GEANT4 HADRONIC PHYSICS

Geant4 Training Event – Calorimetry in HEP

DESY Zeuthen

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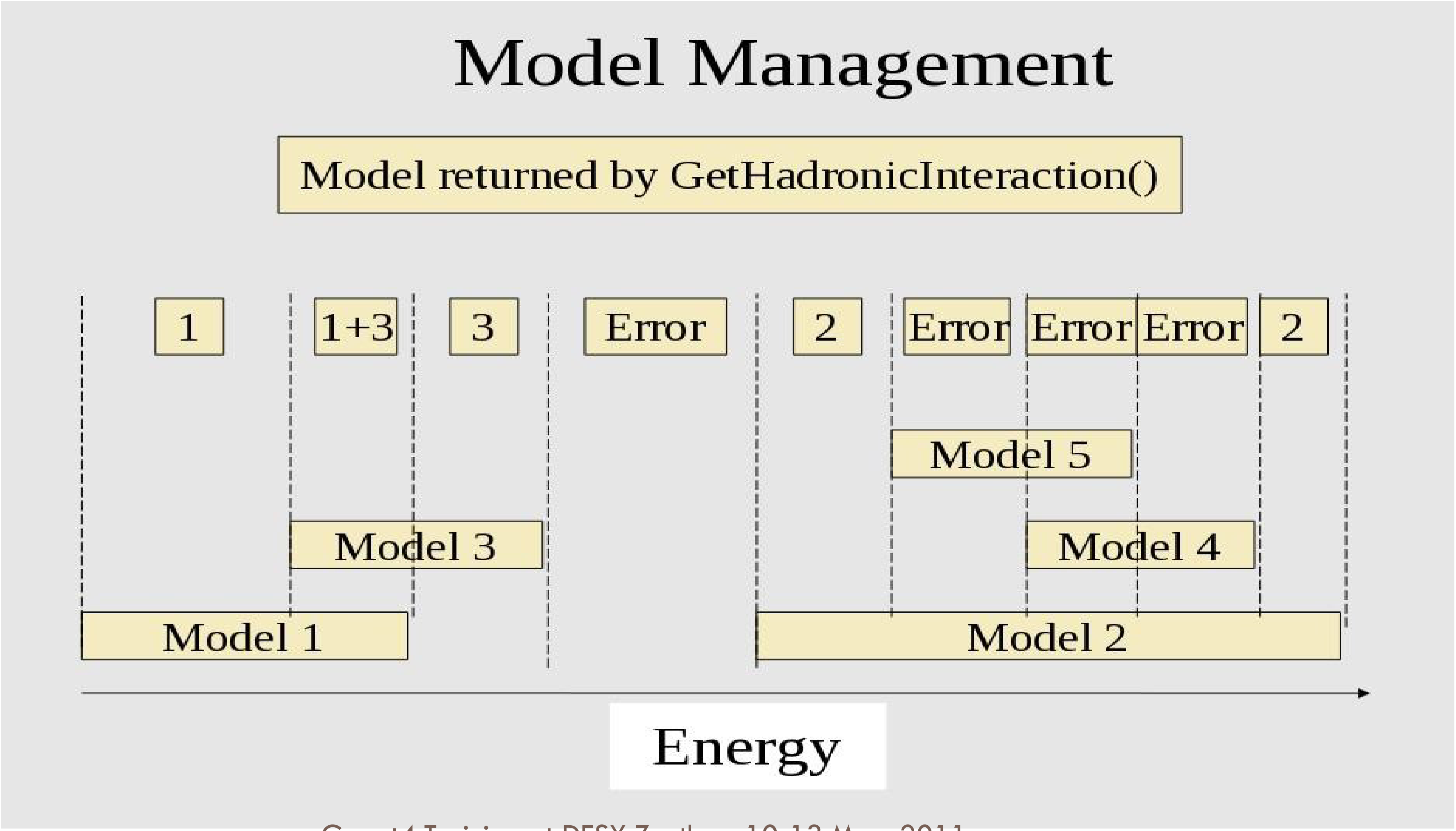
Based on lectures developed by Dennis Wright

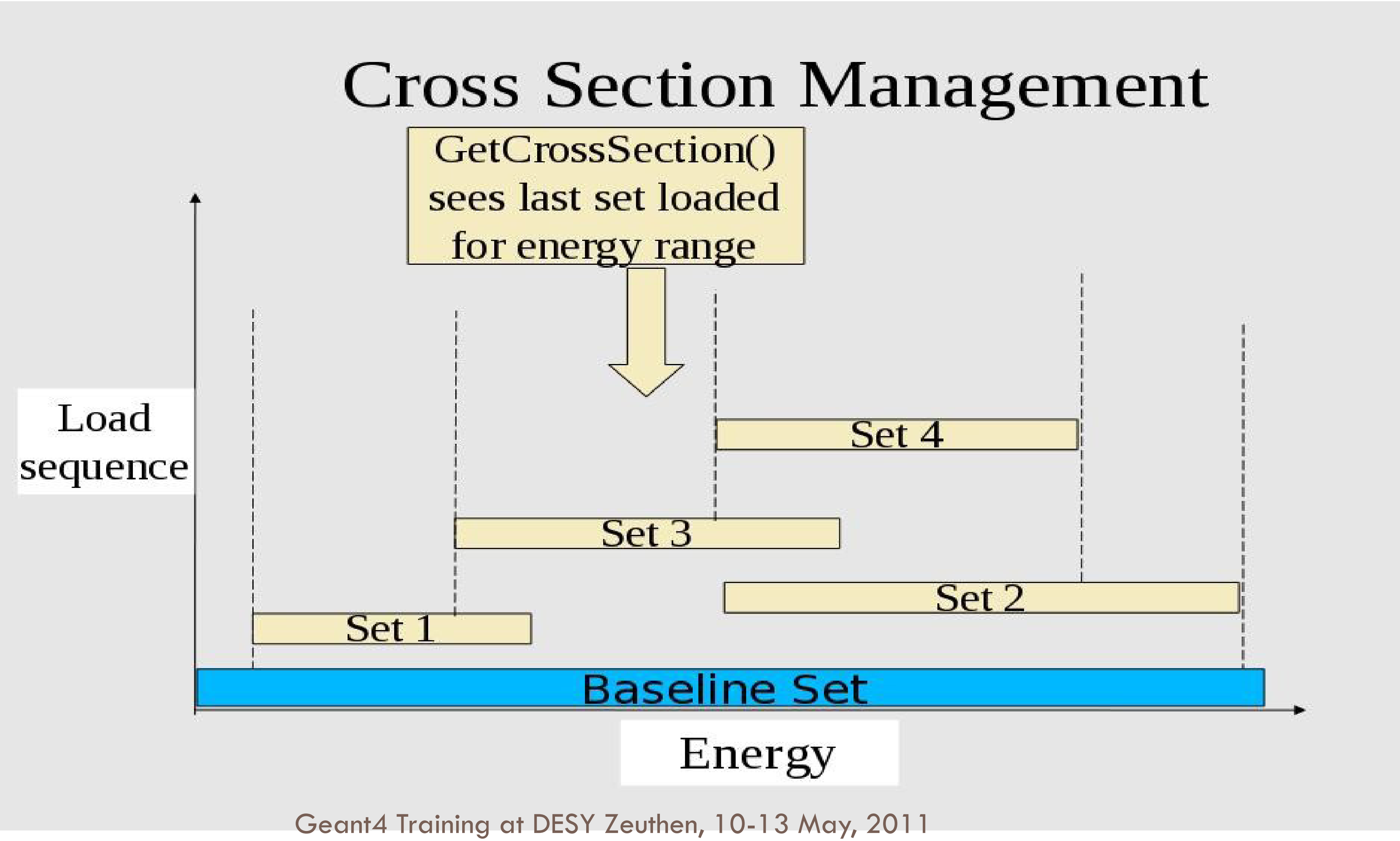
Geant4 hadronic physics

- Simulation of elastic and inelastic hadron/ion reactions with atomic nuclei
  - Energy range from zero up to 100 TeV
- Cross sections and sampling of final state are independent
- Model approach:
  - different models for different energy range and particle type
  - It is not possible to create one universal model

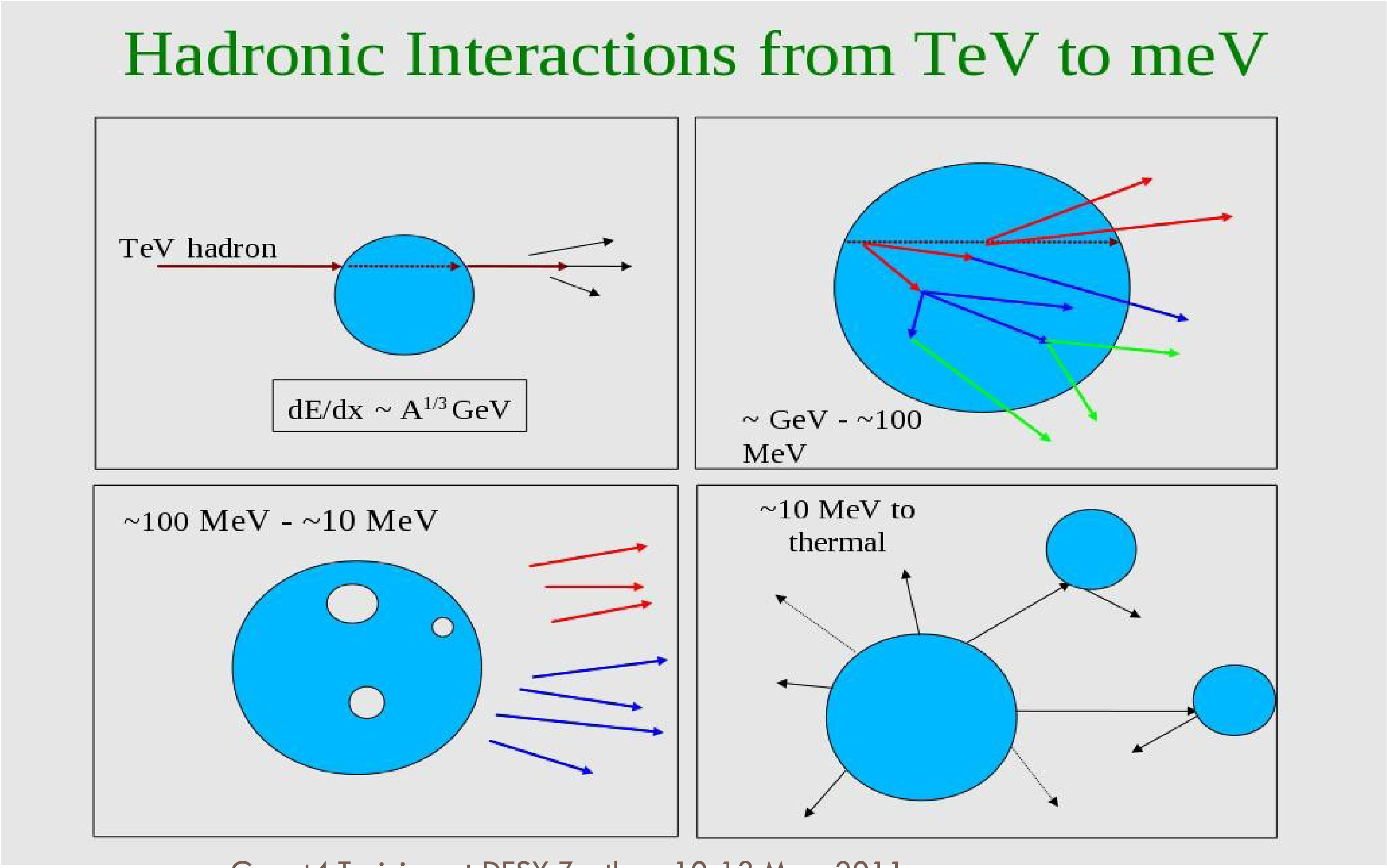
Hadronic process should have set of models covered required energy range



Hadronic process should have set of cross sections for required energy range



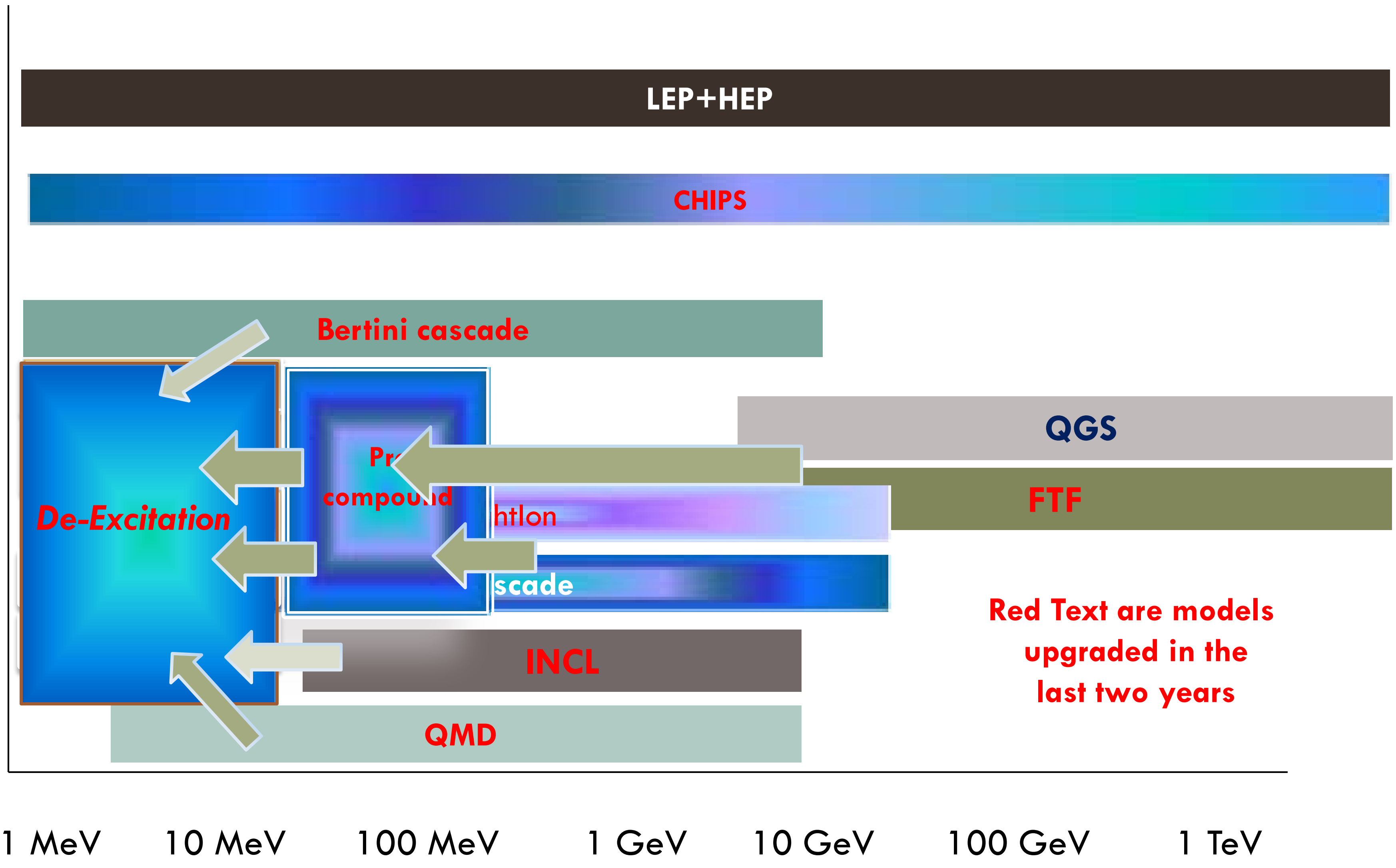
Hadronic inelastic interaction includes several stages using different sub-models

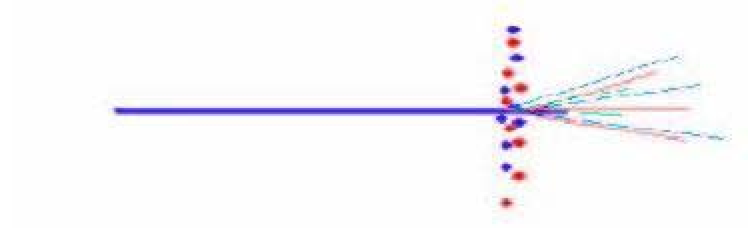


Main choice for hadronic physics:

- When starting hadronic physics simulation one needs to choose a combination of models and cross sections
- User should ask himself:
  - What string model?
  - What cascade model?
  - What pre-compound/de-excitation model?
  - Are high precision neutron models needed?
- Geant4 include number of professionals with 10-30 years of expertise in specific hadronic models
  - They usually are responsible for their own models

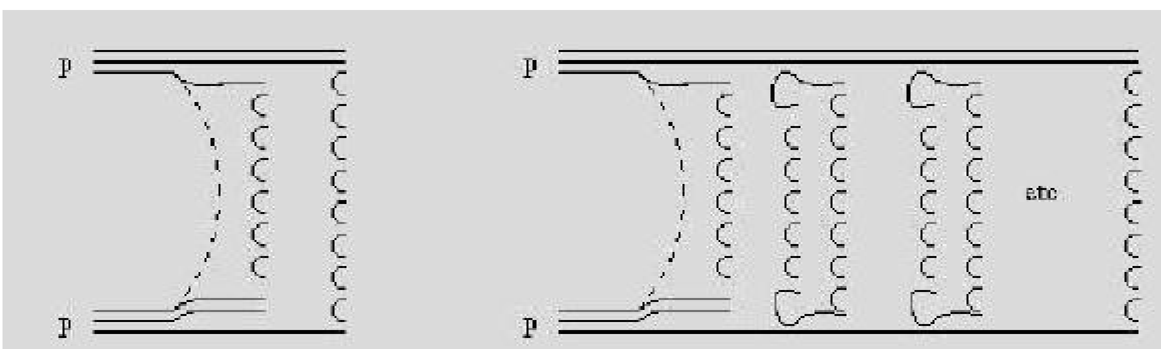
Geant4 hadronic models





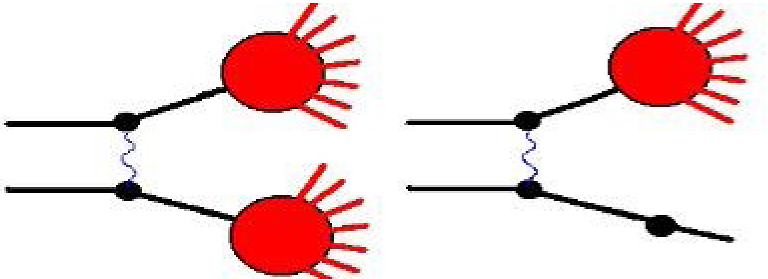
Quark-Gluon String

- One of the Geant4 QCD string models
- valid from 20 GeV - 1TeV
- In this model, two or more strings are stretched between the partons (quarks or gluons) within the hadrons



Fritiof Fragmentation Model

- Alternative QCD string fragmentation model
  - valid from 3 GeV - 1TeV
- This model applies at much lower energies due to
  - ability to handle lower string masses
  - Reggeon cascade
  - Natural introduction of diffraction processes
- Model uses a different set of fragmentation functions and relies more on fitted parameters than QGS model



Bertini Cascade - favourite for LHC

- 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)
  - Original author Stepanov (ITEP, Moscow)
  - Current responsible D.Wright (SLAC, Stanford, CA)
- Core code:
  - elementary particle collider: uses modified 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
  - more precise for A > 10

Binary Cascade – today favorite for medical and space applications

- Modeling sequence similar to Bertini, except that
  - Nucleus consists of nucleons
  - hadron-nucleon collisions
    - handled by forming resonances which then decay according to their quantum numbers
    - Elastic scattering on nucleons
  - particles follow curved trajectories in nuclear potential
  - Geant4 native PreCompound model is used for nuclear de-excitation after cascading phase
- 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
  - valid for incident π^+, π^- from 0 to 1.3 GeV
- A variant of the model, G4BinaryLightIonReaction, is valid for incident light ions
  - or higher if target is made of light nuclei
- Alternative new model QMD (T.Koi) was recently released
  - May be recommended for light media

Chiral Invariant Phase Space (CHIPS)

- Unique model, based on a thermodynamic treatment of bubbles of quark-gluon plasma
  - can be used to represent any excited hadron system or ground state hadron
- Currently used for
  - capture of negatively charged hadrons at rest
  - anti-baryon nuclear interactions
  - gamma-nuclear and lepto-nuclear reactions
- CHIPS is an alternative method for the fragmentation of excited nuclei for any other model
- Author Mikhail Kosov (ITEP, Moscow, Russia)

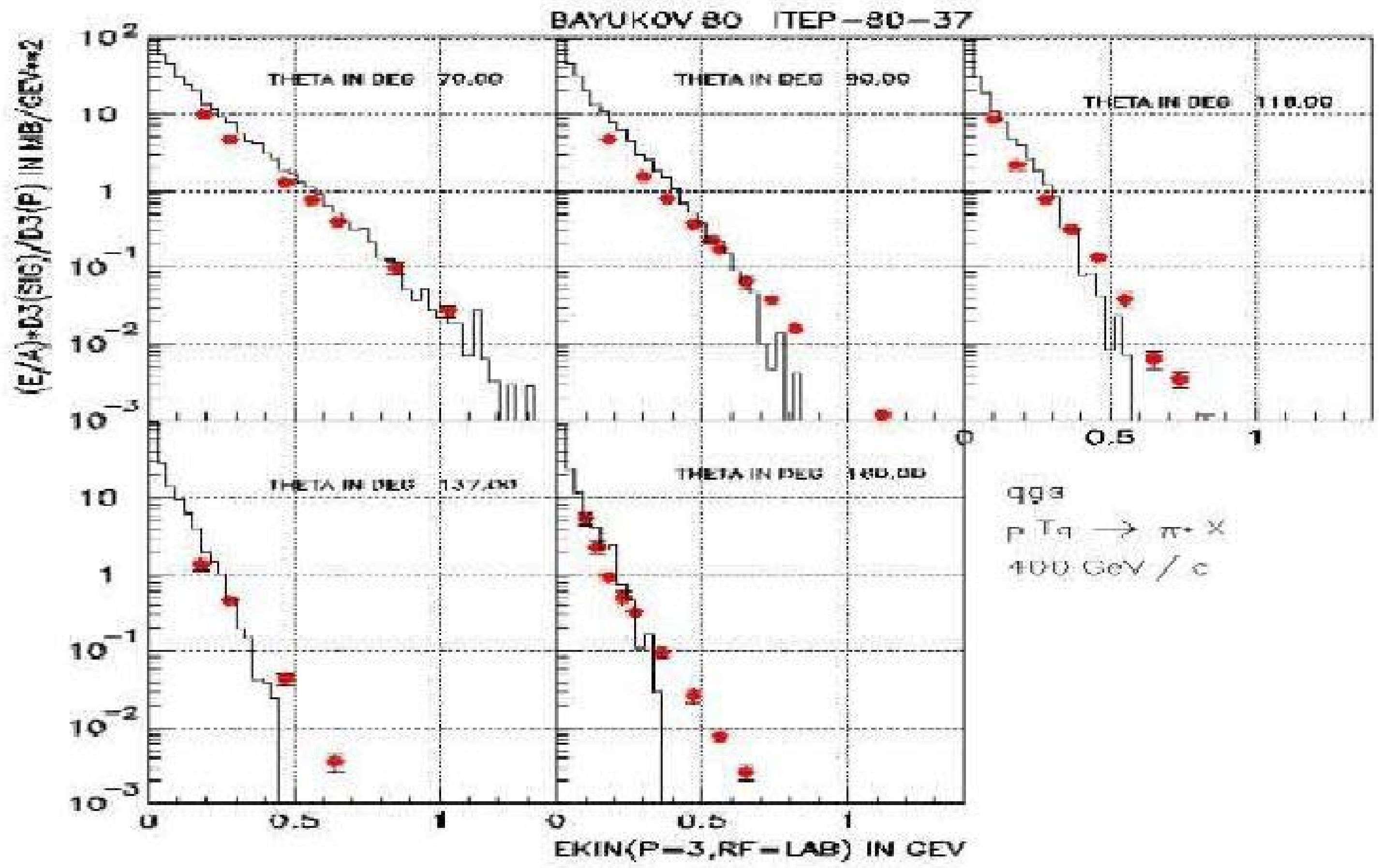
Liege Cascade (INCL) model

- 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 was released with 9.2 in December 2008
  - ABLA is included as well
  - Helsinki University group is responsible

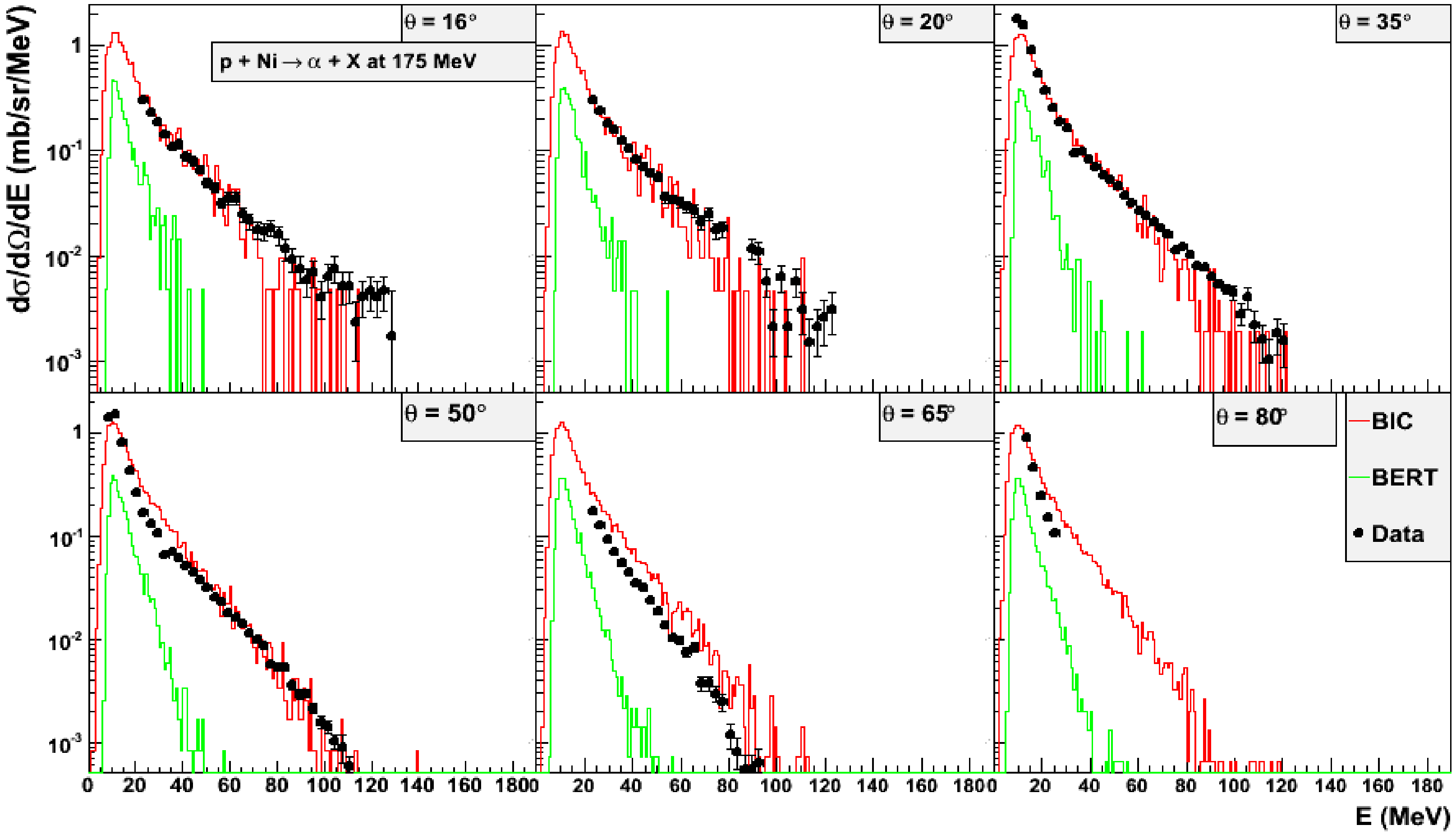
Geant4 hadronic physics

- General comment:
  Theory of inelastic hadronic interactions is not fully established from 1st principles, so phenomenology and parameterisations based on data are used, naturally different competitive models are being developed inside Geant4

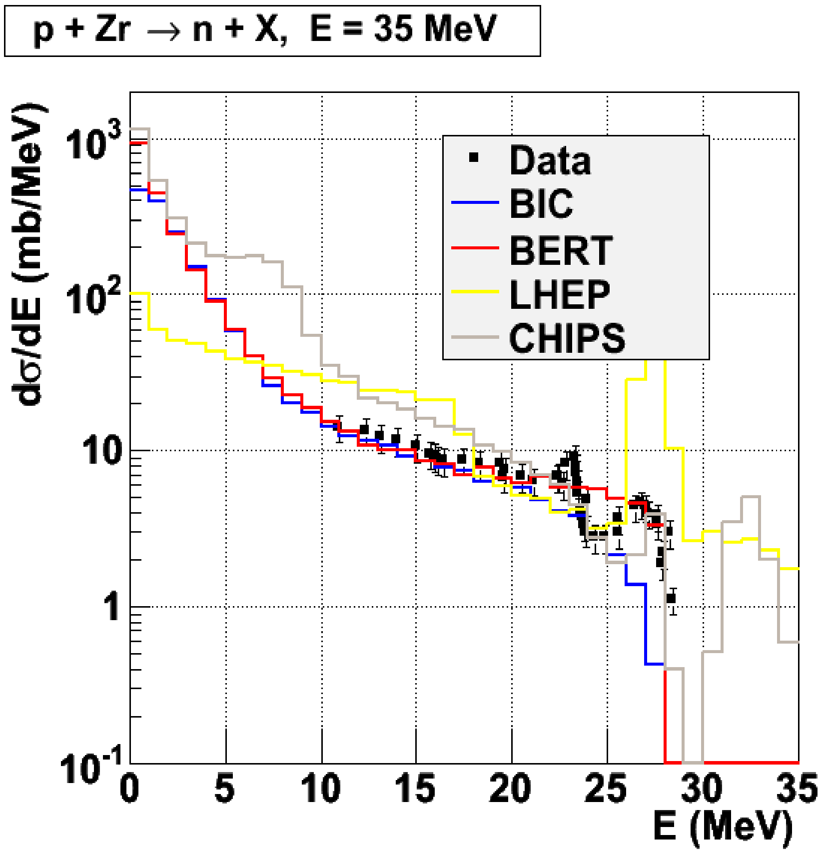
QGS Results at 400 GeV/c p Ta->π^+ X

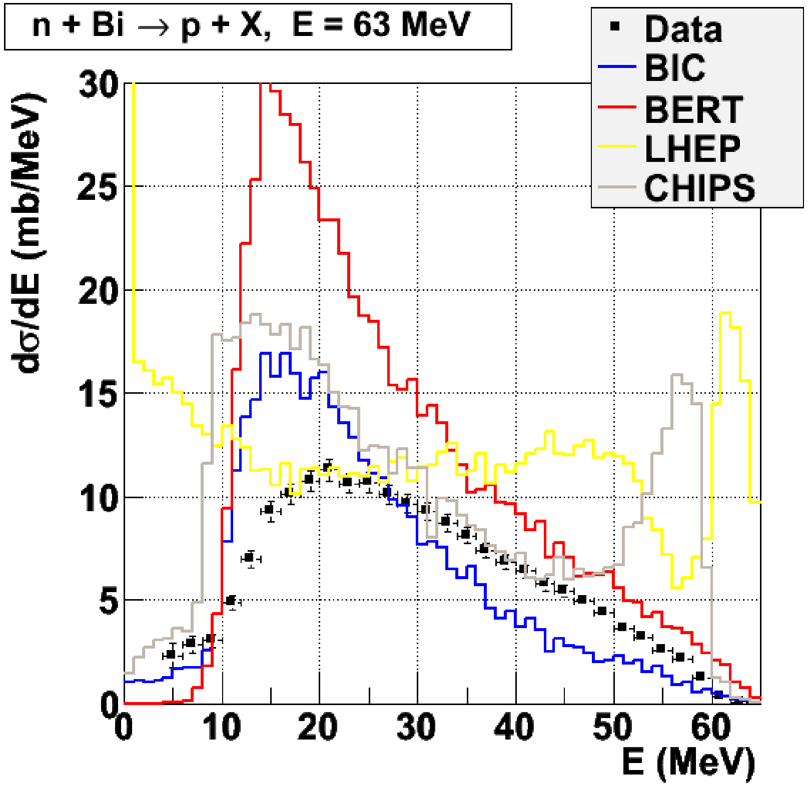


Hadronic validation: ^{4}He ion emission in proton nuclear reaction



Proton and Neutron production





Low energy neutron physics (< 20MeV)

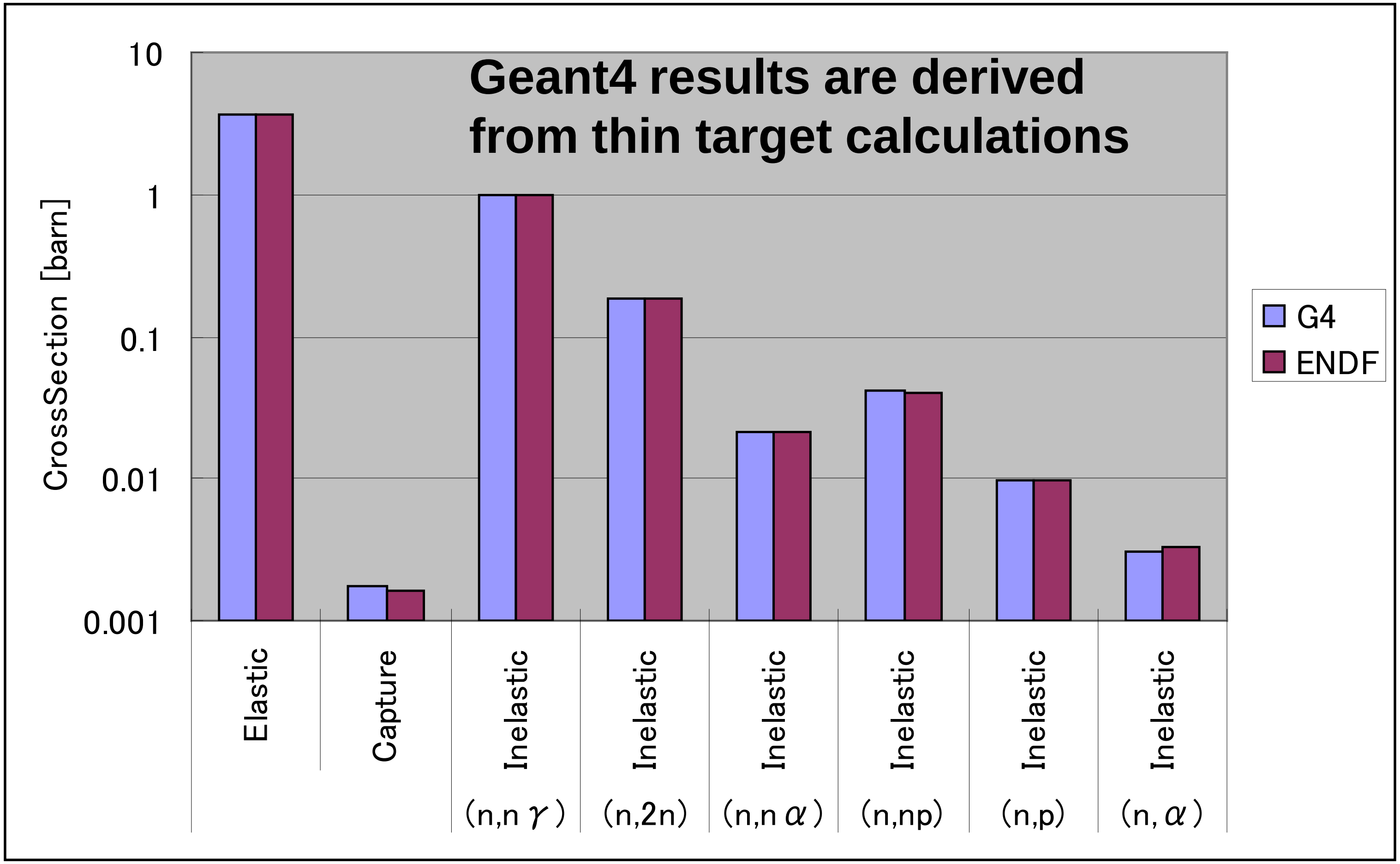
- High Precision Neutron Models and Cross Sections
  - G4NDL database (G4NEUTRONHPDATA)
  - ENDF – the main source of the data
    - Elastic
    - Inelastic
    - Capture
    - Fission
- NeutronHPorLEModel(s) – alternative to "standard" models
- ThermalScatteringModels (and Cross Section data Sets)
  - Very low-energy processes taking into account molecular effects

G4NeutronHPInelastic

- Currently supported final states are (nA) nγs (discrete and continuum), np, nd, nt, n 3He, nα, nd2α, nt2α , n2p, n2α, np , n3α, 2nα, 2np, 2nd, 2nα, 2n2α, nX, 3n, 3np, 3nα, 4n, p, pd, pα, 2p d, dα, d2α, dt, t, t2α, 3He, α, 2α, and 3α.
- Secondary distribution probabilities are supported
  - isotropic emission
  - discrete two-body kinematics
  - N-body phase-space distribution
  - continuum energy-angle distributions
    - legendre polynomials and tabulation distribution
    - Kalbach-Mann systematic $A + a \longrightarrow C \longrightarrow B + b$, C:compound nucleus
  - continuum angle-energy distributions in the laboratory system

Verification of High Precision Neutron models
Channel Cross Sections

20MeV neutron on ^{157}Gd



Radioactive decay

- To simulate decay of radioactive nuclei
- Empirical and data-driven models
- Models of α, $\beta^{\pm}$ decays, and e^{-} capture are implemented
- Data derived from Evaluated Nuclear Structure Data File (ENSDF)
  - Nuclear half-lives, level structure, nuclear decay branching ratio, Q-value of decays, the data directory $G4RADIOACTIVEDATA
- If the daughter of a nuclear decay is an excited isomer, its prompt nuclear de-excitation is treated using photon evaporation code – data-base of γ lines and nuclear levels in $G4LEVELGAMMADATA

Reference Physics Lists

- Reference physics lists attempt to cover a wide range of use cases
  - Extensive validation by LHC experiments for simulation hadronic showers
    - QGSP_BERT, or QGSP_BERT_EMV were used in production for LHC in 2010
    - QGSP_FTFP_BERT_EML – current default for CMS
    - QGSP_BERT_CHIPS – current default for ATLAS, ALICE
    - QGSP_BERT_EMV – current default for LHCb
    - New FTF_BIC is a promising alternative
    - QGSP_BERT_EMY – first variant for medical users
  - user feedback is welcome
- Reference Physics Lists use modular design including following constructors (builders):
  - EM (default is standard EM)
  - Extra EM (gamma- and electro- nuclear processes)
  - Decay
  - Hadron elastic scattering
  - Hadron inelastic Interaction
  - Ion-nuclear interactions
  - User can add extra physics constructor – StepLimiter, Optical, RadioactiveDecay…

Hands on reference Physics Lists

- Copy $G4INSTALL/examples/hadronic/Hadr00 to your local area
- cd Hadr00
- gmake
- setenv PHYSLIST QGSP_BERT
- $G4WORKDIR/bin/$G4SYSTEM/hadr00 hadr00.in > result.log
- Study result.log file

Thank you for your attention!