Development of the EvtGen package for the LHC and ATLAS

J. Catmore, R. Jones, M. Smizanska
Lancaster University, LA1 4YB, United Kingdom

Abstract

The EvtGen package has been developed for the LHC experiments within the LCG project. The adaptation of the package to the LHC context has necessitated effort in both physics and software. Interfaces have been created to enable the use of EvtGen within the simulation and data-handling frameworks of the LHC experiments. Modifications have been made to meet the requirements of simulating beauty events produced in proton proton collisions, with which the LHC B-physics studies are primarily concerned. Here we review the programme of work carried out by ATLAS, including both software and physics related activities. The results of validation simulations are shown, and future plans are discussed.

INTRODUCTION

In both the preparatory and running stages of any particle physics experiment, reliable Monte Carlo data, which adequately reflects the behaviour of the decaying and final-state particles, is essential. Feasibility studies, where the likely experimental limits on a given measurement are estimated, are particularly dependent on such simulated data. The development of software packages (known as *Event Generators*) which can produce Monte Carlo data efficiently is consequently of significant importance to the LHC project. This work takes place within the auspices of the LCG project.

CHARACTERISTICS OF BEAUTY EVENTS

Decays involving beauty particles can reveal subtle physics phenomena, and due to the high production rate of b-quarks in the LHC, beauty studies form a significant part of the accelerator's scientific programme. Beauty quarks are massive but live long enough to form bound states, so the sector is characterised by a wide range of decay channels with a variety of topologies and multiplicities. An event generator which adequately captures the physics of beauty events must be able to account for cascade decays involving multiple vertices. Given that the angular distributions of final-state decay products often carry information on underlying physics, the package must also be able to handle a wide range of spin configurations. Quantum effects such as CP-violation and mixing play a significant role and must also be captured by the generator.

THE EVTGEN PACKAGE

EvtGen [1] was first developed within the BaBar collaboration. Written in C++, it is a particle decay simulator which is specifically designed for the needs of B-physics studies.

Firstly, the formalism of *spin density matrices* is included in the code. This facilitates the inclusion of spin effects into the simulation, and consequently allows the user to study the distribution of the decay angles of the final states.

Secondly, the input data for each decay process is passed to the code as a *complex amplitude* as opposed to the usual case where probabilities are used directly. In cases where a number of complex amplitudes are invoked for the same process, these are added before the decay probabilities are calculated and consequently the *interference terms*, which are of significant importance in many B-physics studies, are included. Such terms are lost in a conventional "probability-based" generator. The complex amplitudes are encoded as C++ classes which are referred to as *models*. All these models inherit from a single base class, in which is included a range of tools for the construction and manipulation of the amplitudes.

The package also uses a novel *nodal* decay algorithm, where each decay step is treated independently. This feature addresses the problem of the cascade decays which typify B-physics events. In a conventional Monte Carlo generator kinematics for the whole chain would be generated at once, and the accept-reject decision applied on the result. Apart from the difficulty in calculating the maximum probability for the whole process, this method is inefficient as a rejection leads to the whole chain being re-generated from scratch. The node-wise method of EvtGen avoids this, by generating kinematics for each step separately. As can be seen from the description in [1], this approach does lead to increasingly complex spin density matrices being attached to the amplitudes for each node, but the computation time required to calculate these is very much less than that which would be needed to continually re-generate kinematics for the whole decay tree.

EvtGen is controlled by means of a decay table, which lists all possible decay processes, their branching ratios and the model (amplitude) which is to be used to decay them. A user decay table can be written to over-ride the default table and thereby close off unwanted processes.

THE LHC VERSION OF EVTGEN

In 2001 it was decided that, due to the highly attractive features of EvtGen and its wide use at the B-factories, the code would be adopted for use in the LHC. The effort is directed within the Generators work package of the LCG project, and involves physicists from LHCb, ATLAS and CMS.

LHC conditions versus "B-factories"

The differences between the so-called "B-factories" and the LHC are considerable. The B-factories study collisions of electrons and positrons as opposed to the LHC which uses protons. The LHC will thus produces a full complement of B-hadron species and excited states in every run, whereas the B-factories can be tuned precisely to one particular resonance. The energy scales are also different. Furthermore, the LHC scientific programme is wider than those of the B-factories - EvtGen is required by LHC groups studying Higgs decays, super-symmetry and top processes as well as beauty physics.

Software scheme

EvtGen has been successfully integrated into the software infrastructures of the three experiments. Here a description is given of the ATLAS implementation [5], but a similar scheme is used by both LHCb and CMS.

The entire event generation procedure occurs within the ATLAS offline data processing suite, ATHENA [4]. The proton-proton collisions, up to and including the production of the initial state B-hadrons, are handled by the standard LHC event generation packages (Pythia [7], Herwig [3]. Neither these packages nor EvtGen are actually part of ATHENA - the libraries reside in an external space and are accessed via interface algorithms, which are part of ATHENA.

The Pythia interface, guided by an ATHENA job options script, activates the external Pythia libraries and obtains the initial-state particles. Approximately half of these B-hadrons are then "frozen" through an additional job options script, which orders the Pythia interface to refrain from from decaying them. The remainder are decayed by Pythia according to the Lund String Model which describes higher multiplicities [7].

The B-hadrons whose decay is suspended are then collected by the EvtGen interface algorithm which, having read in the type and kinematics of the hadrons, invokes the LHC-EvtGen libraries to effect the decay. EvtGen is guided by means of the default and user decay tables, which are passed to ATHENA along with the job options scripts.

The data is passed between the Pythia and EvtGen interfaces via the transient data store StoreGate. The format used is HepMC [6], the common LHC object-oriented Monte Carlo event record. At the end of the chain, once all the decays are complete, the EvtGen interface writes the results in HepMC format and passes them to StoreGate. These events are either written directly to disk, or passed through some event filter for further processes.

This scheme is shown in graphical form in figure .

Physics modifications in LHC-EvtGen

The B-factories are tuned to produce copious quantities of the $\Upsilon\,(4s)$ resonance, which can decay into two coherent B-mesons. These resonances form a substantial part of the research programmes of the B-factories and the BaBar version of EvtGen naturally has apparatus for generating them and handling the coherent behaviour of the resulting mesons. In the LHC, the beauty hadrons are produced in the proton-proton collision, and consequently are *incoherent*. To account for this, a range of new decay models have been constructed by a number of LHCb and ATLAS groups.

B-jet multiplicities are also an issue, in that EvtGen has been tuned in a manner appropriate to BaBar, not the LHC. The re-tuning exercise has not yet been performed, so all strong and electromagnetic decays are left to Pythia. Furthermore, a number of Fortran components in BaBar-EvtGen have been removed to ensure compatibility with current versions of Pythia.

Finally, studies which depend on the spin of the parent particle (such as on the production polarization of heavy B-baryons [12][13]) need a special treatment, as Pythia, which produces them, does not deal with spin. In these cases, EvtGen *imposes* spin and polarization on the initial-state particles where this is required.

VALIDATION EXERCISES

Extensive validation exercises have been performed across the three LHC experiments. The results of such an exercise carried out in ATLAS is shown here.

The angular distribution of the final states of $B_s \rightarrow J/\psi\,(\mu\mu)\,\phi\,(KK)$ was studied. Neutral B_s^0 mesons are thought to oscillate between the state and anti-state, leading to mass eigenstates which are linear combinations of the flavour eigenstates [8]. New physics may provide additional sources of CP-violation and will thus influence the rates at which this mixing occurs. In order to access experimentally the degree of CP-asymmetry and thereby gain access to the new physics indicators, it is necessary to measure the relative strengths of the CP-odd and CP-even decay amplitudes. This is achieved by means of an *angular analysis*.

The decay of a scalar B_s meson into two muons and two kaons, via the vector-vector intermediate state $J/\psi\phi$, is parameterized by three decay angles as shown in figure 2. When the LHC is running these events will be identified and the the decay angles calculated. This angular data will then be fitted to a derived probability density function whose variables include the CP-violating parameters of interest.

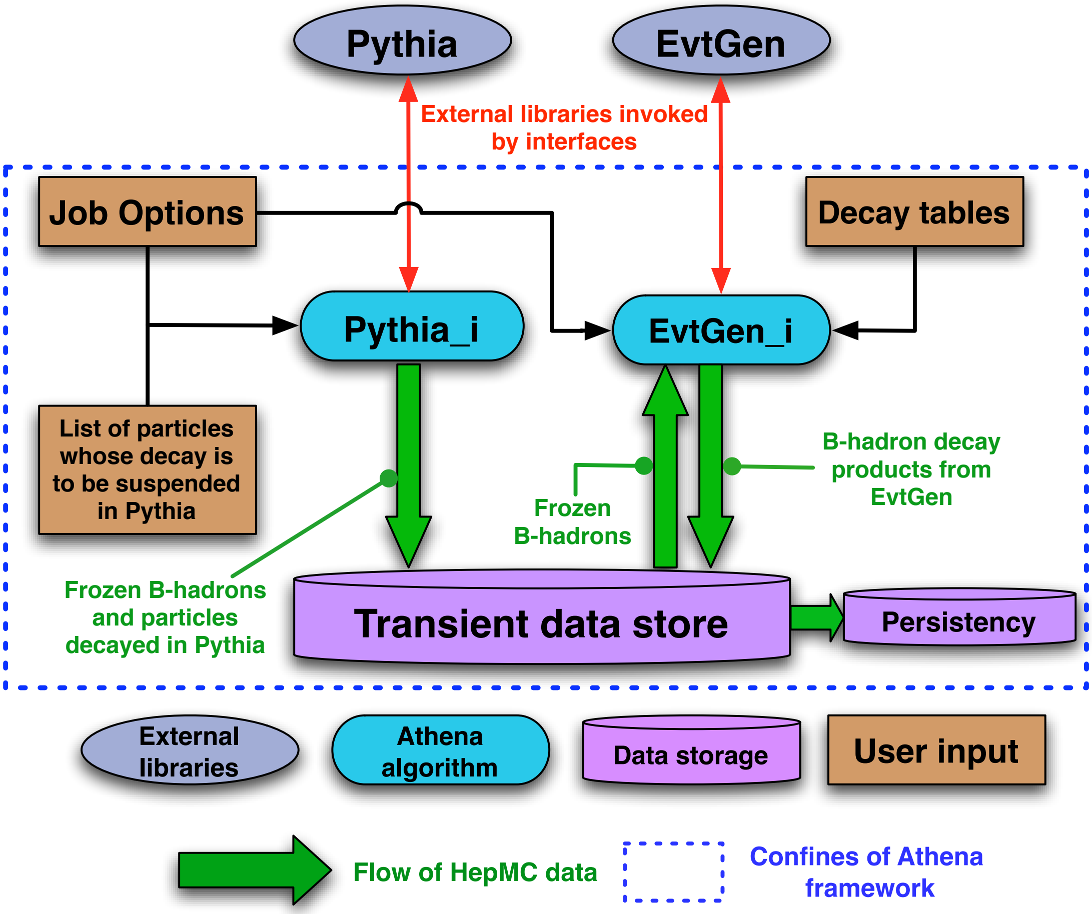

Figure 1: Scheme of software used for event generation with EvtGen in ATLAS.

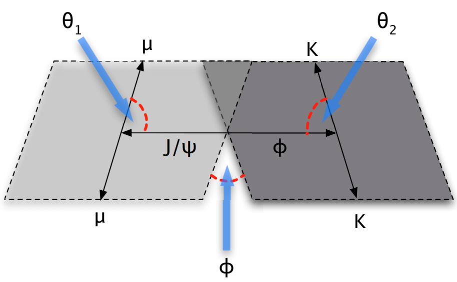

Figure 2: Decay angles parameterizing the decay $B_s \to J/\psi\,(\mu\mu)\,\phi\,(KK)$.

A range of feasibility studies have been performed to assess the capability of ATLAS in making this measurement [9][10][11]. These simulations have required Monte Carlo data whose angular distributions have the appropriate information on CP-violation, mixing and new physics contributions encoded within them. Using the scheme described above, over 100000 events were produced with an EvtGen model specially written for this task. The distribution of the ϕ angle is shown in figure 3; the red dots indicate the data from EvtGen whereas the blue points show data produced by performing simple accept-reject Monte Carlo on the theoretical probability density function (against which the real data will be fitted). A good match is seen.

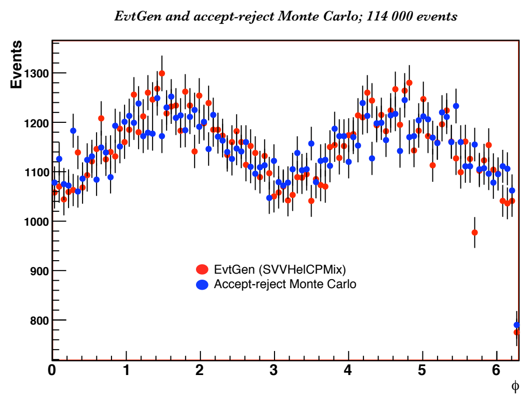

Figure 3: Time-integrated distribution for the ϕ angle in $B_s \to J/\psi\,(\mu\mu)\,\phi\,(KK)$.

ATLAS also made a similar exercise on the production polarization of Λ_B baryons, a summary of which can be found in [12] and [13].

EvtGen is now used across ATLAS, and collaborators use both the existing code, and also are implementing new theoretical models in the framework.

ACKNOWLEDGEMENTS

The authors would like to extend their thanks to the authors of EvtGen, Anders Ryd and David Lange, for many valuable discussions. We are also grateful to Patrick Robbe and Nick Brook of the LHCb Collaboration for their help and advice.

REFERENCES

[1] D. Lange, Nucl. Inst. Meth A**462**, 152 (2001)

[2] T. Sjöstrand *et al*, Computer Phys. Commun. **135**, 238 (2001)

[3] G. Corcella *et al*, JHEP 0101 (2001) 010 [hep-ph/0011363]; hep-ph/0210213.

[4] The Athena website, http://atlas.web.cern.ch/Atlas/GROUPS/SOFTWARE/OO/architecture/index.html

[5] J. Catmore, M. Smižanská, ATLAS internal communication ATL-COM-PHYS-2004-041 (2004)

[6] M. Dobbs, J. Hansen, Comput. Phys. Commun., **134**, 41 (2001)

[7] T. Sjöstrand *et al*, Computer Phys. Commun. **135** 238 (2001)

[8] P. Ball, R. Fleischer *et al* (editors), *B Decays at the LHC*, CERN-TH/2000-101 (2000)

[9] M. Smizanska, Nucl.Instrum.Meth. A**446**, 138-142 (2000)

[10] J. Catmore, “The ATLAS B-physics programme”, Proceedings of the 20th Lake Louise Winter Institute, 20-26 February 2005. To appear in World Scientific

[11] R. Jones, ”High precision measurements of B_s mixing parameters from $B_s \rightarrow J/\psi\phi$ in the ATLAS experiment”, Proceedings of the 10th International Conference on B-physics at Hadron Machines (BEAUTY2005), 20-24 June 2005. To appear in Nucl. Phys. B - Proc. Suppl.

[12] M. Biglietti *et al*, ATLAS note CERN-ATL-COM-PHYS-2005-018

[13] M. Biglietti *et al*, presentation at CHEP2006 (ID 388)