ISAPP School 2024 · KIT / Bad Liebenzell

GEANT4 Simulations for Rare Event Searches

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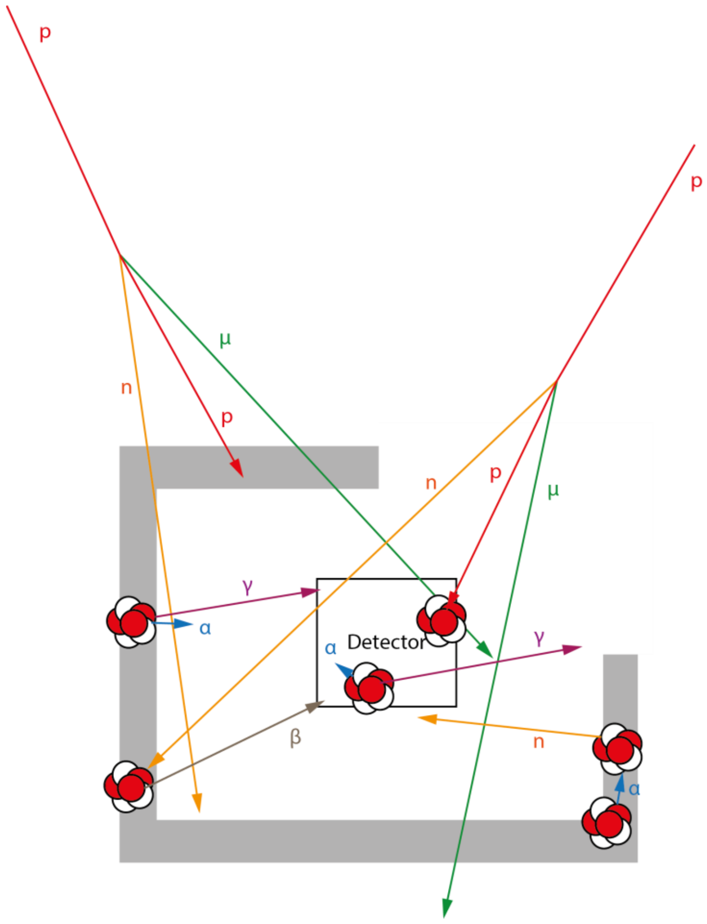
3/3: Radioactive Backgrounds
for Shallow Sites (e.g. reactor based neutrino experiments)
and Deep Underground Experiments (e.g. Dark Matter Searches)

Background Sources

Background sources: sources of primary particles in the MC simulation

- **Cosmogenic background**
  - Primary cosmic rays (p, ^{A}X) on surface
  - Secondary cosmic rays (n, μ) produced by nuclear spallation in the atmosphere
  - Radioactive activation / transmutation of elements by cosmic rays
- **Radiogenic background** caused by natural radioactivity
  - EM background (α, β, γ) from
    - Natural radioactive decay chains (^{232}Th, ^{235}U, ^{238}U)
    - Other natural radionuclides, e.g. ^{40}K
    - Anthropogenic radionuclides, e.g. ^{90}Sr, ^{137}Cs
  - Neutron background from
    - (α,n) reactions on e.g. ^{14}N
    - Spontaneous fission of e.g. ^{238}U
    - μ-induced spallation of high-Z nuclides*



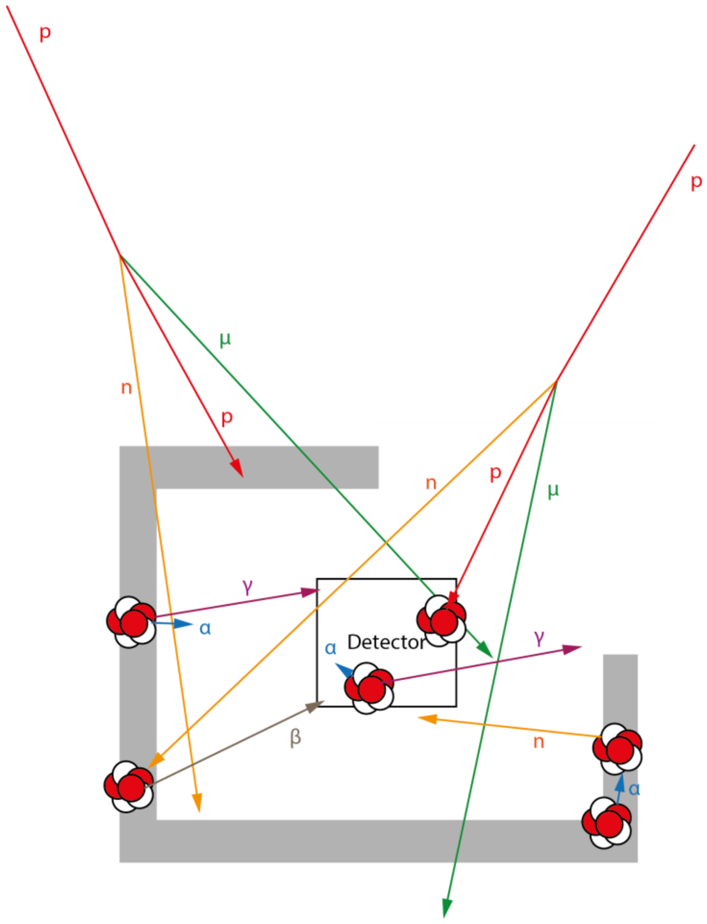
*__Nuclide__: any type of atomic nucleus $_{Z}^{A}X$

Background Sources

Background sources: sources of primary particles in the MC simulation

- **Cosmogenic background**
  → dominant at **shallow sites**,
  e.g. neutrino experiments at nuclear reactors

- **Radiogenic background** caused by natural radioactivity
  →dominant at **deep underground sites**
  e.g. direct Dark Matter searches



***Nuclide**: any type of atomic nucleus $_{Z}^{A}X$

Background Mitigation

External (ambient) background
= originate outside of the detector

- Can be **shielded** by placing an absorber between background source and detector
- May be actively rejected by operating an auxiliary detector (=**veto**, tuned to the background) in anti-coincidence with the main detector
- Only **long-rage** background radiation is detectable: γ, n, μ, energetic β

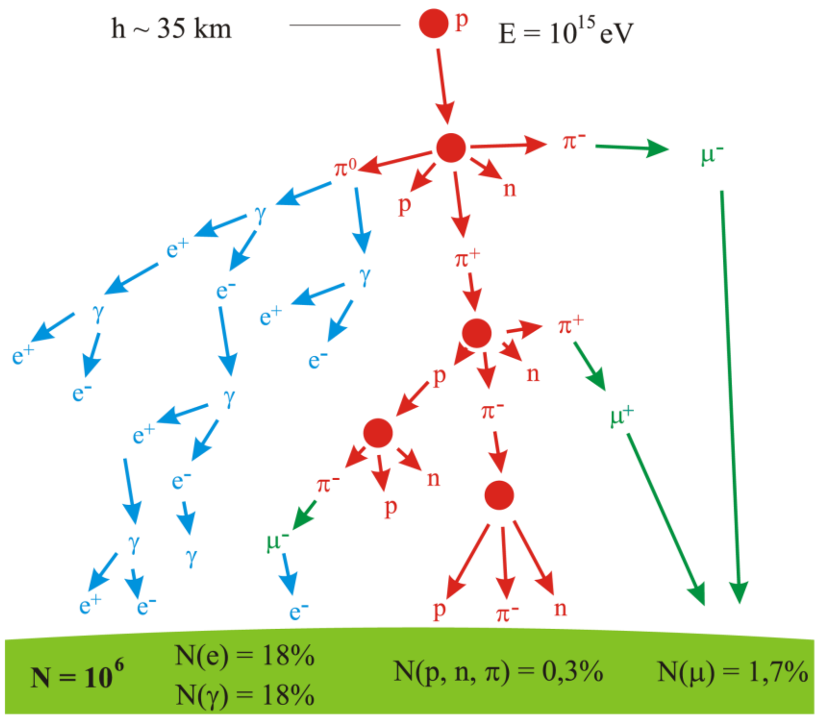
Internal background
= originate inside the detector

- Can not be shielded
- Select building materials with low radioactive contamination (= high **radiopurity**) during so-called *assay* or *screening* measurement
- Radiochemical purification of the building materials may be needed
- Also **short-range** background radiation is detectable: α, low-energy β

Prompt Cosmogenic Background

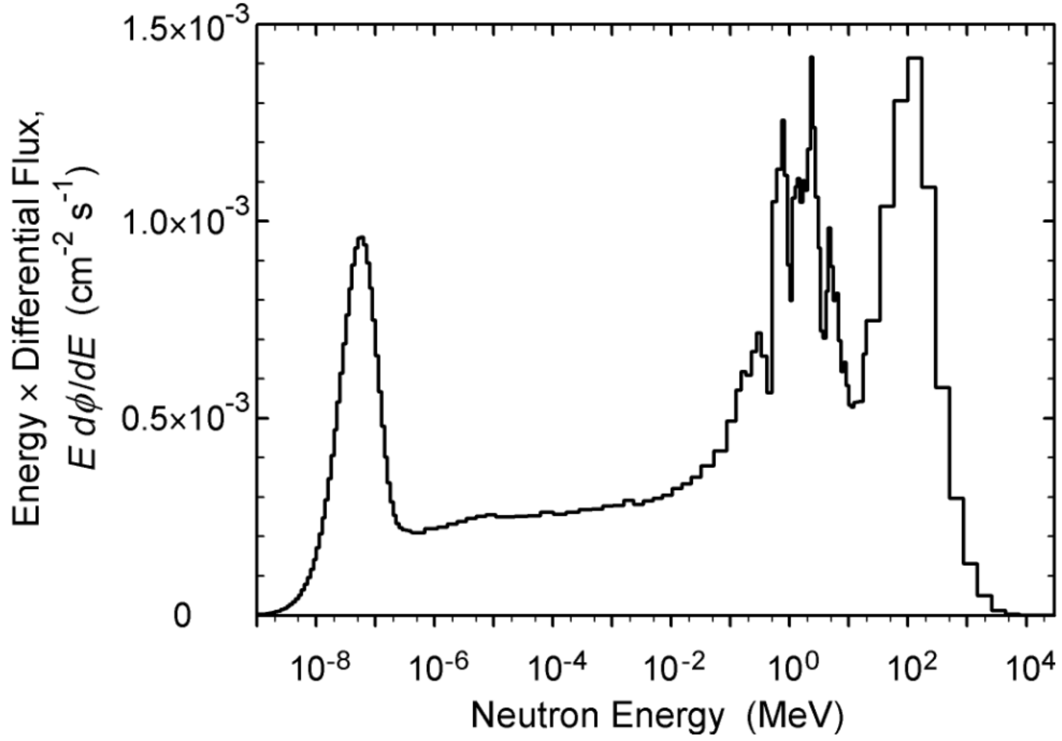
Primary and secondary cosmic rays can be

- Simulated from first principle with dedicated codes, e.g. CORSIKA
- Sampled from parameterisations of measured fluxes of secondary particles, e.g. [T. K. Gaisser, 2016] for muons
  → **feed into Primary Particle Generators in Geant4**
- Use existing Primary Particle Generators like CRY or develop your own, e.g. [H. Kluck, 2013].



[Mpfiz via wikipedia]

Atmospheric Neutrons



[M. S. Gordon et al., IEEE Trans. Nucl. Sci., 51.6 (2004) 3427-3434]

- At ground, **atmospheric neutrons** can reach up to ~10 GeV
- Thermal neutrons at ~10 meV
- Actual spectrum depends on atmospheric conditions, and hence on the location:

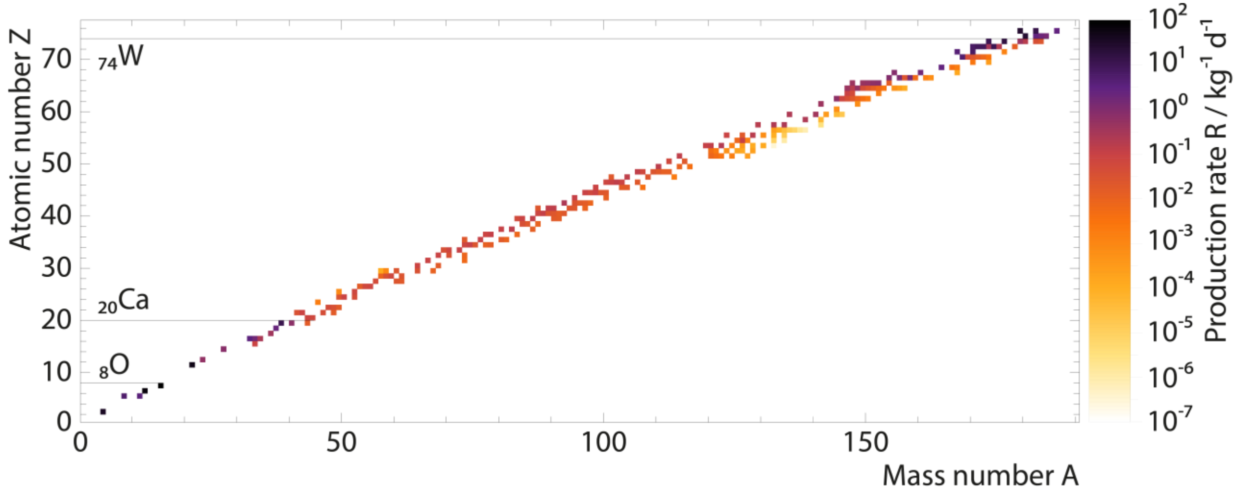
← IBM T. J. Watson Research Center in Yorktown Heights, NY

Cosmogenic Activation

Activation of materials due to **production of radionuclides via atmospheric n** (and to a lesser extend due to μ) can be

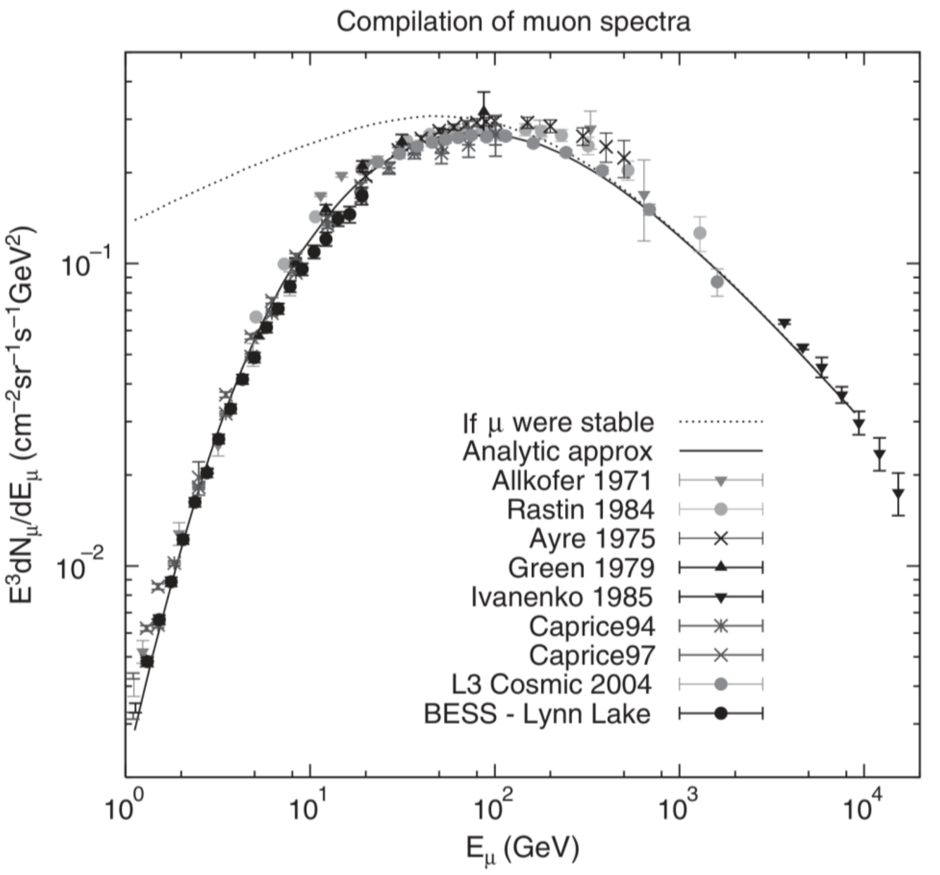
- Directly simulated in Geant4 via ParticleHP physics
- **Simulate only the decay** of the radionuclides in Geant4; **scale the decay spectra** with the production rates calculated with external, specialized tools (TALYS, ACTIVIA)
- Decay is delayed w.r.t. the prompt cosmic rays

Cosmogenic activation in $CaWO_4$ calculated with ACTIVIA



[H. Kluck et al., J. Phys.: Conf. Ser. 2156 (2021) 012227]

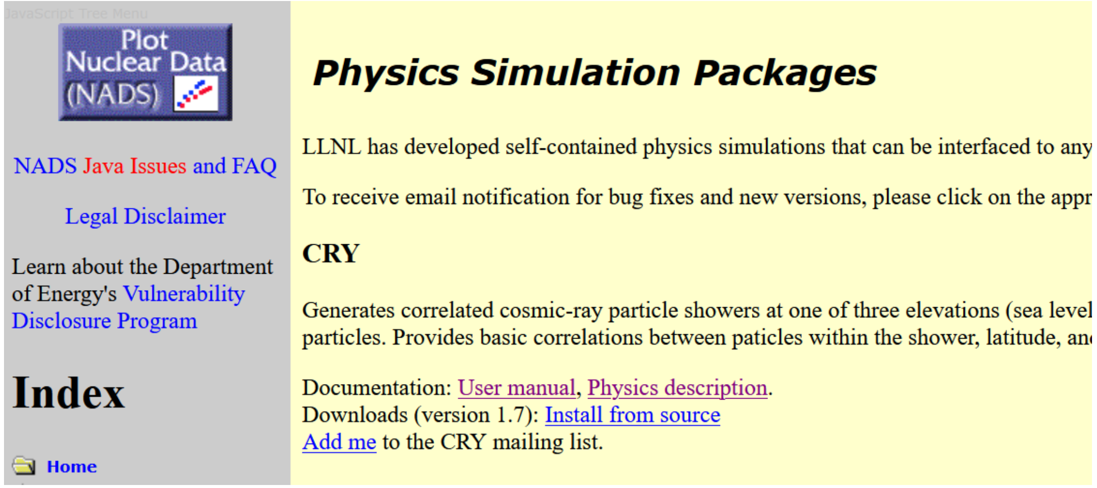
Atmospheric Muons



- At ground, **atmospheric muons** can reach up to >10 TeV
- Low energy part ~<10 GeV is affected by:
  - Atmospheric condition
  - Geomagnetism
  - Solar activity
- Spectrum can be described by Gaisser's parametrisation

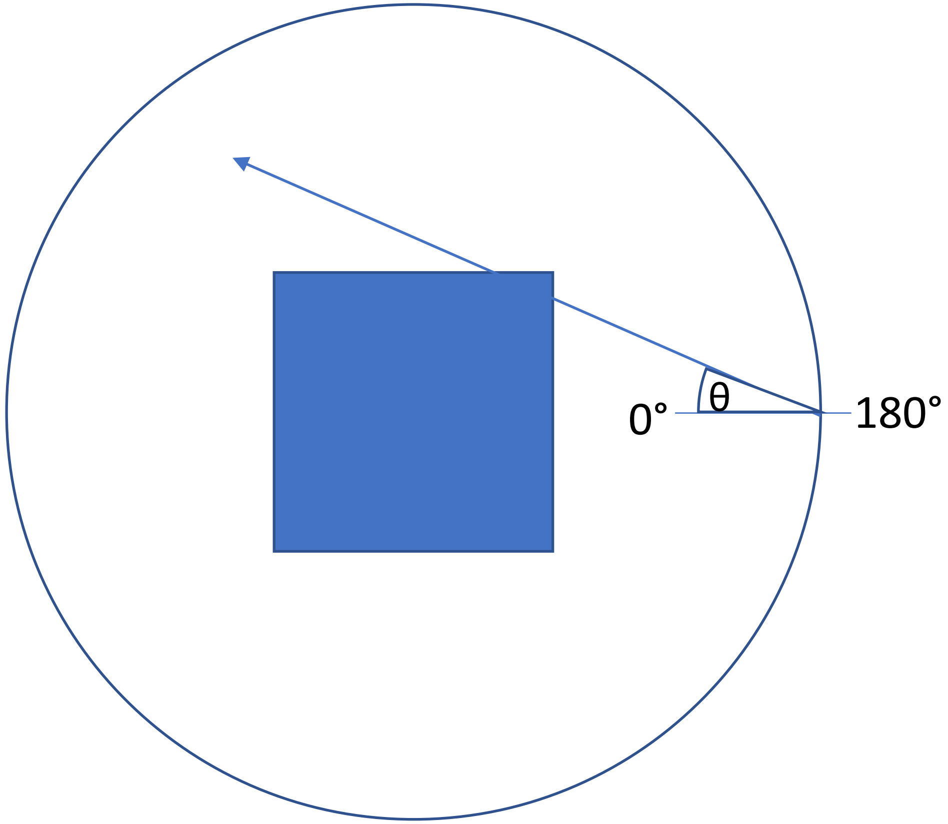
[T. K. Gaisser et al., *Cosmic Rays and Particle Physics* (2nd Ed.), Cambridge, 2016]

CRY



- Geant4 has no built-in particle generator for atmospheric n/μ
- In **this lecture**, we will assume initial spectrum is flat and **use GPS**
- For more realistic spectrum: CRY
- Advantages:
  - Easy to include (next slide)
  - Full shower, i.e. several primaries per event
  - μ, n, p, e^-, e^+, pions
- Disadvantages:
  - No overburden
  - Only three altitudes
- Only option for even more details: self-developed code

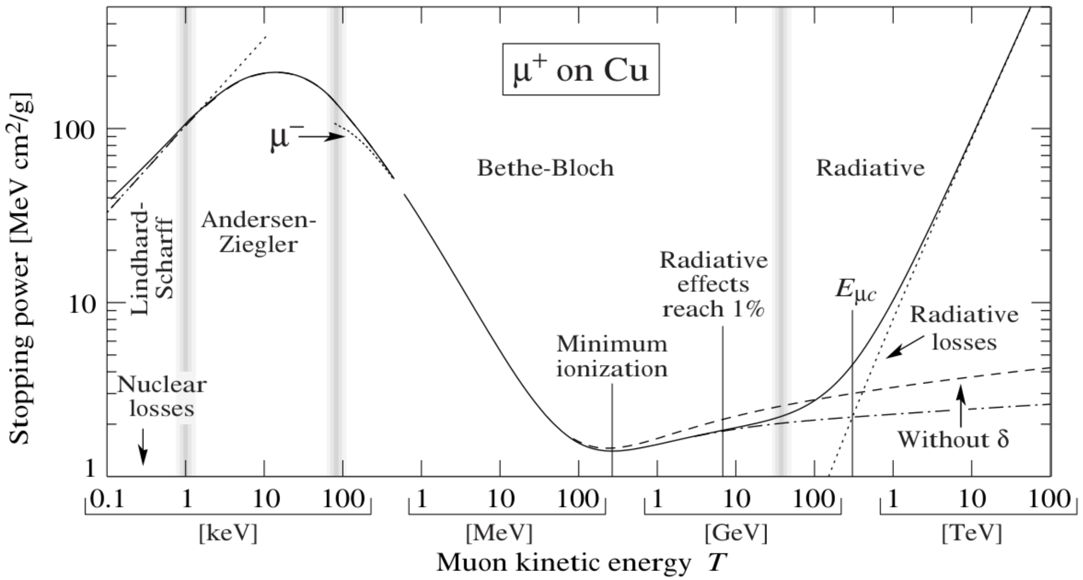
Using GPS for Atmospheric Particles



- Shooting `<particle>` with `<energy>` from a sphere of `<radius>` inwards on a volume

```
/gps/pos/type Surface
/gps/pos/shape Sphere
/gps/pos/radius <radius>
/gps/pos/centre 0. 0. 0. mm
/gps/particle <particle>
/gps/energy <energy>
/gps/ang/type iso
/gps/ang/surfnorm false
/gps/ang/mintheta 0 deg
/gps/ang/maxtheta 90 deg
```

Average Muon Energy Loss / Stopping Power



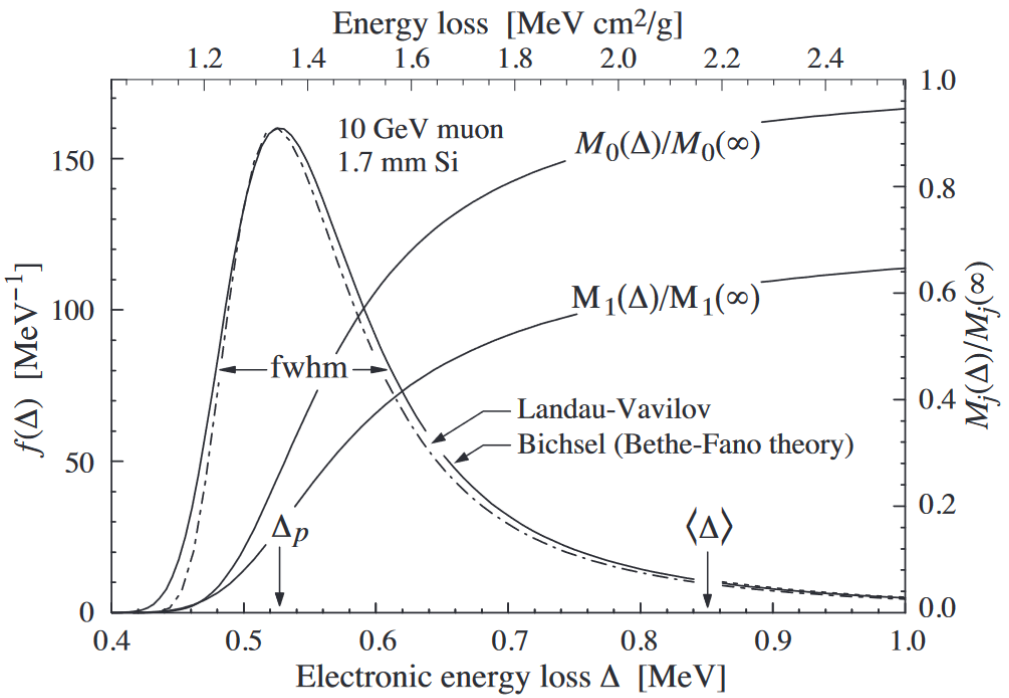
[D. E. Groom et al., Atom. Data Nucl. Data Tab., 78.2 (2001) 183-356]

- **Minimum ionising** muons loss ~2 MeV cm^2 g^{-1} e.g. for Ge (ρ=5.3 g cm^{-3}): ~10.6 MeV cm^{-1}
- In general, **stopping power**

$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E) \cdot E$$

with **material dependent** electronic contribution *a* and radiative contribution *b*

Muon Energy Fluctuation



[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022 (2022) 083C01]

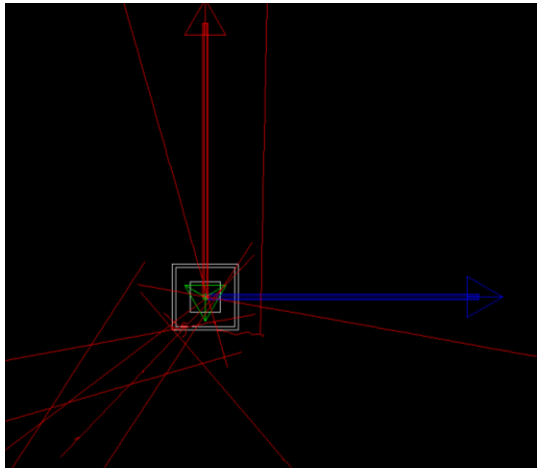
- PDF of muon energy loss is asymmetric with a heavy tail towards higher energies
  → **Average energy loss** $\langle\Delta\rangle$ is not the **most probable energy loss** Δ_p
- The actual energy loss can be fitted with a Landau function

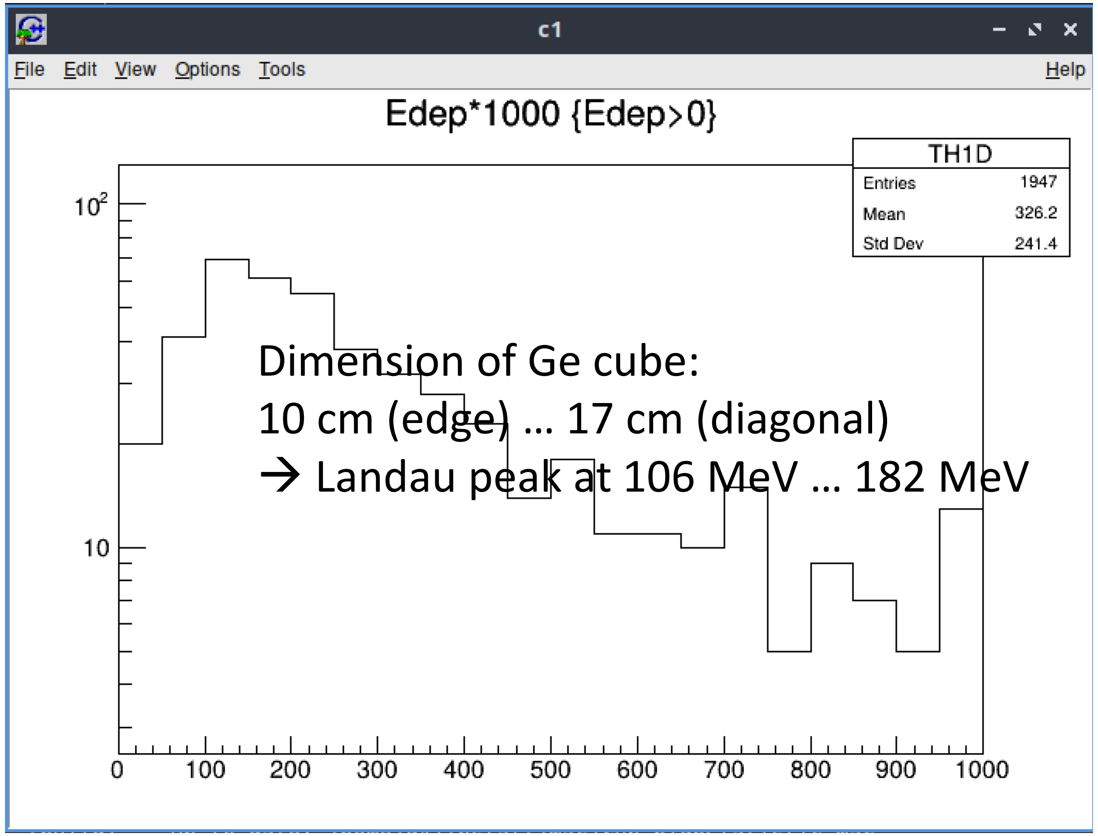
Hands-on

- Copy ./mac/vis_run.mac to ./mac/vis_run_atm.mac and modify the GPS commands
  - To use a Sphere as surface source
  - Centred around our geometry
  - With a diameter large enough to enclose the “shell” volume
  - Select mu- of 100 GeV as particle
  - Isotropic distributed between 0° and 90°
  - Simulate 10 events
- Run the simulation, open the produced scene-0.heprep.zip to check if the particles are generated as expected
- Copy ./mac/run.mac to ./mac/run_atm.mac and replace the GPS commands with the ones from above
- Set “/event/verbose” and “/tracking/verbose” to 0 and run the simulation for 10000 events
- Open the produced cube.root and create a histogram of Edep between 0 and 1GeV - does the spectrum looks like expected?

Hands-on

```
/gps/pos/type Surface
/gps/pos/shape Sphere
/gps/pos/radius 25 cm
/gps/pos/centre 0. 0. 0. mm
/gps/particle mu-
/gps/energy 100. GeV
/gps/ang/type iso
/gps/ang/surfnorm false
/gps/ang/mintheta 0 deg
/gps/ang/maxtheta 90 deg
```

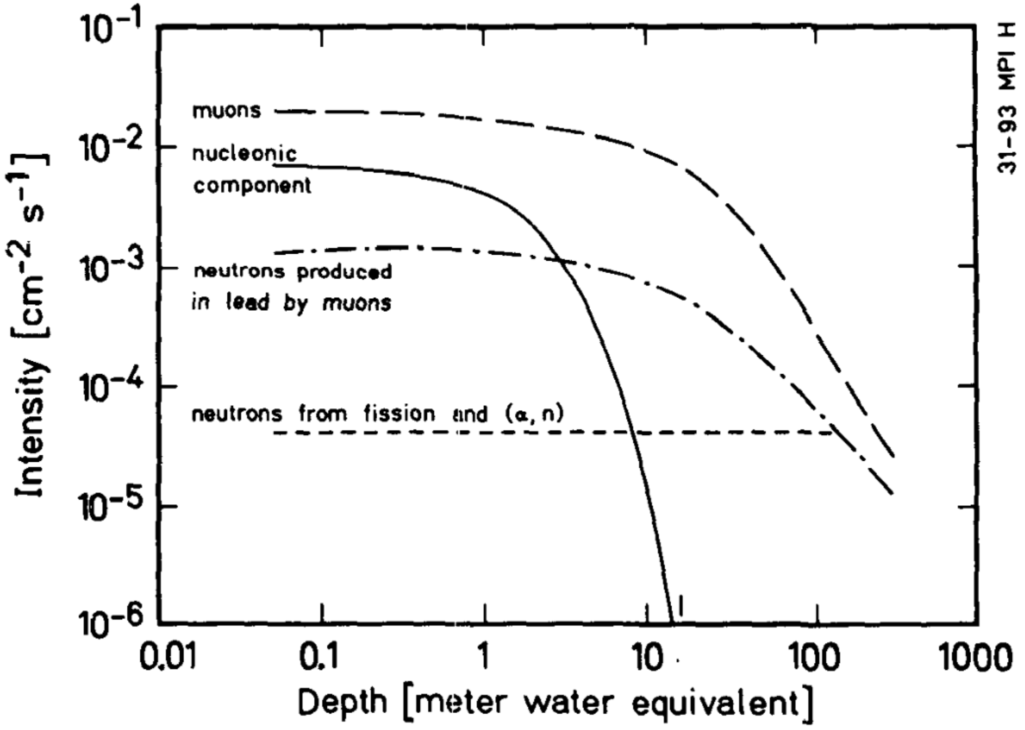




Dimension of Ge cube:
10 cm (edge) … 17 cm (diagonal)
→ Landau peak at 106 MeV … 182 MeV

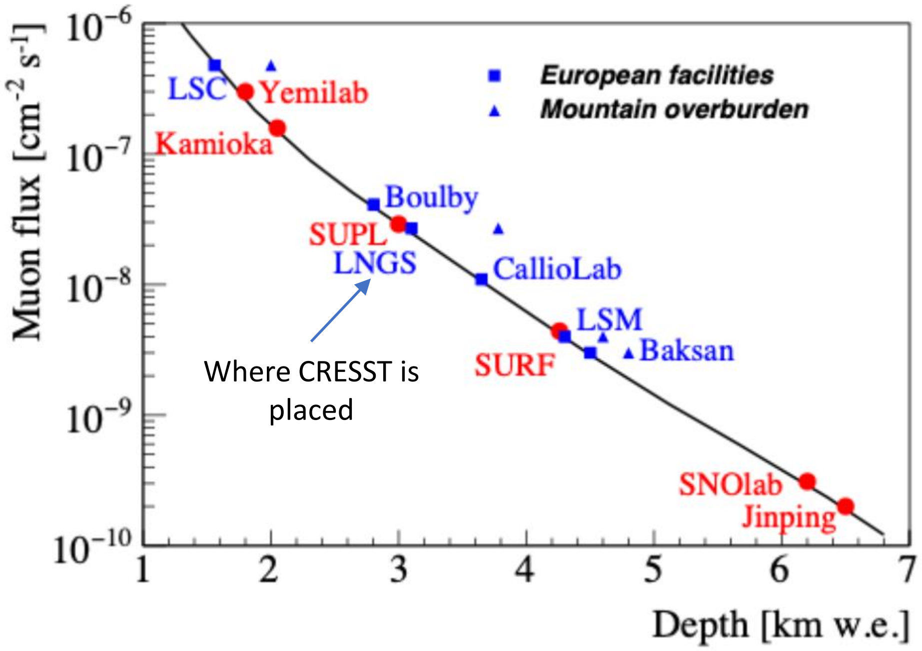
Deep-underground Laboratories

- Rock, concrete etc. above the experiment shields against atmospheric μ (and p, n)
- Shielding power of this **overburden** is given as column density *X*
  $$X = \rho \cdot l$$
  along the μ track length *l*
- Given relative to the shielding power of a water column of 1 m height in **meter water equivalent**:
  1 m w.e. = 10^2 g cm^{-2}



[G. Heusser, Annu. Rev. Nucl. Part. Sci., 45 (1995) 543-590]

Deep-underground Laboratories



[A. Ianni, SciPost Phys. Proc. 12 (2023) 007]

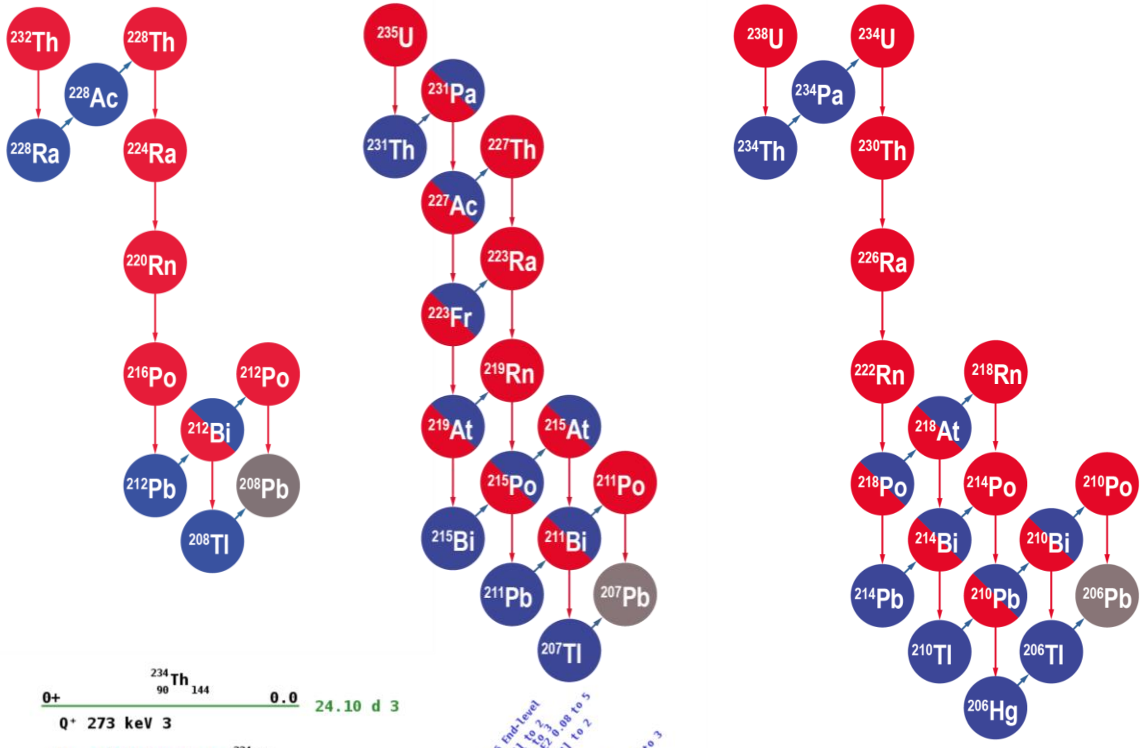
→ **Reduction of μ-flux** by up to ~10^8 is possible (Jinping lab)
→ Deepest lab in Europe: LSM; largest lab in Europe: LNGS
→ Simulation of shielding power needs be-spoken primary particle generator that **considered the topography of the rock overburden** e.g. [H. Kluck, 2013]

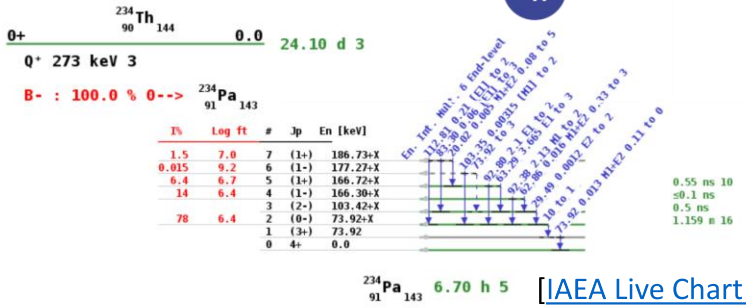
Radioactive Decay

- α-, β^--, β^+- and Electron Capture (EC)-decay
  → G4RadioactiveDecay
- If daughter nucleus is in excited state, de-excitation via γ*-emission or Internal Conversion (IC=e^- emission)
  → G4PhotoEvaporation
- Subsequent atomic relaxation (fluorescence, Auger electron-emission)
- Information about decay channels and nuclear level scheme:
  - IAEA Live Chart of Nuclides
  - R. B. Firestone, *Table of Isotopes***, 1999, Wiley-VCH

→**Very helpful to check correctness of simulation**, e.g. Q-value

Natural radioactive decay chains of ^{232}Th, ^{235}U, ^{238}U



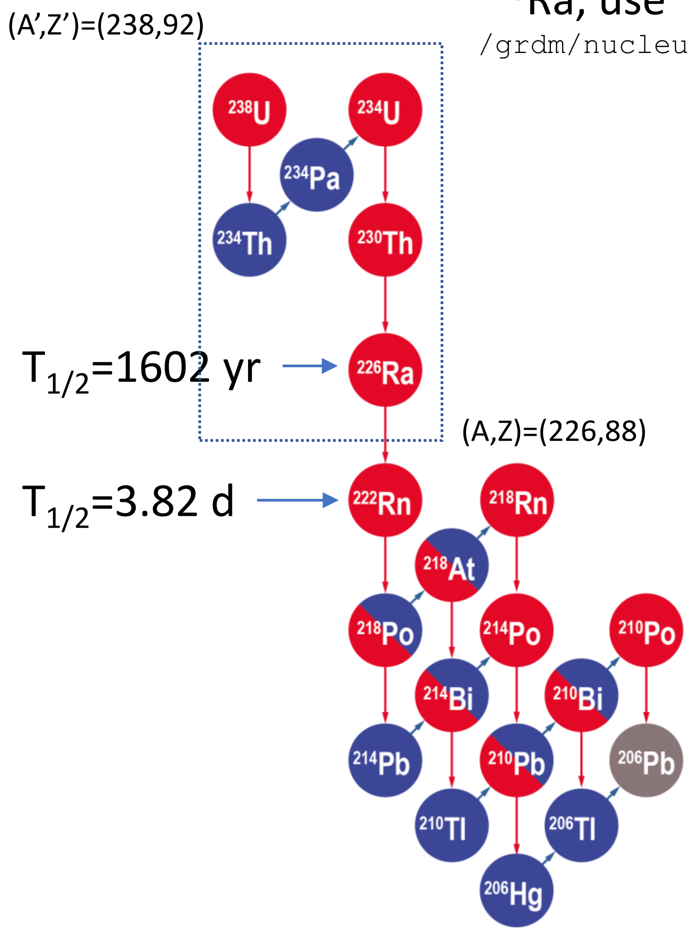


[IAEA Live Chart of Nuclides]

*Gamma-ray: em radiation emitted through *nuclear* de-excitation; ****Isotope**: nuclides *belonging to a given element*, i.e. same atomic number Z, but different atomic mass A

Secular Equilibrium

- Activity of parent nuclide = activity of daughter nuclide
- If parent nuclide has long half-life and short-lived daughter nuclide is removed (e.g. radiochemical purification)
  →**Equilibrium is broken**
- Use `/grdm/nucleusLimits A A’ Z Z’` command to break decay chain



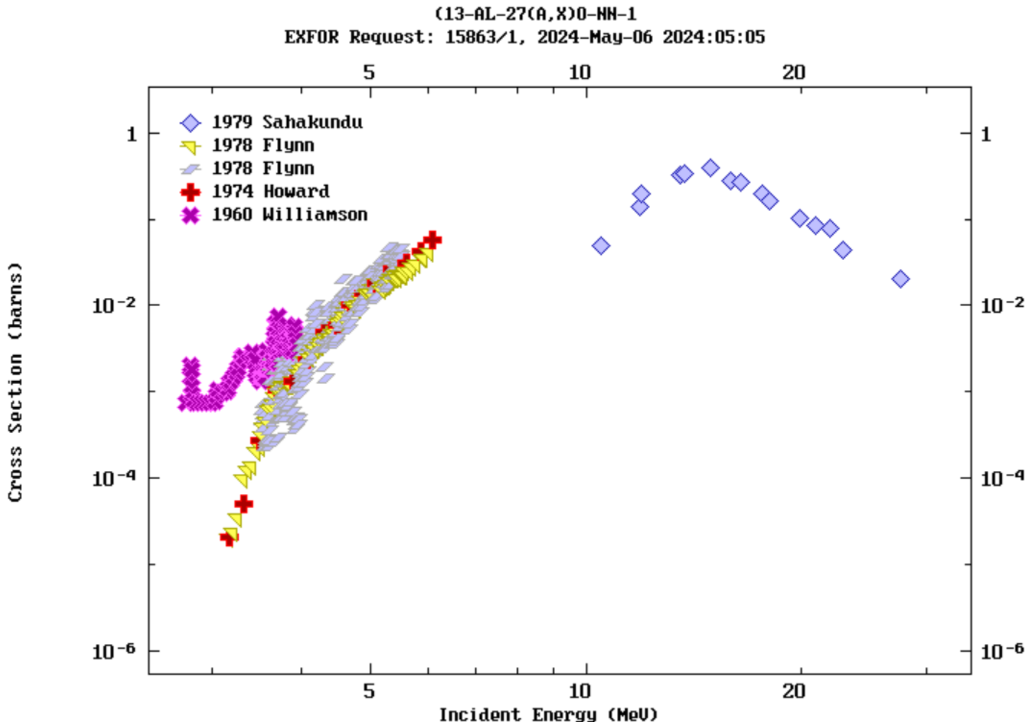
To simulate only the upper half of the ^{238}U decay chain until ^{226}Ra, use
`/grdm/nucleusLimits 226 238 88 92`

(α,n) reactions

(α,n) reactions can be

- Directly simulated in Geant4 (with input from TALYS via the TENDL data library)
  → G4ParticleHP
- **Simulate only the neutron propagation** in Geant4 and **obtain neutron spectra and yield from specialised codes**
  - SOURCES4 (proprietary code)
  - NeuCBOT (open source)
- Cross sections for (α,n) reactions often inconsistent
  → Simulation is only as good as input data

For example, measured cross sections for $^{27}Al(\alpha,n)^{30}P$



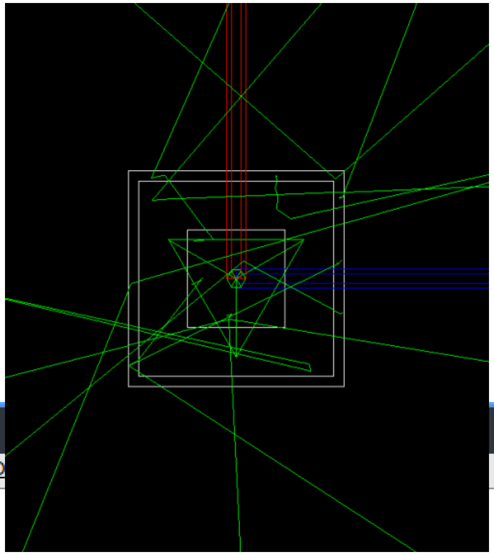
[IAEA, Experimental Nuclear Reaction Data (EXFOR)]

Hands-on

- Assume the Cu of “shell” (m=23.7 kg) is contaminated with 500 uBq/kg of ^{58}Co from cosmogenic activation, calculate how many events need to be simulated for 100 d measuring time
- Copy ./mac/vis_run.mac to ./mac/vis_run_Cu.mac and adapt the GPS commands by
  - Selecting ^{58}Co as primary particle
  - Placing it inside the “shell” volume by using the “/gps/pos/confine” command
- Run the simulation with 10 events, open the produced scene-0.heprep.zip to check if the particles are generated as expected
- Copy ./mac/run.mac to ./mac/run_Cu.mac and replace the GPS commands with the ones from vis_run_Cu.mac
- Set “/event/verbose” and “/tracking/verbose” to 0 and run the simulation for the number of events equivalent to 100 d measuring time
- Open the produced cube.root and create a histogram of Edep between 0 and 2 MeV
  - does the spectrum looks like expected?

Hands-on

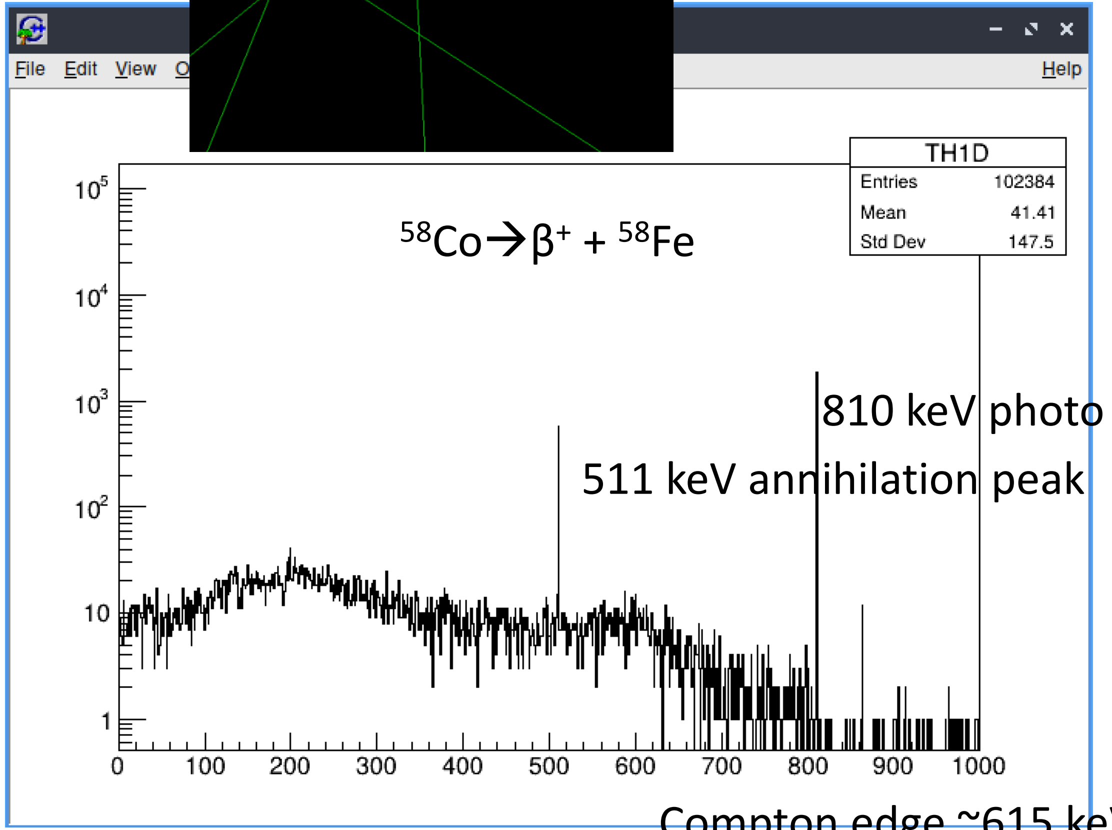
```
/run/initialize
#Place 58Co ions
/gps/pos/type Volume
/gps/pos/shape Para
/gps/pos/halfx 12 cm
/gps/pos/halfy 12 cm
/gps/pos/halfz 12 cm
/gps/pos/paralp 0
/gps/pos/parthe 0
/gps/pos/parphi 0
/gps/pos/centre 0. 0. 0. mm
/gps/pos/confine shell
/gps/particle ion
/gps/ion 27 58
/gps/energy 0 MeV
/gps/ang/type iso
#500 uBq/kg * 23.7 kg * 3600 s/h * 24 h/d * 100 d
/run/beamOn 102384
```



Gamma

#	E_γ [keV]	I_γ(abs) [%]
1	810.7593 *20*	**99.45 *1***
2	863.951 *6*	0.686 *10*
3	1674.725 *7*	0.517 *10*

[IAEA Live Chart of Nuclides]



Questions, Comments, Feedback

Additional Information

Gaisser Parameterisation

$$\frac{\mathrm{d}N_i(E_i,X)}{\mathrm{d}X} = -\frac{N_i(E_i,X)}{\lambda_i} - \frac{N_i(E_i,X)}{d_i} + \sum_{j=i}^{J} \int_E^{\infty} \frac{F_{ji}(E_i,E_j)}{E_i} \frac{N_j(E_j,X)}{\lambda_j} \, \mathrm{d}E_j .$$

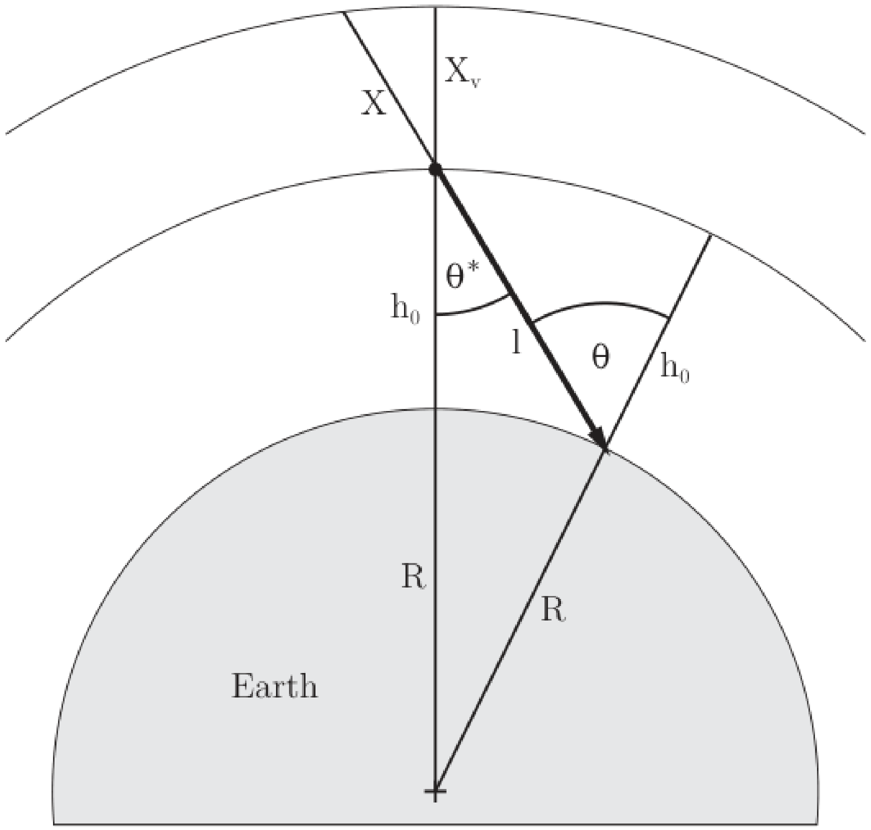
$$\begin{aligned} \pi^{\pm} &\rightarrow \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu) \quad (\sim 100\%) \\ K^{\pm} &\rightarrow \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu) \quad (\sim 63.5\%). \end{aligned}$$

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} \simeq S_\mu(E_\mu) \frac{N_0(E_\mu)}{1 - Z_{NN}} \left\{ \mathcal{A}_{\pi\mu} \frac{1}{1 + \mathcal{B}_{\pi\mu} \cos\theta \, E_\mu/\epsilon_\pi} + 0.635 \, \mathcal{A}_{K\mu} \frac{1}{1 + \mathcal{B}_{K\mu} \cos\theta \, E_\mu/\epsilon_K} \right\} .$$

- The **Gaisser parameterisation** describes the development of particle cascades with a set of coupled equations
- For muons, mainly the decay of pions and kaons are feeding the cascade
- Given as function of E_μ at *ground level* and zenith angle

[T. K. Gaisser et al., *Cosmic Rays and Particle Physics* (2nd Ed.), Cambridge, 2016]

Zenith Angles



- Due to Earth's curvature, the **zenith angle** at *ground* θ is different from the zenith angle at the *production vertex* θ^*
- Production height is h_0 ~17 km
- In general, track length also depends on altitude of experiment

Gaisser Parameterisation II

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} \simeq S_\mu(E_\mu) \frac{N_0(E_\mu)}{1 - Z_{NN}} \left\{ \mathcal{A}_{\pi\mu} \frac{1}{1 + \mathcal{B}_{\pi\mu} \cos\theta \, E_\mu/\epsilon_\pi} + 0.635 \, \mathcal{A}_{K\mu} \frac{1}{1 + \mathcal{B}_{K\mu} \cos\theta \, E_\mu/\epsilon_K} \right\}.$$

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} \approx \frac{0.14 \, E_\mu^{-2.7}}{\mathrm{cm}^2 \, \mathrm{sec} \, \mathrm{sr} \, \mathrm{GeV}} \left\{ \frac{1}{1 + \frac{1.11 \, E_\mu \cos\theta}{115 \mathrm{GeV}}} + \frac{0.054}{1 + \frac{1.11 E_\mu \cos\theta}{850 \mathrm{GeV}}} \right\}.$$

- Below ~200 GeV, the suppression S_μ due to **muon decay** and **energy loss** in the atmosphere has to be considered
- Above, it can be neglected
  - Relativistic time dilation
  - Small energy loss relative to initial energy
    → **Gaisser's Parameterisation**

[T. K. Gaisser et al., *Cosmic Rays and Particle Physics* (2nd Ed.), Cambridge, 2016]

Muon Range

- To stop a 1 TeV-muon in concrete*:
  - $\rho = 2.3 \text{ g cm}^{-3}$
  - $a = 2.605 \text{ MeV cm}^2 \text{ g}^{-1}$
  - $b = 3.752 \cdot 10^{-6} \text{ cm}^2 \text{ g}^{-1}$
  - → $X = 1.5 \cdot 10^5 \text{ g cm}^{-2}$
  - → $d = \frac{X}{\rho} = 65 \text{ km}$
- Energy loss in 10 m w.e.

  $$E = \frac{dE}{dX} \cdot X = 6.6 \text{ GeV}$$

  i.e. <1% of initial energy

- Get the **muon range** via the *Continous Slowing Down Approximation* (CSDA): assume *a* and *b* are constant in energy:

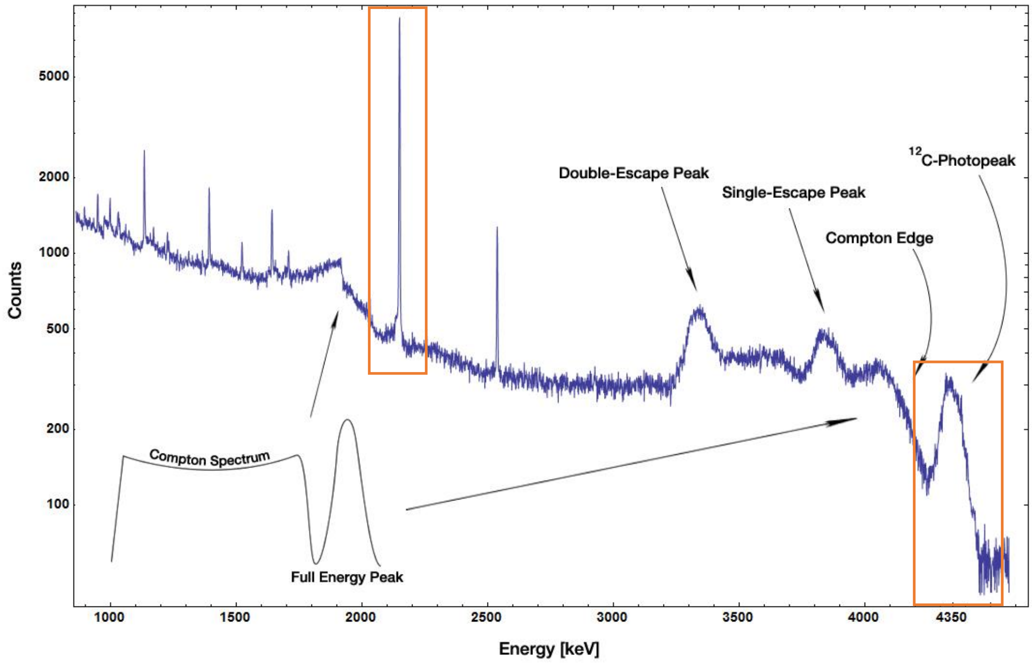
  $$X(E) = \int_{E_0}^{E} \left(\frac{dE'}{dX} \right)^{-1} \mathrm{d}E'$$

- CSDA overestimate the muon range for E>1 TeV as it ignores discrete but high energetic scatterings
- **No significant shielding** against muons at **shallow sites**

* From table IV-2 of [D. E. Groom et al., Atom. Data Nucl. Data Tab., 78.2 (2001) 183-356]; caution: a="Ionization", b=("Brems"+"Pair prod"+"Photonucl")/*T*

Photopeak

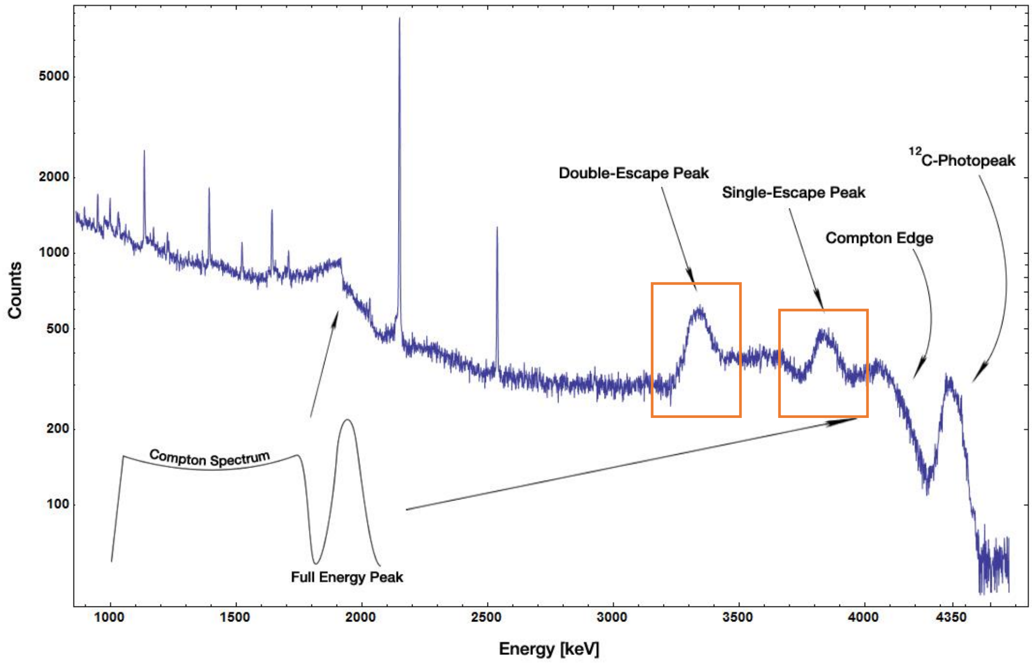
- If the **full energy** E_γ of a γ-ray is absorbed in the detector via the photoelectric effect
  → **photopeak** at E_γ
- Similar if an α is absorbed



[Allen McC via Wikipedia]

Escape Peak

- If E_γ > 2*511 keV
  → Pair creations of e^+e^-
  → Creation of positronium
  → Annihilation, 2 γ-rays of 511 keV each
- If both γ-rays get absorbed
  → photopeak at E_γ
- If only one γ-ray gets absorbed
  → **Single-escape peak** at E_γ-511 keV
- If no γ-ray gets absorbed
  → **Double-escape peak** at E_γ-1022 keV
- Similar, if after photo absorption, a fluorescence X-ray E_X escape
  → Peak at E_γ-E_X



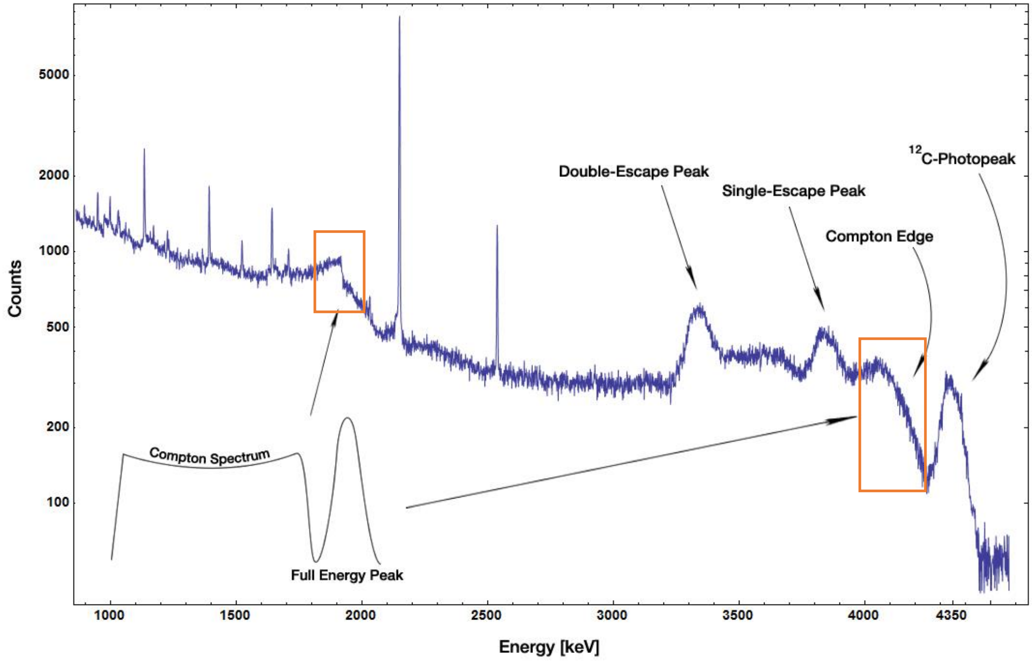
[Allen McC via Wikipedia]

Compton

- Compton scattering: incoherent scattering of a γ-ray with an atomic electron, transferring some energy to the electron
- If scattered γ-ray leaves the detector, only the transferred energy is visible
- Maximum transferred energy for backscattering

$$E_{\text{max}} = E_\gamma \left(1 - \frac{1}{1 + \frac{2E_\gamma}{m_\text{e}c^2}}\right)$$

→ **Compton edge** at E_{max}
→ **Compton continuum** between 0 and E_{max}



[Allen McC via Wikipedia]

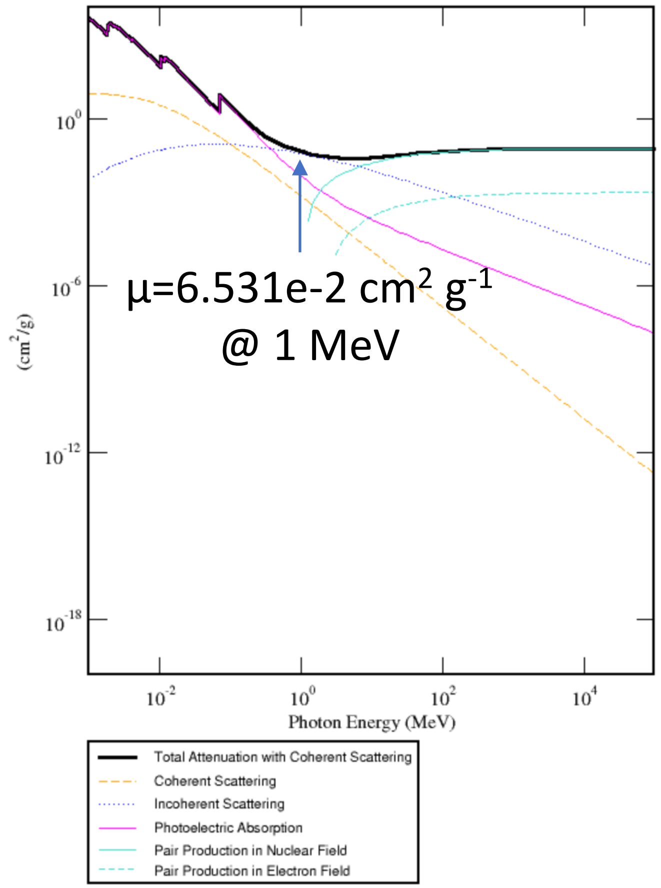
Leakage

- If the detector dimensions are smaller then the absorption length, the incident particle may deposit only a part of its energy and escape the detector with the remaining energy (~ energy may **leak out of the detector**)
- For example, to contain a 1 MeV-γ-ray in a $CaWO_4$ detector:

$$\lambda^{-1} = \mu \cdot \rho$$
$$= 6.531 \cdot 10^{-2}\ \mathrm{cm}^2\mathrm{g}^{-1} \cdot 6.06\ \mathrm{g\ cm}^{-3}$$
$$= 0.396\ \mathrm{cm}^{-1}$$
$$\rightarrow \lambda = 2.53\ \mathrm{cm}$$

- Set Geant4's range cut to a value smaller then the detector dimension, so that the leakage can be properly simulated

Attenuation μ for $CaWO_4$

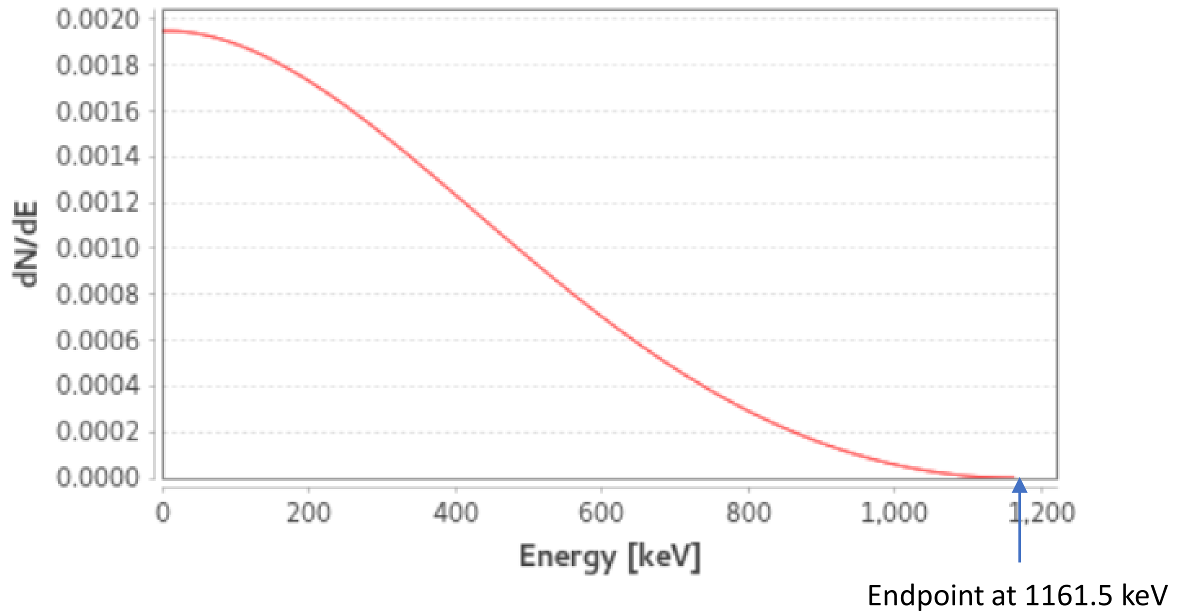


[XCOM]

Beta spectrum

- Beta decay
  $^{A}_{Z}X \rightarrow\ _{Z+1}^{A}Y + \overline{\nu_e} + e^-$
- Continuous spectrum
- Endpoint of the spectrum = Q-value – neutrino mass

Beta spectrum of ^{210}Bi



[IAEA Live Chart of Nuclides]

Include CRY

- ```
  MyPGA::MyPGA(){
    Setup=new CRYSetup(…);
    GenPrimaries = new CRYGenerator(Setup);
  }
  ```
- ```
  MyPGA::GeneratePrimaries(G4Event *evt){
    std::vector<CRYParticle*> primaries;
    GenPrimaries->genEvent(&primaries);
    for(auto* p : primaries){
      //Get pos, energy, etc. from p and fill
      //it into vertex and particle
      …
      auto* vertex   = new G4PrimaryVertex (…)
      auto* particle = new G4PrimaryParticle(…)
      vertex->SetPrimary(particle);
      evt->AddPrimaryVertex(vertex);
    }
  }
  ```

- Call it from ParticelGeneratorAction (PGA) (similar to Geant4’s GPS)
- Multiple primaries per event possible → loop over it
- Need to “translate” CRY data types to Geant4 data types