Geant4 10.4

Hadronic Physics III

Geant4 Tutorial at Lund University

6 September 2018

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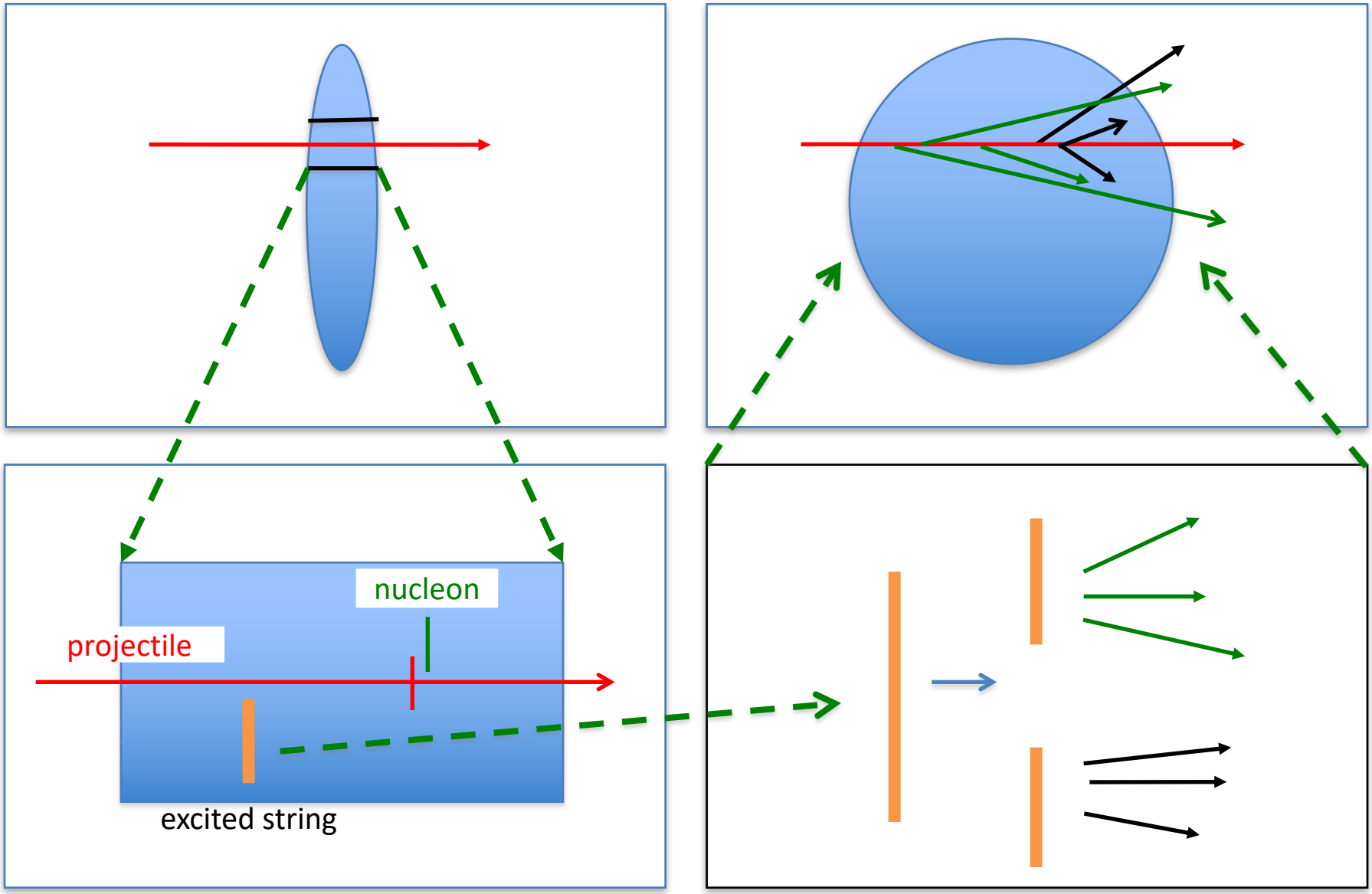
Outline

- QCD string models
  - Quark-gluon string (QGS) model
  - Fritiof (FTF) model
- Gamma- and lepto-nuclear models
- Radioactive decay

High Energy Nuclear Interaction



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 path collide with neighbors
  - n + n → $n\Delta$, NN, $\Delta\Delta$, $N\Delta$
  - 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

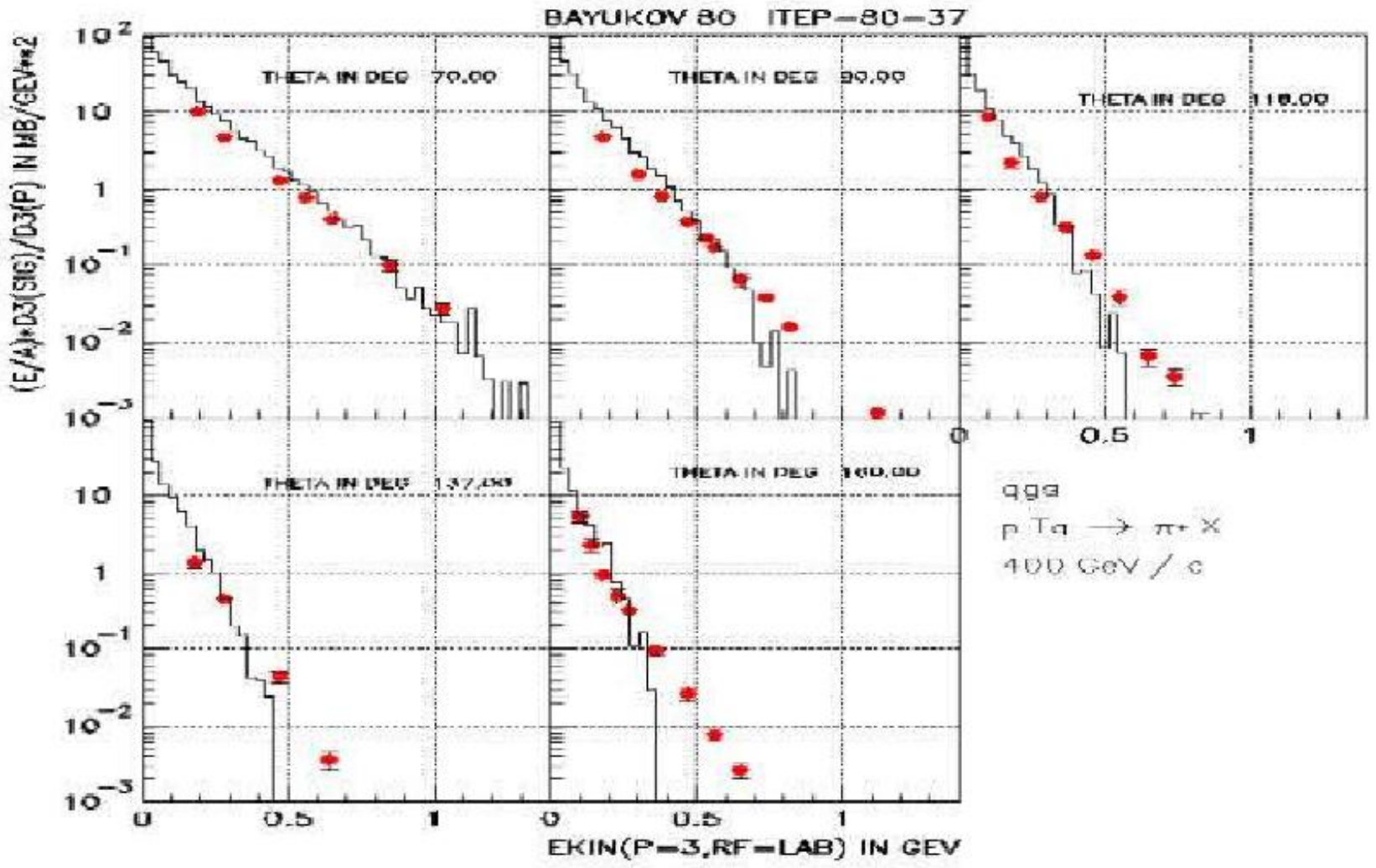
How the String Model Works (FTF Model)

- 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

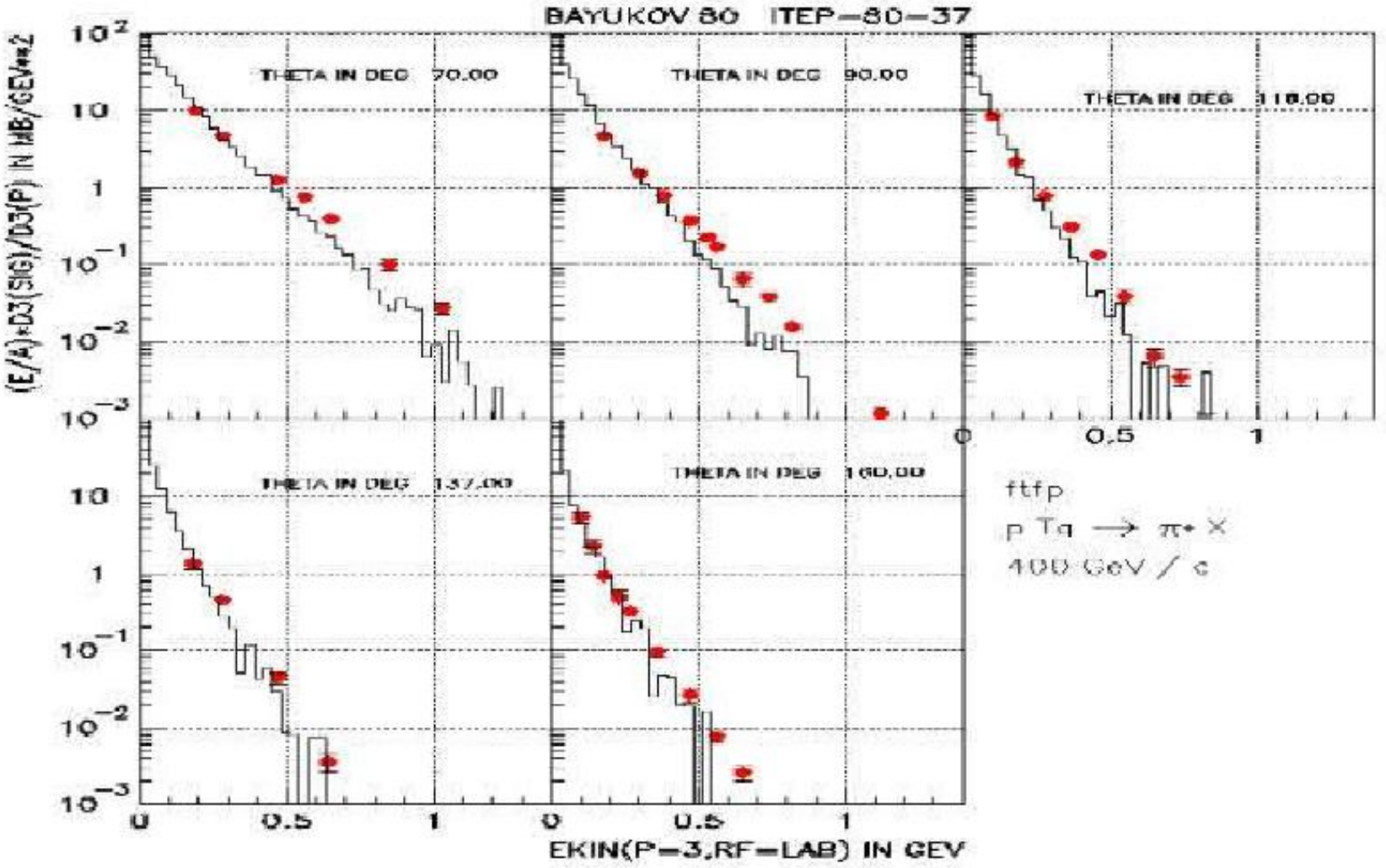
Two QCD String Models Available

- 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

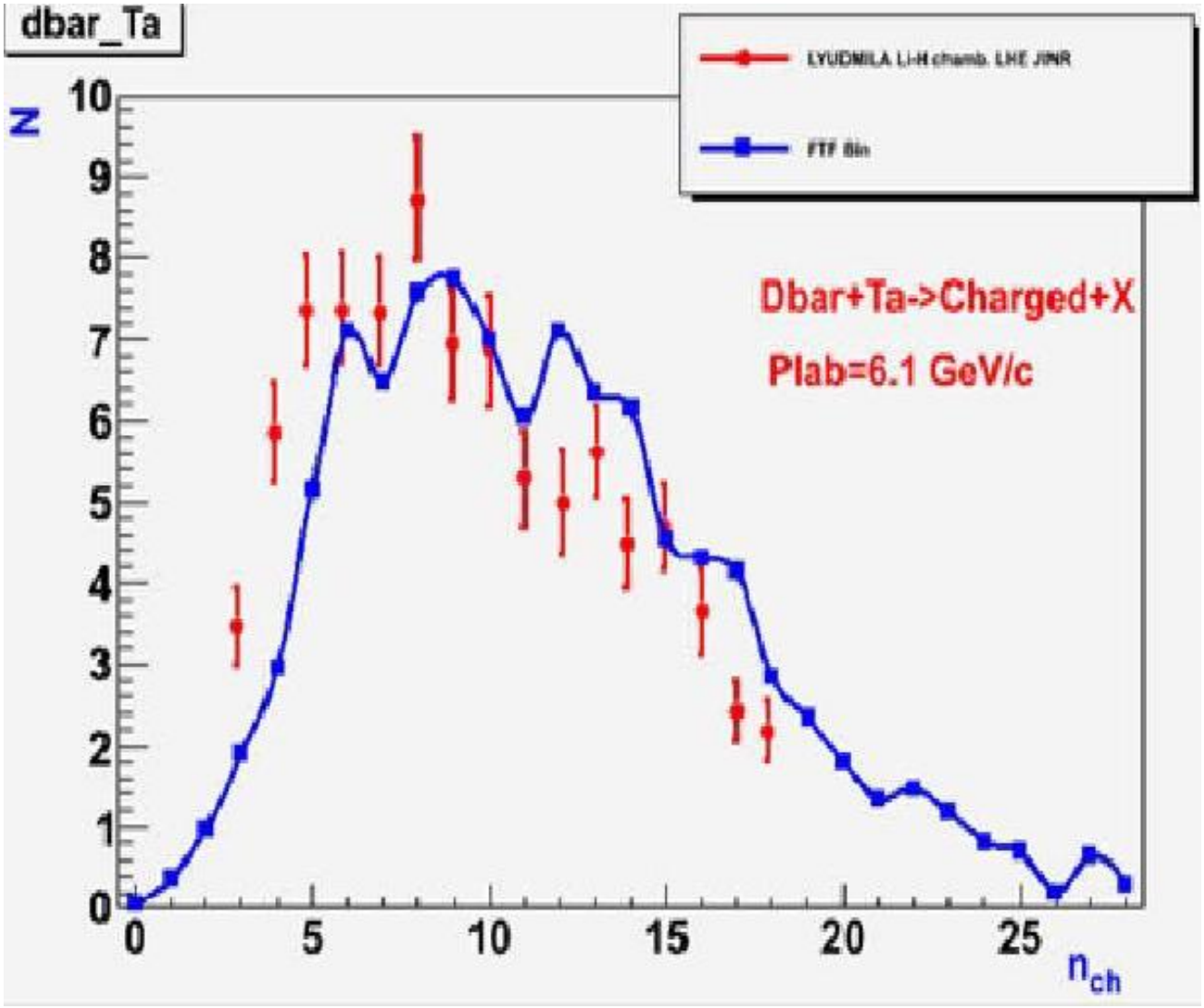
QGS Validation



FTF Validation



FTF Anti-deuteron Scattering



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)

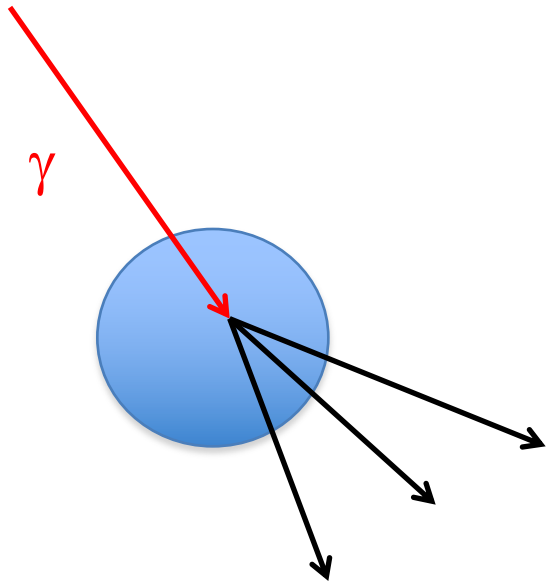
Gamma- and Lepto-nuclear Processes

- 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)

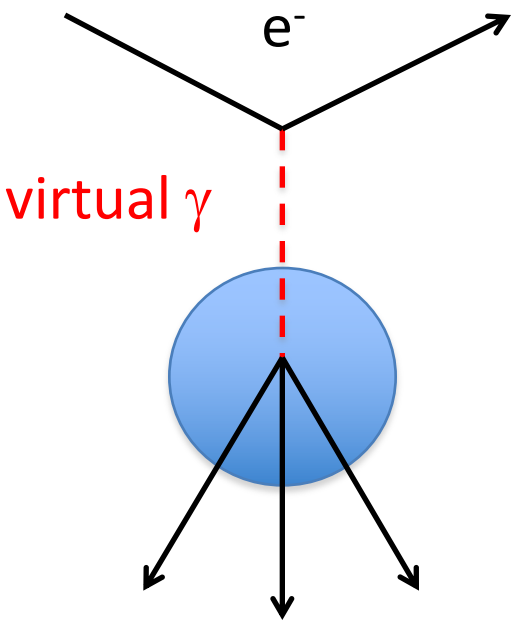
Gamma- and Lepto-nuclear Models

Gamma-nuclear



π s and nucleons

Lepto-nuclear



πs and nucleons

Gamma- and Lepto-nuclear Models

- G4MuonVDNuclearModel
  - Kokoulin model of EM cross section and virtual photon generation
  - Weizsacker-Williams conversion of virtual to real gamma
  - For $E_\gamma < 10$ GeV, direct interaction with nucleus using Bertini cascade
  - For $E_\gamma > 10$ GeV, conversion of γ to π^0, then interaction with nucleus using FTFP model

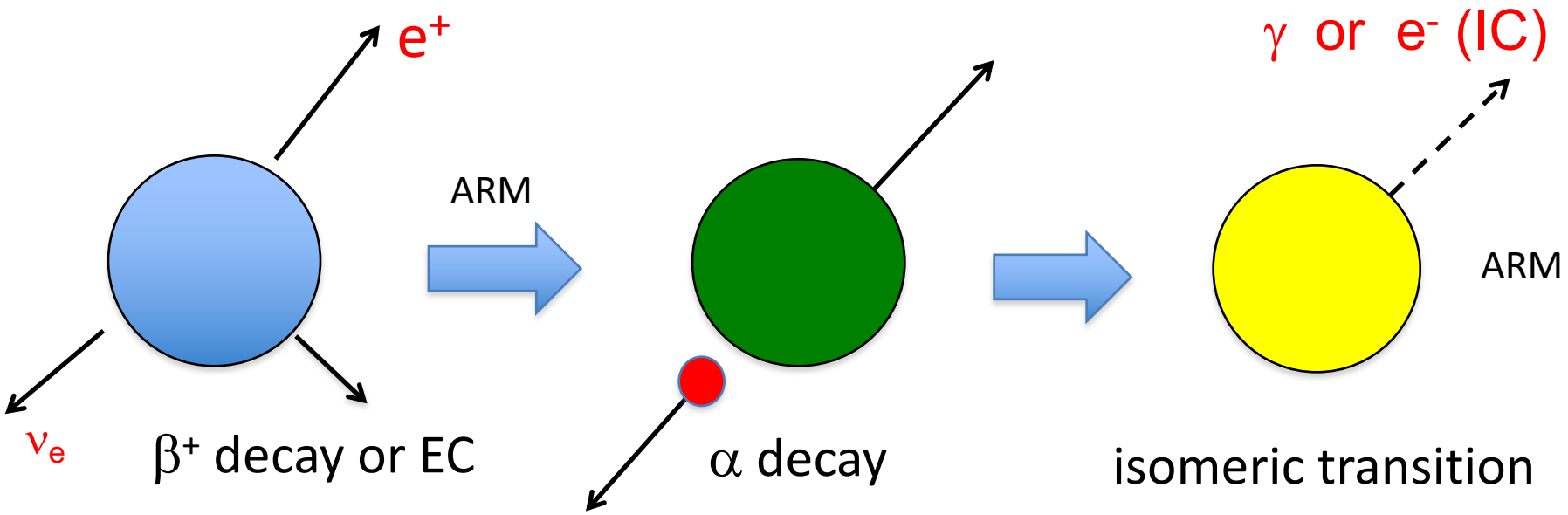
- G4ElectroVDNuclearModel
  - Kossov model of EM cross section and virtual photon generation
  - all else identical to that in G4MuonVDNuclearModel

- For gamma-nuclear reaction
  - Bertini cascade below 3.5 GeV
  - QGSP from 3 GeV to 100 TeV

Radioactive Decay

- Process to simulate radioactive decay of nuclei
  - in flight
  - at rest
- α, β^+, β^-, γ decay, electron capture (EC) implemented
- Empirical and data-driven
  - data files taken from Evaluated Nuclear Structure Data Files (ENSDF)
    - as of Geant4 10.3, these are in RadioactiveDecay5.0
  - half lives, nuclear level structure for parent and daughter nuclides, decay branching ratios, energy of decay process
  - currently 2792 nuclides, including all meta-stable states with lifetimes > 1 ns

Radioactive Decay Chain



EC: electron capture

IC: internal conversion

ARM: atomic relaxation model

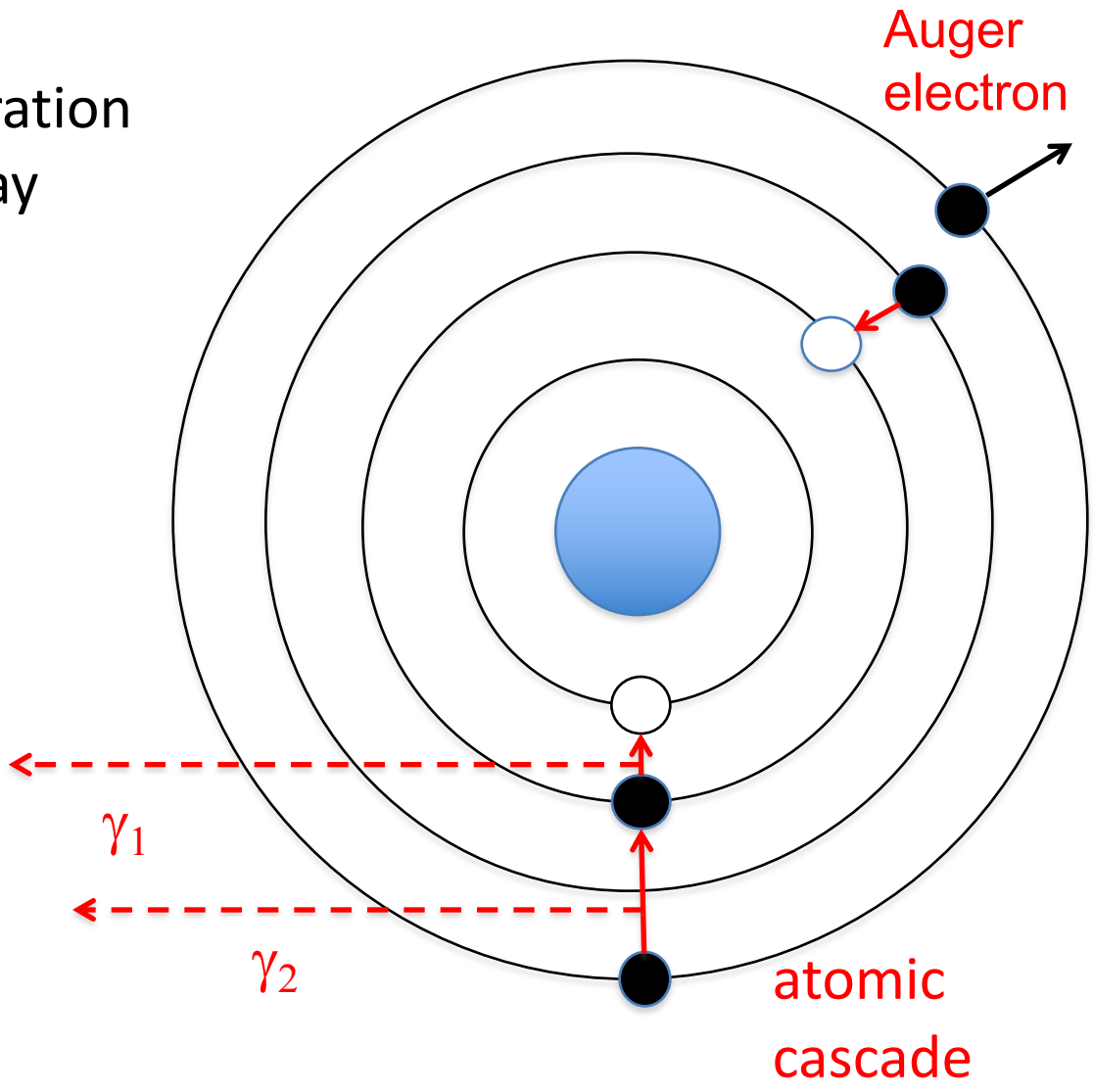
Atomic Relaxation Model

electron shell configuration may change after decay

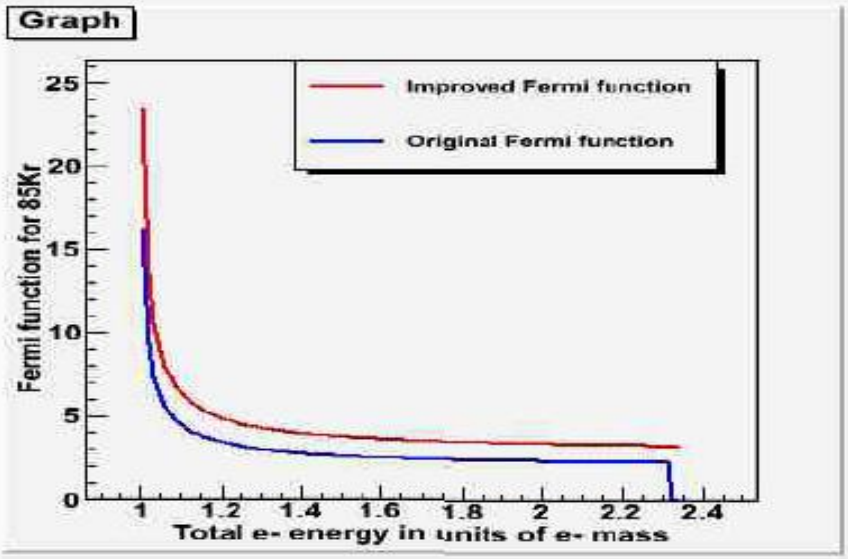
inner holes filled by atomic cascade

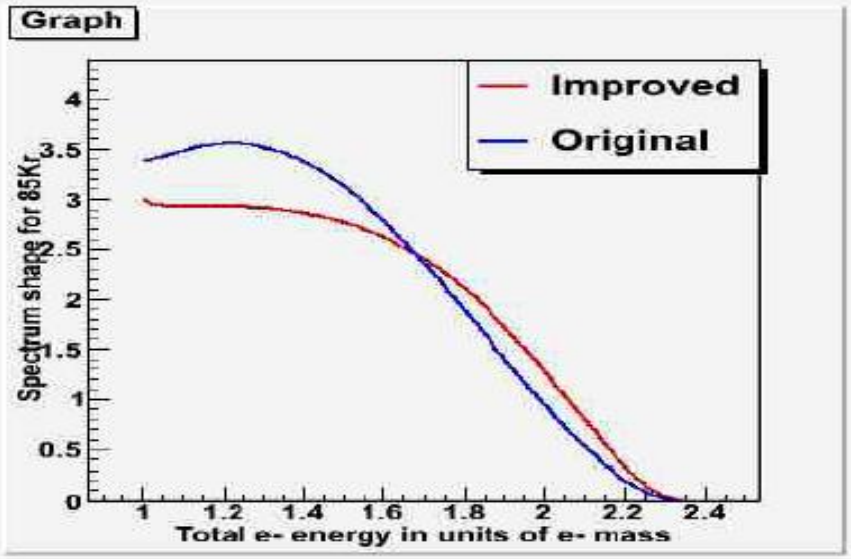
either photons or Auger electrons are emitted

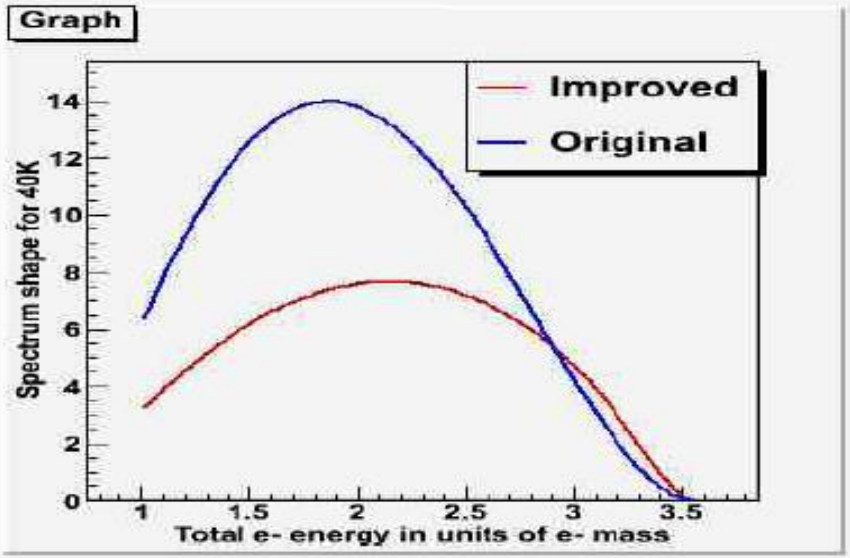
fluorescence option also available

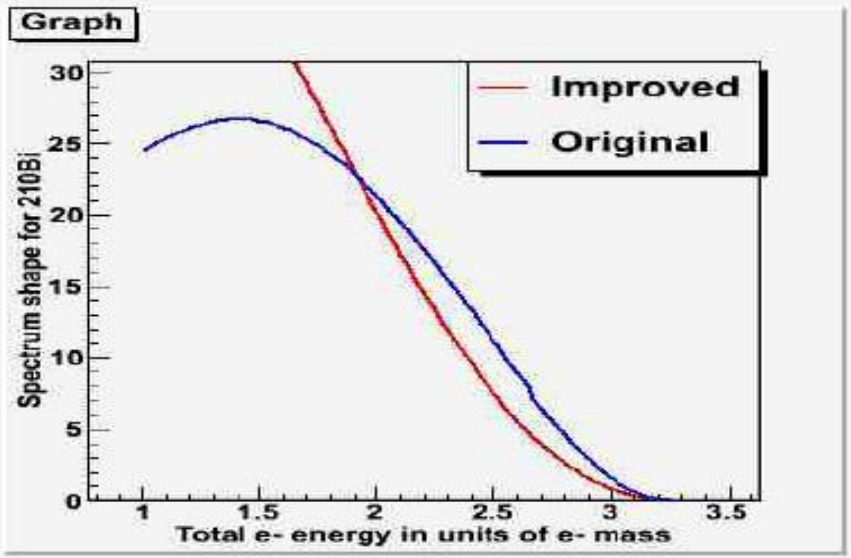


β Decay Spectrum Shapes









Gamma (or electron) Emission

- If daughter of nuclear decay is an isomer, prompt de-excitation is done by using G4PhotonEvaporation
  - uses ENSDF files with all known gamma levels for 2071 nuclides
    - as of Geant4 10.3, these are in PhotonEvaporation4.3
  - internal conversion is enabled as a competing process to gamma de-excitation
- Nuclides with LT < 1 ns decay immediately
- Option to enable atomic relaxation after decay
  - atomic cascade
  - Auger
  - fluorescence

Biased Mode

- G4RadioactiveDecay has several biasing options
  - amplify rare decay branches
  - set all decay branches equal
  - “splitting” : perform nuclear decay N times for each event
  - activation: integrate decay chain over time windows using Bateman equations
  - collimation of decay products
  - enable/disable decay in various geometry volumes

- Options activated by UI commands

Using Radioactive Decay

- Can be accessed with messengers (biasing options, etc.)
- To put in your physics list:

```
G4RadioactiveDecay* rDecay = new G4RadioactiveDecay;
G4PhysicsListHelper* plh = G4PhysicsListHelper::GetPhysicsListHelper();
rDecay->SetICM(true);                 // internal conversion
rDecay->SetARM(true);                 // atomic relaxation
plh->RegisterProcess(rDecay, G4GenericIon::G4GenericIon() );
```

- Set environment variables to point to:
  - RadioactiveDecay5.2
  - PhotonEvaporation5.2

Summary

- Two QCD string models are available for implementing high energy interactions
  - Fritiof (FTF) : the more versatile, covers many particle types, larger energy range
  - Quark-Gluon String (QGS)

- Gamma-nuclear and lepto-nuclear processes are available for nuclear reactions initiated by non-hadrons

- Radioactive decay
  - α, β, IT and EC decays available
  - can run in analog or biased modes