Geant4 Overview

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Outline

- Geant4 in general
- Toolkit capabilities
- Physics
  - Organization of hadronics
- Survey of hadronic models

Geant4 General Notes

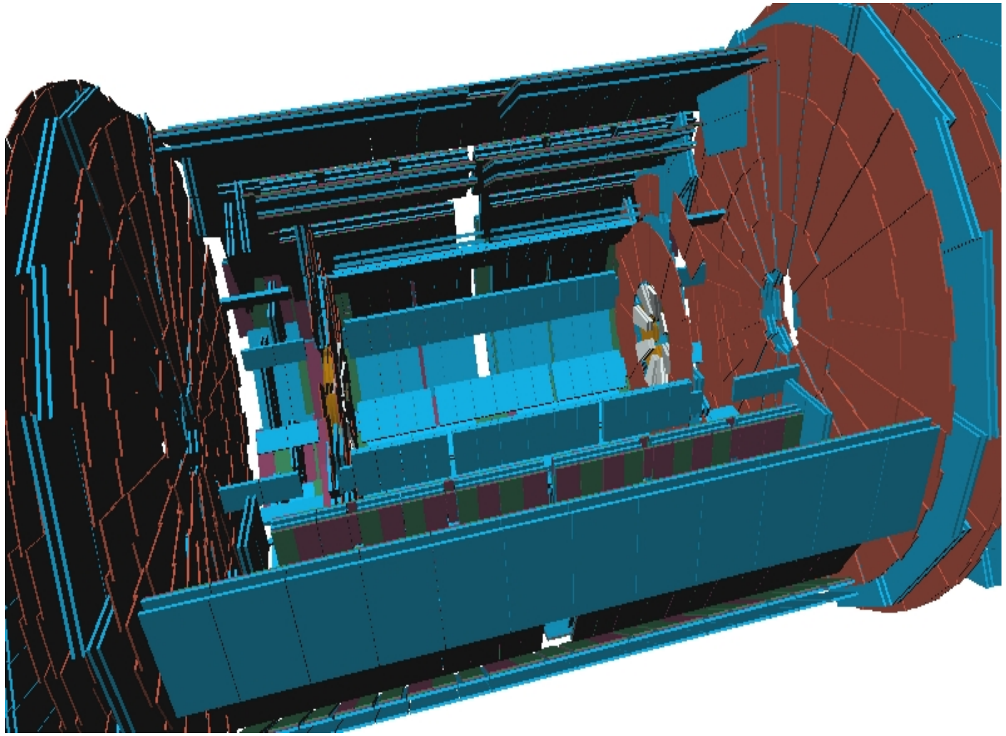
- Geant4 is an object-oriented C++ toolkit
  - the goal is to provide all that is needed to build a wide variety of physics simulation applications
    - range of physics models,
    - tracking, geometry hit collection and scoring
    - and auxiliary components
  - code is open, modular – available for all to download
    - Anyone can inspect, understand, tailor, revise, … improve.
  - extensive documentation and tutorials provided
- Principal references:
  - NIM A506, 250 (2003) and IEEE Trans. Nucl. Sci. 53, 270 (2006)

Some application areas

- High energy and nuclear physics experiments
  - ATLAS, BaBar, CMS, LHCb, HARP, ..
- Satellite and space applications
  - GLAST, ca 15 ESA satelites, ..
- Medical
  - Imaging (eg GATE PET & SPECT tool)
  - Hadrontherapy

Geant4 Geometry

- Large number of volume shapes (CSG + BREP)
- Hierarchical combination of volumes
- Extremely versatile
- Materials
  - isotopes, elements, compounds, phase, temp
  - user-created or use NIST database



Further capabilities

- External EM fields affect charged particles
- Tracks 'hit' user-written detectors
- Scoring radiation observables
- Event biasing

- Auxiliary capabilities
  - Visualisation via several systems
  - Input/Output ('persistency') for geometry, events

Physics Choices and ‘Physics Lists’

- User has the final say on the physics chosen for the simulation. He/she must:
  - select the relevant particles and physics processes from those provided, for each particle type
  - validate the selection for the application area
- ‘Physics Lists’ represent this collection
- Deciding or creating the physics list is the user's responsibility
  - reference physics lists are provided by Geant4
    - are continuously-tested and widely used configurations (eg QGSP)
  - other ‘educated-guess’ configurations for use as starting points.

Electromagnetic Physics in Geant4

- “standard” package (1 keV and up)
  - multiple scattering, ionization, bremsstrahlung
  - Compton, pair production, photo-electric, annihilation
  - synchrotron, Cerenkov, transition radiation, high energy muon processes
- “low energy” package
  - uses database information to extend interactions below 1 keV
  - many of the same processes as offered in “standard”
- optical photons
  - reflection/refraction, absorption, Rayleigh, wavelength shifting

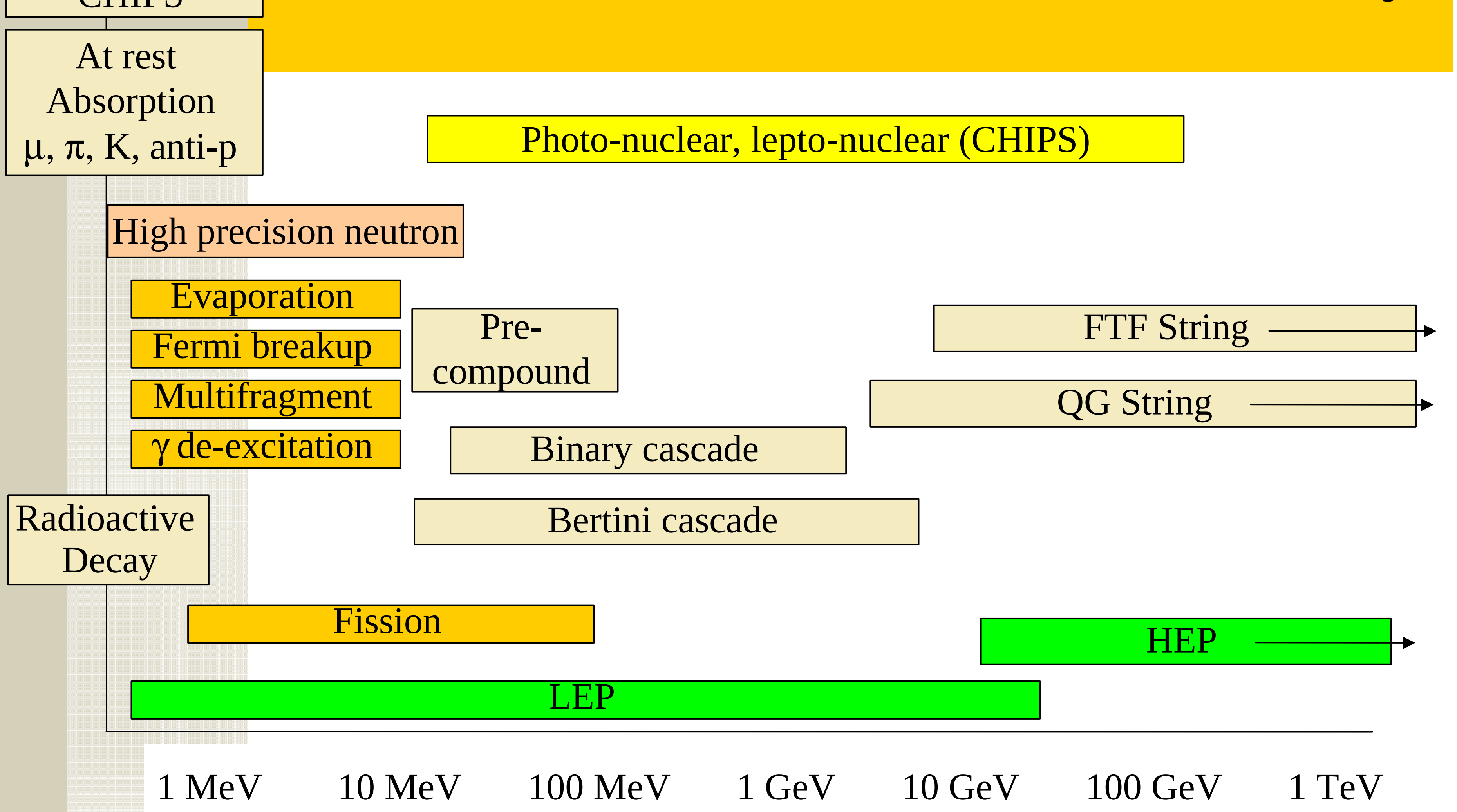
Geant4 Hadronics Philosophy

- Offer a choice of processes, models, and cross sections
- Develop a hadronics framework which is modular
  - allows users to substitute specialized physics
  - easier to add new models, cross sections as they become available
- Separate total and reaction cross sections from final state generators
  - allows easy update, multiple implementations of cross sections
  - final state generators maintain cross sections specific to model

Geant4 Hadronics Evolution

- Original goal: develop hadronic toolkit for high energy interactions at LHC
  - GHEISHA inherited from Geant3 and recast into C++
  - Quark Gluon String model and pre-compound/evaporation
  - Data driven neutron interaction
- Expanded goals and modelling options (2001-)
  - CHIPS and Cascade models (Binary, 'Bertini')
  - Ion interactions: ablation/abrasion, EM dissociation
- New models (high, low and intermediate energy) are added, with further improvements in existing models
  - Different options available for most energies, particles

Hadronic Inelastic Model Inventory



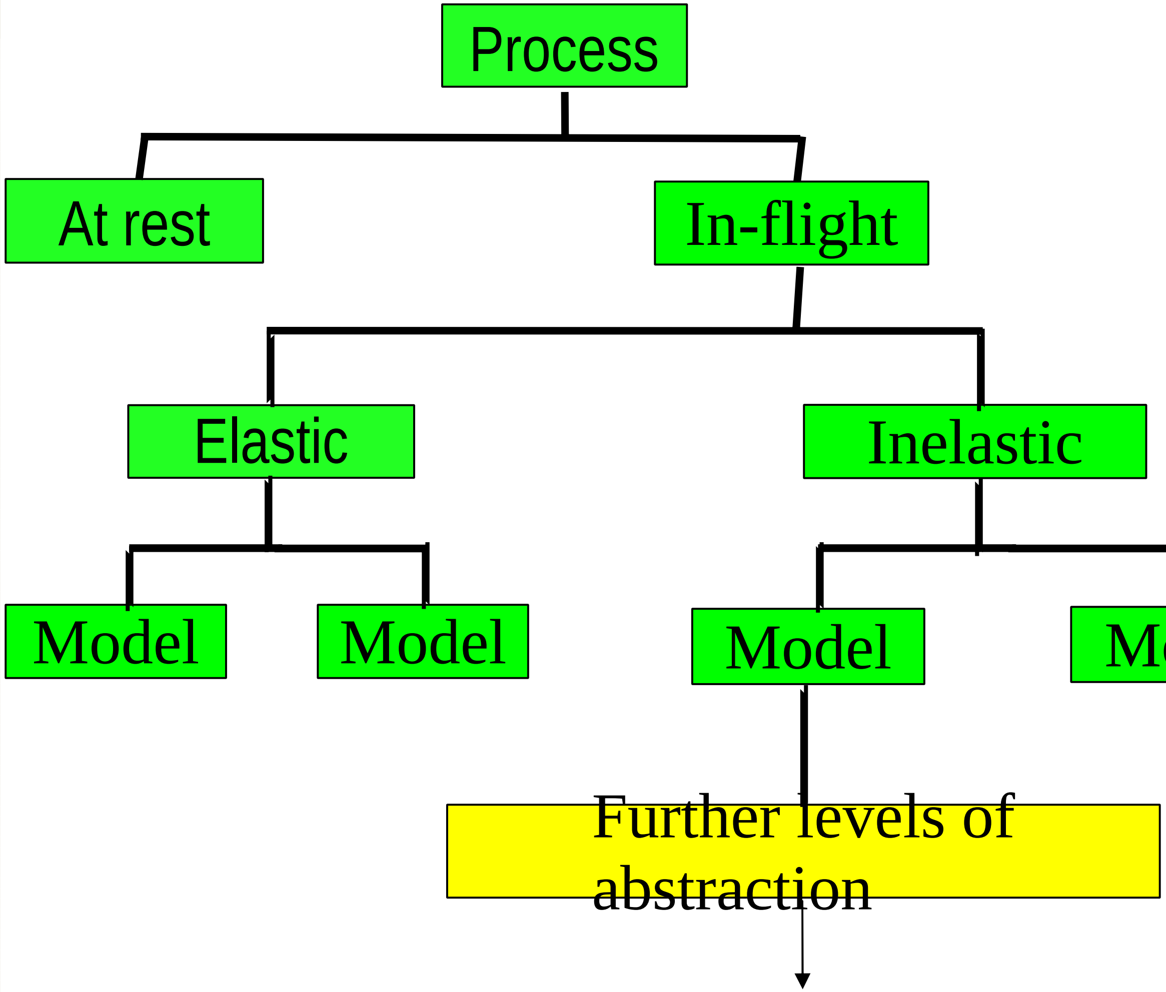
Survey of Hadronic Models

- Three broad categories of processes/'models':
  - tabulated: based on (large) databases
  - parametrized: key aspects parameterised for speed
    - Parameters determined from fits to data
  - theory-based: based on (theoretical) models
    - Parameters, if any, chosen by comparing with thin-target data

‘Theoretical’ models

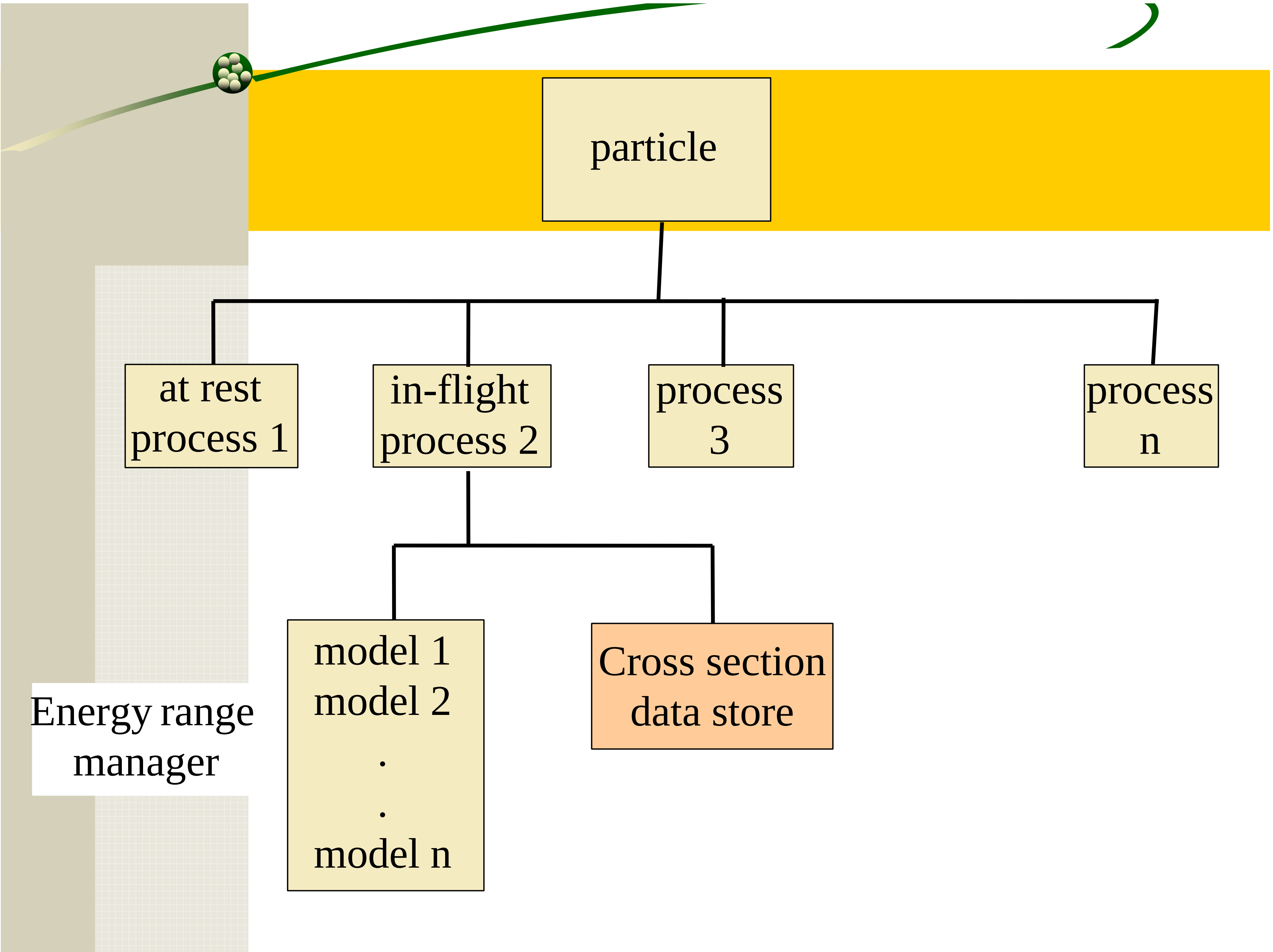
- Evaporation and pre-compound models
- Cascade and CHIPS
  - Bertini-like
  - Binary Cascade
  - Chiral Invariant Phase Space
- Quark-Gluon String (QGS) model
  - And ‘variant’ FTF model, using Fritiof approach

Hadronic Model Organization



Hadronic Processes

- At rest
  - stopped μ^-, π^-, K^-, anti-proton, Σ^-, anti-Σ^+
  - radioactive decay
- Elastic
  - models for π, K, p, n, hyperons
- Inelastic
  - different models for π, K, p, n, hyperons
  - ions
  - – capture in flight
    - (n,γ), π^-
  - – fission
    - neutron-induced
- Photo-nuclear, lepto-nuclear
  - – (neutrino-nuclear not verified yet)


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

Low and High Energy Parametrized Models

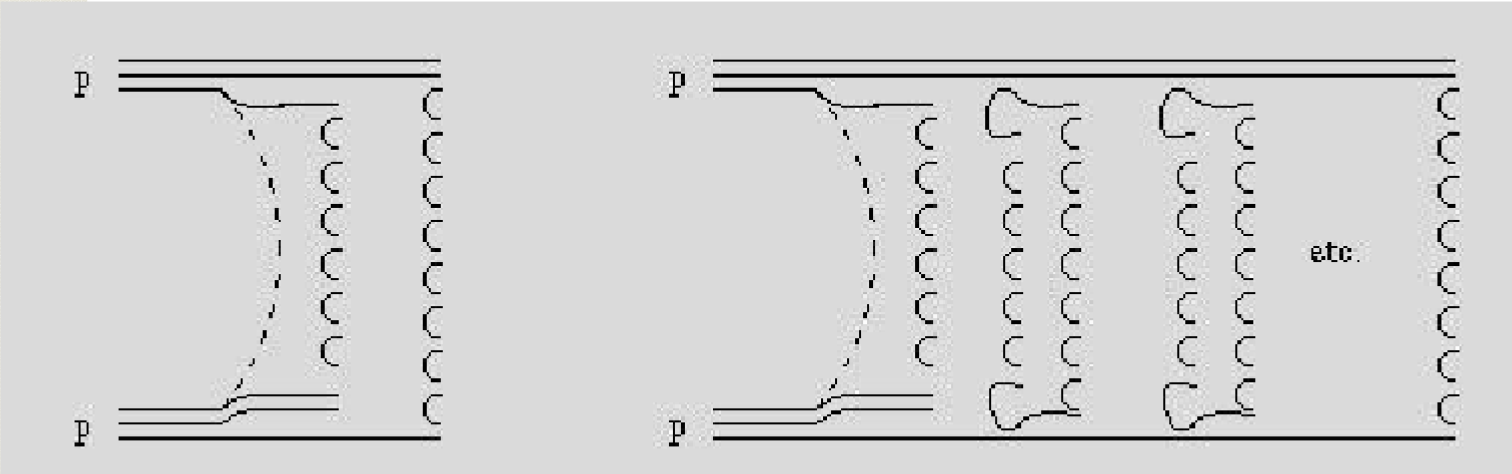
- Re-engineered, C++ version of GHEISHA
- Two pieces
  - LEP inelastic: parameters tuned for 0 – 30 GeV
  - HEP inelastic: parameters tuned for 20 GeV – 10 TeV
- Valid for all long-lived hadrons
- Also in this category:
  - elastic (all hadrons)
  - neutron capture
  - neutron-induced fission

Low and High Energy Parametrized Models

- Modelling
  - initial interaction, fragmentation of hadrons, intra-nuclear cascade, nuclear de-excitation all simulated
  - but each of these phases is parametrized
  - no modelling of target nucleus
  - no intra-nuclear tracking
  - not intended to conserve energy/momentum event-by-event
- Originally designed for shower studies
  - fast
  - originally used for higher energies (> 10 GeV), but tuned for lower energies as well (LEP part)

Quark Gluon String Model

- Interaction modelled using pomerons
  - Hadrons exchange one or several Pomerons
- Parton interaction, colored quarks
  - Valence and sea quarks
- Strings hadronize



FTF String Model

- Uses much the same machinery as Quark-Gluon String model
  - pomeron exchange, detailed nuclear model
- String excitation follows Fritiof approach
  - diffractive excitation:
    - sample the transverse part of the transferred momentum from a parametrized gaussian
    - calculate longitudinal part using light-cone constraints
  - only momentum exchanged, not partons
  - hadron-structure function parameters differ from QGS model

Binary Cascade

- Hybrid between classical cascade and full QMD model
- Detailed 3-D model of nucleus
  - nucleons placed in space according to nuclear density
  - nucleon momentum according to Fermi gas model
- Collective effect of nucleus on participant nucleons described by optical potential
  - numerically integrate equation of motion
- Particle interaction by resonance formation and decay

Bertini-like Cascade

- The Bertini model is a classical cascade:
  - it is a solution to the Boltzmann equation on average
  - no scattering matrix calculated
- Core code:
  - elementary particle collider: uses free-space cross sections to generate secondaries
  - cascade in nuclear medium
  - pre-equilibrium and equilibrium decay of residual nucleus
  - Nucleus modelled as shells of different densities

Precompound and Nuclear De-excitation Models

- Precompound Model – used to take the nucleus from a highly excited state down to equilibrium
- May be used:
  - by itself for p, n below 170 MeV or
  - as a “back-end” for cascade or high energy models
- Model begins with nuclear excitation energy, a set of excitons, and a parametrized level density
- Excitons are decayed until equilibrium is reached, then control is transferred to competition of low energy models
  - evaporation, fission, Fermi breakup, multi-fragmentation, photon evaporation

High Precision Neutrons

- data-driven, based on G4NDL data library which consists of data from ENDF, JENDL, CENDL, BROND, JEF, MENDL
- covers
  - elastic
  - inelastic (n, p, d, t, ^{3}He, α in up to 4-body phase space final states)
  - radiative capture (discrete + continuous gamma spectra)
  - fission
- incident energies from thermal to 20 MeV
- modeling:
  - cross sections, angular distributions, final states all tabulated
  - sample from interpolated data tables

Chiral Invariant Phase Space (CHIPS) Model

- Theory-driven model based on quasmons (an ensemble of massless partons uniformly distributed in invariant phase-space)
  - a quasmon can be any ground state hadron or excited system of hadrons
- Quasmon hadronizes by internal quark fusion and/or quark exchange with partons in neighbouring nucleon clusters
- Originally developed as a final state generator
  - now used for:
    - nuclear capture of negatively charged hadrons
    - gamma-nuclear reactions
    - lepto-nuclear reactions

Absorption At Rest

- Processes available to handle all negative, long-lived hadrons
  - anti-proton and and anti-sigma+ included
- Also for μ^-, τ^-
- Above processes implemented by CHIPS model
- Alternative processes available for μ, π

Coherent Elastic Scattering

- Tabulated models for pp, np elastic scattering from 10 -1200 MeV
  - data from SAID database (Arndt, 1998)
- Glauber model approach for h-A scattering
  - all hadrons (incident energy 1 GeV < E < 300 GeV)
  - two-gaussian form for nuclear density (edge of nucleus is most important)
  - fitting of nuclear density parameters done from A = 4 to A = 208 using data from p-A elastic scattering at 1 GeV
  - also uses total h-A cross section data

Binary Light Ion Model

- Based on the binary cascade model
- For ion-ion collisions $A_{projectile}$ or A_{target} < 13
  - this limitation due to lack of correlation between projectile and target nucleons
- $E_{projectile}$ < 10 GeV/N
- Initial state of cascade formed by including positions and momenta of projectile nucleons with those of target
- Final state fragments formed by statistical combination of ejected p, n
- Transition to pre-compound model governed by $E_{ex} = \Sigma(E^P_{fermi} - E^P)$; P is index of nucleon participant

Abrasion/Ablation Model

- A simplified macroscopic model for nucleus-nucleus collisions
  - based largely on geometric arguments
  - non-relativistic dynamics
  - faster, but less accurate than binary light ion
- Appropriate for collisions of all A, E < 10 GeV/N
- First phase is Wilson abrasion
  - overlap region between projectile and target is sheered off
  - spectator nucleons in target and projectile assumed to undergo little change
- Second phase is ablation, which is handled by Geant4-implemented de-excitation models:
  - Evaporation, fission, Fermi breakup, multi-fragmentation

Electromagnetic Dissociation Model

- Describes the emission of p,n due to hard virtual photon spectrum from high-Z, relativistic nuclei
- Dipole and quadrupole fields of the target nucleus are used to calculate the virtual photon spectrum
- Integrated photo-nuclear cross sections and virtual photon flux used to get total electro-dissociation cross section
- Proton emission cross section is a Z-dependent fraction of the total e.d. cross section
  - neutron emission cross section is the remainder
- Two-body decay of excited nucleus
  - nucleon emitted isotropically in rest frame of nucleus

Radioactive Decay

- Tabulated model for α, β^+, β^- emission and electron capture in nuclei
  - β and ν spectra sampled from either 3-body or tabulated data
- Data from ENSDF (evaluated nuclear structure data file)
  - half lives
  - nuclear level structure for parent or daughter
  - decay branching ratios
  - energy of the decay process
- If daughter is an excited isomer, prompt nuclear de-excitation is performed with Geant4 photon evaporation model

Survey of 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 parametrize c.s.
  - some represent large databases
  - some are purely theoretical

Default Cross Sections

- Elastic, inelastic from GHEISHA with modifications
  - for p-A, π–A, use tabulated fits to data
  - interpolate in A where there is no data
  - for all others, make particle-specific corrections to p-A, π–A cross sections
- Capture
  - for neutrons only
  - $\sigma = 11.12\ \sigma(Z)\ /\ KE^{0.577}$
- Fission
  - for neutrons only
  - direct table lookup for $^{233,235}U$, ^{239}Pu, KE < 10 MeV
  - all others: table lookup x (38.7 $Z^{4/3}$ /A – 67) up to 1 TeV

Alternative Cross Sections

- Low energy neutrons
  - G4NDL available as Geant4 distribution data files
  - elastic, inelastic, capture, fission
  - Available with or without thermal cross sections
- “High energy” neutron and proton reaction σ
  - 14 MeV < E < 20 GeV
- Pion reaction cross sections
- Ion-nucleus reaction cross sections
  - Good for E/A < 10 GeV

Hadronics Summary

- *Hadronic processes require physics models and cross sections*
  - *user must choose (carefully)*
  - *more than one model and/or cross section allowed*
- *Many models offered – three main types:*
  - *tabulated*
  - *parameterized*
  - *theory-driven*
- *Most cross section sets provided by default*
  - *alternative cross sections are available*

Other Summary

- G4 provides full detector simulation capabilities & more
  - Flexible geometry modeler for many, complex volumes
  - Tracking, event biasing, scoring, hit creation
- Configurations of physics models provide physics options
  - Tailored for sets of application areas
  - Created, tested for key application areas
    - QGSP, LHEP, QGSC, with emerging cascade options (eg QGSP_BIC)
  - Starting points for further refinements, also by users
- Standard models of EM interactions (EM physics)
    - and extensions to low energies, specialised modeling

Backup slide(s)

EM production threshold

- Thresholds
  - Charged particles are tracked down to zero energy
  - Production threshold for delta electrons expressed in length
- Threshold in length chosen in order to optimise CPU use

Geant4 Parameterised models

- Are used in many areas
  - They form the LHEP physics list
  - Used where alternative models cannot bridge energy ‘gap’
  - Used for most interactions of Σ, Ω, ..
- Benefit from their speed and versatility

Geometry (2)

- Solid based geometry
  - Easy for user to describe
- Built-in navigator
  - Also tools to validate/check geometry model
- Multiple levels of hierarchy
  - To describe complex structures
    - LHC detectors of few million of volumes