Hadronic Physics II

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Mihaly Novak
based on Dennis Wright's lectures

Outline

- QCD string models
  - FTF, QGS
- Hadron Elastic Processes
- Low Energy Hadron Physics
- Gamma- and Lepto-Nuclear Models

How the **String Model** Works (FTF Model)

- Lorentz contraction turns nucleus into pancake
- All nucleons within 1 fm of path of incident hadron are possible targets
- Excited nucleons along the path collide with neighbours
  - n + n → nΔ, NN, ΔΔ, NΔ, …
  - essentially a quark-level cascade in vicinity of path → Reggeon cascade
- All hadrons treated as QCD strings
  - projectile is quark-antiquark pair or quark-diquark pair
  - target nucleons are quark-diquark pairs

How the String Model Works (FTF Model)

- Hadron excitation is represented by stretched string
  - string is set of QCD color lines connecting the quarks
- When string is stretched beyond a certain point it breaks
  - replaced by two shorter strings with newly created quarks, anti-quarks on each side of the break
- High energy strings then decay into hadrons according to fragmentation functions
  - fragmentation functions are theoretical distributions fitted to experiment
- Resulting hadrons can then interact with nucleus in a traditional cascade

Two QCD String Models Available

- **Fritiof** (**FTF**) valid for:
  - p, n, π, K, Λ, Σ, Ω from **3 GeV** to ~TeV
  - anti-proton, anti-neutron, anti-hyperons at all energies
  - anti-d, anti-t, anti-^{3}He, anti-α with momenta between 150 MeV/nucleon and 2 GeV/nucleon
- **Quark-Gluon String** (**QGS**) valid for:
  - p, n, π, K from **15 GeV** to ~TeV
- Both models handle:
  - building 3-D model of nucleus from individual nucleons
  - splitting nucleons into quarks and di-quarks
  - formation and excitation of QCD strings
  - string fragmentation and hadronization
- FTF is more phenomenological while QGS is more theory driven
  - relies more on fitted parameters than QGS
  - FTF uses a different set of fragmentation functions(LUND) than QGS
  - FTF can be used down to lower energies

Hadron **Elastic Scattering**

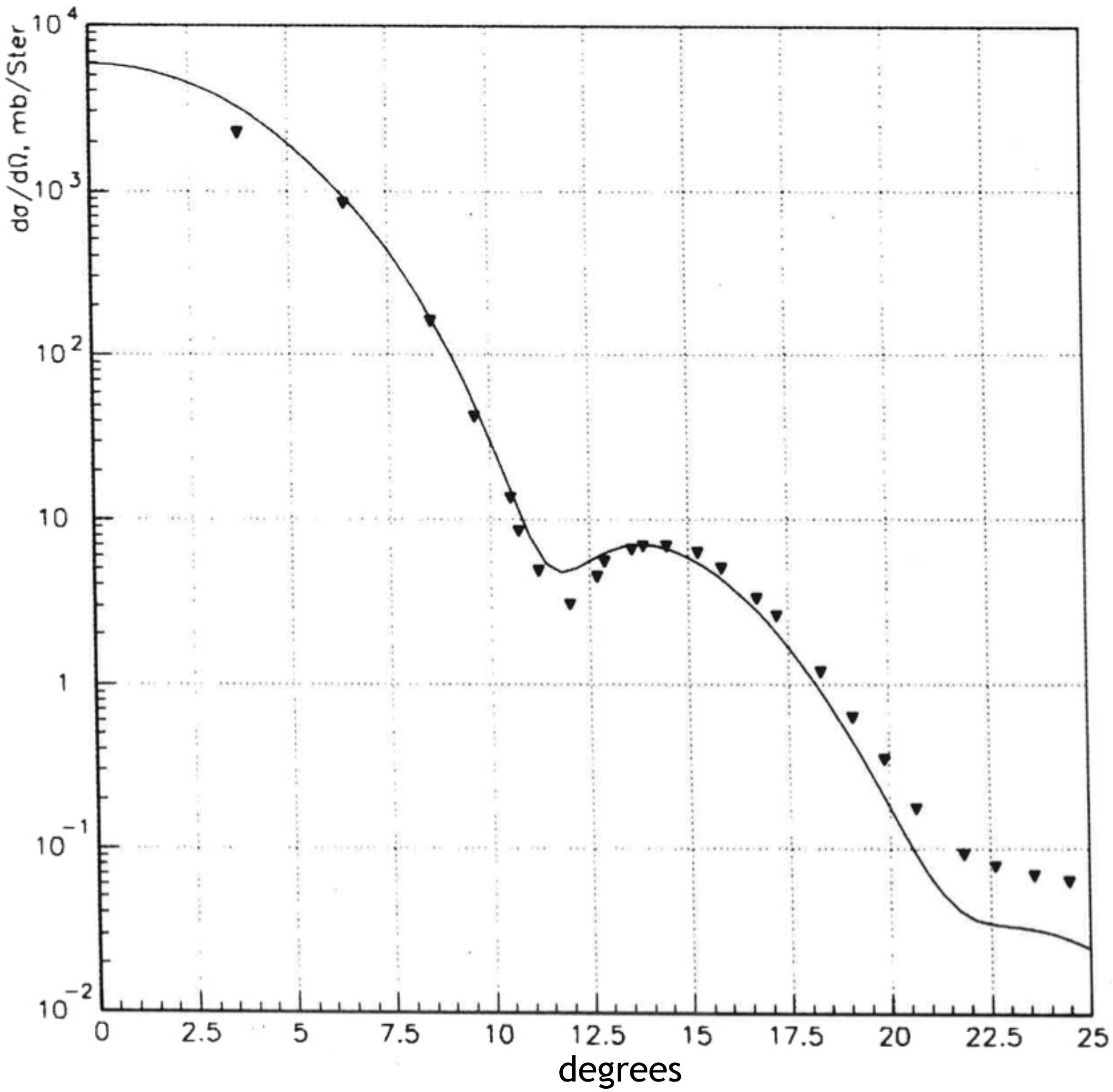
- G4HadronElasticProcess: general elastic scattering
  - valid for all energies, all projectiles
  - includes p, n, π , K, hyperons, anti-nucleons, anti-hyperons, …
  - uses proton cut values (scaled by Z) as a kinematical limit for recoiled nucleus generation

- Implemented by
  - elastic cross section data sets
  - elastic models

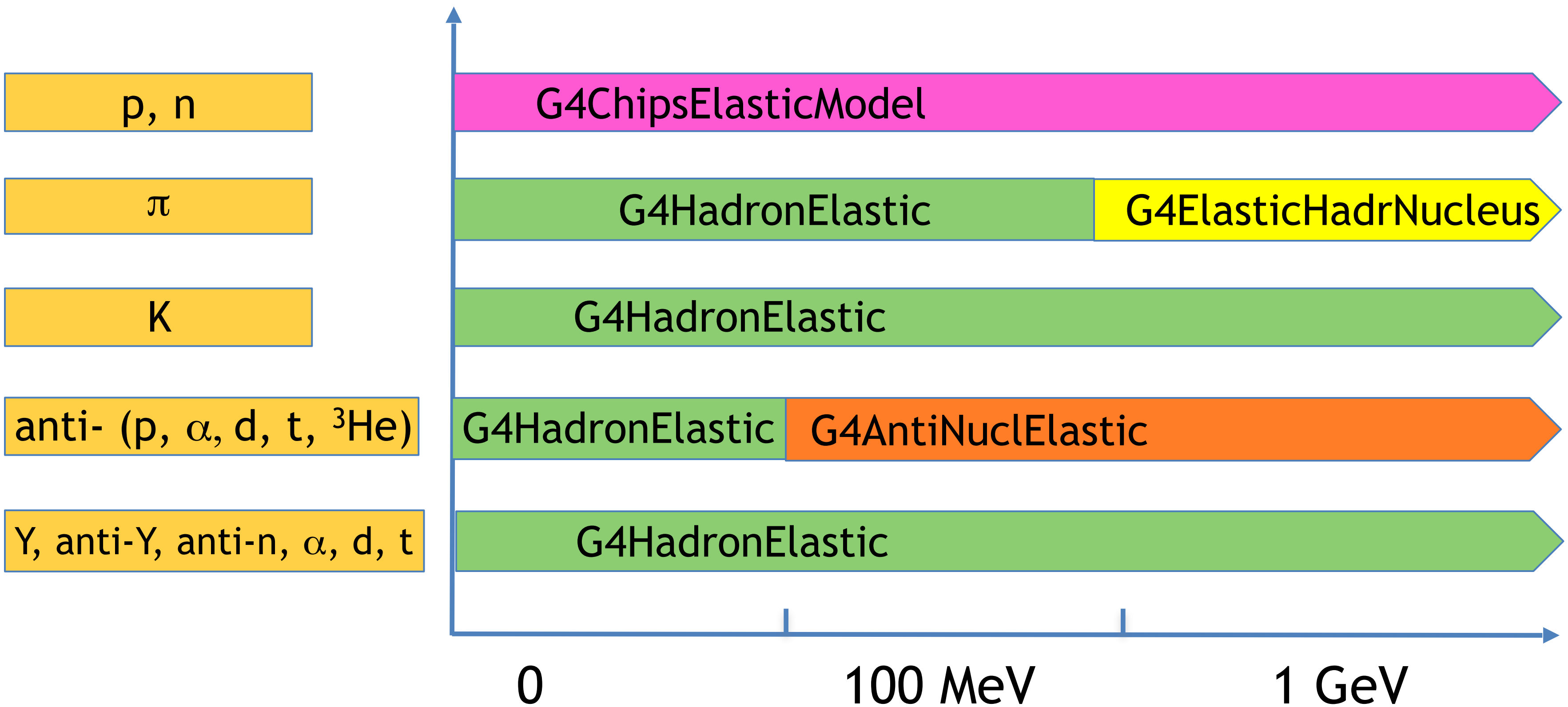
Hadron Elastic Cross Sections

- G4HadronElasticDataSet (from Geant4/Gheisha)
- G4ComponentAntiNuclNuclearXS
  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach
- G4BGGPionElasticXS
  - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above
- G4ChipsNeutron(Proton)ElasticXS
  - elastic cross sections extracted from CHIPS framework

G4ElasticHadrNucleusHE (1 GeV p on C)



Hadronic Models Implementing G4HadronElasticProcess



Low Energy Hadron Physics

- Below 20 MeV incident energy, Geant4 provides several models for treating n, p, d, t, ^{3}He and α interactions in detail
- The high precision models (**NeutronHP, ParticleHP**) are data-driven and depend on a large database of cross sections, etc.
  - the G4NDL database can be downloaded from the Geant4 web site (see also https://www-nds.iaea.org/geant4/)
  - TENDL optional database is also available
  - elastic, inelastic, capture and fission models all use this isotope-dependent data
- There are also models to handle **thermal scattering** from chemically bound atoms

High Precision (HP) Particles

- **NeutronHP:** Geant4 Neutron Data Library (G4NDL)
  - contains the data files for the high precision neutron models
  - includes both cross sections and final states
  - based on Evaluated Nuclear Data File (ENDF)
  - elastic, inelastic, capture, fission
- **ParticleHP:** models provide elastic, inelastic, capture and fission for incident n, p, d, t, ^{3}He, α
  - below 20 MeV for **n**
  - below 200 MeV **for charged**
  - also depends on large database (ENDF)
  - alternative dbs ready: TENDL, IAEA medical, IBANDL
  - recently merged with **NeutronHP**
  - good comparisons so far with MCNP

Example: G4ParticleHPElastic

- Handles elastic scattering of n, p, d, t, ^{3}He, α by sampling differential cross section data
  - interpolates between points in the cross section tables as a function of energy
  - also interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
  - scattered particle and recoil nucleus generated as final state

- Note that because look-up tables are based on binned data, there will always be a small energy non-conservation
  - true for inelastic, capture and fission processes as well

Thermal Neutron Scattering from Chemically Bound Atoms

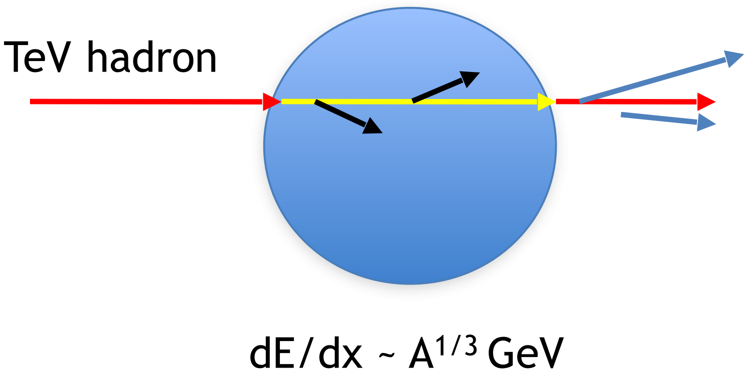
- At thermal energies, atomic motion, vibration, rotation of bound atoms affect neutron scattering cross sections and the angular distribution of secondary neutrons
- The energy loss (or gain) of such scattered neutrons may be different from those from interactions with unbound atoms
- Original HP models included only individual Maxwellian motion of target nucleus (free nucleus gas model)
- New behaviour handled by model and cross section classes
  - G4HPThermalScatteringData, and
  - G4HPThermalScattering

LEND – the new Livermore Neutron Models

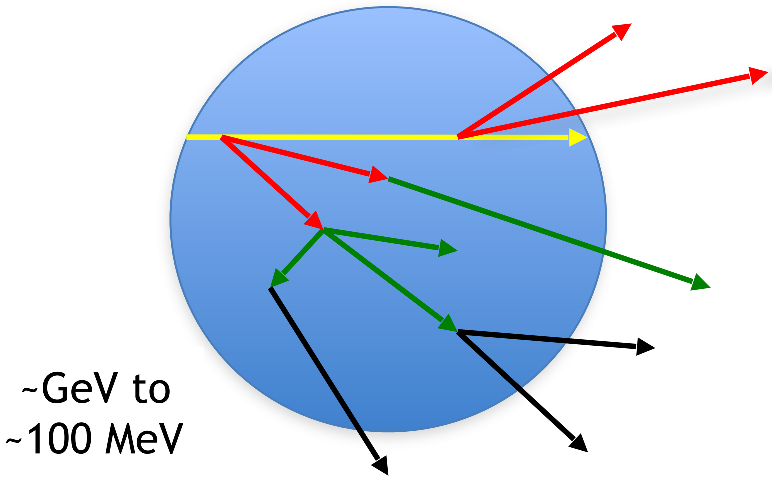
- An alternative to the HP models
  - better code design
  - faster
  - Livermore database not yet as extensive G4NDL
- Corresponding model for each model in HP
  - elastic, inelastic, capture, fission

Packaged Physics Lists naming convention: try it now!

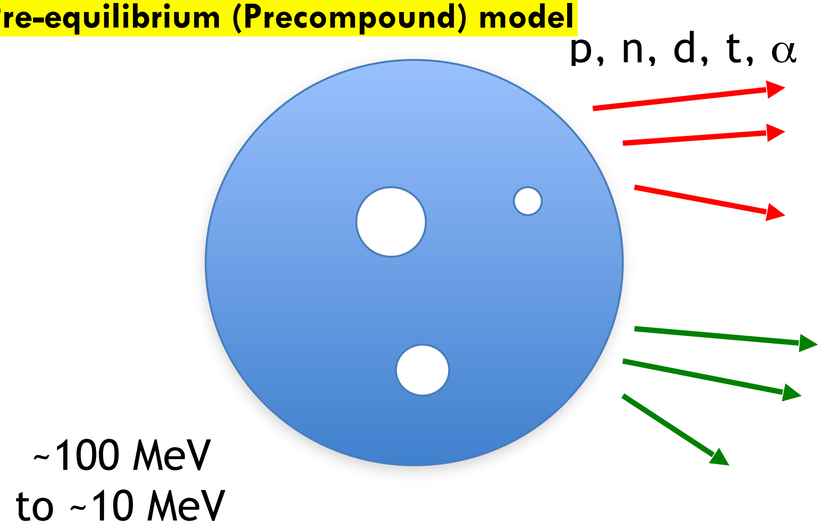
String model



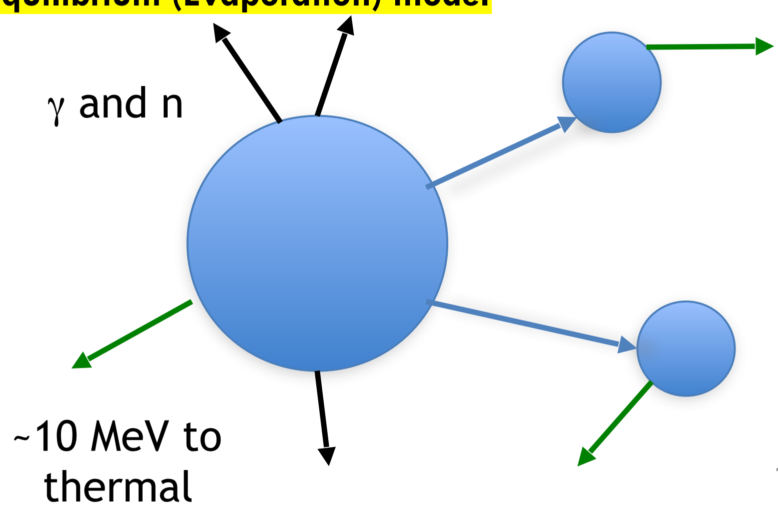
Intra-nuclear cascade model



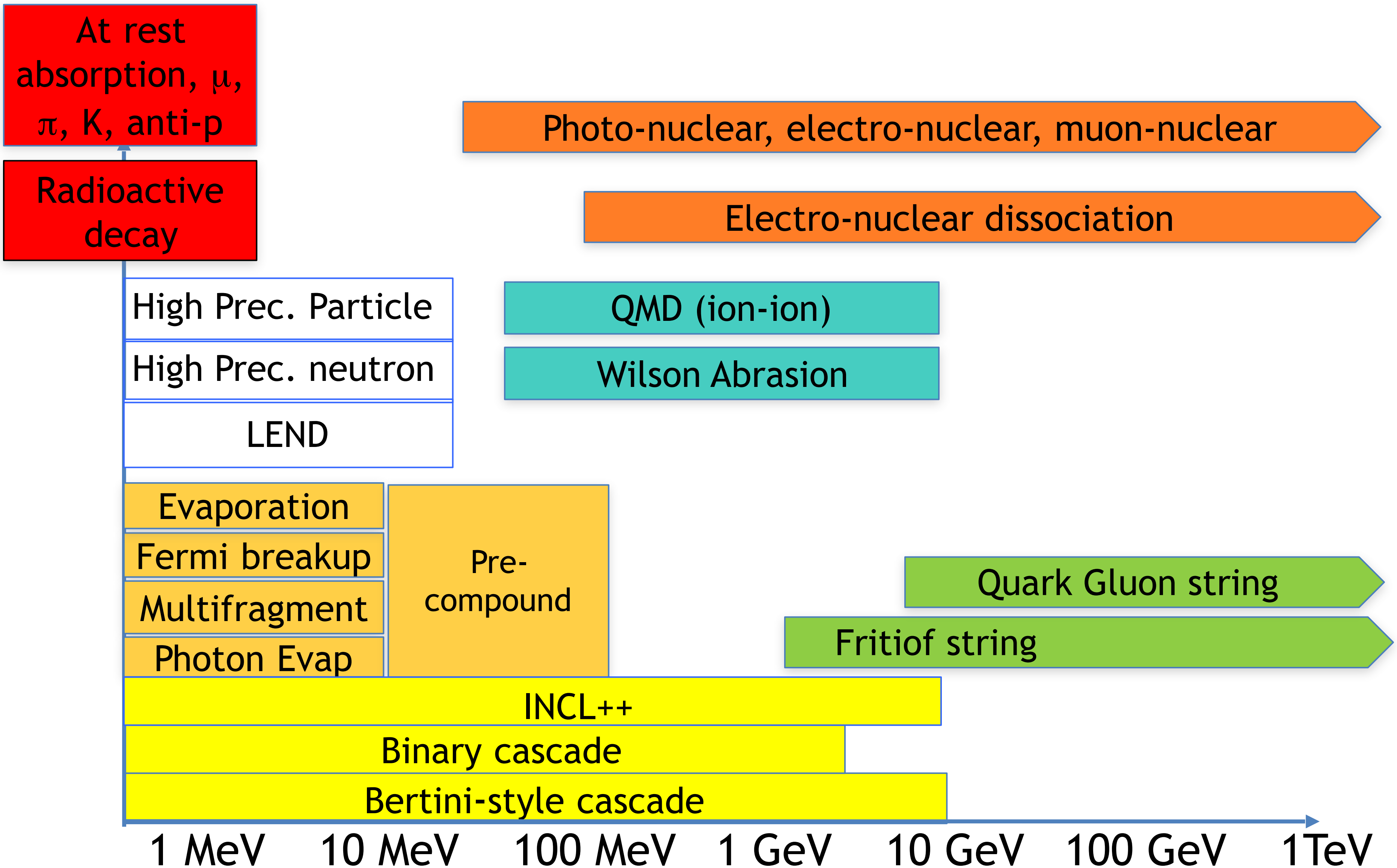
Pre-equilibrium (Precompound) model



Equilibrium (Evaporation) model



Packaged Physics Lists naming convention: try it now!



Packaged Physics Lists: naming convention

- **Some Hadronic options:**
  - "QGS" Quark Gluon String model (> ~15 GeV)
  - "FTF" FRITIOF String model (> ~5 GeV)
  - "BIC" Binary Cascade model (< ~10 GeV)
  - "BERT" Bertini Cascade model (< ~10 GeV)
  - "P" `G4Precompound` model used for de-excitation
  - "HP" High Precision neutron model (< ~20 MeV)
- **Some EM options:**
  - No suffix: standard EM i.e. the default `G4EmStandardPhysics` constructor
  - "EMV" `G4EmStandardPhysics_option1` CTR: HEP, fast but less precise
  - "EMY" `G4EmStandardPhysics_option3` CTR: medical, space sci., precise
  - "EMZ" `G4EmStandardPhysics_option4` CTR: most precise EM physics
- **Name decoding:** String(s)_Cascade_Neutron_EM
- **The complete list of pre-packaged physics list with detailed description can be found in the documentation ("*Guide for Physics Lists*"):**
  - http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsListGuide/html/index.html

Packaged Physics Lists: naming convention (example)

- **FTFP_BERT:**
  - Recommended by Geant4 developers for HEP applications
  - Includes the standard EM physics i.e. `G4EmStandardPhysics` CTR
  - "FTF" FRITIOF string model (> 4 GeV)
  - "BERT" Bertini Cascade model (< 5 GeV)
  - "P" `G4Precompound` model used for de-excitation

- **QGSP_BIC_HP(_EMZ):**
  - Recommended for medical applications (experimental QGSP_BIC_AllHP)
  - "QGS" Quark Gluon String model (> 12 GeV)
  - "FTF" FRITIOF String model (9.5 - 25 GeV)
  - "P" `G4Precompound` model used for de-excitation
  - "BIC" Binary Cascade model (200 MeV - 9.9 GeV)
  - "HP" High Precision neutron model (< ~20 MeV)
  - "EMZ" `G4EmStandardPhysics_option4` CTR (or EMY that's a bit less precise)

Gamma- and Lepto-nuclear Processes

- Geant4 models which are neither exclusively electromagnetic nor hadronic
  - gamma-nuclear
  - electro-nuclear
  - muon-nuclear
- Geant4 processes available:
  - G4PhotoNuclearProcess (implemented by two models)
  - G4ElectronNuclearProcess (implemented by one model)
  - G4PositronNuclearProcess (implemented by one model)
  - G4MuonNuclearProcess (implemented by two models)

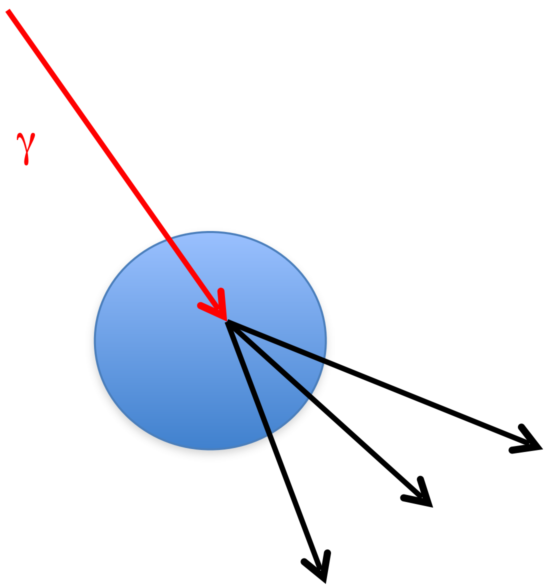
Gamma- and Lepto-nuclear Processes

- Gammas interact directly with the nucleus
  - at low energies they are absorbed and excite the nucleus as a whole
  - at high energies they act like hadrons (pion, rho, etc.) and form resonances with protons and neutrons

- Electrons and muons cannot interact hadronically, except through virtual photons
  - electron or muon passes by a nucleus and exchanges virtual photon
  - virtual photon then interacts directly with nucleus (or nucleons within nucleus)

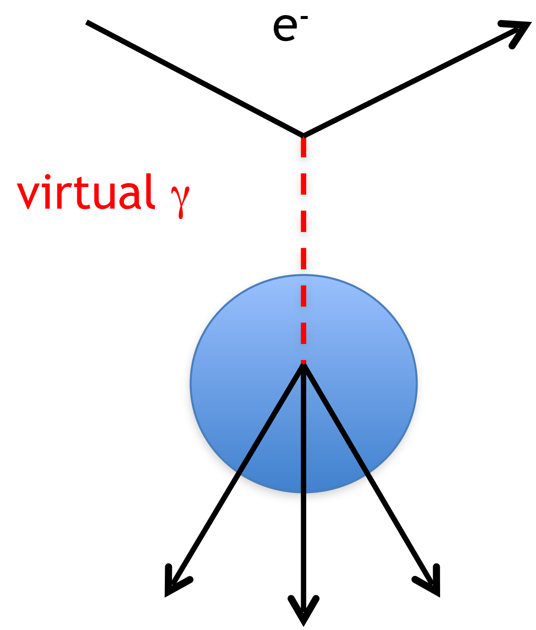
Gamma- and Lepto-nuclear Models

Gamma-nuclear



π s and nucleons

Lepto-nuclear



πs and nucleons

Summary

- Geant4 provides FTF and QGS string models for high energy hadron nucleon interactions

- Hadron elastic scattering
  - now several models which improve on the old Gheisha version
  - cross sections now usually based on Glauber approach

- Specialized high precision models (n, p, d, t, ^{3}He, α)
  - HP models which use G4NDL, now based entirely on ENDF/B-VII
  - alternative LEND (Livermore) models are faster but currently less extensive – use the ENDF.B-VII library