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Improving the Medium and Low Energy Physics Models in Geant4

Dennis H. Wright*
SLAC National Accelerator Lab
E-mail: dwright@slac.stanford.edu

on behalf of the Geant4 hadronic working group

A reliable simulation of showers in high energy calorimeters depends critically on hadronic models at low and medium energies (< 10 GeV). The shower width and resolution are strongly influenced by the cascade, precompound and de-excitation models, while the time dependence and energy deposition are affected by low energy neutron models.
Recent extensions of the cascade models, along with their validation against multi-GeV data, will be discussed. The Bertini cascade now handles gamma- and lepton-induced reactions, and can be used to re-scatter within the nucleus the products of an initial high energy collision from one of the QCD string models. The INCL++ model has been extended to handle light ion projectiles, up to and including carbon nuclei.
Improvements in the Geant4 precompound model, including its interface to the cascade models, will also be discussed.
Recent results from fine-grained calorimeters indicate that the propagation of low energy neutrons (sub-thermal to 20 MeV), is important for reproducing the time structure of showers. Improvements in the existing neutron model, including the upgrade of the neutron database and the introduction of an alternate neutron model, will be presented.

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*Speaker.

1. Medium and Low Energy Hadronic Processes in Calorimetry

The simulation of showers initiated by $\sim$ TeV hadrons in calorimeters depends on parton string models to describe the hadron-nucleus interaction. The length of the shower is driven in large part by the details of these models. The propagation of secondaries from this interaction is handled by medium and low energy hadronic models which play a large role in defining the width, resolution and time structure of the shower. These models are therefore crtitcal for reliable shower simulations.

Discussed here are the medium and low hadronic energy models used in the Geant4 physics lists to describe shower development and propagation. These physics lists, or variations of them, are currently used by all of the LHC detector collaborations as well as by Calice and various ILC detector development groups. Improvements of the intra-nuclear cascade, precompound, low energy neutron, stopping, capture and radioactive decay models are all briefly mentioned along with their effects on shower parameters.

2. Intra-nuclear Cascade Models

The Geant4 Bertini-style cascade [1] has been used perennially in physics lists and has undergone nearly continuous improvement since its addition to Geant4. It is generally preferred in simulations because it produces wider showers than other cascade codes, and because it can now be invoked for all long-lived hadron species. It has recently been extended to other particle types: gammas from 10 MeV to 10 GeV incident energy, electrons and positrons of 10 GeV and below, and stopped muons.

This code has been extended to provide interfaces to models outside its range of applicability. For the case of high energy interactions where the Fritiof [2] (FTF) model is used, secondaries from the first interaction are often too high in energy to be passed to a nuclear precompound model. The higher energy intra-nuclear cascade model would be a better intermediate stage in the de-excitation of the target nucleus. The FTF-Bertini interface has been developed for this purpose and is now being tested.

The Bertini-style cascade has its own precompound and de-excitation codes, but they are not as well developed as the native Geant4 precompound and de-excitation models. In order to exploit the advantange of the native code, an interface of the Bertini code to the G4Precompound model was developed. Using this interface produces superior results at energies below about 75 MeV.

The INCL cascade [3] was introduced into Geant4 several years ago as an alternative to the Bertini and Binary [4] cascade codes. It had its origins in the Liege intra-nuclear cascade and was translated from its original Fortran into C++. It has recently been replaced by the completely re-designed and upgraded INCL++. It is a more data-driven approach to the intra-nuclear cascade than the Bertini or Binary codes and includes such features as light cluster formation at the end of the cascade phase. After the INCL precompound phase the native Geant4 de-excitation code is used to complete the reaction.

In addition to the usual pion and nucleon projectiles, the model can now handle light ion projectiles up to ^{12}C, and is valid for incident energies up to 3 GeV. Validations have shown this model to be quite good at spallation energies, as shown in Fig. 1.

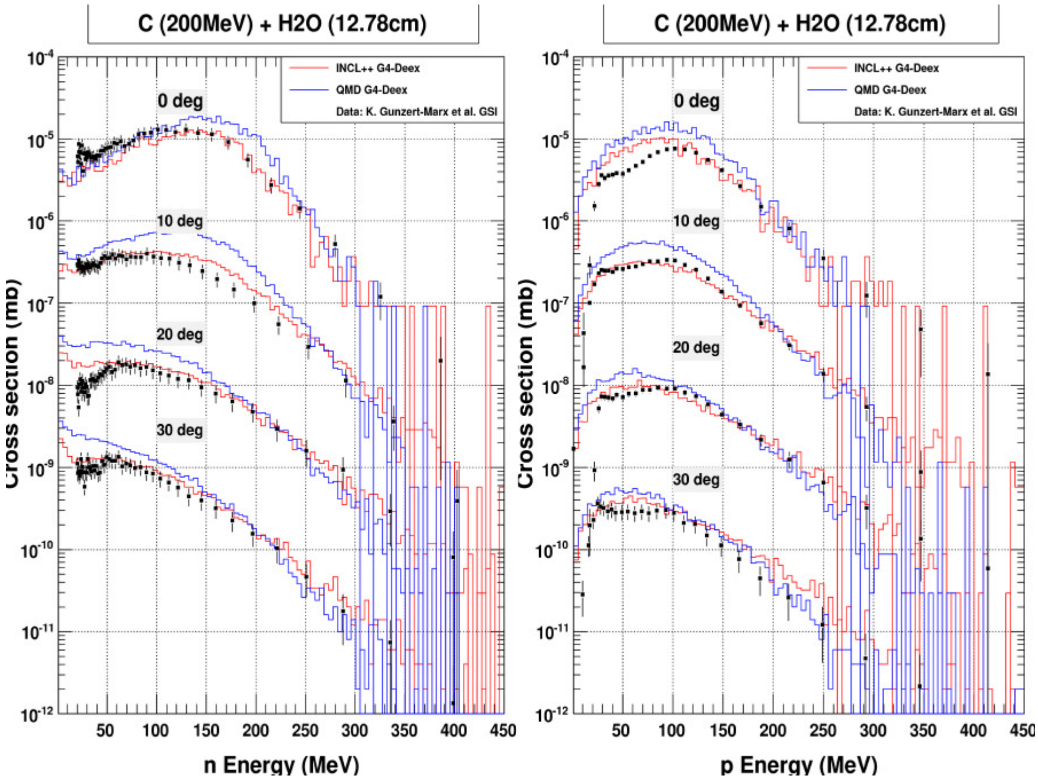

Figure 1: Ion-ion collisions at 200 MeV with the INCL++ model. Red (lower) histogram: INCL++, blue (upper) histogram: G4QMD model, data: Gunzer-Marx et al. [6].

3. Precompound Model

The native Geant4 precompound model [5] has seen many improvements over the last few years, and as such is the preferred model for proton and neutron induced reactions below 170 MeV. It is currently used to de-excite the nucleus after the high energy interactions modeled by the FTF or QGS string models.

Once the precompound stage is complete, the model calls evaporation, multi-fragmentation and Fermi breakup models to de-excite the residual nucleus. Each of these models, too, have undergone extensive review and improvement.

As mentioned above, G4Precompound is now interfaced to two different cascade models (Bertini, Binary) and two string models (QGS and FTF). INCL++, while it doesn't use the G4Precompound model, is interfaced to the native Geant4 de-excitation codes in order to extend its range down to 0 MeV.

4. Low Energy Neutrons

Although low energy (sub-thermal - 20 MeV) neutron propagation may seem to have little to do with high energy calorimetry, a precise treatment of elastic, inelastic and capture processes at these energies has a large effect on some calorimeter observables such as energy deposition and time structure. The effect on the time structure can be seen in Fig. 2. Two Geant4 models which

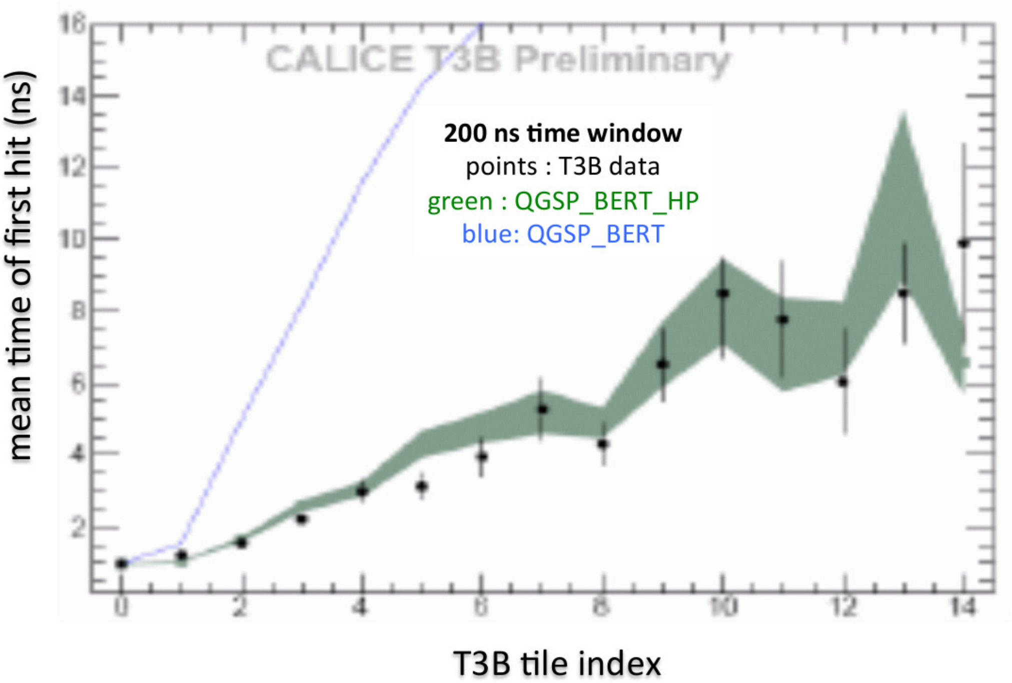

Figure 2: Time structure of shower in the Calice test calorimeter with (green band) and without (blue line) the propagation of low energy neutrons using the HP neutron models.

treat neutrons in this regime are the High Precision (HP) and LEND. The HP models are data-driven codes based on the G4NDL database, which in turn is based on the ENDF/B-VII database [7]. In the past, data in G4NDL was taken from eight different databases, including ENDF, JENDL, JEFF, ENDL, MENDL and CENDL. This caused confusion when the provenance of any part of the data was required. This problem was recently resolved by basing G4NDL entirely on ENDF/B-VII and making the other databases available in their entirety as alternatives.

LEND models were developed as an alternative to the HP models and are based on the GIDI (General Interaction Data Interface) developed at Livermore. In the future, ENDF, JEFF, JENDL and ENDL will be converted to this format. A big advantage of the LEND models over the HP is speed. Due to the precalculation of Doppler broadening, a factor of five improvement has been seen in some applications.

5. Deprecated Models

Two long-standing Geant4 models have been deprecated as they have been replaced by more performant codes. These are the Chiral Invariant Phase Space (CHIPS) [8] and the Low and High Energy Parameterized (LHEP) models. Essential pieces of the CHIPS code have been extracted and refactored into new classes so its modeling capabilities have not entirely disappeared. The LHEP models are re-engineered C++ versions of the Gheisha [9] Fortran code and were the first hadronic models in Geant4. However, they were highly parameterized and did not treat individual interactions in detail. In fact, they did not conserve energy and momentum on an event-by-event basis.

6. Stopping Models

As a result of the these deprecations, several new stopped particle interaction models were developed to replace the old ones. Models handling pion, kaon and sigma absorption are now based on the Bertini-style cascade. Although it has not historically been used for stopped particles, the Bertini code performs rather well in this case because it bypasses the cascade and goes straight to its precompound model to generate the necessary particle-hole states.

Similarly, the FTF model is usually never used for stopped particles because there is no energy available for string formation. However with proton-antiproton annihilation, 2 GeV are available and low-mass strings can be produced. As a result this model is now used for antiproton absorption.

A new stopped muon absorption model was also developed as an alternative to the CHIPS-based model used in some physics lists, which was known to poorly reproduce the resultant neutron spectra. The new model, also based on the Bertini cascade, does an excellent job reproducing the neutron spectra.

7. Radioactive Decay

Not related to high energy calorimetry, but worth mentioning, is the improved radioactive decay model. Based on the ENSDF [10] database, the number of isotopes the model can handle is 2248. This includes 534 nuclear states that now have precise beta decay spectra due to the recent addition of the 1st, 2nd and 3rd unique forbidden shapes. Directional biasing of nuclei was also added as a means of speeding up certain reactions. The production and propagation of isomers and metastable states is currently under development and should be complete by the end of this year.

8. Summary

Most of the above changes to the medium and low energy Geant4 models have combined to make a significant improvement in calorimeter observables. Of particular note is the resolution of the visible energy of the shower. Fig. 3 shows the progress toward more realistic resolution since Geant4 release 9.3 in 2010. Improvement and extensions of the models will continue, guided by new results coming from LHC and Calice calorimeters.

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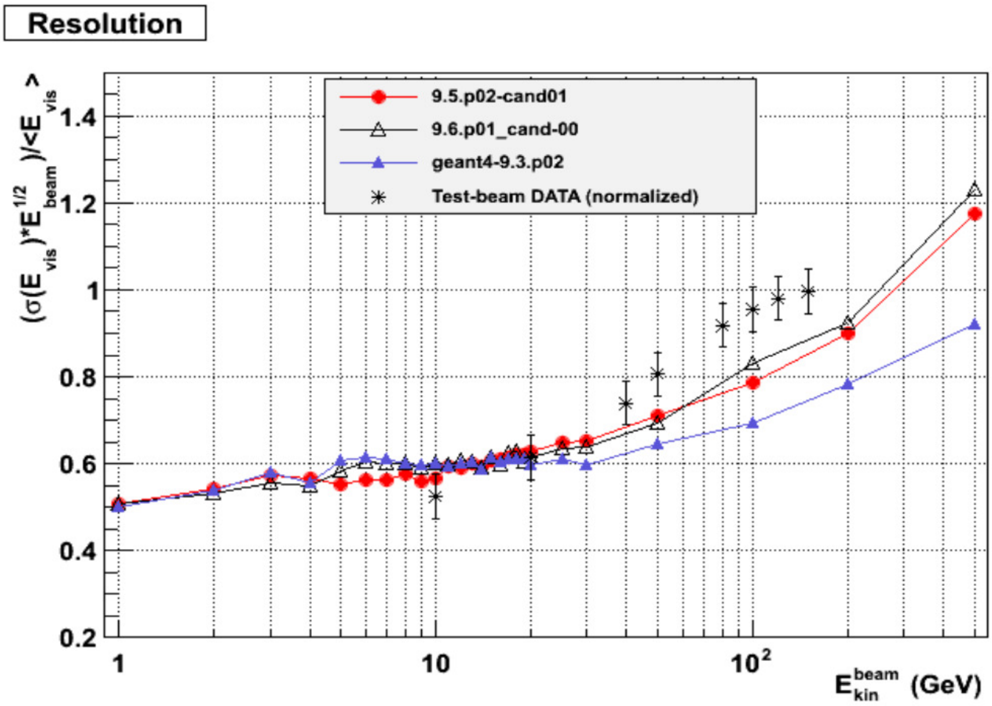

Figure 3: Visible energy resolution in the ATLAS [11] liquid argon-copper calorimeter as compared to several Geant4 releases over time.

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