

Geant 4

Hadronic physics

<http://geant4.cern.ch>

PART I

Intro to the philosophy of hadronic processes

Hadronic physics challenge

- Even though there is an underlying theory (QCD), applying it is much more difficult than applying QED for simulating EM interactions
- We must deal with at least **three energy régimes**:
 - Chiral perturbation theory (< 100 MeV)
 - Resonance and cascade region (100 MeV – 20 GeV)
 - QCD strings (> 20 GeV)
- Within each regime there are **several (sub)-models**:
 - Many of these are **phenomenological**

The Geant4 philosophy of hadronics (1/2)

- Provide a **general model framework** that allows implementation of **processes** and **models at many levels**
- Separate models and processes in framework:
 - Hadronic models and cross sections implement processes → **multiple models for the same process** (e.g. in different energy ranges)
- Provide processes containing:
 - Many possible models and cross sections
 - Default cross sections for each model

Models under continuous development

The Geant4 philosophy of hadronics (2/2)

- Provide several optional models and cross section sets in each energy region
- Let the user decide which physics is best:
 - Complex task is handled with physics lists → set of physics models attached to the various particles (in given energy ranges)
- Validate new models against latest data:
 - Extensive and systematic validation program
- Understand the trade-off between performance, physics and general applicability vs. energy – there is only one nature

The Geant4 physics lists

- A key point for the user is to **choose the proper physics list** for his/her own specific application. To start:
 - have a look at the **physics lists** of the **advanced examples** released with Geant4
 - use one of the **educated guess physics lists** provided by Geant4 for **different use cases**

Information to help users to **choose the proper physics list** is available at the website:

[http://geant4.cern.ch/support/proc_mod_catalog/
physics_lists/physicsLists.shtml](http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/physicsLists.shtml)

Geant4 process

- A process uses **cross sections** to decide when and where an interaction will occur:
 - ① ■ `GetPhysicalInteractionLength()`
 - Many **processes** will be in **competition** (one of them has to be chosen)
- A process uses an **interaction model** to generate the **final state**:
 - ② ■ `DoIt()`
- Three types of process (possibly mixed):
 - `AtRest`, `AlongStep` (*continuous*), `PostStep`
- Each particle has its own process manager
- Each process has a **set of models** coordinated with **energy range** manager

Hadronic process

- **At rest**
 - Stopped muon, pion, kaon, anti-proton
 - Radioactive decay
 - Particle decay (decay-in-flight is PostStep)
- **Elastic**
 - **Same process** to handle all long-lived hadrons (multiple models available)
- **Inelastic**
 - **Different processes** for each hadron (possibly with multiple models vs. energy)
 - Photo-nuclear, electro-nuclear, mu-nuclear
- **Capture**
 - Pion- and kaon- in flight, neutron
- **Fission**

PART II

Hadronic cross sections

Cross sections

- **Default cross section sets** are provided for each type of hadronic process:
 - Fission, capture, elastic, inelastic
- Can be **overridden** or **completely replaced**
- Different types of cross section sets:
 - Some contain only a few numbers to **parameterize** cross section
 - Some represent large **databases** (data driven models)
- Cross section management
 - `GetCrossSection()` → sees last set loaded for energy range

Alternative cross sections

- To be used for specific applications, or for a given particle in a given energy range, for instance:
- *Low energy neutrons*
 - elastic, inelastic, fission and capture (< 20 MeV)
- *Neutron and proton inelastic cross sections*
 - $20 \text{ MeV} < E < 20 \text{ GeV}$
- *Ion-nucleus reaction cross sections (several models)*
 - Good for $E/A < 1 \text{ GeV}$
- *Isotope production data*
 - $E < 100 \text{ MeV}$
- *Photo-nuclear cross sections*

Information on the available cross sections at http://geant4.cern.ch/support/proc_mod_catalog/

[cross_sections/](#)

PART III

**Final states of hadronic
processes:
overview of the available models**

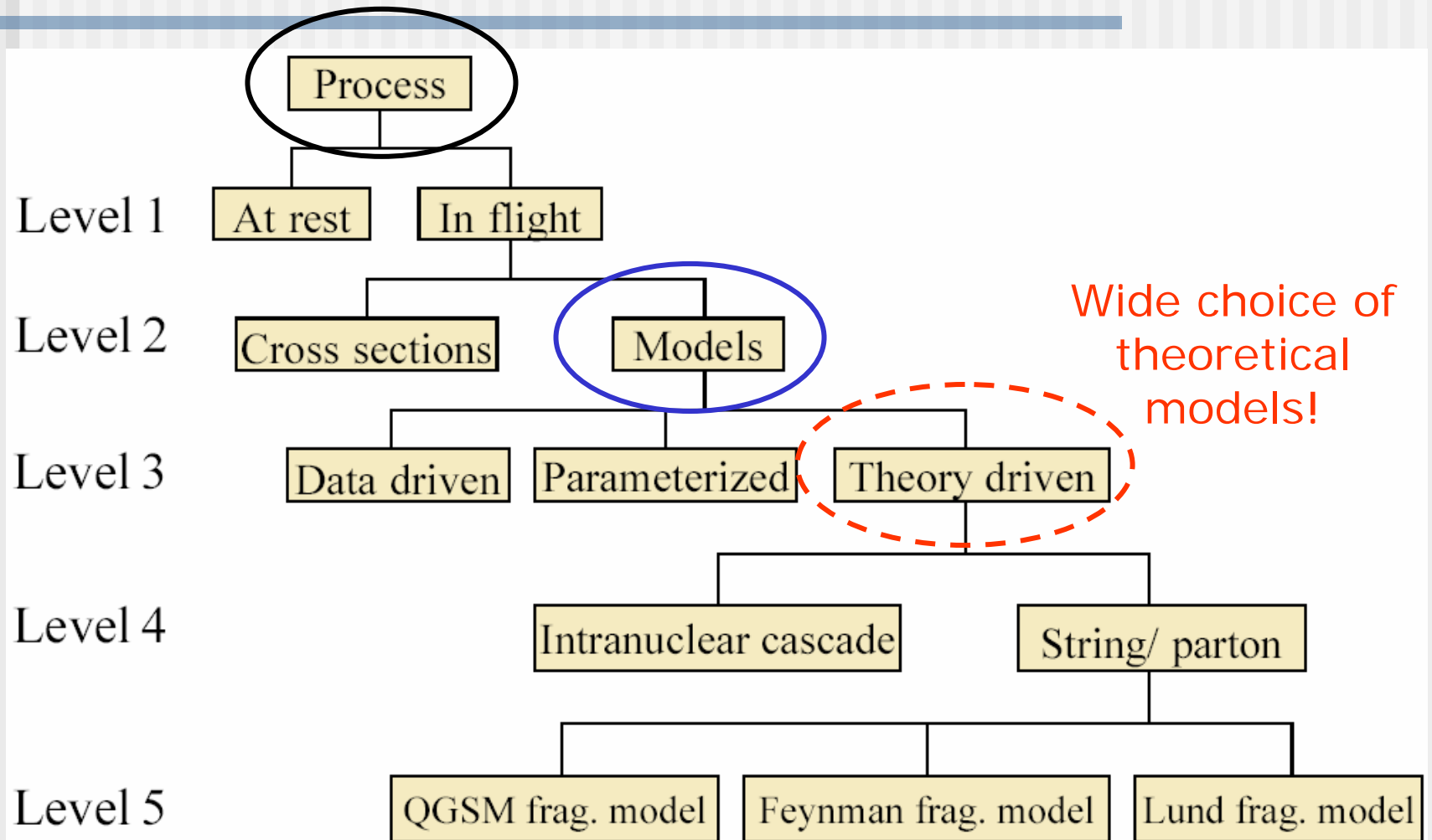
Different types of hadronic shower models

1. Data driven models
2. Parametrisation driven models
3. Theory driven models

Information on the available models at:

http://geant4.cern.ch/support/proc_mod_catalog/models

Models in hadronic framework



Data driven models (1/2)

- Characterized **by lots of data**:
 - Cross sections
 - Angular distribution
 - Multiplicity and final states
- To get **interaction length** and **final state**, models simply **interpolate data** read from a database:
 - Usually *linear interpolation* of cross section, and *Legendre polynomials*
- Examples:
 - Coherent elastic scattering (pp, np, nn)
 - Radioactive decay ($T_{1/2}$ and decay channels)
 - Neutrons ($E < 20$ MeV), for isotopes and/or natural elements

Data driven models (2/2)

- Transport of **low-energy neutrons** in matter:
 - The energy coverage of these models is from **thermal energies** to **20 MeV**
 - The modeling is based on the data formats of **ENDF/B-VI**, and all distributions of this standard data format are implemented
 - Includes cross sections and final state information for *elastic and inelastic scattering, capture, fission and isotope production*
 - The file system is used in order to allow granular access to, and flexibility in, the use of the **cross-sections for different isotopes, and channels**
 - Code in sub-directory:
`/source/processes/hadronic/models/neutron_hp`

G4NeutronHPInelastic

- Currently supported **final states** are:

$(n, n\gamma)$ (discrete and continuum), $(n, n2p)$, (n, nd) , (n, nt) , $(n, n^3\text{He})$,
 $(n, n\alpha)$, $(n, nd2\alpha)$, $(n, nt2\alpha)$, $(n, n2p)$, $(n, n2\alpha)$, $(n, n3\alpha)$, $(n, 2n\alpha)$,
 $(n, 2np)$, $(n, 2nd)$, $(n, 2n\alpha)$, $(n, 2n2\alpha)$, (n, nX) , $(n, 3n)$, $(n, 3np)$,
 $(n, 3n\alpha)$, $(n, 4n)$, (n, p) , (n, pd) , $(n, p\alpha)$, $(n, 2p)$, (n, d) , $(n, d\alpha)$,
 $(n, d2\alpha)$, (n, dt) , (n, t) , $(n, t2\alpha)$, $(n, ^3\text{He})$, (n, α) , $(n, 2\alpha)$ and $(n, 3\alpha)$

→ **available channels** for a target isotope depend on the **database files** in the `inelastic/FS` directory

- **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 $A + a \rightarrow C \rightarrow B + b$, C: compound nucleus

G4NDL (Geant4 Neutron Data Library)

- The data are including both **cross sections** and **final states** → directory **\$G4NEUTRONHPDATA**
- The data are derived **evaluations** based on the following **evaluated data libraries** (in alphabetic order)
 - Brond-2.1, CENDL2.2, EFF-3, ENDF/B-VI.0, 1, 4, FENDL/E2.0, JEF2.2, JENDL-FF, JENDL-3.1,2, MENDL-2
- The **data format is similar ENDF**, however it is not equal to
- Additional environment variables to **control NeutronHP processes**:
 - **G4NEUTRONHP_NEGLECT_DOPPLER** to neglect Doppler broadening (speeds the simulation up),
 - **G4NEUTRONHP_SKIP_MISSING_ISOTOPES** to force the exact isotope file (do not use natural composition if the file is not available)

Parametrisation driven models (1/3)

- Depend on **both data and theory**:
 - Enough data to **parameterize** cross sections, multiplicities, angular distributions
- Fit of **experimental data** with appropriate **parametrizations**, plus some theory
- **Final states** determined by **theory**, sampling:
 - Use conservation laws to get charge, energy, etc.
- Examples:
 - Fission
 - Capture
 - **LEP**, GEISHA-based **HEP** models → see next slide

Parametrisation driven models (2/3)

- Based on **GEISHA** package of Geant3.21, **two** sets of **models** exist for **inelastic scattering** of particles in flight:
 - **Low energy models** – LEP: **$E < 30 \text{ GeV}$**
 - /hadronic/models/low_energy
 - **High energy models** – HEP: **$10 \text{ GeV} < E < 15 \text{ TeV}$**
 - /hadronic/models/high_energy
- **LEP** and **HEP** can be applied to $p, n, \pi, K, \Lambda, \Sigma, \Xi, \alpha, t$ and d
- **Original approach** to primary interaction, nuclear excitation, intra-nuclear cascade and evaporation is **kept**

Parametrisation driven models (3/3)

- After the initial interaction of hadron with nucleons in the nucleus:
 - highly excited hadrons **fragmented** into more hadrons
 - residual clusters decayed in **nucleons** and π 's
 - remnant nucleus is de-excited by emission of **p, n, d, t** and α
- LEP and HEP models are **fast** in terms of CPU but **not very detailed** (to have a more precise simulation, one should use **cascade models**)
- **Fission, capture** and **coherent elastic scattering** are also modeled through parametrised models (\rightarrow see next slide)

Hadron elastic scattering

- Default: parametrized GHEISHA-style (**G4LElastic**)
 - classical scattering (not all relativistic)
 - simple parameterization of cross section, angular distribution
 - can be used for all long-lived hadron projectiles, all energies
- Other alternative (specialized) models for coherent elastic scattering:
 - G4LEpp for (p,p), (n,n): taken from detailed phase-shift analysis, good up to 1.2 GeV
 - G4LEnp for (n,p): same as above
 - G4HadronElastic for (h,A): nuclear model details included as well as interference effects, good for 1 GeV and above, all long-lived hadrons
 - G4QElastic for (p,A), (n,A): parameterization of experimental data by M. Kossov, part of CHIPS modeling

Theory driven models (1/3)

- Dominated by **theory** (QCD, strings, chiral perturbation theory)
- Data used mainly for **normalization** and **validation**
- **Final states** determined by **sampling theoretical distributions**
- Philosophy implies the usage physics lists, providing the **wanted collection of models**, such as:
 - *Parton string* models at high energies, of *intra-nuclear transport* models at intermediate energies, and of *statistical break-up* models for de-excitation...

Theory driven models (2/3)

- Parton string
 - Projectiles with $E > 5 \text{ GeV}$ (up to 100 TeV)
 - de-excitation either by CHIPS or pre-compound models
- Chiral invariant phase space, CHIPS
 - All energies
 - Quark-level event generator for the fragmentation of hadronic systems into hadrons
 - Interactions between hadrons are treated as purely kinematic effects of quark exchange
 - Decay of excited hadronic systems is treated as the fusion of two quark-partons within the system
 - Includes non-relativistic phase space of nucleons to explain evaporation
- Nuclear de-excitation and break-up

Theory driven models (3/3)

■ Fritiof-based models

- Handles the **formation of strings** in the initial collision of a hadron with a nucleon in the nucleus. String **fragmentation into hadrons** is handled by the **Lund fragmentation model**.
- **De-excitation** of the remnant nucleus is handled either by the **CHIPS** models or by **precompound** models (see next slides)
- handles **p, n, pions and kaons**
- from **15 GeV to 100 TeV**

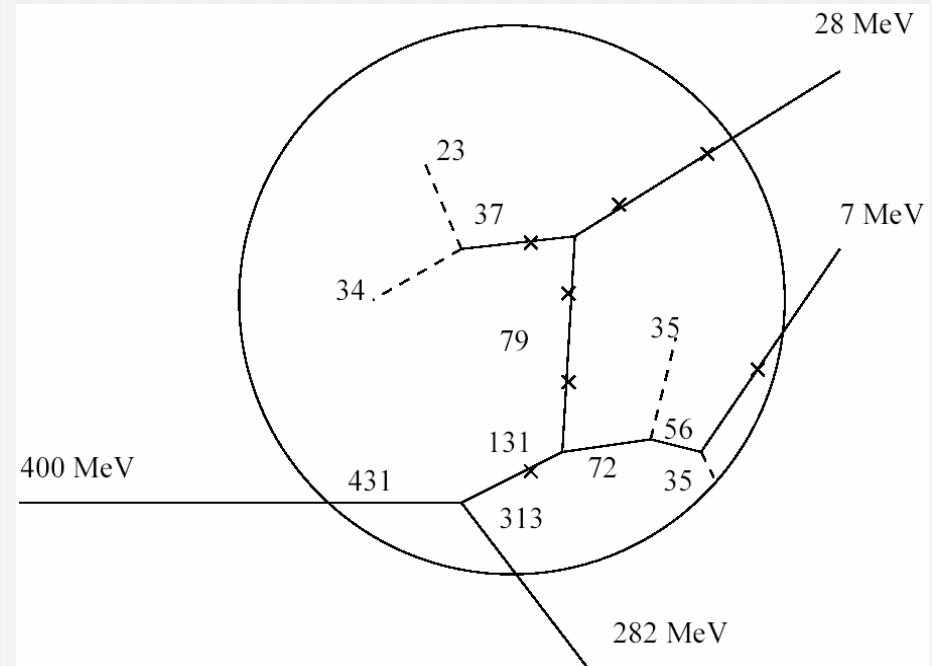
Area of theory-driven models under active development → check in the Geant4 webpage

Bertini cascade (1/2)

- Collection of **theory driven models** with parametrisation features:
 - `/hadronic/models/cascade`
- Intermediate energies **~1 MeV – 10 GeV**
- Models included:
 - Bertini intra-nuclear cascade (INC) model with excitons
 - *Pre-equilibrium* model
 - *Nucleus explosion* model
 - Fission model
 - *Evaporation* model
- **Slower** but **more accurate** than parametrized models

Bertini cascade (2/2)

- For $A > 4$ a nuclei model is composed of **three concentric spheres**
- Impulse distribution in each region follows **Fermi distribution** with zero temperature
- Particle treated: **p, n, pions, photon evaporation** and **nuclear isotope remnats**
- Final states, will be included for K^+ , K^- , K^0 , $K^0\text{-bar}$, Λ , Σ^+ , Σ^0 , Σ^- , Ξ^0 and Ξ^-



Schematic presentation of the intra-nuclear cascade. A hadron with 400 MeV energy is forming an INC history. Crosses present the Pauli exclusion principle in action.

Binary cascade

- Nucleus is **explicitly modeled** in **G4BinaryCascade**
 - Nucleons have **momentum** and are placed in space
 - momentum taken into account for scattering
 - hadron-nucleon collisions including **re-scattering**
 - particles follow **curved trajectories** in **nuclear potential**
 - At end of cascade, nucleus and exciton system is passed to **pre-equilibrium model** (precompound → see next slides)
- Binary cascade model handles 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**

Liege cascade models

INCL 4.2 cascade model (Liege cascade) available in Geant4 (re-engineered from FORTRAN)

`hadronic/models/incl`

- handles primary: p , n , π , d , t , ${}^3\text{He}$ and α
- valid from **200 MeV to 3 GeV** and for **target nuclei** from **C to U**
- Uses **ABLA** or **HETC models** for nuclear **evaporation** below 200 MeV (produce p , n , α and nuclear fragments)

Area under active development → check in the
Geant4 webpage

Precompound model

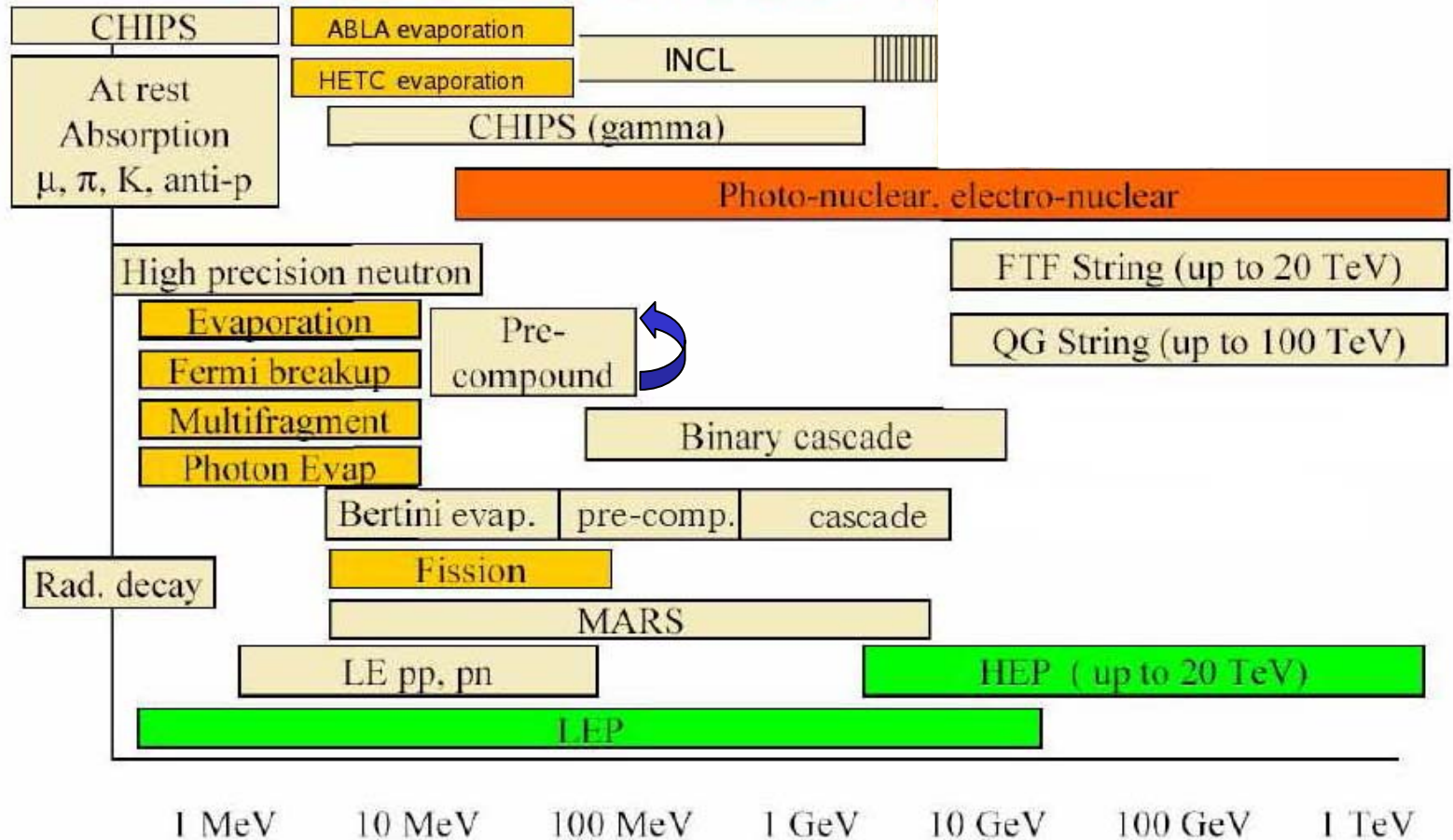
- `G4PrecompoundModel` is used for nucleon-nucleus interactions at low energy and as **nuclear de-excitation model** within higher-energy models (e.g. Fritiof, parametrized, cascades, parton strings, ...)
 - valid for **p,n** up to **170 MeV**
 - takes a nucleus from a highly-excited state down to equilibrium energy by emitting p, n, d, t, ^3He and α
 - once equilibrium is reached, other models called to take care of **nuclear evaporation** (\rightarrow next slide) and **break-up** (not directly callable by the user)
- Alternative to **CHIPS-based** de-excitation

Evaporation models

- Geant4 provides several different implementations for evaporation models:
 - G4Evaporation (default), HETC evaporation, INUCL evaporation and ABLA
- Models predict the final state as results of an excited nucleus ($A > 16$) break-up by evaporation
 - takes as input A , Z , 4-momentum, angular-momentum, excitation energy
 - produces p , n , γ , d , t and α
 - fission of heavy nuclei with $A > 65$

Hadronic model inventory

http://geant4.cern.ch/support/proc_mod_catalog/models

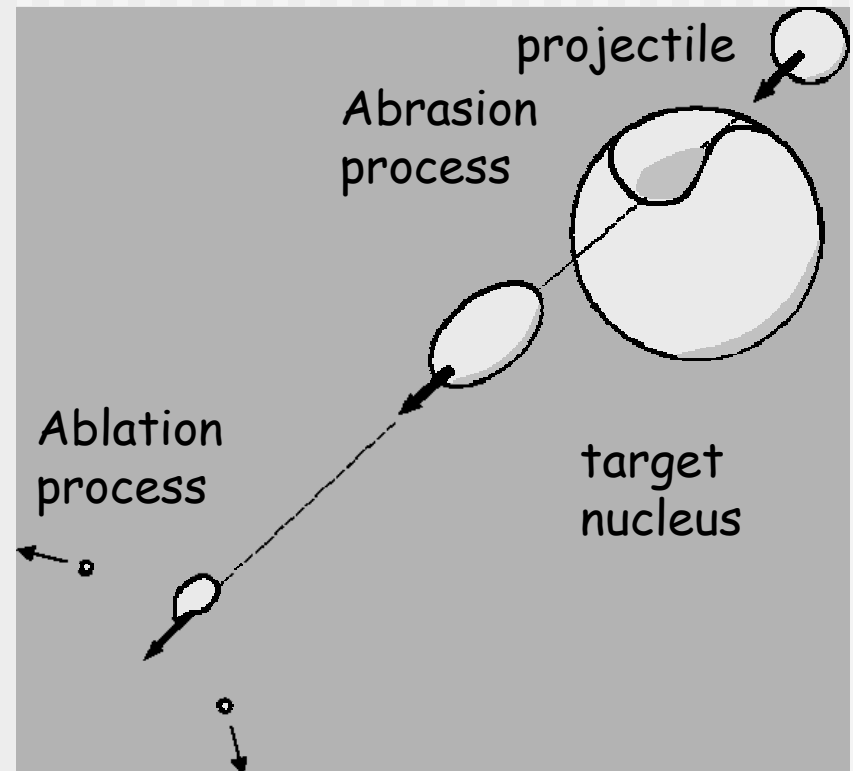


Ion inelastic interactions

- Many **cross section formulae** for **N-N collisions** are included in Geant4
 - Tripathi, Shen, Kox and Sihver
- These are **empirical** and **parameterized** formulae with theoretical insights.
- `G4GeneralSpaceNNCrossSection` was prepared to assist users in **selecting the appropriate cross section formula**
- **Final state** according to models:
`G4BinaryLightIon` (variant of Binary cascade),
`G4WilsonAbrasion` or `G4EMDissociation`

G4WilsonAbrasionModel and G4Wilson AblationModel

- G4WilsonAbrasionModel is a simplified **macroscopic model** for **nuclear-nuclear interactions** based largely on **geometric arguments**
- The speed of the simulation is found to be **faster** than models such as **G4BinaryCascade**, but **at the cost of accuracy**
- A nuclear **ablation** has been developed to provide a **better approximation** for the final nuclear fragment from an abrasion interaction → **de-excitation of nuclear pre-fragments**



Radioactive decay

- To simulate the **decay** of **radioactive nuclei**
- Empirical and data-driven model
- α , β^+ , β^- decay and **electron capture** (EC) are implemented
- Data derived from Evaluated Nuclear Structure Data File (ENSDF)
 - nuclear *half-lives*, *level structure* for the parent or daughter nuclide, nuclear decay *branching ratios*, *Q-value* of the decay process → directory
\$G4RADIOACTIVEDATA
- If the daughter of a nuclear decay is an **excited isomer**, its **prompt nuclear de-excitation** is treated using the `G4PhotonEvapolation` → database of γ lines and nuclear levels in **\$G4LEVELGAMMADATA**
- **Internal conversion** is also implemented

Where to find additional info

- Complete **description** of the **models** (with details, paper references, formulas) can be found in the Geant4 **Physics Reference Manual**:

<http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html>

(From the Geant4
home page →
User Support →
Physics Reference
Manual)

Intranuclear Cascade Model

The basic steps of the INC model are summarized as follows:

1. the space point at which the incident particle enters the nucleus is selected uniformly over the projected area of the nucleus,
2. the total particle-particle cross sections and region-dependent nucleon densities are used to select a path length for the projectile,
3. the momentum of the struck nucleon, the type of reaction and the four-momenta of the reaction products are determined, and
4. the excitation model is updated as the cascade proceeds.
5. If the Pauli exclusion principle allows and $E_{particle} > E_{cutoff} = 2 \text{ MeV}$, step (2) is performed to transport the products.

After the intra-nuclear cascade, the residual excitation energy of the resulting nucleus is used as input for non-equilibrium model.

Nuclear Model

Some of the basic features of the nuclear model are:

- the nucleons are assumed to have a Fermi gas momentum distribution. The Fermi energy is calculated in a local density approximation i.e. the Fermi energy is made radius-dependent with Fermi momentum $p_F(r) = \left(\frac{2\pi^2 \rho(r)}{3}\right)^{1/3}$.
- Nucleon binding energies (BE) are calculated using the mass formula. A parameterization of the nuclear binding energy uses a combination of the Kammell mass formula and experimental data. Also, the asymptotic high temperature mass formula is used if it is impossible to use experimental data.

Initialization

The initialization phase fixes the nuclear radius and momentum according to the Fermi gas model.

If the target is hydrogen ($A = 1$) a direct particle-particle collision is performed, and no nuclear modeling is required.

If $1 < A < 4$, a nuclear model consisting of one layer with a radius of 8.0 fm is created.

For $4 < A < 11$, the nuclear model is composed of three concentric spheres $i = \{1, 2, 3\}$ with radius

$$r_i(\alpha_i) = \sqrt{C_1^2 \left(1 - \frac{1}{A}\right) + 6.4 \sqrt{-\log(\alpha_i)}}$$

PART IV

It's the user's turn now:

physics lists for hadrons

Physics Lists – putting physics into your simulation

- User **must implement a physics list**:
 - Derive a class from `G4VUserPhysicsList`
 - Define the `particles` required → `ConstructParticle()`
 - Register models and cross sections with `processes` and processes with particles → `ConstructPhysics()`
 - Set secondary `production cuts` → `SetCuts()`
 - In `main()`, register your physics list `with the Run Manager`
- **Care is required**:
 - `Multiple models`, cross sections `allowed per process`
 - No single model covers `all energies`, or all particles
 - `Choice of model` is heavily `dependent on physics studied`

Ready physics lists

- It is not immediate to say what's the **appropriate physics list** one has to use for his/her own application → usually a **problem for newcomers!**
- 1. use the **physics lists** of the **advanced examples** released with Geant4 (many use-cases covered)
- 2. ready-for-the-use **hadronic physics lists available** for **different common use-cases**, e.g.:
 - Low and high energy nucleon penetration **shielding**
 - **Medical** neutron applications
 - **Low background** experiments (underground)

Info to help users to **choose the proper physics list**:

http://geant4.cern.ch/support/proc_mod_catalog/

[physics_lists/physicsLists.shtml](http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/physicsLists.shtml)

Webpage for reference physics lists

[Download](#) | [User Forum](#) | [Gallery](#)
[Contact Us](#)

Geant 4

[Home](#) > [User Support](#) > [Process/model catalog](#) > [Physics Lists](#)

Physics Lists

Introduction

Given the toolkit nature of Geant4, a choice of physics processes is available. The choices offer either different detail of physics modeling or different physics modeling descriptions. It is the choice of the user to decide how much detail in the physics modeling is needed, weighing the detail against cpu performance. A user can construct his own physics list, or use one of the physics lists offered below, or modify any of the offered physics lists.

Reference Physics Lists

Please see the [detailed description](#) for a full description of all reference physics lists including our current understanding of physics performance. The reference physics lists are part of the Geant4 source code and are distributed as an integral part of Geant4 from the [Geant4 download area](#). Physics lists include those originally named 'educated guess physics lists'. Nearly all these lists are suitable for all primary particles and for a wide range of energies. There are four families of lists:

- **LHEP** or parameterised modeling of hadronic interactions.
- **QGS**, or lists based on a modeling using Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions, and Kaons.
- **FTF**, or lists based on a modeling using the FTF model for high energy hadronic interactions of protons, neutrons, pions, and Kaons; FTF is FRITIOF like string model.
- several more specialised lists.

All of the lists in the first three families share components to attach certain types of processes to groups of particles. The classes of components are:

- electromagnetic interactions for all particles and electromagnetic processes for leptons and gammas. Three different settings are offered
 - the default setting using standard parameters tuned for best physics performance
 - using parameters optimised for better CPU performance at the cost slightly less precise physics. This is identified in physics lists by the extension **_EMV**.
 - a set of experimental parameters, used by physics lists with the extension **_EMX**
- Inelastic interactions for hadrons
- Elastic scattering of hadrons off nuclei
- Capture at rest for negative charged hadrons and muons
- Decay of unstable particles in flight and at rest
- specialised treatment of low energy neutrons (< 20MeV)

Physics Lists in Geant4 examples

Other Physics Lists

Code Example (1/4)

```
G4ParticleDefinition* proton=
    G4Proton::ProtonDefinition();
G4ProcessManager* protonProcessManager =
    proton->GetProcessManager();

// Elastic scattering
G4HadronElasticProcess* protonElasticProcess =
    new G4HadronElasticProcess();

G4LElastic* protonElasticModel =
    new G4LElastic();

protonElasticProcess->
    RegisterMe(protonElasticModel);

protonProcessManager->
    AddDiscreteProcess(protonElasticProcess);
```

retrieve the
process
manager for
proton

create the
process for
elastic
scattering

get the **LE parametrized
model** for elastic scattering

register the **model** to
the **process**

attach the **process**
to **proton**

Code example (2/4)

```
...
// Inelastic scattering
G4ProtonInelasticProcess* protonInelasticProcess
    = new G4ProtonInelasticProcess();
G4LEProtonInelastic* protonLEInelasticModel
    = new G4LEProtonInelastic();
protonLEInelasticModel->
    SetMaxEnergy(20.0*GeV);
protonInelasticProcess->
    RegisterMe(protonLEInelasticModel);
G4HEProtonInelastic* protonHEInelasticModel =
    new G4HEProtonInelastic();
protonHEInelasticModel->SetMinEnergy(20.0*GeV);
protonInelasticProcess
    ->RegisterMe(protonHEInelasticModel);
```

creates the **process** for inelastic scattering

gets the **LEP model** up to 20 GeV

registers LEP model to the process

gets the **HEP model** from 20 GeV

registers HEP model to the process

Model 1

Model 2

Code example (3/4)

Model for FS
Model for XS

```
G4NeutronInelasticProcess*
```

```
theNeutronInelasticProcess = new  
    G4NeutronInelasticProcess();
```

creates the **process**
for **neutron inelastic**
scattering

```
G4NeutronHPInelastic* theHPInelastic  
    = new G4NeutronHPInelastic();
```

```
theNeutronInelasticProcess  
    ->RegisterMe(theHPInelastic);
```

gets and
registers the
data-driven **HP**
model for
neutron inelastic

```
G4NeutronHPInelasticData* theHPInData  
    = new G4NeutronHPInelasticData();
```

retrieves the **HP**
cross section
table (data-
driven)

```
theNeutronInelasticProcess->  
AddDataSet(theHPInData);
```

attach the **cross**
section to the **process**

Code example (4/4)

```
const G4IonTable *theIonTable =
  G4ParticleTable::GetParticleTable()->GetIonTable();
G4RadioactiveDecay* theRadioactiveDecay =
  new G4RadioactiveDecay();
for (G4int i=0; i<theIonTable->Entries(); i++)
{
  G4String particleName =
    theIonTable->GetParticle(i)->GetParticleName();
  if (particleName == "GenericIon") {
    G4ProcessManager* pmanager =
      theIonTable->GetParticle(i)->GetProcessManager();
    pmanager->AddProcess(theRadioactiveDecay);
  }
}
```

gets the **table of ions** and **particles** defined

creates the **process** for radioactive decay

loop on table to **look for ions**

retrieve process manager for ions and **register** Radioactive Decay

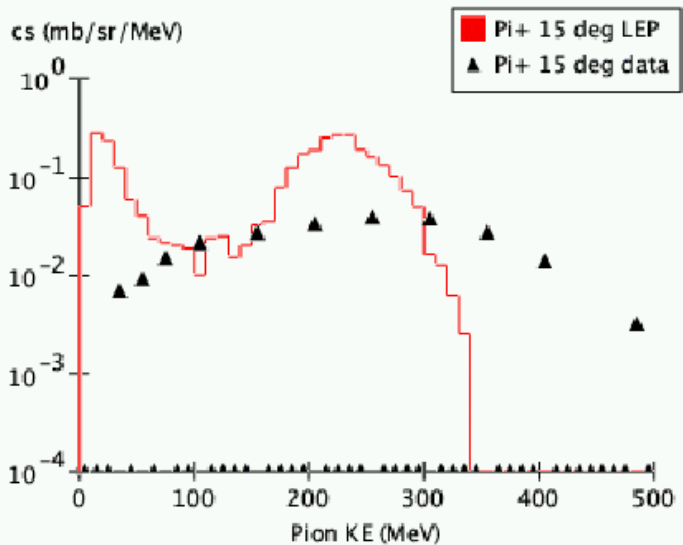
PART V

**Validation of hadronic physics
models:**
a quick overview

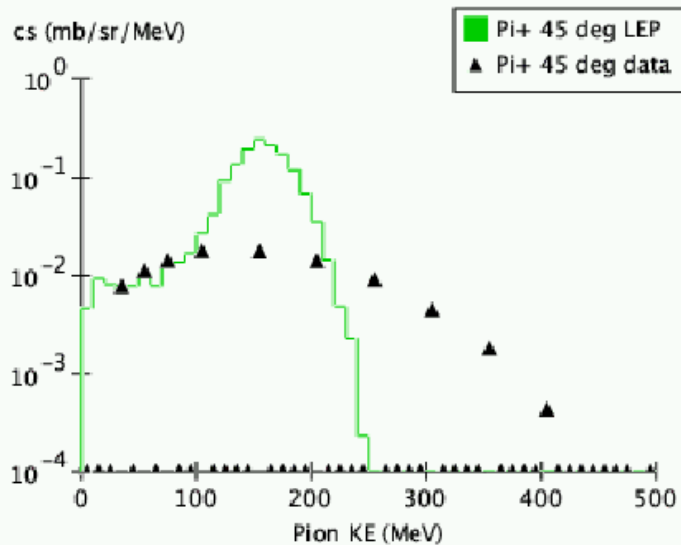
Hadronic validation

- A **website** is available to collect relevant **information** for validation of **Geant4 hadronic models** (plots, tables, references to data and to models, etc.)
`http://geant4.fnal.gov/hadronic_validation/validation_plots.htm`
- Several **physics lists** and several **use-cases** have been considered (e.g. thick target, stopped particles, low-energy)
- Includes **final states** and **cross sections**

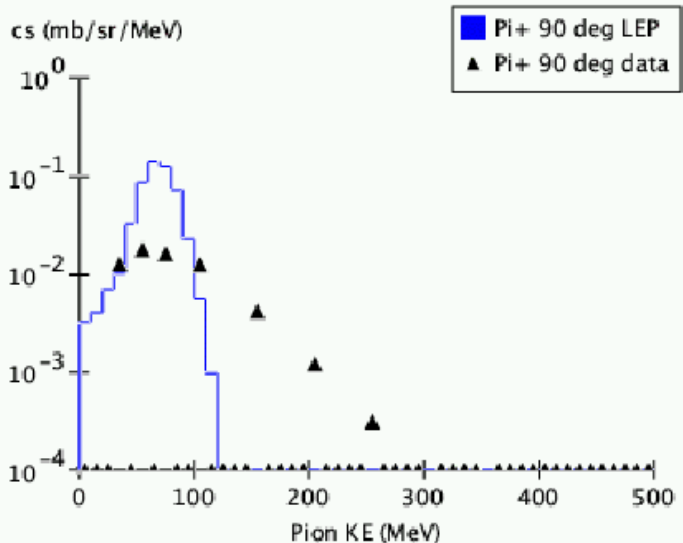
730 MeV p on C



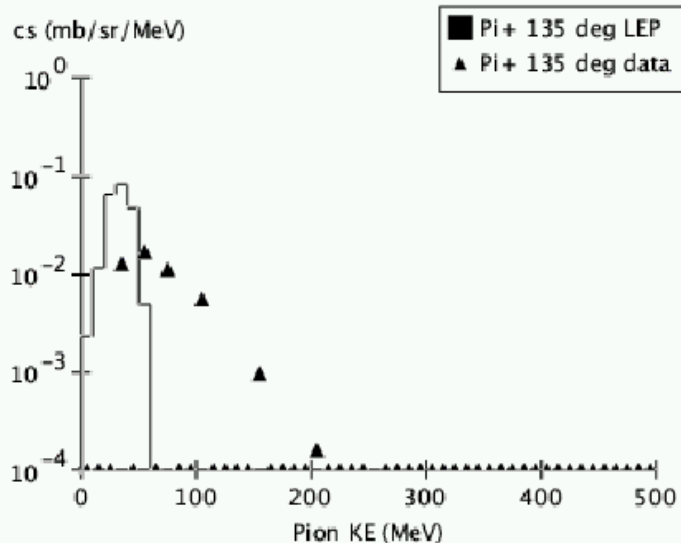
730 MeV p on C



730 MeV p on C

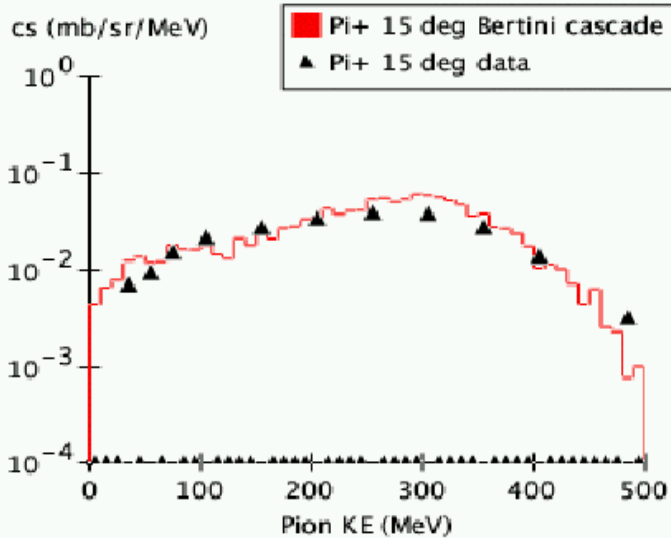


730 MeV p on C

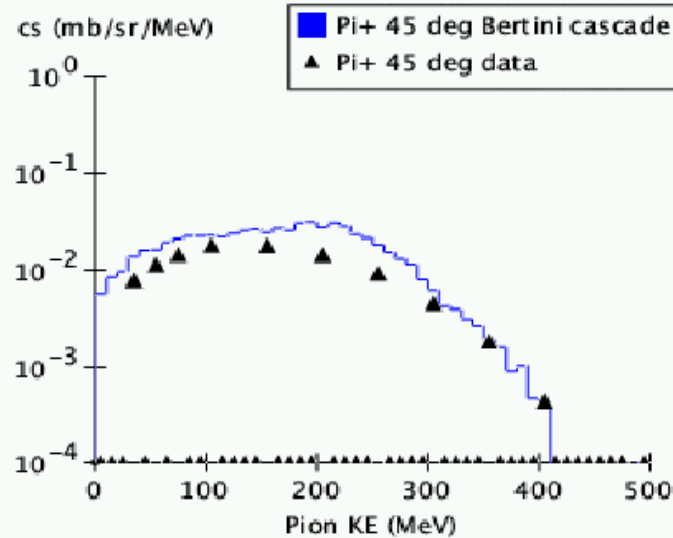


Geant3.21-
based
Geant4 **LEP**
model: pion
production
from 730
MeV protons
on Carbon
→ fast, but
not working
very well
for this purpose

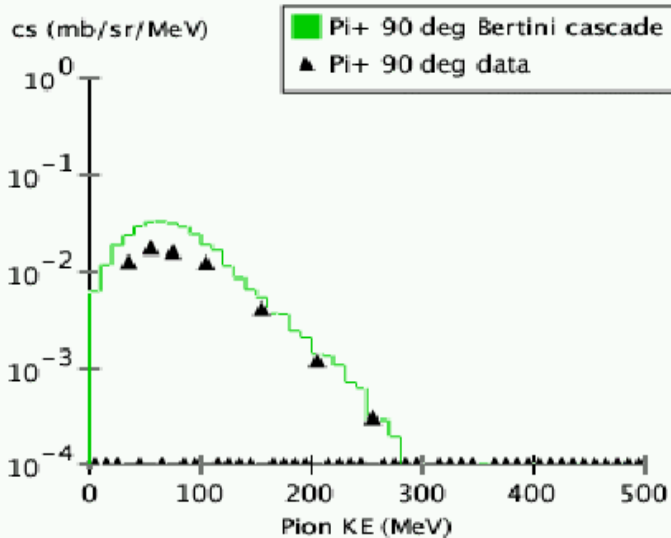
730 MeV p on C



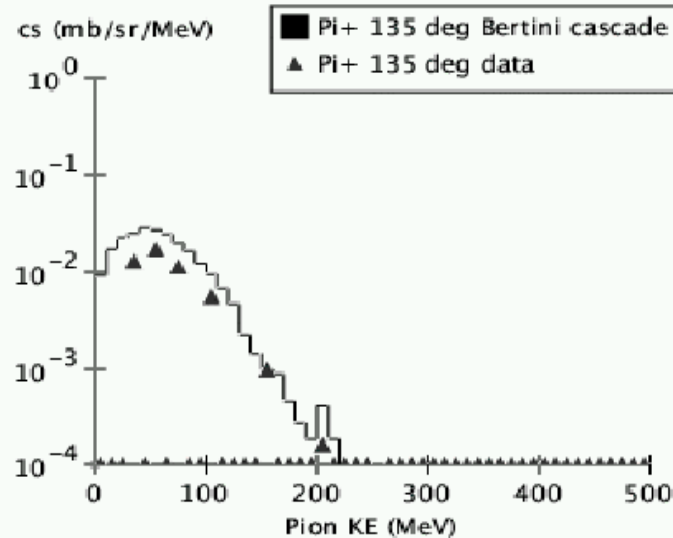
730 MeV p on C



730 MeV p on C

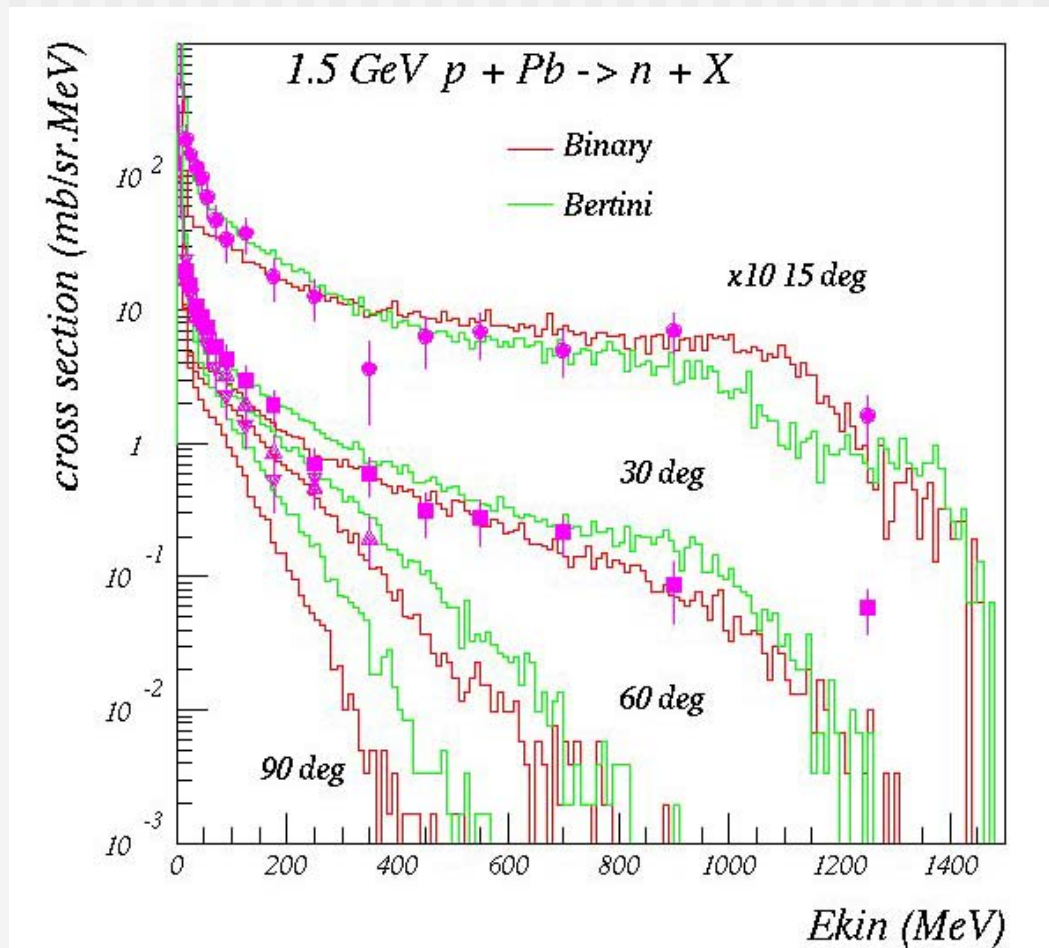


730 MeV p on C



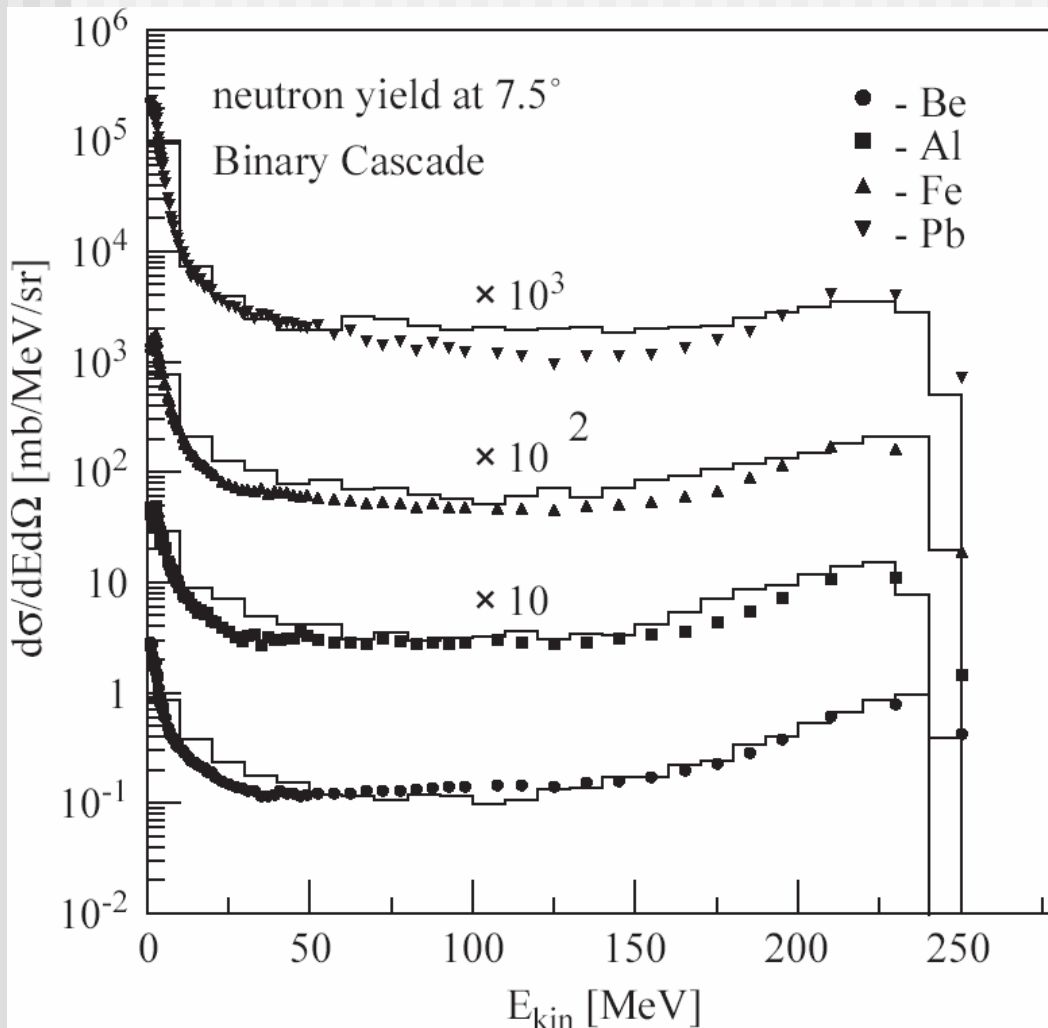
Bertini cascade
model: **pion production**
from 730 MeV
proton on
Carbon →
much **more appropriate**
than the
previous one,
for this application

Nuclear fragmentation

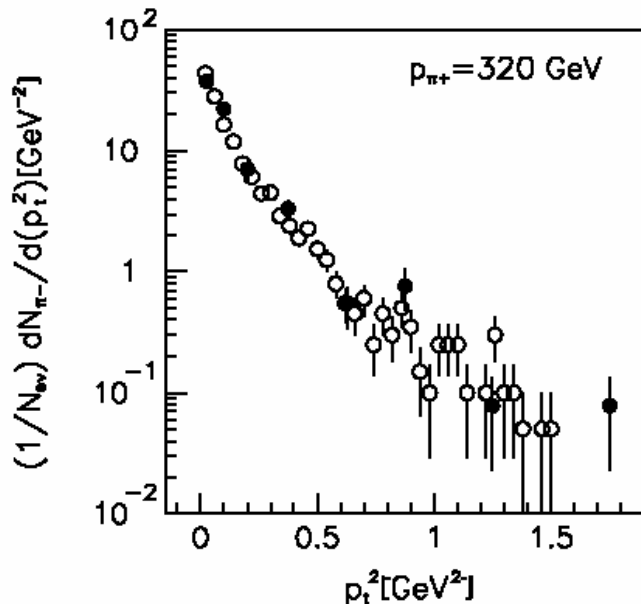
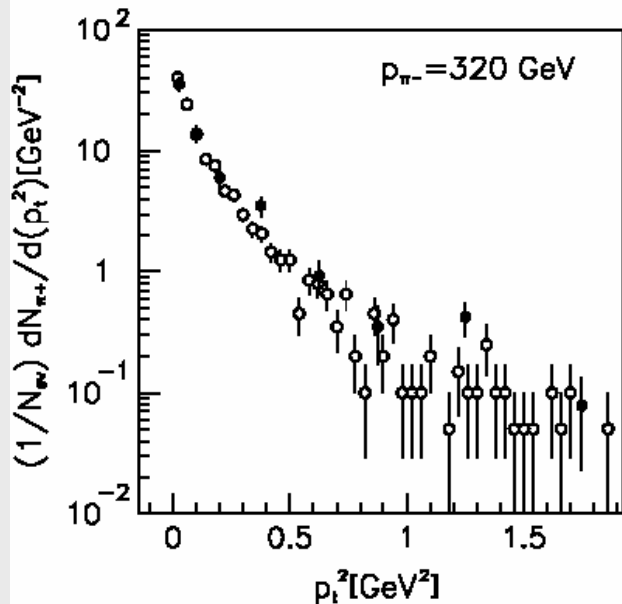
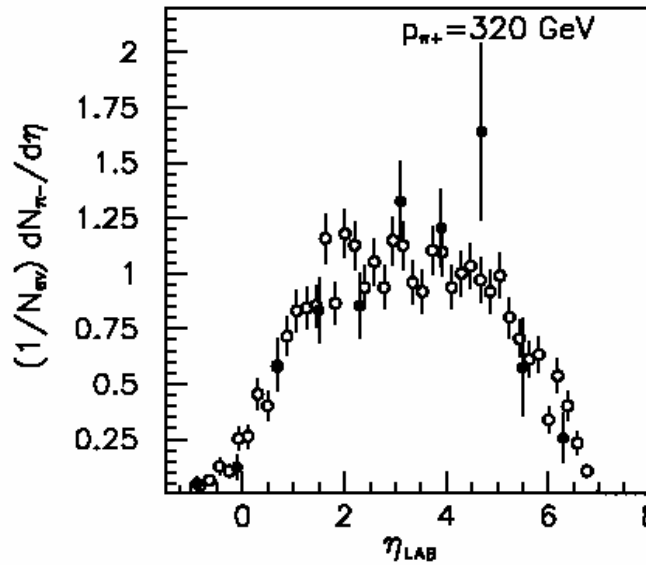
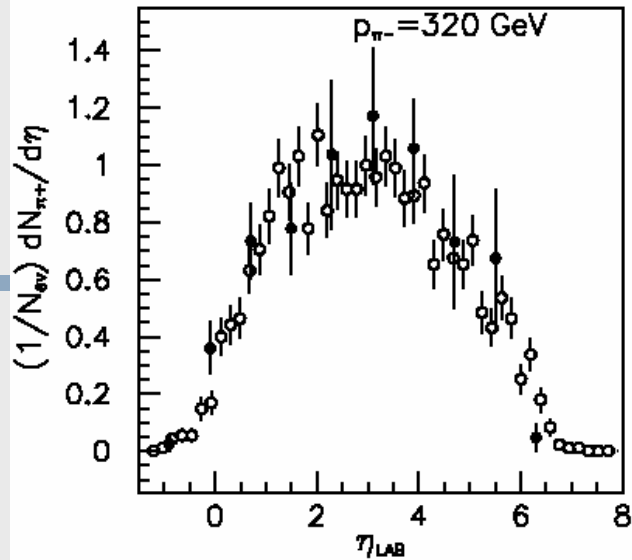


Bertini and **Binary**
cascade models:
neutron production
vs. angle from 1.5
GeV protons on Lead

Neutron production by protons

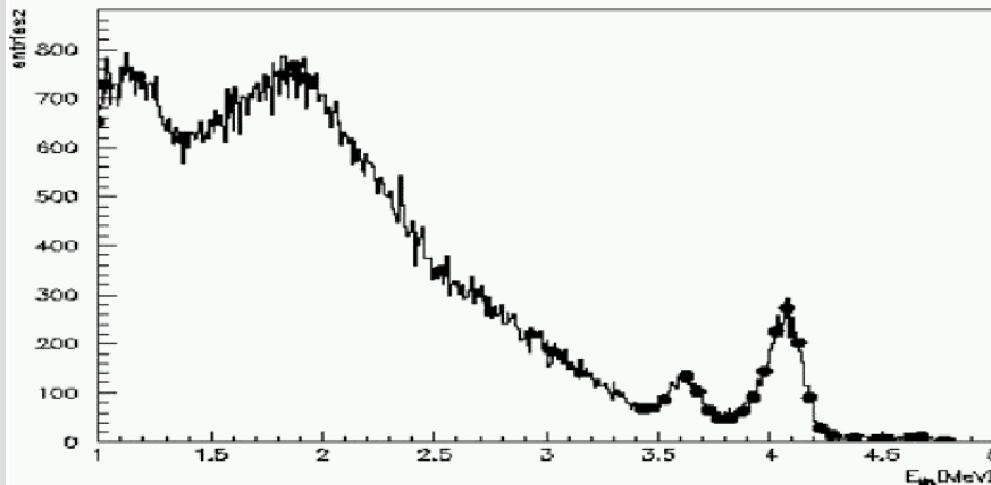
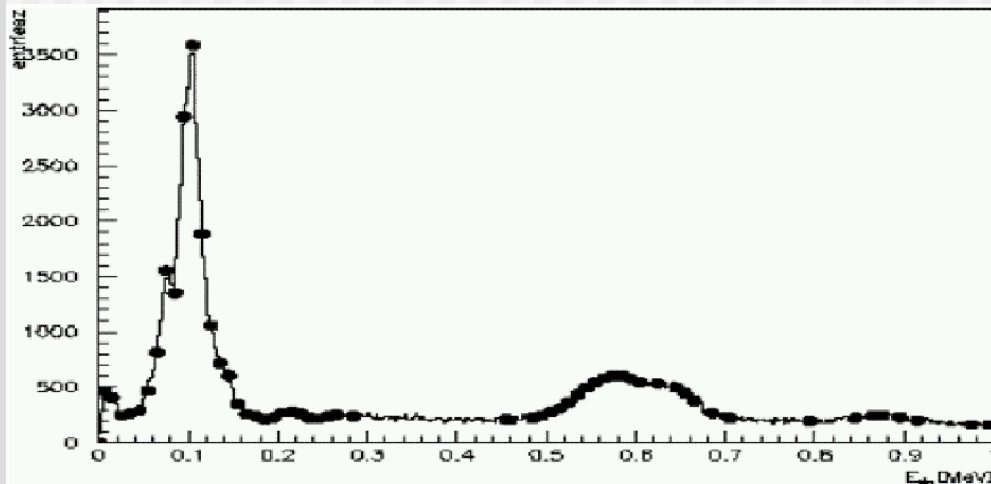


Binary cascade
model: double
differential cross-
section for **neutrons**
produced
by **256 MeV protons**
impinging on
different targets



Comparison of differential pion yields for positive and negative pions in pion-Mg reactions at 320 GeV lab momentum. The dots are data and the open circles are Monte Carlo predictions by G4QGSMoel

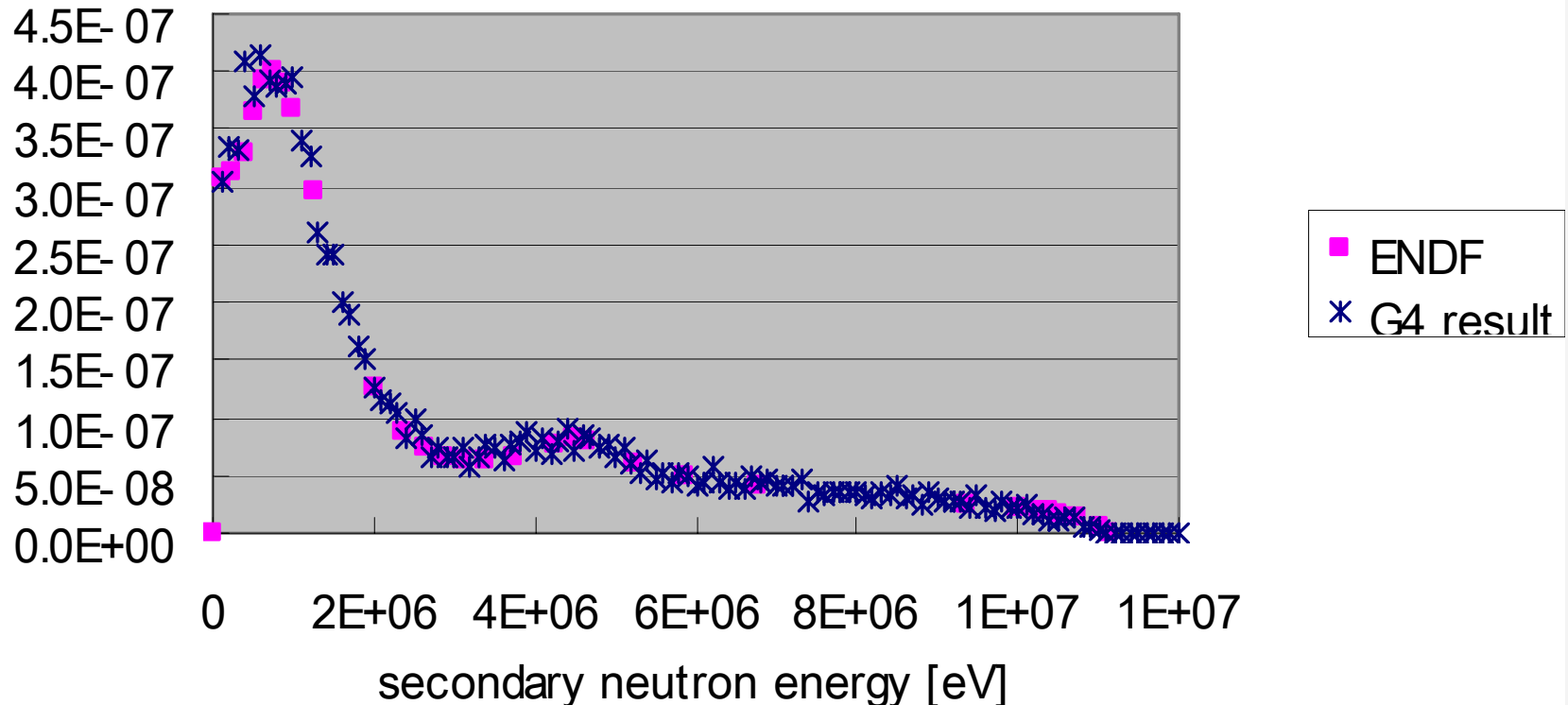
γ -rays from neutron capture



Geant4 simulation
(**HP neutron models**) of γ -rays
from **14 MeV**
neutron capture on
uranium

Spectrum of secondary particles from G4NeutronHPInelastic

$^{154}\text{Gd}(n,2n)$ channel



G4EMDissociationModel for ion-ion inelastic interactions

Target Emulsion nuclei: Ag 61.7%, Br 34.2%, CNO 4.0% and H 0.1%

Projectile	Energy [GeV/nuc]	Product from ED	G4EM Dissociation [mbarn]	Experiment [mbarn]
^{24}Mg	3.7	Na-23 + p	124 ± 2	154 ± 31
^{28}Si	3.7	Al-27 + p	107 ± 1	186 ± 56
^{28}Si	14.5	Al-27 + p	216 ± 2	165 ± 24 128 ± 33
^{16}O	200	N-15 + p	331 ± 2	293 ± 39 342 ± 22

M A Jilany, *Nucl Phys*, **A705**, 477-493, 2002.

PART VI

Summary and conclusions

Summary (1)

- Geant4 hadronic physics allows user to **choose how a physics process** should be implemented:
 - **cross sections** (→ interaction length)
 - **models** (→ final state)
- **Many models** and **cross sections** available to choose from
 - appropriate for **specific particles** and **energy range**
 - hadronic framework makes it easier for users to add more

Summary (2)

- Parameterized models (LEP, HEP) handle the most particle types over the largest energy range
 - based on *fits to data* and some theory
 - not very detailed, but fast
- Cascade models (Bertini, Binary, Liege) are valid for fewer particles over a smaller energy range
 - more *theory-based*
 - more detailed, but slower
- User has to find the best **trade-off**

Summary (3)

- High Precision Neutron models are data driven models and its used *evaluated data libraries*
- However the **library is not complete** because there are no data for several key elements.
- Geant4 has abundant processes for **Ion inelastic interactions**
- **Theory-based** parton-string models are available to simulate **high-energy hadronic** interactions (from tens of GeV up to tens of TeV)
- **Validation is ongoing** and the results show **reasonable agreement** with data. This work continues

Conclusion

- Geant4 provides a large number of **hadronic physics models** for use in simulation
- **Cross sections**, either calculated or from databases, are available **to be assigned to processes**
- Interactions are implemented by **models** which are **then assigned to processes**
- For hadrons there are **many models to choose from**, so example **physics lists are provided by use-case** (see Geant4 manual and website) and in the **advanced examples**

PART VII

Backup

References to NN Cross Section Formulae implemented in Geant4

- Tripathi Formula
 - NASA Technical Paper TP-3621 (1997)
- Tripathi Light System
 - NASA Technical Paper TP-209726 (1999)
- Kox Formula
 - Phys. Rev. C 35 1678 (1987)
- Shen Formula
 - Nuclear Physics. A 49 1130 (1989)
- Sihver Formula
 - Phys. Rev. C 47 1225 (1993)

G4NeutronHPorLEModels

- Many elements remained **without data** for G4NeutronHP models.
- Those models make up for such data deficit.
- If the High Precision **data are not available** for a reaction, then **Low Energy Parameterization Models will handle the reaction**.
- Those can be used for not only for **models** (final state generator) but also for **cross sections**.
- Elastic, Inelastic, Capture and Fission models are prepared.