Hadronic Physics I

Geant4 Users' Tutorial
CERN
15-19 February 2010
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Outline

- Overview of hadronic physics
  - processes, cross sections, models
  - Elastic scattering
  - Inelastic scattering
    - From high energy down to rest

Challenge

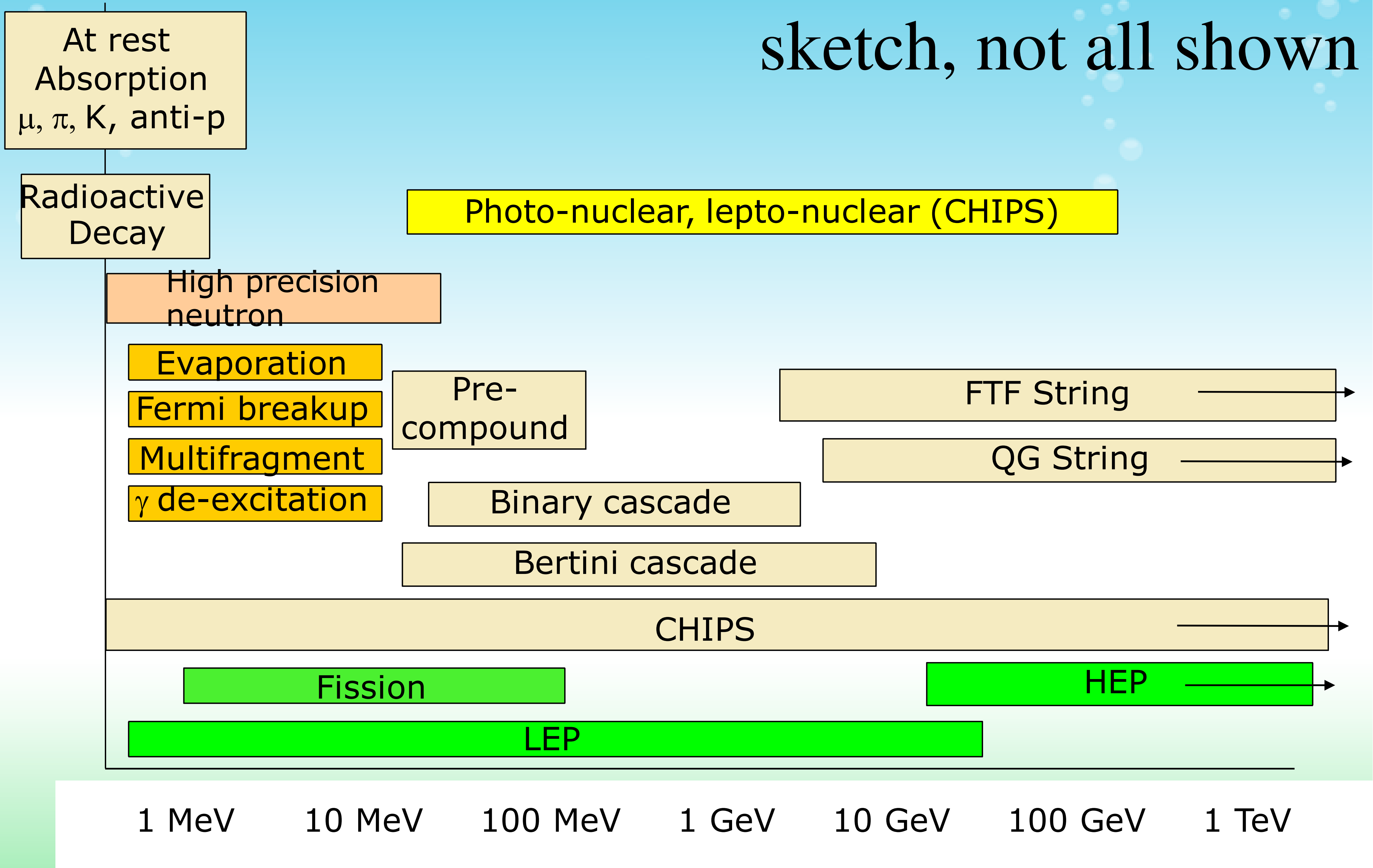
- Hadronic interaction is interaction of hadron with nucleus
  - strong interaction
- QCD is theory for strong interaction, so far no solution at low energies
- Simulation of hadronic interactions relies on
  - Phenomenologial models, inspired by theory
  - Parameterized models, using data and physical meaningful extrapolation
  - Fully data driven approach
- Applicability of models in general are limited
  - range of energy
  - Incident particles types
  - Some to a range of nuclei

Geant4 Hadronics Philosophy

- Offer a choice of processes, models, and cross sections
  - No model matches the requirements of all application domains
- Developed a modular hadronics framework
  - Makes it easy to add new models, cross sections
    - allows users to substitute specialized physics
  - Separate total and reaction cross sections from final state generators (Model)
    - allows easy update, multiple implementations of cross sections
    - different final state generators for different energies

Hadronic Process/Model Inventory

sketch, not all shown



At rest Absorption μ, π, K, anti-p

Radioactive Decay

Photo-nuclear, lepto-nuclear (CHIPS)

High precision neutron

Evaporation

Fermi breakup

Multifragment

γ de-excitation

Pre-compound

FTF String

QG String

Binary cascade

Bertini cascade

CHIPS

Fission

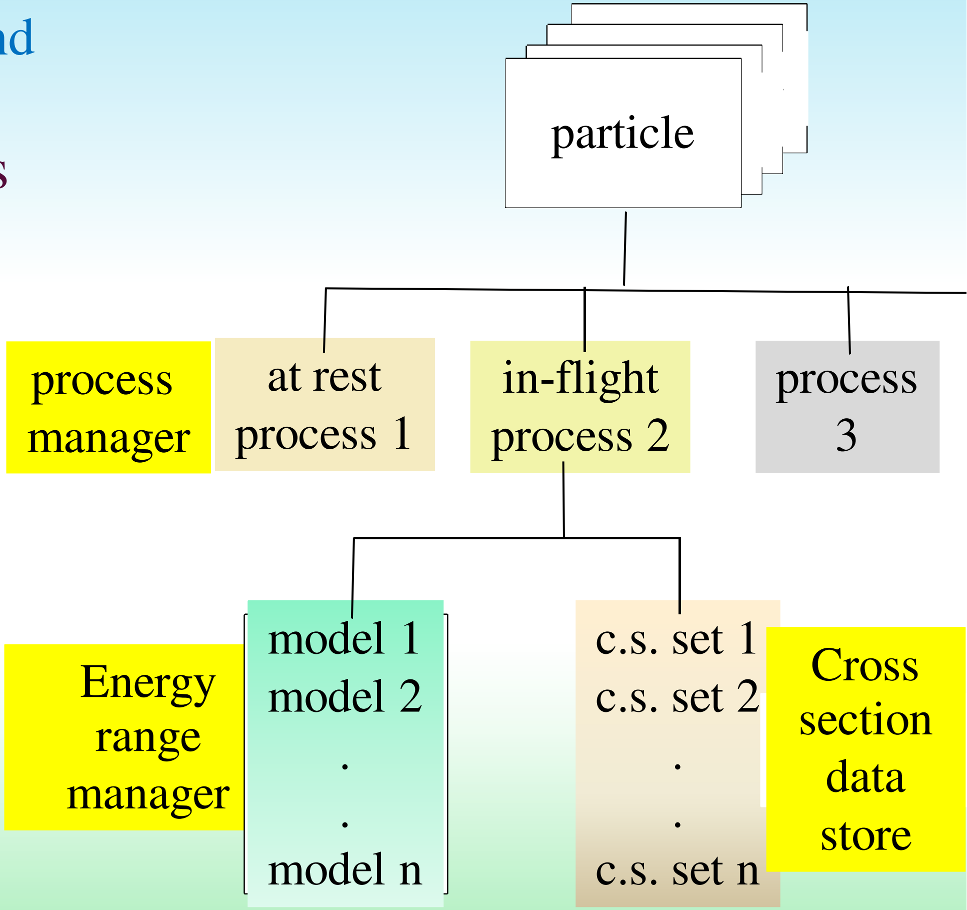
HEP

LEP

1 MeV, 10 MeV, 100 MeV, 1 GeV, 10 GeV, 100 GeV, 1 TeV

Hadronic Processes, Models, and Cross Sections

- Hadronic process may be implemented
  - directly as part of the process, or
  - Separating final state generation(models) and cross sections
- For models and cross sections there often is a choice of models or datasets
  - Physics detail vs. cpu performance
- Choice of models and cross section dataset possible via
  - Mangement of cross section store
  - Model or energy range manager



Cross Sections

- Default cross section sets are provided for each type of hadronic process for all hadrons
  - elastic, inelastic, fission, capture
  - can be overridden or completely replaced

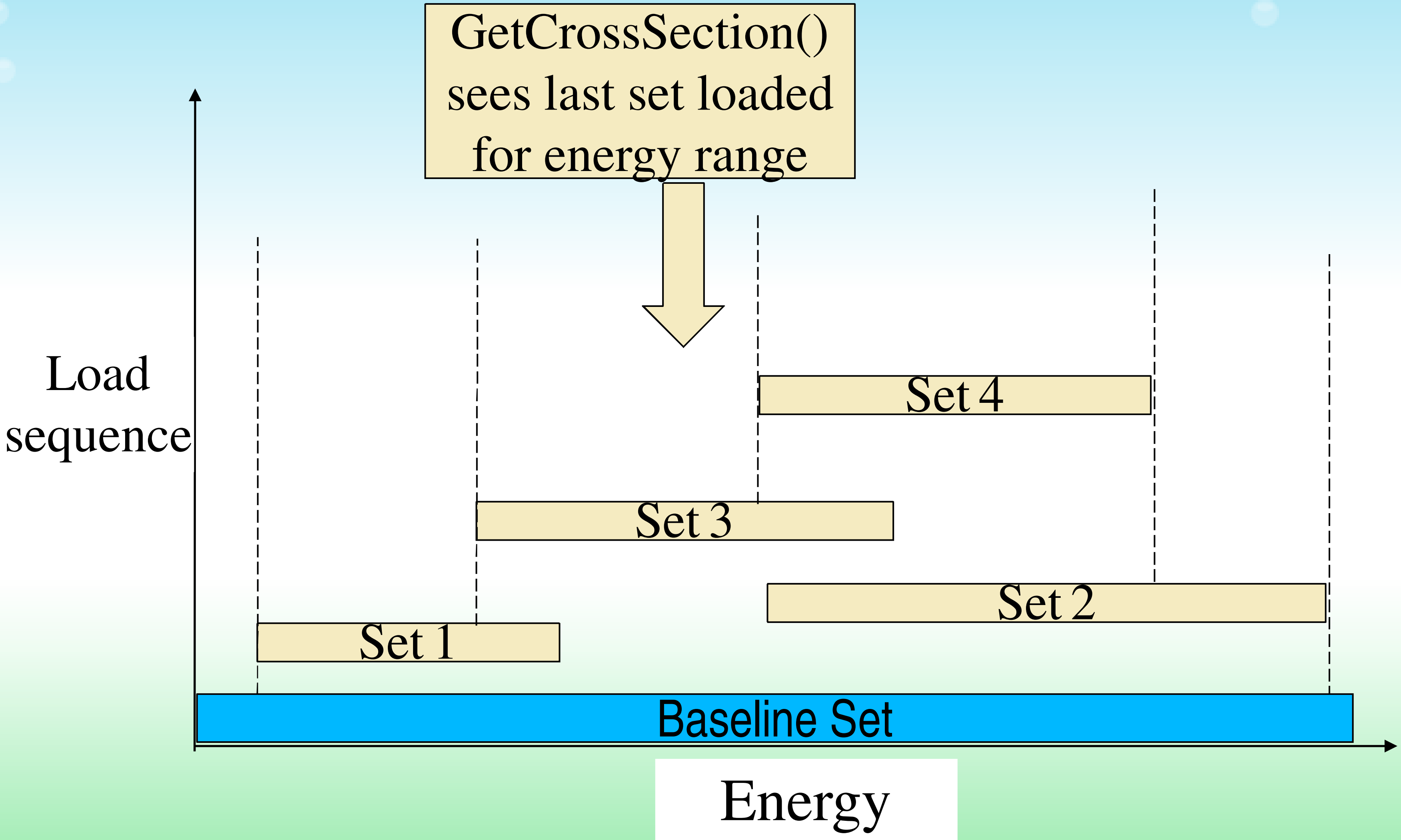
- Common Interface to different types of cross section sets
  - some contain only a few numbers to parameterize cross section
  - some represent large databases
  - some are purely theoretical

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
  - 14 MeV < E < 20 GeV, Axen-Wellisch systematics
  - Barashenkov evaluation
  - Simplified Glauber-Gribov Ansatz (E > ~GeV)
- Pion reaction cross sections
  - Barashenkov evaluation
  - Simplified Glauber-Gribov Ansatz (E > ~GeV)
- Ion-nucleus reaction cross sections
  - Good for E/A < 10 GeV

- In general, except for G4NDL, no cross section for specific final states provided
  - User can easily implement cross section and model

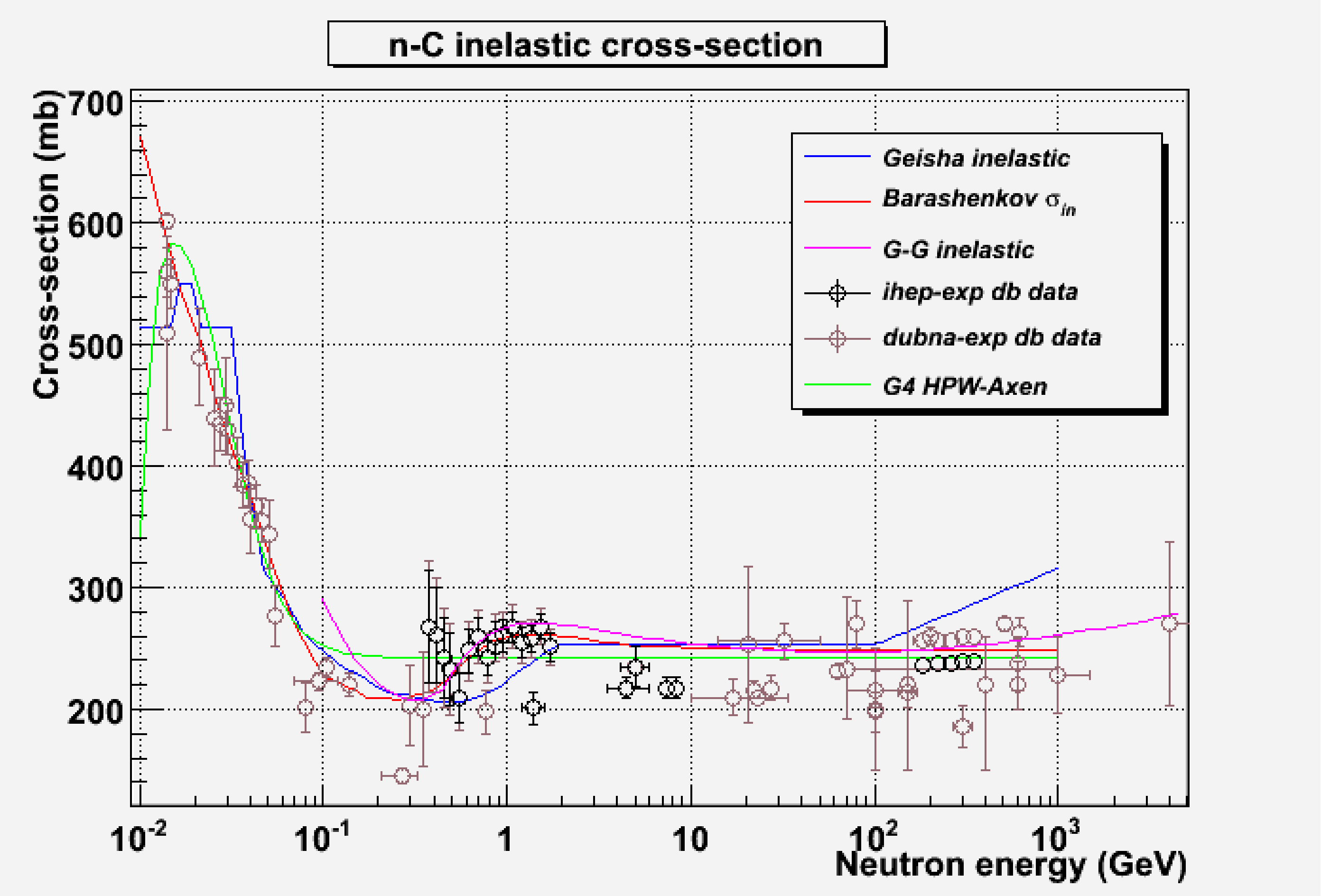
Cross Section Management



Cross section validation

- Neutron Carbon

from validation pages:
http://cern.ch/geant4/results/validation_plots/cross_sections/hadronic/inelastic/index.shtml



MODELING INTERACTIONS

Hadronic Models – Data Driven

- Characterized by lots of data
  - cross section
  - angular distribution
  - multiplicity
  - etc.
- To get interaction length and final state, models interpolate data
  - cross section, coefficients of Legendre polynomials
- Examples
  - neutrons (E < 20 MeV)
  - coherent elastic scattering (pp, np, nn)
  - Radioactive decay

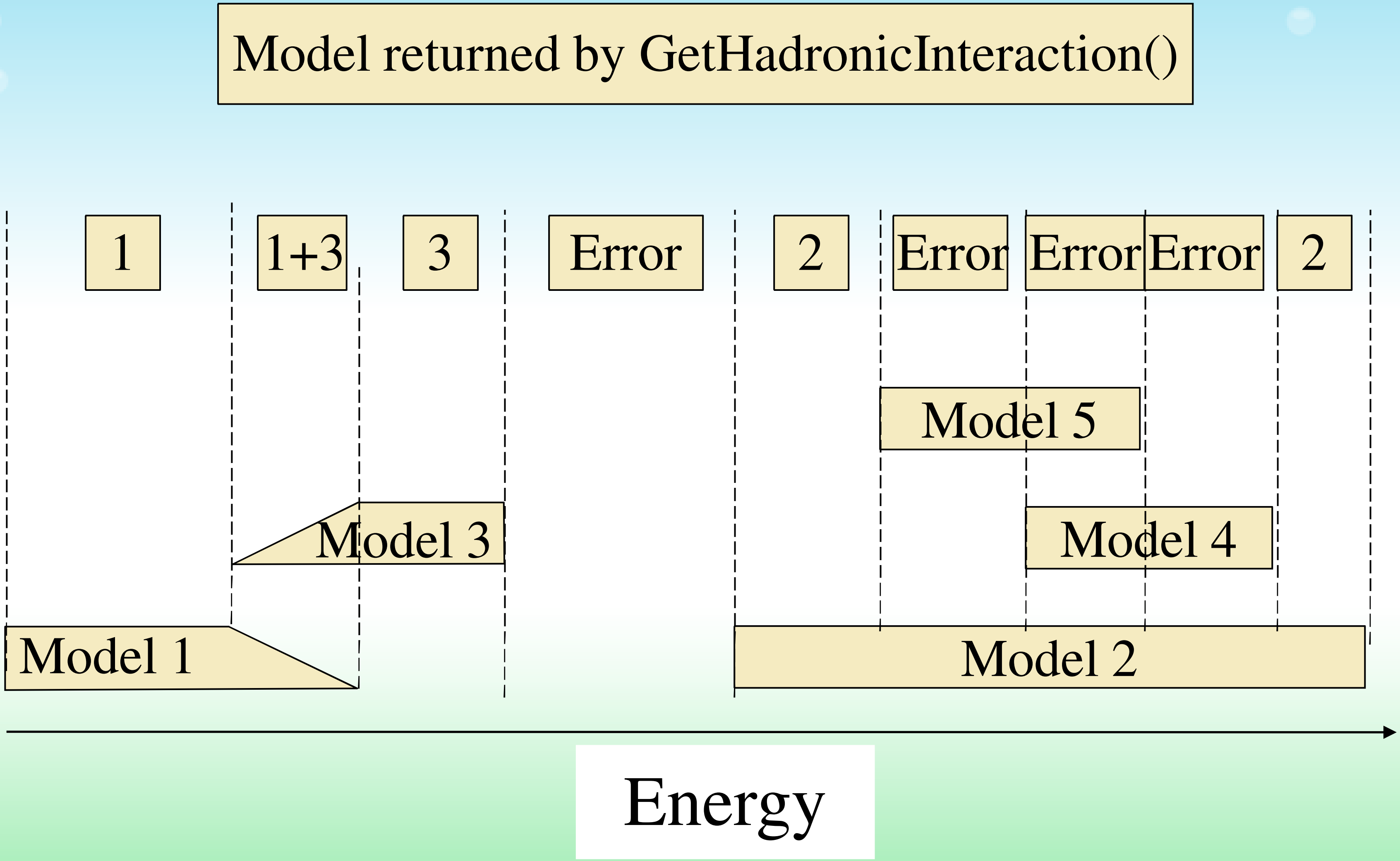
Hadronic Models - Parameterized

- Depend mostly on fits to data and some theoretical distributions
- Examples:
  - Low Energy Parameterized (LEP) for < 50 GeV
  - High Energy Parameterized (HEP) for > 20 GeV
  - Each type refers to a collection of models
  - Both derived from GHEISHA model used in Geant3

Hadronic Models – Theory Driven

- Based on phenomenological theory models
  - less limited by need for detailed experimental data
  - Experimental data used mostly for validation
- Final states determined by sampling theoretical distributions or parameterizations of experimental data
- Examples:
  - quark-gluon string (projectiles with E > 20 GeV)
  - intra-nuclear cascade (intermediate energies)
  - nuclear de-excitation and breakup
  - chiral invariant phase space

Model Management



ELASTIC INTERACTIONS

Hadron Elastic Scattering

Processes

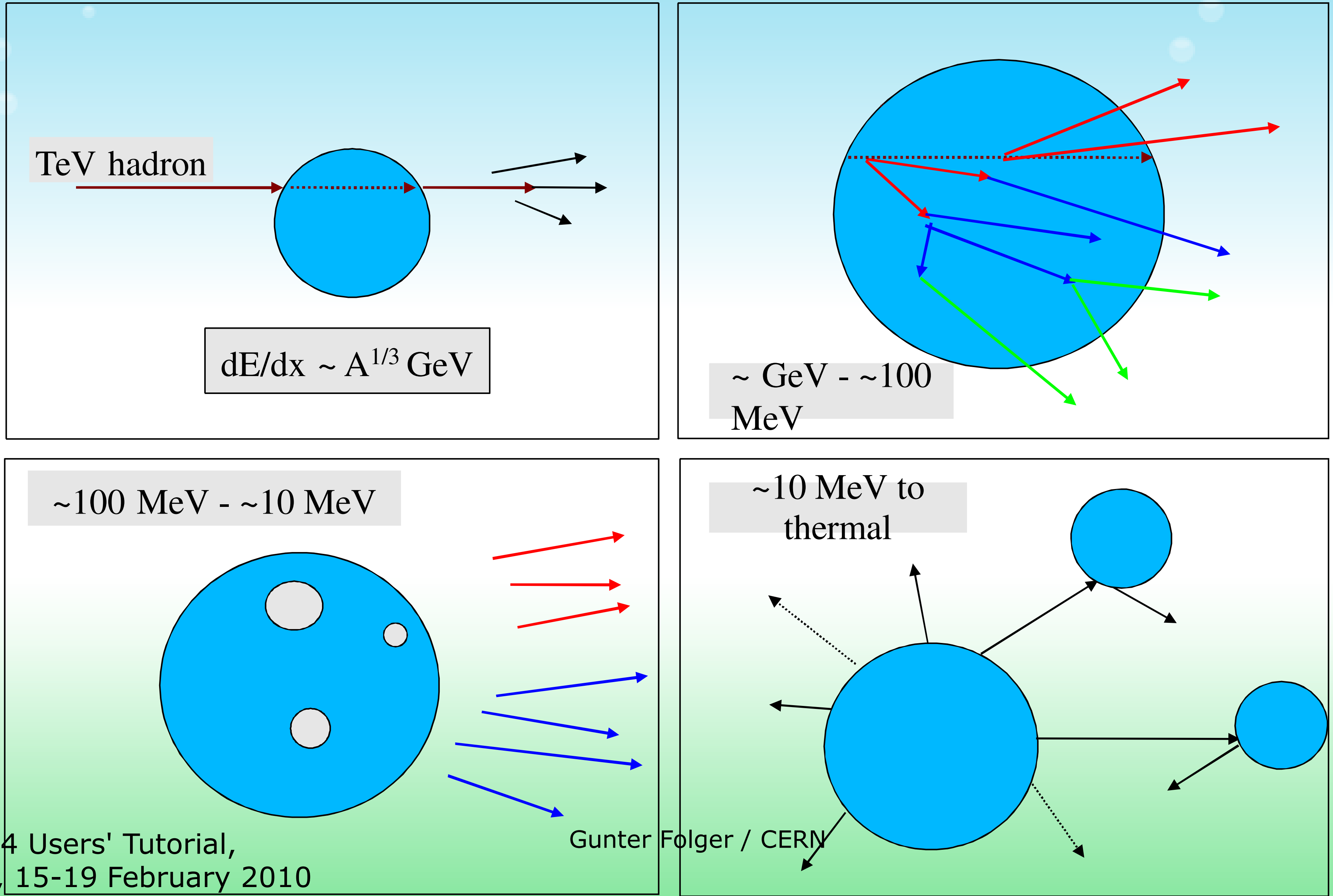
- G4HadronElasticProcess
  - Used in LHEP, uses G4LElastic model
- G4UHadronElasticProcess
  - Uses G4HadronElastic model, combined model
    - p,n use G4QElastic
    - Pion with E > 1GeV use G4HElastic
    - G4LElastic otherwise
    - Options available to change settings, expert use

Hadron Elastic Scattering
Models

- G4LElastic, origin in Gheisha models
  - Simple parameterization of cross sections and angular distribution
  - Applicable for all long lived hadrons at all energies
- G4QElastic
  - New parameterization of cross section in function of E, t, (A,Z); t is momentum transfer $(p - p')^2$ (Mandelstam variable)
  - Applicable for proton and neutron at all energies
- G4DiffuseElastic
  - Scattering particle (wave) on nucleus viewed as black disk with diffuse edge
  - Applicable p, n, pi, K, lambda, …
- G4HElastic
  - Glauber model for elastic scattering
  - Applicable for all stable hadrons
- G4LEpp/G4LEnp
  - taken from detailed phase-shift analysis by SAID
  - for (p,p), (n,n)/(n,p), (p,n) :, good up to 1.2 GeV

INELASTIC INTERACTIONS

Hadronic Interactions from TeV - meV



Exercise

- Tasks 5a: Get an overview of physics
  - Using QGSP_BERT physics list
- Dump list of processes
  - Which particles are defined?

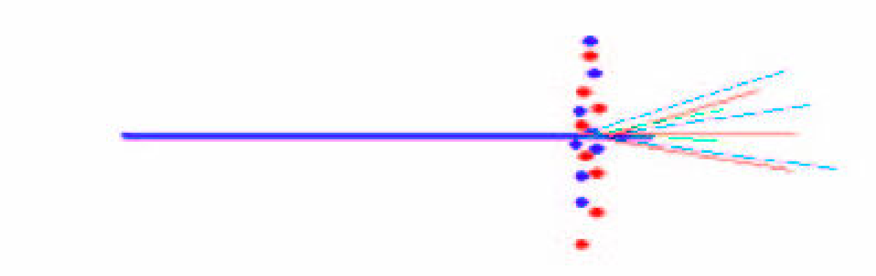
- Look at models in main processes for most common particles

String Models – QGS and FTF

- For incident p, n,π,K
  - QGS model also for high energy γ when CHIPS model is connected
- QGS ~10 GeV < E < 50 TeV
- FTF ~ 4 GeV < E < 50 TeV

- Models handle:
  - selection of collision partners
  - splitting of nucleons into quarks and diquarks
  - formation and excitation of strings
- String hadronization needs to be provided
- Damaged nucleus remains. Another Geant4 model must be added for nuclear fragmentation and de-excitation
  - pre-compound model,
  - CHIPS for nuclear fragmentation
  - Binary Cascade and precompound for re-scattering and deexcitation

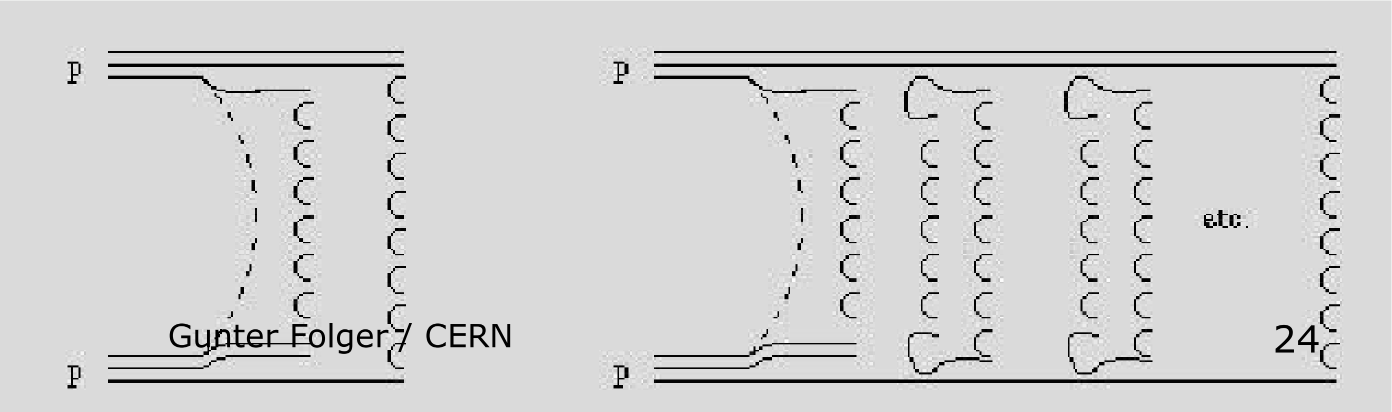
String Model Algorithm



- Build up 3-dimensional model of nucleus
- Large γ-factor collapses nucleus to 2 dimensions
- Calculate impact parameter with all nucleons
- Calculate hadron-nucleon collision probabilities
  - use Gaussian density distributions for hadrons and nucleons
- Form strings
- String formation and fragmentation into hadrons

Quark Gluon String Model

- Two or more strings may be stretched between partons within hadrons
  - strings from cut cylindrical Pomerons
- Parton interaction leads to color coupling of valence quarks
  - sea quarks included too
- Partons connected by quark gluon strings, which hadronize



Fritiof Model

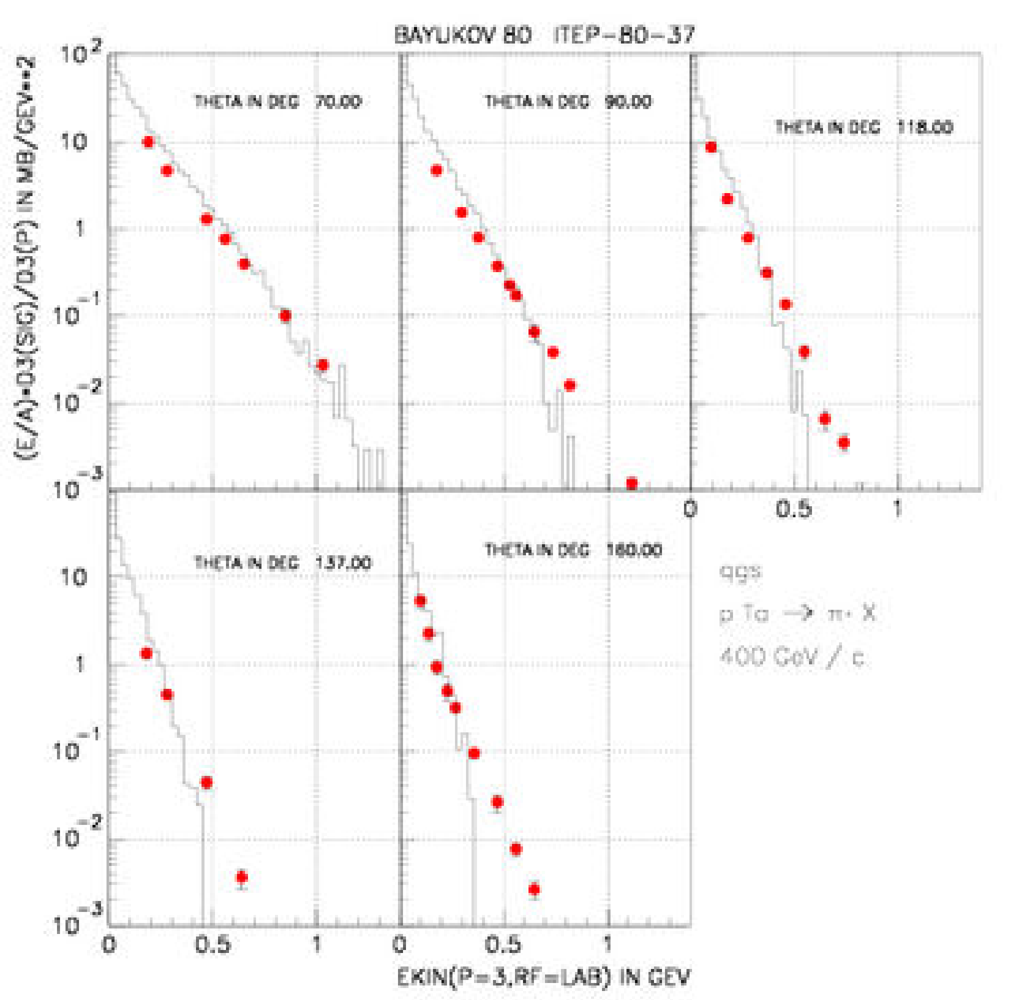
- String formation via scattering of projectile on nucleons
  - momentum is exchanged, increases mass of projectile and/or nucleon
  - Sucessive interactions further increase projectile mass
  - Excited off shell particle viewed as string
  - Lund string fragmentation functions used
- FTF model has been significantly improved in the last year

Longitudinal String Fragmentation

- String extends between constituents
- Break string by inserting q-qbar pair according to
  - u : d : s : qq = 1 : 1 : 0.27 : 0.1
- At break -> new string + hadron
- Created hadron gets longitudinal momentum from sampling fragmentation functions
- Gaussian Pt , <Pt> = 0.5 GeV

Validation of String Models

- **QGS:** Pi+ production in scattering of protons (400 GeV/c) off Tantalum: invariant cross section d2σ/dΩ/dT
- **FTF:** pi+/- production in scattering of protons (158GeV/c) off Carbon invariant cross section d2σ/dp$_T$/dx_F



C.Alt et.al. (Na49 collaboration, Eur.Phys.J.C49 (2007) 897-917

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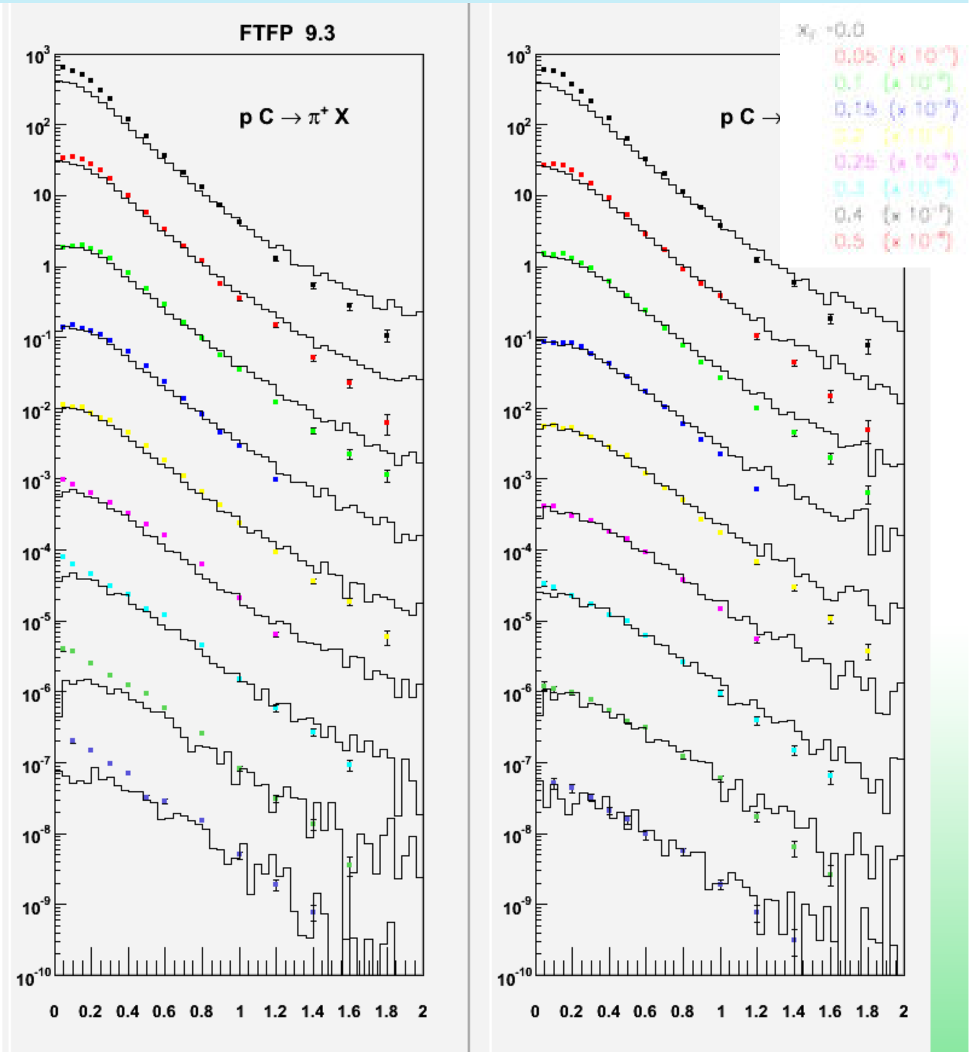
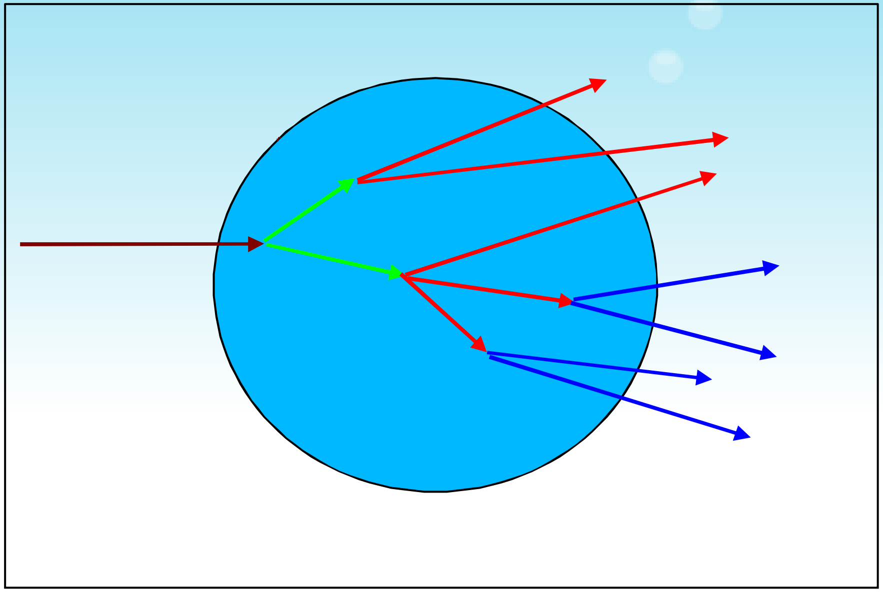


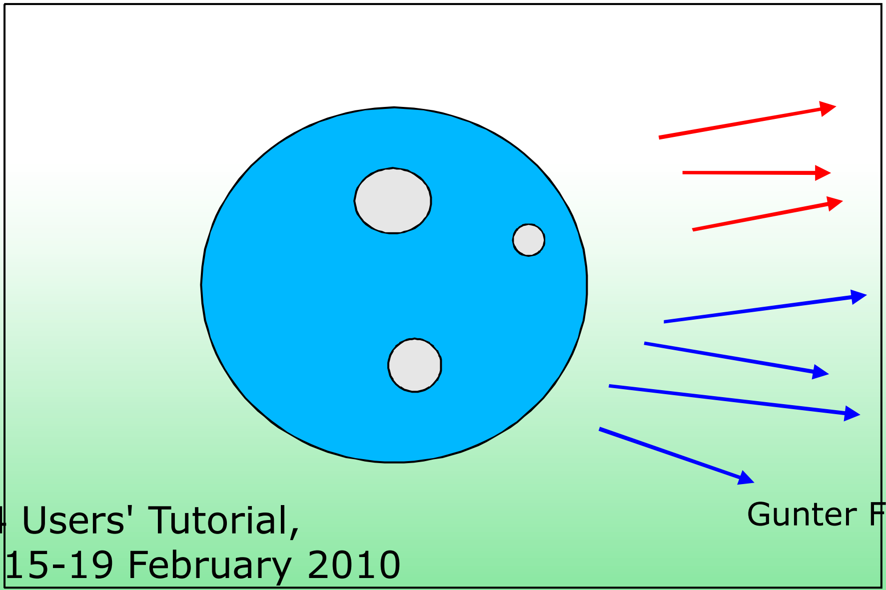
How to Use String Model (QGS)

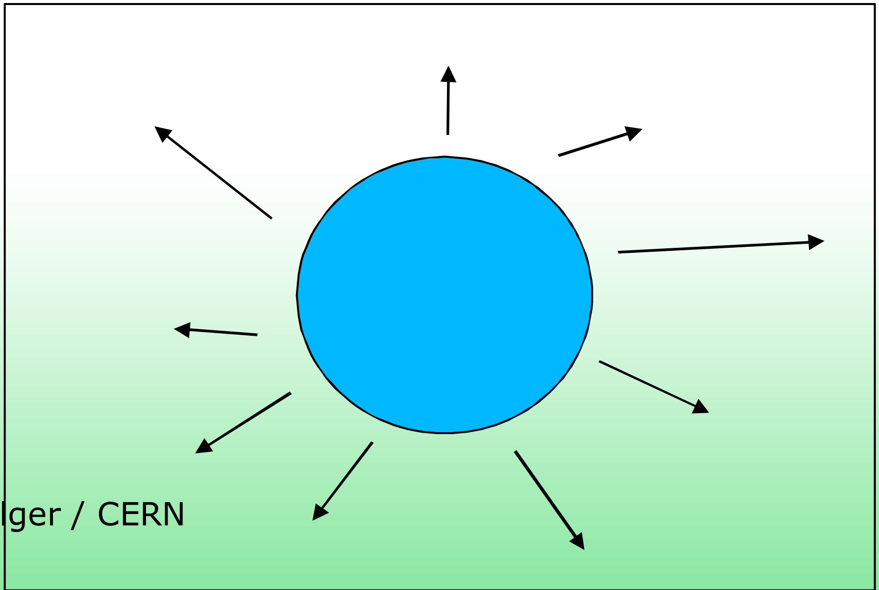
-
  ```
  theModel = new G4TheoFSGenerator("QGSP");

  theStringModel = new G4QGSModel< G4QGSParticipants >;
  theStringDecay = new G4ExcitedStringDecay(new
  G4QGSMFragmentation);
  theStringModel->SetFragmentationModel(theStringDecay);

  theCascade = new G4GeneratorPrecompoundInterface;
  thePreEquilib = new G4PreCompoundModel(new G4ExcitationHandler);
  theCascade->SetDeExcitation(thePreEquilib);

  theModel->SetHighEnergyGenerator(theStringModel);
  theModel->SetTransport(theCascade);
  theModel->SetMinEnergy(12.*GeV);
  theModel->SetMaxEnergy(100*TeV);

  G4ProtonInelasticProcess* piproc = new G4PionPlusInelasticProcess();
  piproc -> RegisterMe(theModel);

  ... Add lower energy model....
  proton_manager -> AddDiscreteProcess(pproc);
  ```

Cascade models (100 MeV – GeVs)

- Bertini Cascade
- Binary Cascade
- INCL/ABLA







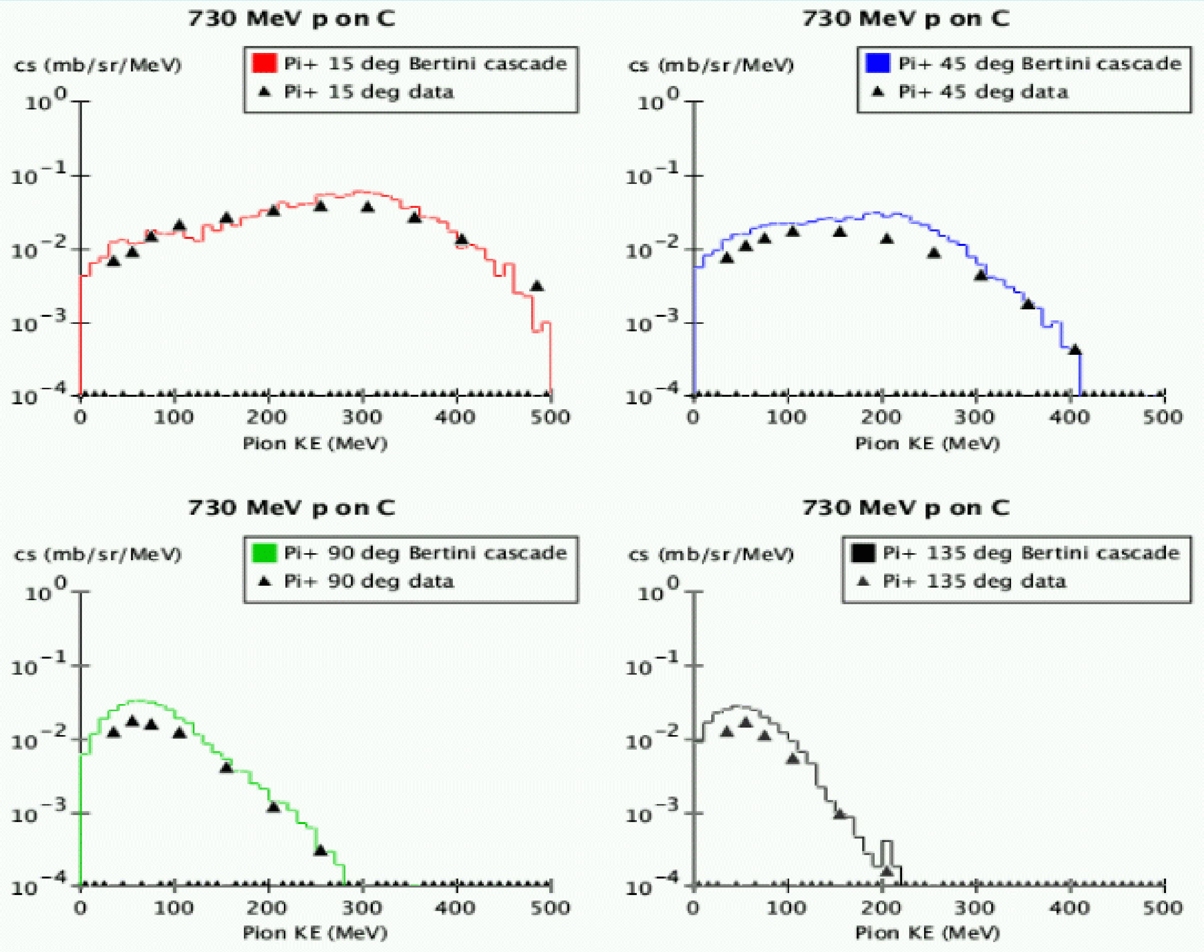
Bertini Cascade Models

- The Bertini model is a classical cascade:
  - it is a solution to the Boltzman equation on average
  - no scattering matrix calculated
  - can be traced back to some of the earliest codes (1960s)
- 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
  - 3-D model of nucleus consisting of shells of different nuclear density
- In Geant4 the Bertini model is currently used for p, n, π, K^+, K^-, K^0_L, K^0_S, Λ, Σ^+, Σ^-, Ξ^-, Ξ^0, Ω^-
  - valid for incident energies of 0 – 10 GeV

Bertini Cascade details

- Modeling sequence:
  - incident particle penetrates nucleus, is propagated in a density-dependent nuclear potential
  - all hadron-nucleon interactions based on free-space cross sections, angular distributions, but no interaction if Pauli exclusion not obeyed
  - each secondary from initial interaction is propagated in nuclear potential until it interacts or leaves nucleus
  - during the cascade, particle-hole exciton states are collected
  - pre-equilibrium decay occurs using exciton states
  - next, nuclear breakup, evaporation, or fission models

Validation of Bertini Casacde



How to use Bertini Casacde

-
  ```
  G4CascadeInterface* bertini = new
  G4CascadeInterface();
  G4ProtonInelasticProcess* pproc = new
  G4ProtonInelasticProcess();
  pproc -> RegisterMe(bertini);
  proton_manager ->
  AddDiscreteProcess(pproc);
  ```

Binary Cascade

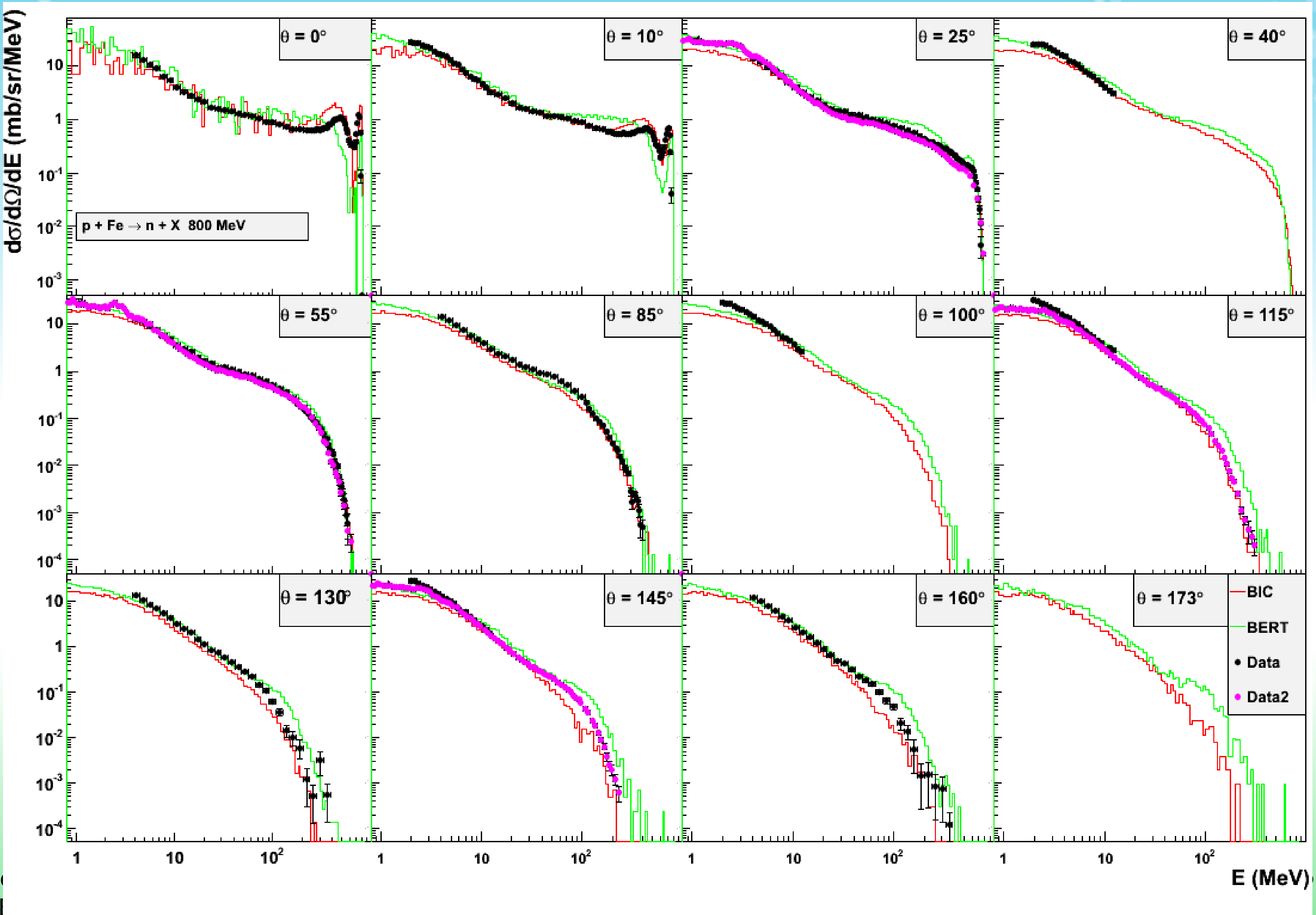
- Modeling sequence, specific to Binary Cascade
  - Nucleus consists of nucleons
    - Placed in space following density distribution
    - Carrying Fermi momentum
  - hadron-nucleon collisions
    - handled by forming resonances which then decay according to their quantum numbers
      - Delta (10) and Nucleon (15) resonances
    - Elastic scattering on nucleons
  - particles follow curved trajectories in nuclear potential
  - Pauli blocking
  - G4PreCompound model is used for nuclear de-excitation after cascading phase

Binary Cascade

- In Geant4 the Binary cascade model is currently used for incident p, n and π
  - valid for incident p, n from 0 to 10 GeV
    - Good up to ~ 3GeV
  - valid for incident π^+, π^- from 0 to 1.3 GeV
  - Limitation is due to resonances

- A variant of the model, G4BinaryLightIonReaction, is valid for incident light ions
  - or higher if target is made of light nuclei

Validation of Binary Cascade



How to use Binary Cascade

- G4BinaryCascade* binary = new G4BinaryCascade(); G4PionPlusInelasticProcess* pproc = new G4PionPlusInelasticProcess(); pproc -> RegisterMe(binary); piplus_manager -> AddDiscreteProcess(pproc);

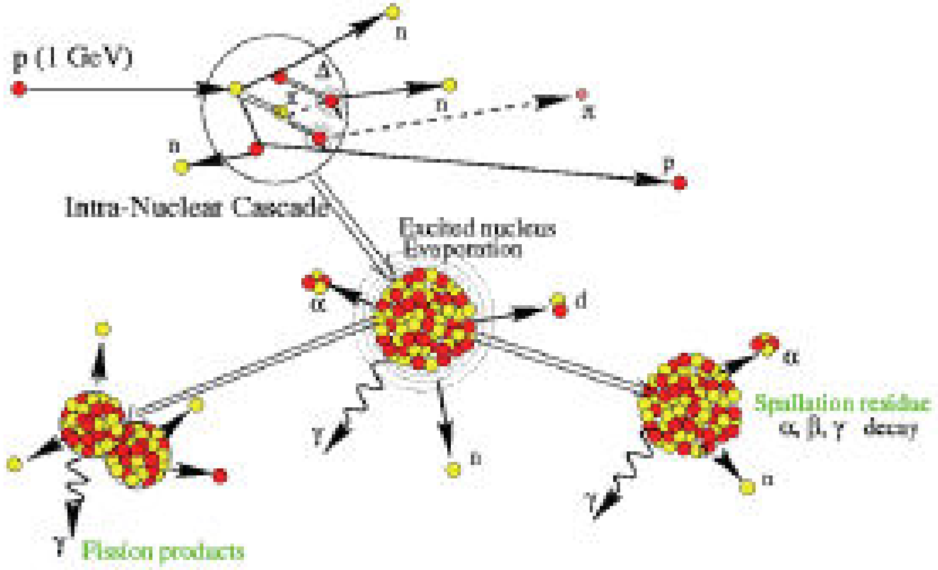
Liege Cascade model

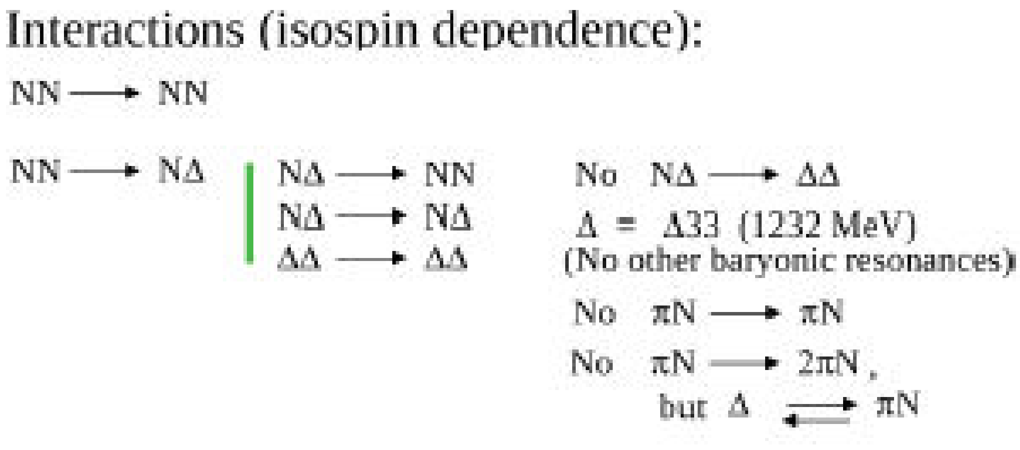
- Well established code in nuclear physics
  - Well tested for spallation studies
  - Uses ABLA code for nuclear de-excitation
- Valid for p, n, pions up to 2-3 GeV
  - Not applicable to light nuclei (A< 12-16)
- Authors collaborate with Geant4 to re-write code in C++
  - First version released with 9.2 in 12/2008
  - ABLA is included as well

INCL intra-nuclear cascade and ABLA de-excitation

Projectile	p, n, π, deuteron, triton, He3, alpha
Energy range	150 MeV - 3 GeV
Target nuclei	Carbon - Uranium

Table: Model validity range




Interactions (isospin dependence):

$NN \longrightarrow NN$

$NN \longrightarrow N\Delta$

$N\Delta \longrightarrow NN$

$N\Delta \longrightarrow N\Delta$

$\Delta\Delta \longrightarrow \Delta\Delta$

No $N\Delta \longrightarrow \Delta\Delta$

Δ = Δ33 (1232 MeV)

(No other baryonic resonances)

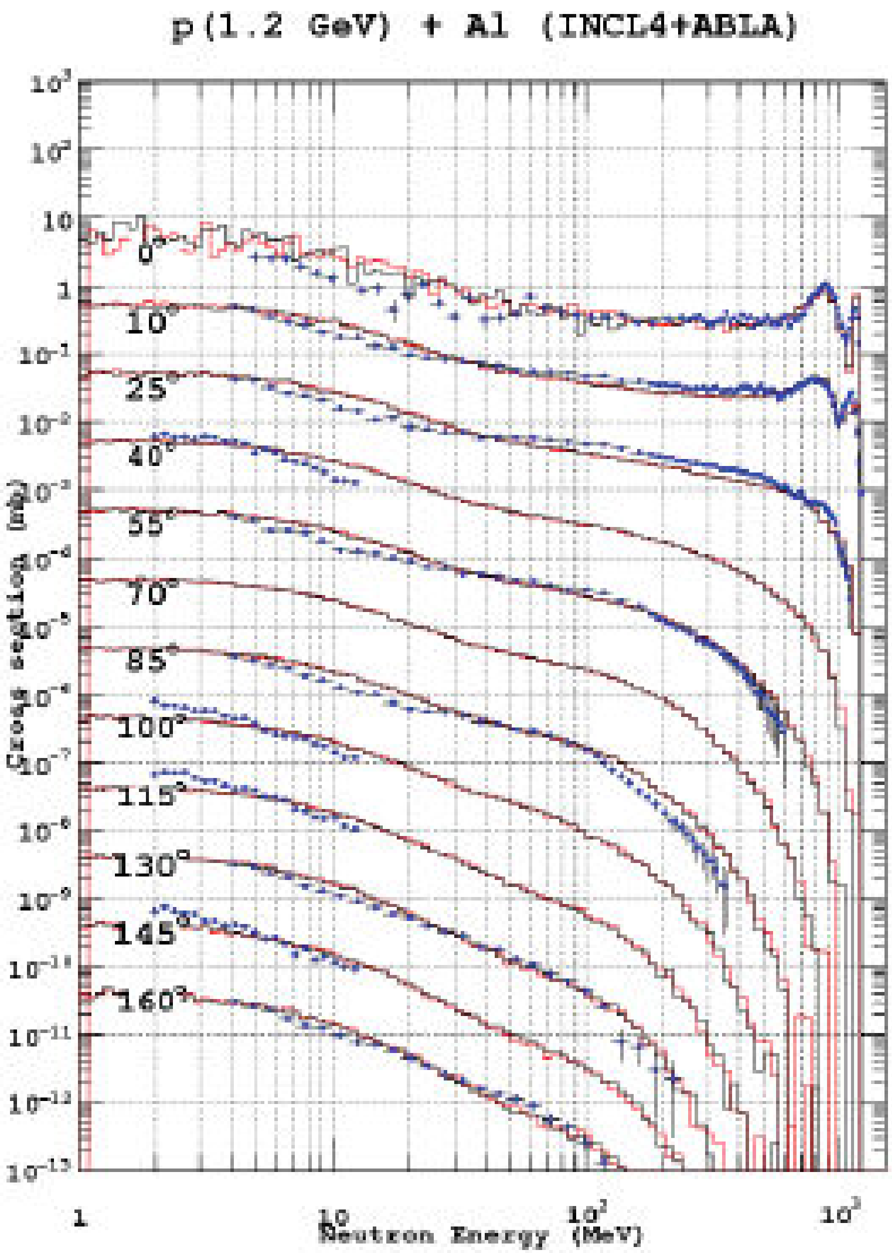
No $\pi N \longrightarrow \pi N$

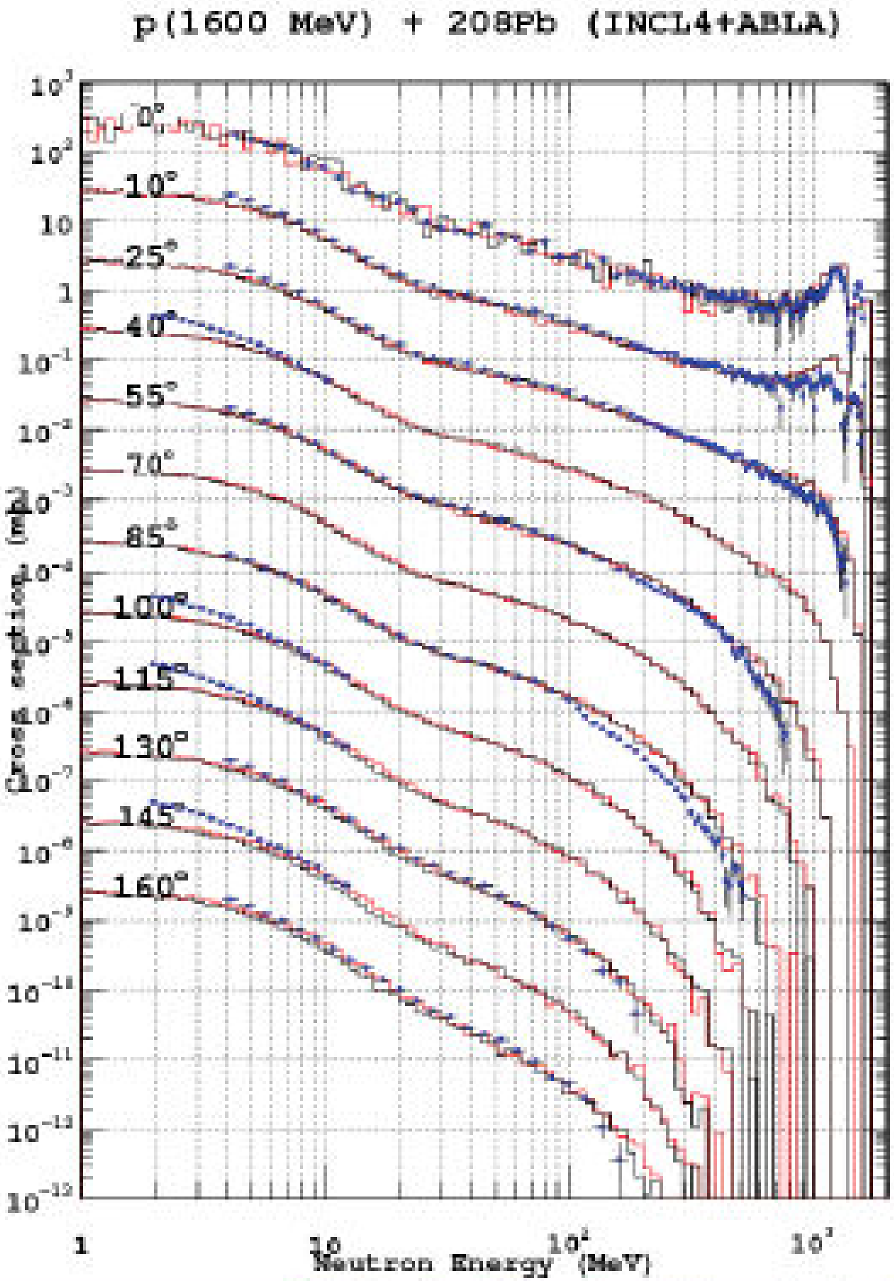
No $\pi N \longrightarrow 2\pi N$,

but $\Delta \rightleftarrows \pi N$

- INCL tracks particles (p, n, π, Δ) and their binary collisions.
- Stop the cascade when stopping time is reached and treat the remnant nucleus with ABLA de-excitation (evaporation of p, n, α or fission).

INCL/ABLA: Double-differential neutron energy spectra


p(1.2 GeV) + Al (INCL4+ABLA)


p(1600 MeV) + 208Pb (INCL4+ABLA)

Plots by P. Kaitaniemi

Precompound Model

- G4PreCompoundModel
  - for nucleon-nucleus interactions at low energy
  - as a nuclear de-excitation model within higher-energy codes
  - valid for incident p, n from 0 to 170 MeV
  - takes a nucleus from a highly-excited set of particle-hole states down to equilibrium energy by emitting p, n, d, t, 3He, alpha
  - once equilibrium state is reached, four other models are invoked via G4ExcitationHandler to take care of nuclear evaporation and breakup
    - these models not currently callable by users
- The parameterized and cascade models all have nuclear de-excitation models embedded

Equilibrium models

- Fermi breakup
  - Light nuclei, (A,Z) < (9,17)
- Multifragmentation
  - Highly excited nuclei
- Evaporation
  - Emission of p,n, d, t, alpha;
  - or using GEM up to Mg
- Gamma emission
  - Both discrete and continous

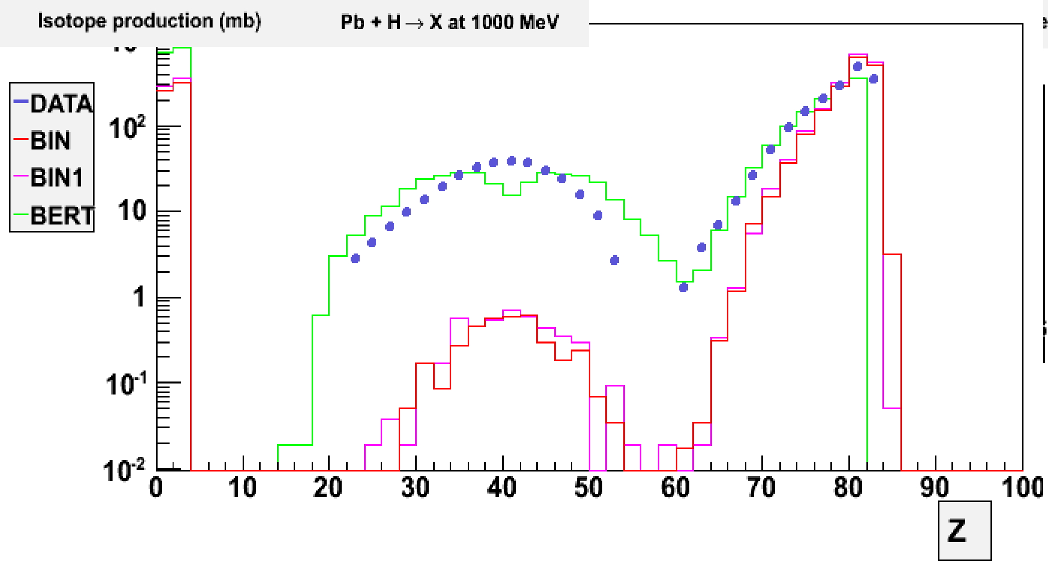
- G4Precompound and the equilibrium models were significantly improved in 9.3

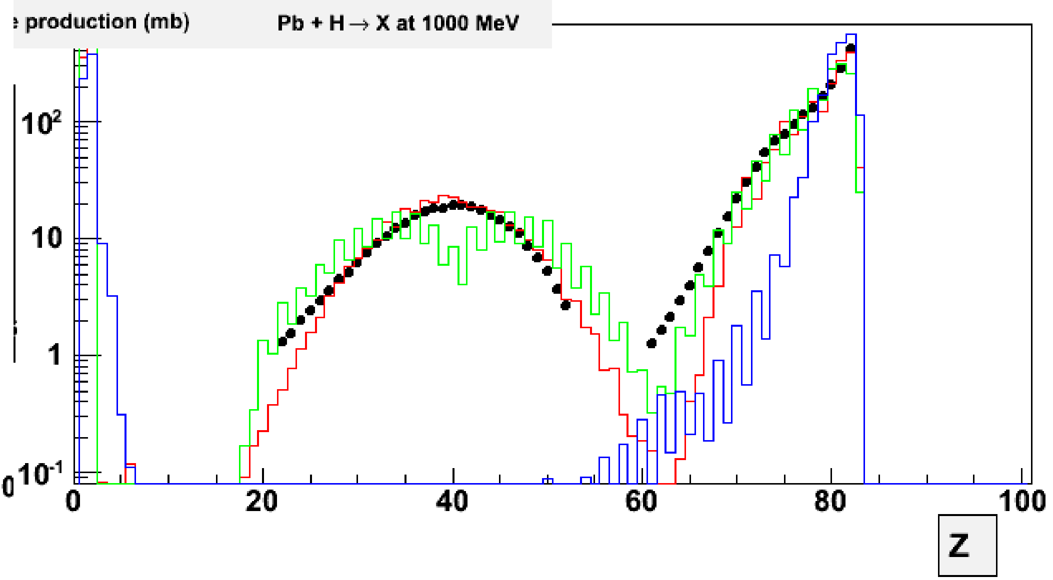
Validation Precompound & de-excitation models

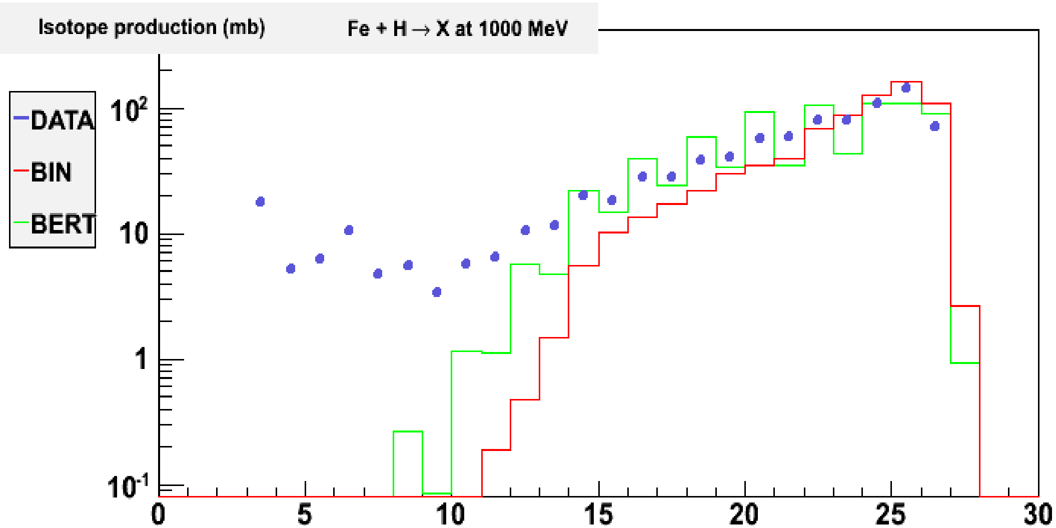
Isotope production at 1000 MeV in inverse kinematics

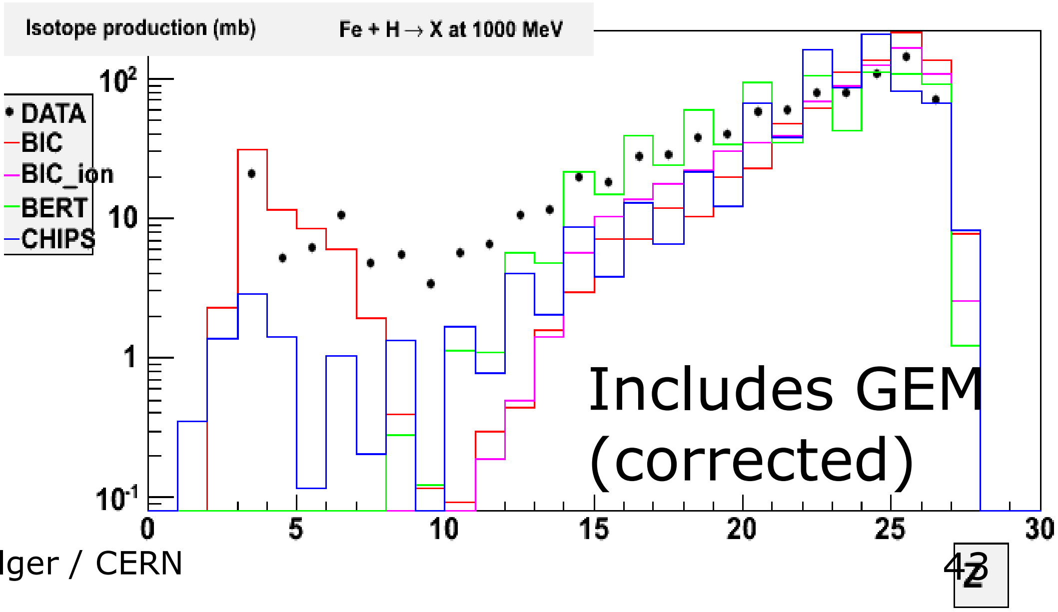
BEFORE 9.2p01

NOW 9.3









Includes GEM (corrected)

Using the PreCompoundModel

-
  ```
  G4Processmanager * procMan = G4Neutron::Neutron()->GetProcessManager;
  // equilibrium decay
  G4ExcitationHandler*  theHandler = new G4ExcitationHandler;
  // preequilibrium
  G4PrecompoundModel* preModel = new G4PrecompoundModel(theHandler);

  G4NeutronInelasticProcess* nProc = new G4NeutronInelasticProcess;

  // Register model to process, process to particle
  nProc->RegisterMe(preModel);
  procMan->AddDiscreteProcess(nProc);
  ```

Low energy neutron transport NeutronHP

- Data driven models for low energy neutrons, E< 20 MeV, down to thermal
  - Elastic, capture, inelastic, fission
    - Inelastic includes several explicit channels
  - Based on data library derived from several evaluated neutron data libraries

- More details in lecture tomorrow

At Rest

- Most Hadrons are unstable
  - Only proton and anti-proton are stable!
  - I.e hadrons, except protons have Decay process
- Negative particles and neutrons can be captured (neutron, μ^-), absorbed (π^-, K^-) by, or annihilate (anti-proton, anti-neutron) in nucleus
  - In general this modeled as a two step reaction
    - Particle interacts with nucleons or decays within nucleus
    - Exited nucleus will evaporate nucleons and photons to reach ground state

Capture Processes

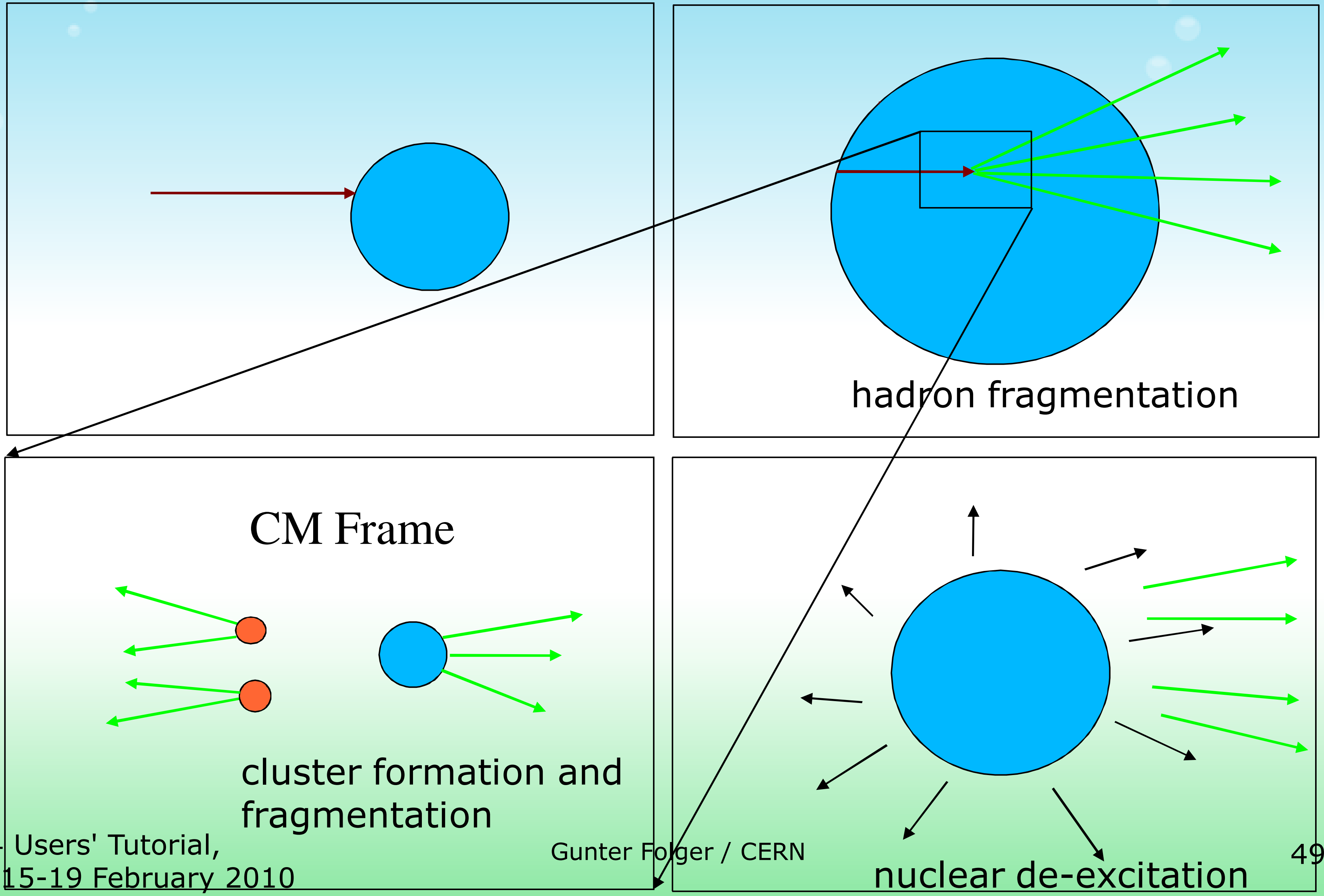
- At Rest Capture Processes
  - G4MuonMinusCaptureAtRest
  - G4PionMinusAbsorptionAtRest
  - G4KaonMinusAbsorption
  - G4AntiProtonAnnihilationAtRest
  - G4AntiNeutronAnnihilationAtRest
- Alternative model implemented in CHIPS
  - G4QCaptureAtRest
    - Applies to all negative particles, and anti-nucleon
- Neutron with E < ~30 MeV can also be captured
  - G4HadronCaptureProcess uses following models:
  - G4LCapture (mainly for neutrons), simple + fast
  - G4NeutronHPCapture (specifically for neutrons), detailed cross sections, slow

Using Capture processes

-
  ```
  // Muon minus
  aProcMan = G4MuonMinus::MuonMinus()-
  >GetProcessManager();
  G4MuonMinusCaptureAtRest * theMuonMinusAbsorption = new
  G4MuonMinusCaptureAtRest();
  aProcMan->AddRestProcess(theMuonMinusAbsorption);

  // PionMinus
  aProcMan = G4PionMinus::PionMinus()->GetProcessManager();
  G4PionMinusAbsorptionAtRest  * thePionMinusAbsorption = new
  G4PionMinusAbsorptionAtRest();
  aProcMan->AddRestProcess(thePionMinusAbsorption);
  ```
- … etc…, OR using CHIPS process

-
  ```
   // Using Chips Capture Process
  aProcMan = G4PionMinus::PionMinus()->GetProcessManager();
   G4QCaptureAtRest *  hProcess = new G4QCaptureAtRest();
  aProcMan ->AddRestProcess(hProcess);
  ```

LEP (0-40 GeV), HEP (25GeV – TeVs)



LEP, HEP models

- Parameterized models, based on Gheisha
- Modeling sequence:
  - initial interaction of hadron with nucleon in nucleus
  - highly excited hadron is fragmented into more hadrons
  - particles from initial interaction divided into forward and backward clusters in CM
  - another cluster of backward going nucleons added to account for intra-nuclear cascade
  - clusters are decayed into pions and nucleons
  - remnant nucleus is de-excited by emission of p, n, d, t, alpha
- The LEP and HEP models valid for p, n, K, Λ, Σ, Ξ, Ω, α, t, d
- LEP valid for incident energies of 0 – ~30 GeV
- HEP valid for incident energies of ~10 GeV – 15 TeV

LEP and LEP models

- Providing processes for all particles
  - Elastic scattering
  - Inelastic processes
    - “production”
    - Capture
    - Fission
- Originally created to simulate hadronic showers
  - Shape in general well described
  - e/pi, response, resolution less well
  - Often worst in describing thin target data
- Very fast, but simply physics modeling
- Energy/momentum often not conserved

Using the LEP and HEP models

- G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess();
- G4LEProtonInelastic* LEproton = new G4LEProtonInelastic();
- G4HEProtonInelastic* HEproton = new G4HEProtonInelastic();
- HEproton -> SetMinEnergy(25*GeV);
- LEproton -> SetMaxEnergy(55*GeV);
- pproc -> RegisterMe(LEproton);
- pproc -> RegisterMe(HEproton);
- proton_manager -> AddDiscreteProcess(pproc);

Not yet covered

- CHIPS
- Ion induced interactions
  - Binary light ion cascade
  - QMD model
  - Wilson Abrasion/Ablation models available
  - EM Dissociation model
- Electro-nuclear interactions
- Radioactive decay
- Isotope production model

Summary hadronics

- Geant4 hadronic physics framework allows for physics process implemented as:
  - Process
  - cross sections plus model, or combination of models
- Many processes, models and cross sections to choose from
  - hadronic framework also allows users to add his own cross section or model
- Recent improvements and additions in
  - FTF model
  - Precompound and de-excitation models
  - Liege cascade implementation, including ABLA
  - Elastic scattering
  - Cross sections
- Validation of models and cross sections
  - http://geant4.fnal.gov/hadronic_validation/validation_plots.htm

Backup slides