Introduction to Geant4 Physics Overview

Koi, Tatsumi
SLAC SCCS

Based on Presentations at SLAC Geant4 Tutorial 2007

Outline

- Geant4 Physics Overview
- Process
- Physics List
- Standard EM
- Low Energy EM
- Hadron Physics
- Cuts, Decay and Optical
- Event biasing

Geant4 Physics

- Geant4 provides a wide variety of physics components for use in simulation
- Physics components are coded as processes
  - a process is a class which tells a particle how to interact
  - user may write his own processes (derived from Geant4 process)
- Processes are grouped into
  - electromagnetic, hadronic, and decay categories

Geant4 Physics: Electromagnetic

- standard – complete set of processes covering charged particles and gammas
  - energy range 1 keV to ~PeV
- low energy – specialized routines for e+, e-, g, charged hadrons
  - more atomic shell structure details
  - some processes valid down to 250 eV or below
  - others not valid above a few GeV
- optical photon – only for long wavelength photons (x-rays, UV, visible)
  - processes for reflection/refraction, absorption, wavelength shifting, Rayleigh scattering

Geant4 Physics: Hadronic

- Pure hadronic (0 - ~100 TeV)
  - elastic
  - inelastic
  - capture
  - fission
- radioactive decay
  - at-rest and in-flight
- photo-nuclear (~10 MeV - ~Tev)
- lepto-nuclear (~10 MeV - ~Tev)
  - e+, e- nuclear reactions
  - muon-nuclear reactions

Geant4 Physics Decay and Parameterized

- Decay processes include
  - weak decay (leptonic decays, semi-leptonic decays, radioactive decay of nuclei)
  - electromagnetic decay (π^0 , etc. decay)
  - strong decays not included here (they are part of hadronic models)
- Parameterized processes
  - electromagnetic showers propagated according to parameters averaged over many events
  - faster than detailed shower simulation

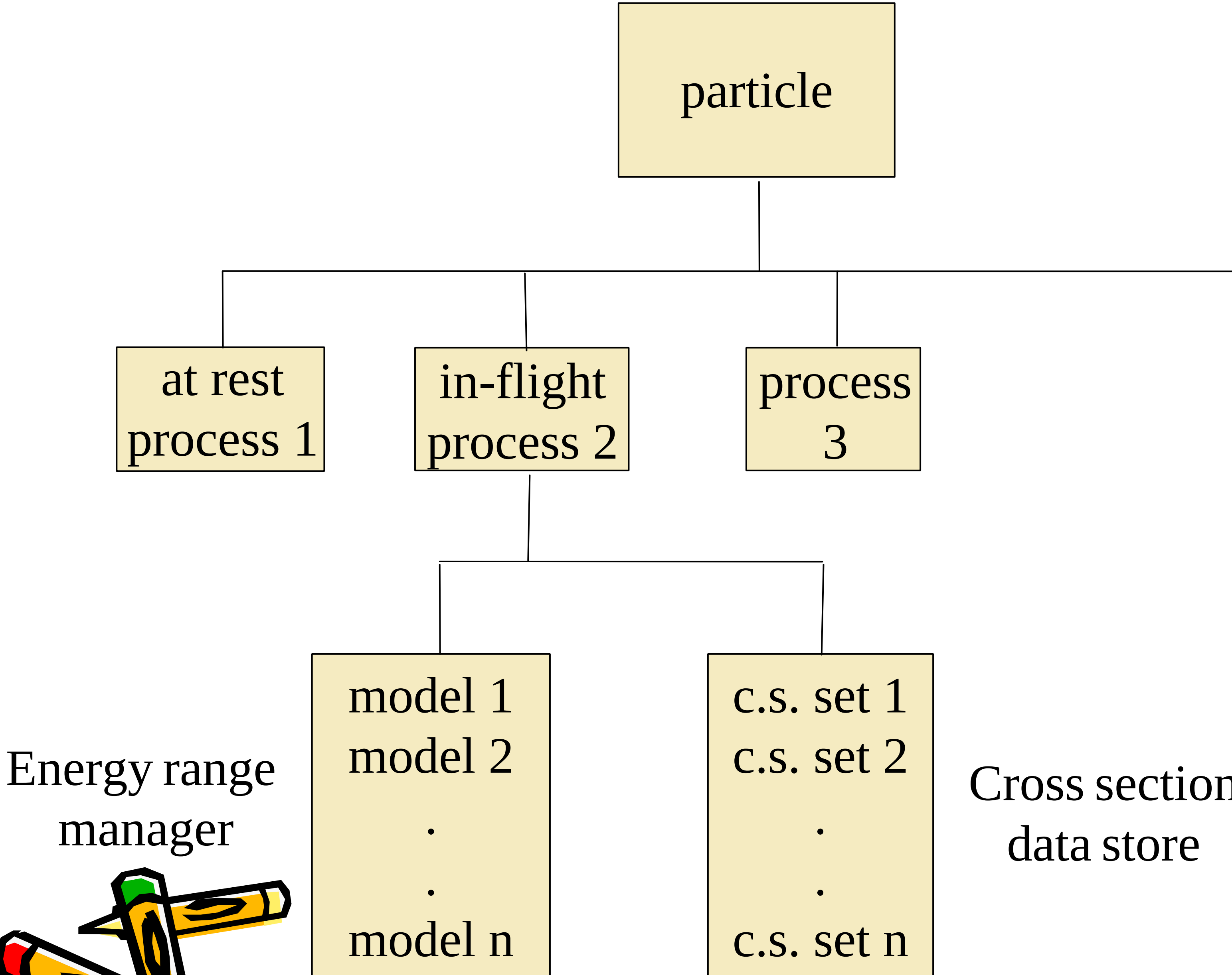
Physics Processes

- All the work of particle decays and interactions is done by processes
  - transportation is also handled by a process

- A process does two things:
  - decides when and where an interaction will occur
    - method: GetPhysicalInteractionLength()
    - this requires a cross section, decay lifetime
    - for the transportation process, the distance to the nearest object along the track is required
  - generates the final state of the interaction (changes momentum, generates secondaries, etc.)
    - method: DoIt()
    - this requires a model of the physics

Handling Multiple Processes

- Many processes (and therefore many interactions) can be assigned to the same particle
- How does Geant4 decide which interaction happens at any one time?
  - interaction length or decay length is sampled from each process
  - shortest one happens, unless
  - a volume boundary is encountered in less than the sampled length. Then no physics interaction occurs (just simple transport).
  - the processes that were not chosen have their interaction lengths shortened by the distance traveled in the previous step
  - repeat the procedure


particle
at rest process 1
in-flight process 2
process 3
process n
model 1
model 2
.
.
model n
c.s. set 1
c.s. set 2
.
.
c.s. set n
Energy range manager
Cross section data store

Summary (1)

- Geant4 supplies many physics processes which cover electromagnetic, hadronic and decay physics
- Many processes may be assigned to one particle
  – which one occurs first depends on cross sections, lifetimes, and distances to volume boundaries

Physics List

What is a Physics List?

- A class which collects all the particles, physics processes and production thresholds needed for your application
- It tells the run manager how and when to invoke physics
- It is a very flexible way to build a physics environment
  - user can pick the particles he wants
  - user can pick the physics to assign to each particle
- But, user must have a good understanding of the physics required
  - omission of particles or physics could cause errors or poor simulation

Why Do We Need a Physics List?

- Physics is physics – shouldn't Geant4 provide, as a default, a complete set of physics that everyone can use?
- No:
  - there are many different physics models and approximations
    - very much the case for hadronic physics
    - but also the case for electromagnetic physics
  - computation speed is an issue
    - a user may want a less-detailed, but faster approximation
  - no application requires all the physics and particles Geant4 has to offer
    - e.g., most medical applications do not want multi-GeV physics

Why Do We Need a Physics List? (2)

- For this reason Geant4 takes an atomistic, rather than an integral approach to physics
  - provide many physics components (processes) which are de-coupled from one another
  - user selects these components in custom-designed physics lists in much the same way as a detector geometry is built
- Exceptions:
  - a few electromagnetic processes must be used together
  - future processes involving interference of electromagnetic and strong interactions may require coupling as well

G4VUserPhysicsList

- All physics lists must derive from this class
  - and then be registered with the run manager
- Required Methods
  - ConstructParticle() - choose the particles you need in your simulation and define all of them here
  - ConstructProcess() - for each particle, assign all the physics processes important in your simulation
  - SetCuts() - set the range cuts for secondary production
  - What's a range cut?
  - => essentially a low energy limit on particle production
  - more on this later

Pre-packaged Physics Lists (1)

- Our example deals mainly with electromagnetic physics
- A complete and realistic EM physics list can be found in novice example N03
  - good starting point
  - add to it according to your needs
- Adding hadronic physics is more involved
  - for any one hadronic process, user may choose from several hadronic models to choose from
  - choosing the right models for your application requires care
  - to make things easier, hadronic physics lists are now provided according to some use cases

Pre-packaged Physics Lists (2)

- Referred to as “hadronic physics lists” but include electromagnetic physics from example N03
- Can be found on the Geant4 web page at http://geant4.web.cern.ch/geant4/physics_lists
- Caveats:
  - these lists are provided as a “best guess” of the physics needed in a given case
  - the user is responsible for validating the physics for his own application and adding (or subtracting) the appropriate physics
  - they are intended as starting points or templates

Summary (2)

- All the particles, physics processes, and production cuts needed for an application must go into a physics list
- Some pre-packaged physics lists are provided by Geant4 as starting points for users
  - electromagnetic physics lists
  - hadronic physics lists
- Care is required by user in choosing the right physics to use

Standard EM

'Standard' em physics : the model

The projectile is assumed to have an energy ≥ 1 keV.

- The atomic electrons are quasi-free : their binding energy is neglected (except for photoelectric effect).
- The atomic nucleus is fixe : the recoil momentum is neglected.

The matter is described as homogeneous, isotropic, amorphous.

1. Common to all charged particles
   - ionization $(\sim keV \longrightarrow)$
   - Coulomb scattering from nuclei $(\sim keV \longrightarrow)$
   - Cerenkov effect
   - Scintillation
   - transition radiation
2. Muons
   - (e+,e-) pair production $(\sim 100GeV \longrightarrow)$
   - bremsstrahlung $(\sim 100GeV \longrightarrow)$
   - nuclear interaction $(\sim 1TeV \longrightarrow)$
3. Electrons and positrons
   - bremsstrahlung $(\sim 10MeV \longrightarrow)$
   - e+ annihilation

4. Photons

- gamma conversion ($\sim 10MeV \longrightarrow$)
- incoherent scattering ($\sim 100keV \longrightarrow \sim 10MeV$)
- photo electric effect ($\longleftarrow \sim 100keV$)
- coherent scattering ($\longleftarrow \sim 100keV$)

5. Optical photons

- reflection and refraction
- absorption
- Rayleigh scattering

Total :$\sim$ 15 processes $\longrightarrow$ $\sim$ 40 classes

+ $\sim$ 10 classes for the materials category

Summary (3)

- Standard EM physics processes are available for gammas and charged particles from 1 keV and up
- EM processes must be ordered in the physics list
- EM processes are based on theoretical cross sections with corrections. During simulation, quantities are taken from tables calculated at initialization time
- Multiple scattering is handled by model functions which represent fits to Lewis transport theory results (not Moliere)
- Energy-range relation is used to compute energy loss, and to control step lengths and secondary production

Low Energy Electromagnetic Physics

Low Energy Electromagnetic Physics

- A package in the Geant4 electromagnetic package
  - in …geant4/source/processes/electromagnetic/lowenergy/
- A set of processes extending the coverage of electromagnetic interactions in Geant4 down to “low” energy
  - 250 eV (in principle even below this limit) / 100 eV for electrons and photons
  - down to the approximately the ionization potential of the interacting material for hadrons and ions
  - up to 100 GeV (unless specified)
  - all processes are based on theoretical models and on exploitation of evaluated data ; they involve two distinct phases :
    - calculation and use of total cross sections
    - generation of the final state
- A set of processes based on detailed models
  - shell structure of the atom
  - precise angular distributions

Overview of LowEM physics

- **Photons**
  - Compton Scattering
  - Compton Scattering by Linearly Polarized Gamma Rays
  - Rayleigh Scattering
  - Gamma Conversion
  - Photoelectric effect
- **Electrons**
  - Bremsstrahlung
  - Ionisation

Come in **two "flavours"** of models:
- based on the **Livermore Library**
- à la **Penelope** (+ positron annihilation)

- **Hadrons and ion ionisation**
  - Energy loss of slow & fast hadrons
  - Energy loss in compounds
  - Delta-ray production
  - Effective charge of ions
  - Barkas and Bloch effects (hadron sign + relativistic)
  - Nuclear stopping power
  - PIXE

Atomic relaxation
- Fluorescence
- Auger process

In progress

- Extensions down to the eV scale :
  The Geant4 DNA project
  - in water (for radiobiology studies)
  - in semiconductor materials (for radiation damage to components)

- Difficult domain
  - models must be specialized by material
  - cross sections, final state generation, angular distributions

http://www.ge.infn.it/geant4/dna

Summary (4)

- OO technology provides the mechanism for a rich set of electromagnetic physics models in Geant4
  - further extensions and refinements are possible, without affecting Geant4 kernel or user code
- Two main approaches in Geant4
  - standard
  - Low Energy (Livermore Library / Penelope)
- each one offering a variety of models for specialized applications
- Extensive validation activity and results
- More on Physics Reference Manual and web site

Hadron Physics

Hadronic Processes, Models and Cross Sections

- In Geant4 physics is assigned to a particle through processes
- Each process may be implemented
  - directly as part of the process, or
  - in terms of a model class
- In Geant4 hadronic physics there are sometimes many models for a given process
  - user must choose
  - can have more than one per process
- A process must also have cross sections assigned
  - here too, there are options

Hadronic Models – Data Driven

- Characterized by lots of data
  - cross section
  - angular distribution
  - multiplicity
  - etc.
- To get interaction length and final state, models interpolate data
  - cross section, coef of Legendre polynomials
- Examples
  - neutrons (E < 20 MeV)
  - coherent elastic scattering (pp, np, nn)
  - Radioactive decay

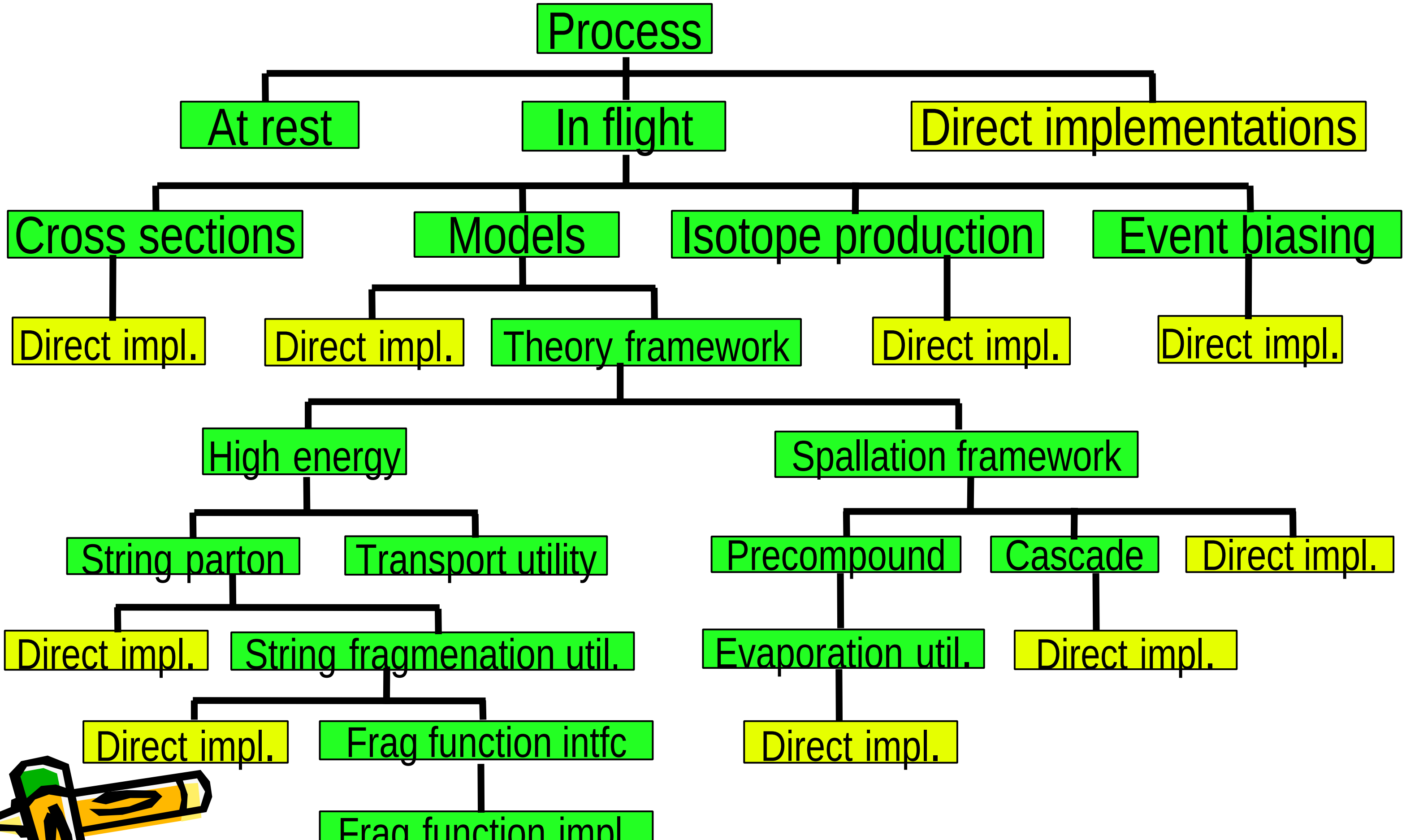
Hadronic Models – Theory Driven

- Dominated by theory (quark-gluon strings, chiral perturbation theory, …)
  - not as much data to tie things down
- Final states determined by sampling theoretical distributions
- Examples:
  - quark-gluon string (projectiles with E > 20 GeV)
  - intra-nuclear cascade (intermediate energies)
  - nuclear de-excitation and breakup
  - chiral invariant phase space (up to a few GeV)

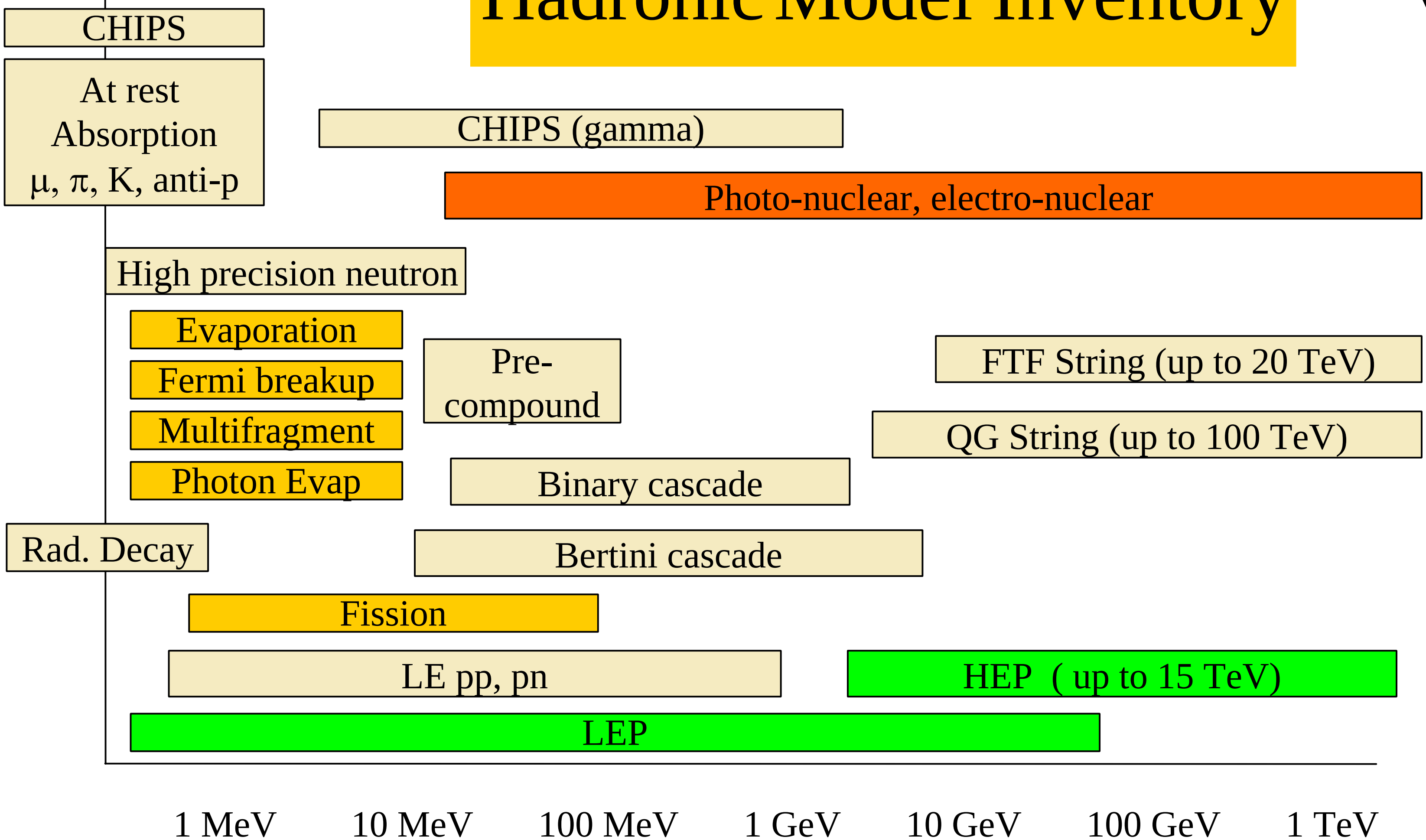
Hadronic Models - Parameterized

- Depend mostly on fits to data and some theoretical distributions
- Two models available:
  - Low Energy Parameterized (LEP) for < 20 GeV
  - High Energy Parameterized (HEP) for > 20 GeV
  - Each type refers to a collection of models
- Both derived from GHEISHA model used in Geant3
- Core code:
  - hadron fragmentation
  - cluster formation and fragmentation
  - nuclear de-excitation

Hadronic Model Organization



Hadronic Model Inventory



Low energy (< 20MeV) neutrons physics

- High Precision Neutron Models (and Cross Section Data Sets)
  - G4NDL
    - ENDF
  - Elastic
  - Inelastic
  - Capture
  - Fission
- NeutronHPorLEModel(s)
- ThermalScatteringModels (and Cross Section data Sets)
- JENDL High Energy Files (cross sections < 3GeV)

Ion Physics

- Inelastic Reactions
  - Cross Sections
    - Tripathi, Shen, Kox and Sihver
    - G4GeneralSpaceNNCrossSection
  - Model
    - G4BinaryLightIon
    - G4WilsonAbrasion
    - G4QMD
- Electromagnetic Dissociation
- Radio Active Decay

Summary (5-1)

- Geant4 hadronic physics allows user to choose how a physics process should be implemented:
  - cross sections
  - models
- Many processes, models and cross sections to choose from
  - hadronic framework makes it easier for users to add more
- Two main types of elastic scattering are available:
  - GHEISHA-style
  - coherent
- Precompound models are available for low energy nucleon projectiles and nuclear de-excitation

Summary (5-2)

- Cascade models (Bertini, Binary) are valid for fewer particles over a smaller energy range
  - more theory-based
  - more detailed
  - slower
- Parameterized models (LEP, HEP) handle the most particle types over the largest energy range
  - based on fits to data and some theory
  - not very detailed
  - fast

Summary (5-3)

- High Precision Neutron models are data driven models and its used evaluated data libraries.
- However the library is not complete because there are no data for several key elements.
- Geant4 has abundant processes for Ion interactions with matter and also without matter.
- Without any extra modules, users may simulate ion transportation in the complex and realistic geometries of Geant4.
- Validation has begun and the results show reasonable agreement with data. This work continues.

Isotope Production

- Useful for activation studies
- Covers primary neutron energies from 100 MeV down to thermal
- Can be run parasitically with other models
- G4NeutronIsotopeProduction is currently available
  - G4ProtonIsotopeProduction not yet completed

Summary (5-4)

- Two string models (QGS, FTF) are provided for high energy (>20 GeV) interactions
- The Chiral Invariant Phase Space model is available for:
  - capture at rest
  - anti-baryon annihilation
  - gamma and lepto-nuclear interactions
  - nuclear de-excitation
- Other models/processes available include:
  - capture at rest and in flight
  - fission
  - neutron-induced isotope production

Cuts, Decay and Optical Processes

Threshold for Secondary Production (1)

- Every simulation developer must answer the question: how low can you go?
  - at what energy do I stop tracking particles?
- This is a balancing act
  - need to go low enough to get the physics you're interested in
  - can't go too low because some processes have infrared divergence causing CPU time to skyrocket
- The traditional Monte Carlo solution is to impose an absolute cutoff in energy
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point

Threshold for Secondary Production (2)

- But, such a cut may cause imprecise stopping location and deposition of energy
- There is also a particle dependence
  - range of 10 keV γ in Si is a few cm
  - range of 10 keV e- in Si is a few microns
- And a material dependence
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - if the cutoff is OK for Pb, it will likely be wrong for the scintillator which does the actual energy deposition measurement

Threshold for Secondary Production (3)

- Geant4 solution: impose a production threshold
  - this threshold is a distance, not an energy
  - default = 1 mm
  - the primary particle loses energy by producing secondary electrons or gammas
  - if primary no longer has enough energy to produce secondaries which travel at least 1mm, two things happen:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero energy using continuous energy loss
- Stopping location is therefore correct
- Only one value of production threshold distance is needed for all materials because it corresponds to different energies depending on material.

Threshold for Secondary Production (4)

- Geant4 recommends the default value of 1mm
  - user needs to decide the best value
  - this will depend on the size of sensitive elements within the simulated detector, and on available CPU
- This value is set in the SetCuts() method of your physics list.
- Instead of “secondary production threshold distance” it is more convenient to simply say “cuts”
  - but please remember that this does not mean that any particle is actually stopped before it runs out of energy

The Decay Process

- Derived from G4VRestDiscreteProcess
  - decay can happen in-flight or at rest
- Should be applied to all unstable, long-lived particles
- Different from other physical processes:
  - mean free path for most processes: $\lambda = N \rho \sigma / A$
  - for decay in-flight: $\lambda = \beta \gamma c \tau$
- Same decay process for all eligible particles
  - decay process retrieves BR and decay modes from decay table stored in each particle type

Available Decay Modes

- Phase space:
  - 2-body e.g. $\pi^0 \to \gamma\gamma$, $\Lambda \to p\ \pi^-$
  - 3-body e.g. $K^0_L \to \pi^0\ \pi^+\ \pi^-$
  - many body
- Dalitz: $P^0 \to \gamma\ l^+\ l^-$
- Muon decay
  - V – A, no radiative corrections, mono-energetic neutrinos
- Leptonic tau decay
  - like muon decay
- Semi-leptonic K decay: $K \to \pi\ l\ \nu$

Pre-assigned Decays

- Geant4 provides decay modes for long-lived particles
  - user can re-define decay channels if necessary
- But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4
  - user must "pre-assign" to particle:
    - proper lifetime
    - decay modes
    - decay products
  - decay process can invoke decay handler from the generator
    - must use G4VExtDecayer interface
- Take care that pre-assigned decays from generators do not overlap with those defined by Geant4
  - K^0_S , τ

Optical Photons(1)

- Technically, should belong to electromagnetic category, but:
  - optical photon wavelength is >> atomic spacing
  - treated as waves -> no smooth transition between optical and gamma particle classes
- Optical photons are produced by the following Geant4 processes:
  - G4Cerenkov
  - G4Scintillation
  - G4TransitionRadiation
- Warning: these processes generate optical photons without energy conservation

Optical Photons (2)

- Optical photons undergo:
  - Rayleigh scattering
  - refraction and reflection at medium boundaries
  - bulk absorption
  - wavelength shifting
- Geant4 keeps track of polarization
  - but not overall phase -> no interference
- Optical properties can be specified in G4Material
  - reflectivity, transmission efficiency, dielectric constants, surface properties
- Photon spectrum properties also defined in G4Material
  - scintillation yield, time structure (fast, slow components)

Summary (6)

- The precision of particle stopping and the production of secondary particles are determined by a secondary production threshold
- There is one decay process for all long-lived, unstable particles
- Optical processes handle the reflection, refraction, absorption, wavelength shifting and scattering of long-wavelength photons

Event Biasing

- Geant4 simulation:
  - Analogue == regular processing
  - Non-analogue/event biased simulation == manipulated processes and/or process list
    - I.e, manipulate processing to effectively apply B(x) in place of N(x)
- Geant4 provides
  - Several built-in general use biasing techniques
  - Utility class, G4WrapperProcess to support user defined biasing
- Expect biasing to be used by experienced users
  - Should understand what a particular biasing technique does, it's constraints and side effects
  - Understand how processing works in Geant4

Built in Biasing Options

Biasing Technique	First Release Version
Primary particle biasing	3.0
Radioactive decay biasing	3.0
Mars hadronic leading particle biasing	4.0
General hadronic lead particle biasing	4.3
Hadronic cross section biasing	4.3
Geometrical Importance sampling	5.0
Geometrical weight window and weight cutoff	5.2

Summary (7)

- Number of popular event biasing techinques built into Geant4
- User defined biasing supported through G4WrapperProcess
- Ongoing developments aim to improve exiting Geant4 biasing, and provide new event biasing and scoring methods
- Documentation at
  - http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/ch03s07.html

Thank you for listening!!