

Detector Simulation — Geant4

EHEP 2024 School
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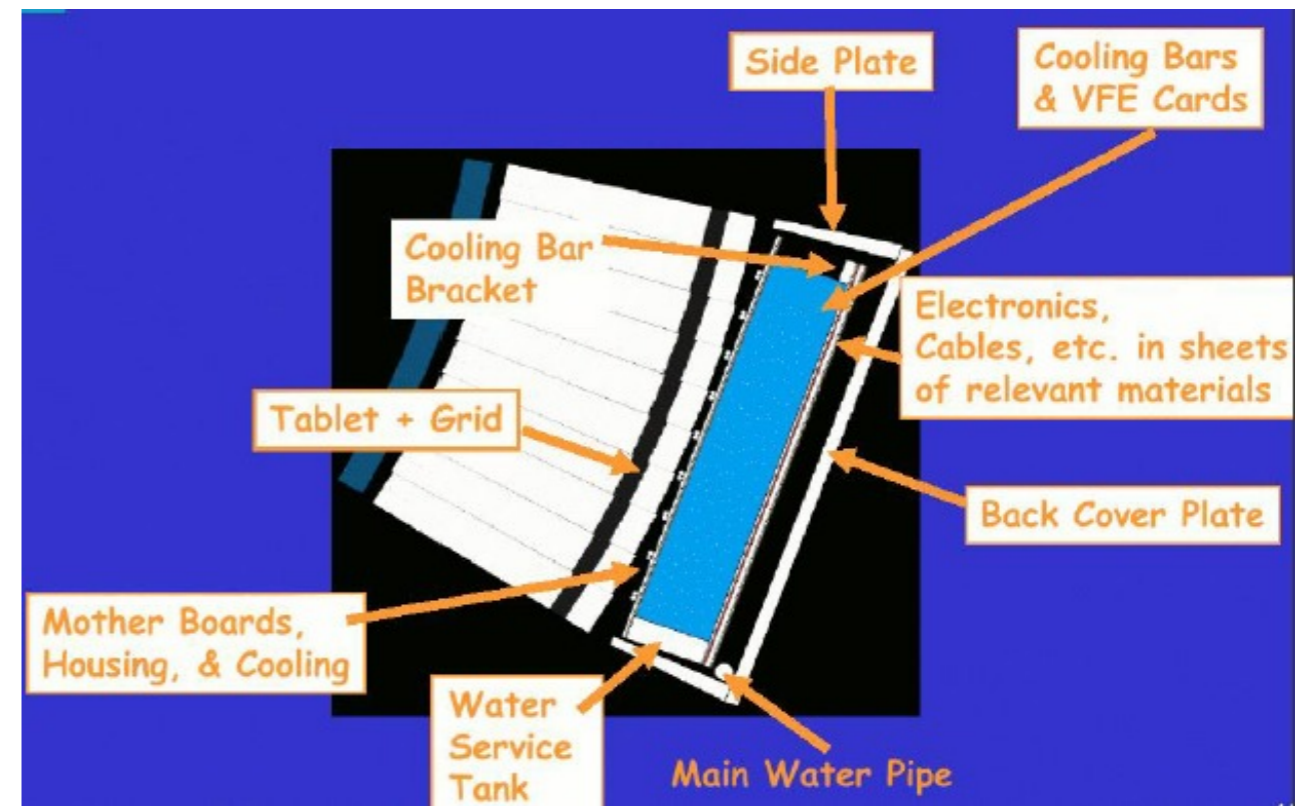
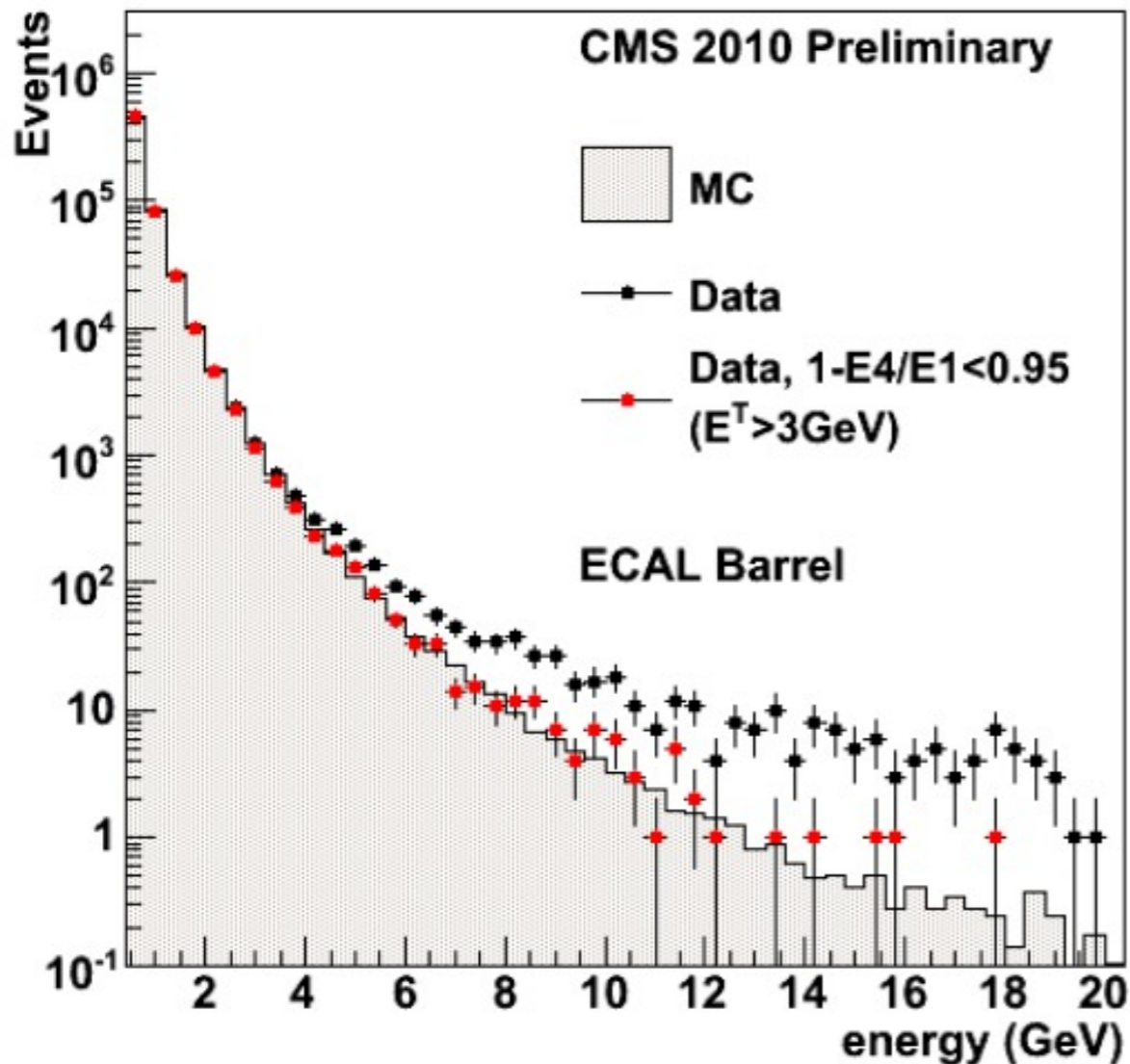
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Simulation

- Detectors in nuclear and high-energy physics are getting more and more complex
 - carrying out an experiment with such a complex detector and interpreting the outcome needs some additional help
 - do a mock experiment on the computer with known sources and some model of the detector and see if the final results match the source
 - also use such mock experiments to design the detector to be used, in particular for very expensive experiments (space science, collider physics)
- Radiation is used in many other applications: medical diagnosis, medical treatment, non-destructive ways to probe structures
 - exposing living beings to radiation requires careful evaluation of the amount of radiation to be used
- Use the Monte Carlo technique to study these phenomena and Geant4 is a toolkit to enhance such a study

Understanding Issues

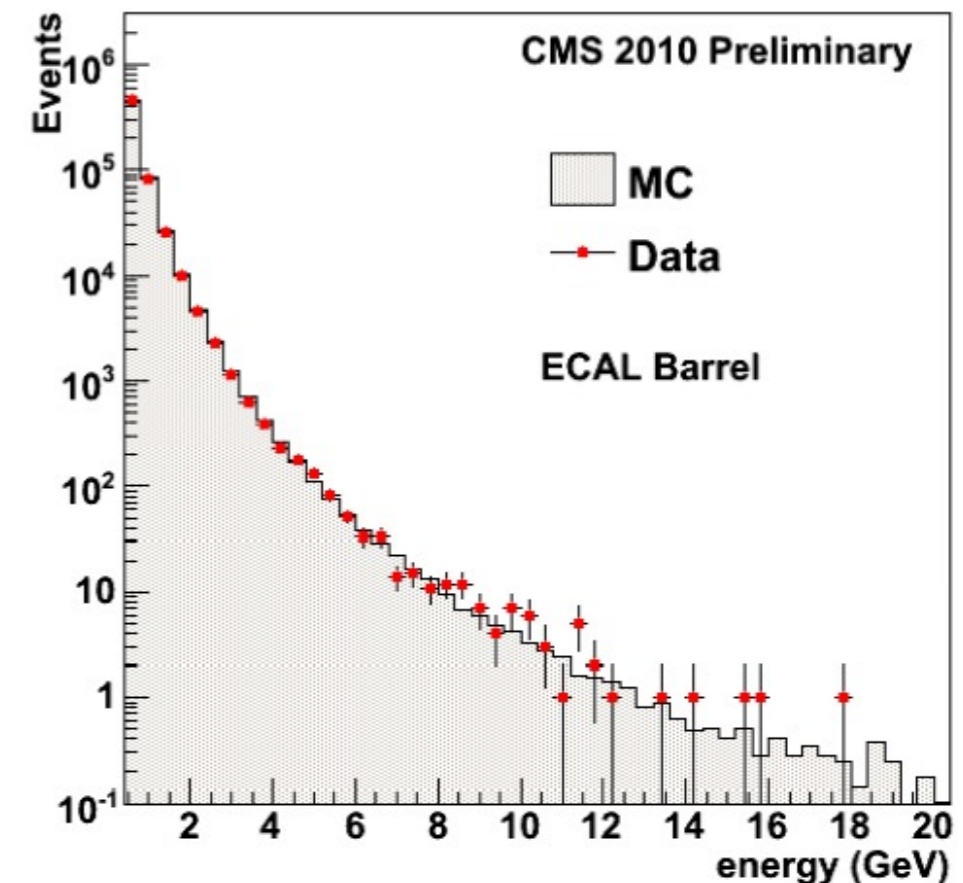
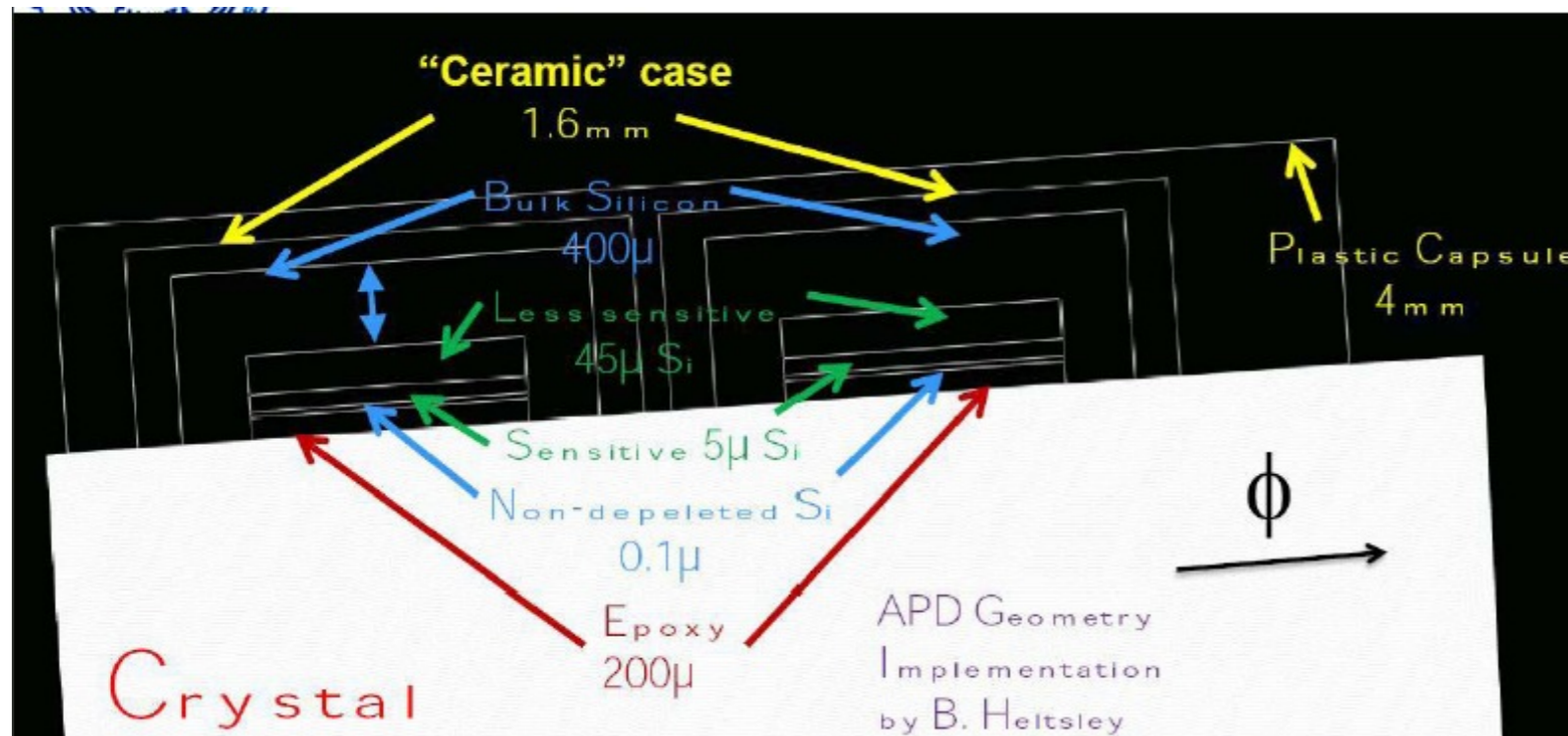
- During early studies of collisions at the large hadron collider, CMS experiment observed some unusual number of events in their detector system



- CMS measured energy deposited in a crystal calorimeter. The excess was observed at higher energies

Understanding Issues

- CMS tried to understand the readout unit of the calorimeter and realised there could be excess energy if some heavily ionising particles go through the readout unit. This excess is not light produced in the crystal but charge deposited in the readout unit



- Simulating the readout unit removed the observed excess
- A qualitative as well as quantitative understanding of everything observed is crucial in providing results with the highest precision and confidence
- Simulation and Geant4 provide this confidence

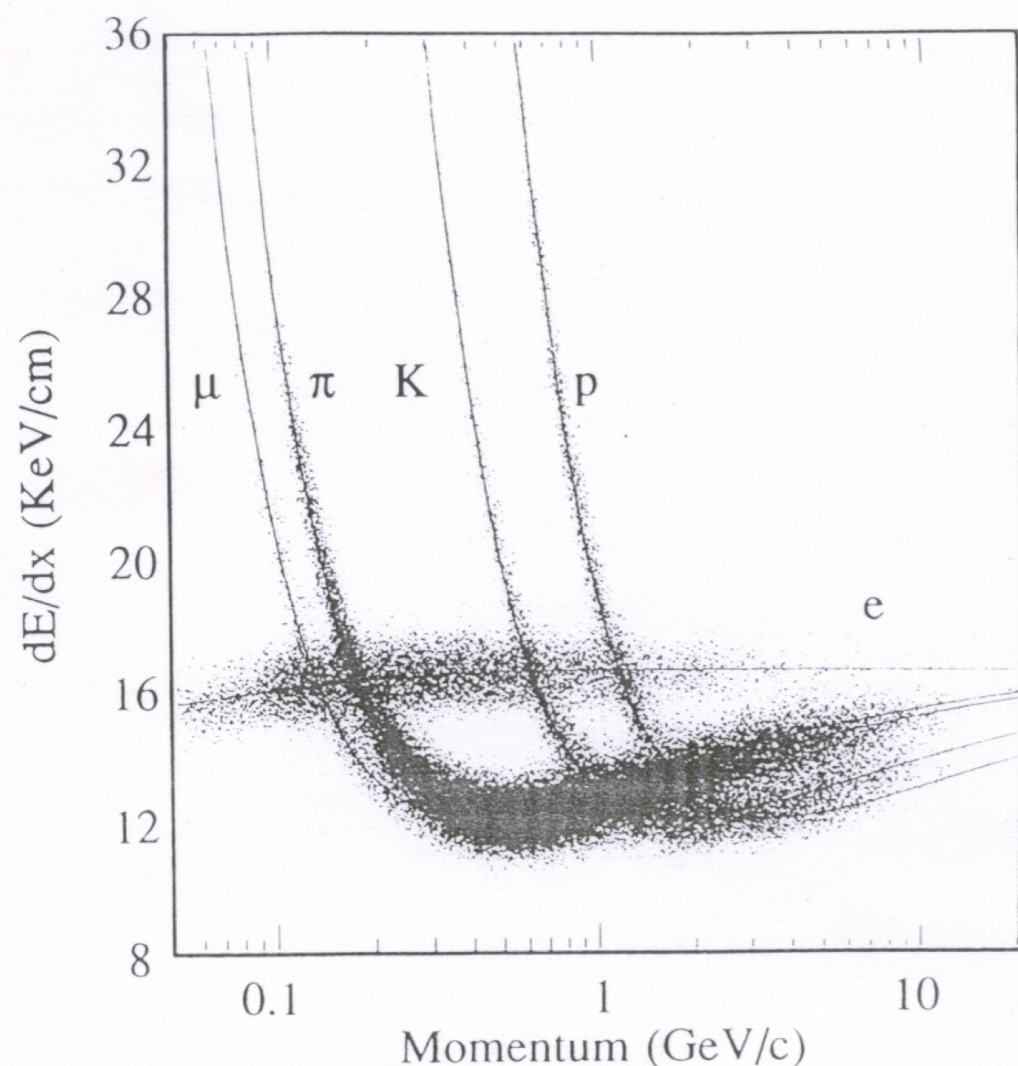
Components

- Detector Simulation needs
 - Knowledge of the detector components
 - How particle interacts with matter
 - Monte Carlo methods
 - Geant4 as a tool

Interaction of Particles with Matter

Interaction of particles with matter

- The first thing is to understand how particles (radiation) behave when they pass through matter
- Charged particles passing through matter interact with nuclei as well as with atomic electrons. The physical processes are broadly classified into two categories:
 - Discrete processes (bremsstrahlung, annihilation, elastic, ...)
 - Continuous processes (energy loss, multiple scattering, ...)
- Continuous energy loss (charged particles in the matter)

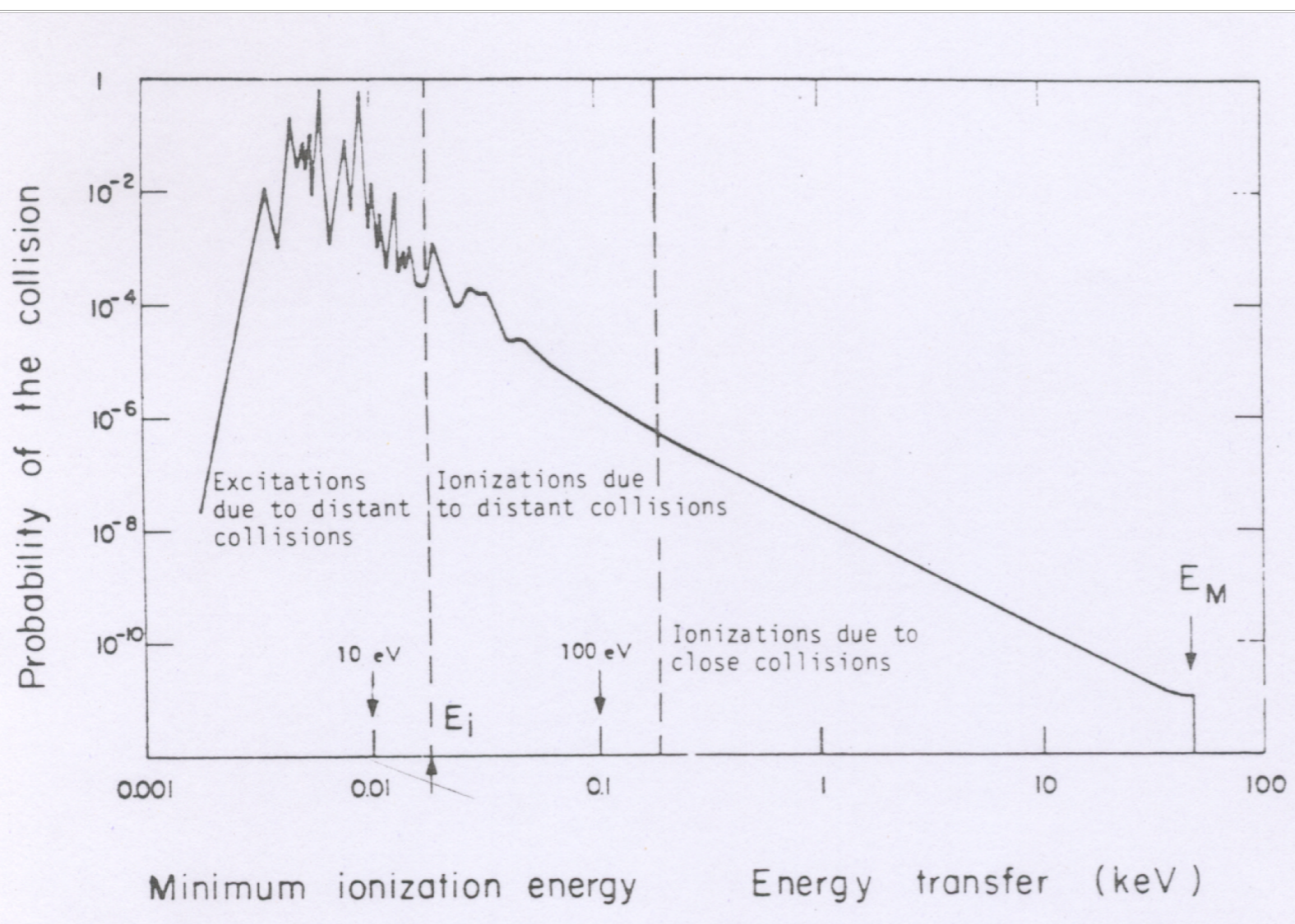


$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

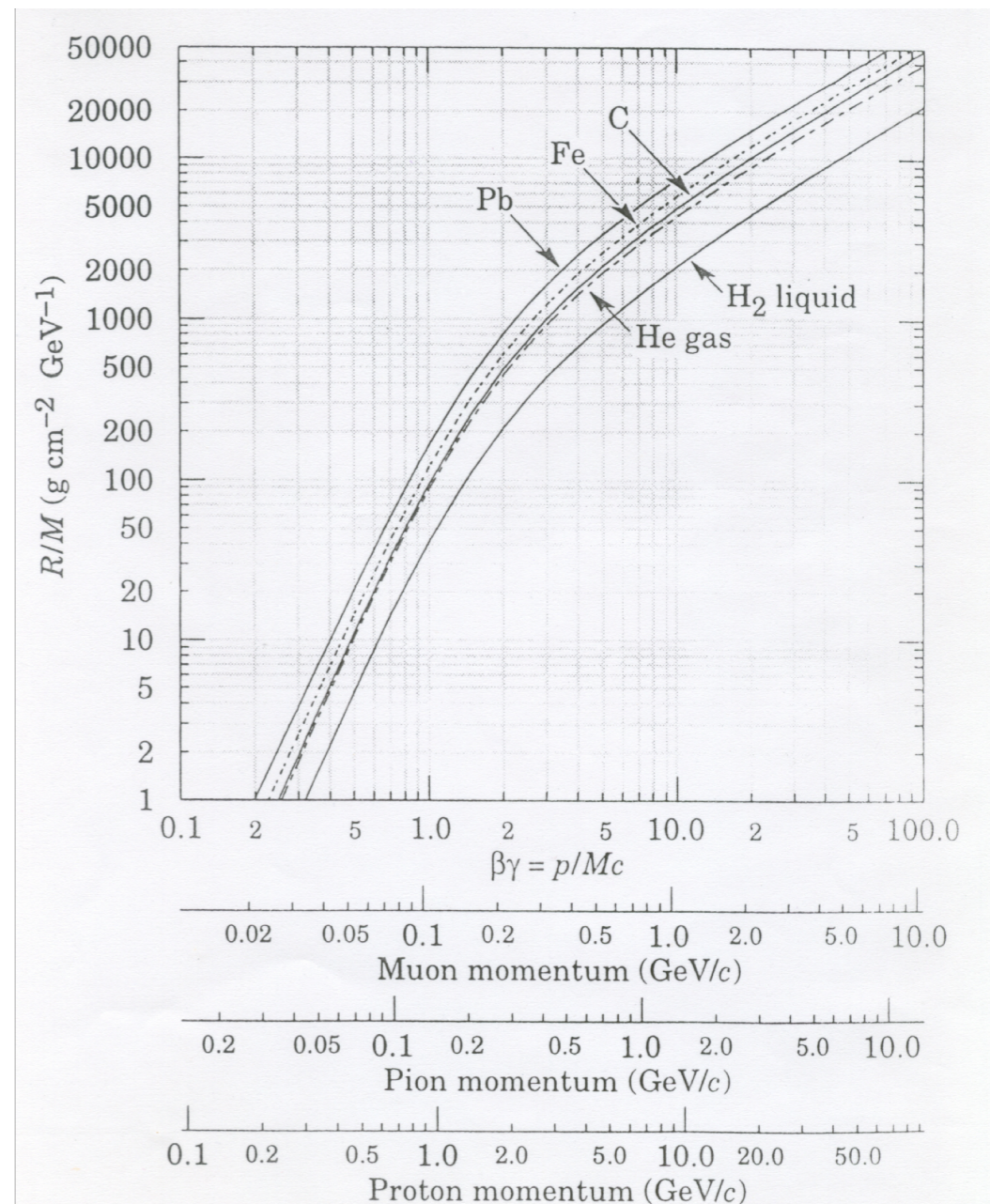
- At small β , $-dE/dx$ decreases with momentum
- A minimum is reached at $\beta\gamma \approx 4$
- At large β , γ^2 term dominates \rightarrow relativistic rise
- At very large $\beta\gamma$, saturation due to screening \rightarrow density effect

Energy Loss

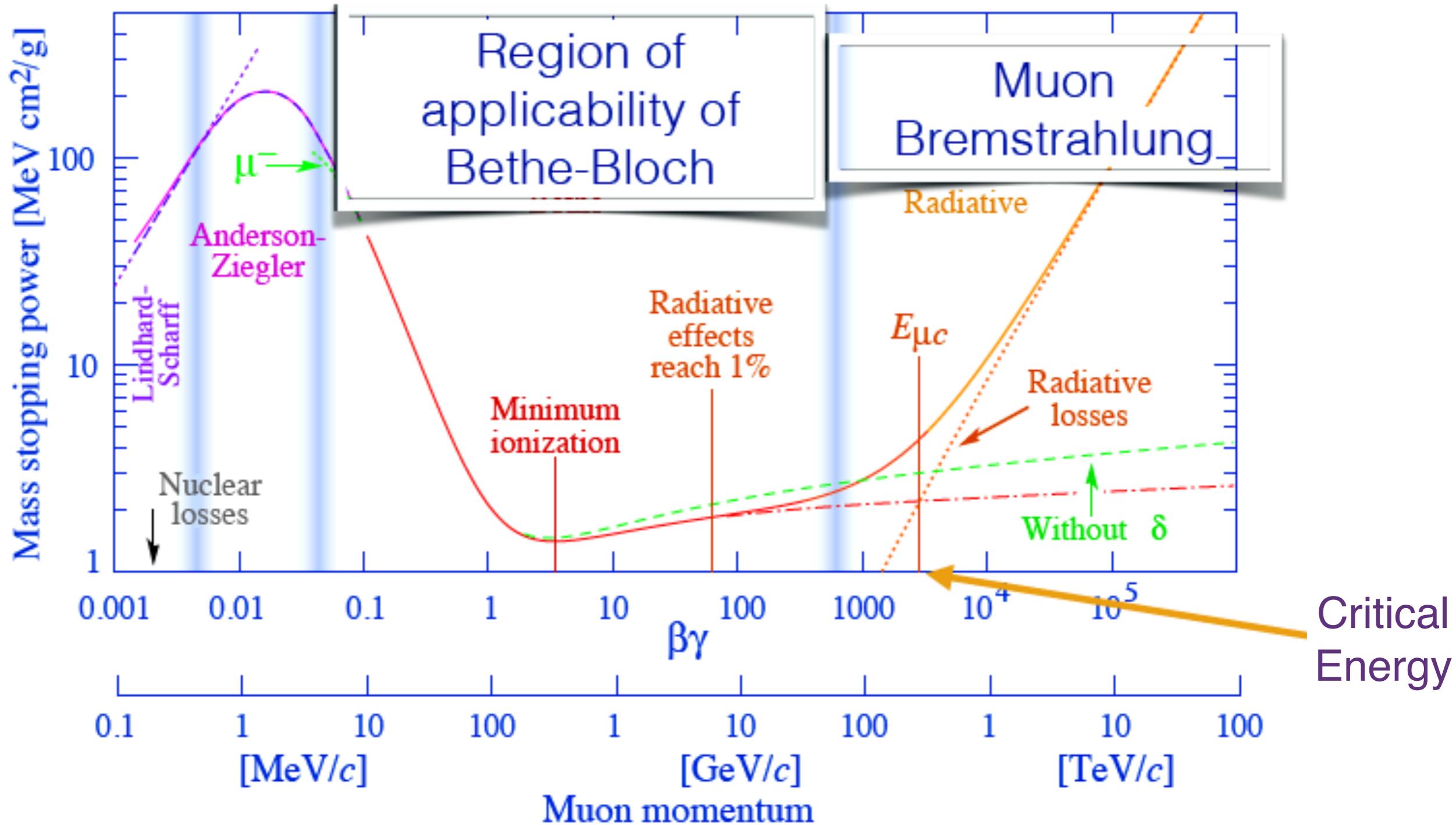
- Individual collisions are classified as
 - Distant collision: atoms react as a whole → excitation, ionization
 - Close collision: with atomic electrons → knock-on
 - Very close: with nuclei → radiation
- If no discrete process happens, particles eventually stops after losing all energies



Detector Simulation



Stopping Power

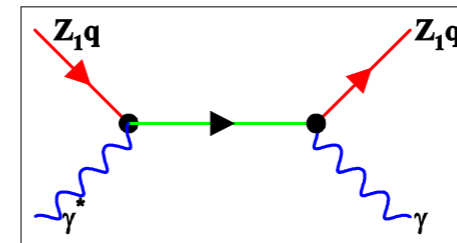


- Stopping power for a muon in copper as a function of muon momentum

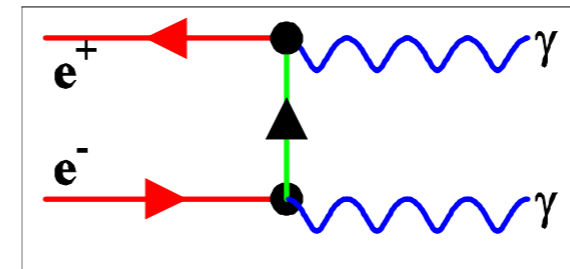
Discrete processes

- Discrete processes:

- Bremsstrahlung

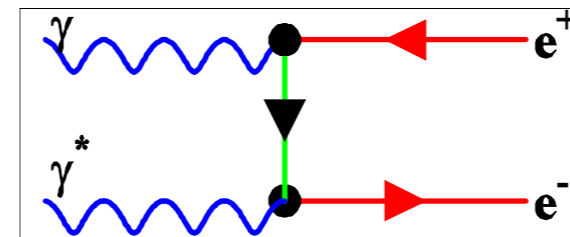


- Annihilation (positron)

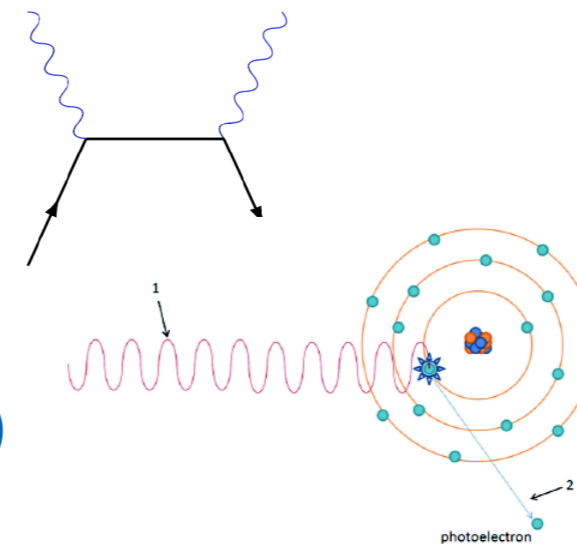


- Elastic Scattering

- Pair production $\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$



- Compton scattering $\sigma_{CS} \approx Z \frac{\ln E_\gamma}{E_\gamma}$



- Photoelectric

$$\sigma_{PE} \approx Z^5 \alpha^4 \frac{m_e c^2}{E_\gamma}$$

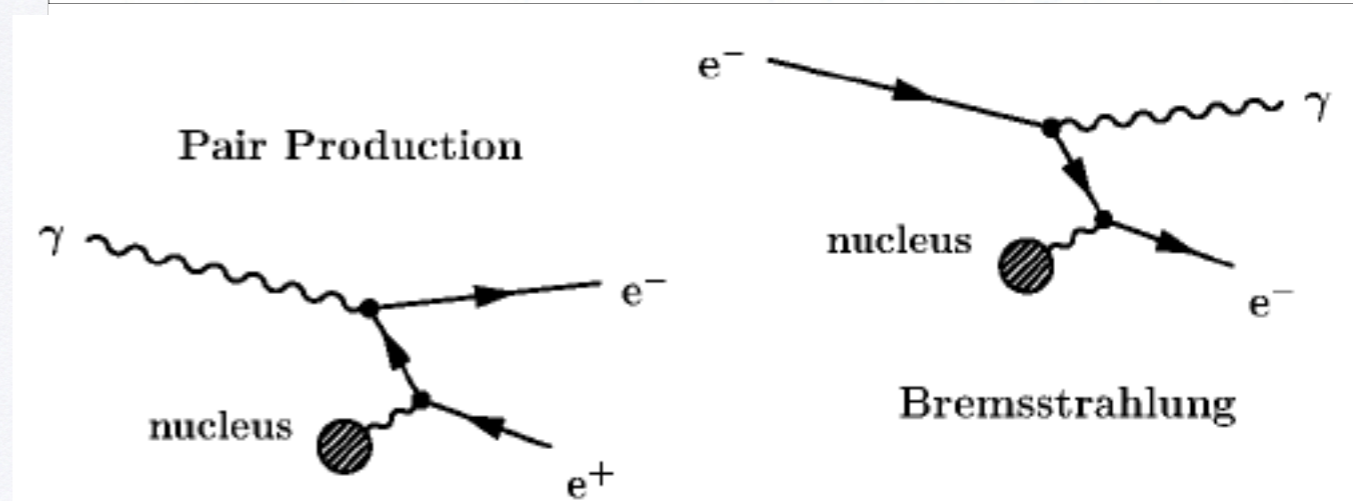
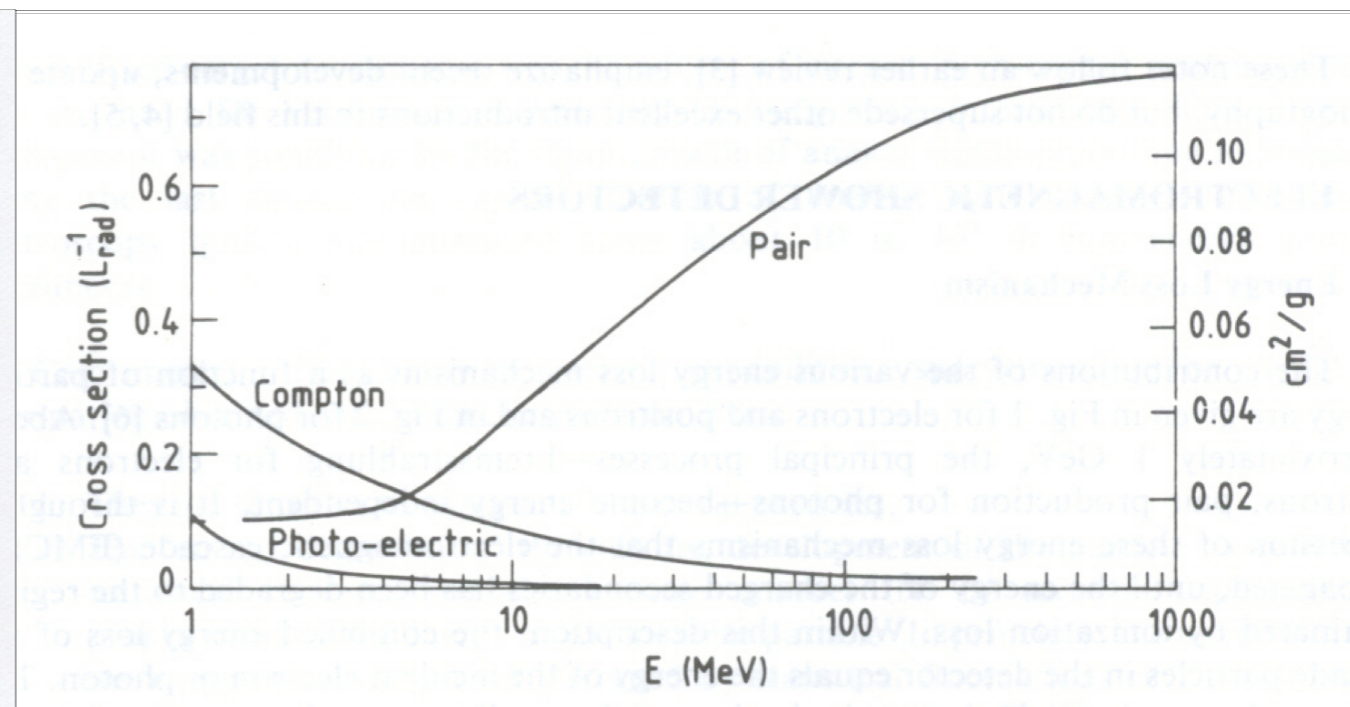
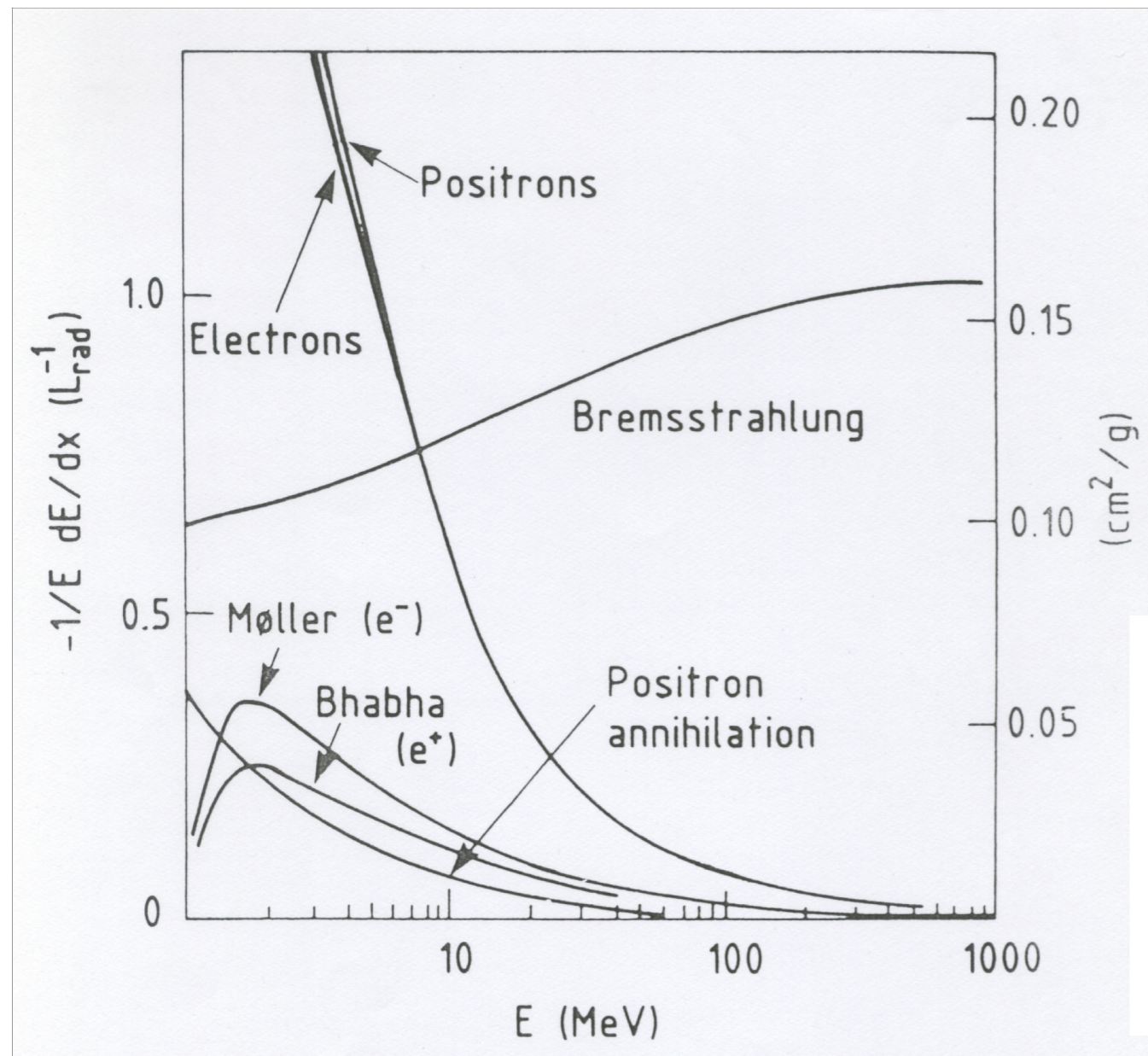
- Decays of unstable particles (em/weak)

- Strong interaction for hadrons

Unchanged	Breaks
coherent	incoherent
elastic	inelastic

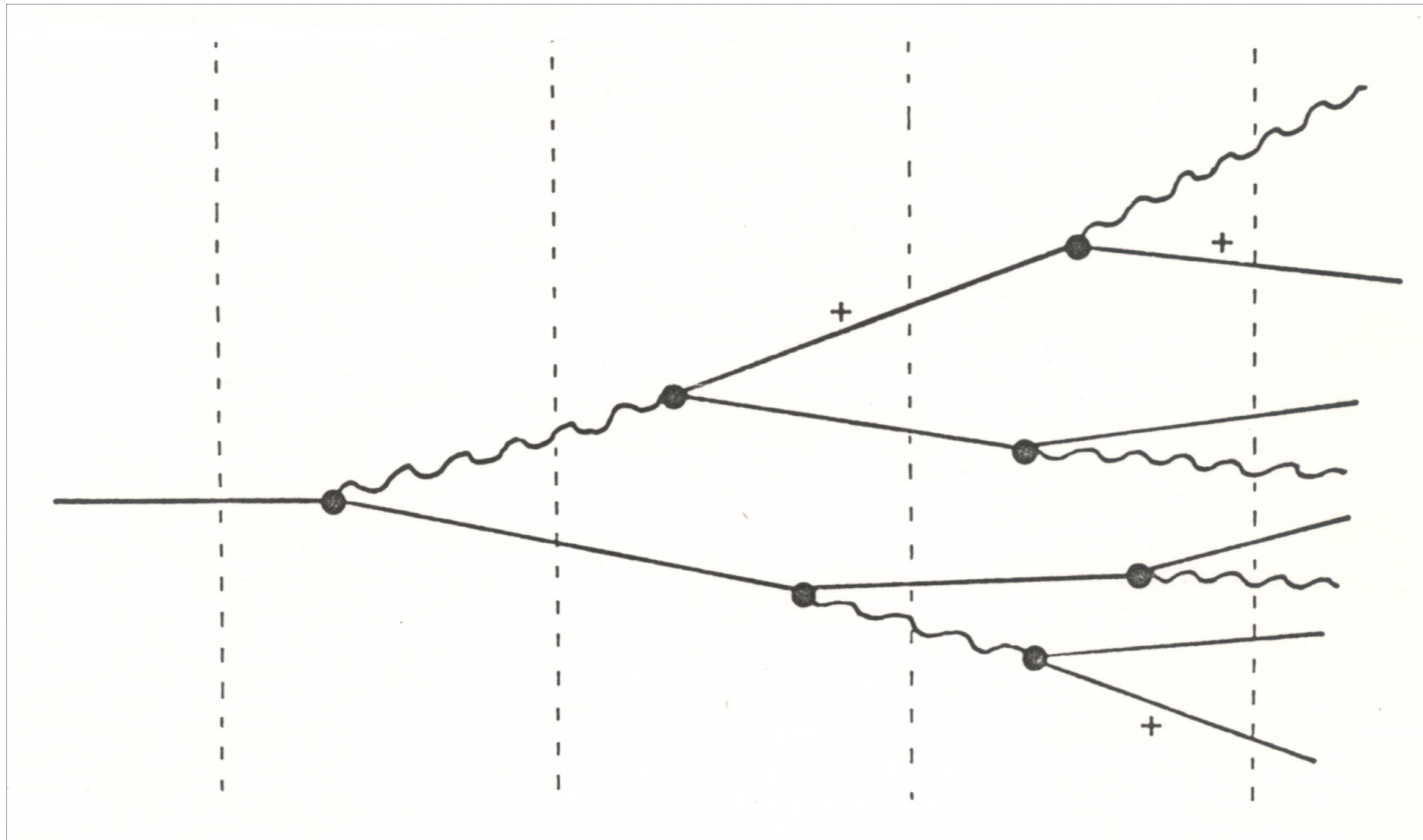
❖ target
❖ projectile

Electromagnetic Shower



- At energies above 100 MeV, e^\pm loses energy mainly through bremsstrahlung emitting photons
- At similar energies, γ 's interact mainly through pair production generating e^\pm
- At high energies, $\sigma(E) \sim \text{constant}$

EM Showers



- $e^+/e^-/\gamma$ cascade (degrading energy in each stage) mainly through successive bremsstrahlung and pair production
- The number of particles in the shower increases till the energies of the particles reach $E \rightarrow \epsilon_c$, critical energy
- Beyond this energy, ionization/excitation takes over and the shower decays out

EM Shower Parameters

- Energy loss due to radiation is governed by L_R , the radiation length of the material traversed. L_R in $\text{g}\cdot\text{cm}^{-2}$

$$-\frac{dE}{dx} = \frac{E}{L_R} \quad -\frac{1}{L_R} = 4\alpha N_A Z^2 r_e^2 \left[\ln(183 \cdot Z^{-\frac{1}{3}}) + \frac{1}{18} \right]$$

- Both bremsstrahlung and pair production are highly forward peaked. Lateral growth of the shower comes dominantly from multiple scattering at these energies
- Low energy end of a shower is generated through the collision process

$$-\frac{\Delta E}{\Delta x} \Big|_{\text{collision}} = -\frac{\epsilon_c}{L_R} \quad \epsilon_c \simeq \frac{610}{Z + 1.24} \text{ (MeV)}$$

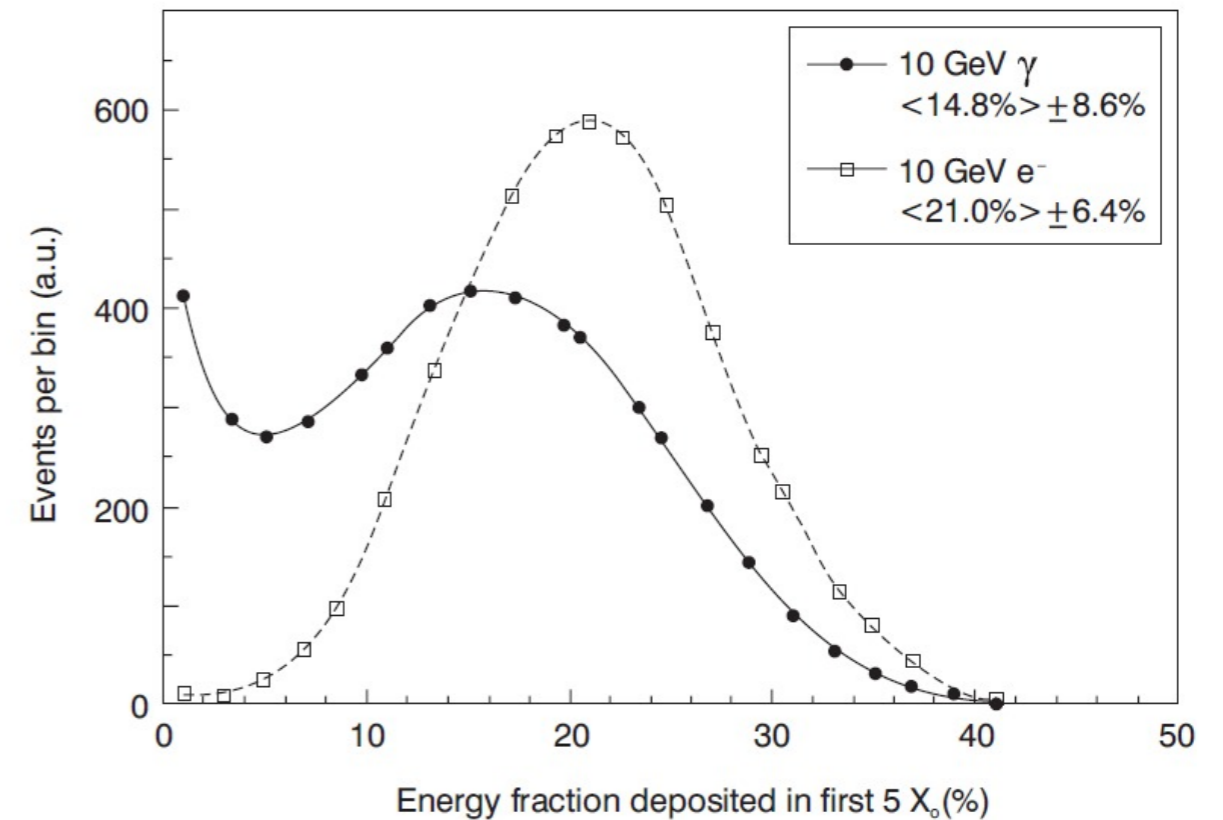
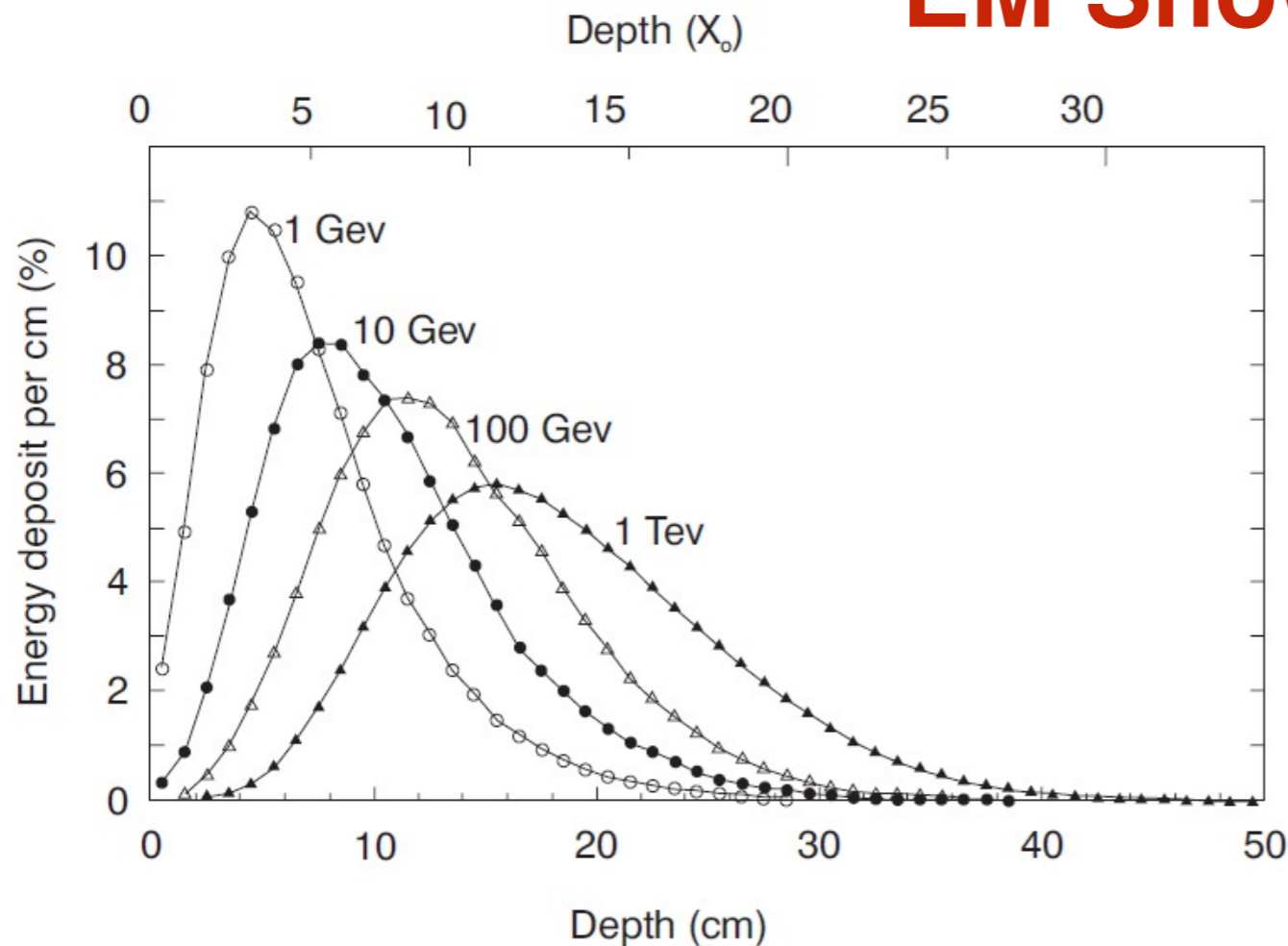
- Beyond shower maximum, there is an exponential decay of the shower $[\exp(-t/\lambda_{\text{Att}})]$

$$\lambda_{\text{Att}} \simeq (3.4 \pm 0.5)L_R$$

- Angular distribution for Compton scattering, the photo-electric effect is isotropic causing a further increase in the lateral size of the shower
- The shower profile is determined by Moliere radius ρ_M . 95% of the energy deposited is contained in a cylinder of radius $2\rho_M$.

$$\rho_M = 21 \frac{L_R}{\epsilon_c} \simeq 7 \frac{A}{Z} \text{ g} \cdot \text{cm}^{-2}$$

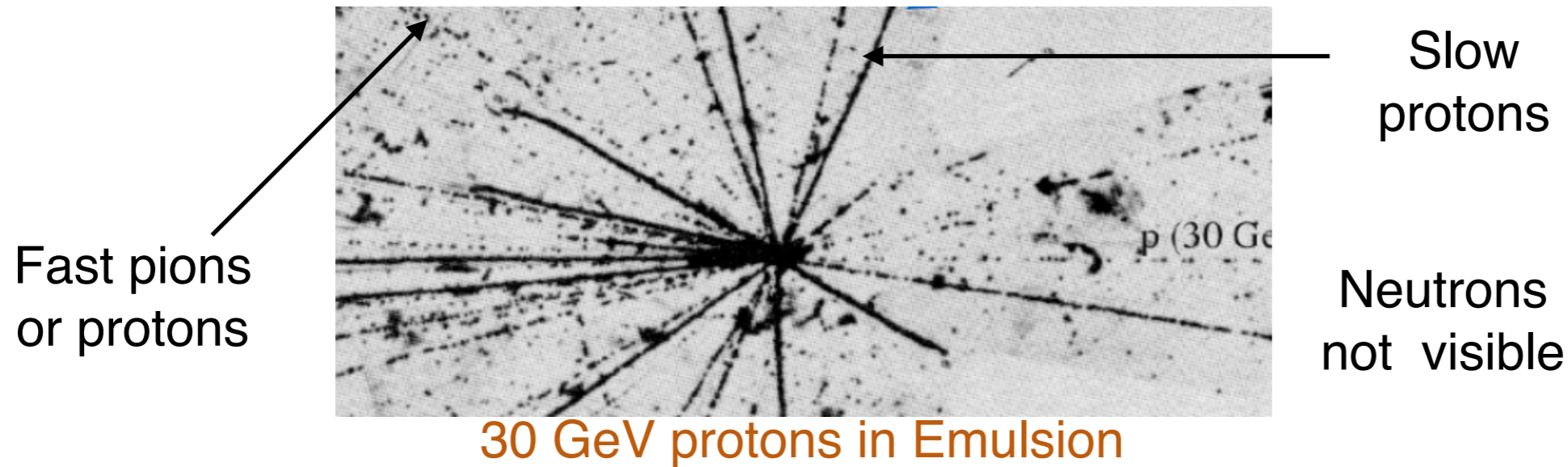
EM Showers



- 98% of the shower is contained in $(t_{\max} + 4\lambda_{\text{att}})$ where the position of shower maximum t_{\max} increases only logarithmically with incident energy E .
- The lateral size of the shower changes with shower depths – broader at or beyond the shower maximum.
- While radiation length (hence shower length) depends strongly on material, lateral size is roughly material-independent.
- Showers initiated by electrons and photons are different in the first few radiation lengths. For a fully absorbed shower, the difference is reduced.

Hadronic Showers

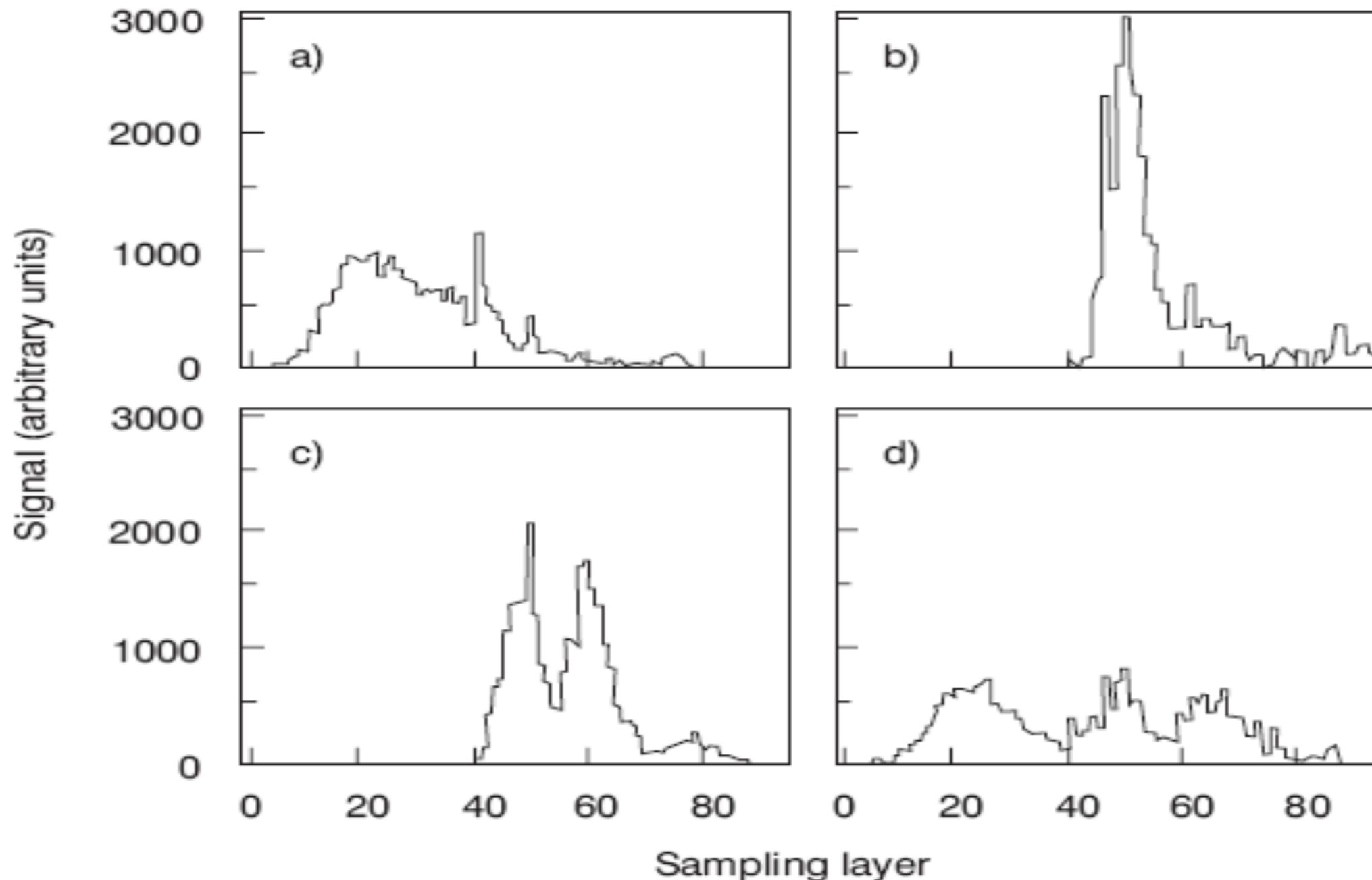
- They are similar to electromagnetic showers, but with greater variety and complexity due to hadronic processes



- The strong interaction is responsible for
 - Production of hadronic shower particles, $\sim 90\%$ of these are pions. Neutral pions decay to 2γ 's which develop em showers
 - Interaction with the nucleus – neutrons/protons are released from the nucleus and the binding energy is lost from producing more shower particles
- EM showers produced by π^0 's develop in the same way as those due to e^\pm/γ 's. Fraction of π^0 increases with energy. Typically EM energy fraction is $\sim 30\%$ at 10 GeV increasing to $\sim 50\%$ at 100 GeV.
- The remaining energy is carried by ionizing particles, neutrons and invisible components (lost in binding energies or carried by ν 's from decays). In lead they are roughly in the ratio $56:10:34$ and two-thirds of ionizing energy is due to protons.

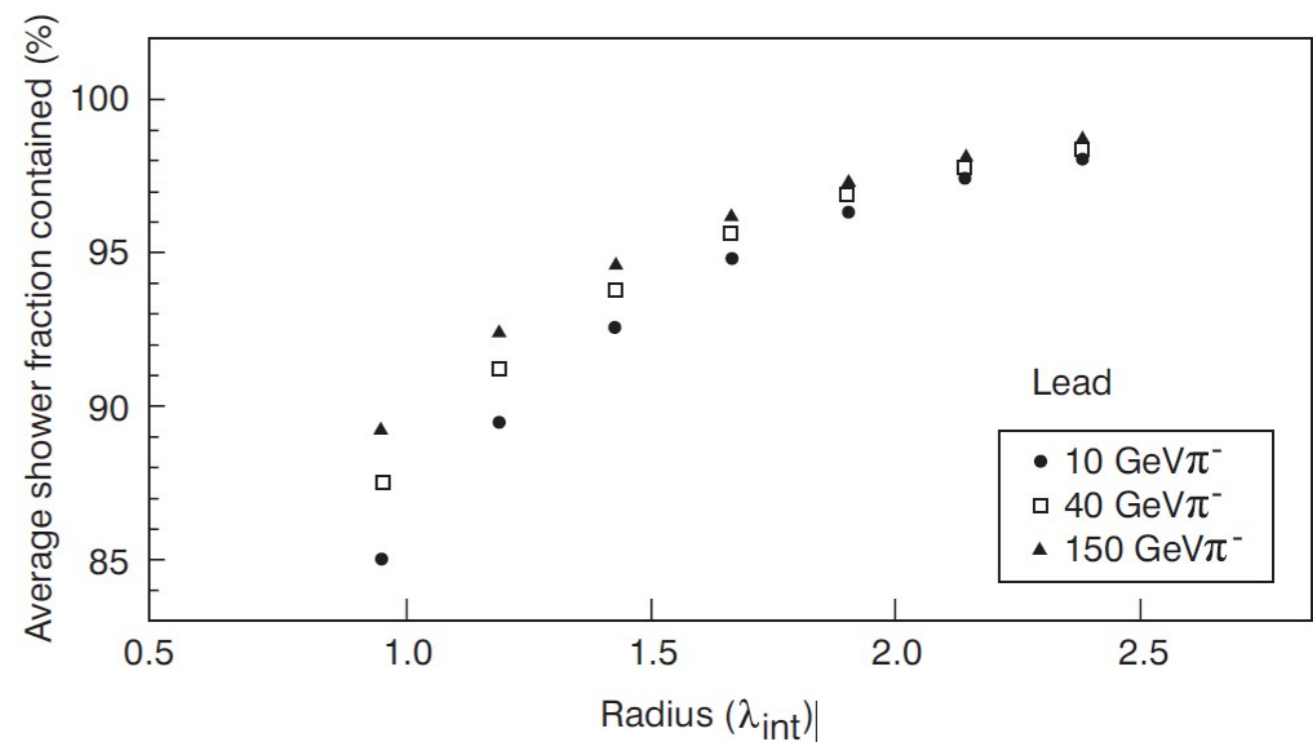
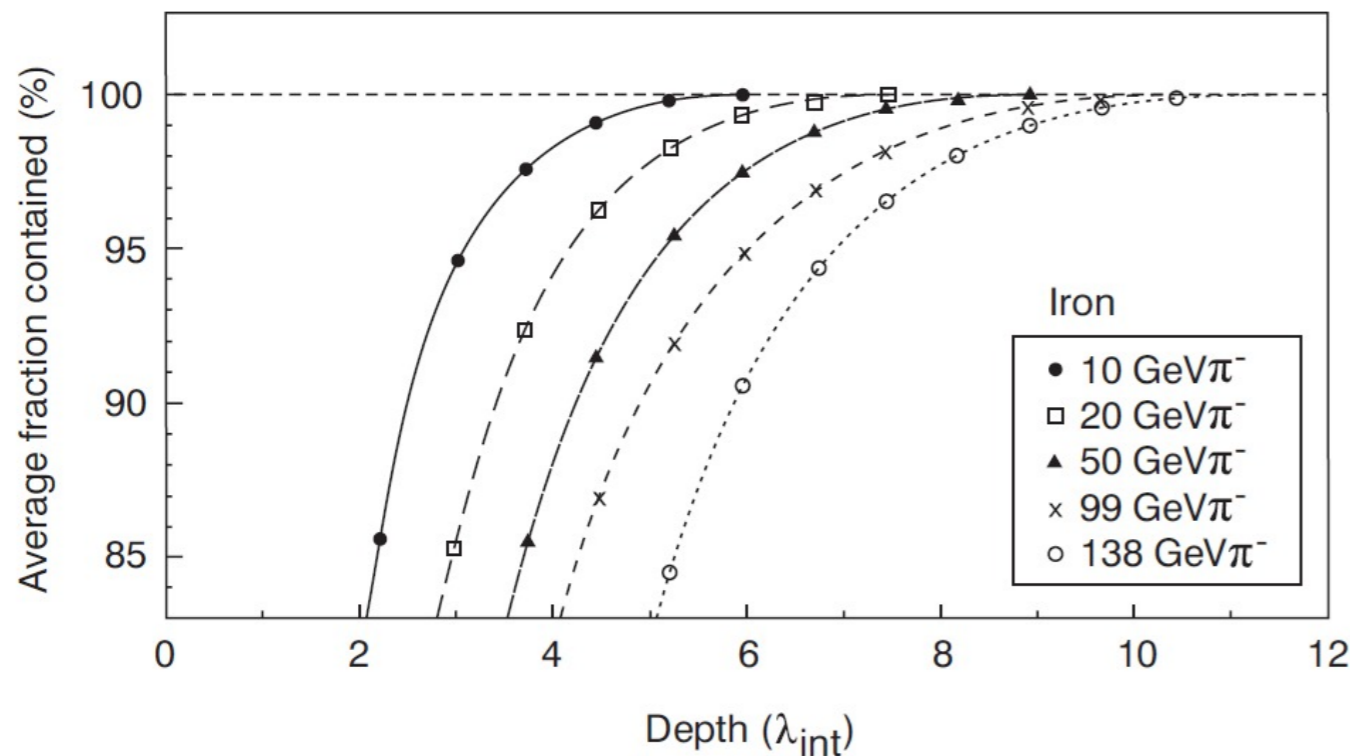
Fluctuations in Hadronic Shower

- There is a large variety of profiles in hadronic showers
- This depends on π^0 multiplicity in each step of interactions
- Leakage plays an important role even though the average containment is high



Hadronic Shower

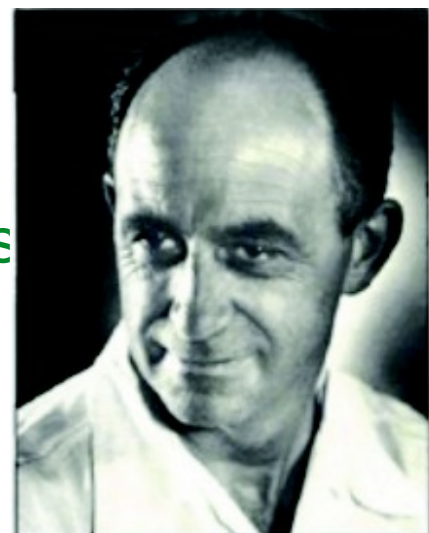
- The typical scale is collision length $\lambda = \frac{A}{N_A \rho \sigma_{aA}}$
- Shower maximum occurs at $t_{\max}(\lambda) \sim 0.2 \ln E + 0.7$
- Decay of shower is slower: power law ($\lambda E^{0.13}$) rather than logarithmic in E
- The transverse dimension is controlled by λ – laterally it takes less material to contain the shower at higher energies (larger fraction of EM energy)



Monte Carlo methods

History

- “After spending a lot of time trying to estimate success by combinatorial calculations, I wondered whether a more practical method might be to lay it out say one hundred times and simply observe and count the number of successful plays” - **S. Ulam** playing Solitaire while recovering from an illness during **1946**
- **1943** saw the first electro-mechanical computers solving non-linear equations. **Ulam's** idea led **von Neumann** to think of using this new device to carry out the statistical sampling. He together with **Richtmeyer** worked on “Statistical Methods in Neutron Diffusion” in **1947**
- The first calculation was done on the **ENIAC** computer in **1948**, with the code finalised by December **1947**
- **Metropolis** christened the name “**Monte Carlo**” and gave rise to **MANIAC** — Mathematical and Numerical Integrator and Computer
- **Enrico Fermi** had the idea even **15** years earlier than **Ulam** and astonished his Roman colleagues by accurately predicting experimental results using statistical techniques. He created an analogue machine **FERMIAC** to study neutron transport while awaiting the arrival of **ENIAC**



Monte Carlo Technique

- Solution of a problem as a parameter of a hypothetical population and constructing a sample of the population to obtain estimates of the parameter
 - ==> use random numbers to construct a sample
- This technique is particularly useful to study particle scattering and absorption because it involves
 - random processes (interaction, scattering, ...)
 - complicated multi-dimensional integration
- The Monte Carlo technique is the ideal way to carry out multi-dimensional integration — the fastest method when the number of dimensions exceeds 3 or 4.

- We may need to carry out an integration:

$$I = \int_0^1 dx_n \cdots \int_0^1 dx_1 F(x_1, \cdots x_n)$$

then with a set of random numbers $x_1, \cdots x_n$ in the range 0 — 1, determine F and this F will be an unbiased estimator of I

- Repeat this estimate a large number of times and the mean value of F , $\langle F \rangle$ will converge to the value of I

Uniform Random Number

Uniform random number

- They can take any value in a continuous range
- One can not predict in advance which value will be taken
- The distribution of variables may be well known
- Distribution of a random variable gives probability of a given value
- Probability distribution function is given by $g(u)du = P(u < u' < u + du)$
- Integral/accumulated distribution function $G(u) = \int_{-\infty}^u g(u)du \Rightarrow g(u) = dG(u)/du$
- $G(u)$ increases monotonically with u . Normalising of g determined by $\int_{-\infty}^{\infty} g(u)du = 1$
- Truly random number : sequence of truly random numbers is completely unpredictable and hence unreproducible
- Can be generated only through random physics processes, e.g., radioactive decay, arrival time of cosmic muon
- Pseudo random number : mid-square : Sequence generated according to a strict mathematical formula but indistinguishable from a sequence which is generated truly randomly
 - Start with random number of r digit
 - Take the middle $r/2$ digit, which is the first random number
 - Square the $r/2$ digit and again
 - Take the middle $r/2$ digit \rightarrow second random number
- Multiplicative linear congruential generator (MLCG), build up a sequence $r_{i+1} = \text{mod}(a \times r_i + c, m)$
 - Choose a, c, m carefully
 - Lower order bits much random than higher order bits, e.g., for random numbers in the range 1-10,
 - * $J = 1 + \text{int}(10 \times r_i)$ better in compare with

Random Number Generators

- * $J = 1 + \text{mod}(100000 \times r_i, 10)$
- Gradual improvement of a,c,m .. (Computer Phys. Comm., 60 (1990) 329)
 - * $a = 23, m = 10^8 + 1$
 - * $a = 65539, m = 2^{29}$
 - * $a = 69069, m = 2^{32}$
 - * $a = 7^5 = 16907, m = 2^{31} - 1$
 - * $a = 1664525, m = 2^{32}$
 - * $a = 742938285, m = 2^{31} - 1$
 - * $a = 40014, m = 2147483563$
 - * $a = 40692, m = 2147483399$
 - * $a = 5^{15}, m = 2^{47}$
- Extension, $r_{i+1} = \text{mod}(a \times r_i + b \times r_{i-1} + c, m)$
- Fibonacci series : $r_i = \text{mod}(r_{i-p} \odot r_{i-q}, m)$
 where \odot is some binary or logical operation (ordinary addition or subtraction, but not exclusive-or) and p and q are the lags with $p > q$

Properties of some Pseudorandom Number Generators :

Generator	Randomness	Portability	Approx period	initialize [wd]	restart [wd]	Disjoint seq
Traditional	unreliable	poor	10^9	1	1	sequential
RANECU	good	good	10^{18}	2	2	$(10^9 \times 10^9)$
RANMAR	good	good	10^{43}	1	100	$(10^9 \times 10^{34})$
RANECU	good	good	10^{170}	1	25	$(10^9 \times 10^{161})$

Arbitrary probability density

- To generate random numbers according to an arbitrary normalised probability density function $F(x)$, there are several methods available. One has to choose the most efficient approach

- Transformation method:

Let there be a random function which can produce a variable x uniformly in the range from 0 to 1: $0 \leq x \leq 1$

This implies that the probability of generating a number between x and $x+dx$:

$$\begin{aligned} g(x)dx &= dx \quad \text{for } 0 \leq x \leq 1 \\ &= 0 \quad \text{for } 0 > x \text{ or } x > 1 \end{aligned}$$

and the probability density function is normalised:

$$\int_{-\infty}^{\infty} g(x)dx = 1$$

Now we would like to generate random numbers y with a probability density function $f(y)$ which also follows:

Transformation Method

$$\int f(y)dy = 1$$

Using the fundamental transformation law of probability

$$\begin{aligned} dx &= f(y)dy \\ \Rightarrow x &= \int f(y)dy + c \end{aligned}$$

So one gets

$$\begin{aligned} |f(y)dy| &= |g(x)dx| \\ \text{or } f(y) &= g(x) \left| \frac{dx}{dy} \right| \end{aligned}$$

This is to be inverted to get

$$y = y(x)$$

Transformation Method (an example)

Let us generate an exponential distribution as an example:

$$f(y)dy = a \cdot \exp(-a \cdot y)dy$$

with $y \geq 0$ and $a > 0$

This satisfies

$$\int_0^{\infty} f(y)dy = 1$$
$$\Rightarrow x = -\exp(-a \cdot y) + c$$

Imposing boundary conditions, namely $x = 0$ at $y = 0$ and $x = 1$ at $y = \infty$, one obtains $c = 1$

Thus

$$y = -\frac{1}{a} \ln(1 - x)$$

Generalised Transformation Method

The transformation method can be generalised to more than one dimension:

x_1, x_2, \dots are random deviates with joint probability distributions

$$g(x_1, x_2, \dots) dx_1 dx_2 \dots$$

y_1, y_2, \dots each is a function of all x 's (number of y 's = number of x 's)

$$\Rightarrow g(y_1, y_2, \dots) dy_1 dy_2 \dots = g(x_1, x_2, \dots) \left| \frac{\partial(x_1, \dots, x_n)}{\partial(y_1, \dots, y_n)} \right| dx_1 dx_2 \dots$$

$\left| \frac{\partial(x_1, \dots, x_n)}{\partial(y_1, \dots, y_n)} \right|$. is the Jacobian determinant of x 's with respect to y 's

Let us have two uniform deviates x_1, x_2 and the variables y_1, y_2 are defined as

$$y_1 = \sqrt{-2 \ln x_1} \cos 2\pi x_2$$
$$y_2 = \sqrt{-2 \ln x_1} \sin 2\pi x_2$$

Generalised Transformation Method

Equivalently

$$x_1 = \exp \left[-\frac{1}{2}(y_1^2 + y_2^2) \right]$$

$$x_2 = \frac{1}{2\pi} \tan^{-1} \left(\frac{y_2}{y_1} \right)$$

The Jacobian determinant:

$$\begin{aligned} \frac{\partial(x_1, x_2)}{\partial(y_1, y_2)} &= \begin{vmatrix} \frac{\partial x_1}{\partial y_1} & \frac{\partial x_1}{\partial y_2} \\ \frac{\partial x_2}{\partial y_1} & \frac{\partial x_2}{\partial y_2} \end{vmatrix} \\ &= - \left[\frac{1}{\sqrt{2\pi}} \exp \left(-\frac{y_1^2}{2} \right) \right] \cdot \left[\frac{1}{\sqrt{2\pi}} \exp \left(-\frac{y_2^2}{2} \right) \right] \end{aligned}$$

Since this is a product of two functions, one of y_1 and one of y_2 , one gets two independent random deviates following the Gaussian distribution of mean 0 and RMS 1:

$$g(y)dy = \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{y^2}{2} \right) dy$$

Law of large numbers

- Concerns sum of a large number of random variables
- Choose n numbers X_i distributed randomly with uniform probability density in the interval a to b

- Evaluate $f(x_i)$ for each value of X_i

$$\frac{1}{n} \sum_{i=1}^n f(x_i) \rightarrow \frac{1}{b-a} \int_a^b f(x) dx \quad \text{for large } n$$

The LHS is a consistent estimator of the integral which implies that the variance of f will be finite

The standard deviation of the estimator $\sim \sqrt{\frac{V(f)}{n}}$

This is the Central Limit theorem

The sum of a large number of independent random variables is always normally distributed, no matter how the random numbers are distributed

The normal distribution is specified by its expectation value a and variance σ^2 :

Gaussian Distribution

$$g(x)dx = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-a)^2}{2\sigma^2}\right) dx$$

If u_i 's are uniform deviates between 0 and 1 $\rightarrow g(u)du = du$

$$\langle u \rangle = \frac{\int_0^1 u \cdot du}{\int_0^1 du} = \frac{1}{2}$$

$$\text{variance } \sigma_u^2 = \frac{\int_0^1 (u - \frac{1}{2})^2 du}{\int_0^1 du} = \frac{1}{12}$$

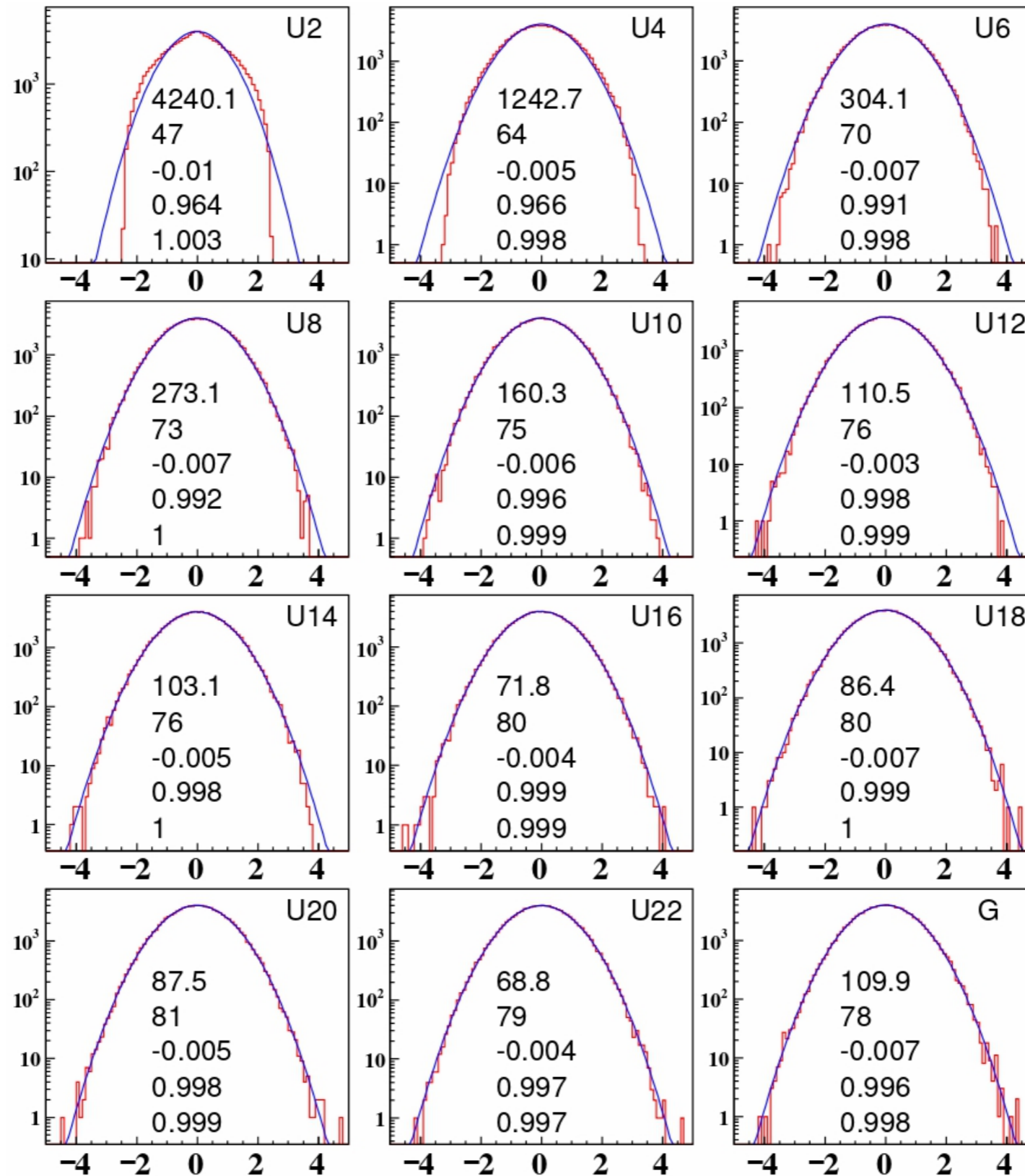
So if one takes the sum of k variables: $u_{(k)} = \sum_{i=1}^k u_i$, then

$$\langle u_{(k)} \rangle = \frac{k}{2}$$

$$\text{variance } \sigma_{u_{(k)}}^2 = \frac{k}{12}$$

By choosing 12 random variables and computing $\sum_{i=1}^{12} u_i - 6$ one gets a normally distributed variable with a mean 0 and variance 1

Gaussian Distributions



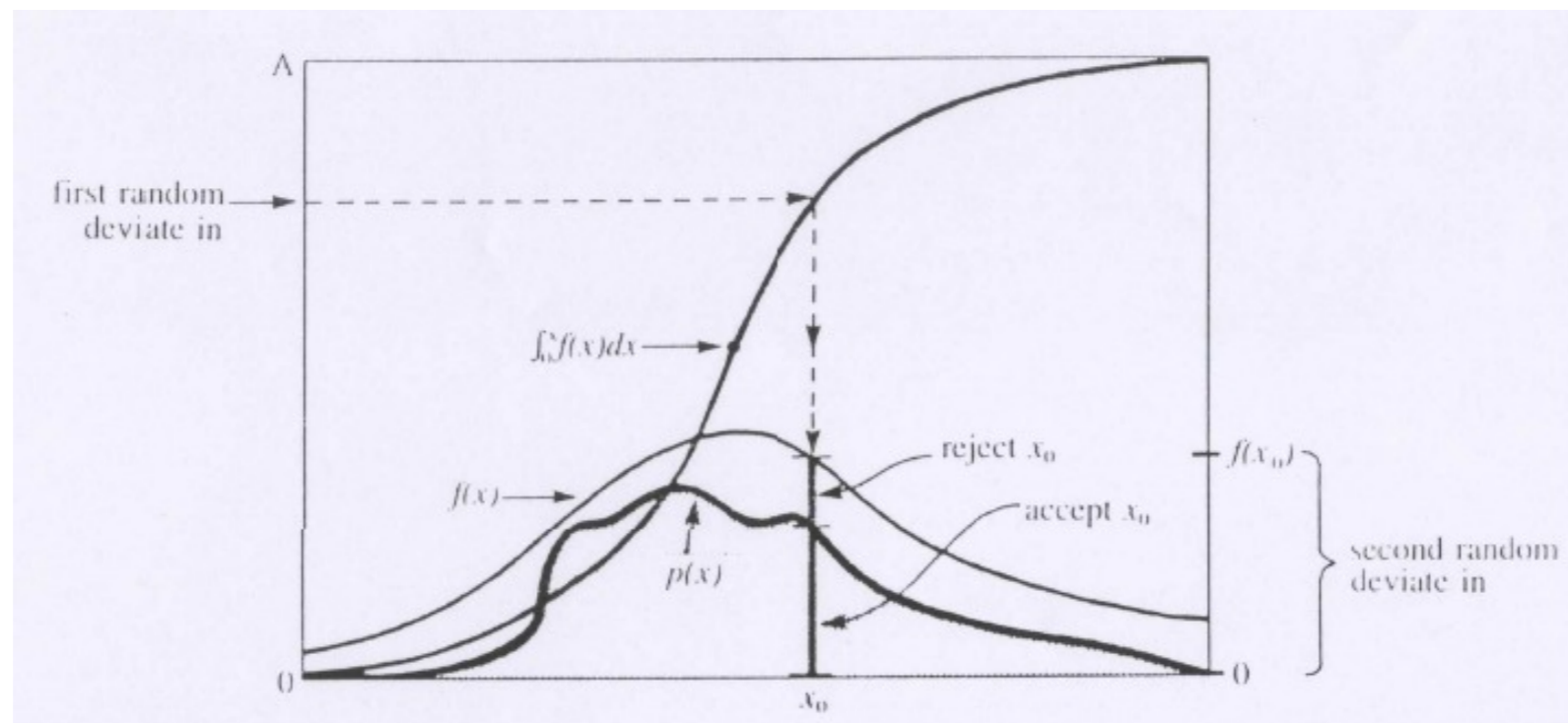
A more general method

- Rejection method:

If the probability distribution function is known and computable, this method can be applied. Here one does not require:

Cumulative distribution function to be available

The distribution function could be inverted



For example, one needs to generate a random number in the range a to b according to a probability distribution function proportional to $p(x)$

choose a function $f(x)$ (comparison function) such that

The corresponding cumulative distribution function is computable and invertible
 $f(x)$ lies above $p(x)$ at all places between a and b

Rejection method

choose x using the transformation method applied to the function $f(x)$

use a second deviate u which is uniformly distributed between 0 and 1. If $p(x)/f(x) \leq u$, then the value of x is to be accepted; otherwise that value of x is to be rejected and a fresh value has to be obtained using the transformation method

A General method

- Express the probability density function as a sum of components:

$$F(\mathbf{x}) = \sum_i^n \alpha_i \cdot f_i(\mathbf{x}) \cdot g_i(\mathbf{x})$$

with α 's positive; $f_i(\mathbf{x})$ normalised probability density functions which can be inverted; and $g_i(\mathbf{x})$ are computable functions which do satisfy the relation

$$0 \leq g_i(\mathbf{x}) \leq 1.$$

Solution to the problem can be obtained as:

- select an integer i randomly within $0 \leq i \leq n$ and with the probability of selecting it: $i \propto \alpha_i$
- select a variable \mathbf{x}' from $f_i(\mathbf{x})$ using the transformation method
- calculate $g_i(\mathbf{x})$ and accept $\mathbf{x} = \mathbf{x}'$ with selection probability $g_i(\mathbf{x})$
- If rejected, go and select i once again and repeat

This is a good method of sampling \mathbf{x} if

- all sub-distribution functions $f_i(\mathbf{x})$ can be easily sampled
- the rejection functions $g_i(\mathbf{x})$ can be quickly computed
- mean number of tries ($\sim \sum \alpha_i$) is not too large

Application to Pair Production

- Pair production: $\gamma\gamma^* \rightarrow e^+e^-$

A photon of energy E produces a pair of electron and positron with the electron carrying an energy fraction ϵ

$$\frac{d\sigma}{d\epsilon} = r_e^2 \frac{\alpha Z}{E^2} [Z + \xi(Z)] ([\epsilon^2 + (1 - \epsilon)^2] [\phi_1(\delta) - F(Z)] + \frac{2}{3}\epsilon(1 - \epsilon) [\phi_2(\delta) - F(Z)])$$

$$\text{with } \delta = \text{screening variable} = \frac{136m}{Z^{1/3} E} \frac{1}{\epsilon(1 - \epsilon)}$$

Rewrite the probability density function for

$$F(\epsilon) = \frac{\alpha_i}{3} \left[\frac{1}{2} - \frac{m}{E} \right]^2 F_1(\delta_{\min}) \cdot \frac{f_i}{\left[\frac{1}{2} - \frac{m}{E} \right]^3} \left(\epsilon - \frac{1}{2} \right)^2 \cdot \frac{g_i}{F_1(\delta_{\min})} + \frac{1}{2} F_2(\delta_{\min}) \cdot \frac{1}{\left[\frac{1}{2} - \frac{m}{E} \right]} \cdot \frac{F_2(\delta)}{F_2(\delta_{\min})}$$

$$\text{with } F_1(\delta) = 3\phi_1(\delta) - \phi_2(\delta) - 2F(Z)$$

$$F_2(\delta) = \frac{3}{2}\phi_1(\delta) + \frac{1}{2}\phi_2(\delta) - 2F(Z)$$

$$\delta_{\min} = \frac{136m}{Z^{1/3} E} \cdot 4$$

Pair Production

Kinematic range for $\epsilon \left(\frac{m}{E} \leq \epsilon \leq 1 - \frac{m}{E} \right)$

Using of symmetry of σ under $\epsilon \leftrightarrow 1 - \epsilon$ restrict $\left(\frac{m}{E} \leq \epsilon \leq \frac{1}{2} \right)$

Define a variable $B = \frac{\alpha_1}{\alpha_1 + \alpha_2}$

- Generate r_0 with $0 \leq r_0 \leq 1$. If $r_0 < B$, choose $i = 1$, else $i = 2$

- Generate r_1 with $0 \leq r_1 \leq 1$. If $i = 1$, $\epsilon = \frac{1}{2} \left[1 - \frac{m}{2E} (1 - r_1)^{\frac{1}{3}} \right]$.

Otherwise estimate $\epsilon = \frac{m}{E} + \left(\frac{1}{2} - \frac{m}{E} \right) r_1$

- Generate r_2 with $0 \leq r_2 \leq 1$. If $r_2 \leq g_i(\epsilon)$, then accept this ϵ , else reject the current values of i , ϵ and try to find i again

GEANT4

Geant4

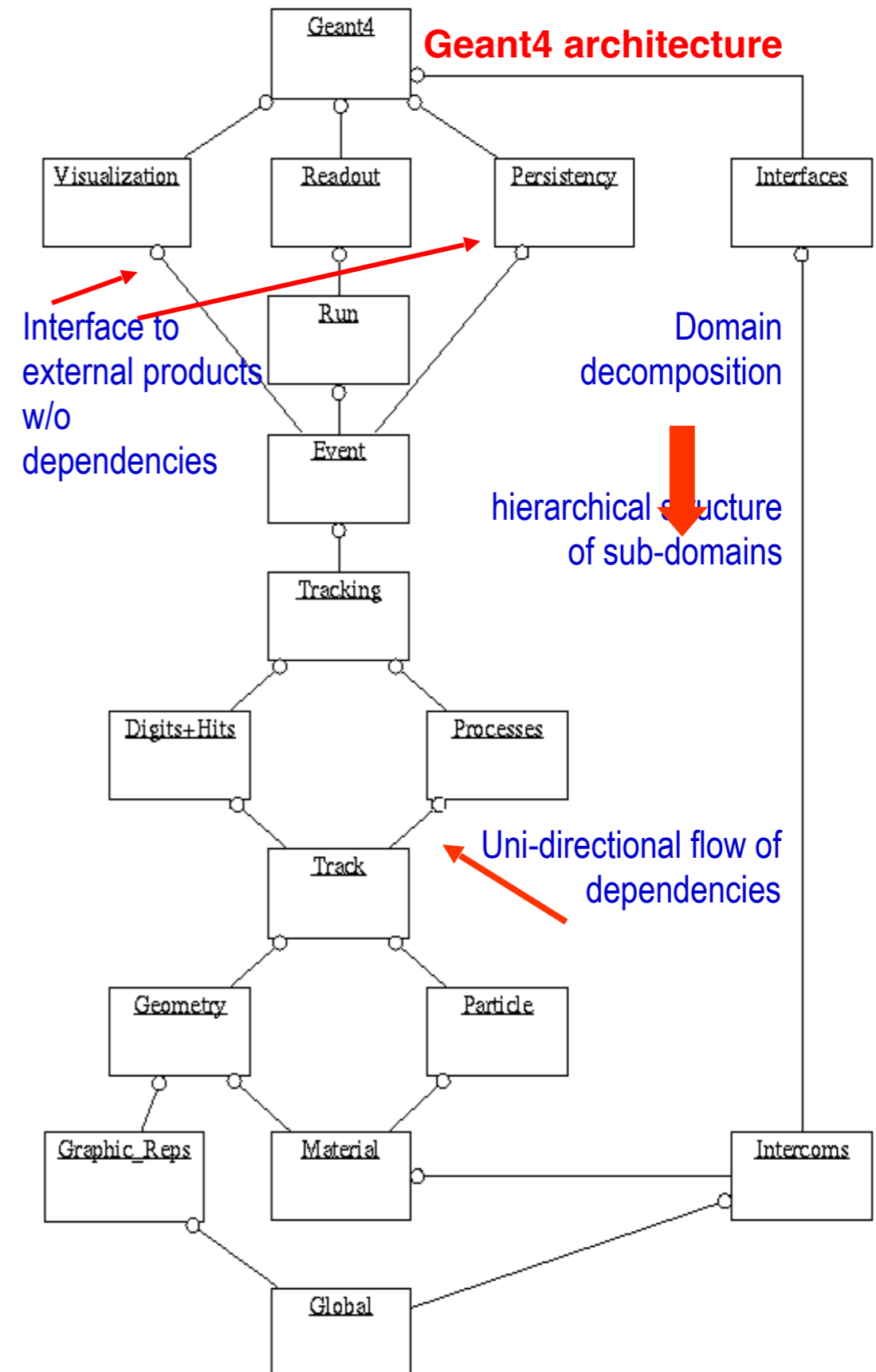
- Geant4 is a toolkit which helps to build an application program for simulating the performance of a detector exposed to radiation
 - Originally built for experiments in high energy and nuclear physics
 - Also finds its application in space physics and medical science
- The public production version has been available since the year 1999
- The package came with several examples to guide buildings of application programs
- It is written mostly in the C++ language using object-oriented technology
- Available as open source through CERN and works on many platforms
 - Latest version **Geant4.11.2**
- Three main reference papers:
 - Nuclear Instruments and Methods A506 (2003) 250
 - IEEE Transactions on Nuclear Science 53 (2006) 270
 - Nuclear Instruments and Methods A835 (2016) 186

Detector Simulation

- Geant4 provides tools for particle transport and also to model experimental environments
- The “User” needs to use Geant4 tools
 - to tell the Geant4 kernel about the simulation configuration
 - to interact with the Geant4 kernel itself
- The “User” must tell Geant4 what he/she only knows
 - The experimental scenario
 - Geometry, materials, sensitive and passive elements
 - Primary particles, radiation environment
 - That the “User” wants to happen during transport
 - which particles are to be tracked
 - which physics processes would be of interest (*and which options for modelling are preferable*)
 - how precise the simulation is going to be

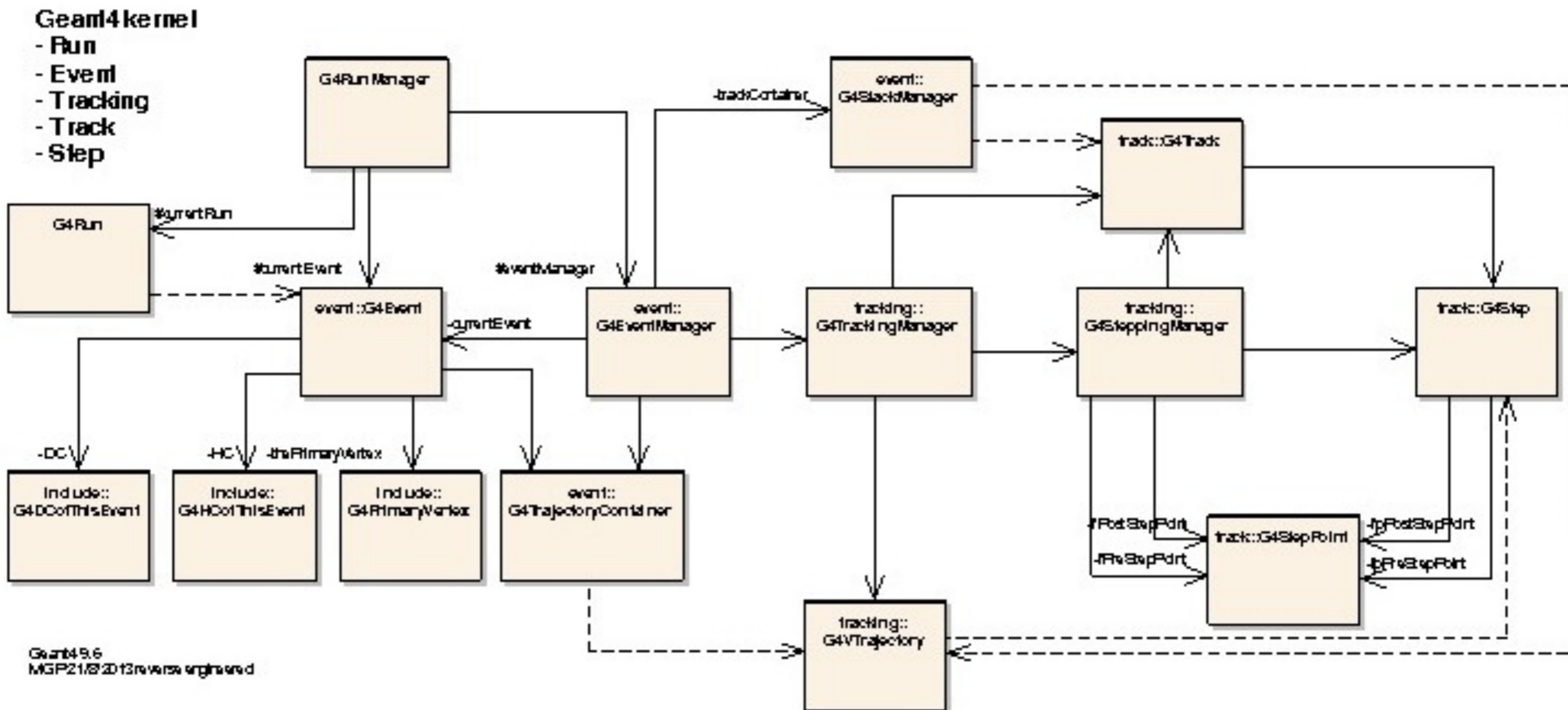
Code Arrangement

- All codes of Geant4 are grouped into 17 categories
- Relationships among classes from two categories:
 - Always one sided
 - No cyclic dependencies
- “Global” is at the lowest level
 - No dependency on any class from other categories of Geant4
- “Geant4” is at the highest level
 - Classes in this category depend on all other categories
- External dependencies:
 - CLHEP (HEP utilities)
 - PTL (for making libs/executable)
 - EXPAT | XML
 - XERCES | parsing
 - ... some Graphics packages ...

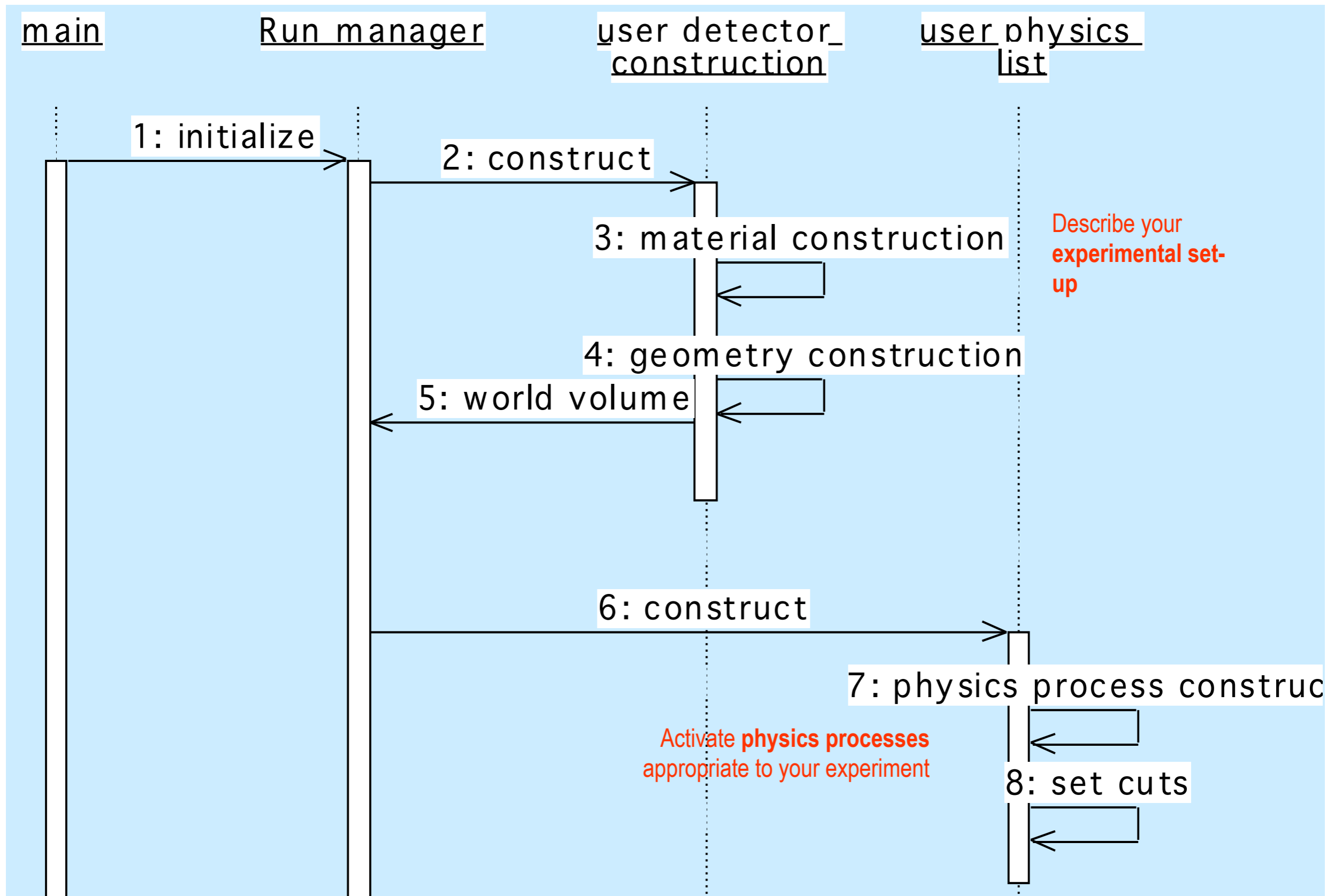


Some of the terminologies

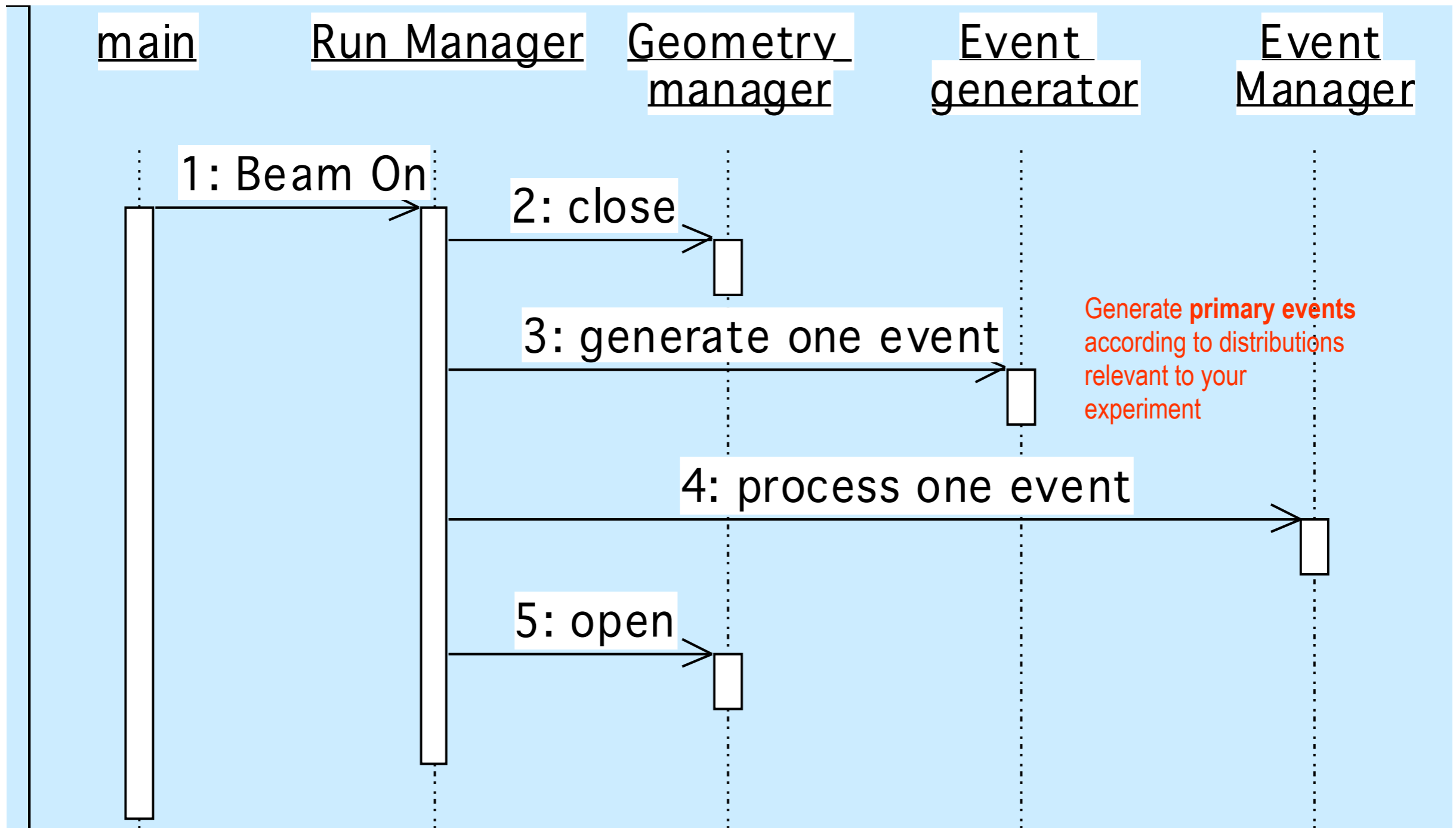
- Run, Event, Track, Step, Stack, ...
- Track vs. Trajectory; Step vs. Trajectory Point
- Particle, Process, Hits, ...



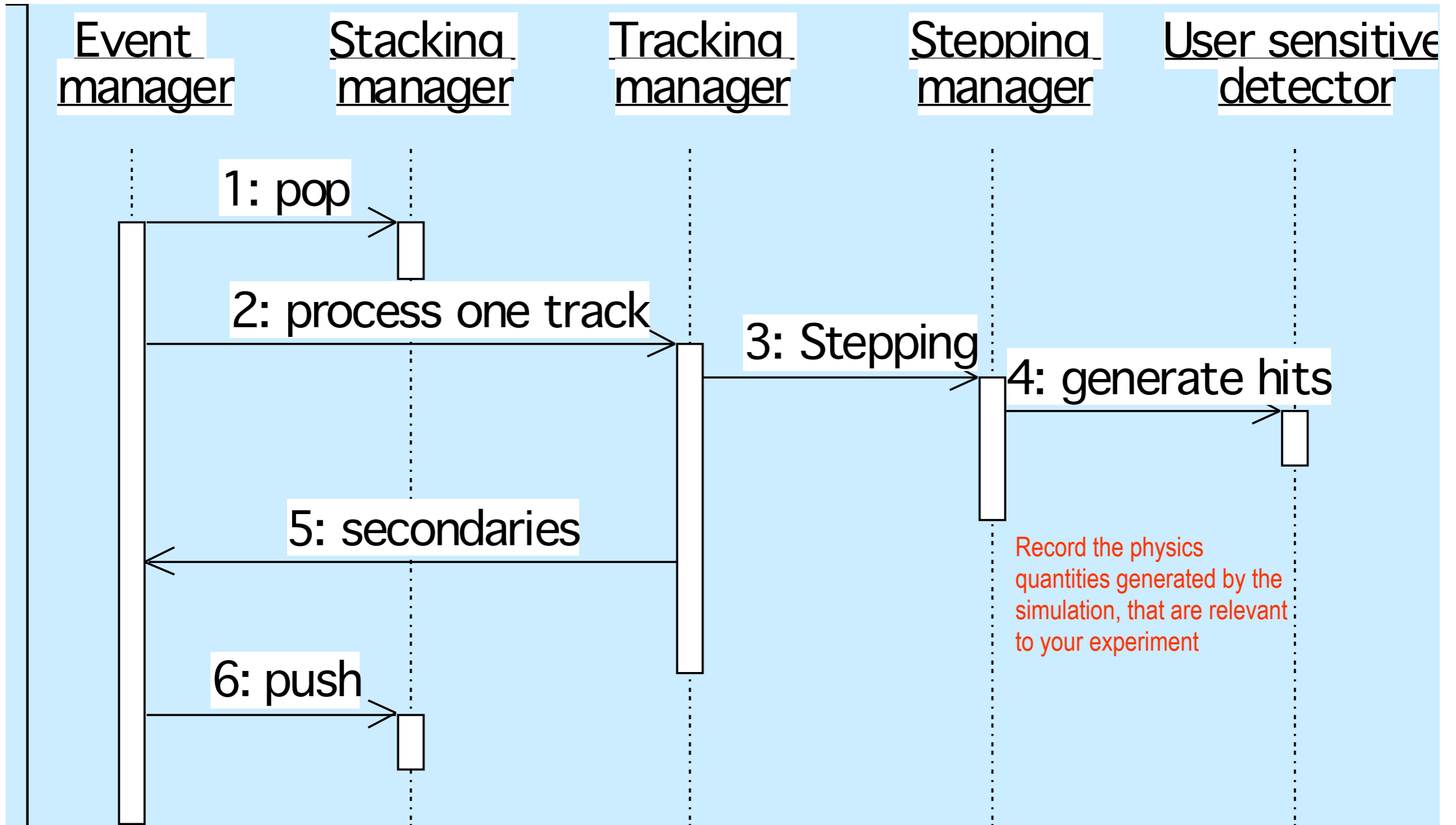
Initialization



Event Loop



Event Processing



Run in Geant4

- Conceptually, a **Run** is a collection of **Events** which share the same detector setup and physics conditions
 - A **Run** consists of one loop over **Events**
- Within a **Run**, the user cannot change
 - the detector setup
 - settings of the physics processes
- As an analogy of the real experiment, a run of Geant4 starts with “**Beam On**”
- At the beginning of a **Run**, the geometry is optimised for navigation and cross-section tables are calculated according to materials which appear in the geometry and with the defined cut-off values
- **G4RunManager** class manages the processing of a **Run**, a **Run** is represented by the **G4Run** class or a user-defined class derived from it
- **G4UserRunAction** is an optional user hook

Event in Geant4

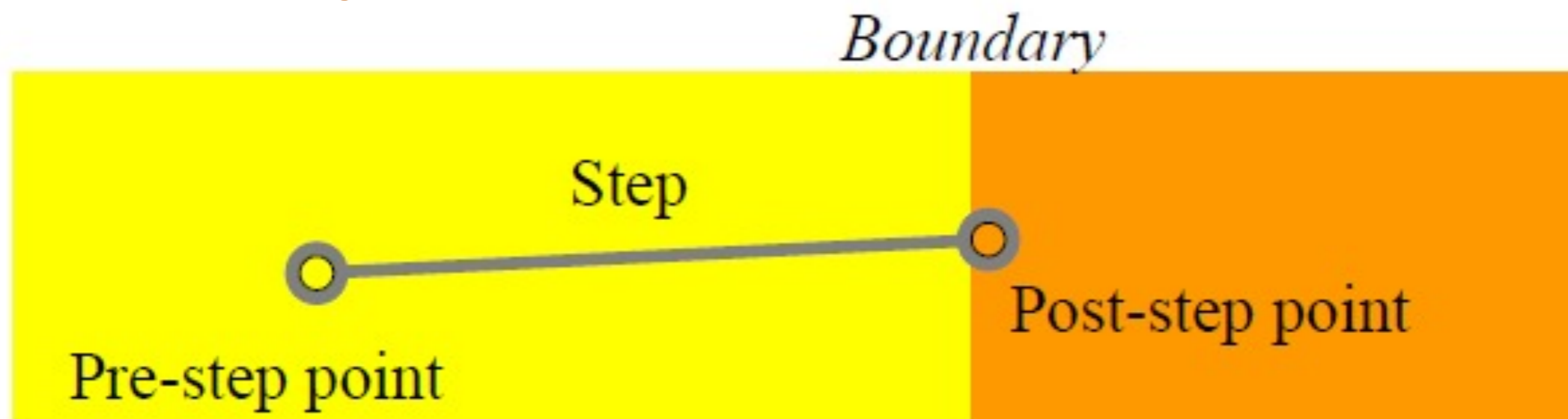
- An **Event** is the basic unit of simulation in Geant4
- At the beginning of processing, primary tracks are generated. These tracks are pushed into a stack
- A track is popped up from the stack one by one and is traced through the detector. The resulting secondary tracks, if any, are pushed into the stack
 - This “tracking” lasts as long as the stack has a track
- When the stack becomes empty, the processing of the event is over
- **G4Event** class represents an **Event**. It has the following objects at the end of its (successful) processing
 - List of primary vertices and particles (as input)
 - Hits and trajectory collections (as output)
- **G4EventManager** class manages the processing of an event
- There is an optional user hook: **G4UserEventAction**

Track in Geant4

- A Track is a snapshot of a particle
 - It has physical quantities of the current instance only. It does not contain a record of previous quantities
 - A Step is a “delta” information of a Track. A Track is not a collection of Steps. Instead, a Track is being updated by the Step.
- The Track object is deleted when
 - it goes out of the world volume,
 - it disappears (through decays, inelastic scattering, ...),
 - it goes down to zero kinetic energy and no “AtRest” additional process is required for the particle, or
 - the user decides to kill it artificially.
- No Track object persists at the end of an event
 - For the record of Tracks, use Trajectory class objects
- G4TrackingManager manages the processing of a Track. A Track is represented by the G4Track class
- There is an optional user hook: G4UserTrackingAction

Step in Geant4

- A **Step** has two points and also “delta” information of a particle (energy loss in the step, time-of-flight spent by the step, etc.)
- Each point knows the volume (and it's material) where it is in. In case a step is limited by a volume boundary, the endpoint will physically stand on the boundary, and it **logically belongs to the next volume**
 - Since each **Step** knows materials of two volumes, boundary processes such as transition radiation or reflection could be simulated
- **G4SteppingManager** class manages the processing of a **Step**, and a **Step** is represented by the **G4Step** class
- **G4UserSteppingAction** is the optional user hook



Trajectory and Trajectory Point

- Please remember, a **Track** does not keep its trace and no **Track** object persists at the end of an **Event**
- **G4Trajectory** is the class which copies some of the information of a **G4Track** object. Likewise, **G4TrajectoryPoint** is the class which keeps some of the information of a **G4Step** object
 - A **G4Trajectory** object has a vector of **G4TrajectoryPoint** objects
 - At the end of event processing, the **G4Event** object has a collection of **G4Trajectory** objects provided
 - `/tracking/storeTrajectory` is set to 1
- Keep in mind the distinction:
 - **G4Track** vs **G4Trajectory**, **G4Step** vs **G4TrajectoryPoint**
- Given that the **G4Trajectory** and **G4TrajectoryPoint** objects persist till the end of an event, one should be careful not to store too many trajectories
 - Avoid storing shower tracks from a high-energy particle
- **G4Trajectory** and **G4TrajectoryPoint** objects store only the minimum information
 - The user can create his/her own **Trajectory/TrajectoryPoint** classes to store the required information. These classes can be derived from the base classes **G4VTrajectory** and **G4VTrajectoryPoint**

Particle in Geant4

- A particle in Geant4 is represented by three layers of classes:
 - **G4Track:**
 - Position, geometrical information, etc.
 - This is a class representing a particle to be tracked
 - **G4DynamicParticle:**
 - “Dynamic” physical properties of a particle, such as momentum, energy, spin, etc.
 - Each G4Track object has its own unique G4DynamicParticle Object
 - This is a class representing an individual particle
 - **G4ParticleDefinition:**
 - “Static” properties of a particle, such as charge, mass, lifetime, decay channels, etc.
 - G4ProcessManager which describes the processes involving the particles
 - All G4DynamicParticle objects of the same kind of particles share the same G4ParticleDefinition

Tracking and Process

- Tracking in Geant4 is universal
 - It is independent of
 - the particle type
 - the physics processes involving the particle
 - It gives the chance to all processes
 - to contribute to the determination of the step length
 - to contribute any possible changes in physical quantities of the track
 - to generate secondary particles
 - to suggest changes in the state of the track
 - e.g. to suspend, postpone or kill it

Process in Geant4

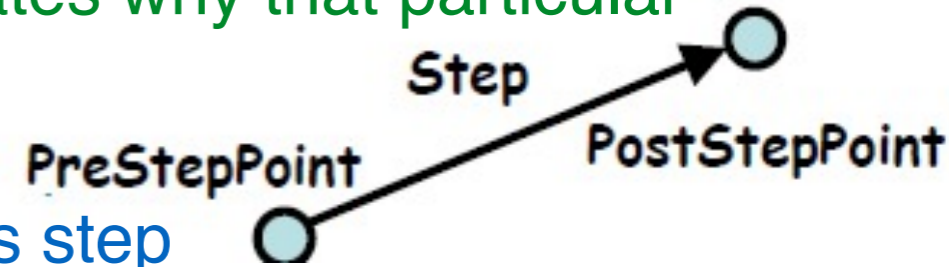
- In Geant4, particle transportation is a process as well, by which a particle interacts with geometrical volume boundaries and fields of any kind
 - Because of this, the shower parametrization process can take over from ordinary transportation without modifying the transportation process
- Each particle has its own list of applicable processes. At each step, all processes involved are invoked to get proposed physical interaction lengths
- The process which requires the shortest interaction length (in space-time) limits the step
- Each process has one or combination of actions with the following nature:
 - At Rest
 - e.g. muons can decay at rest
 - Along Step (a.k.a. continuous process)
 - e.g. Cherenkov process
 - Post step (a.k.a. discrete process)
 - e.g. decay in flight

Track Status

- At the end of each step, the state of a track may change (according to the processes involved)
 - The user can also change the status in **UserSteppingAction**
 - Status, as mentioned below, are artificial, i.e. Geant4 kernel won't set them, but the user can
 - **fAlive**
 - continue the tracking
 - **fStopButAlive**
 - the track has come to zero kinetic energy, but still AtRest process to occur
 - **fStopAndKill**
 - The track has lost its identity because it has decayed, interacted, or gone beyond the world boundary
 - Secondaries will be pushed to the stack
 - **fKillAndSecondaries**
 - kill the current track and also associated secondaries
 - **fSuspend**
 - suspend the processing of the current track and push it and its secondaries to the stack
 - **fPostponeToNextEvent**
 - Postpone processing of the current track to the next events
 - Secondaries are still being processed within the current event

Step Status

- The step status attached to the G4StepPoint indicates why that particular step was chosen
 - “PostStepPoint” gives the status of this step
 - “PreStepPoint” provides the status of the previous step
 - fWorldBoundary
 - step reached the world boundary
 - fGeomBoundary
 - step is limited by a volume boundary except for the world
 - fAtRestDoltProc, fAlongStepDoltProc, fPostStepDoltProc
 - step is limited by AtRest, AlonStep or PostStep process
 - fUserDefineLimit
 - step is limited by the user step limit
 - fExclusiveForcedProc
 - step is limited by an exclusively forced process (e.g. shower parametrisation)
 - fUndefined
 - step not defined
- If the first step in a volume is to be identified, pick fGeomBoundary status in the PreStepPoint
- If a step going out of a volume is to be identified, pick fGeomBoundary status in the PostStepPoint

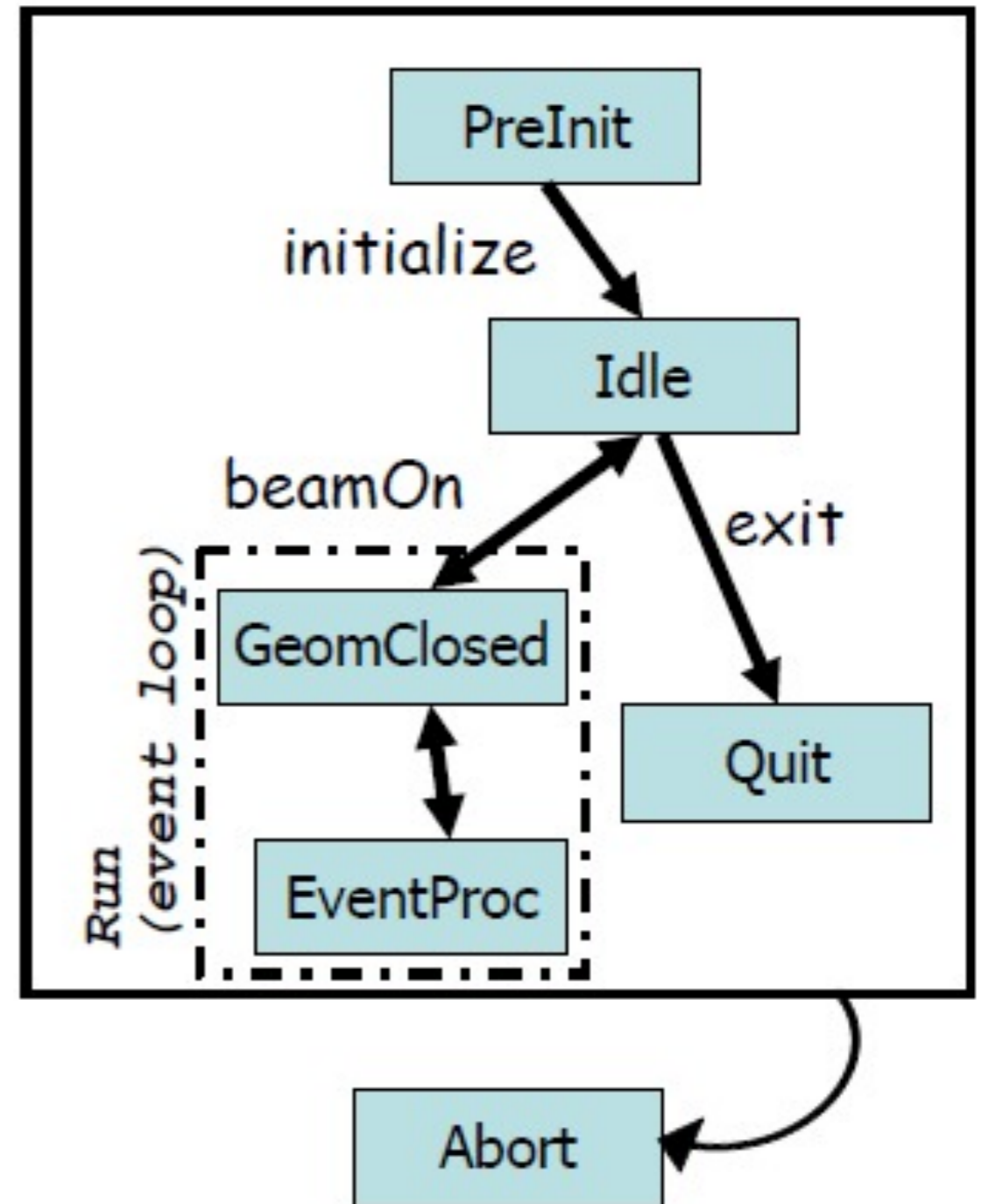


Extraction of Useful Information

- Given geometry, physics and primary track information, Geant4 does proper physics simulation “silently”
 - The user has to add a bit of code to extract useful information
- There are two ways for extraction:
 - Use the user hooks provided by Geant4
 - These are: `G4UserTrackingAction`, `G4UserSteppingAction`,
 - The user has access to almost all information
 - It is straight-forward but do-it-yourself
 - Use Geant4 scoring functionality
 - Assign `G4VSensitiveDetector` to a volume
 - Hits collection is automatically stored in the `G4Event` object, and automatically accumulated if the user-defined Run object is used
 - Use user hooks to get event/run summary
 - The relevant action classes are `G4UserEventAction`, `G4UserRunAction`

Geant4 as a State Machine

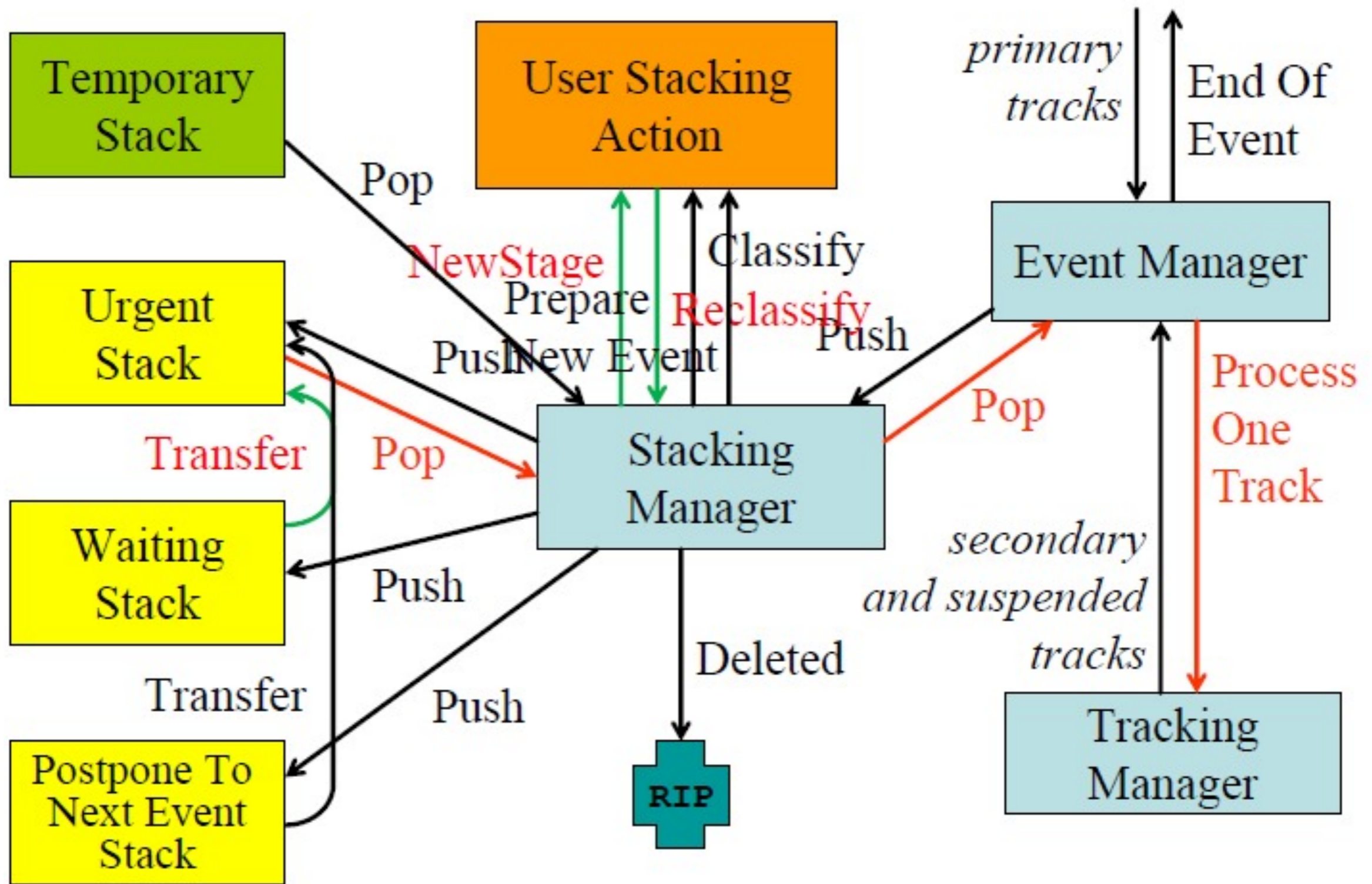
- Geant4 has six application states:
 - **G4State_PreInit**
 - At this state, material, geometry, particle and physics process need to be defined and initialized
 - **G4State_Idle**
 - Geant4 is ready to start a run
 - **G4State_GeomClosed**
 - Geometry is optimised and ready to process an event
 - **G4State_EventProc**
 - An event is being processed
 - **G4State_Quit**
 - (Normal) termination
 - **G4State_Abort**
 - A fatal exception occurred and the program is aborting



Track Stacks in Geant4

- By default, Geant4 has three track stacks:
 - “Urgent”, “Waiting” and “PostponeToNextEvent”
 - Each stack operates in a simple “last-in-first-out” mode
 - User can increase arbitrarily the number of stacks
- Class `ClassifNewTrack()` method of `G4UserStackingAction` class decides which stack each newly created secondary particle to be stored (or be killed)
 - By default, all tracks go to the “Urgent” stack
- A `G4Track` is popped up only from the “Urgent” stack
- Once the “Urgent” stack is empty, all tracks in the “Waiting” stack are transferred to the “Urgent” stack
 - And `NewStage()` method of the `G4UserStackingAction` is invoked
- Utilising more than one stack, the user can control the priorities of processing tracks without paying the overhead of “scanning the highest priority track”
 - Proper selection/abortion of tracks/events with well-designed stack management provides significant efficiency increase of the entire simulation

Stacking Mechanism



Tips of Stacking Manipulation

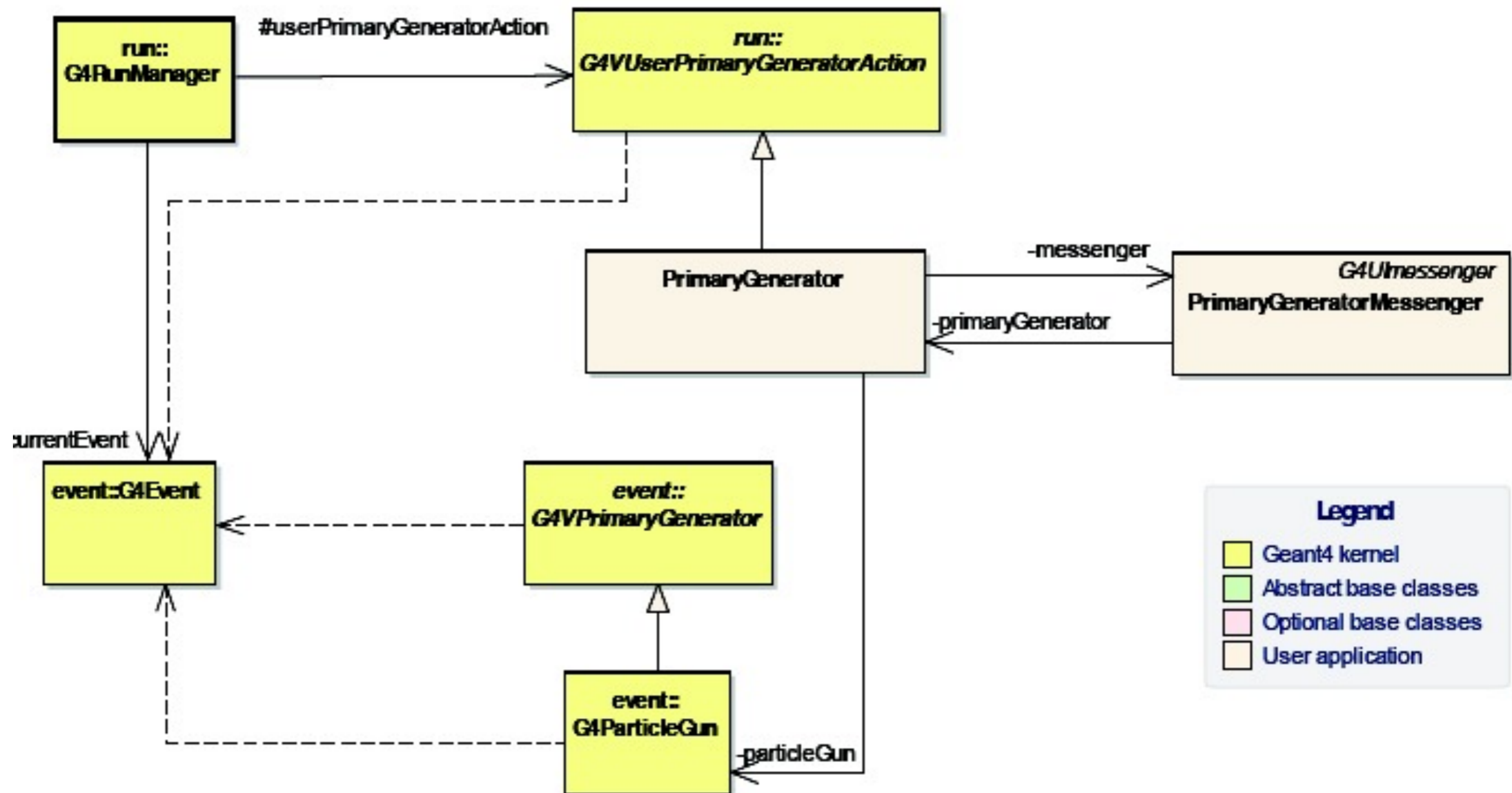
- Classify all secondaries as **fWaiting** until **Reclassify()** method is invoked
 - One can simulate all primaries before any secondary
- Classify secondary tracks below a certain energy as **fWaiting** until the **Reclassify()** method is invoked
 - One can roughly simulate the event before being bothered by low energy electromagnetic showers
- **Suspend** a track on its fly. Then this track and all of the already generated secondaries are pushed to the stack
 - Given the stack is “last-in-first-out”, secondaries are popped out prior to the original suspended track
 - This is quite effective for simulating Cerenkov radiation
- **Suspend** all tracks that are leaving a region, and classify these suspended tracks as **fWaiting** until **Reclassify()** method is invoked
 - One can simulate all tracks in this region prior to other regions
 - Note that some backsplash tracks may come back into this region later

Primary Generator

- Each Geant4 Event starts with the generation of one or multiple primary particles
- The user has to define the properties of primary particles
 - Particle type, e.g. electron, gamma, ion, ...
 - Initial kinematics, e.g. energy, momentum, origin, ...
 - Additional properties, e.g. polarization, ...
- These properties can be divided into:
 - **G4PrimaryVertex**: specifying start point in space and time
 - **G4PrimaryParticle**: specifying initial momentum, polarisation, PDG code, list of daughters for decay chains
- A primary generator is a class derived from **G4VPrimaryGenerator** and has an implementation of the method **GeneratePrimaryVertex()**
 - The primary vertex and the primary particle(s) are added in this method to a Geant4 Event
 - Several event generators are provided in the Geant4 toolkit
 - **G4HEPEvtInterface**, **G4HEPMCInterface**, **G4GeneralParticleSoce**, **G4ParticleGun**

PrimaryGeneratorAction

- This mandatory user action controls the generation of primary particles but does not generate the primaries itself. This task is delegated to G4PrimaryGenerator derived from G4VPrimaryGenerator



PrimaryGenerator

- The primary generator could make use of
 - a built-in generator: G4ParticleGun for producing particles of arbitrary momenta and direction to test a setup
 - an external physics generator which provides a collection of particles emerging from a known physics process (Pythia, Herwig, ...)

```
PrimaryGeneratorAction::PrimaryGeneratorAction(const G4String & parName,  
G4double energy, G4ThreeVector pos, G4ThreeVector momDirection){  
  
    const G4int nParticles = 1;  
    fParticleGun = new G4ParticleGun(nParticles);  
    G4ParticleTable* parTable = G4ParticleTable::GetParticleTable();  
    G4ParticleDefinition* parDefinition = parTable->FindParticle(parName);  
    fParticleGun->SetParticleDefinition(parDefinition);  
    fParticleGun->SetParticleEnergy(energy);  
    fParticleGun->SetParticlePosition(pos);  
    fParticleGun->SetParticleMomentumDirection(momDirection);  
}
```

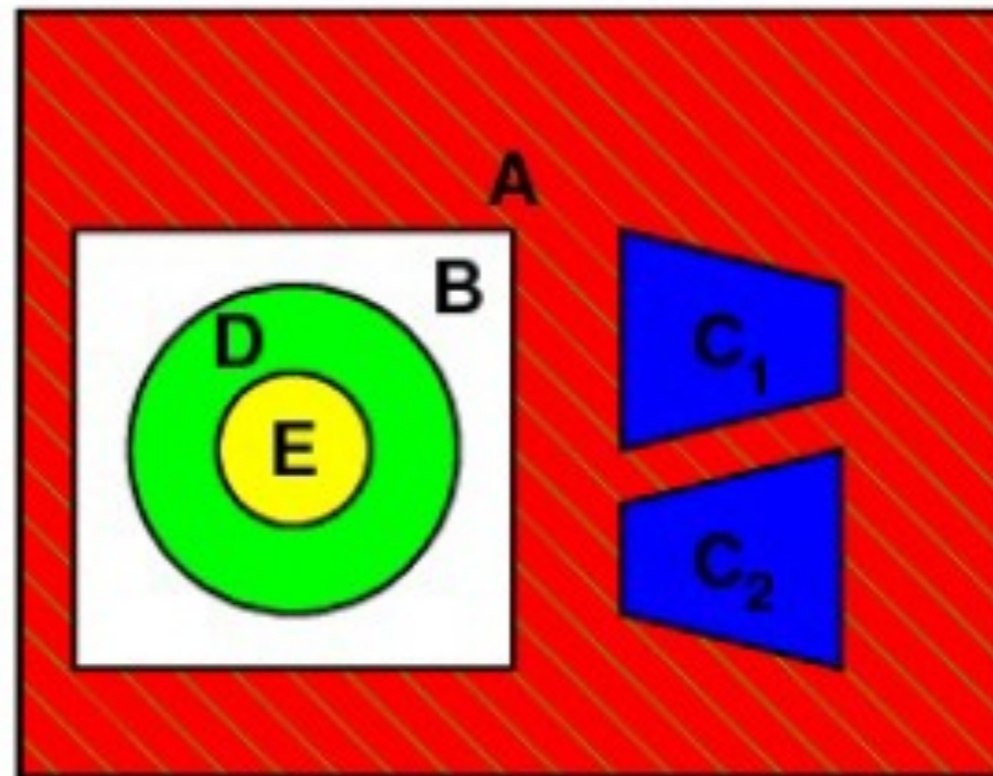
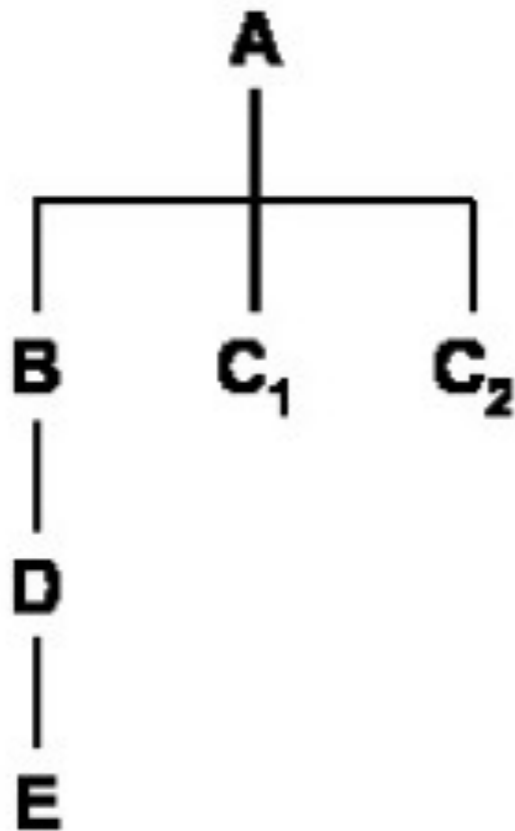
```
PrimaryGeneratorAction::GeneratePrimaries(G4Event* evt){  
  
    //some additional random sampling here  
  
    fParticleGun->GeneratePrimaryVertex(evt);  
  
}
```

Attaching user information

- Abstract classes:
 - The user can use his/her own class derived from the period base class
 - G4Run, G4VHit, G4VDigit, G4VTrajectory, G4VTrajectoryPoint
- Concrete classes:
 - The user can attach a user information class object
 - G4Event — G4VUserEventInformation
 - G4Track — G4VUserTrackInformation
 - G4PrimaryVertex — G4VUserPrimaryVertexInformation
 - G4PrimaryParticle — G4VUserPrimaryParticleInformation
 - G4Region — G4VUserRegionInformation
 - User information class objects are deleted when the associated Geant4 class object is deleted

Modelling of a Detector

- Detectors are modelled by a geometrical shape filled with certain material of known physical properties → “Volume”
- Several volumes can describe different components of the detector system. Put them together in a hierarchical structure:



Composite Volume → Experimental Setup

Material

- Material has a Name, Effective Atomic Number and Weight, Density, Radiation (L_R) and Absorption (λ) length
- It can be defined by specifying these attributes
- If radiation and absorption lengths are not known, one can furnish information regarding the chemical composition and Geant4 will compute the required attributes for the application
- One can also add the state (**solid** | **liquid** | **gas**), isotopic properties, etc. Some of these specifications are essential to study activation, ...
 - Define pseudo-elements:
new G4Material (name, Z, A, density, state, temperature, pressure);
 - Define a mixture of elements in atomic or weighted proportion:
new G4Material (name, density, numComponents);
→AddElement (material, fraction);
G4Element* element = new G4Element (name, symbol, Z, A);
→AddElement (element, nAtom);
 - Build elements from isotopes:
new G4Element (name, symbol, numIsotopes);
G4Isotope* isotope = new G4Isotope (name, Z, N);
→AddIsotope (isotope, abundance);

Volume

- A volume is defined by its shape, dimensional parameters and its material content. A shape with dimensional parameters is called a **Solid** and the association of a **Solid** with a **Material** is called a **LogicalVolume**.
- There are several ways to define a **Solid**:
 - Computed Solid Geometry (CSG): G4Box, G4Trd, G4Trapm G4Tubs, G4Cons, G4Sphere, G4PolyCone,
 - Boundary Representation (BREP): G4BrepSolidPcone, (slower navigation on a standard CPU, but works better in GPU)
 - Boolean: Solids made out by adding, subtracting, intersecting, etc. several solids: G4RotateSolid,
 - STEP: Imported from the CAD system
- System of Units: Though a convention is used internally for the unit system, the recommendation is not to remember them and use the units explicitly:
 - double length = 5 * cm;
 - double angle = 30 * deg;
 - double time = 25 * ns;

Define a Volume

- First define a **Material**, say **Air** consisting of 2 constituent elements **Nitrogen** and **Oxygen** in a given weight proportion (70:30)
 - First define **Nitrogen** and **Oxygen** with their appropriate **Z, A** values:

```
G4Element *eln = new G4Element("Nitrogen","N",Z=7,A=14.01*g/mole);  
G4Element *elo = new G4Element("Oxygen","O",Z=8,A=16.00*g/mole);
```
 - Then define **Air** and add the two elements:

```
G4Material *air = new G4Material("Air",1.205E-03*g/cm3,2);  
air->AddElement(eln,0.7);  
air->AddElement(elo,0.3);
```
- Define a **Solid** of a given name (say **INOM**) as a box of given half length, half width, half thickness:

```
G4Solid* inomSolid = new G4Box("INOM",1606*cm,706*cm,598*cm);
```
- Associate the **Solid** with the **Material** to define the **LogicalVolume**:

```
G4LogicalVolume* inomLog = new G4LogicalVolume(inomSolid,air,"INOML");
```
- The reference frame is a right-handed Cartesian coordinate system with the origin at the centre of the box

Define a Detector Setup

- To define a set up, one needs to
 - define a Master or World reference system
 - position the various components with respect to each other
- Geant4 uses the concept of **PhysicalVolume** which is a **LogicalVolume** positioned in a **Mother** (**PhysicalVolume** or **LogicalVolume**) with a translation vector and a rotation matrix (optional). For the top-level Volume (defining the **World** reference system), the pointer of the Mother Volume should be declared as a **nullPointer**
- One useful way of defining daughter volumes is by dividing an existing mother volume into **n** equal parts along a chosen axis (Cartesian, Cylindrical, or Polar)
 - The creation and positioning are done in two separate steps
- When a daughter is positioned inside a mother, the extent inside the mother occupied by the daughter gets filled with the material of the daughter's volume

Can build up a tree like a Russian doll

Hooks for Positioning

```
G4PhysicalVolume* volume = new G4PVPlacemenet (rot,  
        G4ThreeVector(xpos*cm,ypos*cm,zpos*cm),  
        G4LogicalVolume* current, Name,  
        G4LogicalVolume* mother, false, copyNumber)
```

creates a **PhysicalVolume** volume by positioning a copy with number **copyNumber** of the **LogicalVolume** current inside the **mother** volume **mother** with a **translation vector** (**G4ThreeVector**) and a **rotation matrix** rot (**G4RotationMatrix***)

If one needs to define a rotation matrix by specifying the angles (θ_i, φ_i) of the three axes (as done in **Geant3**), one needs to follow the steps:

```
G4ThreeVector iAxis(sin(thetal*deg)*cos(phil*deg),  
                    sin(thetal*deg)*sin(phil*deg), cos(thetal*deg));  
G4RotationMatrix* rot = new G4RotationMatrix();  
rot->rotateAxis(xAxis,yAxis,zAxis);  
rot->invert();
```

Hooks for Positioning (2)

- For dividing a parent volume into equal parts along a given axis, one needs to create the `LogicalVolume` using the standard steps (defining `Solid`, `Material`, and `LogicalVolume`) and then position multiple replicas through:

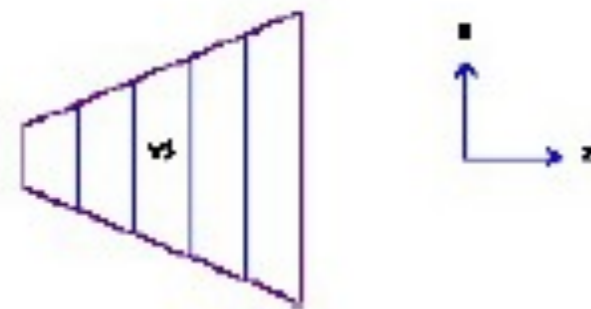
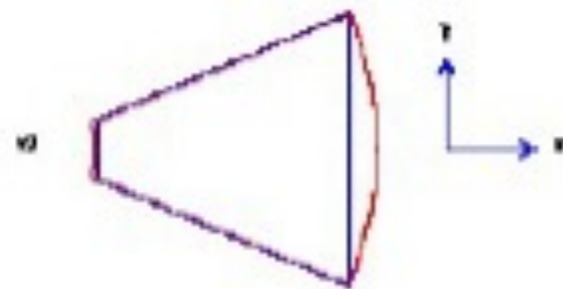
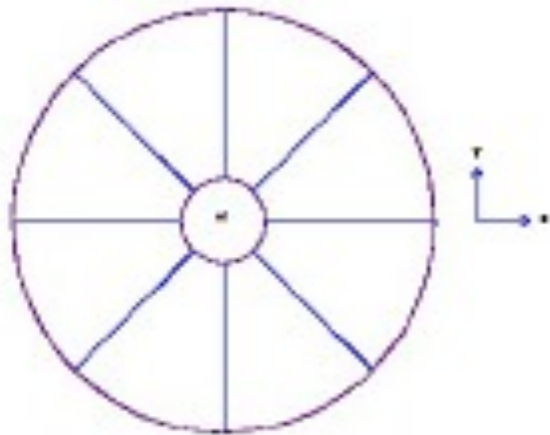
```
G4PhysicalVolume * volume = new G4PVReplica (NAME,  
      G4LogicalVolume* current, G4LogicalVolume* mother,  
      kAxis, nDivision, width, offset)
```

This needs more steps than what used to be in its predecessor Geant3 (GSDVN), but it is more general

- The tree of `PhysicalVolumes` is instantiated at the time of tracking in the form of `G4VTouchable` and the list of `PhysicalVolumes` in the branch will provide the unique identification of a volume

Example

- Construct geometry of a cylindrical drift chamber with 8 sectors each having 5 cells:



- Define volume **VOL1** as a tube with inner and outer radii $R1$, $R2$ and half-length L
- Divide the tube into 8 parts azimuthally and each section is called **VOL2**
- Define a trapezoid of half-length L , width $[R2.\cos(\pi/8) - R1]$ and two edges of dimension $2.R1.\tan(\pi/8)$, and $2.R2.\tan(\pi/8)$. Position this volume **VOL3** inside **VOL2** with the proper translation vector and rotation matrix
- Divide the trapezoid **VOL3** into 5 parts along the z -axis. Each part **VOL4** will be a cell

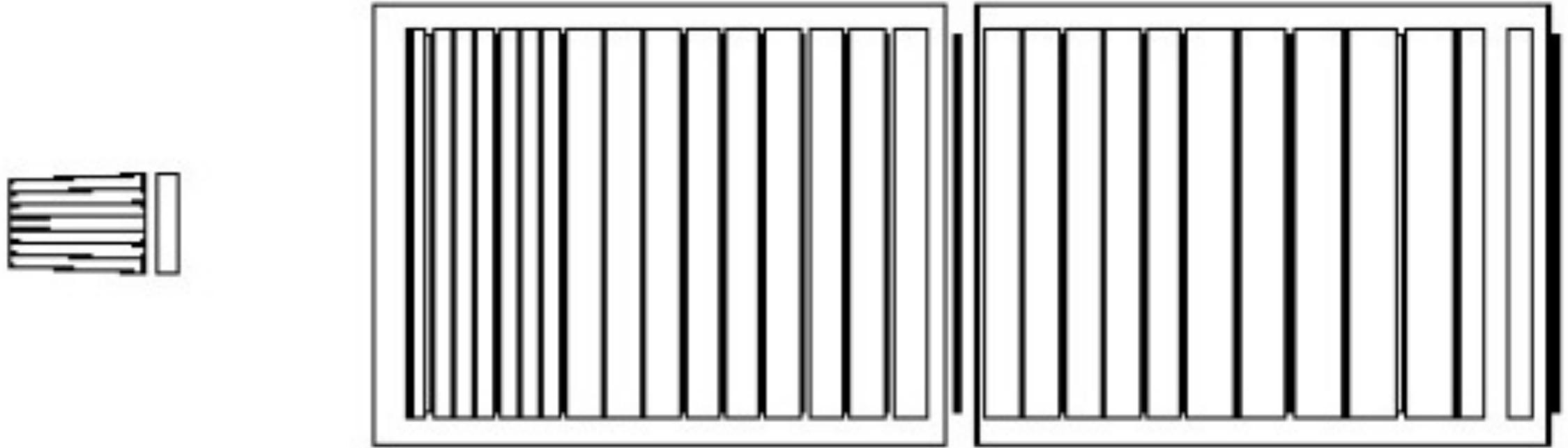
Example

```
// define materials mat1, mat3 for VOL1, VOL3
G4VSolid* solid;
solid = new G4Tubs("VOL1", R1*cm, R2*cm, 0.5*L*cm, 0, twopi);
G4LogicalVolume *v1 = new G4LogicalVolume(solid, mat1, "VOL1");
// divide VOL1 along phi axis
solid = new G4Tubs("VOL2", R1*cm, R2*cm, 0.5*L*CM, -pi/8., pi/4.);
G4LogicalVolume *v2 = new G4LogicalVolume(solid, mat1, "VOL2");
new G4PVDivision ("VOL2", v2, v1, kPhi, 8, pi/4.);
// now the trapezoid
solid = new G4Trd ("VOL3", R1*tan(pi/8.)*cm, R2*tan(pi/8.)*cm, 0.5*L*cm, 0.5*L*CM, 0.5*(R2*cos(pi/8.)-R1)*cm);
G4LogicalVolume* v3 = new G4LogicalVolume(solid, mat3, "VOL3");
// position VOL3 inside VOL2
G4ThreeVector xAxis(0,1.,0), yAxis(0,0,1.), zAxis(1.,0,0);
G4RotationMatrix* rot = new G4RotationMatrix();
rot->rotateAxis(xAxis, yAxis, zAxis);
rot->invert();
new G4PVPlacement (rot, G4ThreeVector(0.5*(R2*cos(pi/8.)+R1)*cm,0,0), "VOL3", v3, v2, false, 1);
// finally the cell
solid = new G4Trd ("VOL4", R1*tan(pi/8.)*cm, R2*tan(pi/8.)*cm, 0.5*L*cm, 0.5*L*CM, 0.5*(R2*cos(pi/8.)-R1)*cm);
G4LogicalVolume* v4 = new G4LogicalVolume(solid, mat3, "VOL4");
new G4PVDivision ("VOL4", v4, v3, kZaxis, 5, 0.2*(R2*cos(pi/8.)-R1)*cm);
```

- This will create the volume tree:



A Practical Example

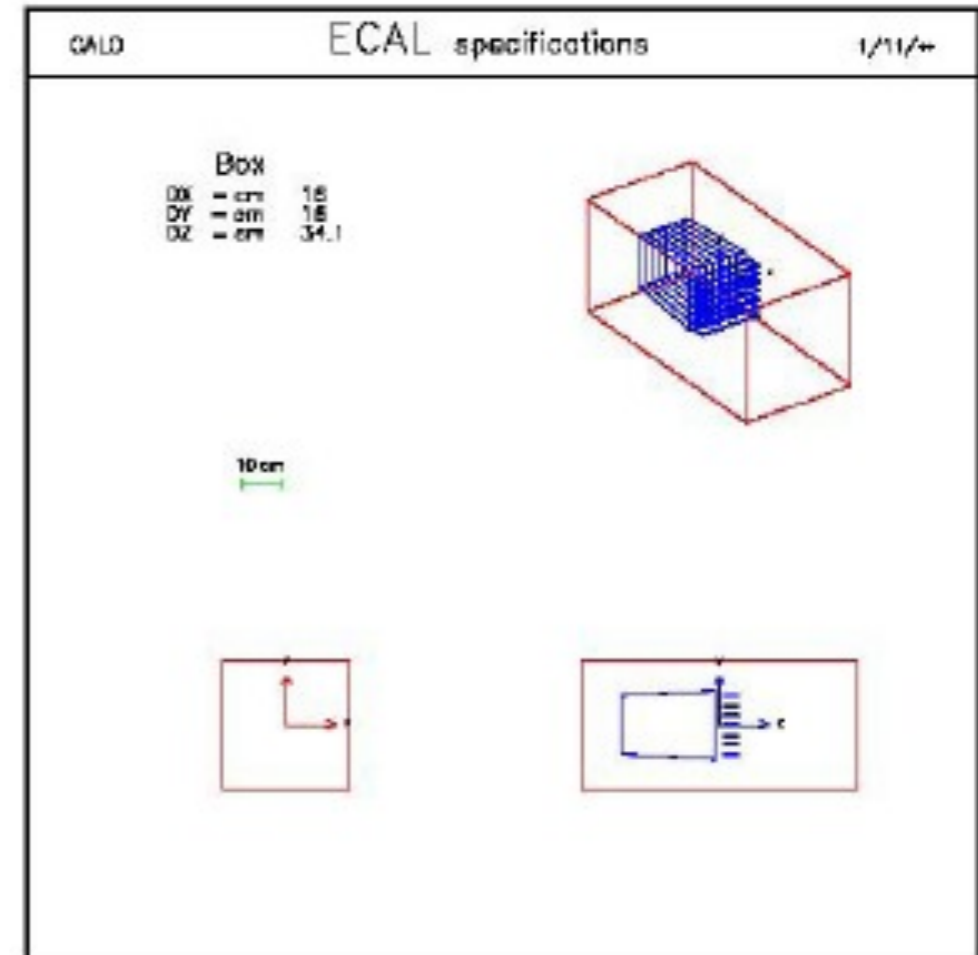
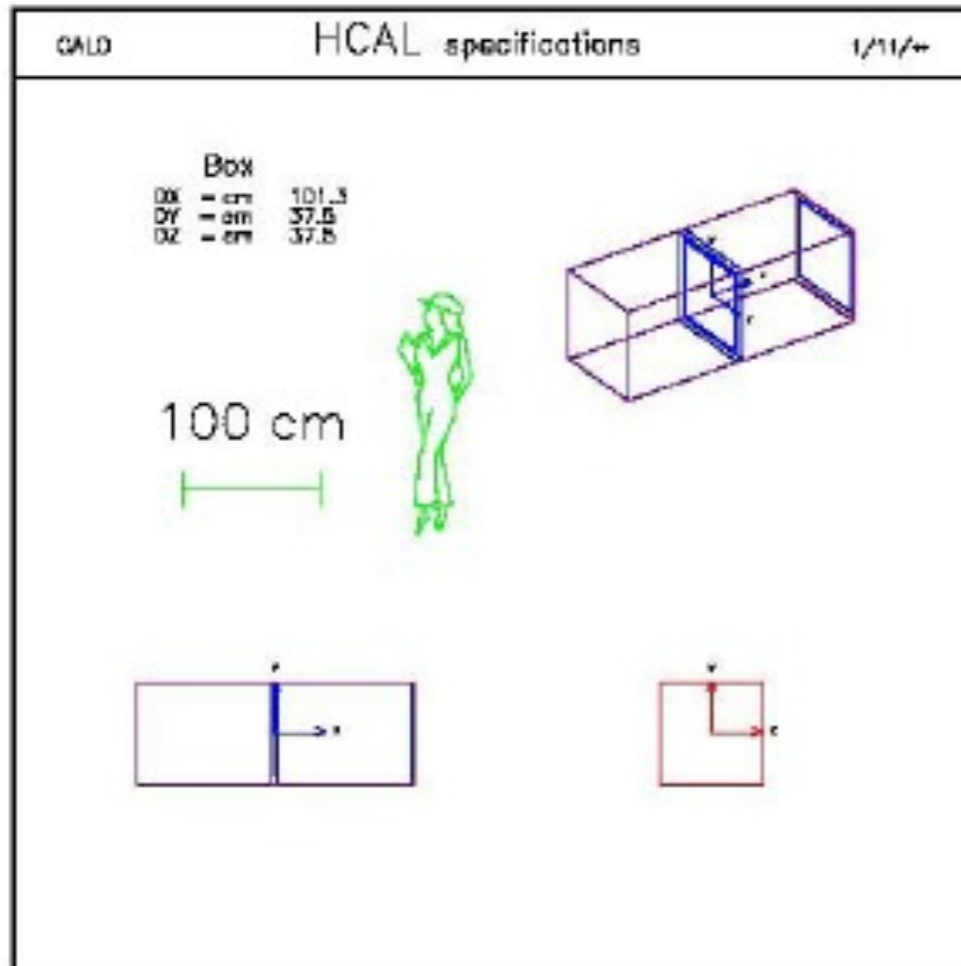


The 1996 CMS Test Beam Setup

- 7 x 7 crystal matrix made out of lead tungstate
- 28 layers of plastic scintillators interleaved with brass plates of varying thickness
- B-field along the z-axis (perpendicular to the beam direction) with maximum field strength of 3 Tesla

Composite-Calorimeter as an Example in Geant4 (advanced)

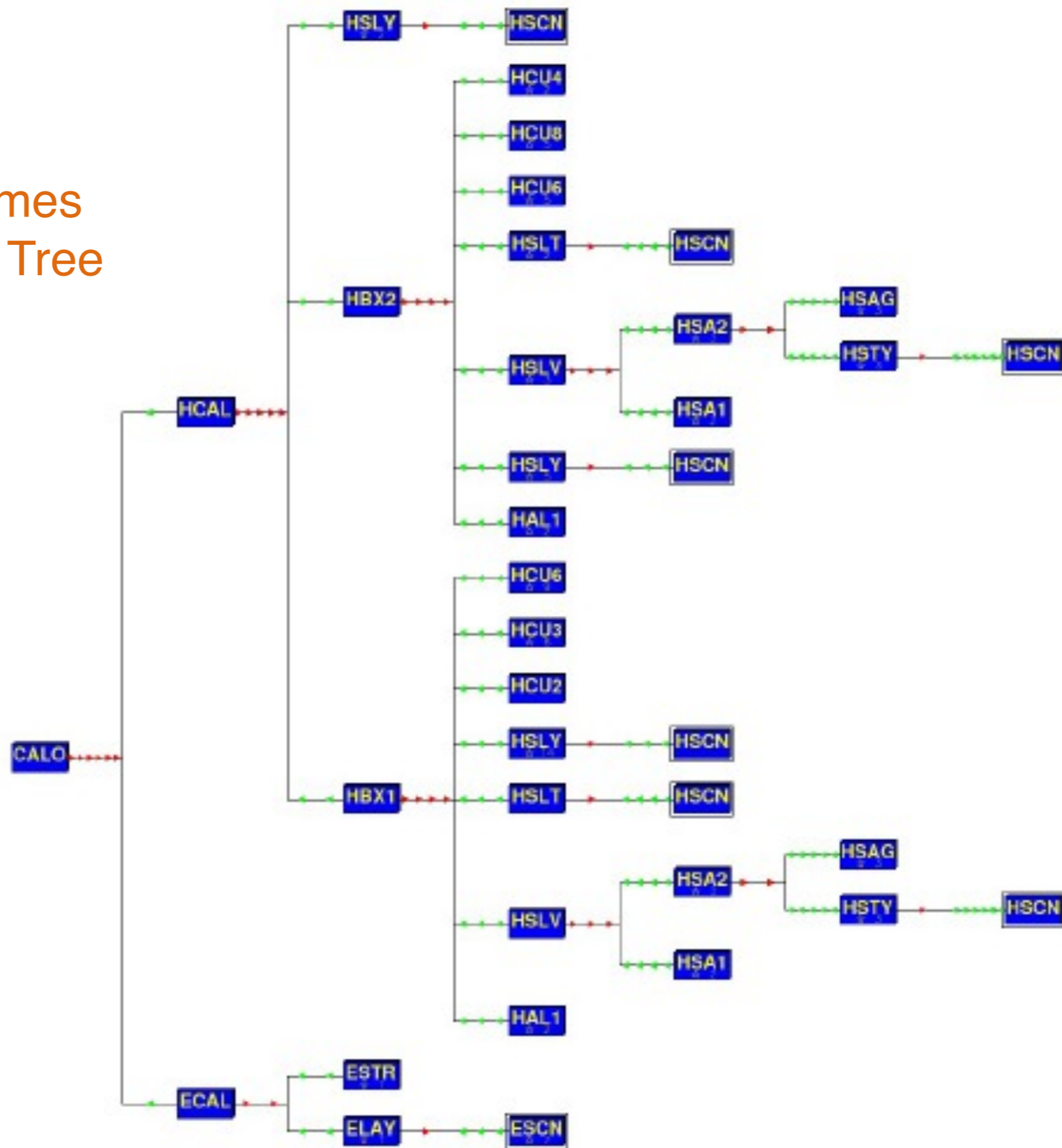
Composite Calorimeter



- **HCAL** (the enclosure for the hadron calorimeter) contains two boxes made out of aluminium each housing absorber plates and scintillator layers
- **ECAL** (the enclosure for the electromagnetic calorimeter) contains the crystal matrix and some support structure
- Both **ECAL** and **HCAL** are placed in a mother volume **CALO** which defines the world volume

Geometry Tree

22 Logical Volumes
8 Levels in the Tree

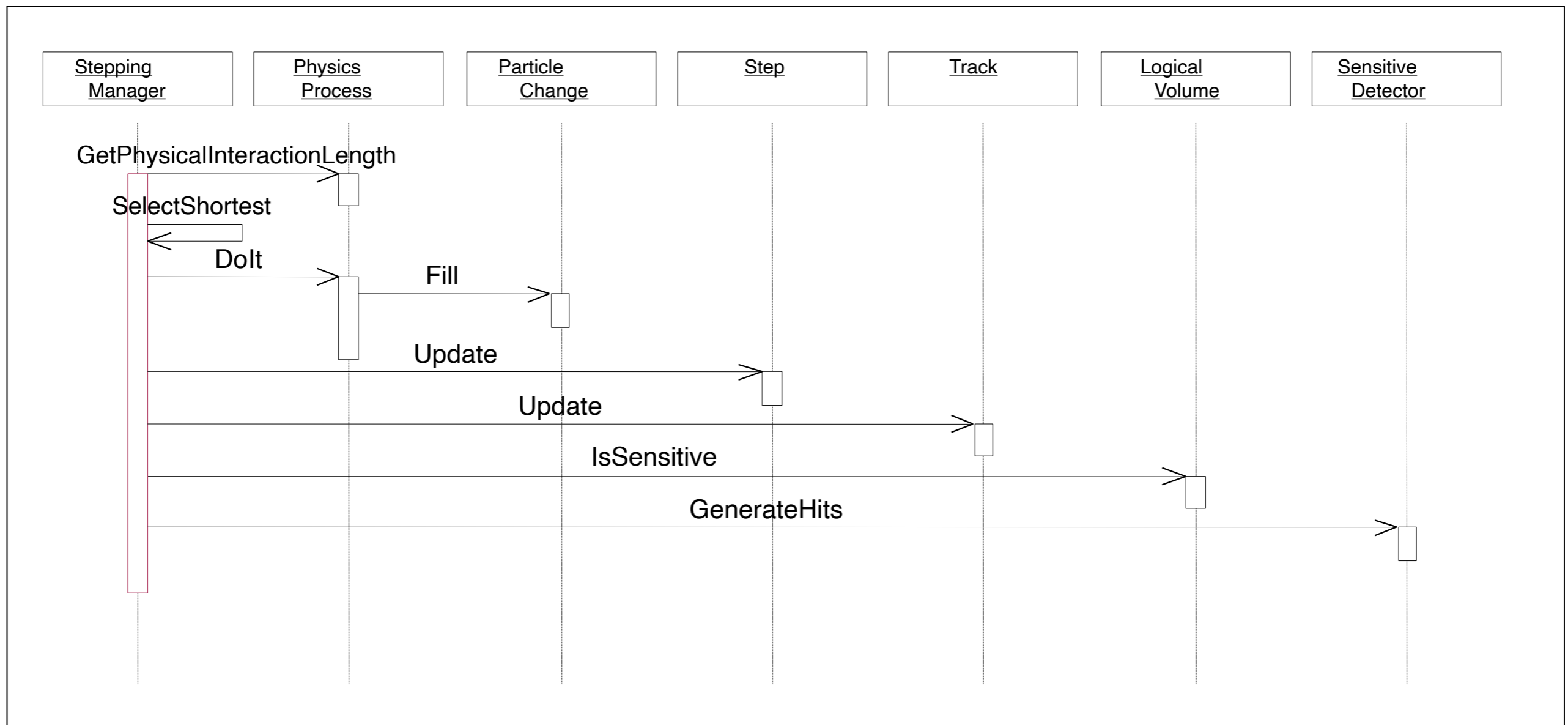


Extraction of Useful information

- Given geometry, physics and primary track generation, Geant4 does proper physics simulation “silently”
 - The user needs to add a bit of code to **extract useful information**
- There are three ways:
 - Use built-in scoring commands
 - Most commonly-used physics quantities are available
 - Use scorers in the tracking volume
 - Create scores for each event
 - Create own Run class to accumulate scores
 - Assign **G4VSensitiveDetector** to a volume to generate “hit”
 - Use user hooks (G4UserEventAction, G4UserRunAction) to get event / run summary
- The user may also use user hooks (G4UserTrackingAction, G4UserSteppingAction, etc.)
 - The user has full access to almost all information

Sensitive Detector

- A **G4VSensitiveDetector** object can be assigned to a **G4LogicalVolume**
- In case a step takes place in a logical volume that has a **G4VSensitiveDetector** object, this **G4VSensitiveDetector** is invoked with the **current G4Step** object



Defining a Sensitive Detector

- The basic strategy

```
G4LogicalVolume* myLogCalor = .....;  
G4VSensitiveDetector* pSensitivePart = new MyDetector("/  
  mydet");  
G4SDManager* SDMan = G4SDManager::GetSDMpointer();  
SDMan->AddNewDetector(pSensitivePart);  
myLogCalor->SetSensitiveDetector(pSensitivePart);
```

- Each detector object must have a unique name

- Some logical volumes can share one detector object

- More than one detector object can be made from one detector class with different detector name

- One logical volume cannot have more than one detector object. But, one detector object can generate more than one kind of hits

- e.g. a double-sided silicon micro-strip detector can generate hits for each side separately

Hit

- Hit is a snapshot of the physical interaction of a Track or an accumulation of interactions of Tracks in the sensitive region of your detector
- A sensitive detector creates Hit(s) using the information given in the G4Step object. The user has to provide his/her own implementation of the detector response
- Hit objects, which are still the user's class objects, are collected in a G4Event object at the end of an event

Hit Class

- **Hit** is a user-defined class derived from **G4VHit**
- The user can store various types of information by implementing one's own concrete **Hit** class. For example:
 - Position and time of the step
 - Momentum and energy of the track
 - Energy deposition of the step
 - Geometrical information
 - or any combination of above
- **Hit** objects of a concrete **Hit** class must be stored in a dedicated collection which is instantiated from **G4THitsCollection** template class
- The collection is associated with a **G4Event** object via **G4HCofThisEvent**
- **Hits** are accessible as collections:
 - through **G4Event** at the end of the event
 - to be used for analyzing an event
 - through **G4SDManager** during processing an event
 - to be used for event filtering

Implementation of Hit class

```
#include "G4VHit.hh"  
class MyHit : public G4VHit  
{  
  public:  
    MyHit(some_arguments);  
    virtual ~MyHit();  
    virtual void Draw();  
    virtual void Print();  
  private:  
    // some data members  
  public:  
    // some set/get methods  
};  
  
#include "G4THitsCollection.hh"  
typedef G4THitsCollection<MyHit> MyHitsCollection;
```


Sensitive Detector class

- The sensitive detector is a user-defined class derived from the class G4VSensitiveDetector

```
#include "G4VSensitiveDetector.hh"
#include "MyHit.hh"
class G4Step;
class G4HCofThisEvent;
class MyDetector : public G4VSensitiveDetector
{
public:
    MyDetector(G4String name);
    virtual ~MyDetector();
    virtual void Initialize(G4HCofThisEvent*HCE);
    virtual G4bool ProcessHits(G4Step*aStep,
                               G4TouchableHistory*ROhist);
    virtual void EndOfEvent(G4HCofThisEvent*HCE);
private:
    MyHitsCollection * hitsCollection;
    G4int collectionID;
```

```
};
```

Types of Hit

- A tracker detector typically generates a hit for every single step of every single (charged) track
 - A tracker hit typically contains
 - Position and time
 - Energy deposition of the step
 - Track identifier
 - Some cell identifier
- A calorimeter detector typically generates a hit for every cell and accumulates energy deposition in each cell for all steps of all tracks
 - A calorimeter hit typically contains
 - Sum of deposited energy
 - Some timing information
 - Cell Identifier
- The user can instantiate more than one object for one sensitive detector class. Each object should have its unique detector name
 - For example, each of the two sets of detectors can have its dedicated sensitive detector objects. But, their functionalities are exactly the same so that they can share the same class. See [examples/extended/analysis/A01](#) as an example

Implementation of Sensitive Detector - 1

```
MyDetector::MyDetector(G4String detector_name)  
    :G4VSensitiveDetector(detector_name),  
    collectionID(-1)  
{  
    collectionName.insert("collection_name");  
}
```

- In the constructor, the name of the hits collection which is handled by this sensitive detector is to be defined
- In case the sensitive detector generates more than one kind of hits (e.g. anode and cathode hits separately), all collection names need to be defined

Implementation of Sensitive Detector - 2

```
void MyDetector::Initialize(G4HCofThisEvent*HCE)
{
    if(collectionID<0) collectionID = GetCollectionID(0);
    hitsCollection = new MyHitsCollection
        (SensitiveDetectorName,collectionName[0]);
    HCE->AddHitsCollection(collectionID,hitsCollection);
}
```

- Initialize() method is invoked at the beginning of each event.
- Get the unique ID number for this collection
 - GetCollectionID() is a heavy operation. It should not be used for every event
 - GetCollectionID() is available after this sensitive detector object is constructed and registered to G4SDManager. Thus, this method cannot be invoked in the constructor of this detector class
- The hits collection(s) are to be instantiated and then attached to the G4HCofThisEvent object given in the argument
- In the case of a calorimeter-type detector, hits for all calorimeter cells may be instantiated with zero energy depositions, and then inserted into the collection

Implementation of Sensitive Detector - 3

```
G4bool MyDetector::ProcessHits
(G4Step*aStep,G4TouchableHistory*ROhist)
{
  MyHit* aHit = new MyHit();
  ...
  // some set methods
  ...
  hitsCollection->insert(aHit);
  return true;
}
```

- This ProcessHits() method is invoked for every step in the volume(s) where this sensitive detector is assigned
- In this method, generate a hit corresponding to the current step (for tracking detector), or accumulate the energy deposition of the current step to the existing hit object where the current step belongs (for calorimeter detector)
- The geometry information is to be collected (e.g. copy number) from “PreStepPoint”
- Currently, the returned boolean value is not used

Implementation of Sensitive Detector - 4

```
void MyDetector::EndOfEvent(G4HCofThisEvent*HCE) {;}
```

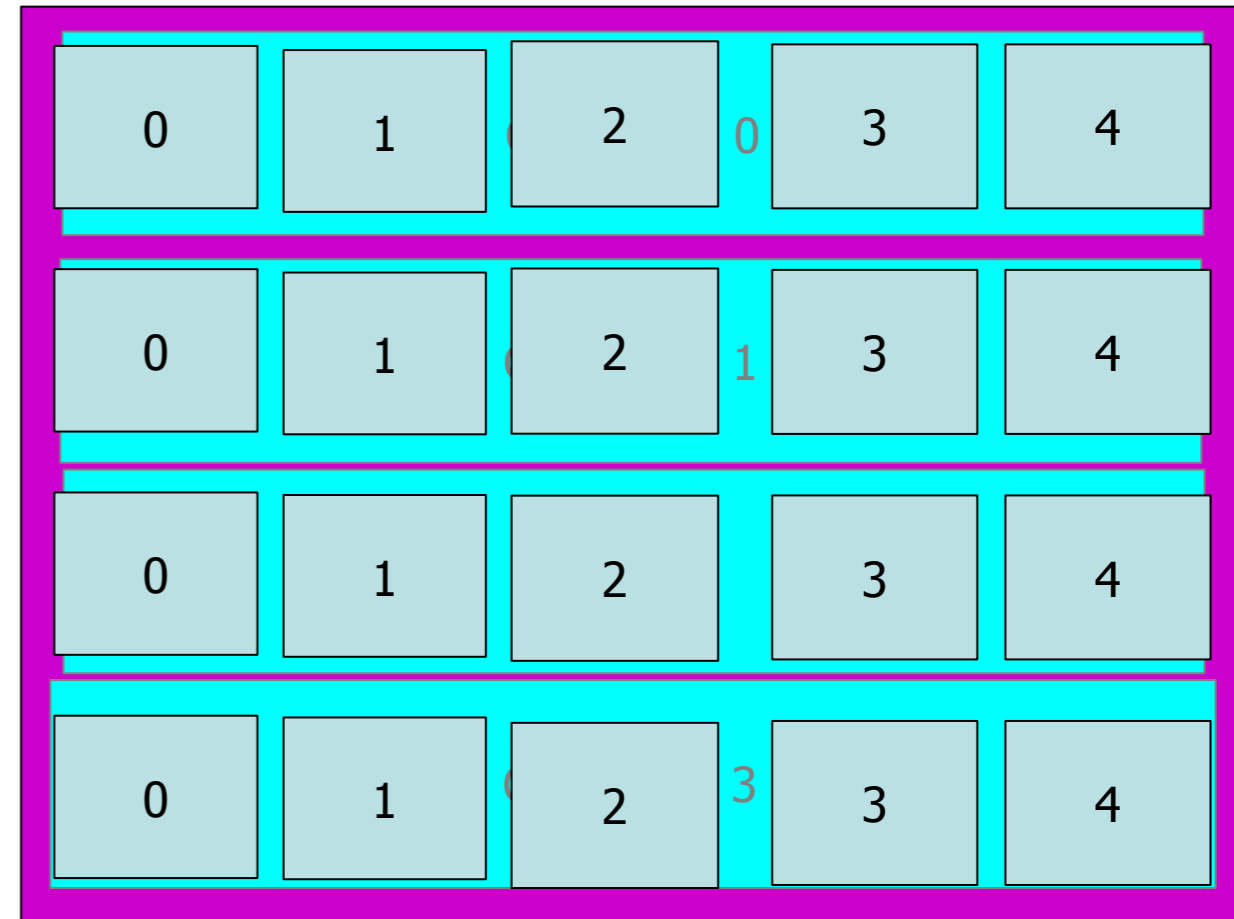
- This method is invoked at the end of processing an event
 - It is invoked even if the event is aborted
 - It is invoked before UserEndOfEventAction

Step Point and Touchable

- As mentioned already, G4Step has two G4StepPoint objects as its starting and ending points. All the geometrical information of the particular step should be taken from “PreStepPoint”
 - Geometrical information associated with G4Track is identical to “PostStepPoint”
- Each G4StepPoint object has
 - Position in the world coordinate system
 - Global and local time
 - Material
 - G4TouchableHistory for geometrical information
- The G4TouchableHistory object is a vector of information for each geometrical hierarchy
 - copy number
 - translation/rotation to its mother
- Since release 4.0, *handles (or smart-pointers)* to touchable are intrinsically used. Touchables are reference counted

Copy Number

- Suppose a calorimeter is made of 4x5 cells
 - and it is implemented by two levels of replica
- In reality, there is only one physical volume object for each level. Its position is parameterized by its copy number
- To get the copy number of each level for the cell when the step belongs to two cells,



- geometrical information in G4Track is identical to that in "PostStepPoint"
- the user cannot get the correct copy number for "PreStepPoint" if one directly accesses the physical volume
- The touchable is to be used to get the proper copy number, transform matrix, etc.

Touchable

- G4TouchableHistory has information on the geometrical hierarchy of the point.

```
G4Step* aStep;  
G4StepPoint* preStepPoint = aStep->GetPreStepPoint();  
G4TouchableHistory* theTouchable =  
    (G4TouchableHistory*)(preStepPoint->GetTouchable());  
G4int copyNo = theTouchable->GetVolume()->GetCopyNo();  
G4int motherCopyNo  
    = theTouchable->GetVolume(1)->GetCopyNo();  
G4int grandMotherCopyNo  
    = theTouchable->GetVolume(2)->GetCopyNo();  
G4ThreeVector worldPos = preStepPoint->GetPosition();  
G4ThreeVector localPos = theTouchable->GetHistory()  
    ->GetTopTransform().TransformPoint(worldPos);
```

G4HCofThisEvent

- A G4Event object has a G4HCofThisEvent object at the end of (successful) event processing. G4HCofThisEvent object stores all hits collections made within the event.
- Pointer(s) to the collections may be NULL if collections are not created in the particular event
- Hit collections are stored by pointers of the G4VHitsCollection base class. Thus, one has to cast them into types of individual concrete classes
- The index number of a Hits collection is unique and unchanged for a run. The index number can be obtained by
`G4SDManager::GetCollectionID("detName/colName");`
- The index table is also stored in G4Run

Usage of G4HCofThisEvent

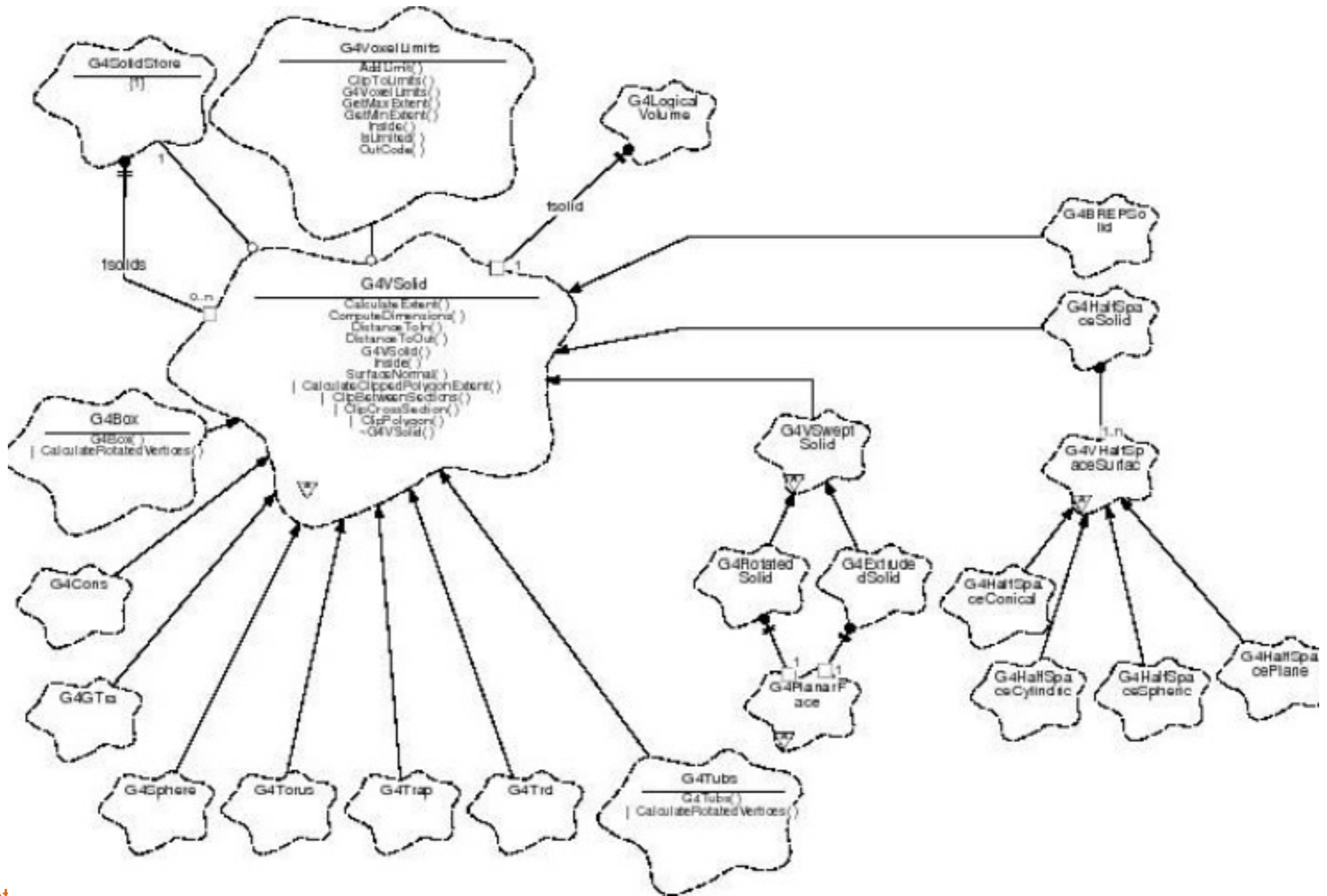
```
void MyEventAction::EndOfEventAction(const G4Event* evt) {
    static int CHCID = -1;
    If(CHCID<0) CHCID = G4SDManager::GetSDMpointer()
        ->GetCollectionID("myDet/collection1");
    G4HCofThisEvent* HCE = evt->GetHCofThisEvent();
    MyHitsCollection* CHC = 0;
    if (HCE) {
        CHC = (MyHitsCollection*)(HCE->GetHC(CHCID)); }
    if (CHC) {
        int n_hit = CHC->entries();
        G4cout<<"My detector has " <<n_hit<<" hits."<<G4endl;
        for (int i1=0;i1<n_hit;i1++) {
            MyHit* aHit = (*CHC)[i1];
            aHit->Print();
        }
    }
}
```

Additional Slides

Bookkeeping Issues

- Connection from G4PrimaryParticle to G4Track
G4int G4PrimaryParticle::GetTrackID()
 - Returns the track ID if this primary particle had been converted into G4Track, otherwise -1
- Connection from G4Track to G4PrimaryParticle
G4PrimaryParticle* G4DynamicParticle::GetPrimaryParticle()
 - Returns the pointer of G4PrimaryParticle object if this track was defined as a primary or pre-assigned decay product, otherwise null
- G4VUserPrimaryVertexInformation, G4VUserPrimaryParticleInformation and G4VUserTrackInformation may be used for storing additional information
 - Information in G4VUserTrackInformation should be then copied to the user-defined trajectory class so that such information is kept until the end of the event

Solids



Hit Collection, Hit Map

- **G4VHitsCollection** is the common abstract base class of both **G4THitsCollection** and **G4THitsMap**
- **G4THitsCollection** is a template vector class to store pointers of objects of one concrete hit class type
 - A hit class (deliverable of **G4VHit** abstract base class) should have its own identifier (e.g. cell ID)
 - **G4THitsCollection** requires the user to implement their own hit class
- **G4THitsMap** is a template map class that stores keys (typically cell ID, i.e. copy number of the volume) with pointers of objects of one type
 - Objects may not be those of the hit class
 - All of the currently provided scorer classes use **G4THitsMap** with simple double
 - Since **G4THitsMap** is a template, it can be used by the sensitive detector class to store hits