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HADRONIC PHYSICS SIMULATION ENGINES FOR GEANT4.

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ABSTRACT

Geant4 comes with a very rich array of modeling possibilities concerning hadronic physics, covering the full spectrum from thermal neutron transport to multi TeV events at LHC, and even higher energies for cosmic ray applications. Geant4 hadronic physics (GHAD) is a tool-kit, and a given physics simulation engine needs to be assembled from the components in the tool-kit, each component representing a particular piece of physics. Given the complexity of the task, we provide a set of educated guesses for frequently occurring use-cases involving hadronic physics. At present time, 19 simulation engines are supported for 14 different use-cases.

The physics simulation engines validated in the course of this study are those recommended. Four physics lists are provided for example for the case of calorimetry: LHEP, QGSP, QGSC, and FTFP. These differ mainly in the physics entering the strongest, determining factor in calorimeter simulation; the first reaction.

We will discuss the system of hadronic simulation engines in geant4, and give detailed insight in two of the above described simulation engines. For the purpose of this study, we will use LHEP and QGSP. *Key Words:* Monte Carlo, hadron, nuclear, modeling

1 INTRODUCTION

Geant4 hadronic physics is different from any other simulation code is so far, as it is conceived as a tool-kit, i.e. a component system. Given this, the problem we encounter is the question, how to make it such that the authors of individual components can work independently, while at the same time the physics concepts stay coherent across the system. This problem was solved by means of technology; in this case a hierarchical set of implementation frameworks, that defines a protocol ensuring consistency of the physics. All cross-section and final state generators that make part of the component system obey this protocol, that is enforced by the compiler of the software.

The result of this approach was a tool-kit of about 100 components, that allows individuals to contribute their particular knowledge, while being able to work, publish, and verify independently. While solving the problem of collaboration, this approach at the same time rendered the system extremely flexible. All components can freely be combined to give a physics simulation engine, where individual components may be as large as all of inelastic scattering, or as small as a description of the charge state of a residual ion after an inelastic nuclear reactions. Specialties can exist in particle type and energy of applicability, as well as target material, or any other conceivable combination of projectile and target properties.

Alternative models, cross-section, and smaller components can hence be part of one tool-kit, being viewed as alternatives with different strength, when it comes to descriptive power and CPU performance. The user of the tool-kit is to decide, what is optimal for his problem.

It was seen very early on, that this approach is not really practical from a user's perspective. Very few people have enough detailed technical and physics insight to be able to configure GHAD correctly. Having the possibility to tailor and modify a simulation engine to make it better suite your purpose is very desirable. Being obliged to do this is not. Having the physics completely transparent, so the details of the modeling can be understood when differences arise is very desirable. Having to understand it all before being able to simulate a problem is not.

We hence made pre-configured simulation engines, as published in this paper.

2 PRE-CONFIGURED SIMULATION ENGINES

The goal is to give an educated guess of a simulation engine for specific frequent areas of usage, that can be used as default for treating a problem, or as a starting point for configuring the component system. We version the simulation engines, so results of different simulations can be compared, and conclusions can be taken. This also facilitates to change those parts of the simulation engines, that need to vary from use-case to use-case.

The simulation engines were first distributed in 1999, and first released to the general public as versioned software in 2002. They were revised over the years to take into account the improved modeling capabilities in the GEANT4 tool-kit[1], and new use-case packages were added as needed.

The code is available from http://www.geant4.com/HAD/HomePage, or together with documentation, and a support organization from http://www.geant4.com.

3 THE USE-CASES AND VALIDATION RESULTS

The use-cases for which the simulation engines were optimized are these at present time:

- High energy physics calorimetry
- High energy physics trackers
- The typical high energy physics detector
- Low energy dosimetric applications with neutrons
- Low energy nucleon penetration shielding
- Linear collider (and other electron or photon induced) neutron fluxes
- High energy penetration shielding
- Medical and military neutron applications
- Low energy dosimetric applications
- High energy production targets
- Medium energy production targets

- LHC neutron fluxes
- Air shower applications
- Low background experiments

The results presented below are illustrating the current state of knowledge concerning concrete simulations, showing comparisons for relevant quantities in selected use-cases, or examples of usage.

3.1 High energy physics calorimetry

The physics lists for this use-case at present are QGSP and LHEP.

In the case of LHEP, parameterization driven modeling is used for all hadronic interactions. In other words, LHEP uses the most CPU effective hadronic modeling available in GHAD; the LEP and HEP parameterized models for inelastic scattering. The modeling parameterizes features of the final states of individual inelastic reactions, like like multiplicities, hence resonances are ignored, and the detailed secondary angular distributions for O(100MeV) reactions are not described perfectly. The total cross-sections, used to calculate the individual reaction sites, are those carried froward from GEANT3.21.

The second physics list, QGSP, uses theory driven modeling for the reactions of energetic pions, kaons, and nucleons. It employs quark gluon string model [2] for the fast 'punch-through' interactions of the projectile with the nuclear medium. The string excitation cross-sections are calculated in quasi-eikonal approximation. A pre-equilibrium decay model [3] with an extensive evaporation phase is the employed to model the behavior of the nucleus and the secondaries from the primary soft reaction. It uses pion cross-section from [4], and the Wellisch-Axen systematics [5] for nucleon induced reactions.

Fig. 1 shows the energy resolution and the e/pi ratio as predicted by these two simulation engines for the ATLAS End-Cap hadronic calorimeter. Data are taken from [6].

3.2 High energy physics trackers

For high energy physics tracking devices, the simulation engines investigated were LHEP, QGSP, QGSC, and FTFP. The simulation engines QGSC and FTFP are variations on QGSP. In the case of QGSC, the pre-compound model is replaced by chiral invariant phase-space decay. In the case of FTFP, the quark gluon string model is replaced by a diffractive ansatz for string excitation.

QGSP turns out to be superior to all alternatives for this use-case. As an example we show in figure 2 a comparison of simulation to data from the ATLAS pixel detector[7]. It shows results from a pion test-beam with pions at 180 GeV impinging perpendicular onto the pixel plane. The resulting signal is clusters of pixels, with individual energy measurement. The signal ratio between the hottest pixel to all signal in the cluster of active pixels is shown.

3.3 The typical high energy physics collider detector

For full HEP detector simulation, we recommend to use QGSP or LHEP, with gamma ad electro nuclear physics added, as well as muon nuclear interactions. The corresponding simulation engines are named QGSP_GN and LHEP_GN.

As an illustration of this use-cae, figure 3 shows an event simulated with QGSP_GN in the LHCb detector at LHC.

3.4 Low energy dosimetric applications with neutrons

Dosimetric applications with neutrons are mostly sensitive to the elastic scattering of neutrons, and their capture. Exceptional cases exist, where the non-elastic cross-sections can be large, and hence these need careful modeling. We provide the LHEP_PRECO_HP simulation engine for the purpose. It is based on LHEP, with the assumption, that the energies considered are mostly below pion production threshold. An exciton pre-equilibrium decay model is used to simulate nucleon-nuclear interactions above 20 MeV, while at lower energies the neutron_hp code, a data driven code for neutron scattering, is used.

In figure 4, we show a comparison of the sampling result of the neutron transport code with the cross-sections from G4NDL3.7.

3.5 Low energy nucleon penetration shielding

For the case of low energy nucleon penetration shielding, one of the crucial quantities is the angular distribution of secondary nucleons. We show as an example in figure 5 the angular distributions of secondary neutrons from 800 MeV protons colliding with lead. The left column shows the experimentals neutron production cross-section, overlaid with the result from the Binary Cascade code [9] at several angles of detection, and the right column shows the ratio of data to Monte Carlo. Data were taken from [8]

3.6 Linear collider (and other electron or photon induced) neutron fluxes

The physics simulation engines for linear collider neutron studies have three special ingredients. First, they use the neutron_hp code at low energies for the simulation of neutron reactions. Then they use chiral invariant phase-pace decay to simulate gamma and electro-nuclear reactions. Last they allow for biasing of the gamma and electro nuclear reactions cross-section, in a way that the electromagnetic shower is undisturbed. The method used alters the reaction cross-section by a multiplicative factor, and the loci of reaction sites are calculate in the usual way. To sustain the electromagnetic shower, the incident particle is re-stacked for continued tracking according to the ratio of the unbiased interaction probability to the biased interaction probability. The secondaries produced, in all cases, are weighted accordingly. The practical result is, that the electromagnetic shower develops as in the unbiased case, but 'parasitic' reaction sites get added to the shower, hence allowing for substantial reduction of computing resources needed to obtain neutron fluences.

4 CONCLUSIONS

We have provided physics simulation engines for use with GEANT4 for specific, common areas of usage. They can be used as a default for treating a problem, or as a starting point for configuring the component system. We version the simulation engines, so results of different simulations can be compared, conclusions can be taken, and simulation engines can be improved.

The simulation engines were first distributed in 1999, and first released to the general public as versioned software in 2002. They were revised over the years to take into account the improved modeling capabilities in the GHAD tool-kit in GEANT4, and new use-case packages were added as needed.

The simulation engines today are in wide use in the various communities, and provided GHAD with a substantial set of readily accessible use-cases. Focusing on the use-case view of the architecture solved the problem of the virtual un-usability of a complex component system by non-experts.

5 REFERENCES

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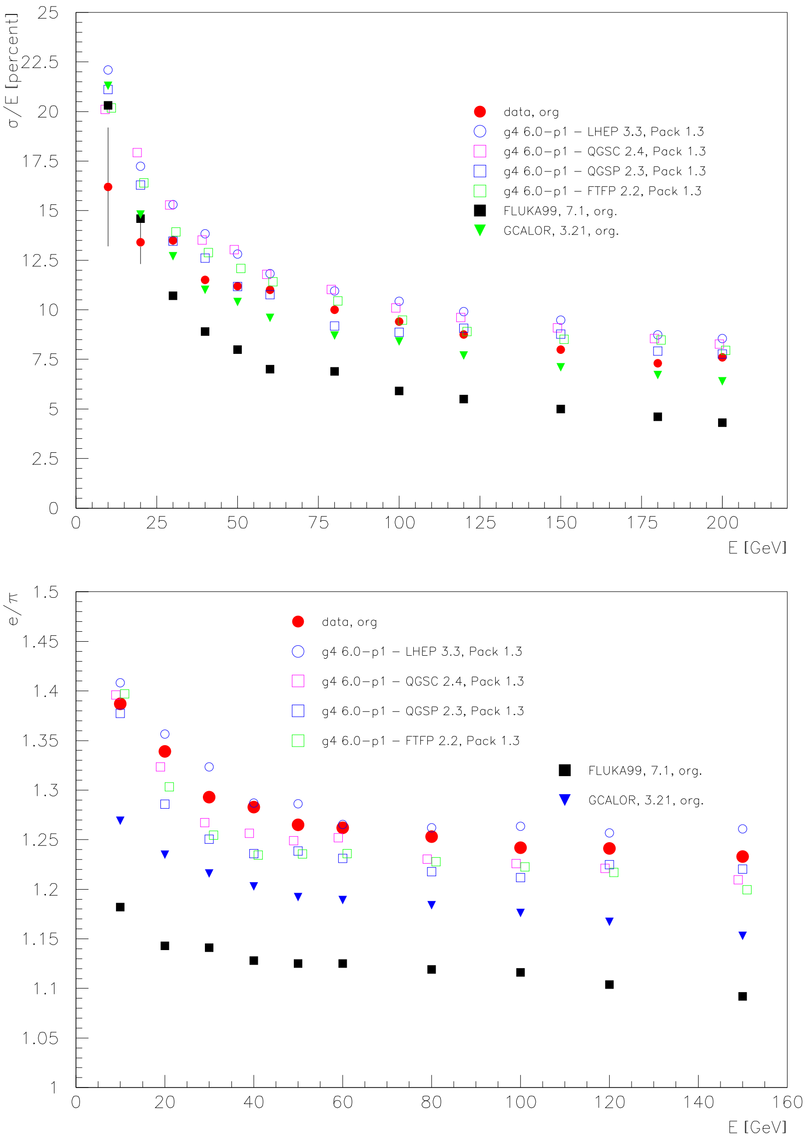

Figure 1: The energy resolution and the signal ratio of electrons to pions in the ATLAS End-Cap hadronic calorimeter as predicted with QGSP and LHEP. Data are taken from [6]

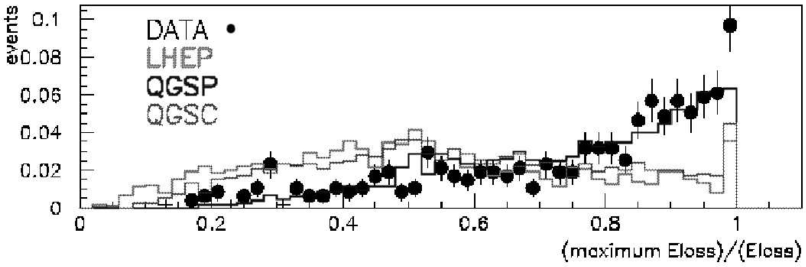

Figure 2: This plot shows results from a ATLAS pixel test-beam, using 180 GeV pions. The signal ratio between the hottest pixel to all signal in the cluster of active pixels is shown[7].

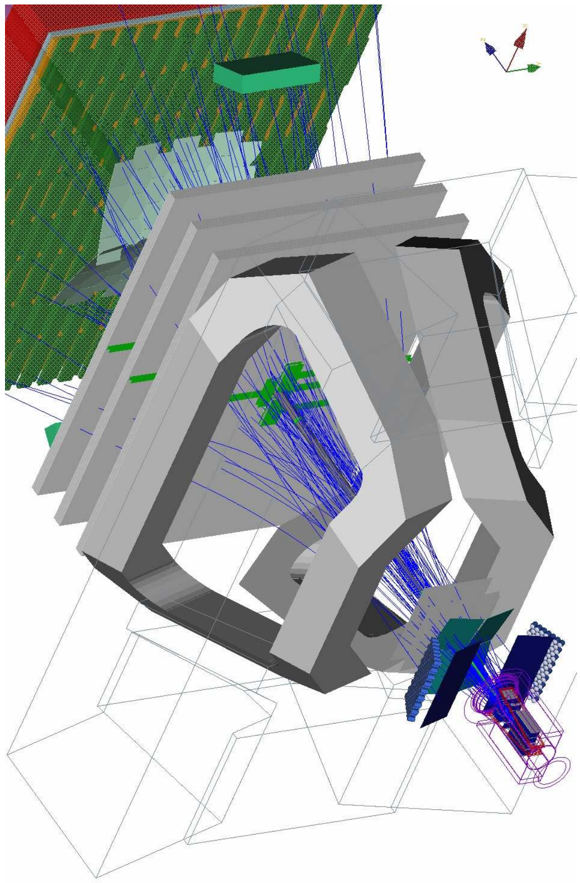

Figure 3: Illustrative picture of a simulated event in the LHCb detector. This picture is a courtesy of the LHCb simulation project.

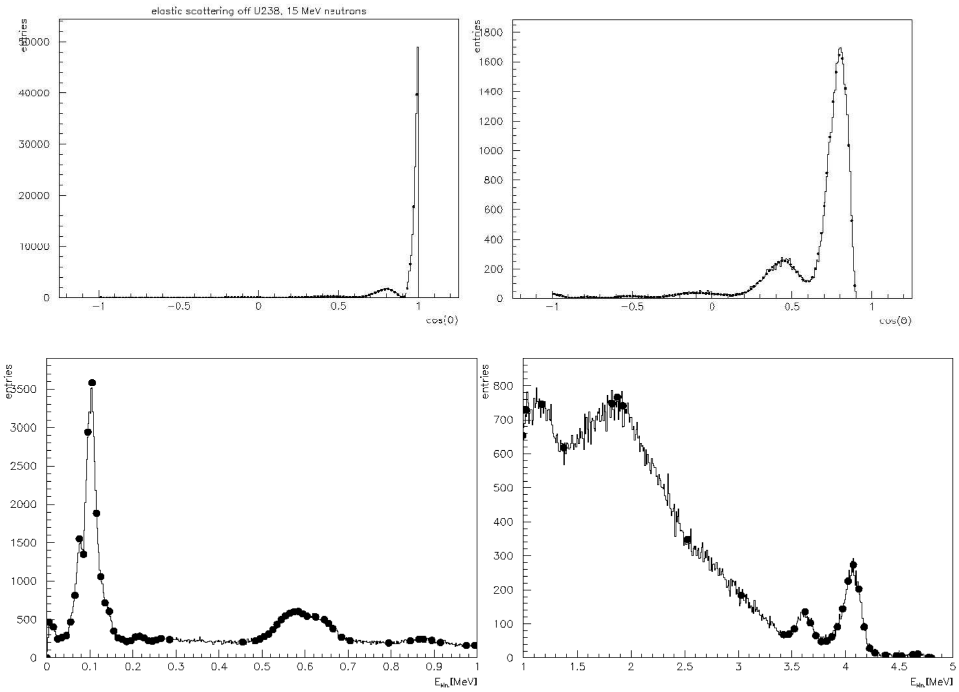

Figure 4: Comparison of the sampling result of the neutron transport code with the cross-sections from G4NDL3.7. The top plots show elastic scattering angular distributions, left with, and right without the forward peak. The lower plots show the energy of gammas from neutron capture.

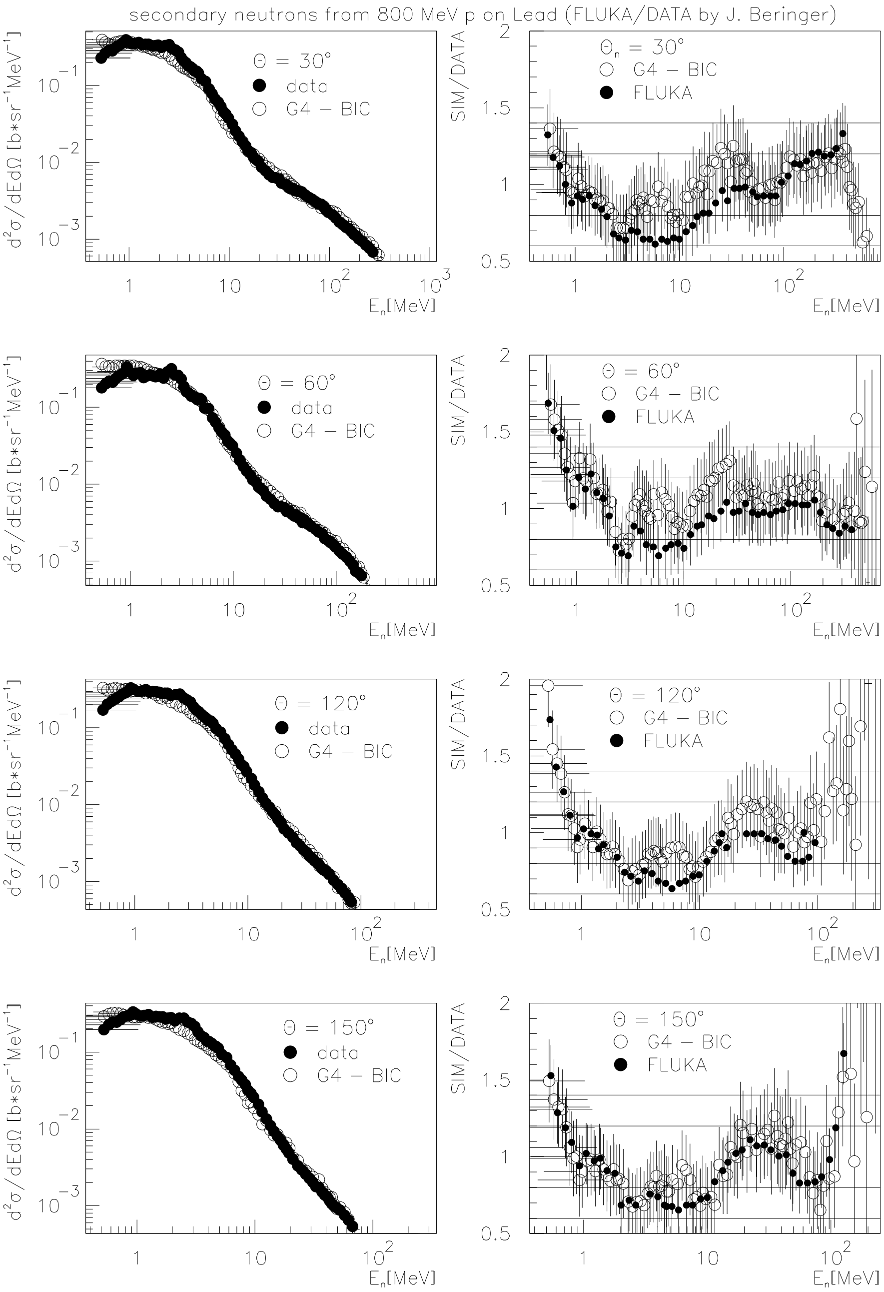

Figure 5: Comparison of data and Binary Cascade for the angular distributions of secondary neutrons from 800 MeV protons colliding with lead. The left column shows the experimentals neutron production cross-section, overlaid with the result from the Binary Cascade code [9] at several angles of detection, and the right column shows the ratio of data to Monte Carlo.