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Hadronic Physics 1

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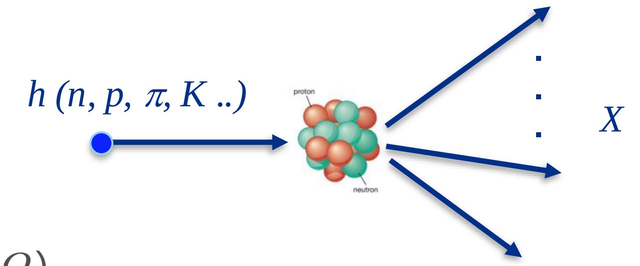
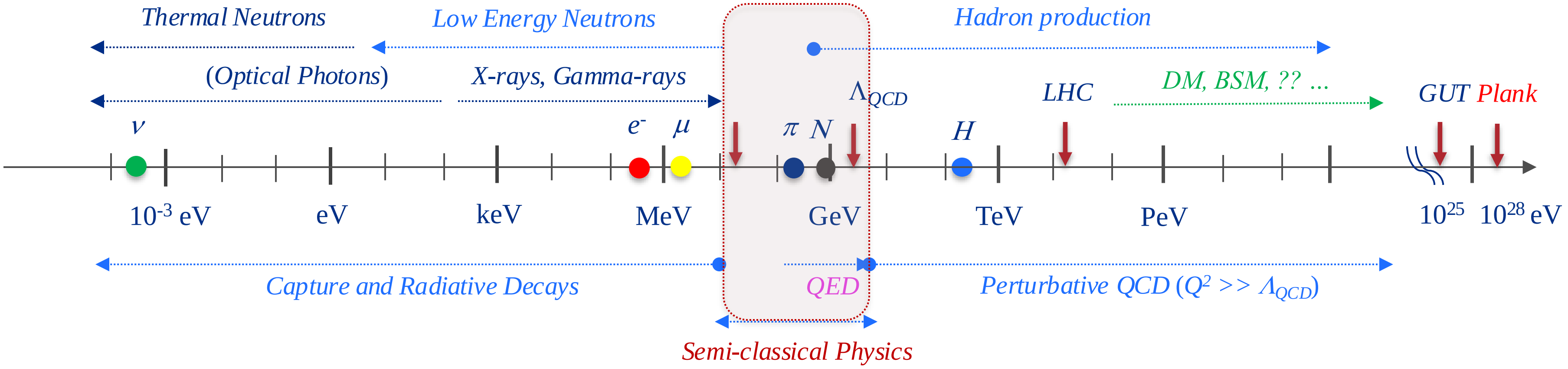
Introduction: What is hadronic physics in Geant4?

- Hadron-nucleus interactions: hadron + nucleus → X
  - Projectile (particle → hadron) (except γ- or lepto-nuclear)
  - Target (Material → Elements → Isotopes → Nucleons)
  - Elastic, inelastic, capture, fission, radiative decays, etc.
  - X is the model-dependent final states (multiplicity, $d^2\sigma/dEd\Omega$)

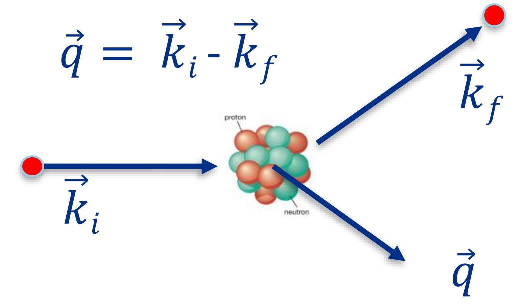


- Hadronic physics involves multiple energy scales using models with varying levels of details

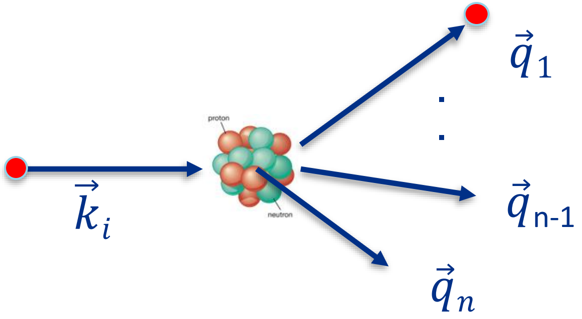


Hadronic Physics Processes

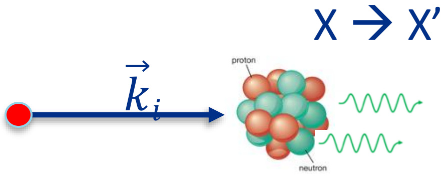
- Type of hadron-nucleus interactions: main categories



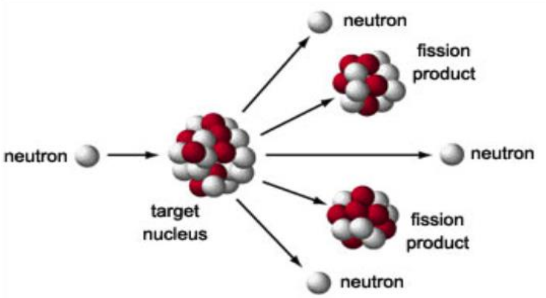
Elastic (kinematics is conserved)



Inelastic (kinematics is not conserved)



Capture (→ level transition, evaporation)



Fission (abrasion and break-up)

Hadronic Physics Processes

- Depend on the particle type and energy
  - G4HadronElasticProcess
  - G4HadronInelasticProcess
  - G4NeutronCaptureProcess
  - G4NeutronFissionProcess
  - G4RadioactiveDecay
  - EM-like Processes (of charged hadrons)
    - Coulomb, multiple scattering
    - Ionization, Bremsstrahlung

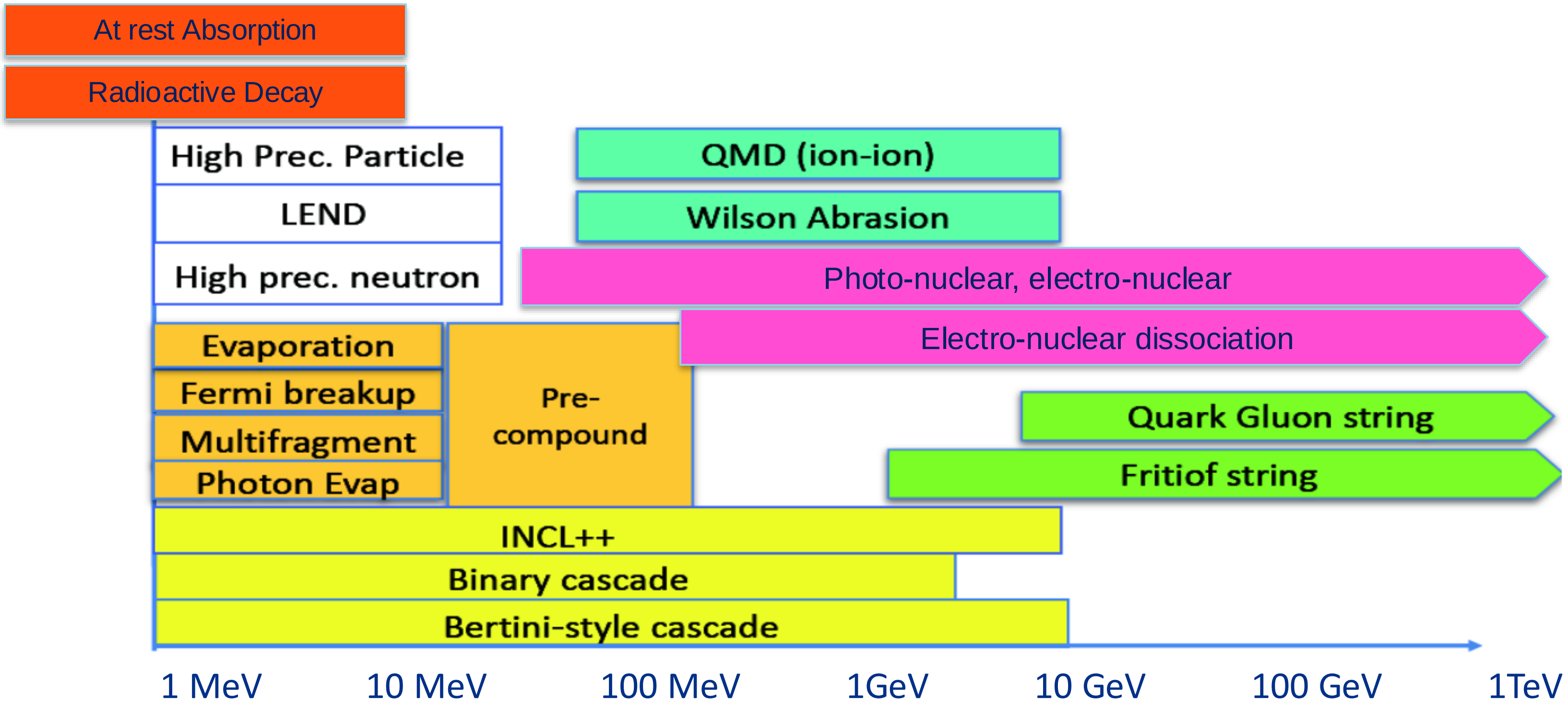
```
./exampleB2a
/particle/select pi+
/particle/process/verbose 0
/particle/process/dump
```

```
-------------------------------------------------------------------
                           Hadronic Processes for pi-
 Process: hadElastic
       Model:            hElasticGlauber: 0 eV  ---> 100 TeV
    Cr_sctns:  BarashenkovGlauberGribov: 0 eV  ---> 100 TeV
 Process: pi-Inelastic
       Model:                       FTFP: 3 GeV ---> 100 TeV
       Model:              BertiniCascade: 0 eV  ---> 6 GeV
    Cr_sctns:  BarashenkovGlauberGribov: 0 eV  ---> 100 TeV
 Process: hBertiniCaptureAtRest
-------------------------------------------------------------------
```

```
G4ProcessManager: particle[pi-]
[0]=== process[Transportation :Transportation] Active
[1]=== process[msc :Electromagnetic] Active
[2]=== process[hIoni :Electromagnetic] Active
[3]=== process[hBrems :Electromagnetic] Active
[4]=== process[hPairProd :Electromagnetic] Active
[5]=== process[CoulombScat :Electromagnetic] Active
[6]=== process[Decay :Decay] Active
[7]=== process[hadElastic :Hadronic] Active
[8]=== process[pi-Inelastic :Hadronic] Active
[9]=== process[hBertiniCaptureAtRest :Hadronic] Active
[10]=== process[StepLimiter :General] Active
[11]=== process[UserSpecialCut :General] Active
```

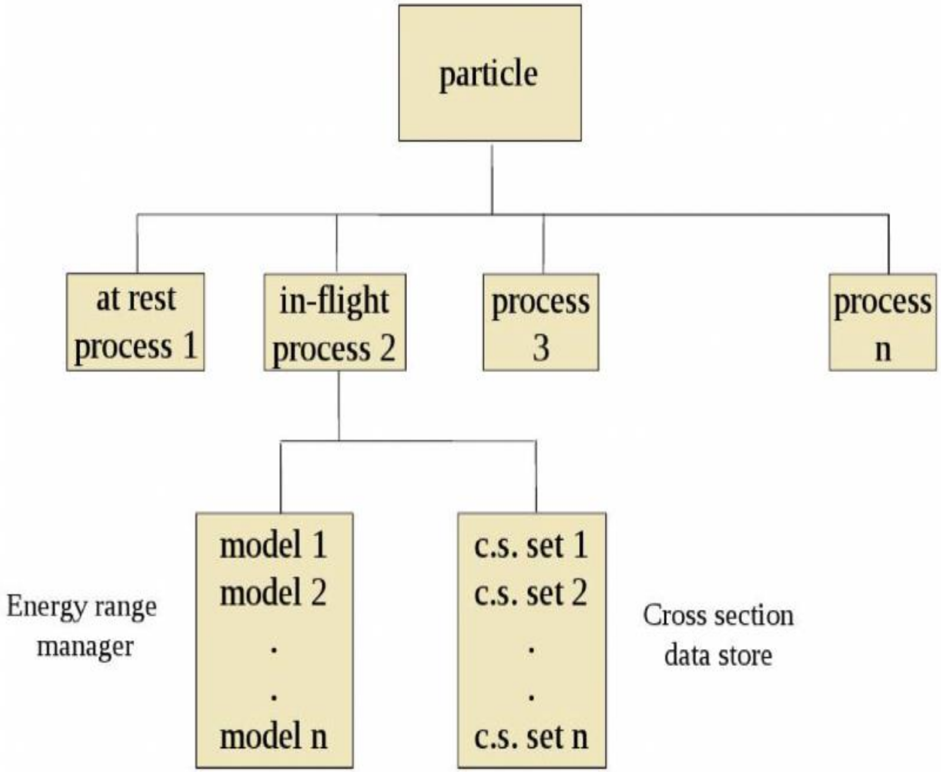
Hadronic Physics Models

- Theory-driven, parameterization, data-driven



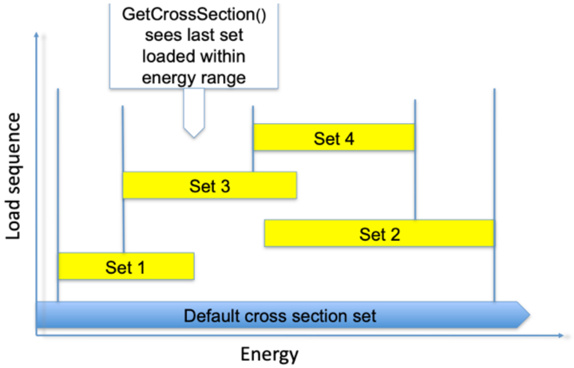
Hadronic Physics Framework: Processes and Models

- Physics interactions (between a particle and material) occur through processes
- Each process may be implemented directly or a model class linked to the process
- Geant4 often provides multiple models for a given process (choose during physics list setup)
- A process must also have (multiple) cross sections (tables) assigned (set up in a physics list)



Hadronic Cross Sections

- Geant4 separates hadronic process cross sections from hadronic final states models
  - Interaction cross sections (probability per unit length) → mean free path → sample interaction length(λ_{int})
  - Differential cross sections → final state distributions (energy, angular direction)
- Default cross section sets are provided for each hadronic process, but they can be overridden or completely replaced by different types of cross section sets by {particle, material, energy}
- Different types of cross section sets
  - Parameterization with "fitted" functions
  - Large databases
  - Purely theoretical (equation-driven)
- Cross section sets are inclusive

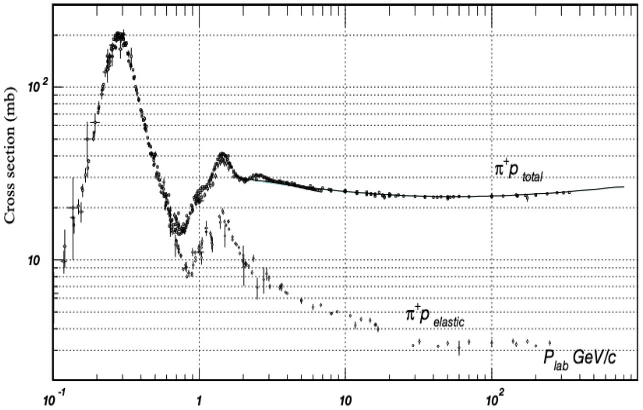


- Hadronic final states models describe the properties of the secondaries from the hadronic interaction (G4HadronicProcess::GetHadronicInteraction())

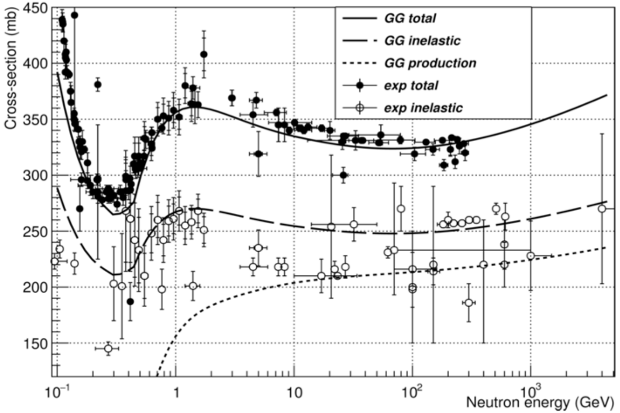
Hadronic Processes and Cross Sections

- Hadron-nucleus cross sections
  - Hadron-nucleon cross sections: PDG parameterization
  - Neutron-nucleus: G4PARTICLEXS4.0 (elastic, inelastic, capture)
  - CHIPS kaon and hyperon nuclear
  - All other hadron-nucleus: Glauber-Gribov cross sections

PDG π^+p



n+Cu



- Nucleus-nucleus and antinucleus-nucleus cross sections

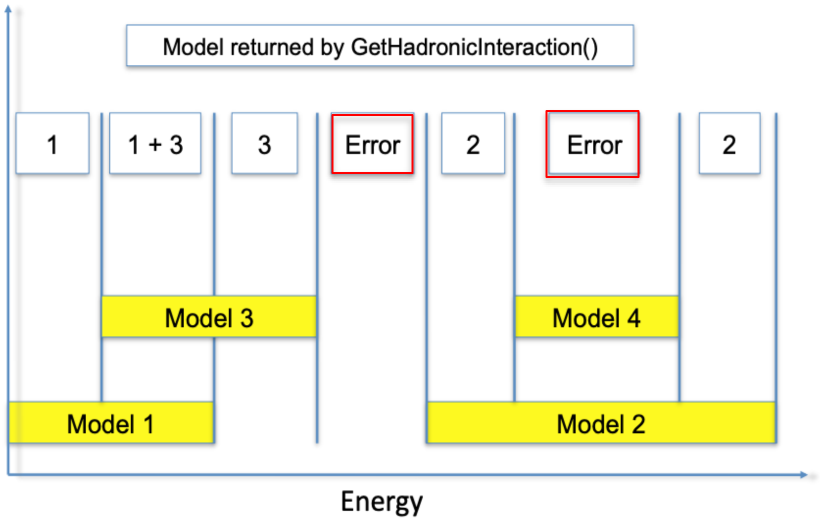
Geant4 Datasets

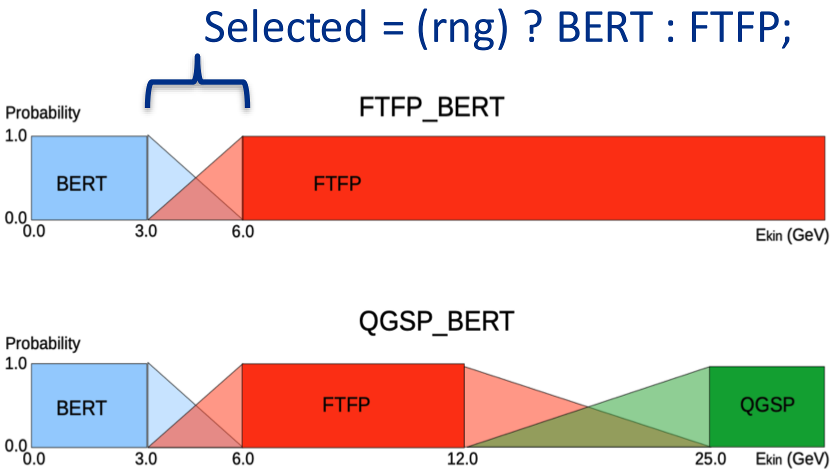
- The cmake option -DGEANT4_INSTALL_DATA=ON automatically download datasets
- Following envs are exported by geant4.sh and linked to dataset files (share/Geant4/data)

Dataset (env)	Data File	Related Process or model
G4ABLADATA	G4ABLA3.3	Data for the ABLA de-excitation model (INCLXX)
G4LEDATA	G4EMLOW8.5	Low-energy electromagnetic data
G4ENSDFSTATEDATA	G4ENSDFSTATE2.3	Nuclear properties from ENSDF
G4INCLDATA	G4INCL1.2	Data for the intranuclear cascade INCLXX model
G4NEUTRONHPDATA	G4NDL4.7.1	Neutron data of cross sections and final state dist.
G4PARTICLEXSDATA	G4PARTICLEXS4.0	Average cross sections derived from G4NDL
G4PIIDATA	G4PII1.3	Proton/alpha ionization (PIXE) cross section library
G4SAIDXSDATA	G4SAIDDATA2.0	SAID database for nucleon and π cross sections
G4LEVELGAMMADATA	PhotonEvaporation5.7	Photon evaporation (deexcitation) data from ENSDF
G4RADIOACTIVEDATA	RadioactiveDecay5.6	Radioactive decay data from ENSDF
G4REALSURFACEDATA	RealSurface2.2	Optical surface reflectance look-up tables

Hadronic model validity range

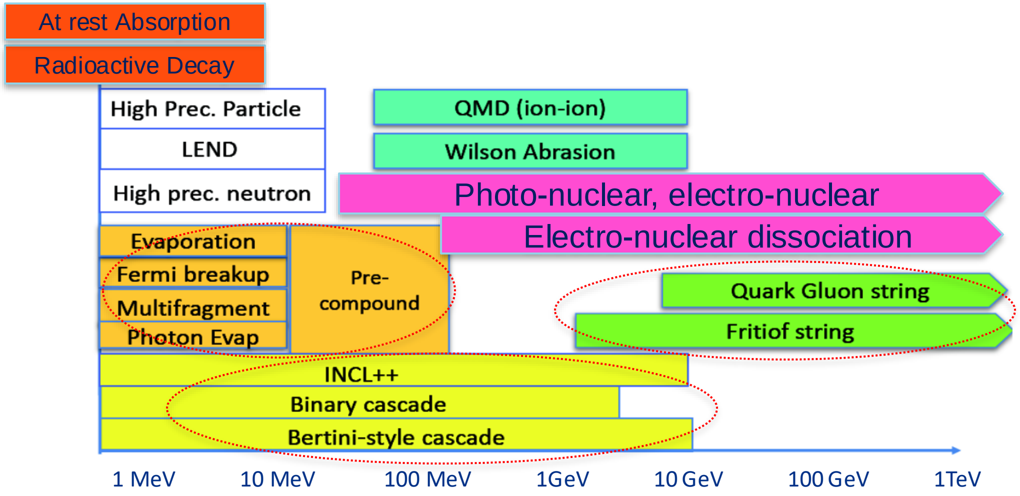
- Processes may have one or more models registered to them: G4HadronicProcess::RegisterMe(…)
  - Each model must have an associated energy - default values can be changed in physics list setup
  - Ranges may overlap at ends, but must not be enclosed (duplicated)
  - No energies may be excluded
  - Overlaps are “interpolated” with linear random selection at each interaction





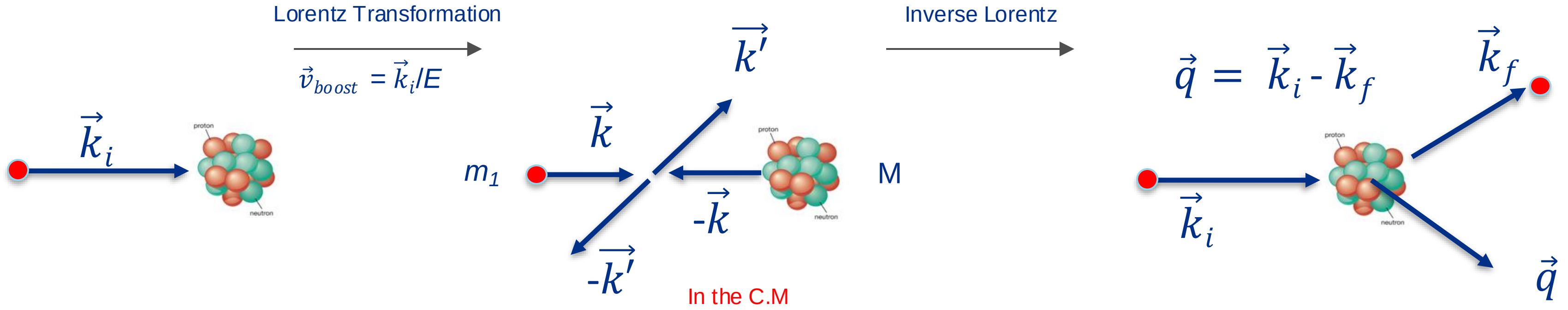
Hadronic Inelastic models at Medium and High Energy

- Intra-nucleus cascade models
  - Bertini (BERT)
  - Binary (BIC)
  - INCL++ (Liege, INCLXX)
- Parton String models
  - Quark-gluon string (QGS)
  - Fritiof (FTF)
- Other associated models
  - Pre-compound (P)
  - de-excitation (evaporation, Fermi-breakup, fission)
- Physics lists: FTFP_BERT, QGSP_BERT, QGSP_BIC, FTFP_INCLXX



Hadron Elastic Scattering Models at Medium and High Energy

- Coherent scattering



- Glauber model: impact parameter($\vec{b}$) and the momentum transfer, $|\vec{q}|^2 = -t$ in the C.M system. Sampling/parameterization of q^2 and $M(\vec{b})$ by A(Z) and particle energy is a core of the model (true for CHIPS)

$$F(q) = \frac{ik}{2\pi} \int d^2 b e^{\vec{q}\cdot\vec{b}} M(\vec{b})$$

Angular Distribution →

$$\frac{d\sigma}{d\Omega_{CM}} = |F(q)|^2$$

Momentum Distribution →

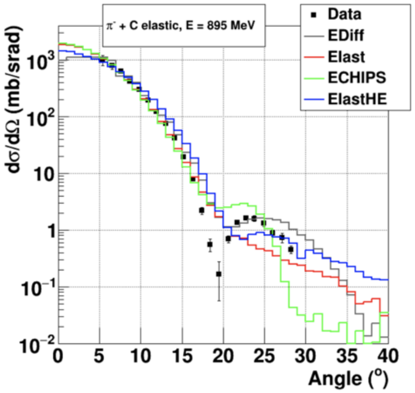
$$\frac{d\sigma}{|dt|} = \frac{d\sigma}{dq^2_{CM}} = \frac{\pi}{k^2_{CM}} |F(q)|^2$$

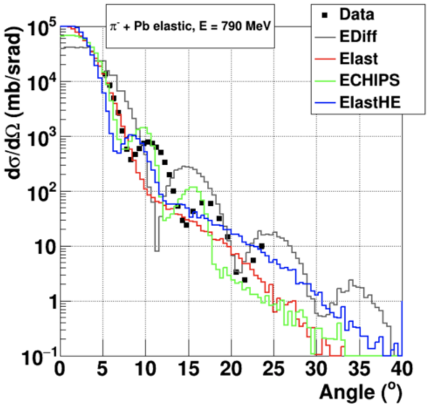
Hadron Elastic Models at Medium and High Energy

- Coherent elastic models

	Model	Differential Cross Section	Energy Range
proton	G4ChipsElasticModel (CHIPS)	BarashenkovGlauberGribov	0-100 TeV
neutron	G4ChipsElasticModel (CHIPS)	G4NeutronElasticXS (CHIPS)	0-100 TeV
pion	G4ElasticHadrNucleusHE (Glauber)	BarashenkovGlauberGribov	0-100 TeV
Kaon, Hyperons	G4HadronElastic (LHEP)	Glauber-Gribov	0-100 TeV
Anti-particles	LHEP/G4AntiNuclElastic	AntiAGlauber	0/100 MeV/100TeV
Nuclear-nuclear	G4NuclNuclDiffuseElastic	Glauber-Gribov	0-100 TeV

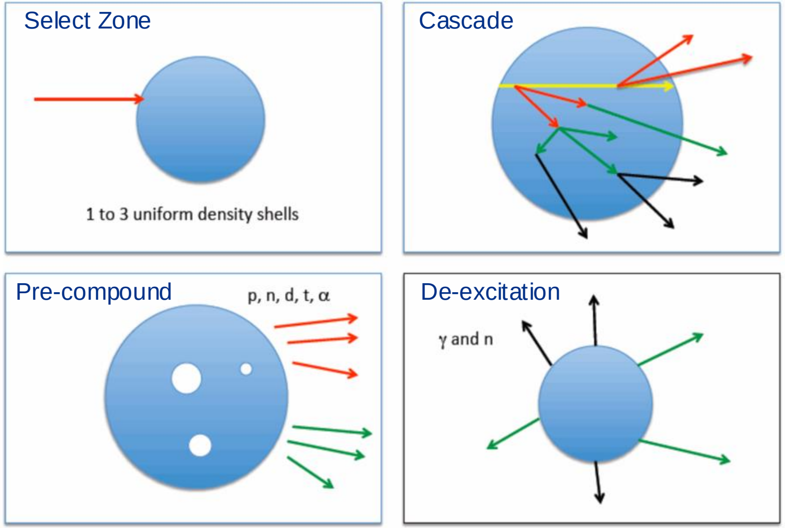
- Comparison to experimental data
  - Data: $\pi^{\pm}$ elastic from EXFOR database
  - Elast: Default elastic model
  - ECHIPS: CHIPS model
  - ElastHE: Glauber-Gribov
  - EDiff: Diffuse model





Bertini Intranuclear Cascade

- Intranuclear treatment of stable hadrons $(p, n, \pi, K, \Lambda, \Sigma, \Xi, \Omega)$ and γs with energies in [0,10] GeV: average solution of particle in medium (Boltzmann equation) – non-QCD cascade
  - Valid in de Broglie wavelength < intranuclear distance
  - Fast (10^{-23} – 10^{-22}): excitation, pre-equilibrium, fission
  - Slow (10^{-18} – 10^{-16}): evaporation
- Intranuclear cascade model
  - Select target nucleus zone (1, 3, 6)
  - Path length (nucleon density, particle-particle xsec)
  - Determine the type of reaction and products (channels)
  - Apply excitation model
  - Pauli exclusion principle and transport particle
  - Particles produced by the reaction will be input to the next cascade
  - Pre-equilibrium and equilibrium decay of residual nucleus



Post Cascade

- Pre-equilibrium model
  - Nucleon states are characterized by the number of excited particles and holes (the excitons)
  - $\Delta p = 0, \pm 1$ $\Delta h = 0, \pm 1$ $\Delta n = 0, \pm 2$, where p is the number of particles, h is number of holes and $n = p + h$ is the number of excitons.
- Fermi Break-up model
  - Light nuclei (A < 12 and 3(A-Z) < Z < 6) and $E_{excitation} > 3\ E_{binding}$
  - Decays nucleus → neutrons and protons and decrease exotic evaporation processes
  - Fission model is phenomenological, using potential minimization
- Evaporation model
  - The emission of particles is computed until the excitation energy falls below some specific cutoff
  - The main chain of evaporation (n, p, d, t, α) is followed until $E_{excitation}$ falls below E_{cutoff} = 0.1 Mev
  - The model ends with an (gamma) emission chain which is followed until $E_{excitation} < E^{\gamma}_{cutoff} = 10^{-15}$ MeV

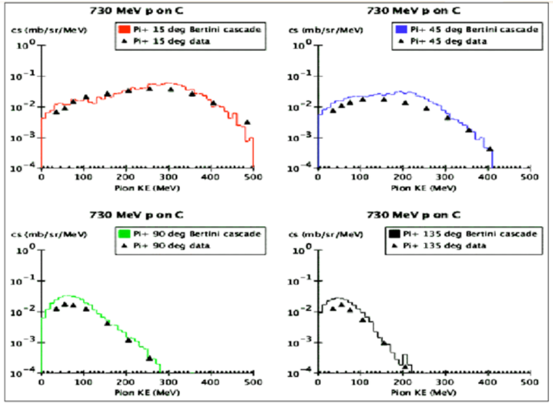
Using Bertini Intranuclear Cascade and Validation

- Add G4CascadeInterface

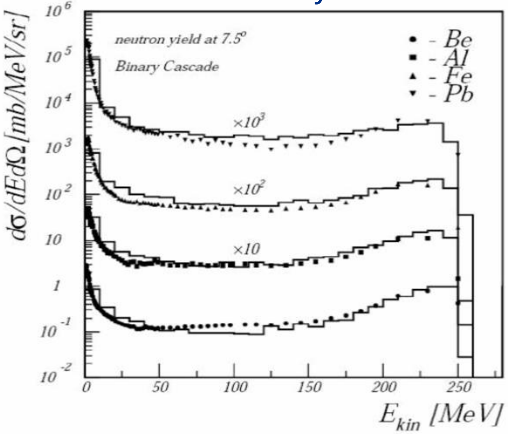
```
G4CascadeInterface* bert = new G4CascadeInterface;
G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess;
pproc->RegisterMe(bert);
protonManager->AddDiscreteProcess(pproc);

// Repeat as necessary for other hadrons
```

- Physics validation of cascade models: examples

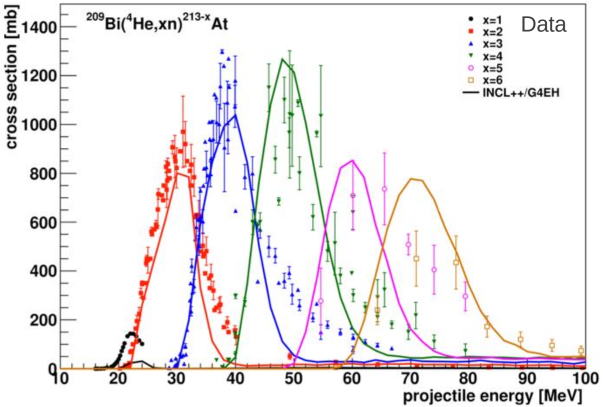
Bertini Cascade 730 MeV *p* + C → π +X



Binary Cascade 250 Mev *p* Neutron yield



INCL++ Excitation functions for (α, *xn*) cross sections on ^{209}Bi

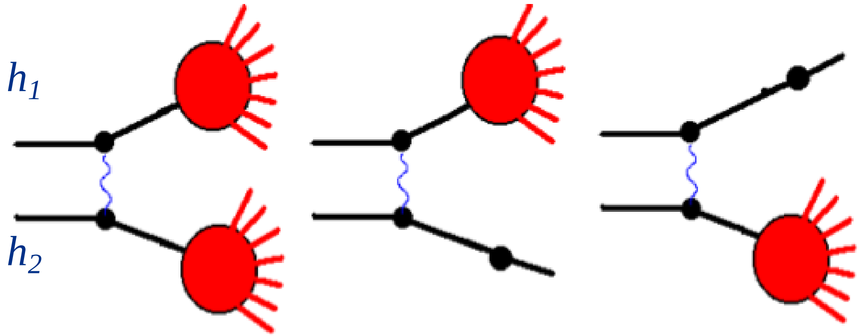


Fritiof (FTF) Model

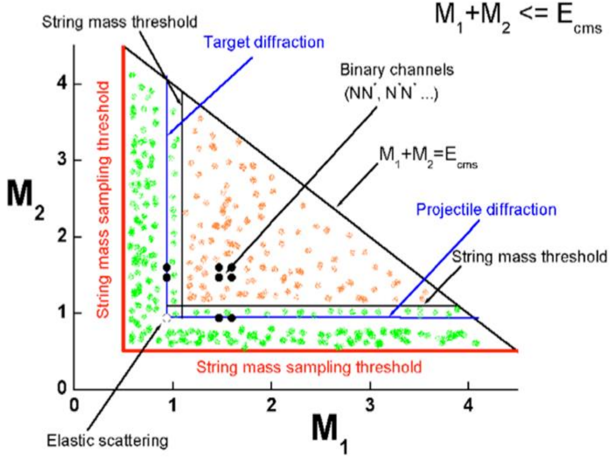
- Hadron-nucleus, nucleus-nucleus, antinucleus-nucleus ($p \gtrsim 3$ GeV per hadron or nucleon).
- Hadron-nucleon interactions are binary reactions ($h_1 + h_2 \rightarrow h_1' + h_2'$) of quark-gluon strings
  - NN → NΔ, πN → πΔ, non-diffractive, single diffractive and annihilation in antibaryon-nucleon interactions
  - Lund string fragmentation model is used for the simulation of unstable object decays

Non-Diffraction

Diffractive dissociations



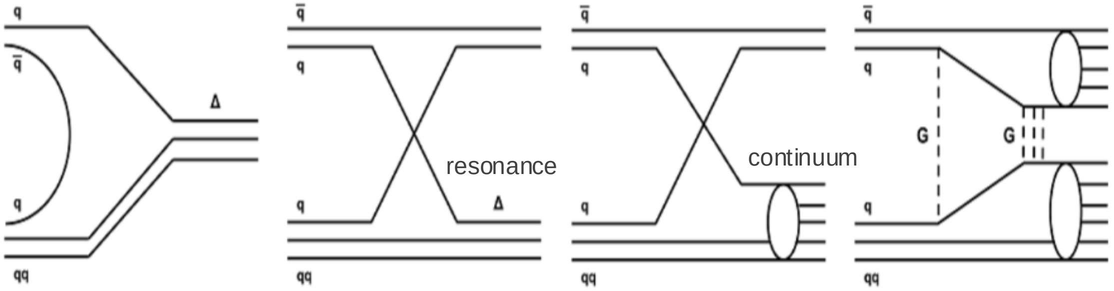
Excited hadron: QCD-strings +LUND



- The reggeon theory inspired model (RTIM) of nuclear destruction is applied for a description of secondary particle intra-nuclear cascading and sampling of string masses.

Fritiof (FTF) Model

- All hadron-nucleon interactions are binary reactions of quark-gluon strings
  - π^-p and π^+p interactions
  - pp and $p\bar{p}$ interactions
  - K^-p and K^+p interactions
  - …



Quark annihilation | Quark exchanges | Pomeron exchanges

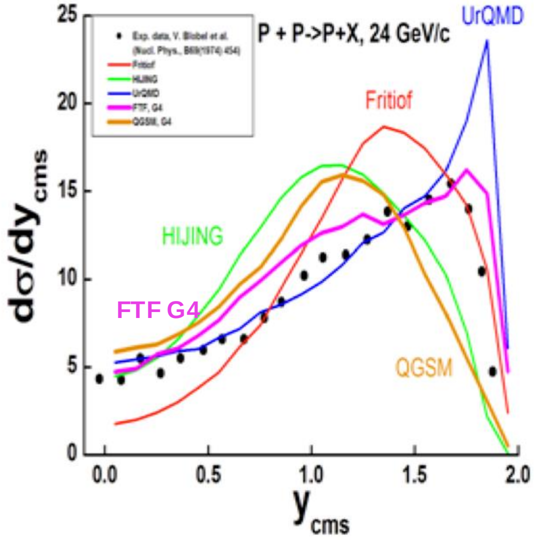
- Reaction cross sections:
  - CHIPS parameterization for inelastic (and elastic) hadron-nucleus cross sections
  - The annihilation cross section decreases rapidly while the cross sections of the quark exchange processes decrease more slowly. The diffraction cross sections grow with energy and reach near-constant values

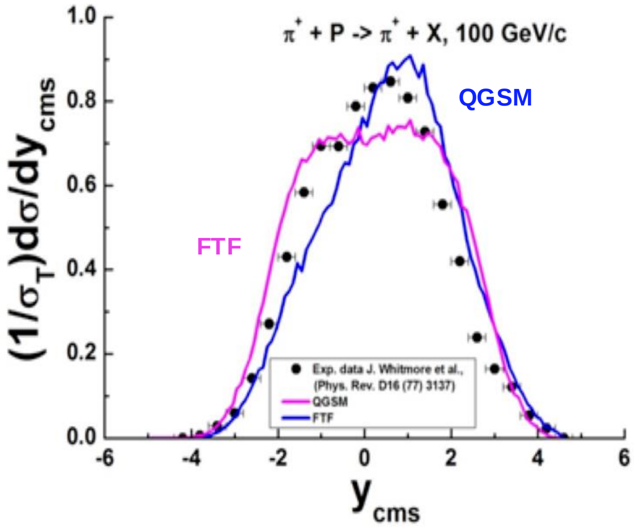
$$\sigma = \sigma_{LE} + \sigma_{As}$$

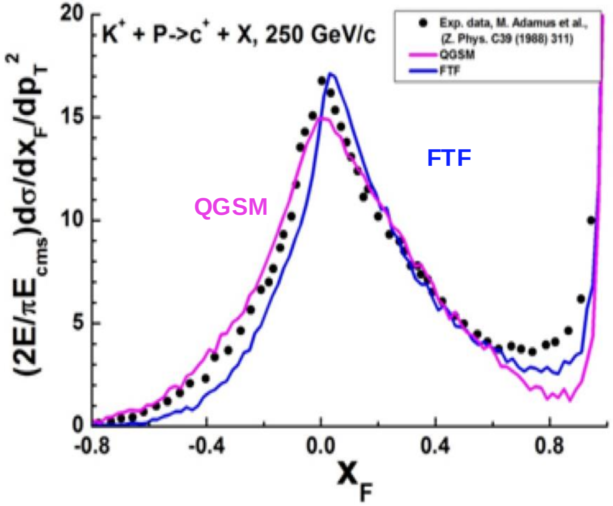
  - A simplified Glauber model is used for sampling the multiplicity of intra-nuclear collisions

Validation of FTF Cross Sections

- Example of FTF spectra compared to other model predictions
  - Inclusive spectrum of proton in p + p → p + X interactions at p_{lab} = 24 GeV/c
  - Rapidity spectrum of π^{+}-mesons in π^{+} + p → π^{+} + X interactions at p_{lab} =100 GeV/c
  - x_F spectrum of positive charged particles in K^{+} + p → c⁺ + X nteractions at p_{lab} =250 GeV/c

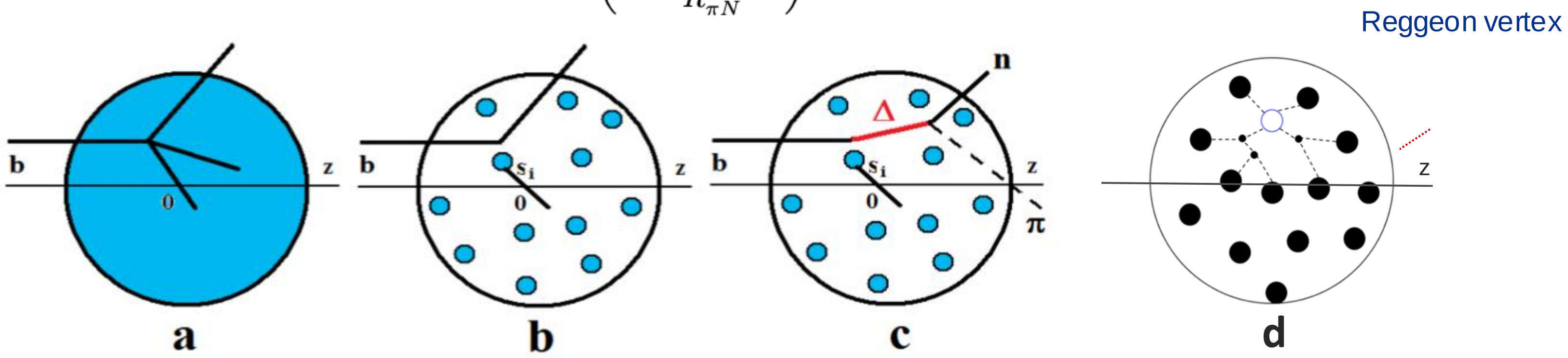






FTF Inter-nuclear Interactions

- Sampling of intra-nuclear collisions
  - a) Classical cascade: interaction probability in the continuous medium, $p(\mathbf{b}, z)$ → elastic, inelastic → next {interaction points or cascades}
  - b) Interaction with a collection of A nucleons in the point {s_i, z | i =1,A} if $|\vec{b} - \vec{s}_i| \leq \sqrt{\sigma^{tot}/\pi}$
  - c) Resonance-nucleon collisions (at high energy → Glauber approximation)
  - d) Reggeon cascading $\phi(|\vec{s}_1 - \vec{s}_2|) \sim \exp\left(-\frac{|\vec{s}_1 - \vec{s}_2|^2}{R^2_{\pi N}}\right)$



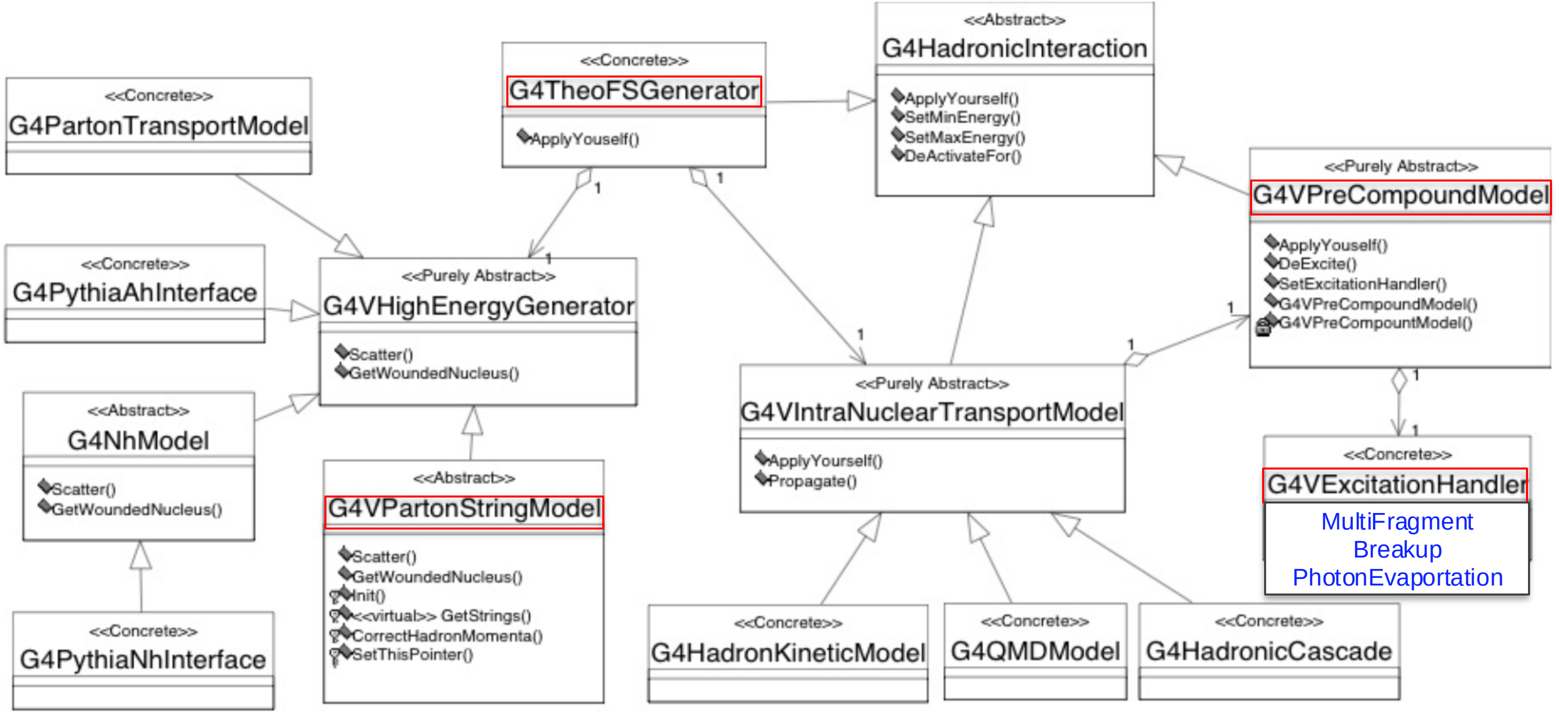
  - Excitation energies of residual nuclei are estimated in the wounded nucleon approximation (coupled to the Precompound model and GEM)

Precompound and De-excitation Models

- The excited nuclear remnant created by FTF (or cascade models) is passed to Precompound and de-excitation models
- Pre-compound model handles
  - Nucleon or pion absorption at low energies (roughly below pion emission threshold)
  - Nuclear fragments resulting from higher energy interactions
  - Wounded nucleus with set of excited particle-hole states
  - Level density of excited (n-exciton) states and transition probabilities (Δn = +2, 0, -2)
  - Resolves to equilibrium, emitting *p, n, d, t*, ^{3}He, *α* and other fragments and calculation of kinetic energies for emitted particle and parameters of residual nucleus
- De-excitation model resolves excess energy in nucleus closer to equilibrium
  - Nuclear evaporation or GEM (general evaporation model)
  - Fermi break-up and nuclear fission (A > 65)
  - Photon evaporation (discrete and continuum gamma emission)

Hadronic Framework

- Use various intra-nuclear transport or pre-compound models together with models simulating the initial interactions at very high energies



Hadronic Inelastic Physics Constructor

- The modular physics list, FTFP_BERT is recommended for HEP and consists of
  - G4HadronElasticPhysics : Hadron elastic physics constructor (CHIPS, GG models, etc.)
  - G4HadronPhysicsFTFP_BERT Hadron inelastic physics constructor (G4HadronPhysicsFTFP_BERT)
    - FTF: (Fritiof) hadronic string model for hadron inelastic process > 3 GeV
    - BERT: (Bertini) intra-nuclear cascade model for the hadron inelastic process < 6 GeV
    - P: Precompound model for nucleus de-excitation + evaporation models below 100MeV
    - Neutron radiative capture, nuclear capture at rest for negatively charged hadrons
  - G4EmStandardPhysics: EM standard physics constructor
  - G4EmExtraPhysics: lepto-nuclear (100MeV) and gamma-nuclear processes (10 MeV – 1.2 GeV)
  - No high-precision treatment of low-energy neutrons and no radiative decays (explained in hadronic physics II), no optical photons

Summary

- Geant4 implements hadronic processes,
  - Two main processes are the hadron elastic and the hadron inelastic processes
  - For negatively charged hadrons the nuclear capture at rest process is included as well
  - For neutrons, the radiative capture process is also included
- In Geant4 hadronic cross section datasets and final states models are clearly separated
- Several final state models are available and applicable to restricted combinations of energies, particles and materials
  - Cascade models (Bertini, Binary, INCL++)
  - Quark-gluon string models (FTF, QGS)
  - Precompound model (P)
- Reference physics lists construct hadronic physics by picking up both hadronic final states models and cross section datasets