Fluctuation of Cosmic Radiation Associated with Winter Thunderstorm Activities and Its Simulation with EGS4/5 and Geant4

Tatsuo TORII
Japan Atomic Energy Agency
Takeshi Sugita
Science System Laboratory Inc.

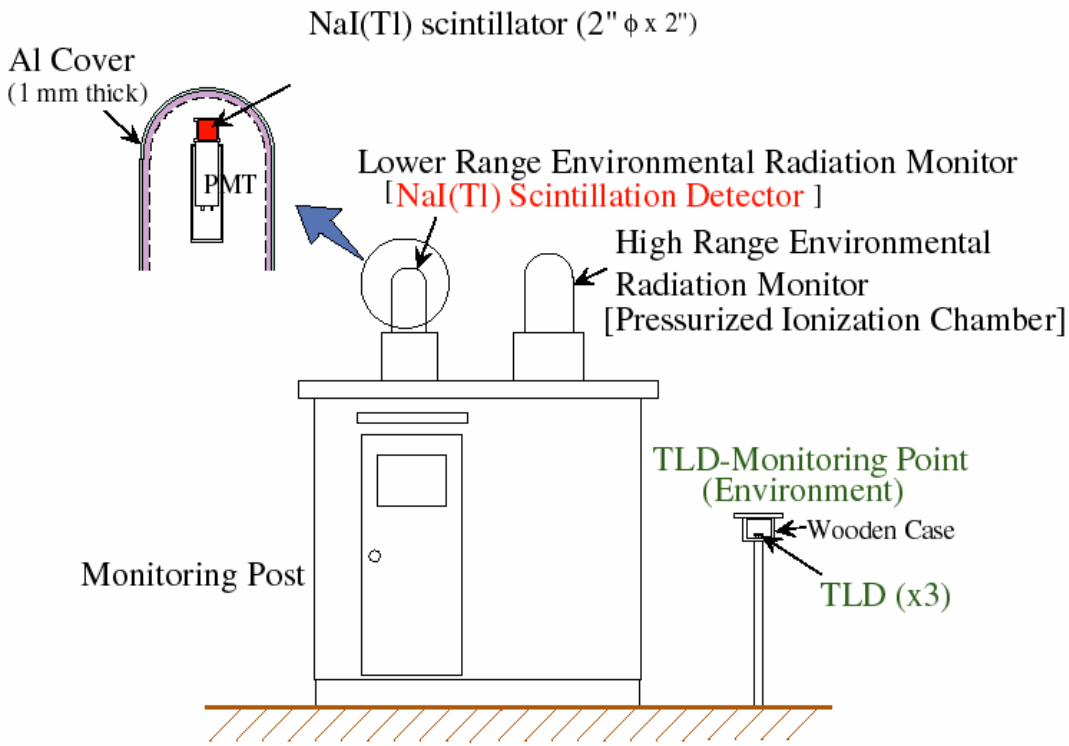
Background and Target of This Research

- Intensive radiations presumably associated with winter thunderstorm activities have sometimes been detected in the northwest coastal area facing the Sea of Japan.
- In order to investigate the intensive radiations caused by thunderstorm electric fields, we have calculated the behavior of secondary cosmic rays (gamma-rays, electron/positron, & muons) and radon progenies in electric fields using the Monte Carlo technique.

  - Measurement of the fluctuation of gamma-ray dose during thunderstorms
    - To confirm the radiation source and energy
    - Environmental Radiation Monitor (MP/MS (Monitoring Post/Station); NaI, IC)
    - Thermoluminescent Dosimeter (TLD)
  - A Monte Carlo calculation of the energetic particle transport in thundercloud electric fields
    - Analyze the energetic electrons/photons/muon behavior in the thunderstorm electric fields to make clear the generation of energetic radiation (bremsstrahlung).

Radiation monitoring in environment

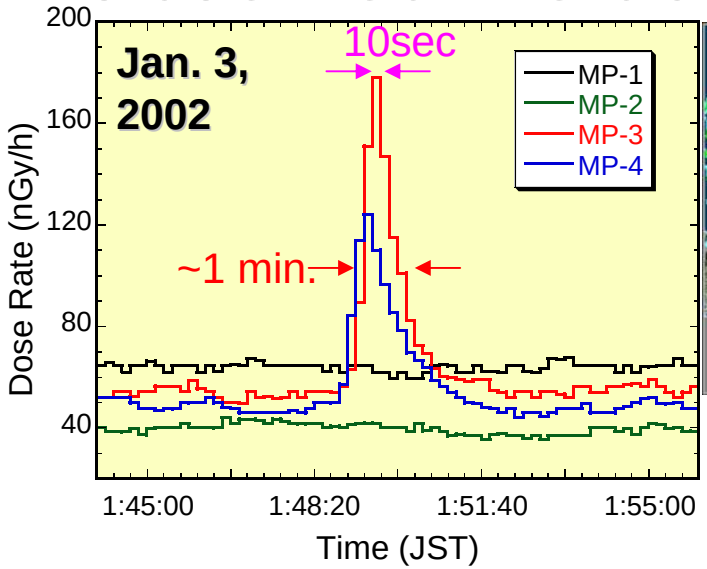
- **Environmental Radiation Monitor**
  - NaI(Tl) Scintillation Detector (2”ϕ *x* 2”)
  - Ionization Chamber (pressurized Ar gas IC)
- **TLD Monitoring Point**
  - Thermoluminescent Dosimeter Panasonic UD-200S (CaSO4:Tm)

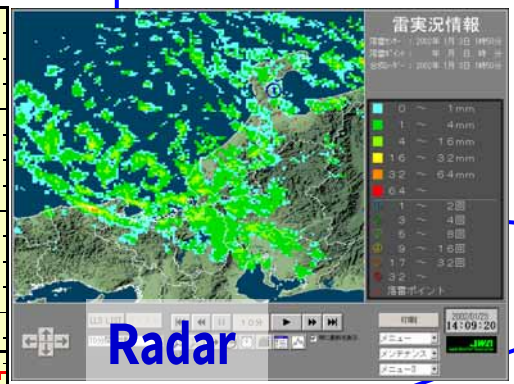


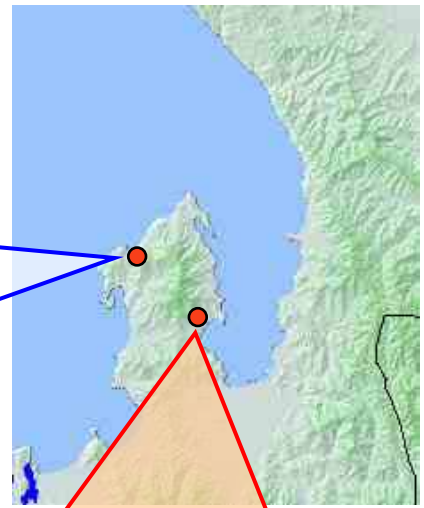
Monitoring Post and TLD-Monitoring Point

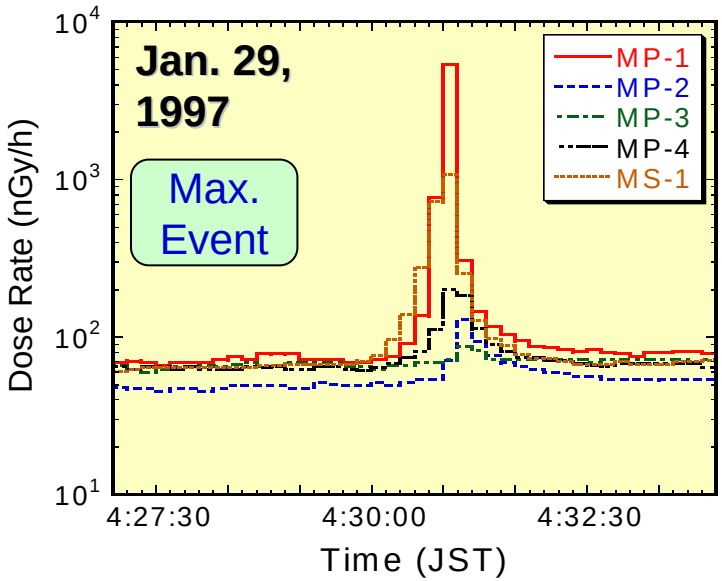
The FBR “Monju” and the Location of Environmental Radiation Monitors

Observed the dose-rate fluctuation



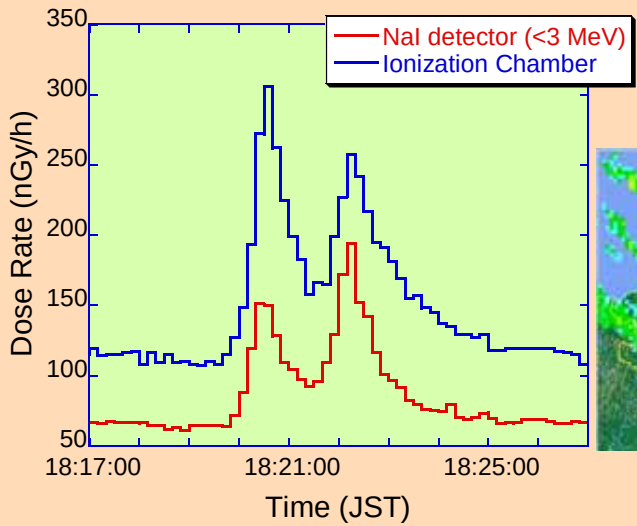






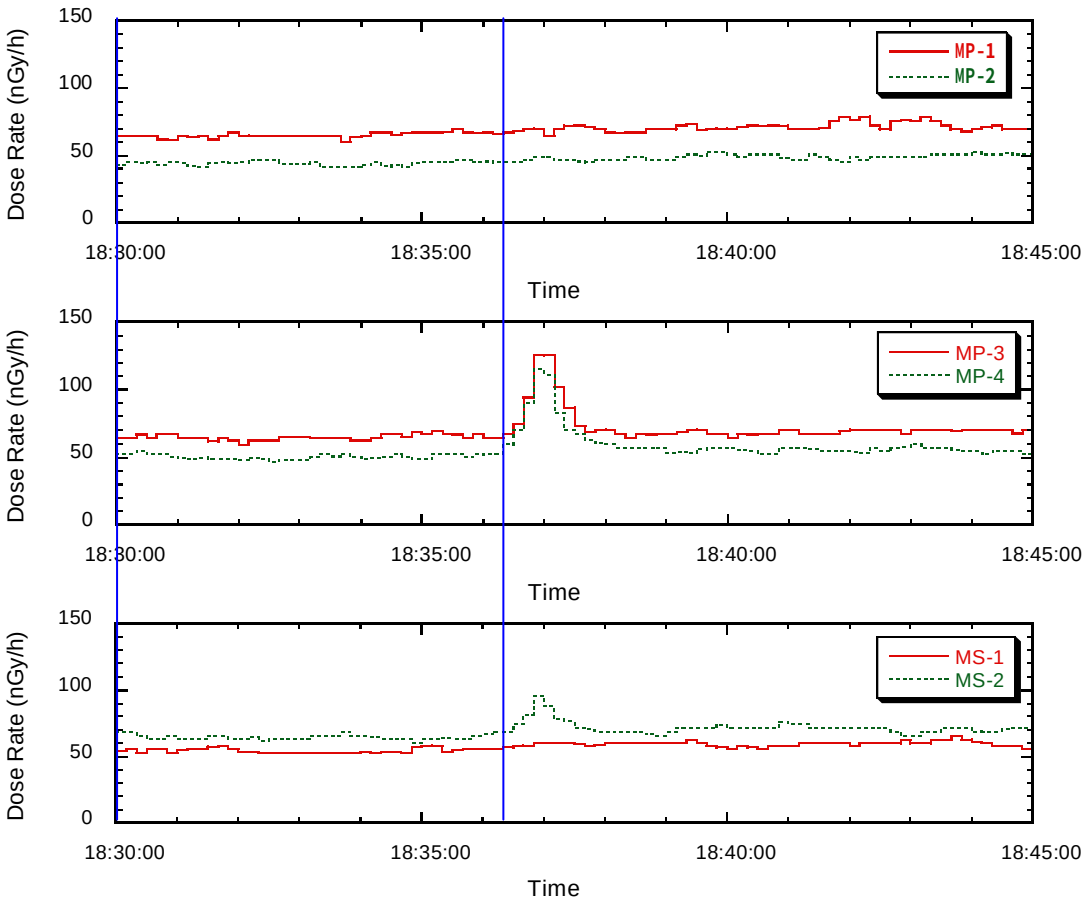
in Monju site

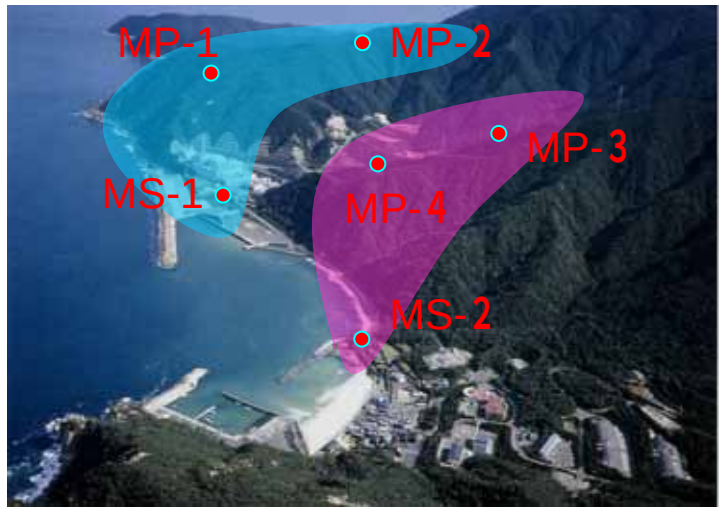
Dec. 10, 2002



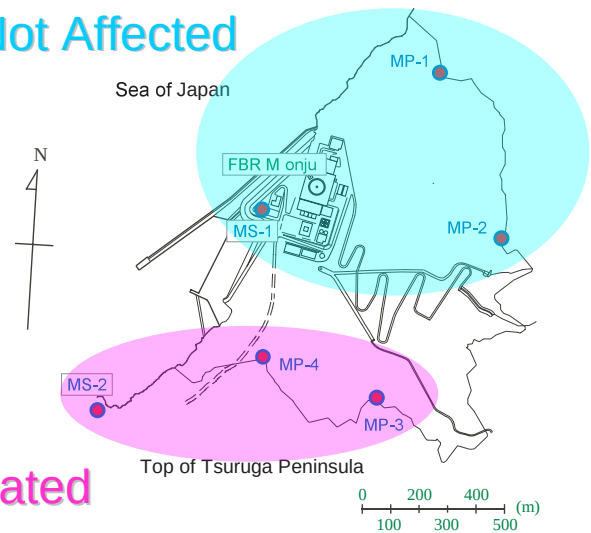
in the Tsuruga Penn. (MS-3)

Observed the dose-rate fluctuation (cont.)





Not Affected

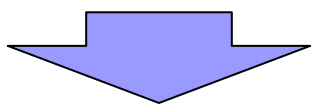


Fluctuated

Observed in Dec. 13, 2003

Features of the Dose-Rate Fluctuation During Thunderstorm Activities

- Observed Only During Winter Thunderstorms
  - Never observed in summer thunderstorms
- Not Related with Individual Lightning Discharges
  - Duration of Enhanced Dose-Rate：Several 10 seconds
- Affected Areas Are Quite Locally
  - In most cases, only 1 or 2 of the monitors situated several hundred meters away from each other indicate dose-rate increases during thunderstorm.
- Radiation Energy (Photons)
  - Pulse Height Distribution of NaI detector shows continuous spectrum up to several MeV.



Acceleration of Charged Particles and Bremsstrahlung Emission in the Thundercloud Electric Fields

Charged Particles in the Atmosphere

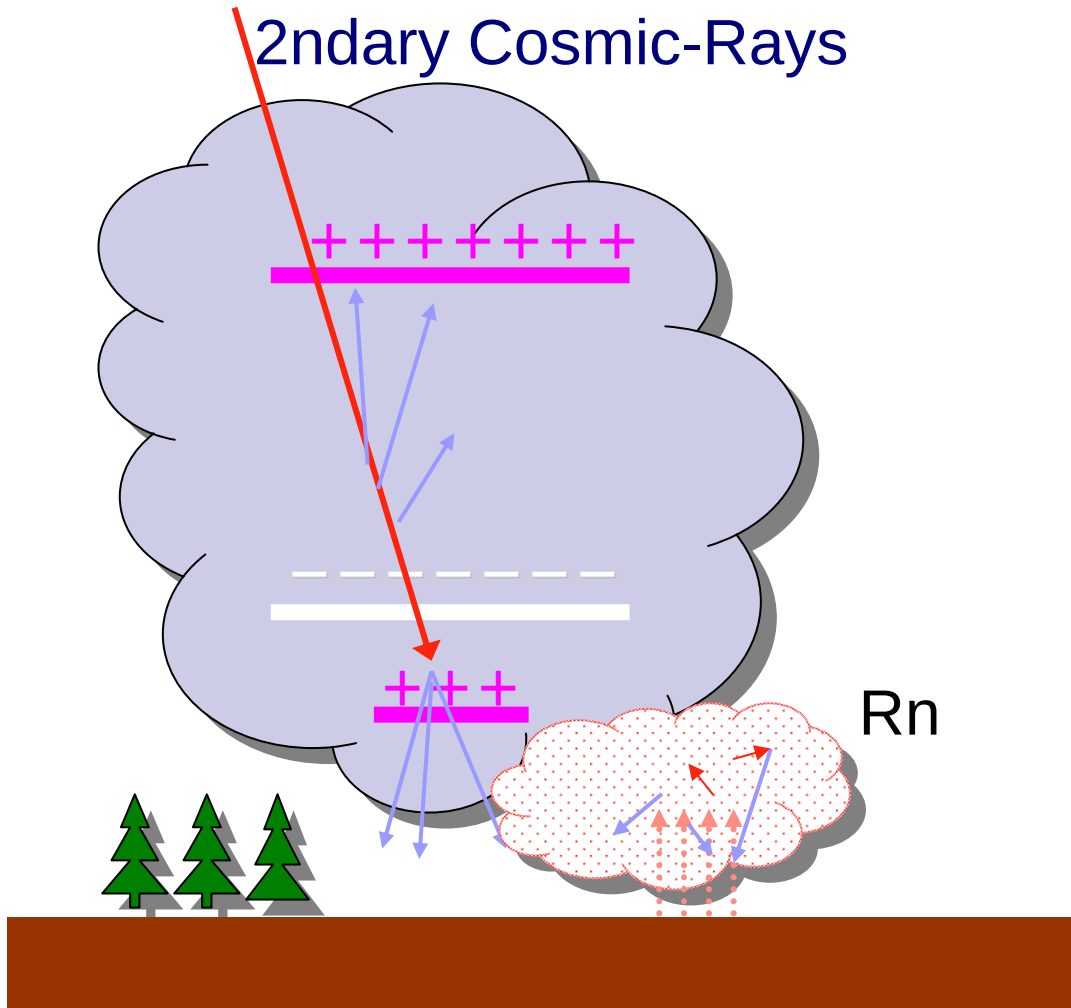
Acceleration of the charged particles caused by thunderstorm E-field
→ Generation of 2ndary electrons and Bremsstrahlung photons

- Rn progeny (β/γ-rays)
  ≦ 3 ~ 4 MeV
- Cosmic rays ($e^{\pm}/\gamma$)
  ~ MeV ~ 10 GeV

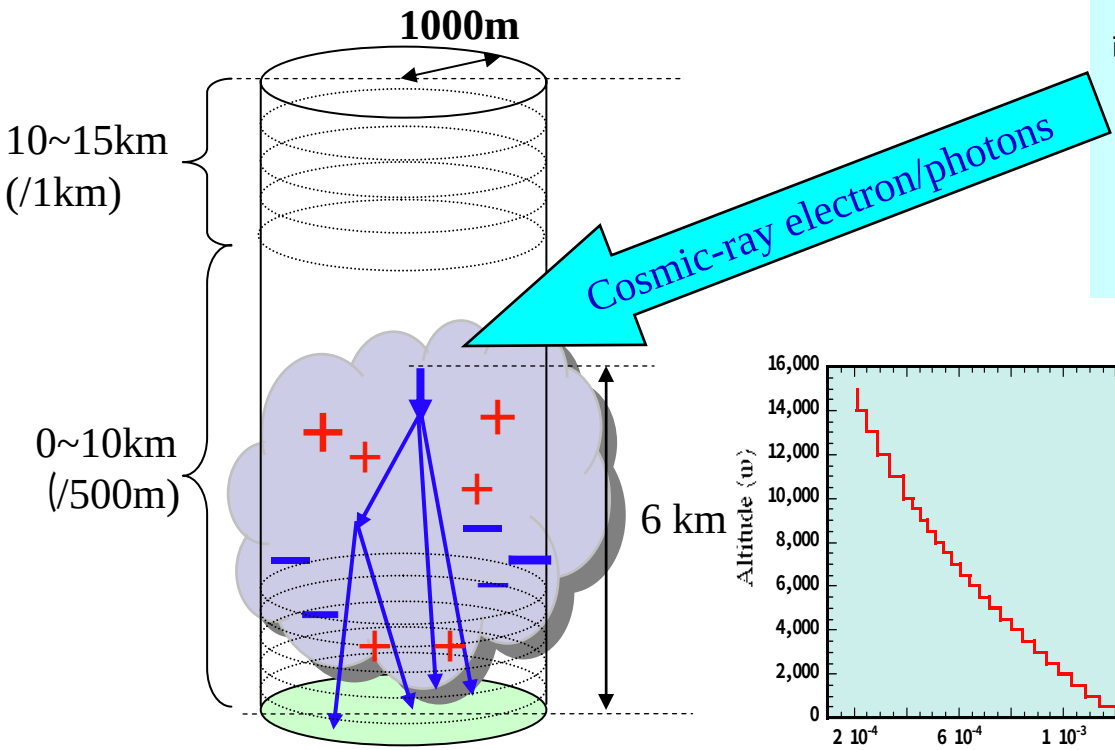
- Cosmic rays (muons)
  ~ GeV ≦

Monte Carlo Calculation
of particle transport

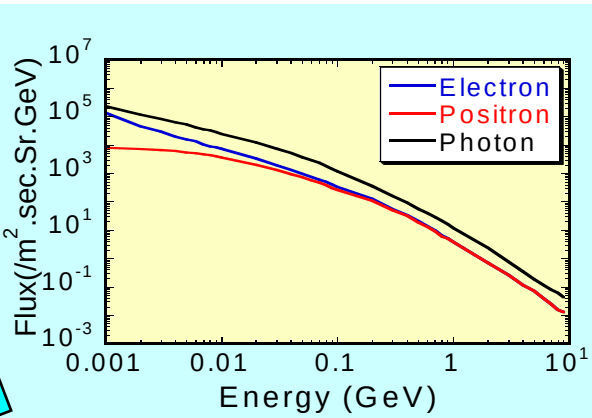
Fluctuation of
Gamma-ray dose



Downward emission of Bremsstrahlung photons

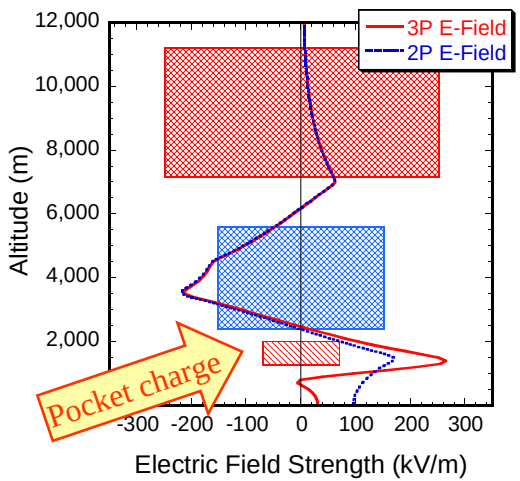


Calculation Model



Energy spectra of EM component of cosmic-rays at the alt. of 6 km

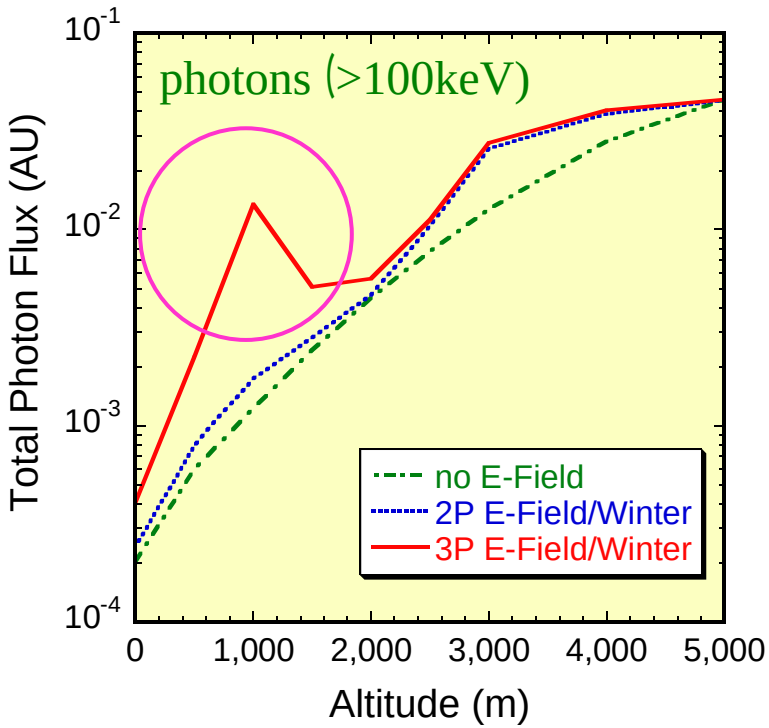
Air Density
(US Standard Atmos.)

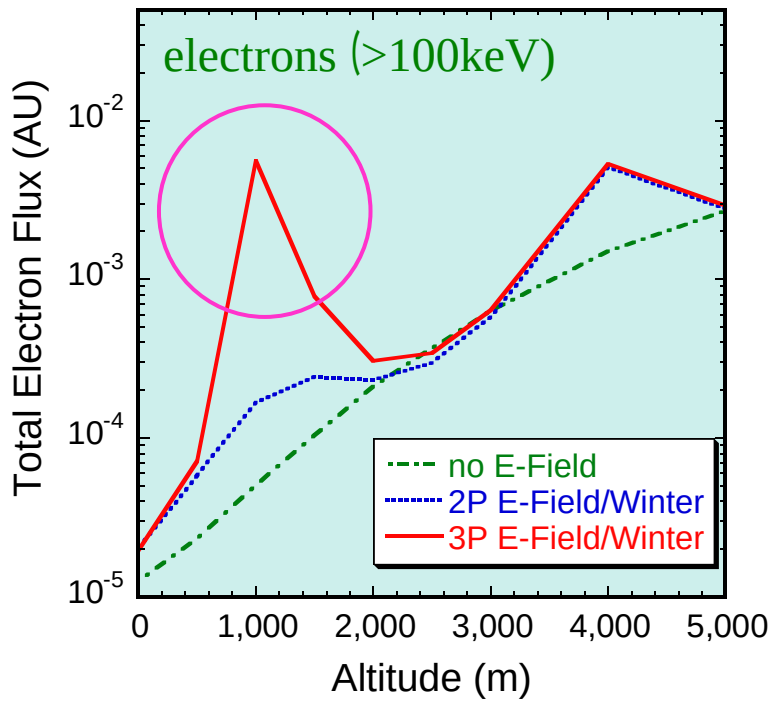


Vertical distribution of E-field

Electron / Photon Fluxes

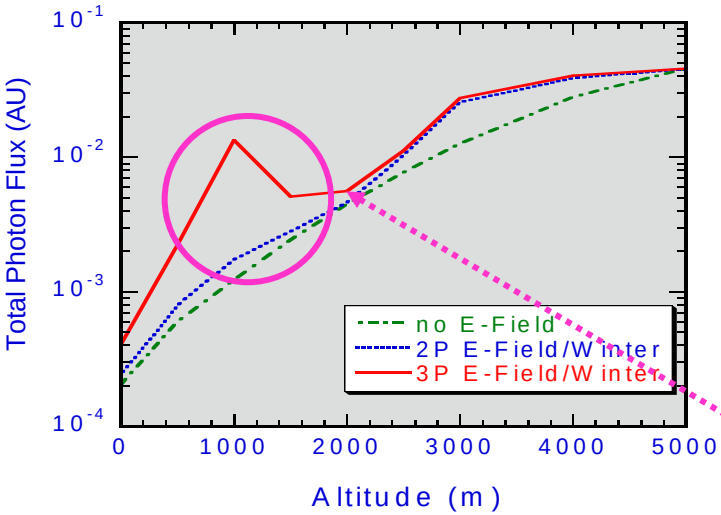
- Source: Cosmic-Ray Electron/Photons -



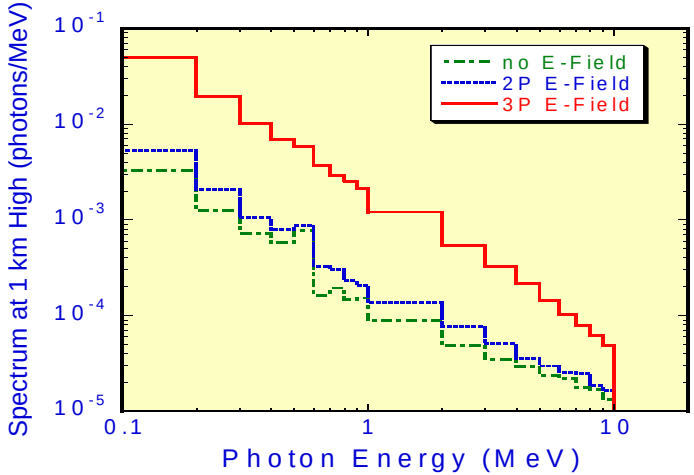


- Electron and photon fluxes rapidly increase at the high electric field region
- Increase of electron flux is 10 times higher than that of photon flux in such region.

Bremsstrahlung in the thundercloud E-Field

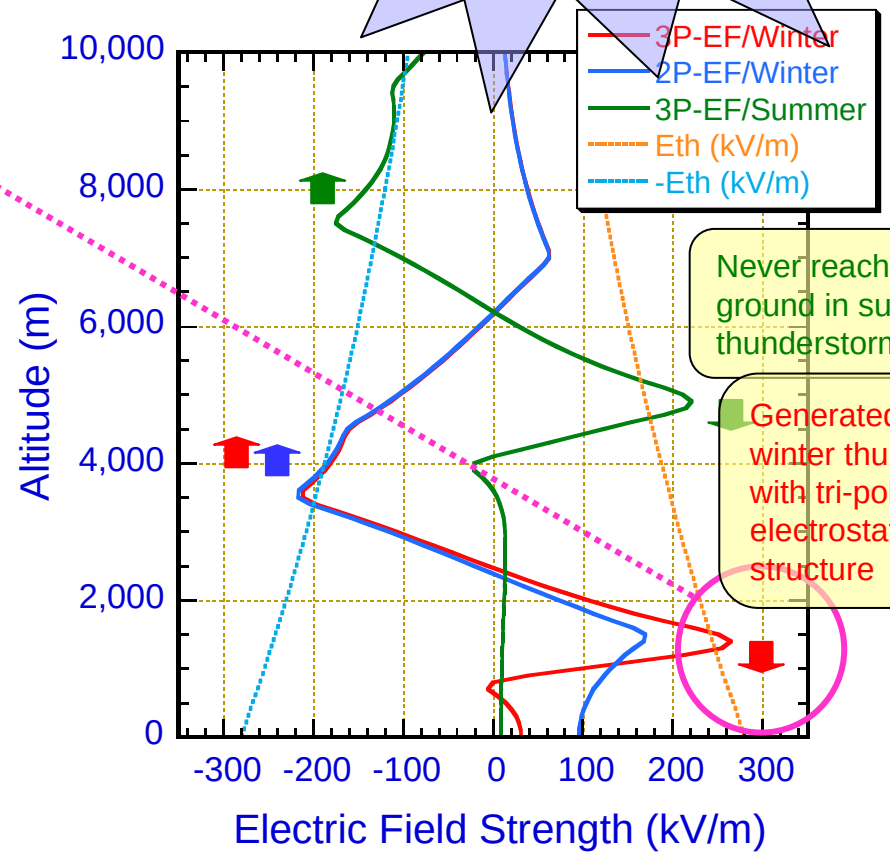


Vertical Distribution of Photon Flux



Energy Spectrum (@1km)

Bremsstrahlung generated in region where threshold (Eth) was exceeded



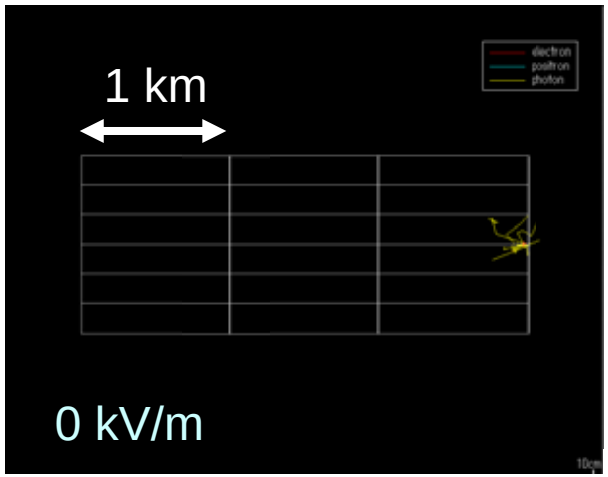
Never reach to the ground in summer thunderstorms

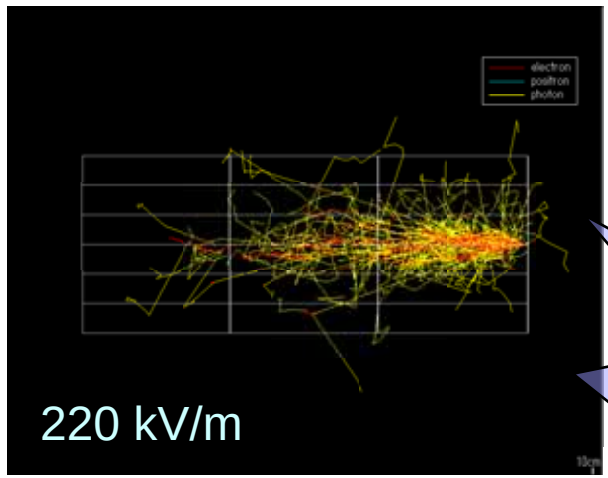
Generated only winter thunderstorm with tri-pole electrostatic structure

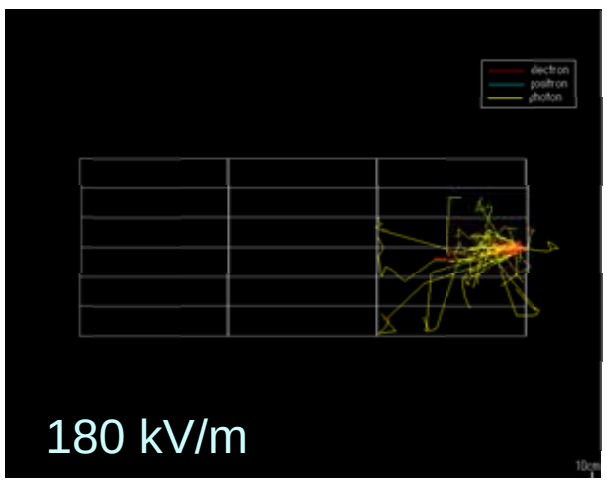
Profile of Electric Field

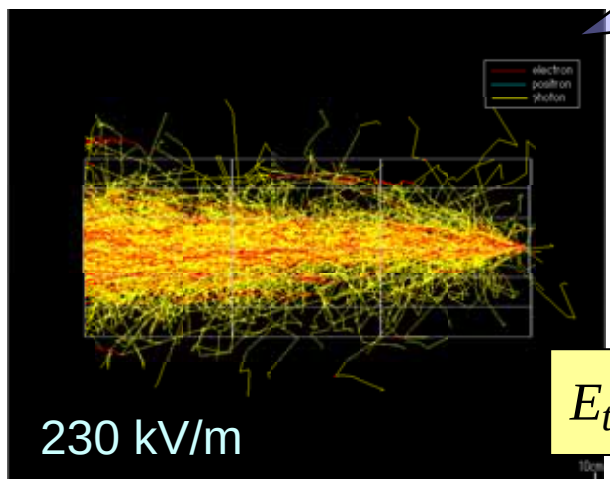
Trajectories of Energetic Electrons / Photons in Uniform E-Field Calculated by ***EGS4*** Code

- Alt. 2km (Density: 1.0066 kg/m^3)
- Incident Electrons：10 MeV (n=25)









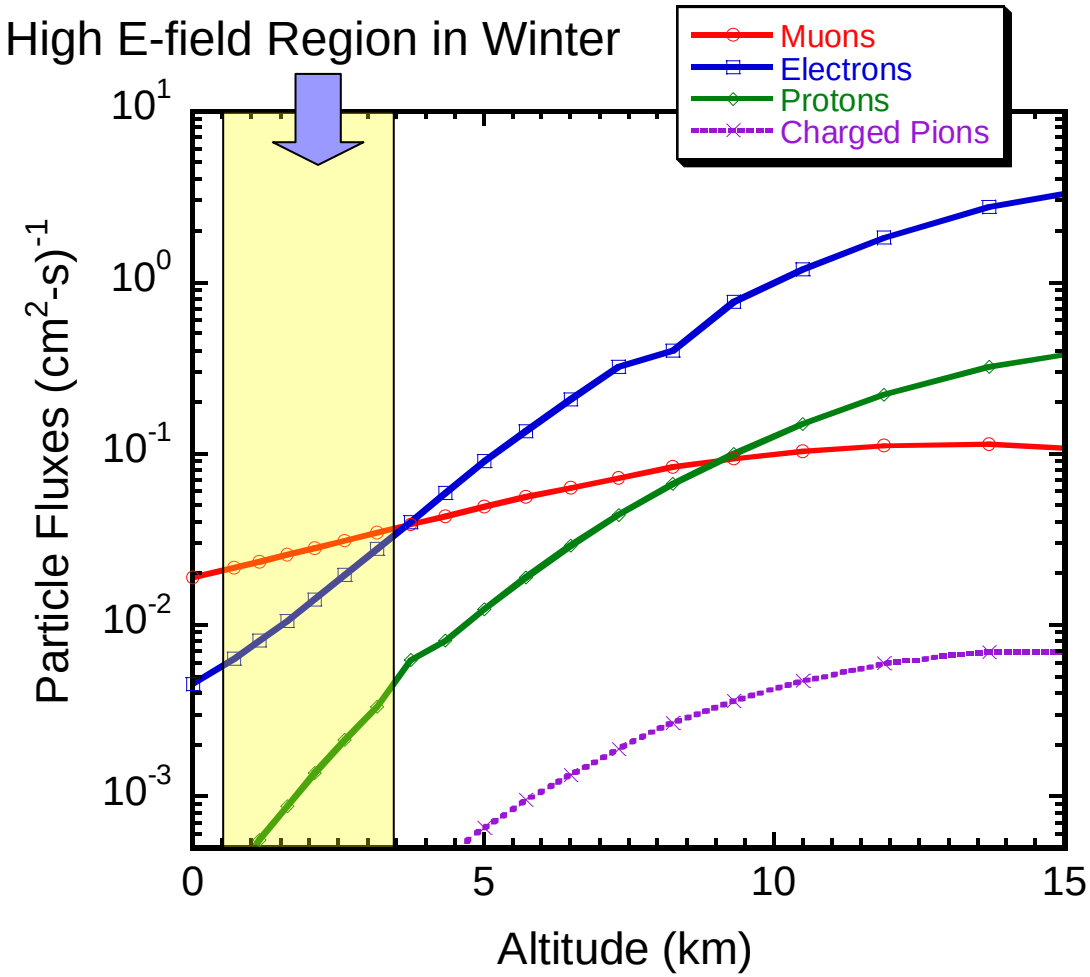
photon
electron
positron

Generation of the EM shower at 230 kV/m in the Alt. of 2 km

Runaway Electrons

$$E_{th} \approx 280 \times P\,[atm]\ \left[kV/m\right]$$

Alt. Distrib. of Cosmic-rays in Atmosphere

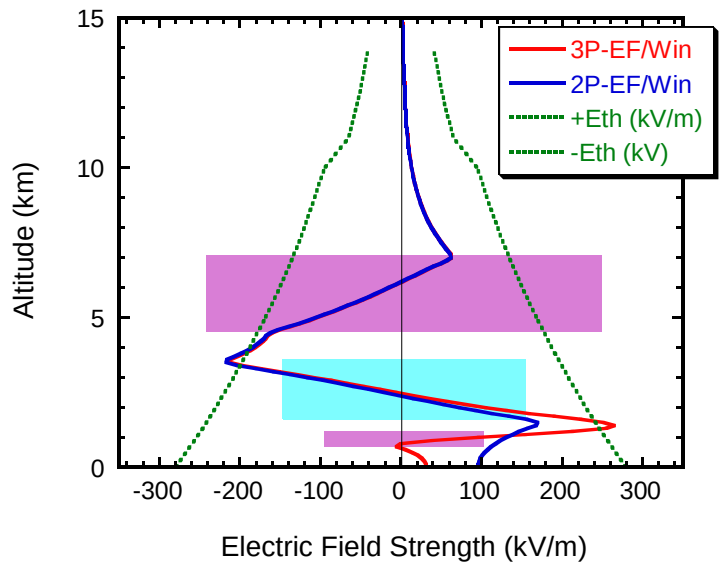


from NCRP Rep. 94 (1987)

Transport Calculation of Cosmic-Ray Muons

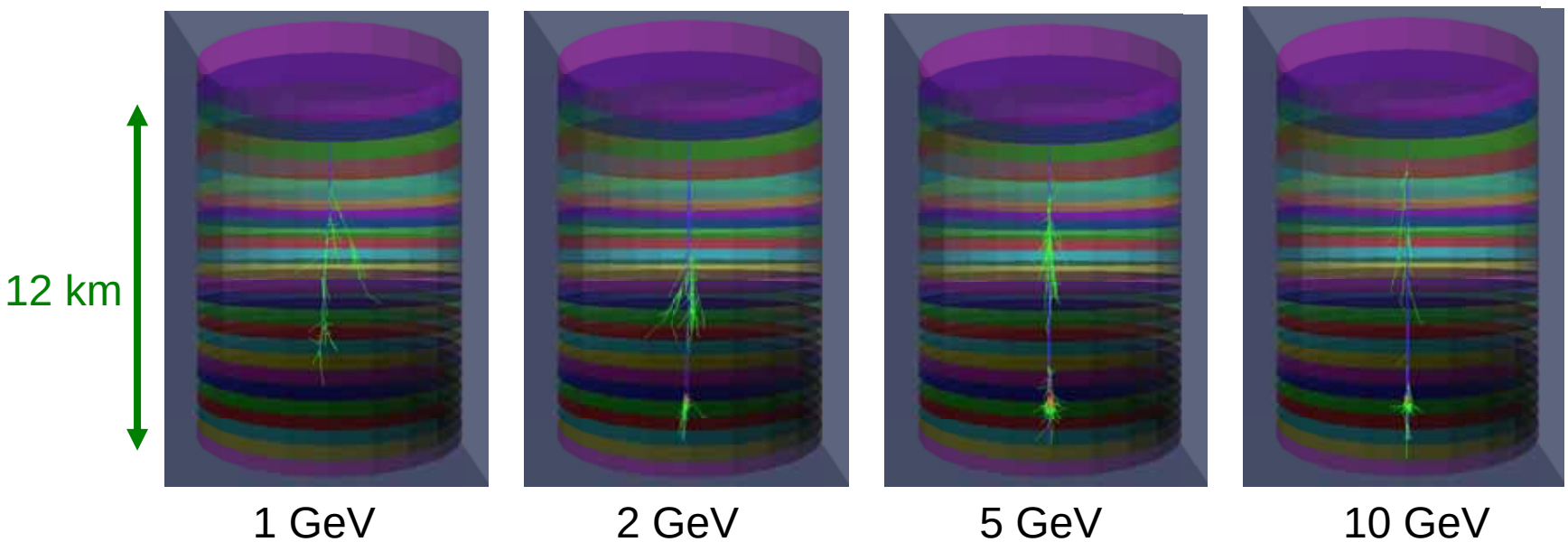
- Simulation of muons and associated particles with Geant4
  - Source: Muons (1~10 GeV)
  - Downward emission at the alt. of 12 km
  - Atmosphere：0 m (ground)～15 km
  - E-Field Structure: Winter Thundercloud (Tri-pole Structure)

Geant4：ver. 5.x, 6.2, 7.x, 8.0



Trajectories of Energetic Particles Originate in Incidence of High Energy Muons to the Thundercloud Electric Field

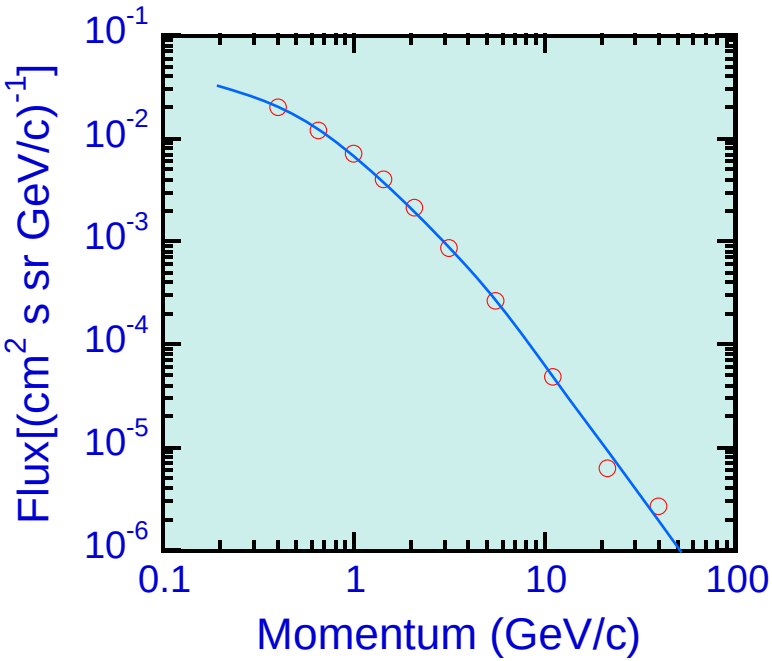
- Alt. of Incident Muons: 12km High.
- Charge and Energy: Positive Muon, 1, 2, 5, 10 GeV
- Number of Histories: 5



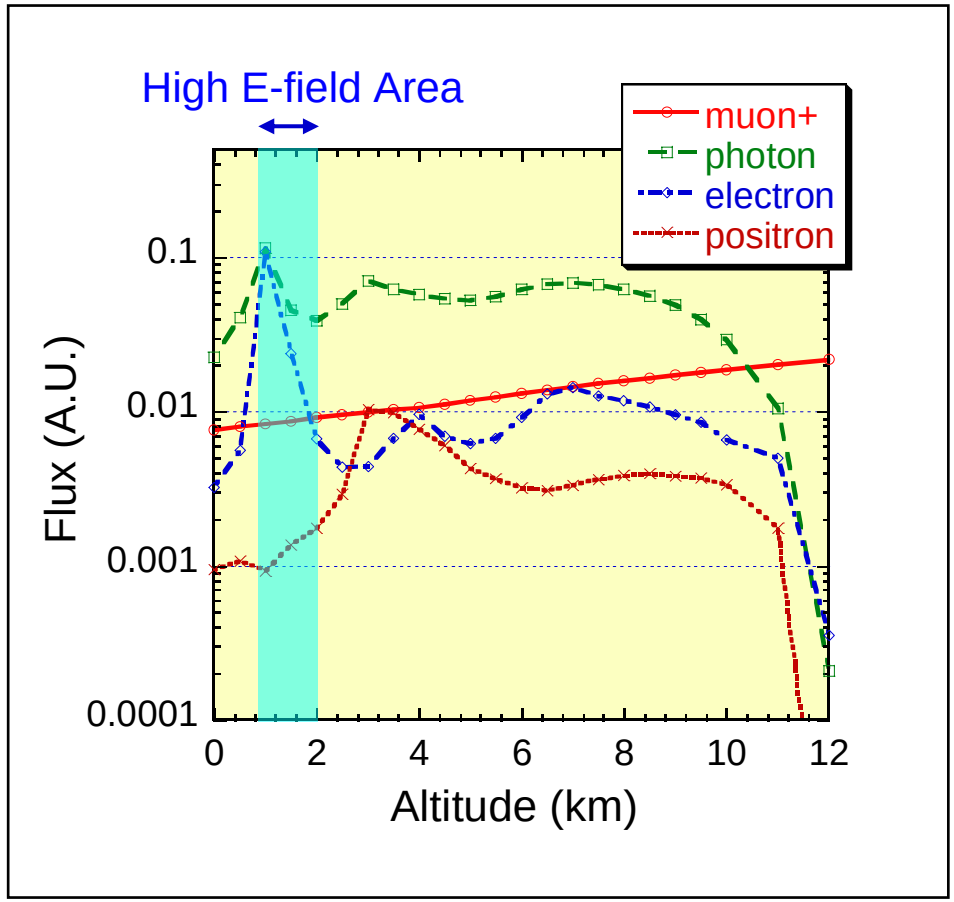
- Same Behavior with the case of Electron/Photon Incidence
- Bremsstrahlung Originated by Muons (> 2 GeV) Reaches to the Ground

Calculated Result for Cosmic-Ray Muons

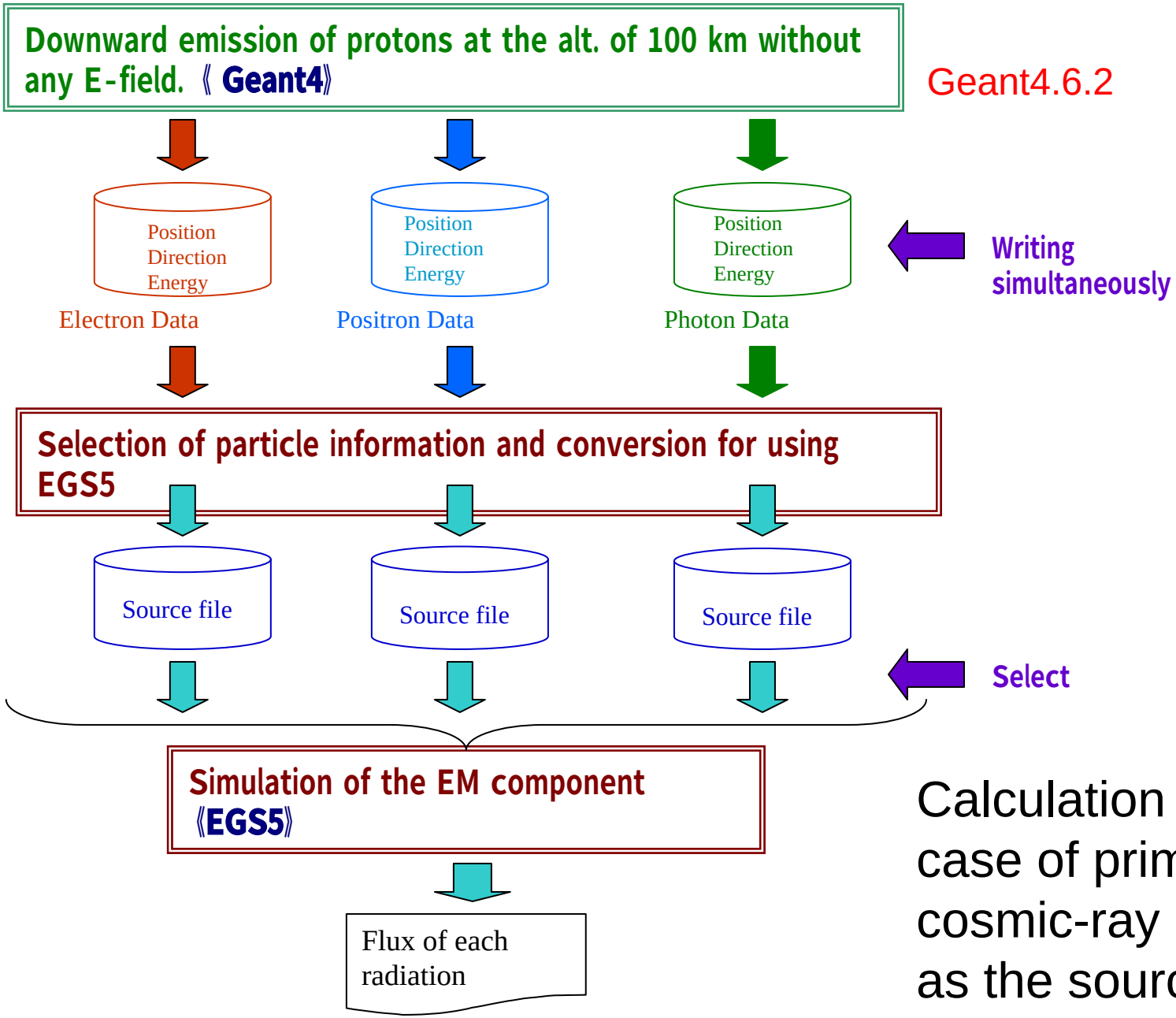
- **e/γ: increase**
- **Muons: not fluctuated**



Spectrum of Cosmic-Ray muons
[S. Coutu et al., Phys. Rev. D **62**, 032001 (2000)]



Vertical Distribution of Energetic Particle Fluxes



Calculation in the case of primary cosmic-ray protons as the source

Calculated Result of EM component

- Source：proton（primary CR）
- Alt.：100km
- Spectrum：LISA（Laser Interferometer Space Antenna）（CRCharging）

Almost same with above calculations

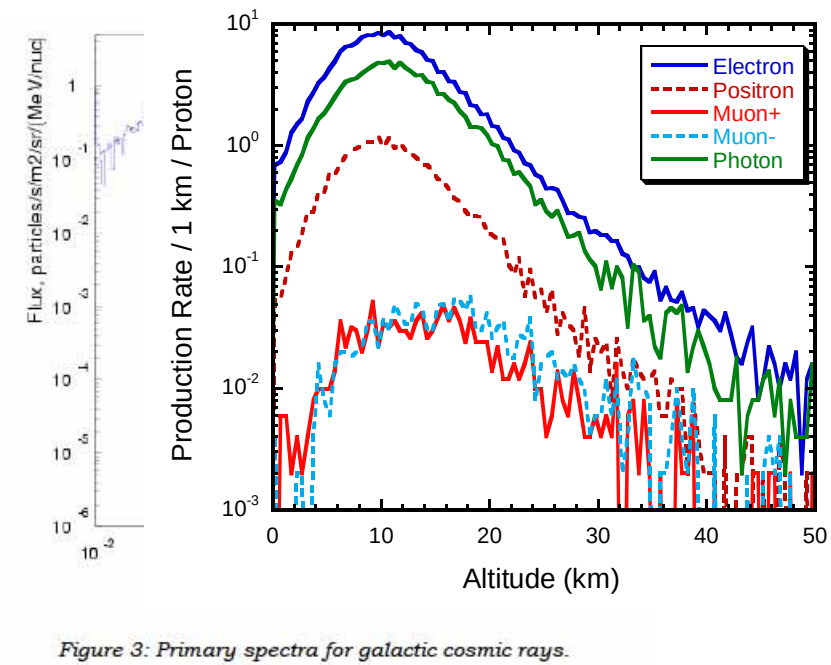
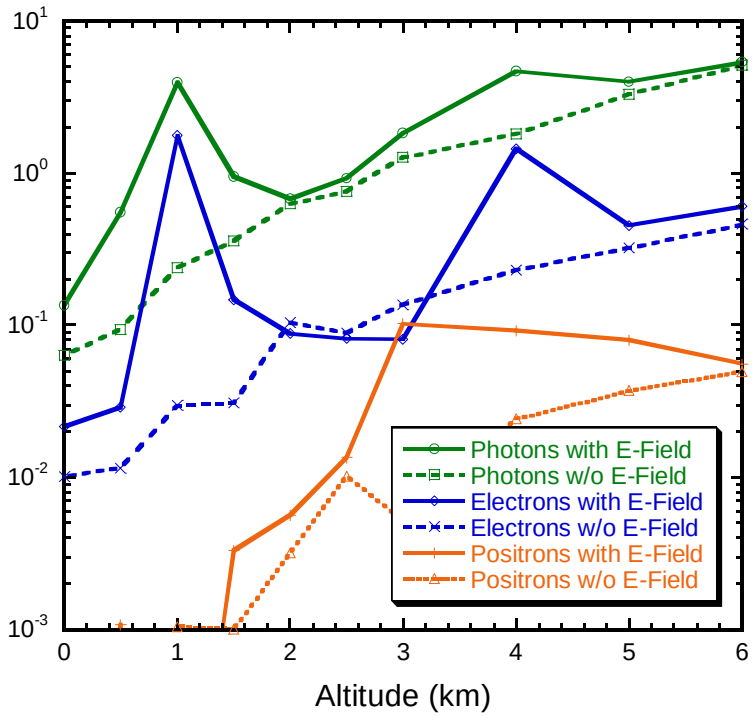


Figure 3: Primary spectra for galactic cosmic rays.

Source spectra

（WP500 Software User's Manual, Imperial College London）

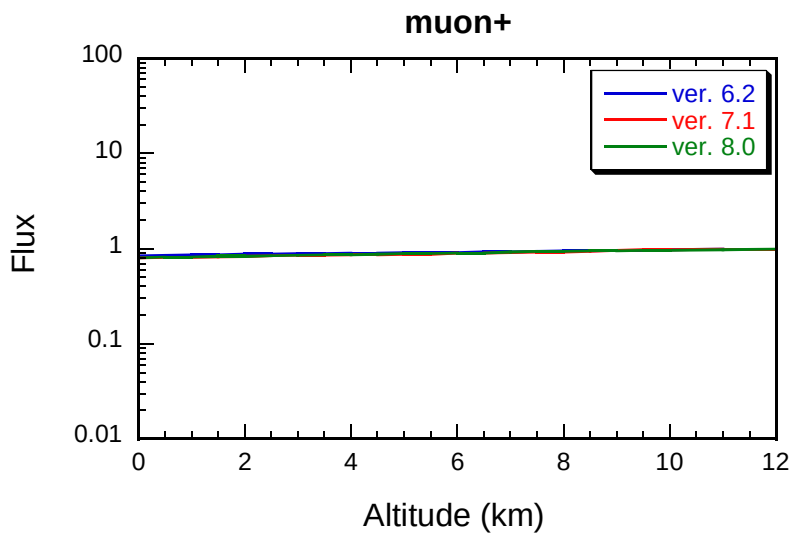


Result（data file：electron）

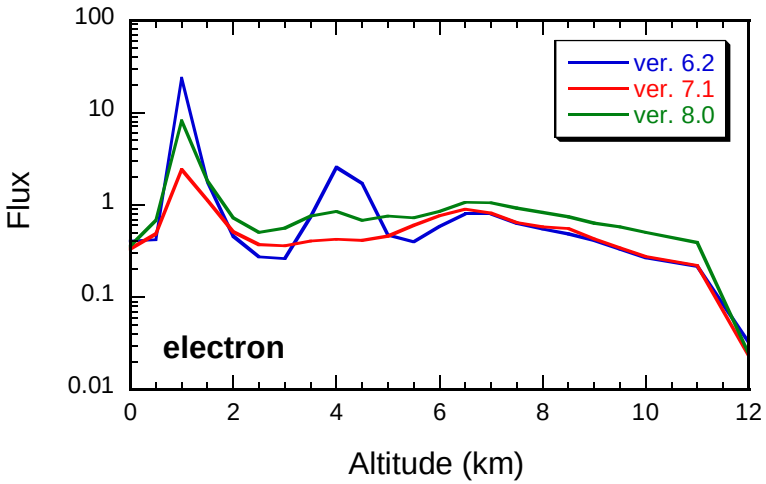
（Alt. distrib.: Photon・Electron・Positron）

Production of knock-on electrons in the atmosphere

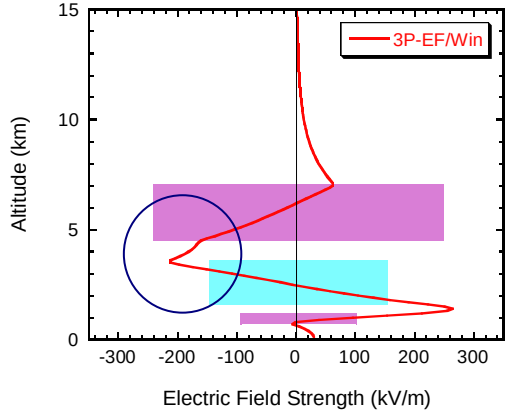
- Version of Geant4 Code Using the Simulation
  - Ver. 6.2.p01
  - Ver. 7.1.p01
  - Ver. 8.0
- Source Condition：
  - μ＋、10GeV
  - Alt.: 12km
  - E-Field：Winter Thundercloud (tri-pole)

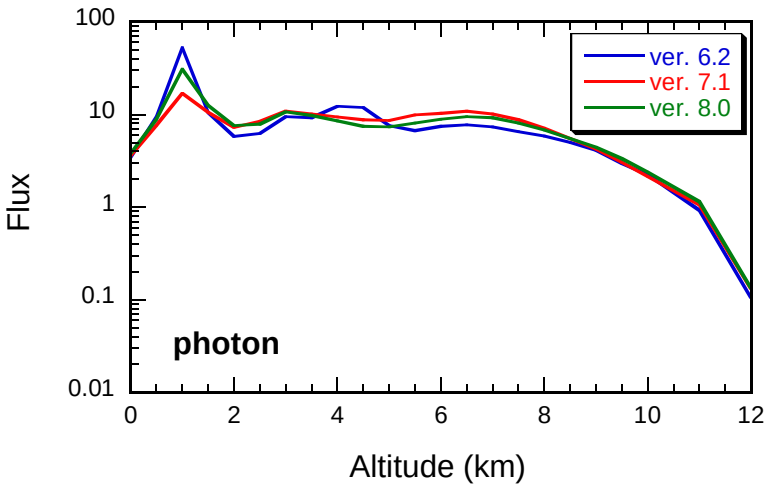


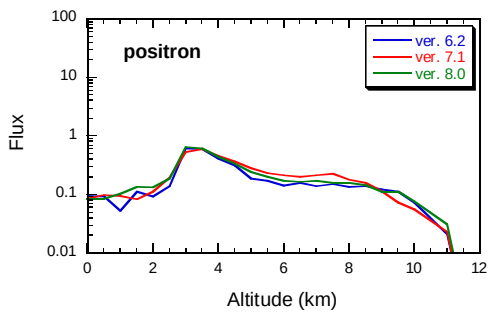
Comparison of Electron and Photon Fluxes



- Production rate : v6.2 > v8.0 > v7.1
- Different flux at the alt. of ~ 4 km







Concluding Remarks

- The photon/electron fluxes increased greatly in the region where the field strength exceeded 280 kV/m-atm.
- Since the high electric field region is formed at low altitude (~1 km) in the winter thundercloud with tri-pole electrostatic structure, there is a possibility that the enhanced radiation (photons, electrons) is observed on the ground.
- Several MeV gamma-rays is reached dominantly on the ground. It is consistent with the observed results during winter thunderstorms.
- The knock-on electrons produced by the cosmic-ray muon transport in air become a “seed” of the electromagnetic shower in thunderclouds.
- In the simulation of EM component in the atmosphere, different electron flux is obtained by using version 6.2, 7.1, and 8.0 of Geant4.
- The reason of this difference is not clear yet.

Thanks.