covered with black cloth to prevent light leaks.

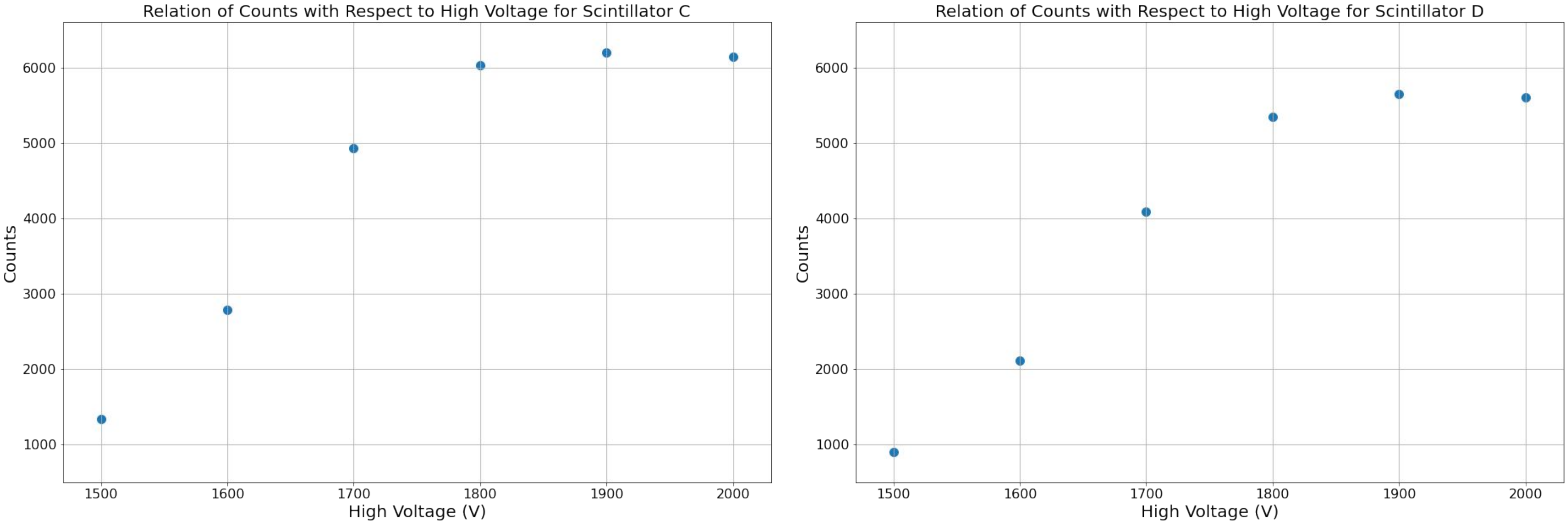
A wooden cover is attached on top for operation to provide mechanical structure.

A PMT is glued to one side to detect the scintillation light.

Calibrating Detector Responses

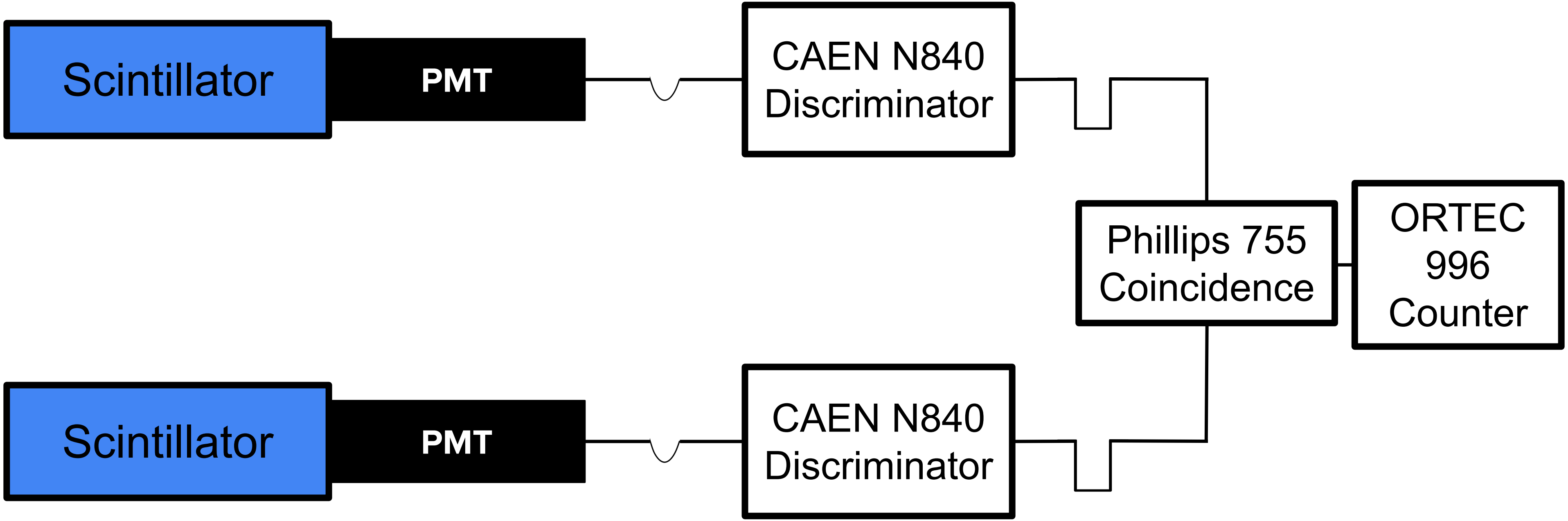


The high voltages needed for efficient operation of counters C and D were determined by counting instances where detectors A, B, and C would detect a signal and instances where detectors A, B, and D would detect a signal over different voltages using coincidences in A and B as a trigger.



Responses of detectors C and D with relation to tested high-voltages (1500 V, 1600, V, 1700 V, 1800 V, 1900 V, and 2000 V), regions where the counts plateau were used to calibrate the responses of detectors C and D

Coincidence Circuit for Cosmic-Ray Muons:



Scintillator

PMT

CAEN N840 Discriminator

Scintillator

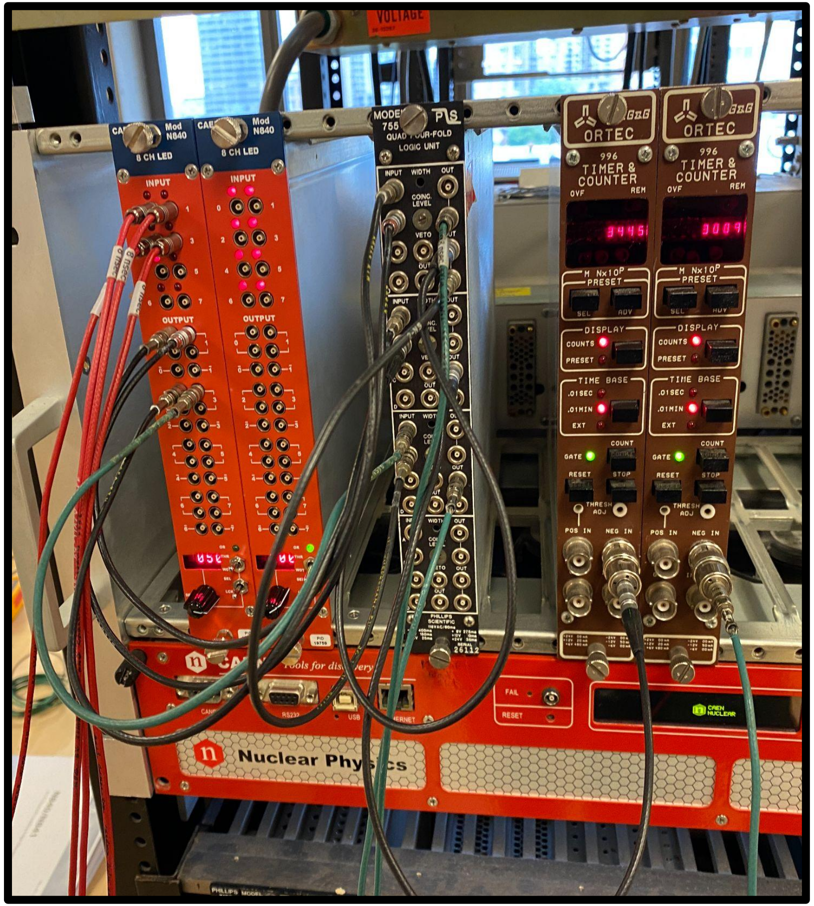
PMT

CAEN N840 Discriminator

Phillips 755 Coincidence

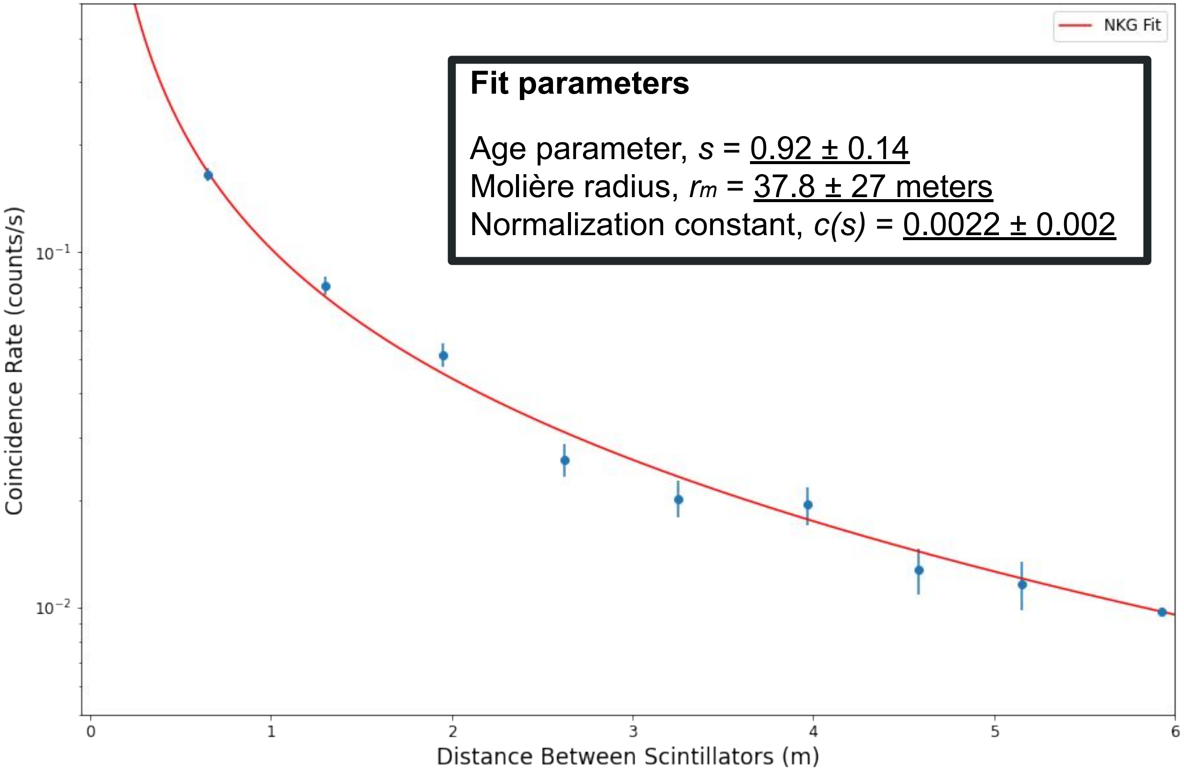
ORTEC 996 Counter

- **NIM Modules**
  - CAEN N840 Discriminator
  - Phillips 755 Logic Unit
  - ORTEC 996 Counter (two counting ABC and ABD coincidences shown)



(Leo, 1994)

$$\rho_{\mathrm{NKG}}(r, s, N_e) = \frac{N_e}{r_{\mathrm{M}}^2} \frac{\Gamma(4.5 - s)}{2\pi\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{r_{\mathrm{M}}}\right)^{s-2} \left(1 + \frac{r}{r_{\mathrm{M}}}\right)^{s-4.5}$$



Fit parameters

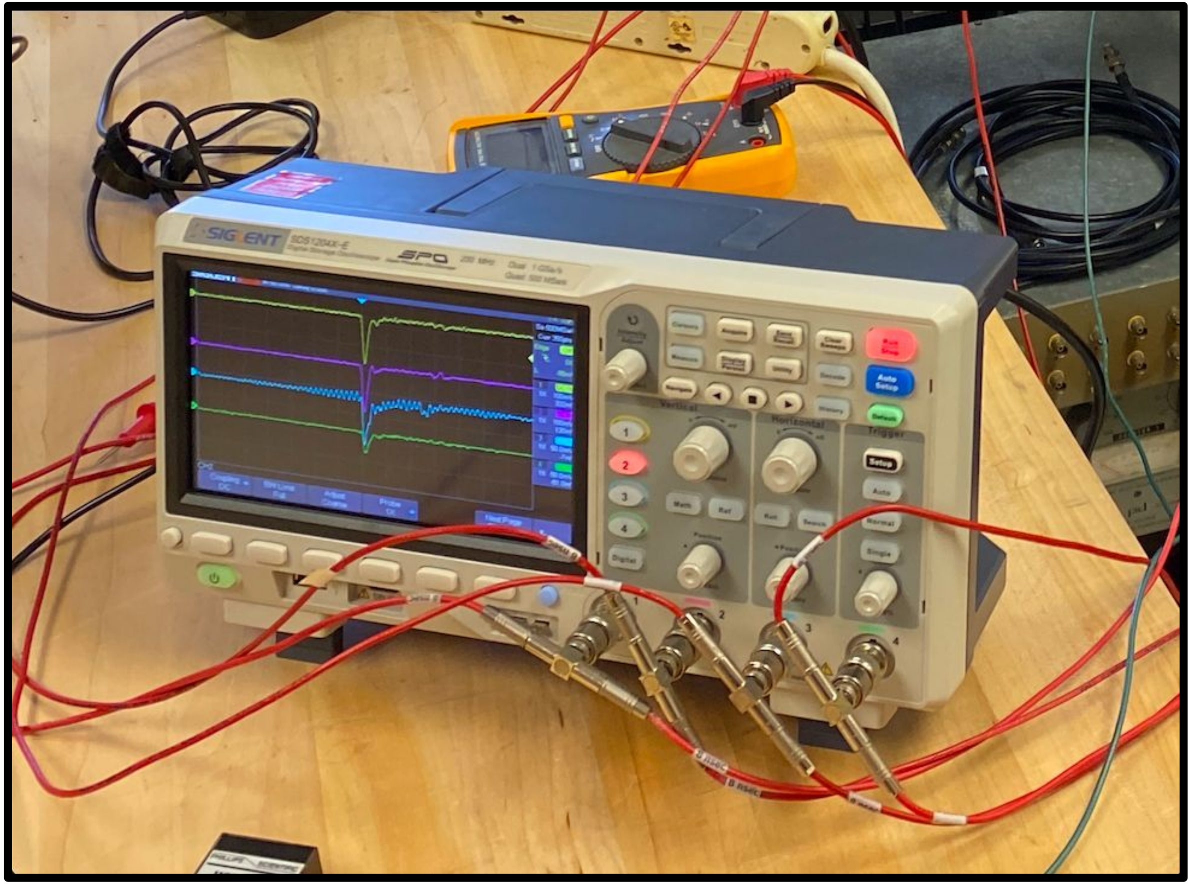
Age parameter, *s* = <u>0.92 ± 0.14</u>
Molière radius, *rm* = <u>37.8 ± 27 meters</u>
Normalization constant, *c(s)* = <u>0.0022 ± 0.002</u>

Distribution of coincidence rate in counts per seconds along with NKG fit, the vertical axis is set to a logarithmic scale.

Time Differences Between Traces Taken With Oscilloscope

Time differences between muon coincidences for a detector separation of 8.9 m were recorded using a SDS1204X-E SIGLENT oscilloscope to control for bursts or other anomalies.

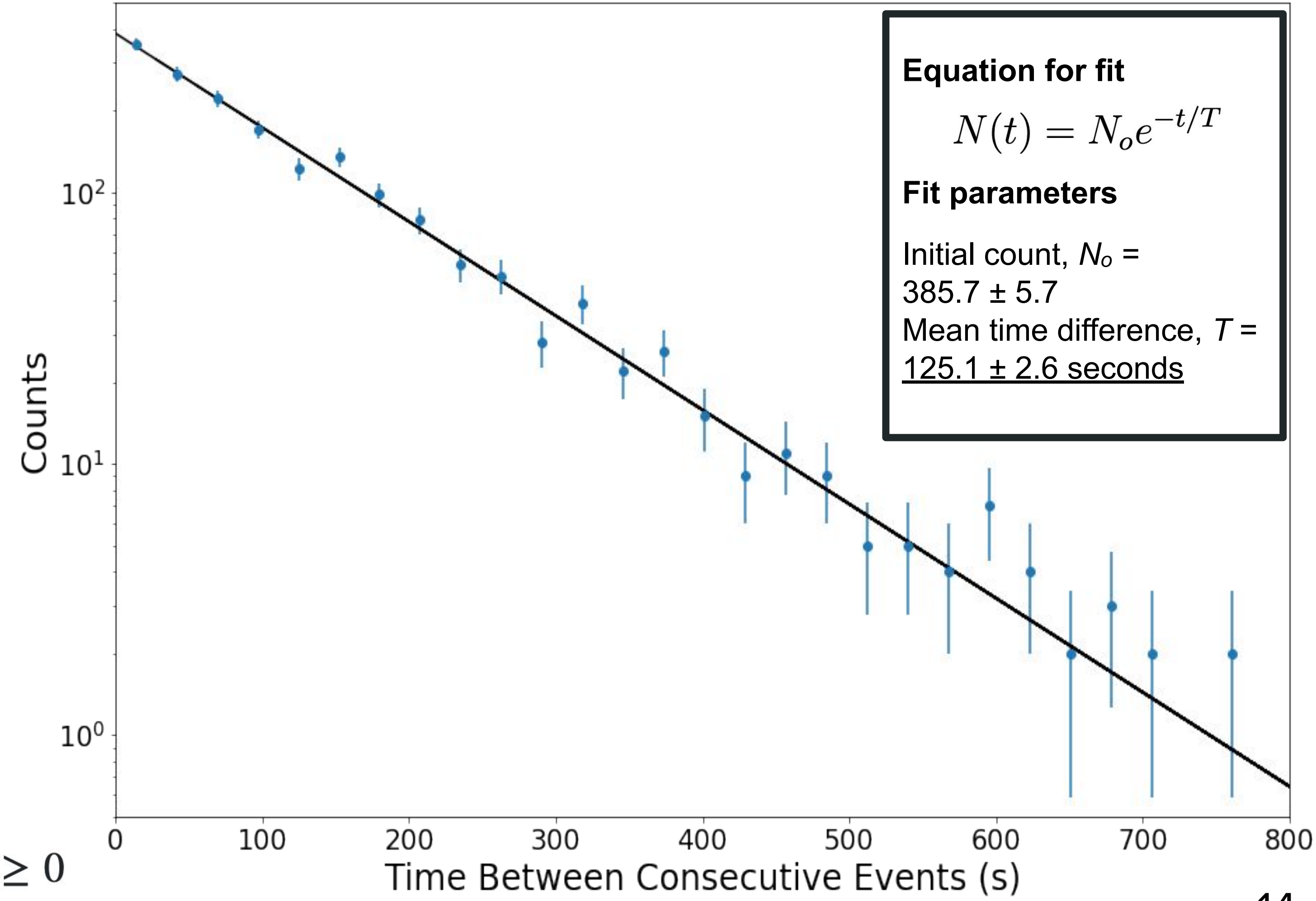
Each coincidence event was recorded, along with a timestamp.



Assuming the timing of the coincidences to be random but at a constant rate, the time differences follow Poisson statistics.

Hence, the probability to wait longer between events declines exponentially with waiting time such that:

$$\Pr(T > t) = e^{-\lambda t} \text{ for } t \geq 0$$



Equation for fit

$$N(t) = N_o e^{-t/T}$$

Fit parameters

Initial count, N_o =
385.7 ± 5.7
Mean time difference, T =
125.1 ± 2.6 seconds

Conclusion

- NKG function demonstrates that air-showers exist and can shed light regarding lateral size
- Poisson nature of arrival times based on exponential pattern of time-differences

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