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Handling of the generation of primary events in Gauss, the LHCb simulation framework

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Abstract. The LHCb simulation application, Gauss, consists of two independent phases, the generation of the primary event and the tracking of particles produced in the experimental setup. For the LHCb experimental program it is particularly important to model B meson decays: the EvtGen code developed in CLEO and BABAR has been chosen and customized for non-coherent B production as occuring in pp collisions at the LHC. The initial proton-proton collision is provided by a different generator engine, currently PYTHIA 6 for massive production of signal and generic pp collisions events. Beam gas events, background events originating from proton halo, cosmics and calibration events for different detectors can be generated in addition to pp collisions. Different generator packages as available in the physics community or specifically developed in LHCb are used for the different purposes. Running conditions affecting the generated events such as the size of the luminous region, the number of collisions occuring in a bunch crossing and the number of spill-over events from neighbouring bunches are modeled via dedicated algorithms appropriately configured. The design of the generator phase of Gauss will be described: a modular structure with well defined interfaces specific to the various tasks, e.g. pp collisions, particle decays, selections, etc. has been chosen. Different implementations are available for the various tasks allowing selecting and combining them as most appropriate at run time as in the case of PYTHIA 6 for pp collisions or HIJING for beam gas. The advantages of such structure, allowing for example to adopt transparently new generators packages, will be discussed.

1. Introduction
The LHCb [1] simulation application, Gauss [2], [3], consists of two independent phases:

(1) the generation of the primary event,

(2) the tracking of the particles produced in the experimental setup (detector).

The first step can be further divided into two important main parts, both using external generator packages. First, the production of particles coming out of the primary pp collision of the LHC beams, which is currently realized by default via the general purpose event generator PYTHIA 6 [4]. Second, the decay and time evolution of the produced particles using mainly the EvtGen [5] package. The simulation software application, Gauss, is interfaced to these two external generators, and provides the necessary algorithms to steer the execution of the different generation sequences, and to ensure the coherence between them. A very generic framework has been designed. The resulting application is flexible enough to be able to generate a very large variety of event types, from beam gas events up to very rare decays of B mesons, allowing different generator packages available in the high-energy physics community to be interfaced to Gauss.

2. General software structure

The structure of the LHCb simulation software is pictured in Fig. 1, where the two main phases are represented: event generation and detector simulation. The simulation part is based on the GEANT4 package [6] and is described in detail in [3]. The generation step deals with the generation of physics events and uses several generic tools to perform the necessary actions.

2.1. Main generation algorithm

The generation of the events is realized in one Gaudi algorithm [7], [8] which implements three main actions:

(1) Initialization: this step mainly deals with the configuration of the algorithm which is obtained from configurables [8], i.e. special python classes built from the C++ components (Services, Algorithms, Tools) which compute from user inputs the value of the parameters to be used for the generation. These values can be for example the energy of the proton beam to consider for the generation, or the crossing angle between the beams.

(2) Event loop execution: the result of this step is the generation of one physics event corresponding to the criteria defined at the initialization (for example events containing a b quark). The generated event is stored in HepMC format [9] and is then transferred to the simulation step, as illustrated in Fig.1. It can optionally be saved on a POOL output file [10] to be analyzed in detail later.
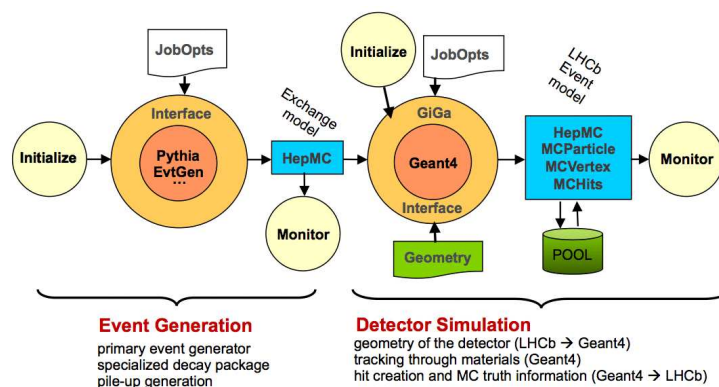

Figure 1. Structure of the Gauss software.

In order to realize all the computations needed for the generation of one physics event, several tools are called by the execute method of the generation algorithm. Each tool has a generic interface and several concrete implementations, which are chosen depending on the configuration of the algorithm. This choice of specialized tools with generic interfaces allows to substitute easily inside the algorithm a method by another one. For example, the generation of beam parameters is usually describing the head-on collision of two proton beams but can be replaced by the description of the collision of one proton beam with one gas molecule in order to simulate beam-gas events. All available tools will be decribed in detail in Sec. 2.2.

(3) Finalization: monitoring counters are printed at this stage. They allow to count the efficiency of the various generator-level selections applied during the event generation, and to know the cross-sections of the generated processes. These counters are available from the log files of the production simulation jobs. A script extracts from these log files the interesting information and computes numerical results which are available in web pages for the physicists analysing the simulated data.

The generation algorithm also accesses generic LHCb common services. A service provides all tools and algorithms with a common random number, including external libraries which are interfaced in such a way that their internal random number generator is replaced by the one of the service. In order to ensure that any event in a sequence of events can be reproduced without generating all preceding events, the random generator seed is set before generating every new event. The seed is set according to a unique combination of integers (run and event numbers) which identify uniquely each event. A particle property service is used to define properties of particles (mass, lifetime, spin, charge and width). This ensures that all LHCb software (including also the reconstruction and the analysis applications) use the same particle properties. The source of data for the particle properties is the review of particle physics of the Particle Data Group (PDG) [11].

2.2. Tools for the generation algorithm
The algorithm described in Sec. 2.1 calls various tools to realize specific computations.

(1) Production Tool: it takes care of the primary pp collision generation: hard process, evolution of the partons up to the formation of hadrons, generation of multiple parton-parton interactions. This is usually realized calling an external generator, such as the general purpose event generators PYTHIA 6, PYTHIA 8 [12], HERWIG [13], Herwig++ [14] or SHERPA [15]. In this case, the tool is an interface to the generator (which can be either written in FORTRAN or in C++ language). The tool also provides the possibility to configure the external generator in various ways, transferring the configuration commands given by the Gauss user through configurable settings of the tools into the format needed by the external generator. The main external generator used up to now is PYTHIA 6. Other implementations of the Production Tool are provided in Gauss for specific purposes: an interface to BCVEGPY [16] for the production of the B_c meson and an interface to HIJING [17] for the simulation of beam-gas events for example. The possibility to use text files as production engines is also provided, either containing fully generated events, or containing parton level events to be hadronized by another generator. The supported file format are the HepMC ASCII file format or Les Houches Event (LHE) files [18].

(2) Decay Tool: it is used to decay hadrons produced by the Production Tool. The primary event generation stops after the hadronization, and then delegates to the decay tool the evolution of decays. Because the LHCb experiment focuses on flavour physics and in particular B physics, it needs a very detailed simulation of B decays, taking into account CP violation effects or angular correlations in decay chains. The EvtGen generator [5] is

very well suited for this purpose since it was developed at CLEO and BABAR, experiments also devoted to B physics.

The SHERPA generator is also interfaced to Gauss as a Decay Tool since it also provides the possibility to implement detailed descriptions of decay properties. One important task of the Decay Tool is to generate signal decays, i.e. to force the signal particle to decay into the decay mode of interest. This allows Gauss users to obtain samples containing only the decay mode under study to be able to determine their reconstruction efficiencies or the biases introduced by the experimental setup.

(3) Sample Generation Tool: unlike the Production Tool which deals with the actual process of generating the primary collision, this tool is used to check the typology of the generated event in order to sample only those events satisfying the requirements of a predefined event type. Several categories of event samples are of interest for the LHCb physics program.

- Minimum Bias: all events generated by the production generator, with no requirement about their content.
- Inclusive: events containing a particle out of a configurable list of particle types. This category is mainly composed of inclusive c and b events, defined as events containing at least one charm hadron or one beauty hadron respectively.
- Signal: all events containing a particle of a given type (the "signal"), like $B_s^0/\bar{B}_s^0$ for example. In each event, one of the signal particle is forced to decay by the decay generator to a predefined decay mode, such as $B_s^0 \rightarrow J/\psi\phi$. In order to speed up the generation of B events for relatively rare signal hadrons (B_s^0 or Λ_b compared to B^+ and B^0 for example), the following method is applied: once an event with a b quark is obtained, the same event is re-hadronized several times until the correct type of B meson is found. This feature is implemented only when using the PYTHIA 6 production generator.
- Special events: events defined with special generator settings, usually containing processes with very low cross-sections, such as Z^0 production.

Since Inclusive and Signal events have a rather large cross section, they are then extracted from Minimum Bias and do not need extra special settings of the production generator.

(4) Pile-Up Tool: more than one interaction can occur in a given bunch crossing in the experiment, hence in one individual simulated event. Additional interactions with respect to the interaction containing the process of interest are called "Pile-Up Interactions". They are generated by Gauss adding Minimum Bias interactions generated by the production generator on top of the main interaction. The Pile-Up Tool is used to provide the computation of the number of interactions in one event, N_{int}. The default and main usage is to generate N_{int} following a Poisson law with mean value ν depending on the total cross-section of the pp collision, σ_{tot}, the instantaneous luminosity, $\mathcal{L}$, and the collision frequency of the LHC bunches, f. ν is determined as:

$$\nu = \frac{\mathcal{L} \cdot \sigma_{tot}}{f}. \tag{1}$$

For the generation of rare processes, since they have very low cross-sections and cannot be extracted out of Minimum Bias, a different scheme has to be adopted to generate directly the correct N_{int} distribution. In this case, events containing one interaction with this rare process have $N_{int} - 1$ following a Poisson distribution with the same mean value ν as described in Eq. 1. The mean number of interactions per event containing the rare process is then $< N_{int} >= \nu + 1$. The possibility to generate single interaction events, for beam-gas generation for example, is also available.

(5) Beam Tool: it generates the kinematics of the LHC proton beams. The main usage is to describe two colliding proton beams, with a crossing angle. The crossing angle is smeared by a Gaussian function with σ equal to: $\sigma = \sqrt{\frac{\epsilon}{\beta^*}}$, where ϵ is the beam emittance and β^* is the beam β-function at the collision point. An implementation of the Beam Tool also provides the possibility to generate a single beam against a fixed target. This is used for the simulation of beam-gas events, where the fixed target is a molecule of the residual gas in the vacuum pipe of the experiment.

(6) Cut Tool: the full simulation of the interactions of the generated events in the LHCb detector is very time consuming. In order to reject as early as possible in the simulation process events which would anyway be rejected by the analysis, selection cuts at the generator level are implemented. The most simple cut applied to the events is to require that the particles of interest travel in the direction of the LHCb detector, which has a limited acceptance, i.e. particles have an angle with respect to the beam direction less than 400 mrad, with $p_z > 0$. A more efficient cut that can be applied on signal particles is to require that all stable decay products not coming from a long lived particle such as Λ have an angle θ with respect to the beam axis $10 < \theta < 400$ mrad for charged particles and $5 < \theta < 400$ mrad for neutral particles. Many other different implementations are available or can be added easily. Kinematic properties of all the particles generated in the event can be used to apply generator level cuts in the Gauss generation phase.

(7) Vertex Smearing Tool: it implements the generation of the luminous region of the LHC collisions at the LHCb Interaction Point. The position of the interaction point is smeared around the mean collision point by Gaussian distributions in x, y and z. For the generation of beam-gas events, only the x and y positions are smeared while the z coordinate has a flat distribution.

2.3. Sequencing of the generation algorithm

The actions done by each tool are steered from the main generation algorithm. As example, the logic of Signal sample generation to obtain one event is described in the following:

(1) Compute the number N_{int} of pile-up interactions for this event, calling the Pile-Up Tool.

(2) Produce N_{int} interactions of type Minimum Bias with the Production Tool. For each interaction, the beam parameters (4-momentum) are obtained from the Beam Tool.

    a) Decay all hadrons produced with the Decay Tool.

    b) Check if one of the interactions contains the signal hadron. If not, go back to 2). This step is arranged by the Sample Generation Tool.

    c) Force the signal particle to decay to the signal requested final state, also using the Decay Tool.

    d) Check if the signal particle meets the requirements of the generator level selection, calling the Cut Tool. If not, go back to 2).

    d) Determine the spatial position of each N_{int} interactions with the Vertex Smearing Tool.

The generation of other types of events (Minimum Bias, Inclusive or Special samples) are simplified adaptations of the scheme described above.

3. Other generators

We already mentioned in Sec.2.2 that in addition to PYTHIA 6 other generators have been interfaced to Gauss as production engines: they consist of PYTHIA 8, HERWIG, Herwig++ and SHERPA. Moreover, for beam gas interactions a special nucleus-nucleus generator, called HIJING is used: it allows to generate protons impinging on any of the residuals gas atoms present

in the vacuum pipe as H, C, O. Machine induced background can also be generated via a special in-house generator that samples the results of beam losses transported to the LHCb cavern. A detailed description of this generator is available in [19]. Finally for special calibration or for beam studies a particle gun algorithm is available with various implementations, for example for optical photons or cosmic rays.

4. Conclusion

The logic and implementation of the generation of physics events for the LHCb simulation software has been described. It allows to interface different generators available within the high-energy physics community and also provides tools to generate events in conditions as close as possible to the real conditions seen at the LHCb experimental setup.

Acknowledgments

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