Eur Phys J C **33**, s01, s1011–s1013 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1411-8

EPJ C direct
electronic only

Physics of shower simulation at LHC, at the example of geant4

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Received: 13 October 2003 / Accepted: 9 March 2004 /

Abstract. The LHC experiments will explore new frontiers of particle physics, and open new ways for experimental research in high energy and nuclear physics. To maximize the physics potential of LHC, we need simulation of lepton and hadron interactions and cross-sections in the collider, shielding, and detectors. We need to be able to predict both the detector responses, and the radiation environments in the context of the planned machine operation scenarios.

This can be realized through detailed simulation of the paths of particles traversing the materials of the experimental set-up.

The experimental conditions posed by the LHC, which will be operating at higher energy, luminosity and precision than the present colliders, are very demanding. Triggered by this challenge, the physics modeling of interactions of leptons and hadrons with nuclei, and the associated final state generators and cross-section calculations, have seen significant advances both on the theoretical and technical level during the last few years.

We will discuss the methods of physics in particle transport, and review recent advances at the example of the GEANT4 simulation tool-kit, that was built for the LHC experiments. The focus will be on soft hadronic and nuclear physics.

1 Introduction

In this communication, we describe new developments and methods of hadronic physics in particle transport. We describe technological innovations and a classification scheme for model approaches, and describe one of the novel theoretical approaches developed in some detail.

2 Computational and process aspects

The methodological innovation in geant4 hadronic physics (GHAD)[1] is its being designed as component system. An open and extendible archtiecture and implementation frameworks achieve a maximum of flexibility and extendibility of the physics modeling. The use of Object Oriented programming, design patterns such as the Chain of Responsability, and abstract interfaces allow independent development of model components, making it such that, while most innovative work was done by few individuals, a wide and dispersed community could contribute to the progress of GHAD over the years. The architecture along with a convention on the definition of cross-sections ensure that the components fit together and can be combined in numerous ways to result in a complete and coherent model of the hadronic interactions of particles with matter. The system is a tool-kit. Depending on the area of interest, the physics modeling most suitable for a concrete problem can be put together in a tailored and optimal form.

3 A classification scheme for modeling approaches

We have introduced a classification scheme for modeling approaches, depending on their relationship to experimental data, hence characterizing both the quality of prediction and the possibility to extrapolate safely beyond the primary area of focus of the model. We define three classes of modeling: Data driven modeling (DDM), theory driven modeling (TDM), and parametrization driven modeling (PDM).

4 The Binary Cascade

In the following, we describe Binary Cascade (BIC)[8] in some detail, as an example for the new TDM approaches introduced in the GHAD R&D effort. BIC introduces a new approach towards intra-nuclear cascade calculations. It uses a detailed 3-dimensional model of the nucleus, and is based exclusively on binary scattering between reaction participants and nucleons within this nuclear model. This makes it a hybrid between a classical cascade code, and a quantum molecular dynamics model (QMD)[2].

In BIC, like in QMD, each participating nucleon is described by a Gaussian wave-package:

$$\phi(x, q_i, p_i, t) = 2/(L\pi)^{3/4} exp(-2/L(x - q_i(t))^2 + ip_i(t)x)$$

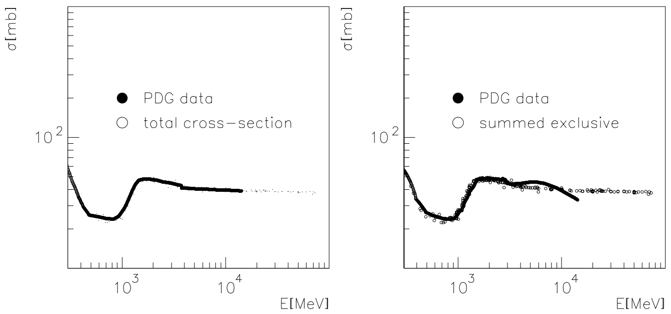

Fig. 1. Comparison of total cross-section in pp scattering with experimental data from the Particle Data Group[3]. The *left plot* shows the total cross-section used, and the *right plot* shows the sum of the cross-sections of all exclusive channels considered in final state generation

Here x, and t are space and time coordiantes, and q_i and p_i are positions in configuration and momentum space.

The total wave-function is assumed to be the direct product of the wave-functions of the participating nucleons and hadrons, where participating means that they are either primary particles, or have been generated or freed in the process of the cascade. Note that we do not take the Slater determinant into account in the description.

For such a wave-form, the equations of motion are identical in their structure to the classical Hamilton equations, and can be solved using numerical integration techniques.

In BIC the Hamiltonian is generated from optical potentials, unlike in QMD where it can be looked at as self-generating from the system configuration.

The imaginary part of the G-matrix acts like a scattering term. It is included using discrete scattering and particle decay in the cascade, with free 2-body cross-sections and a geometrical interpretation of the cross-section, and effective decay width for the strong resonances.

Experimental data are used in the calculation of the total, inelastic and elastic cross-section wherever available.

4.1 Hadron nucleon scattering

For the case of proton-proton(pp) and proton-neutron(pn) collisions, as well as π^+ and π^- nucleon collisions, experimental data are readily available as collected by the Particle Data Group (PDG)[3] for both elastic and inelastic collisions. We use a tabulation based on a sub-set of these data for $\sqrt{S}$ below 3 GeV. For higher energies, parametrizations from the CERN-HERA collection[4] are included.

Figure 1 shows a comparison of the binary cascade total scattering cross-sections with data from the PDG[3]. We also show the corresponding sum of all exclusive channels' cross-sections.

4.2 Channel cross-sections

A large fraction of the cross-section in individual channels involving meson nucleon scattering can be modeled as resonance excitation in the s-channel. This kind of interactions show a resonance structure in the energy dependence of the cross-section, and can be modeled using the Breit-Wigner function

$$\sigma_{res}(\sqrt{s}) = \sum_{FS} \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{\pi}{k^2} \frac{\Gamma_{IS}\Gamma_{FS}}{(\sqrt{s}-M_R)^2+\Gamma^2/4}.$$

Here S_1 and S_2 are the spins of the two fusing particles, J is the spin of the resonance, $\sqrt{s}$ the energy in the center of mass system, k the momentum of the fusing particles in the center of mass system, Γ_{IS} and Γ_{FS} the partial width of the resonance for the initial and final state respectively. M_R is the nominal mass of the resonance.

The initial states in the model at present include all pion nucleon scattering processes. The product resonances taken into account are the Delta resonances with masses 1232, 1600, 1620, 1700, 1900, 1905, 1910, 1920, 1930 and 1950 MeV, and the excited nucleons with masses of 1440, 1520, 1535, 1650, 1675, 1680, 1700, 1710, 1720, 1900, 1990, 2090, 2190, 2220, and 2250 MeV.

4.3 Mass dependent resonance width and partial width

Within the cascade, the resonances produced are assigned masses, distributed according to the production cross-section described above. The masses of these resonances may hence be small or large compared to the PDG value. This has a number of implications, for example that some channels may be closed, and hence has to be accounted for. In general terms, the partial and total width of the strong resonance will depend on the (stochastic) mass of the resonance. We are using an approach also used in rQMD and UrQMD[2] for calculating these width, and write

$$\Gamma_{R\to 12}(M) = (1+r)\frac{\Gamma_{R\to 12}(M_R)}{p(M_R)^{(2l+1)}} \frac{M_R}{M} \frac{p(M)^{(2l+1)}}{1+r(p(M)/p(M_R))^{2l}}. \tag{1}$$

Here M_R is the nominal mass of the resonance, M the stochastic mass, p is the momentum in the center of mass system of the particles, l the angular momentum of the final state, and $r = 0.2$.

4.4 Resonance production cross-section in the t-channel

In resonance production in the t-channel, single and double resonance excitation in nucleon-nucleon collisions are taken into account. The production cross-sections are as much as possible based on parametrizations of experimental data for proton proton scattering. The formula used for parametrizing the cross-sections is motivated by the form of the exclusive production cross-section of the Δ_{1232} in proton proton collisions:

$$\sigma_{AB} = 2\alpha_{AB}\beta_{AB} \frac{\sqrt{s}-\sqrt{s_0}}{(\sqrt{s}-\sqrt{s_0})^2+\beta_{AB}^2} \left(\frac{\sqrt{s_0}+\beta_{AB}}{\sqrt{s}}\right)^{\gamma_{AB}}$$

Table 1. Fitted values of the parameters of the cross-section formula for the individual channels

Reaction	α	β	γ
pp → pΔ_{1232}	25 mbarn	0.4 GeV	3
pp → $\Delta_{1232}\Delta_{1232}$	1.5 mbarn	1 GeV	1
pp → pp*	0.55 mbarn	1 GeV	1
pp → pΔ^*	0.4 mbarn	1 GeV	1
pp → $\Delta_{1232}\Delta^*$	0.35 mbarn	1 GeV	1
pp → Δ_{1232}N*	0.55 mbarn	1 GeV	1

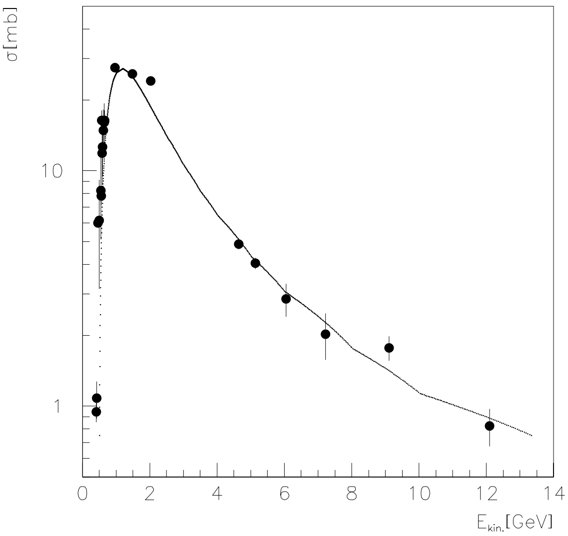

Fig. 2. Comparison of exclusive cross-section in pp scattering with experimental data from the CERN-HERA collection[4]. The *points* are the Δ++ production cross-sections, scaled with the appropriate Clebsh-Gordon corefficient, and the *line* is the binary cascade cross-section

The parameters of the description for the various channels are given in Table 1. For all other channels, the parametrizations were derived from these by adjusting the threshold behavior accordingly. As an example we show in Fig. 2 the delta production cross-section in proton proton scattering, in comparison to experimental data.

Cross-sections for the reminder of the channels are derived from those described above, by applying detailed balance. Also iso-spin invariance is assumed. The formalism used to apply detailed balance is

$$\sigma(cd \to ab) = \sum_{J,M} \frac{\langle j_c m_c j_d m_d \| JM\rangle^2}{\langle j_a m_a j_b m_b \| JM\rangle^2} \cdot \frac{(2S_a+1)(2S_b+1)}{(2S_c+1)(2S_d+1)} \cdot \frac{\langle p_{ab}^2\rangle}{\langle p_{cd}^2\rangle}\sigma(ab \to cd). \quad (2)$$

The work was done in such a manner that the result can be used from within the GHAD frameworks of the geant4 simulation tool-kit. It was released with geant4.

5 Summary

The component approach has proven its ability to enable accumulation of knowledge over time, and the concept of implementation frameworks has proven instrumental in the use of this knowledge.

A classification scheme for modeling approaches has been introduced to navigate the multitude of modeling possibilties in GHAD and other codes, and is valuable for a priori understanding of the extrapolative power of a given modeling approach.

Novel theoretical concepts, such as CHiral Invariant Phase-Space decay[5][6][7] or Binary Cascade[8] have been introduced, and show significant advantages over traditional approaches.

Together with the availability of the known, traditional approaches, this makes the GHAD simulation packages today the most powerful and extensible hadronic simulation toolkit in the world.

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