Geant4 Physics in More Detail

Fermilab Geant4 Tutorial

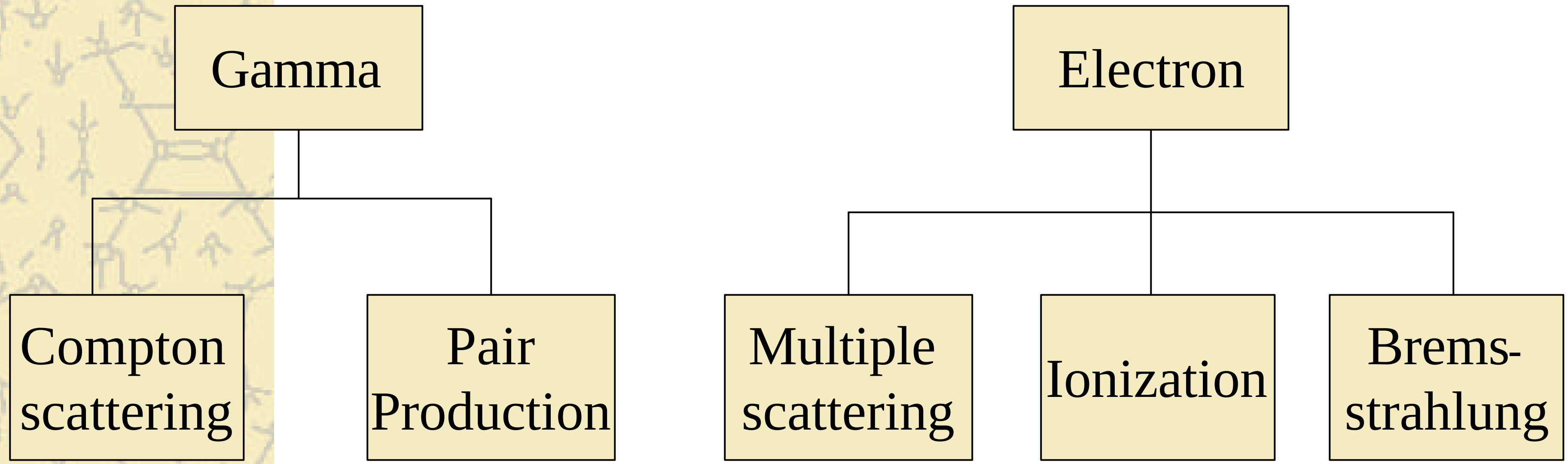
27-29 October 2003

Dennis Wright (SLAC)

Outline

- Review of processes
- Electromagnetic processes
- Optical photons
- Hadronic processes
- Decay

Geant4 Physics is Implemented in Processes which are Assigned to Particles



Each particle class has a process manager to which physics processes are registered

What Does a Process Do?

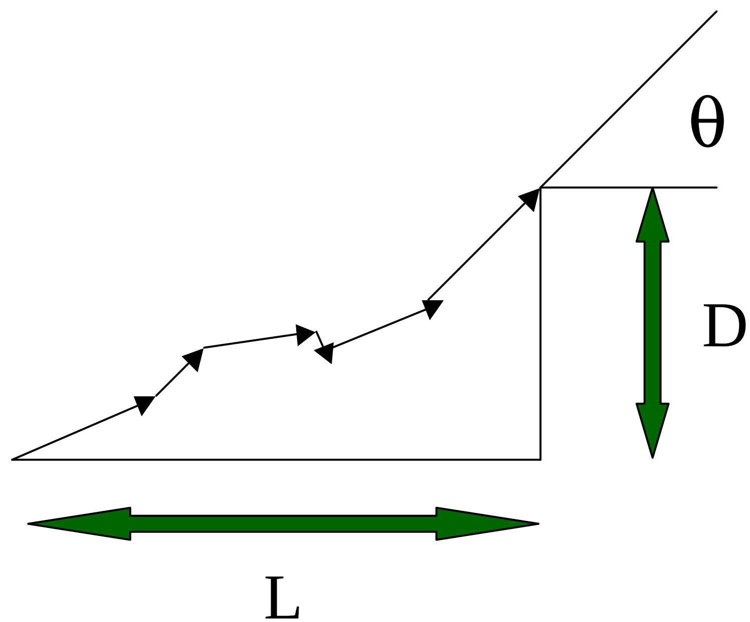
- Decides when and where an interaction will occur using GetPhysicalInteractionLength (GPIL) method
  - Needs cross sections
- Generates the final state using DoIt method
  - Needs interaction model
- Three types of GPIL, DoIt methods
  - PostStep, AlongStep, AtRest

Standard Electromagnetic processes

- Gammas
  - photo-electric effect
  - Compton scattering
  - electron, muon pair production
- Electrons
  - e Ionization, energy loss
  - e Bremsstrahlung
  - e+e- annihilation
  - synchrotron radiation
- Muons
  - mu ionization, energy loss
  - mu bremsstrahlung
  - e+e- pair production
- Charged hadrons
  - ionization, energy loss
- All charged particles
  - multiple scattering
  - transition radiation
  - scintillation
  - Cerenkov radiation

Multiple Coulomb Scattering (1)

- Repeated elastic scattering from nuclei over length L
- Cumulative effect:
  - Net deflection of particle θ
  - Net spatial displacement D
- Typically Moliere theory is used for sampling angles
  - Gaussian for small angles
  - Rutherford for larger angles



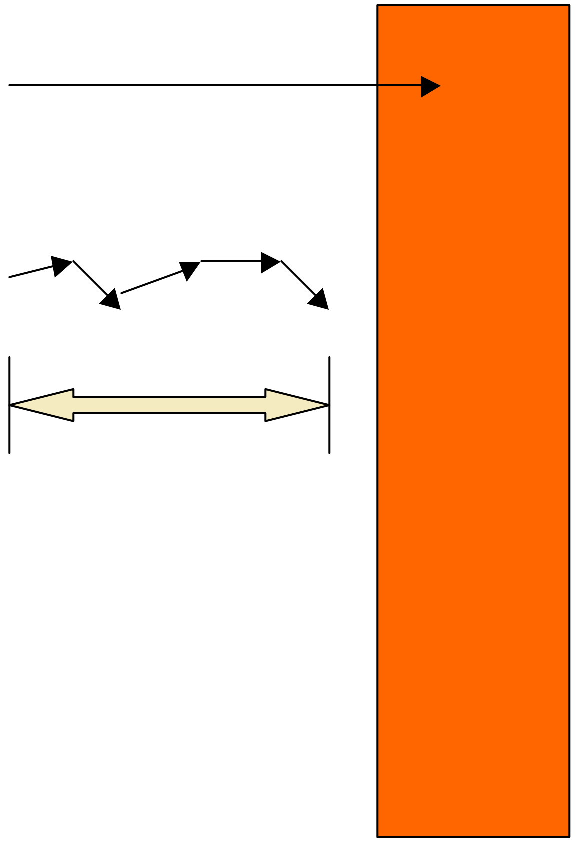
Multiple Coulomb Scattering (2)

- But,
  - Only accurate for small angles
  - Not good for very low E
  - Not good for very low Z or high Z
  - No spatial displacement

- Geant4 uses Lewis theory instead
  - Based on full transport theory of charged particles
  - Model functions used to sample angular and spatial distributions
  - Model parameters determined by comparison to data

Multiple Scattering is "special"

- Physics processes determine the particle's path length
- MS conserves "physical" path length, but effective "geometric" path length is shorter
- Geant4 transportation code uses "geometric" path lengh to see if track hits volumes
- →MS process is always applied next to last (before transportation)



Ionization and Energy Loss (1)

- The primary means of energy loss by charged particles in matter is due to the ejection of atomic electrons
  - Above the range cut: explicit emission of e-
  - Below the range cut: soft e- emission treated as continuous energy loss with fluctuations

- e^- , e^+ treated differently from μ, π, p, etc.
  - Charge difference and small mass important

Ionization and Energy Loss (2)

	Heavy particles	e^- , e^+
Above range cut	$\frac{d\sigma}{dT} \propto \frac{1}{\beta^2 T^2}\left\| 1 - \beta^2 \frac{T}{T_{max}} + \frac{T^2}{2E^2} \right\|$	Moller scattering for e- Bhabha scattering for e+
Below Range cut	Bethe-Bloch dE/dx (truncated)	Berger-Seltzer dE/dx

Energy Loss Fluctuations

- Berger-Seltzer and Bethe-Bloch calculate mean energy loss
- A small number of collisions with large energy transfers introduce fluctuations in energy loss
- Typically, Landau theory is used to simulate fluctuations
  - but this is time-consuming
- Geant4 uses its own very simple model
  - faster
  - good approximation to the Landau form
  - Valid for any thickness of material

EM Cross Sections

- Once range cuts are determined (default is 1 mm) for all particles,
  - Cross sections for all processes, particles and materials are calculated automatically
- Cross sections calculated from theory whenever possible
  - some parameters taken from data (such as IP, shell corrections in energy loss)

Low Energy EM Processes (1)

- Developed for use in medical and space applications
- Optimized for low energy processes where atomic shell structure is important
- Applicable to same energy range as standard EM
  - A few low energy processes go down to 250 eV
- Uses atomic shell cross sections from databases - not parameterized
  - Slower than standard EM processes, but more detailed at low energy

Low Energy EM Processes (2)

- Processes not covered in standard EM:
  - Rayleigh scattering
  - Compton scattering by linearly polarized gammas
  - Fluorescence
  - Auger process
- Processes with improved low energy behavior:
  - Hadron and ion energy loss
  - Electron ionization
  - bremsstrahlung
  - Photo-electric effect

Optical Photon Processes (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:
  - Cerenkov effect
  - transition radiation
  - scintillation
- Warning: these processes generate optical photons without energy conservation

Optical Photon Processes (2)

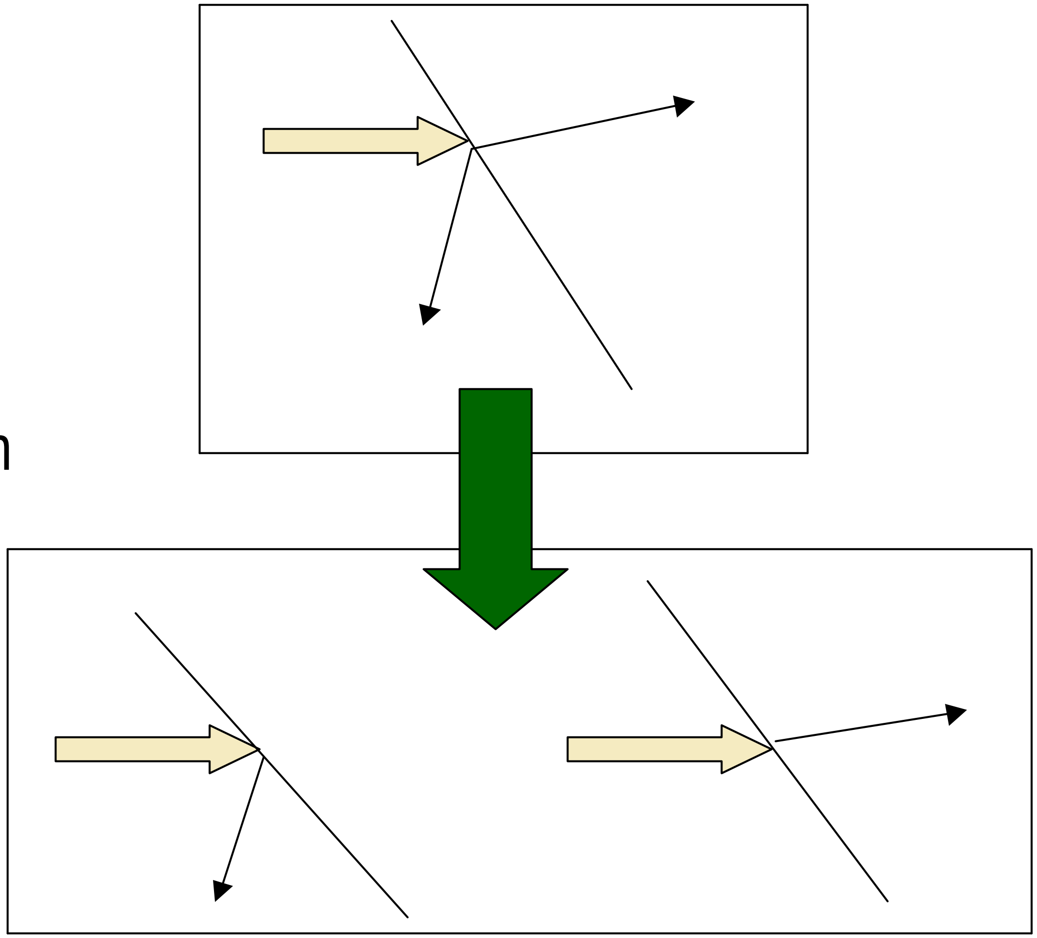
- Optical photons undergo:
  - Refraction and reflection at medium boundaries
  - Bulk absorption
  - Rayleigh scattering

- 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

Optical Photon Tracking

- Geant4 demands particle-like behavior for tracking
  - Thus, no “splitting”
  - Event with both refraction and reflection must be simulated by at least two optical photons

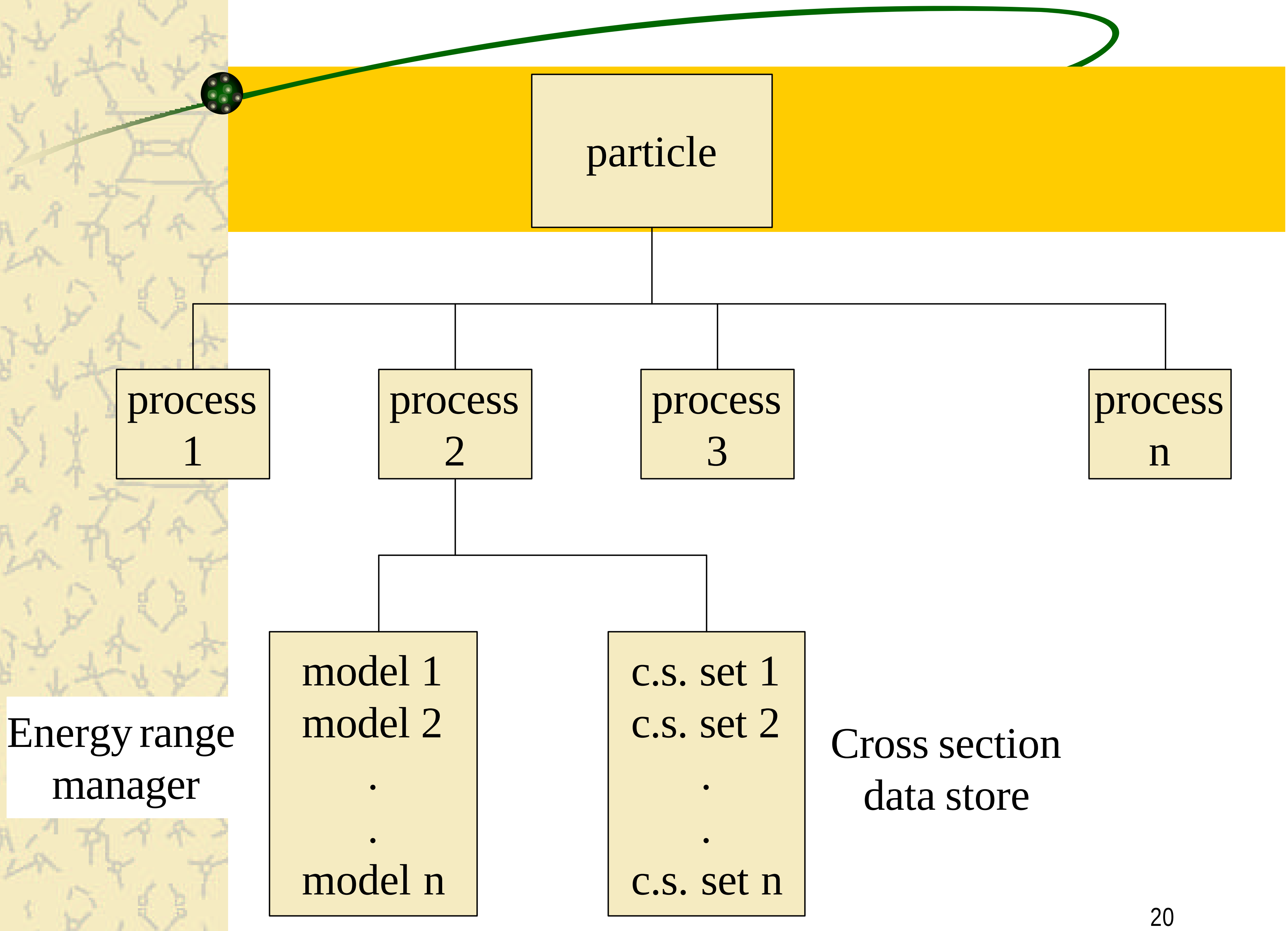


Hadronic Processes

- At rest
  - stopped μ, π, K, anti-proton
  - radioactive decay
- Elastic
  - same process for all long-lived hadrons
- Inelastic
  - different process for each hadron
  - photo-nuclear
  - electro-nuclear
- Capture
  - π^-, K^- in flight
- Fission

Hadronic Processes and Cross Sections

- In Geant4 EM physics: 1 process → 1 model, 1 cross section
- In Geant4 Hadronic physics: 1 process → many possible models, cross sections
  - Mix and match !
- Default cross sections are provided for each model
- User must decide which model is appropriate


particle
process 1
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

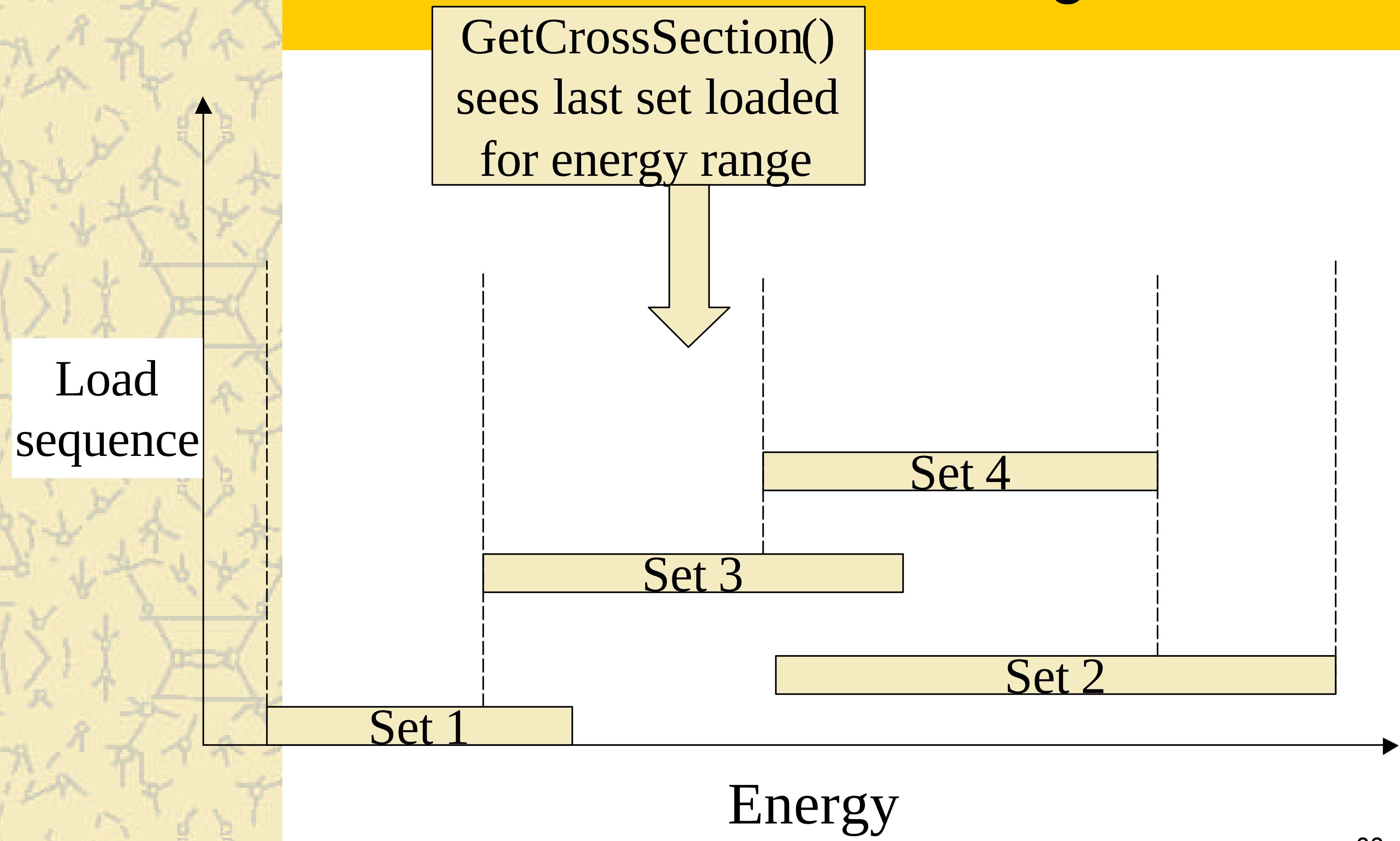
Cross Sections

- Default cross section sets are provided for each type of hadronic process
  - Fission, capture, elastic, inelastic
  - Can be overridden or completely replaced
- Different types of cross section sets
  - Some contain only a few numbers to parameterize c.s.
  - Some represent large databases (data driven models)

Alternative Cross Sections

- Low energy neutrons
  - G4NDL available as Geant4 distribution data files
  - Available with or without thermal cross sections
- "High energy" neutron and proton reaction σ
  - 20 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections
  - Good for E/A < 1 GeV
- Isotope production data
  - E < 100 MeV

Cross Section Management



Hadronic Models – Data Driven

- Characterized by lots of data
  - Cross section
  - Angular distribution
  - Multiplicity
- To get interaction length and final state, models simply interpolate data
  - Usually linear interp of cross section, coef of Legendre polynomials
- Examples
  - Neutrons (E < 20 MeV)
  - Coherent elastic scattering (pp, np, nn)
  - Radioactive decay

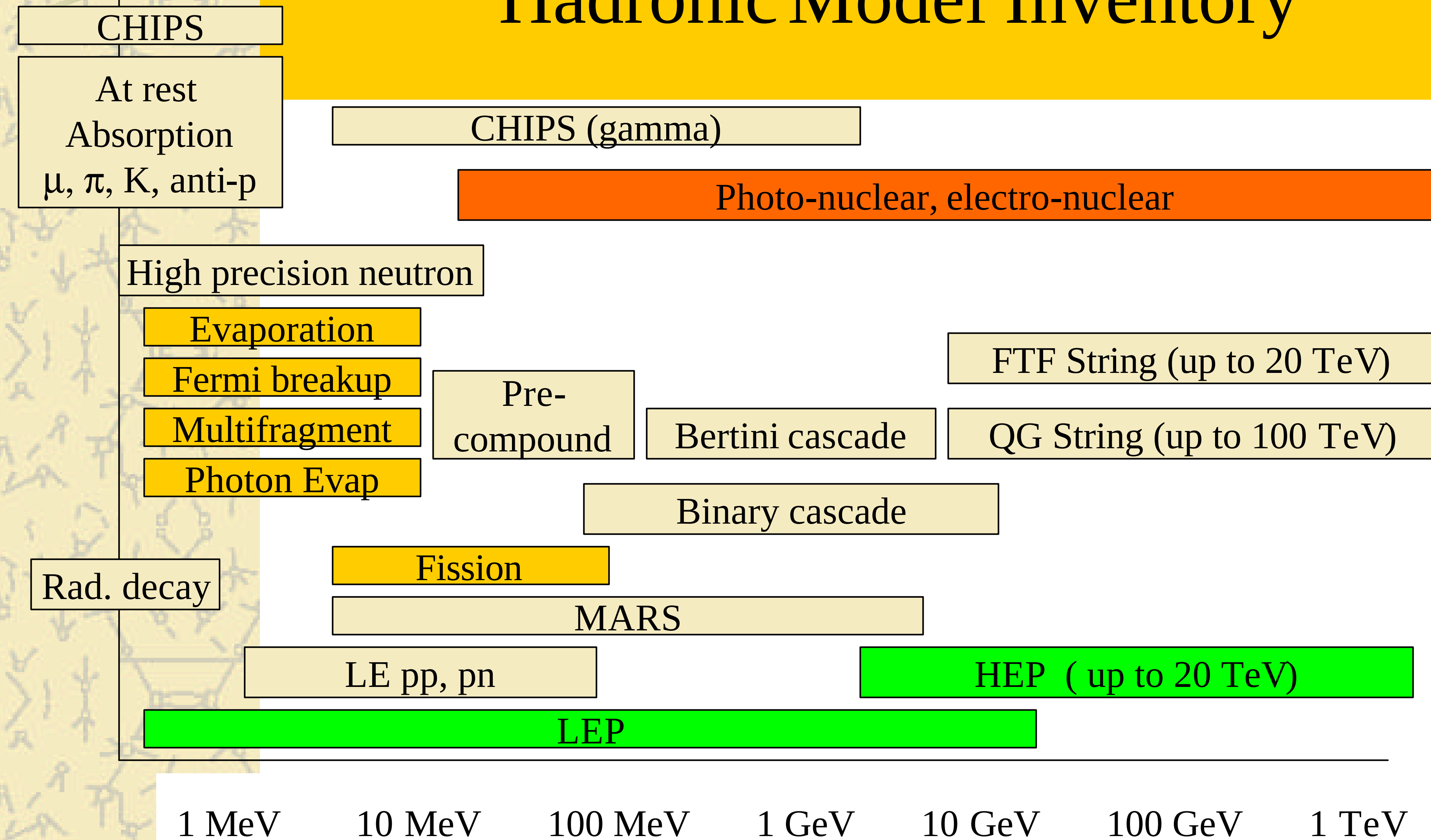
Hadronic Models – Theory Driven

- Dominated by theory (QCD, Strings, ChPT, …)
  – Not as much data (used for normalization, validation)
- Final states determined by sampling theoretical distributions
- Examples:
  – Parton String (projectiles with E > 5 GeV)
  – Intra-nuclear cascade (intermediate energies)
  – Nuclear de-excitation and breakup
  – Chiral invariant phase space (all energies)

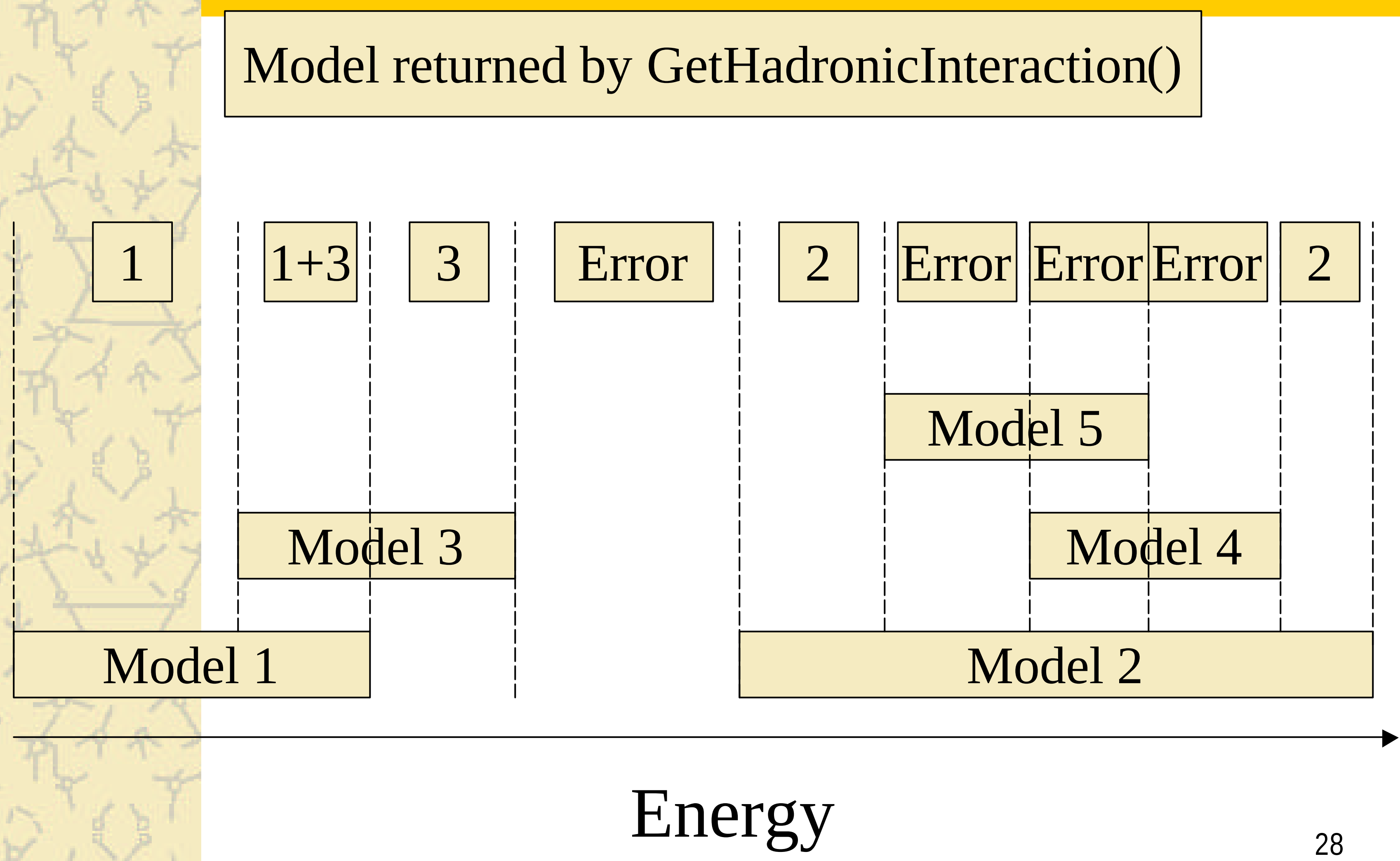
Hadronic Models - Parameterized

- Depends on both data and theory
  - Enough data to parameterize cross sections, multiplicities, angular distributions
- Final states determined by theory, sampling
  - Use conservation laws to get charge, energy, etc.
- Examples
  - LEP, HEP models (GHEISHA)
  - Fission
  - Capture

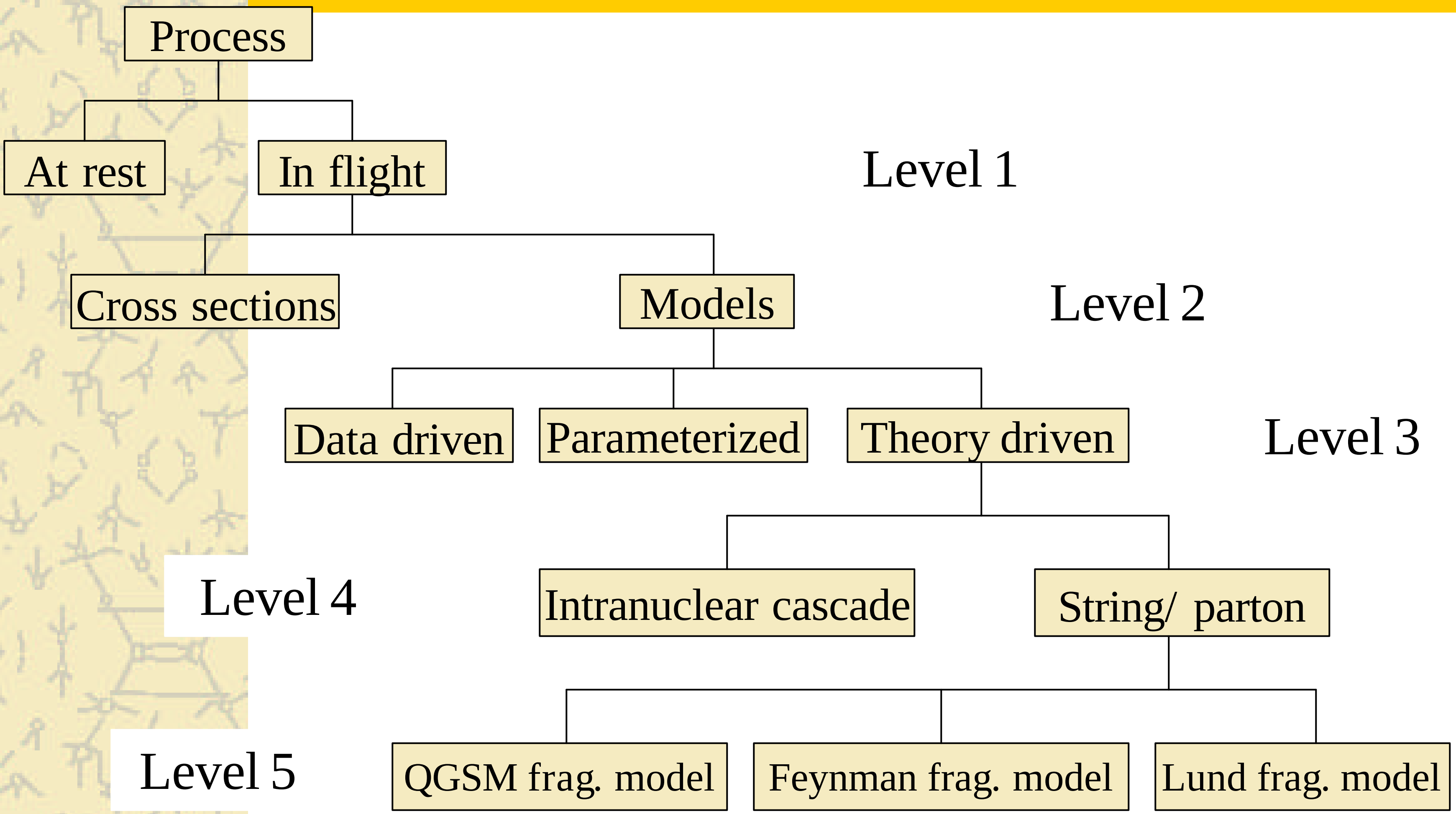
Hadronic Model Inventory



Model Management



Hadronic Process/Model Framework



Code Example

```
void MyPhysicsList::ConstructProton() {
    G4ParticleDefinition* proton = G4Proton::ProtonDefinition();
    G4ProcessManager* protMan = proton→GetProcessManager();
    // Elastic scattering
    G4HadronElasticProcess* protelProc
                                    = new G4HadronElasticProcess();
    G4LElastic* protelMod = new G4LElastic();
    protelProc→RegisterMe(protelMod);
    protMan→AddDiscreteProcess(protelProc);
```

Code Example (continued)

```
// Inelastic scattering
G4ProtonInelasticProcess* protinelProc =
                              new G4ProtonInelasticProcess();
G4LEProtonInelastic* proLEMod = new G4LEProtonInelastic();
protLEMod→SetMaxEnergy(20.0*GeV);
protinelProc→RegisterMe(protLEMod);

G4HEProtonInelastic* protHEMod = new G4HEProtonInelastic();
protHEMod→SetMinEnergy(20.0*GeV);
protinelProc→RegisterMe(protHEMod);
}
```

Physics Lists (1)

- Hadronic part more difficult
  - Multiple models per process allowed
  - Also multiple cross section sets
  - One model does not cover all energies, or all particles
  - Model choice heavily dependent on physics studied
- Example hadronic physics lists available
  - Each designed for specific physics use case
  - Geant4 home page →site index→physics lists

Physics List (2)

- 13 hadronic physics lists available including
  - HEP calorimetry
  - Shielding penetration (high and low energies)
  - Dosimetry
  - LHC, LC neutron fluxes
  - Medical
  - Low background (underground)

The Decay Process

- Should be applied to all unstable, long-lived particles
- Different from other physics processes:
  - Mean free path for most processes: $\lambda = N\rho\sigma/A$
  - For decay: $\lambda = \gamma\beta c\tau$
- 1 process for all eligible particles
  - Decay process retrieves BR and decay modes from decay table stored in each particle type
- Decay modes for heavy flavor particles not included in Geant4
  - Leave that to the event generators
  - Decay process can invoke decay handler from generator

Available Decay Modes

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

Conclusion

- Geant4 provides a large number of electromagnetic, hadronic, decay and optical physics processes for use in simulation
- Cross sections, either calculated or from databases, are available to be assigned to processes
- Interactions are implemented by models which are then assigned to processes. For hadrons there are many models to choose from. For EM usually only one.