GEANT4 in a NUTSHELL

LCD group seminar
Peter Speckmayer
4. August 2009

How does GEANT4 work?

What is simulated in there?

Outline / elements of GEANT4

- Geometry
- Events
- Tracking
    - Step length
    - electromagnetic fields
    - range cut
- Physics processes
    - Electromagnetic processes
        - Multiple scattering
        - Energy loss
    - Hadronic Processes
        - Modeling of final states
- Physics lists

What is Geant4?

- Simulation of interactions of particles with matter

- A toolkit → (user has to wrap code around)
  - Geometry
  - Digitization

- Aim of G4 design:
  - Flexibility
  - Customizable
  - extendable

Geometry

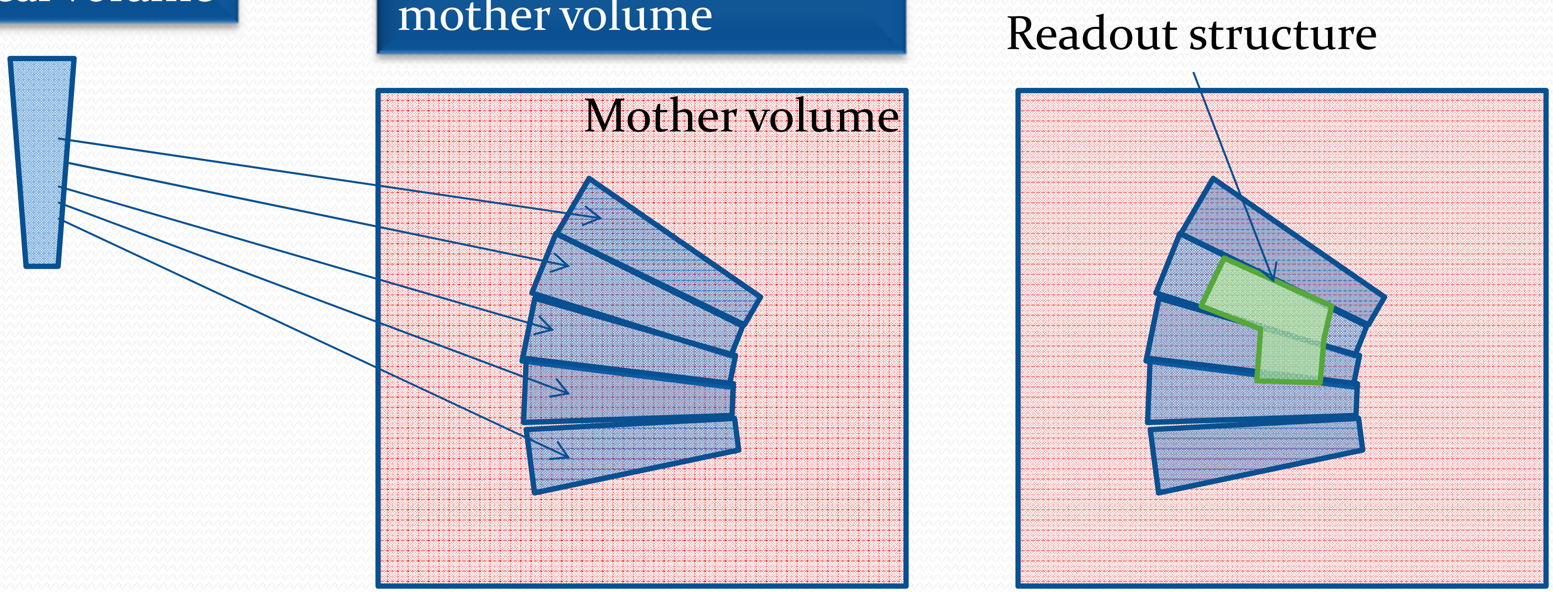
- Description of the detector
  - efficient navigation of particles
- Volumes defined by user with code
  - typically experiments wrap interface around (e.g. compact.xml)
- sensitive “logical volumes” for readout → linked with user defined class for detector response (digitization)

Geometry (detector description)

Logical volume

Logical volumes become "physical" when placed into a mother volume

Readout structure can be different from detector structure



Events

- Event → main unit of simulation

- Before being processed:
  - Primary particles
  - Vertices

- Afterwards:
  - Hits
  - Digitizations (response of parts of the detector)
  - (simulation truth)

Tracking

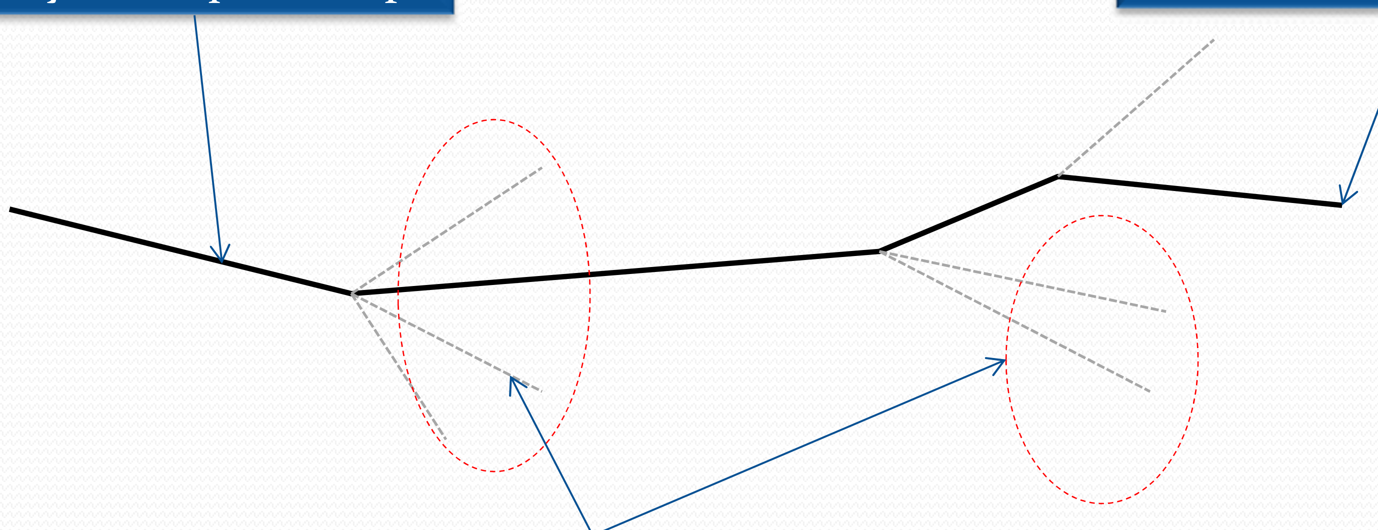
- *Event* → consists of many tracks
- *Track* → "a transported particle"
  - consists of many *steps*
- *Step* → smallest unit

- Particles → not "self moving"
  - Particles are "transported"
  - *transportation* is a (physics)*process* like decay, pair production, …

Tracking

Track:
many subsequent steps

when one track is finished, next particle is taken from the stack



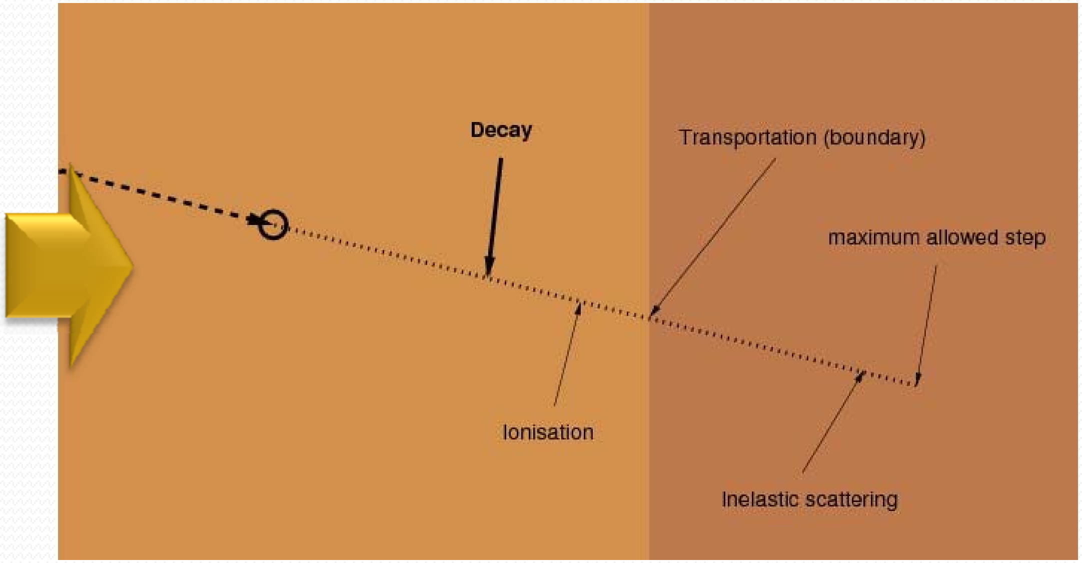
Secondaries:
put into a stack

(three stacks: → prioritize tracks
uninteresting tracks can be suppressed → performance)

Tracking / Step

- all processes propose step length
- shortest one is taken (e.g. decay)

- “post step action” of the limiting step is called



- for particles at rest → a time is proposed

- for processes where energy is lost continuously → preservation of precision is the limiting factor

- tracking decides which processes are invoked → process can demand to be invoked always (e.g. transportation, multiple scattering)

Tracking/ calculating the step length

- Physics processes are associated to every particle
- Each process proposes a step length

probability of not interacting within L

λ .. mean free path

$$P(L) = \exp\left(-\int_0^L \frac{dl}{\lambda(l)}\right) = \eta$$

$$\int_0^L \frac{dl}{\lambda(l)} = -\ln \eta$$

decay:
τ .. mean lifetime
ν .. velocity
γ .. Lorentz factor

$$\frac{L}{\gamma \nu \tau} = -\ln \eta$$

interaction with material:
(composed of isotopes)
ρ .. density of the material
m_i .. mass of the isotope
x_i .. the mass fraction
σ_i .. cross-section of process for this isotope

$$\lambda = 1/\left(\rho \sum_i x_i \sigma_i / m_i\right)$$

$$L\rho \sum_i x_i \sigma_i / m_i = -\ln \eta$$

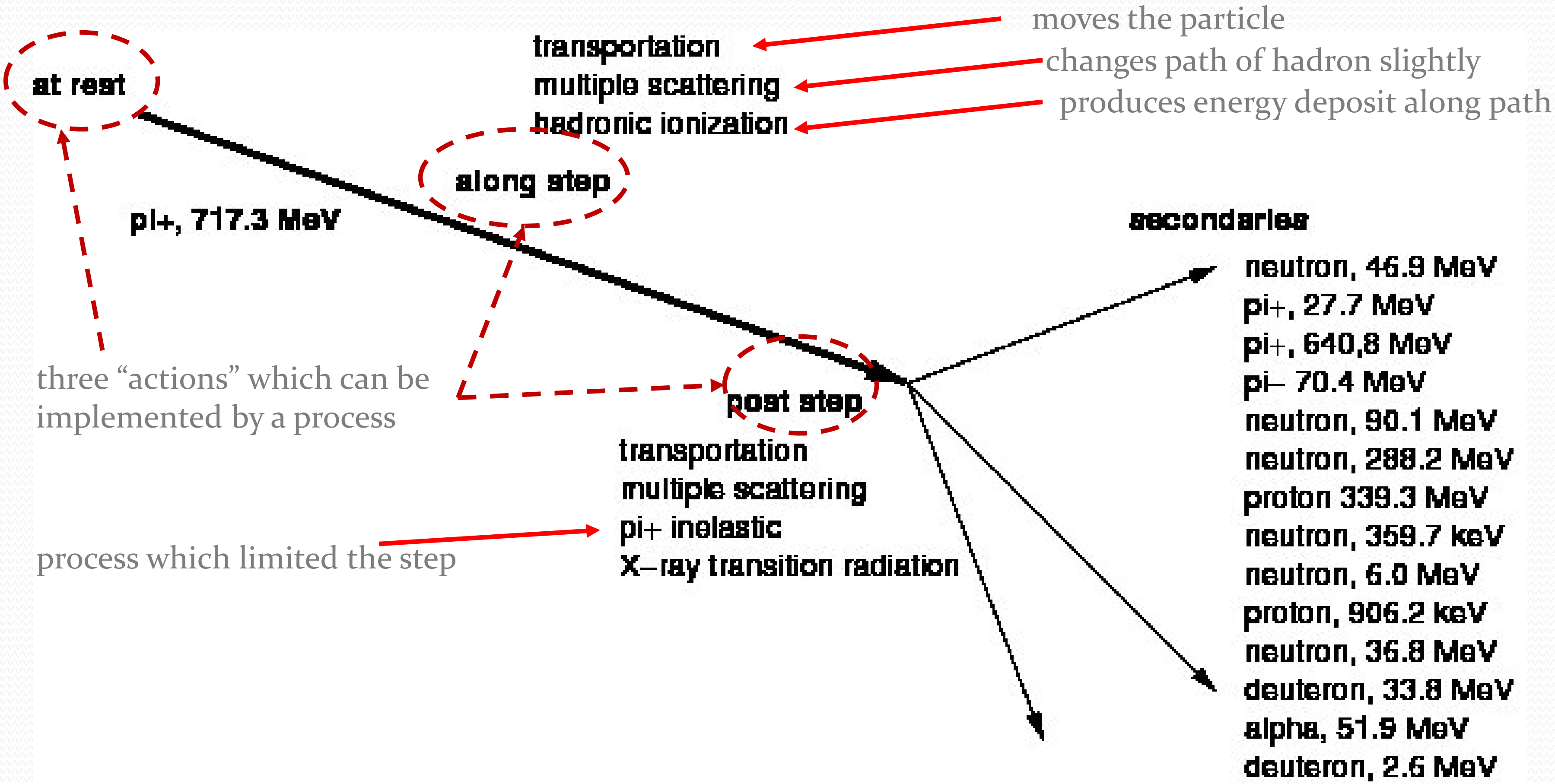
random number [0,1] is thrown → η
length until decay or interaction L is computed

-"transportation"-process → L = length to next boundary
- step as well limited by user defined "maximum allowed step"

Tracking / electromagnetic fields / range-cut

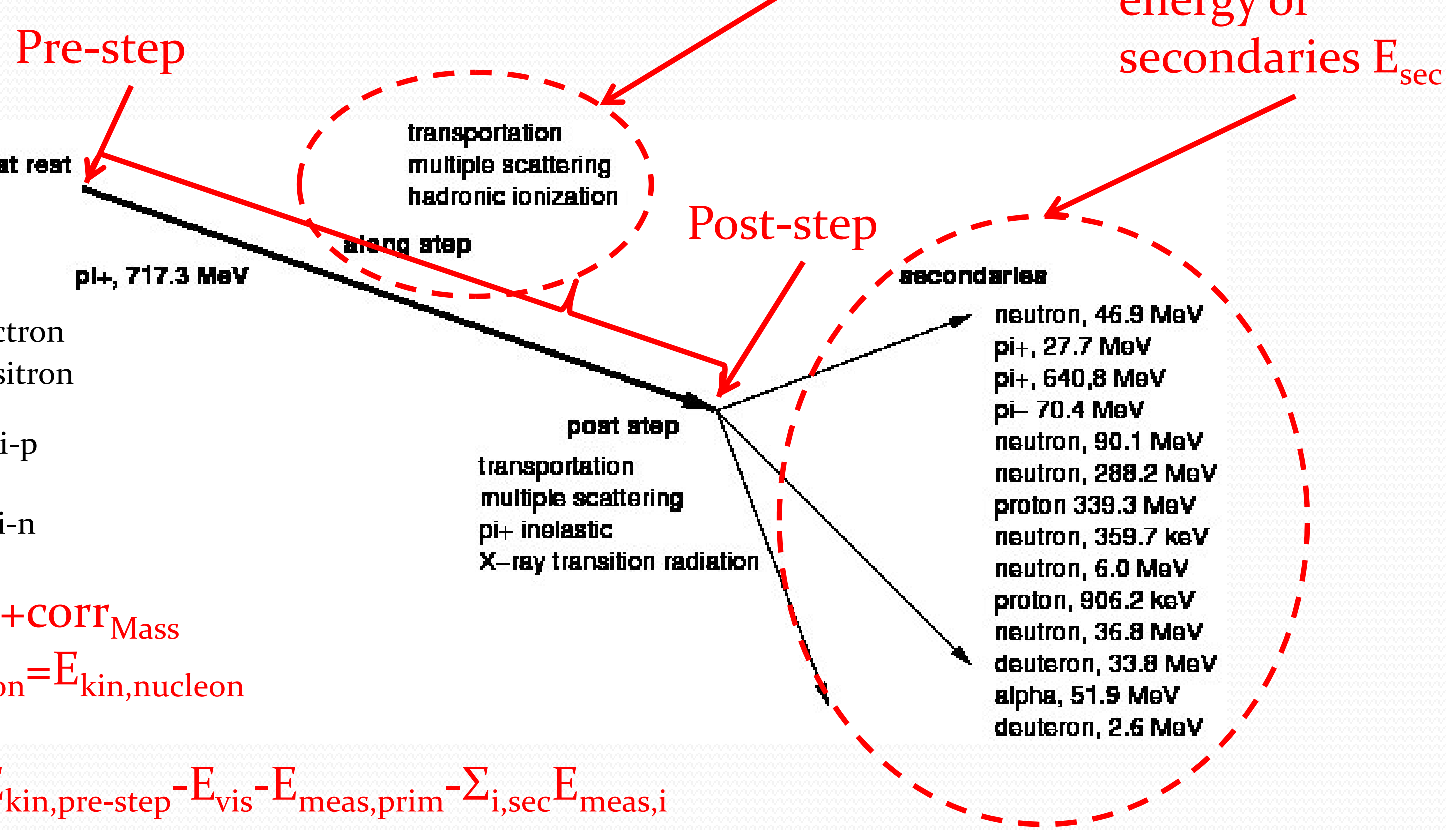
- electromagnetic fields
  - non-linear propagation of charged particles
  - trajectories are computed numerically
  - method used (e.g. Runge-Kutta, helix) depends on smoothness of field
  - intersection with boundaries → chord-approximation
- range-cut
  - particles with short range (less than user defined) are not generated → energy deposited
  - avoids generating many soft photons and e-
  - ranges → in tables (calculated once at G4 startup)

A real MC life example for one step



Visible and invisible energy

- (not part of Geant4)



$$corr_{Mass} = \begin{cases} -m_{e^-} : \text{electron} \\ +m_{e^-} : \text{positron} \\ -m_p : \text{p} \\ +m_p : \text{anti-p} \\ -m_n : \text{n} \\ +m_n : \text{anti-n} \end{cases}$$

$E_{meas} = E_{tot} + corr_{Mass}$

$E_{meas,nucleon} = E_{kin,nucleon}$

$E_{invisible} = E_{kin,pre\text{-}step} - E_{vis} - E_{meas,prim} - \Sigma_{i,sec} E_{meas,i}$

Physics processes and models

- *Process* → specific physical interaction of a particle
- → initial state, final state, cross-section/mean lifetime

- detailed interaction → controlled by a *model*
  - secondaries, kinematics
  - model can be changed easily

- several processes assigned to particle type (energy range)

- Types of processes
  - Decay
  - Electromagnetic processes
  - Hadronic processes
  - Optical processes

Particle decays …

- decay tables in GEANT4 from PDG

- complex decays (e.g. B mesons) are not modeled
  - interface to external event generators provided
    - Geant4 talks to external program, external program calculates decay
  - pre-assigned decay mode
    - event generator simulates decays
    - G4 uses these data when needed

  - what we do?
    - … is slightly different → we provide G4 only with particles which it can handle

Electromagnetic processes

- for interactions of: e-, e+, photons, charged hadrons
- effects of shell structure of atoms are averaged
  - loss of precision (when shell effects are important)

- photons:
  - Compton scattering
  - conversion into electron and muon pairs
  - photo-electric effect

- e- and e+:
  - bremsstrahlung
  - ionization
  - δ-ray production
  - e+ annihilation
  - synchrotron radiation

Electromagnetic processes (2)

- additions in the low energy region (examples)
  - photoelectric effect
  - Compton scattering
  - Rayleigh scattering
  - flourescence emission from excited atoms
  - Auger effect
  - corrections due to the molecular structure of materials
  - corrections due to the effect of the nuclear stopping power
  - Barkas effect

- electromagnetic processes producing hadrons
  - photonuclear and electronuclear reactions
    - → can convert electromagnetical energy flow (e-, e+, photons) to energy flow of mesons, baryons and nuclear fracments
  - hadron production by nuclear interaction of muons

Multiple scattering

- calculated for one step
  - → angular deflection
  - → mean path length correction
  - → mean lateral displacement

- simulated for all charged particles

Energy loss

- e+ and e- → contributions are summed up
  - continuous → ionization, bremstrahlung
  - discrete → Moeller & Bhabha scattering, δ-ray production, hard bremsstrahlung
- muons
  - ionization, bremsstrahlung, pair production
- charged hadrons
  - ionization (including hard δ-ray production)
- mean energy loss is computed, fluctuations are added
- ionization of ions and hadrons:
  - model depends on energy range:
    - >2MeV → Bethe-Bloch formula
    - <1keV → free electron gas model
    - intermediate range → parameterizations based on experimental data

Hadronic processes

- thermal neutrons (0.025eV) → 7TeV → cosmic ray physics
- total cross-sections → parameterized as a function of atomic weight and energy
  - elastic scattering
  - inelastic scattering
  - capture of neutral particles
  - induced fission
- cross-sections: data-driven + theory based approaches for extension to high E and interpolation in regions without data

Modeling of final states

- three possibilities
  - data
  - parameterizations and extrapolations of data
  - theory-driven models

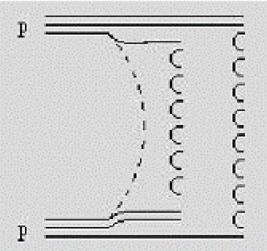
- **data**
  - preferred
  - but not always available → high energies, short life-times, strange baryons, various target materials
  - used mainly for
    - isotope production (induced by n, p), transport of n (low E), photon evaporation (low E), radioactive decay, absorption of particles coming to rest

Modeling of final states

- **parameterized models**
  - mostly rewritten from Geant3 (GEISHA)
  - parameterized:
    - momentum distributions
    - angular distributions
    - extrapolations of cross-sections
  - exist for many reactions and the full range of energies
  - possibility to tune
  - examples:
    - induced fission for n, capture of n, elastic scattering, inelastic final state production, ...

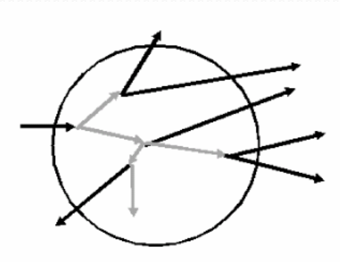
Modeling of final states

- **theory-based models**
  - allow for better extrapolation to energies not assessed in testbeams
  - interactions of hadrons with a nucleus at high E final states (E_{CMS}>O(5GeV))
    - diffractive string excitation model (Fritiof like):
      - the particles which are scattered only exchange momenta. For each of the scattered particles a string is formed where the quark content of the original hadron is randomly assigned to the string ends.
    - quark gluon string model:
      - the quark gluon string model splits a nucleon into a quark and a di-quark. Between those, strings are formed and hadroniyed (by adding a qqbar-pair). The color flow between partons from the interacting particles and the hadron-nucleon interactions are mediated by the exchange of Pomerons.



Modeling of final states

- **theory-based models**
  - intra-nuclear cascade models (E_{CMS}<O(5GeV))
    - Binary cascade model
    - Bertini cascade model
      - step-like concentric nuclear potential
      - projectile transported along straight lines
      - cross sections from data

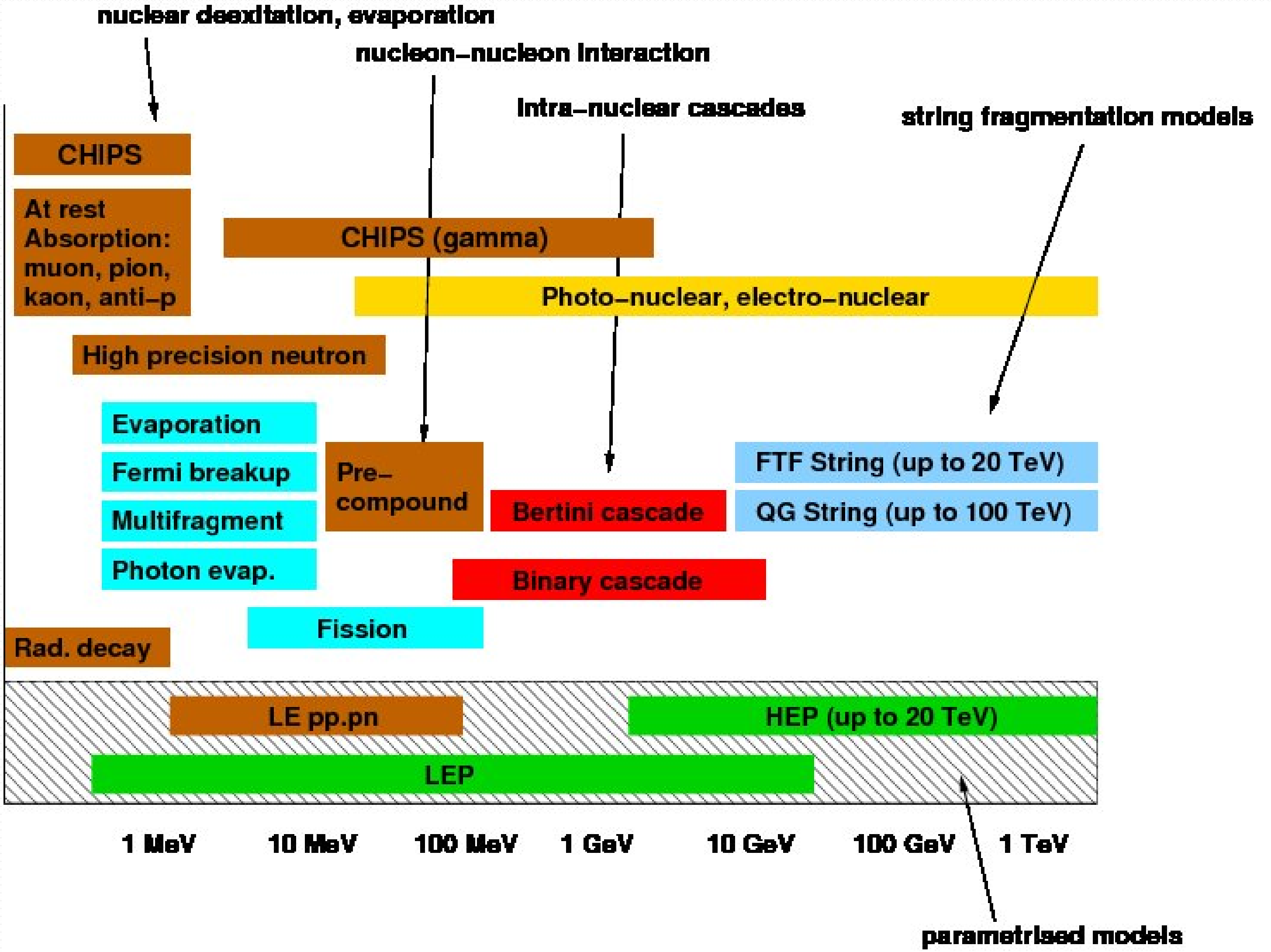


  - for E_{CMS}<O(100 MeV)
    - exciton based pre-compound models available
    - soften the steep quasi-elastic peaks
  - evaporation phase
    - models describe behaviour of excited, thermalised nuclei
      - Weisskopf-Ewing model, Fermi breakup model, multifragmentation, fission
  - atomic relaxation
  - (alternative: CHIPS → thermodynamic approach for fragmentation of excited hadronic systems into hadrons)

Optical processes

- in Geant4 → photons with wavelength >> atomic spacing are called "optical"
- optical properties of a medium can be given as a function of photon wavelength
- implemented processes:
  - Cerenkov process
  - Scintillation: user can define light yield, photon emission spectrum, ...
  - Absorption and Rayleigh scattering
  - Reflection and Refraction → optical boundaries can be defined by the user
  - Transition radiation

Physics processes, overview



Physics lists

- G4 collaboration provides compilations of consistent sets of models → physics lists
- electromagnetic simulations well known → accurate simulations
- modeling of hadrons worse

- LEP and HEP used as fallback solutions and for particles and regions where no other models are defined

- High energy → QGS, FTF

- Transitions between models in different E-regions → smoothed out → continuous transition between models (e.g. QGS to Bertini cascade)

- Physics lists to be mentioned:
  - LHEP
    - old G3 (GEISHA) parametrizations → problematic (energy in processes not conserved, etc.)
    - low energies: LEP, high energies: HEP
  - LCPhys
    - QGS (with precompound) above 12 GeV, LEP between 9.5 to 25 GeV, 0-9.9 GeV Bertini cascade
  - QGSP_BERT
    - QGS (with precompound) above 25 GeV, LEP between 25 and 10 GeV, below that: Bertini cascade
  - FTF_BIC
    - Fritiof with precompound above 5 GeV, below that: Binary cascade → no LEP, no HEP for pi and p

Summary

- GEANT4 is very modular and flexible
  - changes of models for physics processes possible
    - → but: should be done together with GEANT4 collaboration, since set of chosen models should be consistent
- GEANT4 performs good for electromagnetic processes
- GEANT4 gives you results for hadronic processes
  - certainly less accurate than for the electromag. processes
  - has to be validated for the material which is used
  - physics list? → no clear favourite, … again: validation necessary
- Which physics list to choose?
  - QGSP_BERT is used the LHC-experiments
  - LCPhys is used in ILC community (seems to be rather similar to QGSP_BERT)
  - FTF_BIC is complementary to QGSP_BERT → good crosscheck