Detector Simulation

2023 CERN Korean Summer Student Program

Sungkyunkwan University Yuna Lee

Why do we need simulation for detectors?

- Goal: Prove theories through experiments. -> Need to build apparatus.

- Problems

1) Limited money and resource.
2) Not sure if the detector will run according to our needs.
3) Not sure if the data from the detector is accurate and precise.

- Solution: USE SIMULATION!

1) <u>Optimize the design of the detector.</u>
2) <u>Simulate the detector and predict events.</u>

Why do we need simulation for detectors?

3) Test that our simulations are accurate using real data. Correct our simulations if necessary. Once our simulation is an accurate model of our detector, we can use it to correct the data for detector response.

Monte Carlo Simulation

- For LHC experiments, the simulation is made of two steps:

1) Simulation of the p-p collision
2) Simulation of the passage of the produced particle through the experimental apparatus

➢ Monter Carlo radiation transportation, or simply detector simulation

Monte Carlo Simulation

- How do we do detector simulation? Geant4 software (C++) toolkit

➢ Propagates particles through geometrical structures of materials, including magnetic field

➢ Simulates processes the particles undergo (creates secondary particles and decays particles)

➢ Calculates the deposited energy alone the trajectories and allows to store the information for further hits

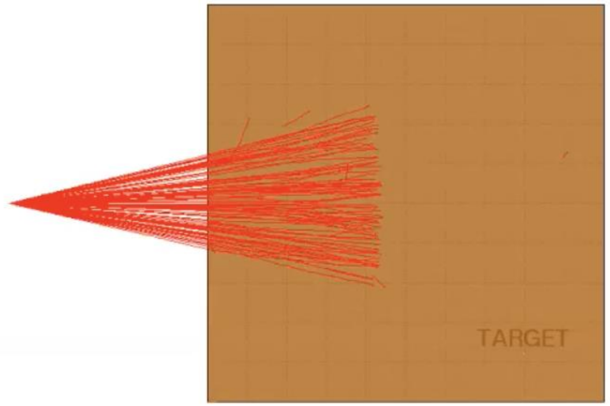
➢ General codes exist for simulating any detector simulation

"Monte Carlo Radiation Transportation Codes"

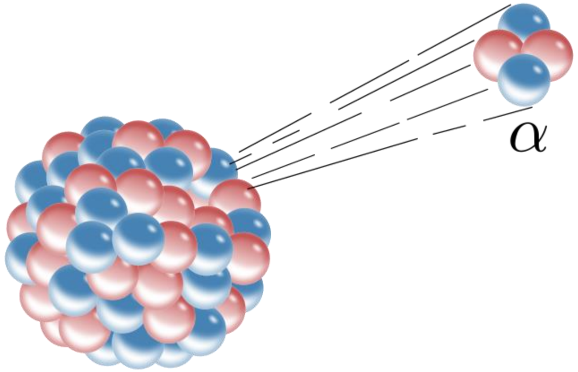
➢ ATLAS, CMS

Basic Ingredients - **(1) Radiation Sources**

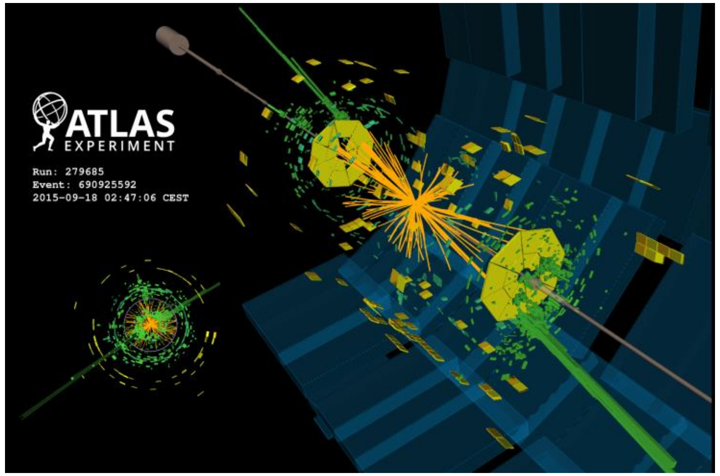
- Particle beam



- Radioactive isotopes



- Particle-Particle Collision



Basic Ingredients - **(2) Geometry**

- Different kind of solids and material can be described in Geant4 by classes.
- Detectors require three main classes:

G4Vsolid – shape, size

G4LogicalVolume – material, sensitivity, user limits, etc.

G4VPhysicalVolume – position, rotation

- CSG (Constructive Solid Geometry) solids
  - G4Box, G4Tubs, G4Cons, G4Trd, …
- Specific solids (CSG like)
  - G4Polycone, G4Polyhedra, G4Hype, ...
- BREP (Boundary Represented) solids
  - G4BREPSolidPolycone, G4BSplineSurface, ...
  - Any order surface
- Boolean solids
  - G4UnionSolid, G4SubtractionSolid, ...

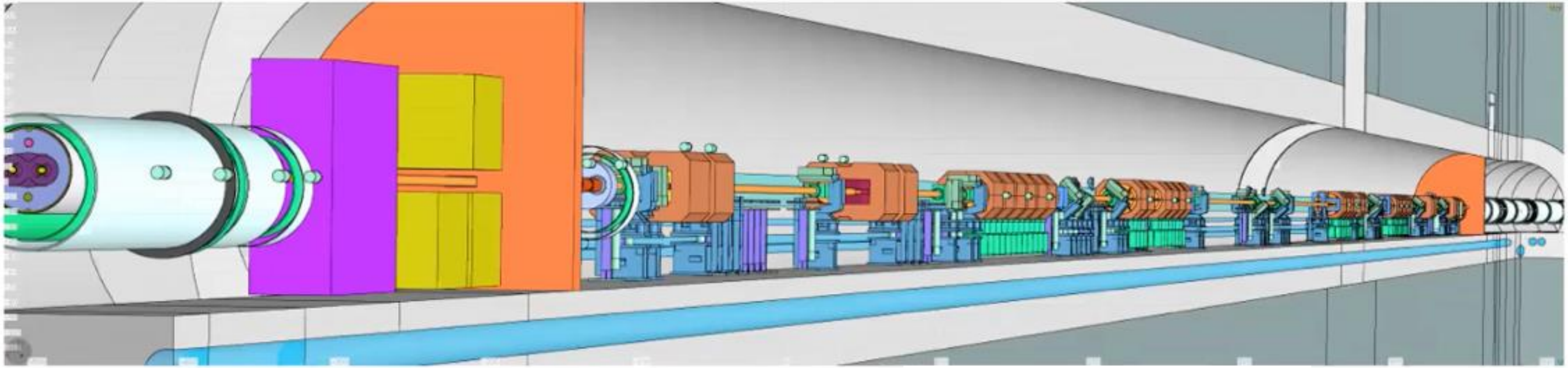
Ex) Constructive solid geometry (CSG)

- ➢ Technique used in solid modeling.
- ➢ Geometric primitives: simplest solid objects used for the representation.

  ex) spheres, cones, pyramids, cylinders, etc.
- ➢ An object is constructed from primitives using Boolean operations

- A material should also be assigned to each volume

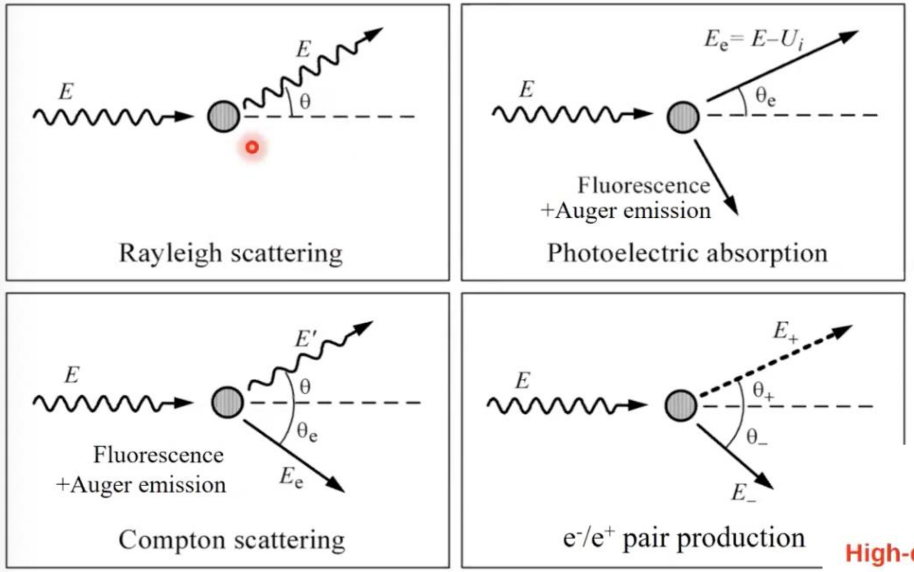
Basic Ingredients - **(2) Geometry**

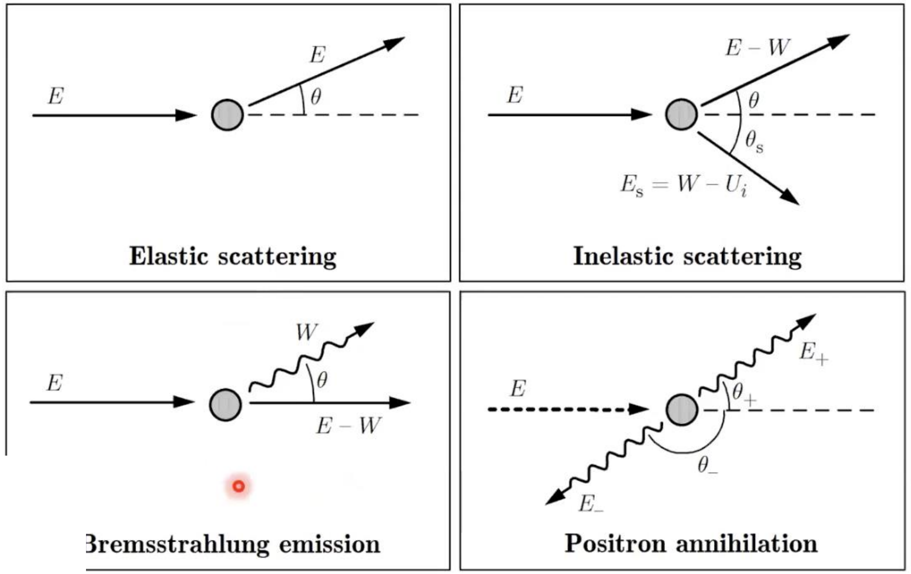


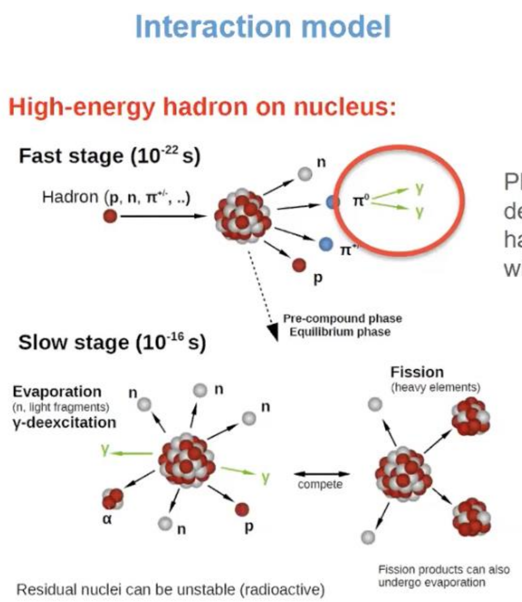
body

body

Basic Ingredients - (3) Radiation-Matter Interactions







Photons from π^0 decay couple hadronic shower with EM shower

And more!

Basic Ingredients - (4) Random Sampling

- We are interested in modeling the radiation transport and the effects of the interactions of radiation with matter.

- Basic quantity to describe radiation is particle density which is number of particles of a species i per unit volume, unit energy, unit solid angle, at a given time.

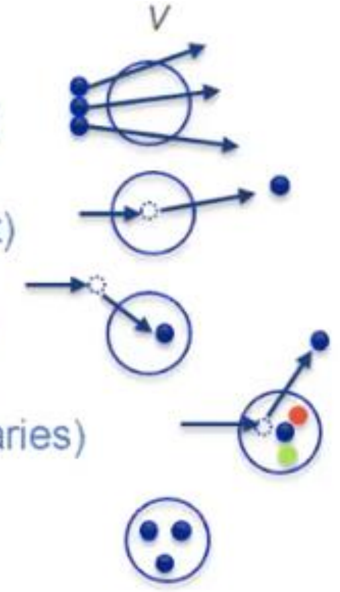
$$n_i(r, E, \Omega, t)$$

r: position, E: energy, Ω: direction, t: time

Basic Ingredients - **(4) Random Sampling**

- Transport equation: determines time evolution of particle density $n_i(r, E, \Omega, t)$ in a small volume V

$$
\begin{aligned}
\int_V \mathrm{d}\boldsymbol{r}\, \frac{\partial n_i(\boldsymbol{r}, E, \Omega, t)}{\partial t} = & -\oint_S \mathrm{d}A\, \mathbf{j}(\boldsymbol{r}, E, \Omega, t)\cdot \hat{\boldsymbol{a}} && \text{(unscattered particles)} \\
& - N \int_V \mathrm{d}\boldsymbol{r}\, n_i(\boldsymbol{r}, E, \Omega, t) v(E) \sigma(E) && \text{(particles scattered out)} \\
& + N \int_V \mathrm{d}\boldsymbol{r} \int \mathrm{d}E' \int \mathrm{d}\Omega'\, n_i(\boldsymbol{r}, E', \Omega', t) v(E') \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega'' \mathrm{d}W''} && \text{(particles scattered in)} \\
& + N \int_V \mathrm{d}\boldsymbol{r} \int \mathrm{d}E' \int \mathrm{d}\Omega' \sum_j n_j(\boldsymbol{r}, E', \Omega', t) v(E') \frac{\mathrm{d}\sigma_{\mathrm{sec},i}}{\mathrm{d}\Omega'' \mathrm{d}W''} && \text{(production of secondaries)} \\
& + \int_V \mathrm{d}\boldsymbol{r}\, Q_{\mathrm{source}}(\boldsymbol{r}, E, \Omega, t) && \text{(source)}
\end{aligned}
$$



Number of target atoms per unit volume (N)

Variation in time of the particle density integrated over a small volume

All the possible effects that can lead to this variation = incoming particles and outgoing particles

Basic Ingredients - (4) Random Sampling

- Transport equation

➢ Integro-differential equation

➢ Analytical/closed solutions only for simplified scenarios

ex) infinite medium, one/few interaction mechanisms, one/few particle species, etc.

- Approach with Monte Carlo!!! It is powerful enough to solve the radiation transport problem for arbitrary radiation sources, complex material geometries and many particle interactions and mechanisms.

Basic Ingredients - (4) Random Sampling

- Computers cannot generate true random number sequences.
- Pseudo-random number generator (PRNG)

➢ algorithm that, given the previous state in the sequence, the next number can be calculated

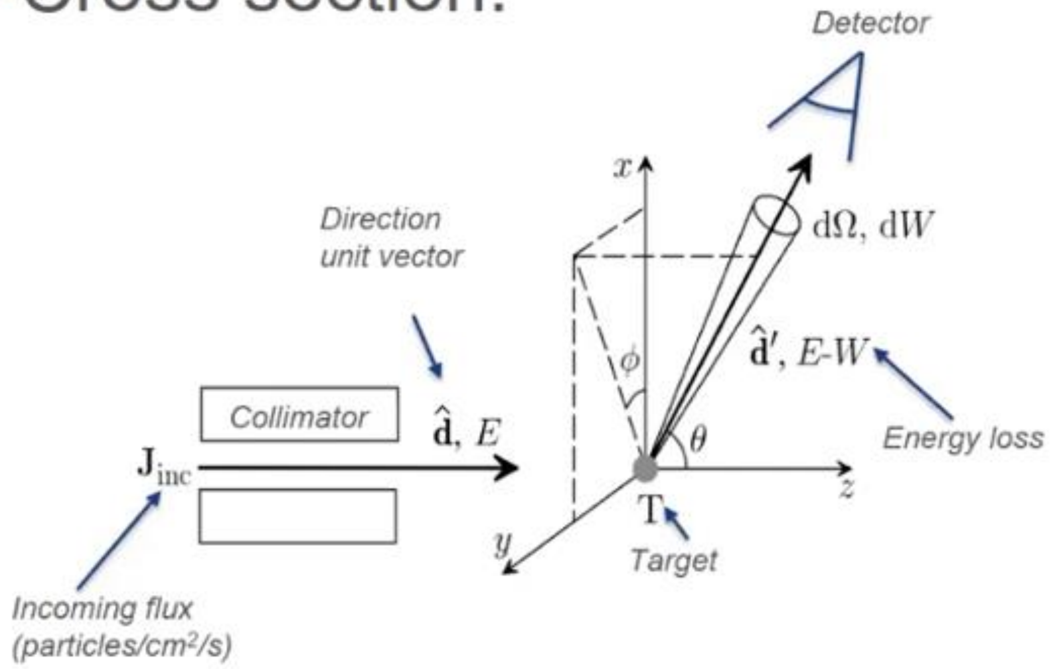
➢ values from 0 to 1

➢ we use PRNG values to sample from partial distribution functions

Basic Ingredients - **(4) Random Sampling**

- Where do we get the partial distribution functions?

Cross section:



Differential cross section

$$\frac{d^2\sigma}{d\Omega\, dW} \equiv \frac{\dot{N}_{count}}{|\mathbf{J}_{inc}|\, d\Omega\, dW}$$

Dimensions: Area / Energy / Solid angle

~likelihood of being scattered into a direction Ω with an energy loss W

Cross section

$$\sigma \equiv \int\int \frac{d^2\sigma}{d\Omega\, dW}\, d\Omega\, dW$$

Dimensions: Area
Typical unit: 1 barn ($=10^{-24}$ cm^2)

~likelihood of being scattered

Basic Ingredients - (4) Random Sampling

- Consider a medium with $\mathcal{N}$ atoms per unit volume

➢ mean free path $\lambda = \frac{1}{\mathcal{N}\sigma}$ is a quantity with units of length that gives the average distance to the next interaction

➢ PDF of the mean free path length is given by

$$p(s) = \mathcal{N}\sigma \exp\left[-s\left(\mathcal{N}\sigma\right)\right]$$

Basic Ingredients - (4) Random Sampling

- Inverse-Transform Method

➢ CDF of the PDF:

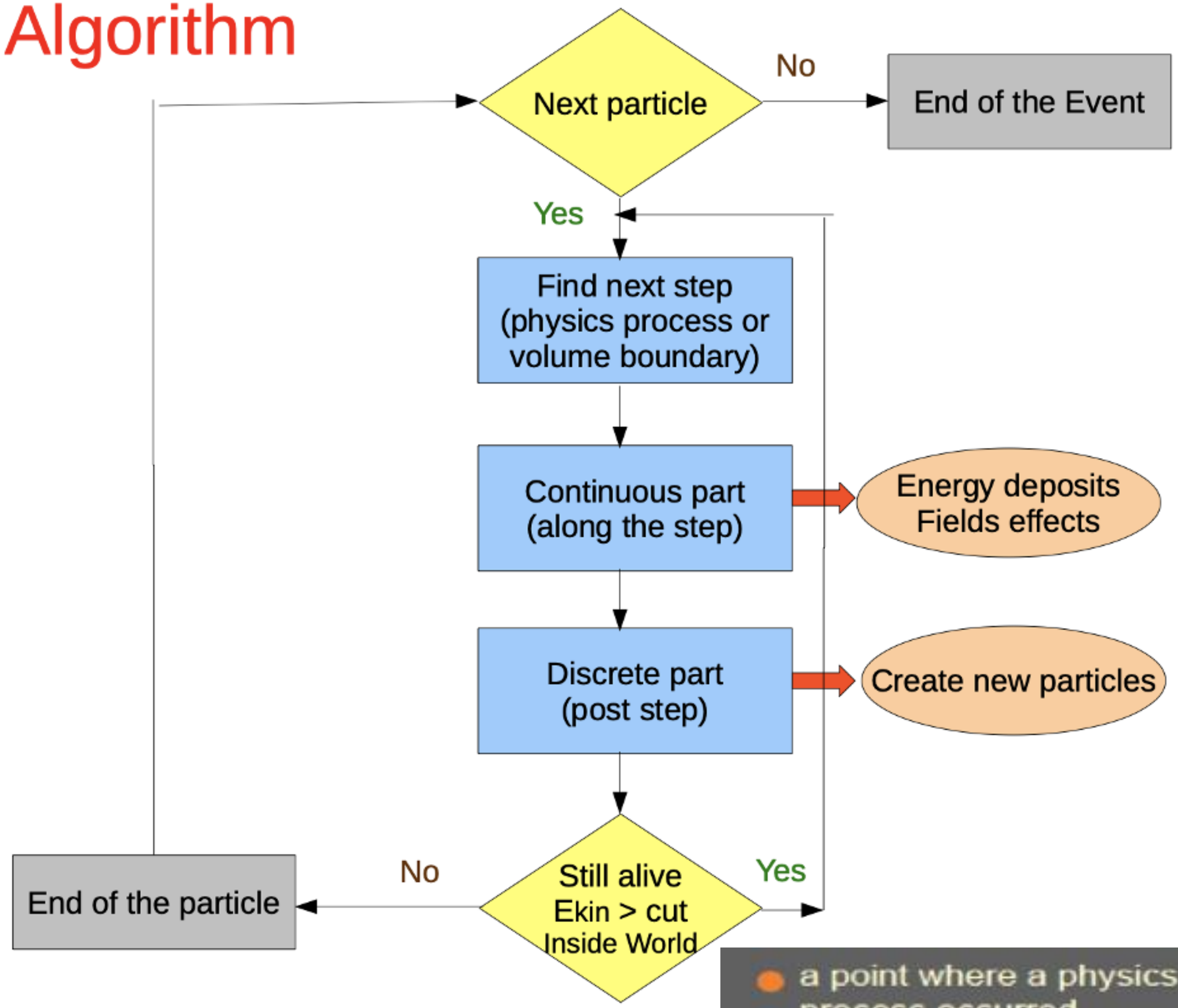
$$\mathcal{P}(x) \equiv \int_{x_{\min}}^{x} p(x')\,\mathrm{d}x'$$

➢ $A = \mathcal{P}(x)$ defines a random variable distributed uniformly in the interval (0,1)

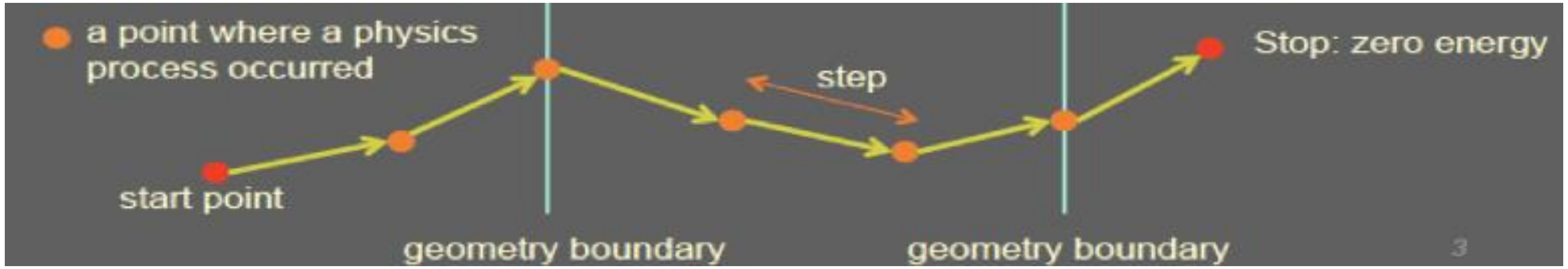
➢ We can calculate $x = \mathcal{P}^{-1}(A)$ as an inverse function by generating random numbers A

➢ Therefore, we can obtain the mean free path of a particle to the next interaction!!

Algorithm



Next particle
No
End of the Event
Yes
Find next step (physics process or volume boundary)
Continuous part (along the step)
Energy deposits Fields effects
Discrete part (post step)
Create new particles
Still alive Ekin > cut Inside World
Yes
No
End of the particle



a point where a physics process occurred
step
Stop: zero energy
start point
geometry boundary
geometry boundary

Accuracy vs Speed

- The simulation time is dominated by the detector simulation.

➢ More accurate physics models are slower and, more importantly create more secondaries and/or steps.

➢ Smaller geometrical details slow down the simulation.

ex) screws, bolts, cables, etc.