Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

Detector Simulation with GEANT

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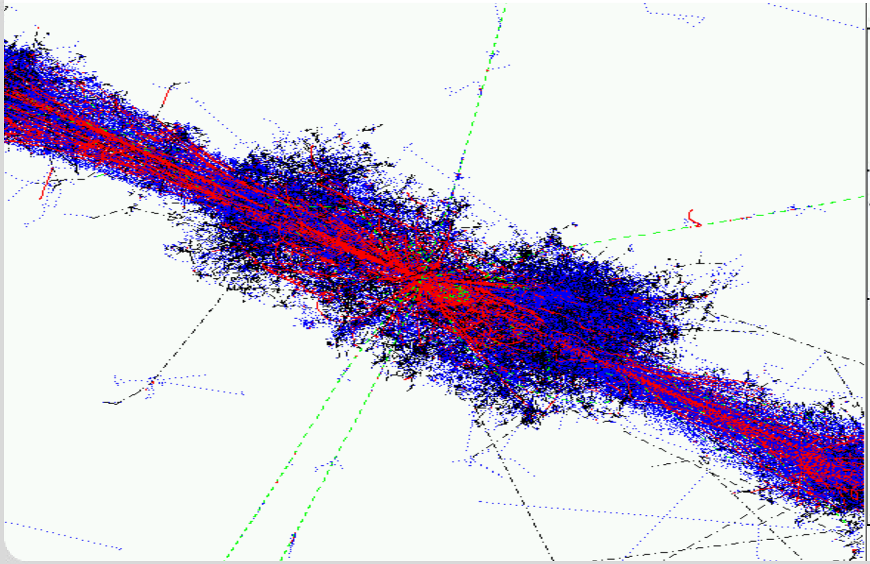
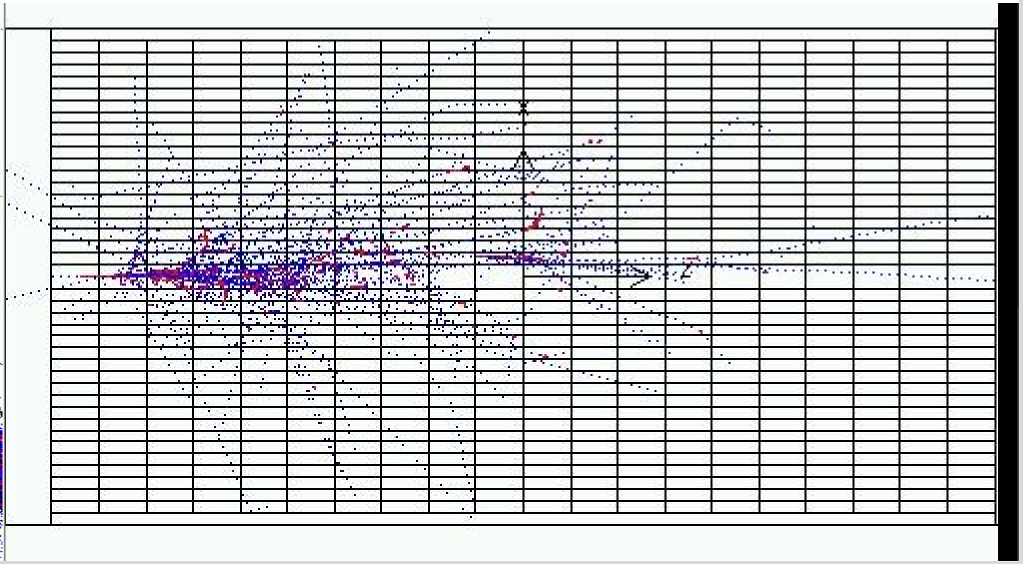




Introduction

Before building (expensive) prototypes of new detectors,
detailed **„simulations“** are performed

Expected observations in an experiment are also
determined via **simulations:**

- underlying physics:
  from Feynman diagram to stable Particles in a detector:
  * **several steps:**
    1. theoretical calculation
    2. „event generator“: production of single events with Monte Carlo method
    3. hadronization (i.e. non-perturbative effects in transition from quarks & gluons → hadrons) [1. - 3. will be dealt with later !]

4. tracking of all stable particles through the detector

simulation of reactions in material as well as
the production of new particles, also in showers
(very compute-intense task !!!)

This last step is the „detector simulation“

Monte Carlo Method

... using detecor simulation as an example:

{ – trace path of ervery particle delivered by event generator

– calculate quantum mechanical interaction probability for every possible (and relevant) procss in volume elements of the detector

– draw a corresponing random numbers to select a process
evaluate chosen process, for example
- additional photon from bremsstrahlung or a charged particle
- deflection of (charged) particle
- energy loss via ionisation
- pair-production, Compton effect or photoeffekt for photons
- nuclear interaction
- production of Cerenkov light
- etc …

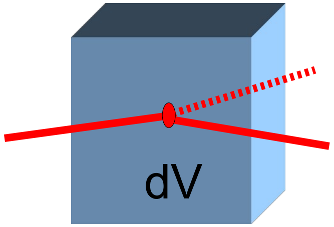
– generate corresponding “detector hits”, depening for example on the enerty deposit in a volume element

Result: simulated detector signal of an event

} **– repeat simulation for a large number of events**

→ Determination ot the statistical distribution of numbers of produced particles and deposited energy and quantities derived from it

Principle of detector simulation



Tracing of all interactions of particles

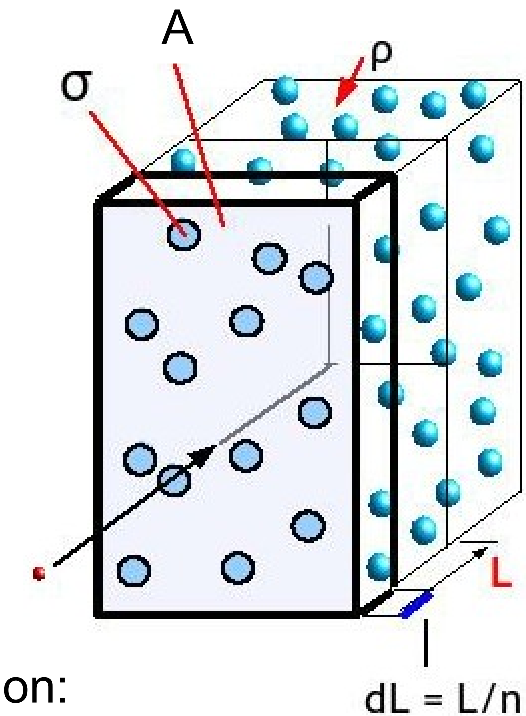
starting poing:
one interaction of a **single particle**
in volume element $dV = A\, dL$

interaction probability w depends on

- cross section σ for a process and
- the number N of t tartets in volume element

$$dN = A\, dL\, \rho\, N_A / m_{Mol} = \rho_n\, A\, dL$$

$$\rightarrow \quad dw = \rho_n\, \sigma\, dL$$



probability to travers a fraction of the distand L/n without any interaction is

$$1 - dw = 1 - \rho_n\, \sigma\, L/n$$

prabability , probability to traverse length L witout interaction:

$$P_{wo} = (1 - \rho_n\, \sigma\, L/n)^n \quad \rightarrow \quad \exp(-\rho_n\, \sigma\, L)$$

$P_{wo}(L)$ is the free pathlength in the material

Principle of detector simulation (2)

By differentiation one obtains from P_{wo} the probability density for the traversed path to the first interaction

$$w(L) = \rho_n \sigma \exp\left(-\rho_n \sigma L\right) = \frac{1}{\lambda} \exp\left(-L/\lambda\right)$$

$\lambda = (\rho_n\, \sigma)^{-1}$: **interaction length**

The **interaction length** in materials with several components is given as the invere sum over densities and cross-sections:

$$\lambda = \left(\sum_j [\rho_{n_j} \sigma(Z_j, E)] \right)^{-1} = \left(\sum_j \frac{1}{\lambda_j} \right)^{-1}$$

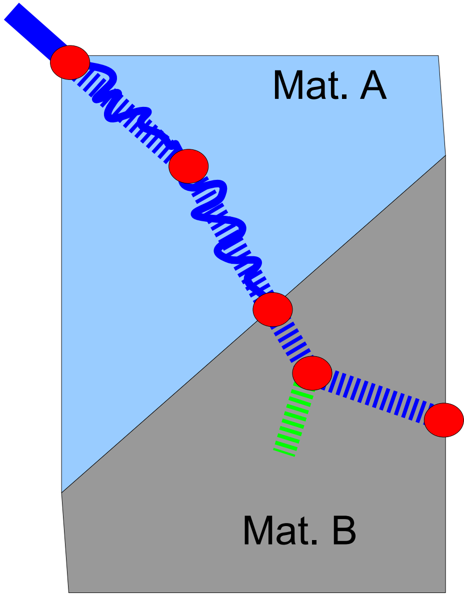
λ is the most important material quantity.

Clearly, λ depends on the kind of process considered

Principle of detector simulation (3)

a simple algorithm for tracing of particle interactions:

1. select a particle to trace from particle list
2. set initial parameters of the particle *(type, location, four-momentum)*
3. calculate λ from ρ_n and σ for given material
4. draw random path lenth L accorind to density $w(L)$
5. propagate particle by distance L or to next material boundary,
   taking into account multiple scattering an deflection in external fields
6. if still in same material:
   let process happen at this location
   – add newly created particle(s) to particle list
   – if original particle still exists:
     energy greater than given "cut-off" energy ?
     ? yes: go to 2.
     ? no: done with this particle, remove from list, go to 1.



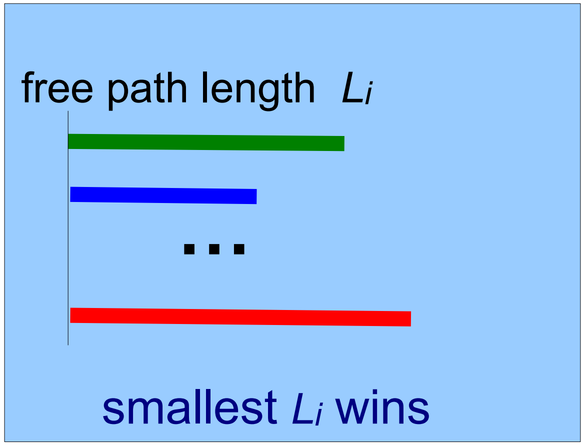
possibly need additional random values from probability distributions:
– energy loss of particle,
– new parameters of particle at the end of this step
– initial parameters of newly created particles

Principle of detector simulation (4)

If there are **several processes** *1, …, p*:

1., 2. as above

3.' determine all interacction lenghts $\lambda_1, \dots, \lambda_p$
4.' draw k random mumbers L_k
and determin $L_i = \min(L_k)$, $1 \leq i \leq k$
5.' propagate particle by distance L_i
6.' let process i happen



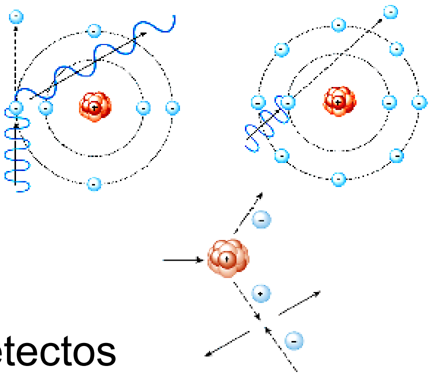
Detector Simulation

hence we need:

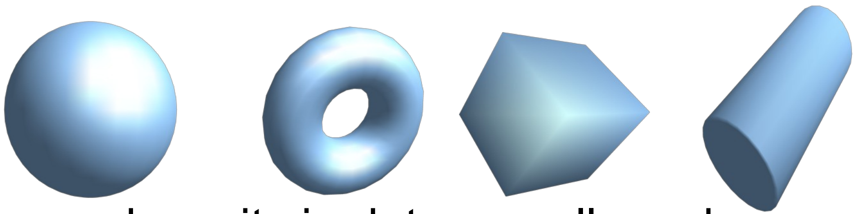
– a list of relevant processes for each particle type
(for short-lived particles, their decay also is such a process)

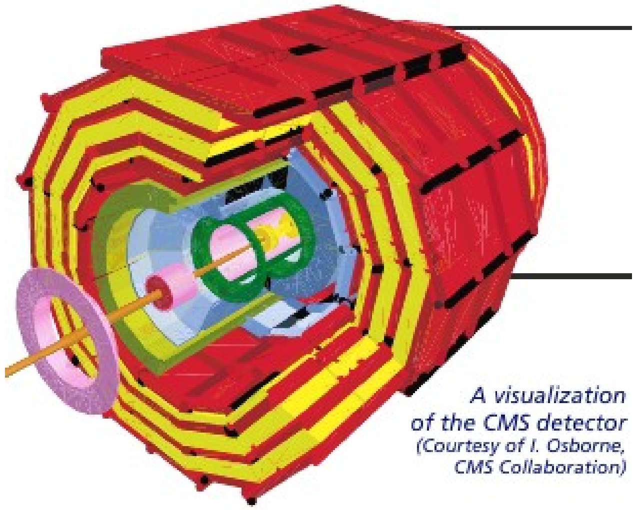
– properties of all materials:
density and cross section for every process depending on particle and material types

– transport rules for particles in materials and fields



– Boundaries between materials
→ geometry of detector volumes, description of complex detectos





A visualization of the CMS detector (Courtesy of I. Osborne, CMS Collaboration)

– storing of energy deposits in detecor cells and simulation of the amount of produced charge or light

– for short-lived particles:
lists of lifetimes and branching ratios

This and a lot more is provided by the simulation package GEANT

The Simulation Package GEANT

Geant 4 - a world-wide collaboration

- open-source tool-kit from particle physics
- Definition of geometry and material properties
- Tracking of a large number of particles in materials,
  with a large number of selectable interaction processes
- Visualisation
- Open interfaces for input and output
  storage of all generated data („persistency“)

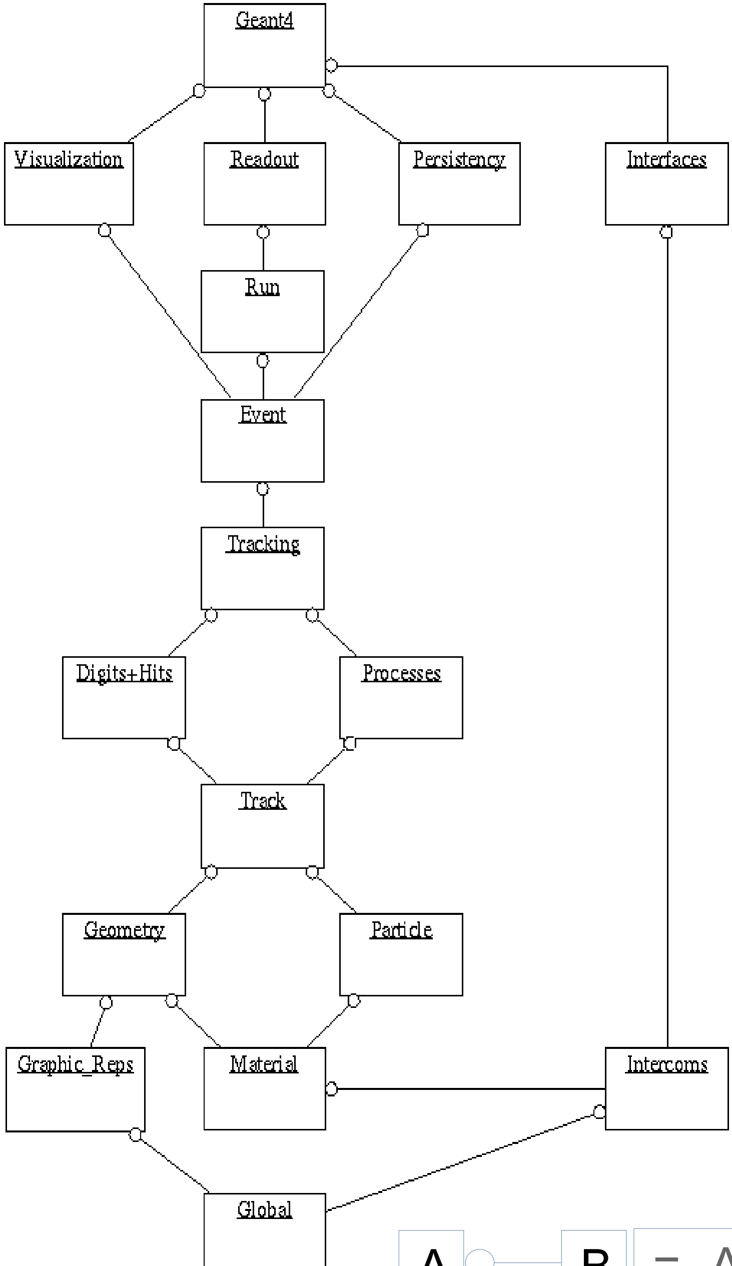
Begining in 1994 as a development project, first release 1998
predecessor: Geant 3 (FORTRAN package),

Applications in nuclear and particle physics, astrparticle physics, medicin and others

see http://geant4.cern.ch/
documention, tutorials, code …

for this course: pre-compiled installation package for
Geant 4 with python interface (Bachelor Thesis M. Burkart)

Structure of Geant 4



Geant-Code is organized in „class categories“

- *Run and Event*
  Generation of events, interface to event generators, production of secondary particles
- *Tracking and Track*
  Propagation of partices in materials and fields
- *Gemometry and Magnetic Field*
  Definition of detector geometry, Interface to CAD systems
- *Particle Definition and Matter*
  Definition of particles and materials
- *Physics*
  Modelling of interactions of particles with materials
- *Hits and Digitisation*
  Generation of „Hits“ (= energy depositions in material), Simulation of detector response
- *Visualisation*
  graphical display of volumes, tracks and hist
- *Interfaces*
  User interface, interfaces to external software,

A B = „A depends on B“

Own Geant applications

Geant4 is a very powerful and hence complex tool
→ familiarization requires some time

Geant4 is used in all particle physics experiments for

– the design of detectors prior to construcion or proto-typing

– the generation of „simulated data" for the developtmet of reconstruction software

– the understaning of signatures resulting from „known" physics

– the determination of the detector response to scenarios of new physics

– as training input to deep-learing algorithms

Simulated data
are extremely important in every phase of an experiment.

Geant 4

European Organization for Nuclear Research

Geant4

A toolkit to simulate the interaction of particles with matter

Collaborators also from non-member institutions, including
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MEPHI Moscow

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Concept

Geant4 simulates the passage of particles through matter.
It provides a complete set of tools for all domains of radiation transport:
- Geometry and Tracking
- Physics processes and models
- Biasing and Scoring
- Graphics and User Interfaces
- Propagation in fields.

A visualization of the CMS detector (Courtesy of I. Osborne, CMS Collaboration)

http://geant4.web.cern.ch/sites/geant4.web.cern.ch/files/geant4/gallery/fullsize/geant4-poster.pdf