

# FastSim: A Fast Simulation for the Super $B$ Detector

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**Abstract.** We have developed a parameterized (fast) simulation for detector optimization and physics reach studies of the proposed Super $B$  Flavor Factory in Italy. Detector components are modeled as thin sections of planes, cylinders, disks or cones. Particle-material interactions are modeled using simplified cross-sections and formulas. Active detectors are modeled using parameterized response functions. Geometry and response parameters are configured using xml files with a custom-designed schema. Reconstruction algorithms adapted from BaBar are used to build tracks and clusters. Multiple sources of background signals can be merged with primary signals. Pattern recognition errors are modeled statistically by randomly misassigning nearby tracking hits. Standard BaBar analysis tuples are used as an event output. Hadronic  $B$  meson pair events can be simulated at roughly 10Hz.

## 1. Introduction

Super $B$  is a proposed next-generation asymmetric  $e^+e^-$  flavor factory designed to run at a baseline luminosity of  $10^{36} \text{ cm}^{-2}\text{s}^{-1}$ , between 50 and 80 times the peak luminosity reached by the earlier B-factories KEKB and PEP-II. The machine is expected to operate mainly at the  $\Upsilon(4S)$  center-of-mass energy with the possibility of running in the energy range between the  $\Psi(3770)$  and  $\Upsilon(5S)$  resonances. The Super $B$  detector concept [1] is based on the BaBar design [2] with significant modifications required to deal with the reduced boost and higher event rates. As a consequence, simple extrapolations of BaBar measurements are not adequate to estimate the physics reach of the experiment. Additionally, to make optimal choices in the Super $B$  detector layout an understanding of the effect of design options on a number of benchmark physics analyses is needed. A detailed simulation of the Super $B$  detector, with its various options, with sufficient statistical precision for a relevant physics result, is beyond the capability of the current Super $B$  computing effort.

To address these needs, a fast simulation (FastSim) program has been developed. FastSim relies on simplified models of the detector geometry, materials, response, and reconstruction to achieve an event generation rate a few orders of magnitude faster than is possible with a Geant4-based [3] detailed simulation, but with sufficient detail to allow realistic physics analyses. In order to produce more realistic results, FastSim incorporates the effects of expected machine and detector backgrounds. FastSim is configurable at runtime, and is compatible with the BaBar analysis framework, allowing sophisticated analyses to be performed with minimal software development.

## 2. Event generation

FastSim uses the same event generation tools used by BaBar. On-peak events ( $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ ), with the subsequent decays of the  $B$  and  $\bar{B}$  mesons, are generated through the EvtGen package [4]. EvtGen also has an interface to JETSET for the generation of continuum  $e^+e^- \rightarrow q\bar{q}$  events ( $q = u, d, s, c$ ), and for the generic hadronic decays that are not explicitly defined in EvtGen. The SuperB machine design includes the ability to operate with a 60 – 70% longitudinally polarized electron beam, which is especially relevant for tau physics studies. Events  $e^+e^- \rightarrow \tau^+\tau^-$  with polarized beams are generated using the KK generator and Tauola [5].

## 3. Detector description

FastSim models SuperB as a collection of *detector elements* that represent medium-scale pieces of the detector. The overall detector geometry is assumed to be cylindrical about the solenoid  $\vec{B}$  axis ( $z$  axis), which simplifies the particle navigation. Individual detector elements are described as sections of two dimensional surfaces such as cylinders, cones, disks and planes, where the effect of physical thickness is modeled parametrically. Thus a barrel layer of Si sensors is modeled as a single cylindrical element. Intrinsically thick elements, such as the electromagnetic (EM) calorimeter crystals, are modeled by layering several elements and summing their effects. Gaps and overlaps between the real detector pieces within an element (such as staves of a barrel Si detector) are modeled statistically.

The density, radiation length, interaction length, and other physical properties of common materials are described in a simple database. Composite materials are modeled as admixtures of simpler materials. A detector element may be assigned to be composed of any material, or none.

Sensitive components are modeled by optionally adding a *measurement type* to an element. Measurement types describing Si strip and pixel sensors, drift wire planes, absorption and sampling calorimeters, Cherenkov light radiators, scintillators, and Time Of Flight (TOF) are available. Specific instances of measurement types with different properties (resolutions) can co-exist. Any measurement type instance can be assigned to any detector element, or set of elements. Measurement types also define the time-sensitive window, which is used in the background modeling.

Magnetic fields are modeled by a map which describes the field vector  $\vec{B}$  at every point in space in the detector volume. The default field map is a simplified solenoid, having constant value within given a radius and Z limits, and being zero outside that. This is adequate for SuperB.

The geometry and properties of the detector elements and their associated measurement types are defined through a set of XML files using the EDML (Experimental Data Markup Language) schema, invented for SuperB.

#### 4. Interaction of particles with matter

The SuperB FastSim models particle interactions using parametric functions. Coulomb scattering and ionization energy loss are modeled using the standard parameterization in terms of radiation length and particle momentum and velocity. Molière and Landau tails are modeled using multiple Gaussian functions. Bremsstrahlung and pair production are modeled using simplified cross-sections. Discrete hadronic interactions are modeled using simplified cross-sections extracted from a study of Geant4 output. Electromagnetic showering is modeled using an exponentially-damped power law longitudinal profile (a simplified version of the gamma distribution in [7] [8]) and a double Gaussian transverse profile [9], which includes the logarithmic energy dependence and electron-photon differences of shower-max.

Unstable particles are allowed to decay during their traversal of the detector. Decay rates and modes are simulated using the BaBar EvtGen code and parameters.

#### 5. Detector response

All measurement types for the detector technologies relevant to SuperB are implemented. Tracking measurements are described in terms of the single-hit and two-hit resolution, and the efficiency. Si strip and pixel detectors are modeled as two independent orthogonal projections, with the efficiency being uncorrelated (correlated) for strips (pixels) respectively. Wire chamber planes are defined as a single projection with the measurement direction oriented at an angle, allowing stereo and axial layers. Ionization measurements ( $dE/dx$ ) used in particle identification (PID) are modeled using a Bethe-Bloch parameterization.

In the EM calorimeter the energy deposits are distributed across a grid representing the crystal or pad segmentation taking into account profile fluctuations and crystals energy resolution. In the Instrumented Flux Return (IFR) the hadronic shower profile produced by charged pions or the ionization energy loss by muons are used to determine the 2-dimensional hits distribution over the scintillator planes, taking into account the intrinsic spatial resolution. The detector response for other hadrons, such as the  $K_L^0$ , is not yet implemented.

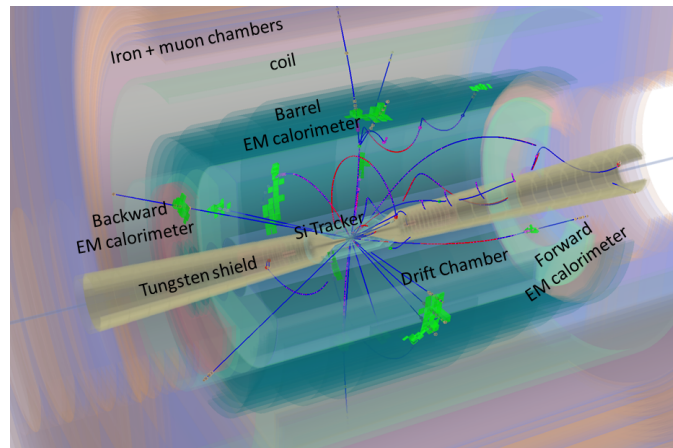
Cherenkov rings are simulated using a lookup table to define the number of photons generated based on the properties of the charged particle when it hits the radiator. Timing detectors are modeled based on their intrinsic resolution.

#### 6. Reconstruction

A full reconstruction based on pattern recognition is beyond the scope of FastSim. However, a simple smearing of particle properties is insensitive to important effects like background particles (see section 7) that can shadow or distort signals from primary particles. As a compromise, FastSim reconstructs high-level detector objects (tracks and clusters) from simulated low-level detector objects (hits and energy deposits), using the simulation truth to associate detector objects. Pattern recognition errors are introduced by perturbing the truth-based association, using models based on observed BaBar pattern recognition algorithm performance.

In tracking, hits from different particles within the two-hit resolution of a device are merged, the resolution degraded, and the resultant merged hit is assigned randomly to one particle. Hits overlapping within a region of ‘potential pattern recognition confusion’, defined by the particle momentum, are statistically misassigned, based on their proximity. The final set of hits associated to a given charged particle are then passed to the BaBar Kalman filter track fitting algorithm to obtain reconstructed track parameters at the origin and the outer detector. Outlier hits are pruned during the fitting, based on their contribution to the fit  $\chi^2$ , as in BaBar.

Ionization measurements from the charged particle hits associated to a track are combined using a truncated-mean algorithm, separately for the Silicon Vertex Tracker (SVT) and Drift Chamber (DCH) hits. The truncated mean and its estimated error are later used in PID algorithms.



**Figure 1.** Reconstructed  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  event with  $B \rightarrow$  hadrons represented using the FastSim event display.

In the EM calorimeter, overlapping signals from different particles are summed across the grid. A simple cluster-finding based on a local maxima search is run on the grid of calorimeter response. The energies deposited in the cluster cells are used to define the cluster energy, position, and shape. A simple track-cluster matching based on proximity of the cluster position to a reconstructed track is used to distinguish charged and neutral clusters.

In the IFR hits are clustered, and clusters are fitted with a straight line (since  $\vec{B}$  is zero outside the solenoid coil). A number of quantities useful to distinguish pions and muons are computed, such as the number of interaction lengths crossed by the particle.

FastSim has an event display which runs as a root macro. Fig. 1 shows a reconstructed  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  event with the  $B$  mesons decaying to hadrons. The subsystems have cylindrical symmetry. Both charged particles and photons (straight segments) are visible. The green lego blocks are reconstructed clusters in the EM calorimeter.

## 7. Machine backgrounds

Machine backgrounds at SuperB are assumed to be dominated by luminosity based sources, such as radiative Bhabha scattering ( $e^+e^- \rightarrow e^+e^-\gamma$ ) and QED two photon processes ( $e^+e^- \rightarrow e^+e^-e^+e^-$ ). Since the bunch spacing (a few ns) is short relative to the time sensitive window of most of the SuperB detectors, interactions from a wide range of bunch crossings must be considered as potential background sources.

Background events are generated in dedicated FastSim or full simulation (based on Geant4) runs. Background events are stored as a *TClonesArray* of *TParticles* [6]. Background events from all sources are overlaid on top of each generated physics event during FastSim particle simulation. The time origin of each background event is assigned randomly across a global window of  $0.5 \mu\text{s}$ . Background events are sampled according to a Poisson distribution given the mean interaction rate. Particles from background events are simulated exactly as those from the physics event, but the detector response they generate is modulated by their different time origin. In general, background particles outside the time-sensitive window of a measurement type do not generate any signal, while those inside the time-sensitive window generate nominal signals. An exponential decay model is used to simulate EM calorimeter response to background particles. Hit-merging, pattern recognition confusion, and cluster merging are performed after background overlay, to model the effect of backgrounds on resolution.

## 8. Analysis tools

Since FastSim is compatible with the BaBar analysis framework, existing BaBar analyses can be run in FastSim with small modifications. For instance, the vertexing tools and combinatorics engines used in BaBar work also in FastSim.

Key ingredients in most of the Super $B$  (and BaBar) physics analyses are the PID selectors, which provide lists of identified particles (pions, kaons, electrons, etc.) selected by combining the PID information measured in the relevant subsystems. For example, a kaon selector developed to separate charged kaons from charged pions combines the ionization energy loss measured in the SVT and DCH, together with the Cherenkov angle measured by the FDIRC, plus, if available, the information from the time of flight detector (TOF) in the forward region, into a single likelihood. A flavor-tagging algorithm ( $B$  vs.  $\bar{B}$  meson identification) is inherited from BaBar. New algorithms based on the Super $B$  detector capabilities, such as the improved transverse impact parameter resolution, have not yet been developed.

The standard BaBar analysis persistence has been adapted to work in FastSim, allowing the use of BaBar analysis macros on FastSim data. A mapping of analysis objects back to the particles which generated them (including background particles) is provided in FastSim, along with the particle genealogy.

Typical per event processing times on a dual quad core Intel(R) Xeon(R) CPU E5520 @ 2.27GHz architecture are 1 ms for particle generation, 10 ms for propagation of particles through the detector, 100 ms for reconstruction, and between 100 and 1000 ms for composites selection, depending on the event complexity.

## 9. Simulation validation and detector studies

FastSim has been validated by simulating the BaBar detector and comparing the output with a detailed (G4) simulation or BaBar data. Most distributions studied agree within 5%.

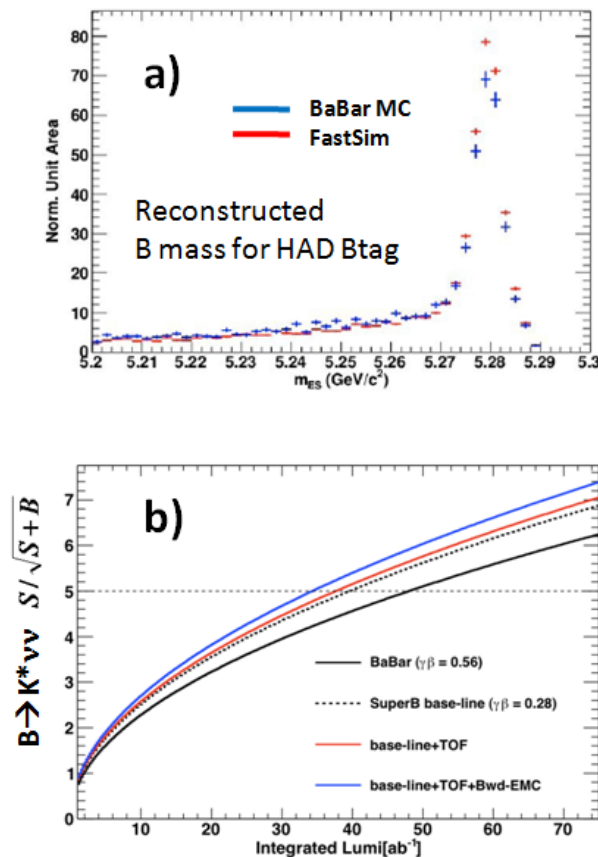
FastSim is being used to optimize the Super $B$  design by studying the performance of different detector layouts in terms of the physics reach in some benchmark channels. For example, the rare decay  $B \rightarrow K^* \nu \bar{\nu}$ , whose branching fraction is potentially sensitive to physics beyond the Standard Model, has been studied in the BaBar configuration and in three Super $B$  detector layouts with or without a forward TOF and backward EM calorimeter. To reduce combinatoric backgrounds, this analysis reconstructs a *tag*  $B$  meson in a hadronic or semi-leptonic decay channel, while reconstructing the signal  $B$  in the remaining part of the event. The top plot of Fig. 2 shows the reconstructed mass of the tag  $B$  mesons selected in hadronic decays, with FastSim superimposed to the BaBar full simulation. The bottom plot shows how  $S/\sqrt{S+B}$  ( $S$ =signal,  $B$ =background) for detecting this rare decay scales as a function of the integrated luminosity, for the different detector layouts. Thus FastSim allows a quantitative comparison of these options in terms of the equivalent additional luminosity it would take to achieve the same sensitivity. FastSim has also been used to test various tracker designs for the mu2e experiment at FNAL, as shown in Fig. 3.

## 10. Conclusions

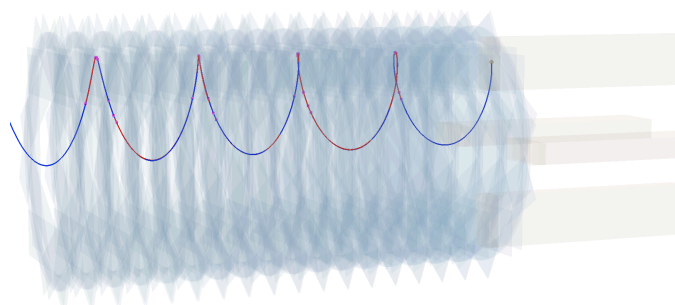
FastSim is a new fast simulation program developed within the Super $B$  project. It has been used to optimize the detector performance. A public version of FastSim is planned to be released in the near future.

## References

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**Figure 2.** Top: Mass of the reconstructed  $B$  decays selected into hadronic final states. Bottom:  $S/\sqrt{S+B}$  in the measurement of  $B \rightarrow K^* \nu \bar{\nu}$  as a function of the integrated luminosity, at BaBar and in three different SuperB detector configurations.



**Figure 3.** Fast Simulation of a signal electron in the Transverse Tracker of the mu2e experiment.

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