

Geant4 Hadronic Physics I

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Cours Geant4

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Outline

- Further reading
- Geant4 Hadronic Physics Working Group
- Hadronic model inventory
- Hadronic framework overview
 - Framework levels, cross sections and physics lists
 - Theory, parametrization, and data driven models
- Bertini cascade and pre-compound, and evaporation models
- Validating physics models

Further reading

- Geant4 site: <http://cern.ch/geant4> (Everything is available here!)
- General Geant4 papers:
 - Geant4 Collaboration, *Geant4 – a simulation toolkit*, Nucl. Instr. and Meth. A 506 (2003) 250–303
 - Geant4 Collaboration, *Geant4 developments and applications*, IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278
- Geant4 Physics Reference Manual
- Geant4 User's Guide For Application Developers
- J.P. Wellisch, Hadronic shower models in GEANT4 – the frameworks, Comput. Phys. Commun. 140 (2001) 65–75

Acknowledgments These slides re-use material prepared by Dennis Wright for SLAC May 2007 Geant4 tutorial

<http://geant4.slac.stanford.edu/SLACTutorial07>

Members

- Aatos Heikkinen (Helsinki Institute of Physics) - coordinator
- Dennis Wright (SLAC) - coordinator
- Makoto Asai (SLAC)
- Pablo Cirrone (INFN)
- Gunter Folger (CERN)
- Vladimir Grichine (CERN)
- Alexander Howard (CERN)
- Vladimir Ivantchenko (ESA, CERN)
- Tatsumi Koi (SLAC)
- Mikhail Kossov (CERN)
- Fan Lei (Qinetiq)
- Maria Grazia Pia (INFN, CERN)
- Alberto Ribon (CERN)
- Nikolai Starkov (CERN)
- Peter Truscott (Qinetiq)

Responsibilities (1/2)

Hadronic Physics Working Group web-page http://geant4.web.cern.ch/geant4/collaboration/working_groups/hadronic/:

Extended example **Hadr01** developed by Vladimir Ivantchenko.

Hadronic Sub-directory	Responsible Developer
cross_sections	<u>Dennis Wright</u>
management	<u>Dennis Wright</u>
models/abrasion	<u>Peter Truscott</u>
models/binary_cascade	<u>Gunter Folger</u>
models/cascade	<u>Aatos Heikinen</u>
models/chiral_inv_phase_space	<u>Mikhail Kossov</u>
models/coherent	<u>Nikolai Starkov</u>
models/de_excitation	<u>Aatos Heikinen</u>
models/em_dissociation	<u>Peter Truscott</u>

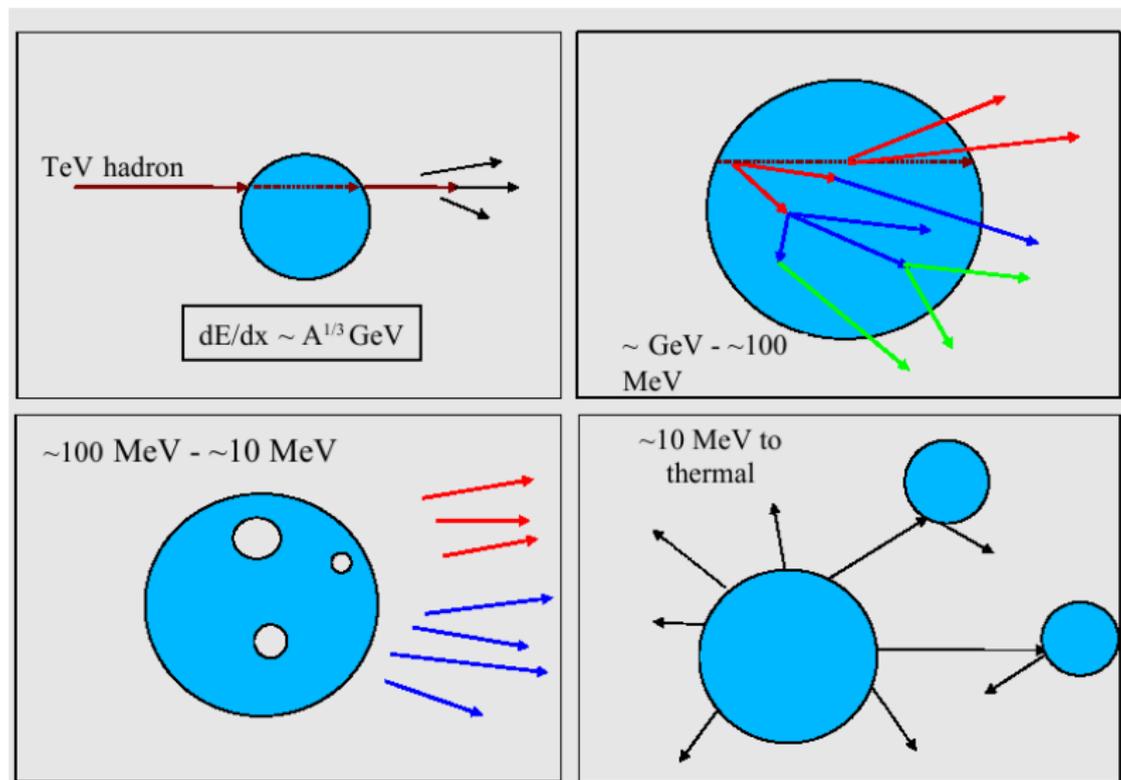
Responsibilities (2/2)

models/high_energy	<u>Dennis Wright</u>
models/im_r_matrix	<u>Gunter Folger</u>
models/inucl	<u>Aatos Heikinen</u>
models/isotope_production	<u>Aatos Heikinen</u>
models/leading_particle	<u>Makoto Asai</u>
models/low_energy	<u>Dennis Wright</u>
models/management	<u>Gunter Folger</u>
models/neutron_hp	<u>Tatsumi Koi</u>
models/parton_string	<u>Gunter Folger</u>
models/photolepton_hadron	<u>Dennis Wright</u>
models/pre_equilibrium	<u>Aatos Heikinen</u>
models/radioactive_decay	<u>Fan Lei</u>
models/theo_high_energy	<u>Gunter Folger</u>
models/util	<u>Gunter Folger</u>
processes	<u>Dennis Wright</u>
stopping	<u>Dennis Wright</u>
util	<u>Dennis Wright</u>

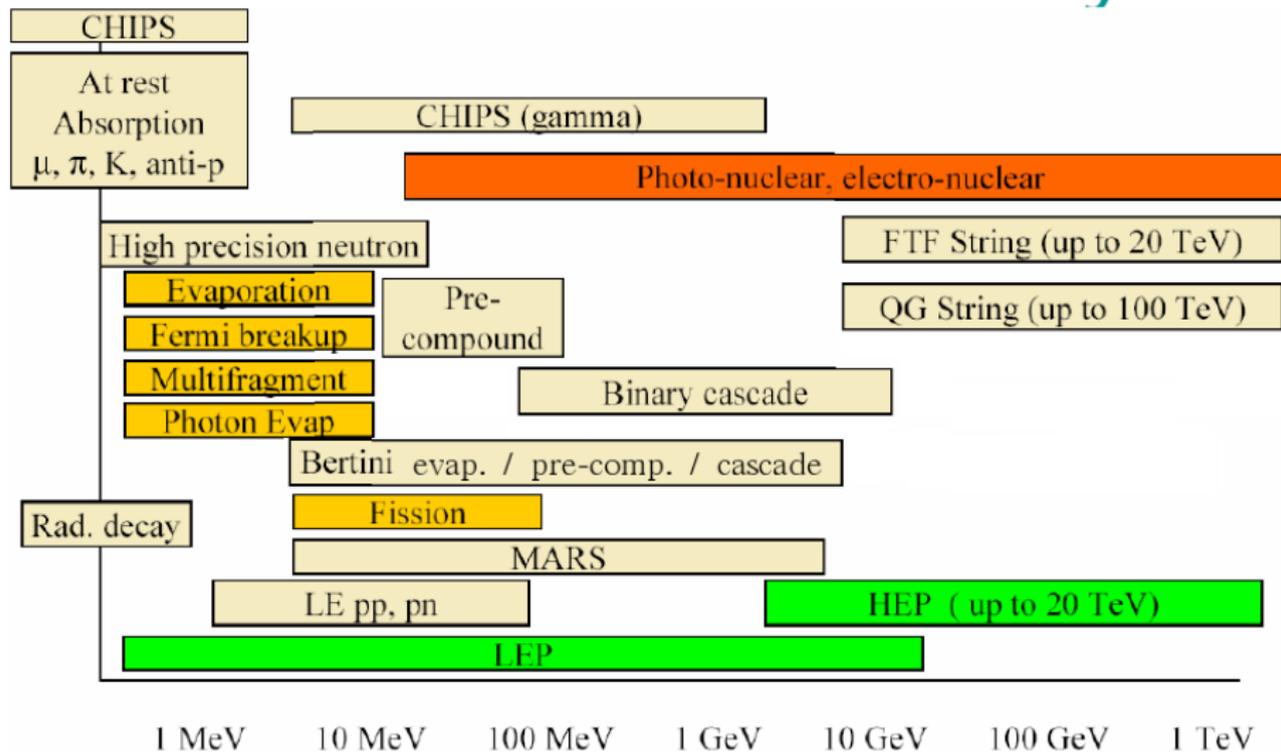
Multidisciplinary applications

- In order to meet multidisciplinary requirements Geant4 hadronic framework provides a large degree of functionality and flexibility
- Each cross-section table or physics model has its own energy range being able to combine more than one models
 - Polymorphism and other advanced OO technologies are used
 - Physics process can have enough energy coverage for wide variety of applications
- Geant4 provides sets of alternative physics models, so that the user can freely choose appropriate models (processes/models) according to the type of application

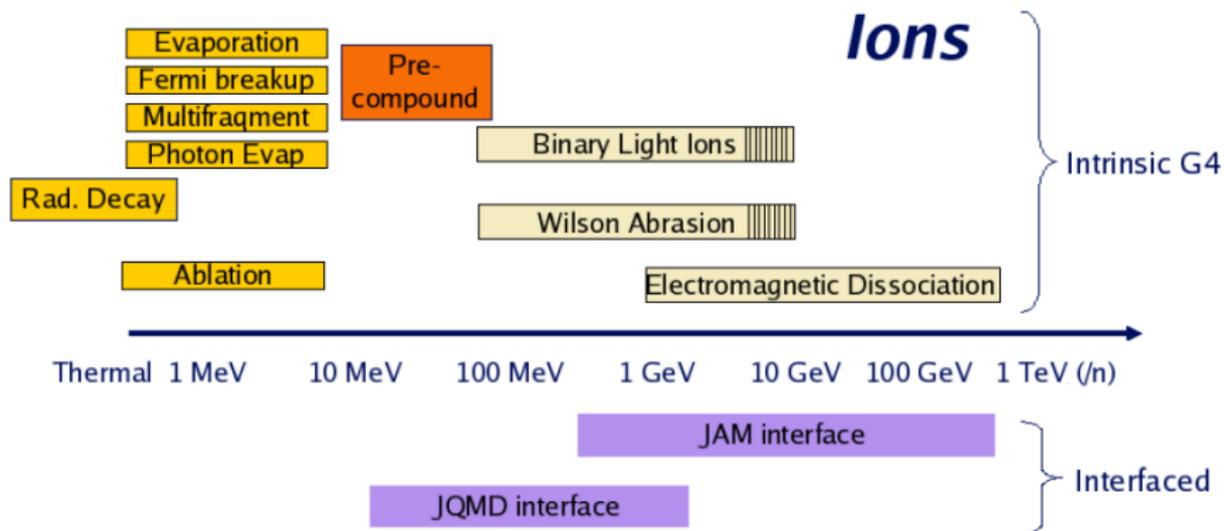
Modeling hadronic physics up to TeV energy range



Hadronic model inventory



Existing Geant4 Nuclear-Nuclear Final State Models

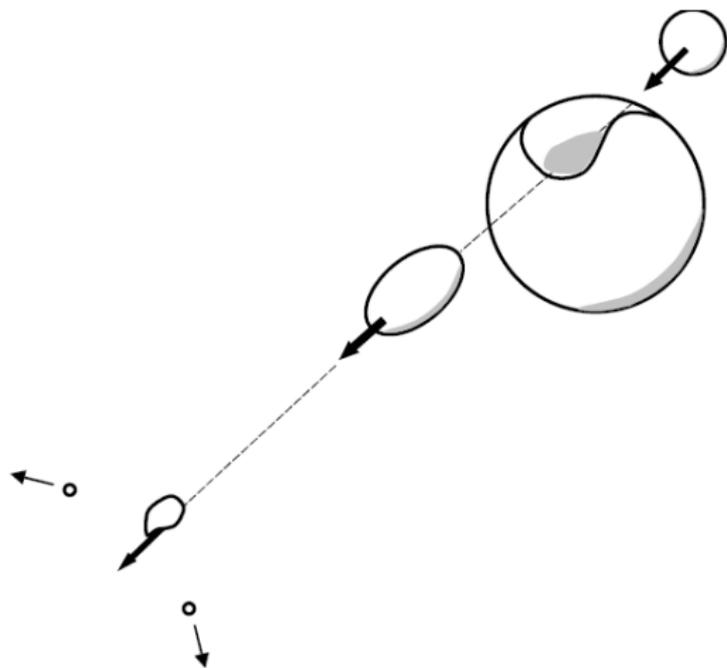


EPAX model also compared with above but not interfaced (REAT-MS)

(from T Koi, 28/07/06)

QinetiQ

Model details are documented in Geant4 Reference Manual



Wilson abrasion model.
[\(http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/html/\)](http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/html/)

Figure 26.1: In the abrasion process, a fraction of the nucleons in the projectile and target nucleons interact to form a fireball region with a velocity between that of the projectile and the target. The remaining spectator nucleons in the projectile and target are not initially affected (although they do suffer change as a result of longer-term de-excitation).

Modular structure of Geant4 hadronic interactions

- Pure hadronic processes valid 0–100 TeV
- $\gamma \mu e$ - nuclear processes valid 10 MeV – TeV
- Hadron ionization for charged hadrons
- At rest
 - Stopped $\mu, \pi K$, anti-proton
 - Radioactive decay
- Elastic
 - Same process for all long-lived hadrons (but different models)
- Inelastic
 - Different process for each hadron
 - Photo-nuclear, electro-nuclear, muon-nuclear
 - Ions
- Capture
 - For neutron
- Fission
 - Neutron-induced

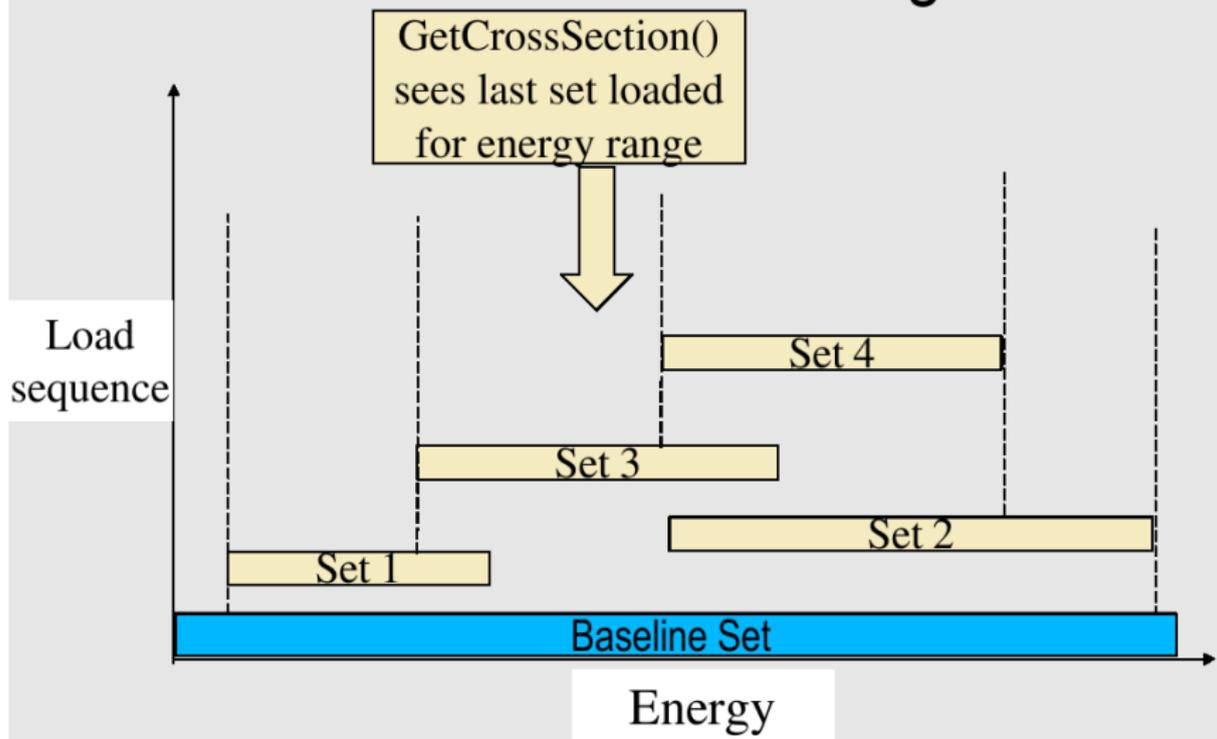
Cross sections

- Default cross section sets are provided for each type of hadronic process:
 - Fission, capture, elastic, inelastic
 - Hadronic framework provides mechanism to override or replace these data sets
- Different types of cross section sets:
 - Some contains only a few numbers to parametrize cross section
 - Some represent large databases (data driven models)
 - Some are not yet fully exposed to framework (such as Bertini data)

Alternative cross sections:

- Low energy neutrons
- Neutron and proton reaction cross sections
 - $20 \text{ MeV} < E < 20 \text{ GeV}$
- Ion-nucleus reaction cross sections

Cross Section Management



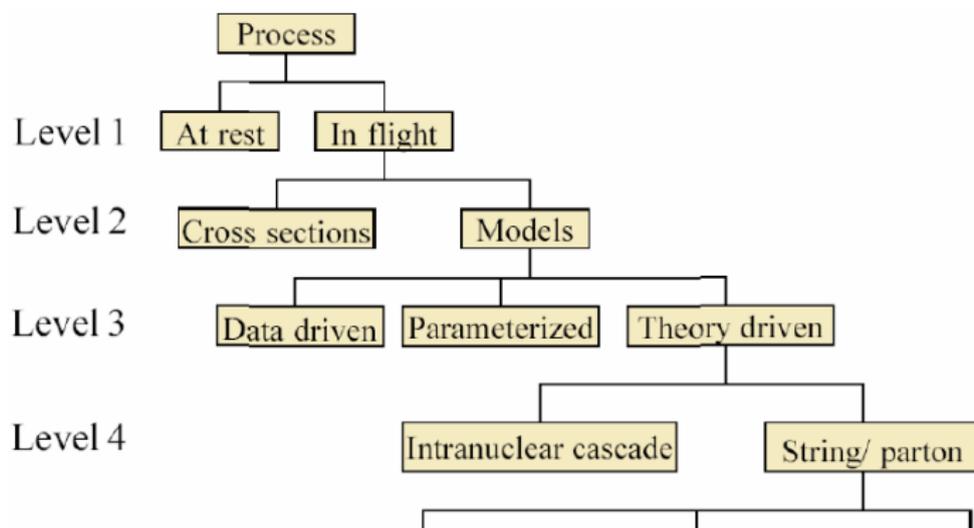
Example: Neutron data files - G4NDL3.10

- External 48 MB set of data derives largely from the ENDF/B-VI library
 - Maintained by Cross Section Evaluation Working Group (CSEWG)
<http://www.nndc.bnl.gov/csewg/>
- Contains cross section data for
 - Elastic, inelastic, and capture processes
 - Thermal scattering
 - Coherent, incoherent, inelastic
 - Isotope production
 - Uranium fission

Also contains data from JENDL library

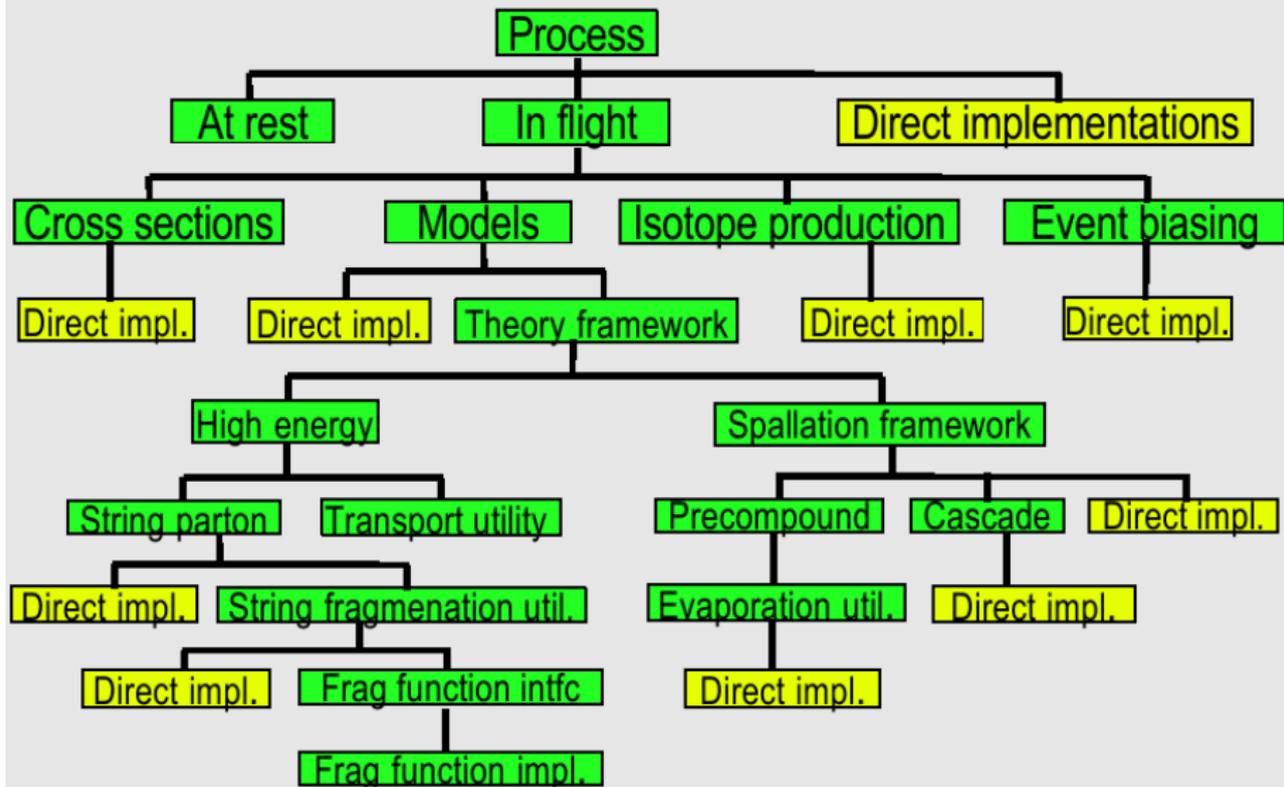
- Nuclear Data Evaluation Center of Japan Atomic Energy Agency

Hadronic framework - levels



(J.P. Wellisch, Hadronic shower models in Geant4 – the frameworks, Computer Physics Communications 140, 2001, pp. 65–75)

Hadronic Model Organization



Theory driven models

- Dominated by theory
 - QCD
 - Strings
 - Chiral perturbation theory
- Data used mainly for normalization and validation
- Final states determined by sampling theoretical distributions
- Theory driven models are often CPU intensive
 - With careful optimization, significant speedup may be achieved

Precompound Models (1)

- **G4PreCompoundModel** is used for nucleon-nucleus interactions at low energy and 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 called 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 in them**

Precompound Models (2)

- Invocation of Precompound model:

```
- G4ExcitationHandler* theHandler = new G4ExcitationHandler;
  G4PrecompoundModel* preModel =
      new G4PrecompoundModel(theHandler);
```

// Create equilibrium decay models and assign to Precompound model

```
G4NeutronInelasticProcess* nProc = new G4NeutronInelasticProcess;
nProc->RegisterMe(preModel);
neutronManager->AddDiscreteProcess(nProc);
```

// Register model to process, process to particle

Evaporation

Just like in case of pre-compound Geant4 actually provide several different implementations for evaporation models:

- Default evaporation *G4Evaporation*
(`hadronic/models/de_excitation/evaporation`)
- HETC evaporation (`hadronic/models/cascade/evaporation`)
- INUCL evaporation
(`models/cascade/cascade/include/G4InuclEvaporation.hh`)
- ABLA evaporation (*to be released 2007*)

The default Geant4 evaporation model

http://wwasd.web.cern.ch/wwasd/geant/geant4_public/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/node62.html

Prediction of final state as result of an excited nucleus ($A > 16$) break-up by the evaporation.

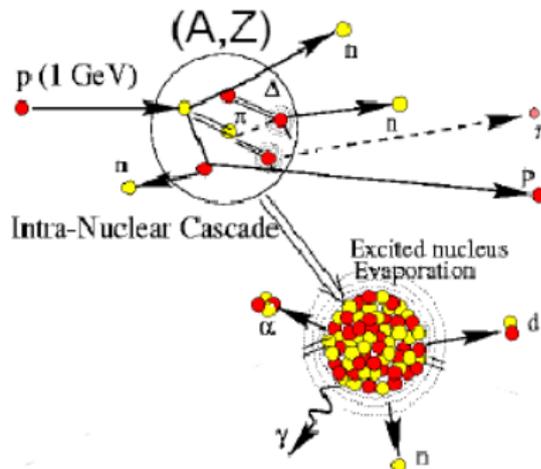
- The initial information for calculation of evaporation stage consists from:
 - Atomic mass number A and charge Z of residual nucleus,
 - Four momentum,
 - Angular momentum and
 - Excitation energy .
- evaporation of γ , n , p , D , T , α
- fission of heavy residual nuclei with $A > 65$
- This model is usually used after:
 - Kinetic stage of nuclear interaction or
 - Another break-up process as the fission or multifragmentation.

Bertini intra-nuclear cascade as an example of theory driven model

Bertini provides a collection of theory driven models with parametrization features $E < 10$ GeV

Models included:

- Bertini INC model with exitons
- Internal pre-equilibrium model
- Nucleus explosion model
- Fission model
- Evaporation model



(Bertini models are provided in the following physics lists: LHEP_BERT, LHEP_BERT_HP, QGSP_BERT, and QGSP_BERT_HP).

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

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

Here $\alpha_i = \{0.01, 0.3, 0.7\}$ and $C_1 = 3.3836A^{1/3}$.

If $A > 11$, a nuclear model with three concentric spheres is also used. The sphere radius is now defined as

$$r_i(\alpha_i) = C_2 \log\left(\frac{1 + e^{-\frac{C_1}{C_2}}}{\alpha_i} - 1\right) + C_1, \quad (24.1)$$

where $C_2 = 1.7234$.

The potential energy V for nucleon N is

$$V_N = \frac{p_F^2}{2m_N} + BE_N(A, Z), \quad (24.2)$$

where p_f is the Fermi momentum and BE is the binding energy.

The momentum distribution in each region follows the Fermi distribution with zero temperature.

$$f(p) = cp^2 \quad (24.3)$$

where

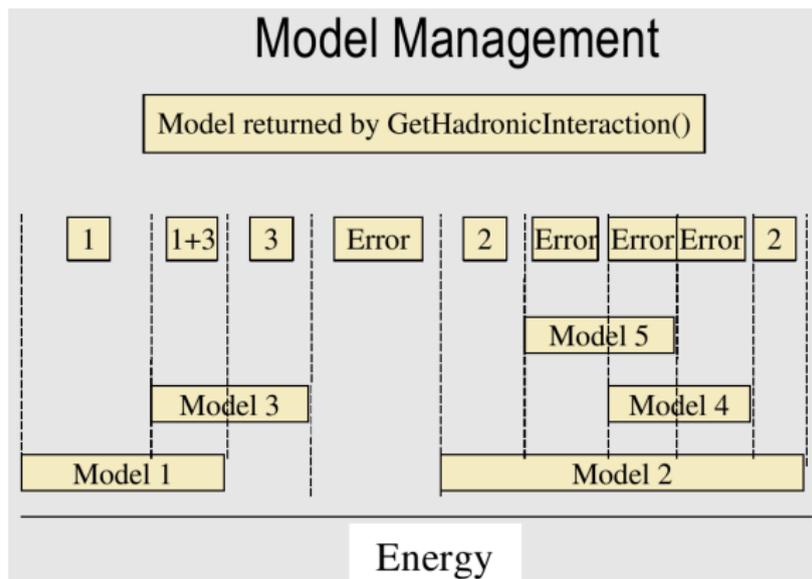
$$\int_0^{p_F} f(p) dp = n_p \text{ or } n_n \quad (24.4)$$

Excerpt from the *Geant4 physics reference manual* describing Bertini model.

Physics lists

Geant4 philosophy implies the usage of physics lists, to provide wanted collection of models, such as:

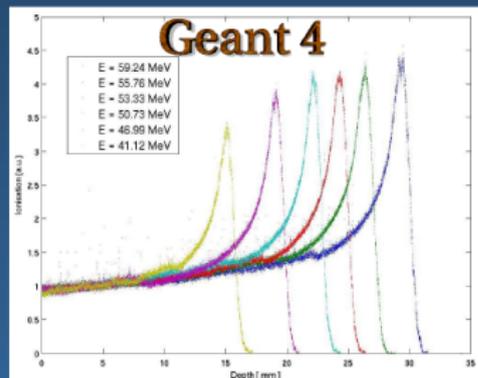
- Parton string models at high energies
- Intra-nuclear transport models at intermediate energies
- Statistical break-up models for de-excitation



Geant 4

Systematic validation of Geant4 electromagnetic and hadronic models against proton data

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CHEP 2006
Mumbai, 13-17 February 2006

LowE EM – ICRU49

BertiniElastic

Bertini Inelastic

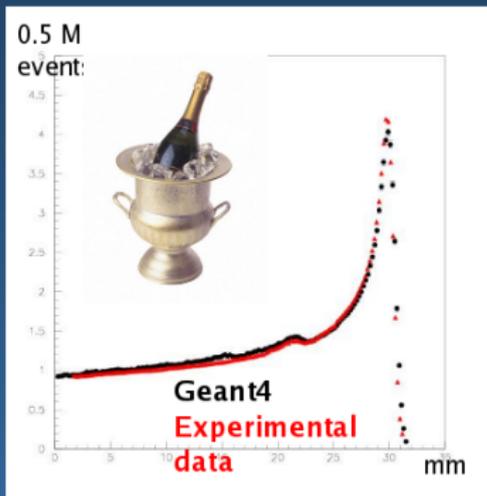
EM + hadronic physics

- Low Energy EM – **ICRU49**: p, ions
- Low Energy EM – Livermore: γ , e-
- Standard EM: e+
- HadronElastic with **BertiniElastic**
- Bertini Inelastic**

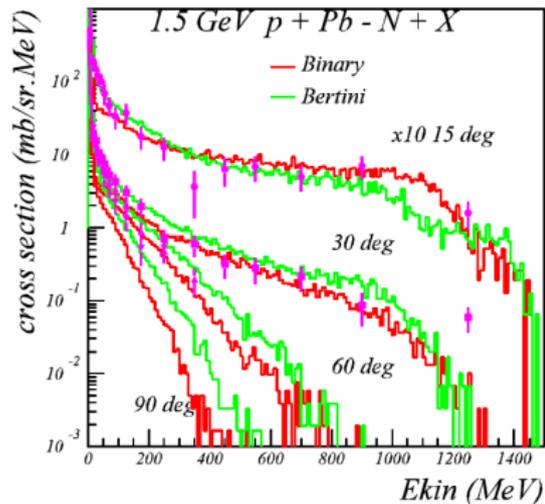
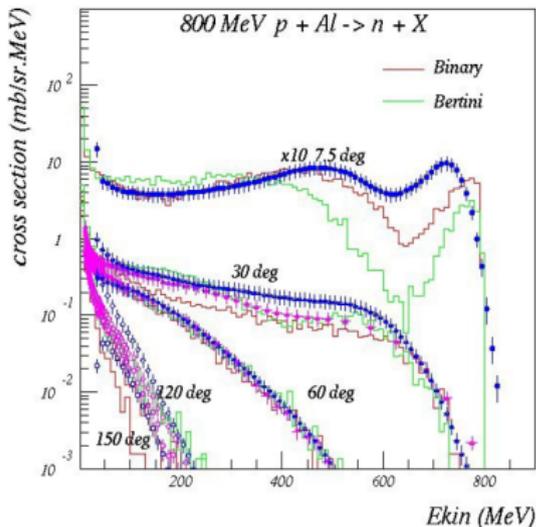
	p-value		
	<u>CvM</u>	KS	AD
Left branch	0.977		
Right branch		0.985	
Whole curve			0.994

CvM Cramer-von Mises test
KS Kolmogorov-Smirnov test
AD Anderson-Darling test

Geant4-INFN (Genova-LNS) Team



Comparing Bertini and Binary cascade models



(V.Ivanchenko)

Summary

- We have described capabilities of Geant4 hadronic physics design required by multidisciplinary applications
 - For hadrons there are many models to choose from, so physics lists are provided by use-case
- Modeling categories theory-driven, parametrized, and empirical formulas (data driven) was introduced
- Multi-layer hadronic framework with cross section treatment was introduced
- Bertini cascade and pre-compound, and evaporation models were briefly discussed
- Recent validation efforts was introduced