# Event Simulation in High-Energy Physics.

by

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## Abstract

Theory of Higgs bosons is outlined, with a brief review of the Standard Model and the Minimal Supersymmetric extension of the Standard Model (MSSM). The potential for Higgs boson discovery at the LHC is briefly surveyed. Introduction to physics modeling, the event generation and detector simulation as designed for the ATLAS detector is presented. Simulations of Higgs two photon decay performed at University of Pittsburgh are also summarized. The Experimental High Energy Physics Group at Pitt is presently involved in the designing and building the ATLAS detector for the LHC. Major efforts of the group have been in the domain of designing and building digital and analog electronics for the calorimeters of the ATLAS detector. Therefore, there is a need to start carrying out physics simulations and analyzing of data in order to be prepared once the detector is running. To analyze the data efficiently, all the analysis tools need to be made available locally. These tools include CERNlib, ROOT, MN_FIT and ATLAS simulation software.


## 1. Introduction

By 2008, the Large Hadron Collider (LHC) will be up and running and it will have one of the most demanding infrastructures for high-performance computing environments. LHC is being designed to carry out experiments closely related to finding the origin of the universe. High-energy physics has often been a front-runner in many high-technology fields and a test bed for new concepts. While the main research goal of the LHC is to improve our understanding of fundamental properties of matter and space, aims quite remote from any short-term practical application, high-energy physics research has led to the development of new analysis tools (synchrotron radiation, medical imaging), of new processes (cancer therapy, food preservation, nuclear waste treatment) and even the birth of a new industry (Internet). [1]

Scientists need highly sensitive and specialized instruments called particle detectors to be able to study fundamental particles at a detailed level at which they can deduce their properties. The LHC detectors (fig. 1) can only be designed and tuned with the help of a precise simulation system reproducing the fine details of each detector as well as the materials been used down to bolts and nuts. No data analysis or physics can be performed without the help of simulated data acting as a reference to the experimental output. All events take in to account the efficiency and acceptance correction factors. These can only be determined by comparing the experimental events to the simulated events. The associated systematic errors also include the simulation uncertainties, so that the quality of a physics result strongly depends on the quality of the physics and detector simulation involved.
A simulation package is an intrinsic part of any high-energy physics experiment in as much as the detectors themselves; it is a mandatory component of any experiment from the design stage to the final result. Simulation is the art of mimicking nature and man-made detectors. The most general simulation package, shown in fig. 2, consists of two main components, namely, the physics modeling leading to the event generation, and the detector simulation. The reconstruction code is common to both the simulation and real data flows. [1]

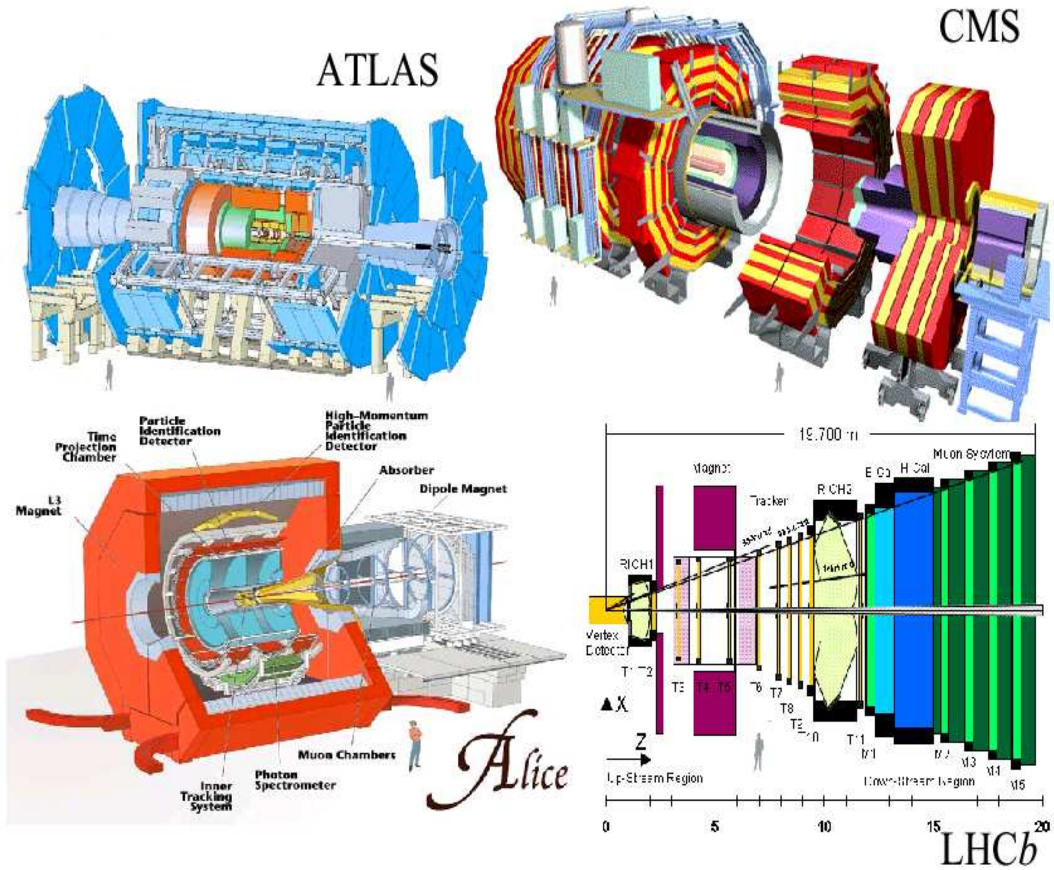


Figure 1: Four detectors at the LHC

## 2. Standard Model

To explain the importance of the LHC for high-energy physics, we need to take a look at the underlying theory, the Standard Model. Over the past fifty years, physicists have created a remarkable picture of the fundamental structure of matter: the Standard Model of Particles and Forces. All 12 matter particles and 4 force carriers discovered so far are used to summarize all that we currently know about the most fundamental constituents of matter and their interactions. [2]
The Standard Model is by now a well tested physics theory, used to explain and precisely predict a vast variety of phenomena. High-precision experiments have repeatedly verified subtle effects predicted by the Standard Model. Fundamental particles bind together to form structures on all scales, from the proton built from three quarks, through atoms and molecules, liquids and solids, to the huge conglomerations of matter in stars and galaxies. They do this through four basic interactions, which we call forces.

The most familiar basic force is gravity. Gravitational interactions are carried by gravitons. It keeps our feet on the ground and the planets in motion around the Sun. On individual particles though, the effects of gravity are extremely small. Only when we have matter in bulk - as in planets - does gravity dominate. A much stronger fundamental force is the electromagnetic one, which manifests itself in the effects of electricity and magnetism. The electromagnetic force binds negative electrons to the positive nuclei in atoms, and underlies the interactions between atoms that give rise to molecules and to solids and liquids. Unlike gravity, it can produce both attractive and repulsive effects. Two other forces are weak and strong forces. The weak force, intermediated by W and Z bosons, leads to the decay of neutrons (which underlies many natural occurrences of radioactivity) and allows the conversion of a proton into a neutron (responsible for hydrogen burning in the center of stars). The strong force holds quarks together inside protons, neutrons and other hadrons by exchange of gluons. It also prevents the protons in the nucleus from flying apart under the influence of the repulsive electrical force between them. This is because, within the nucleus, the strong force is about 100 times stronger than the electromagnetic one. Strong force becomes stronger with distance. The quarks bound within particles, for instance, never appear alone; as you try to pull them apart, the force becomes stronger. This is unlike the more familiar effects of gravity and electromagnetism, where the forces become weaker with distance. [3, 4]

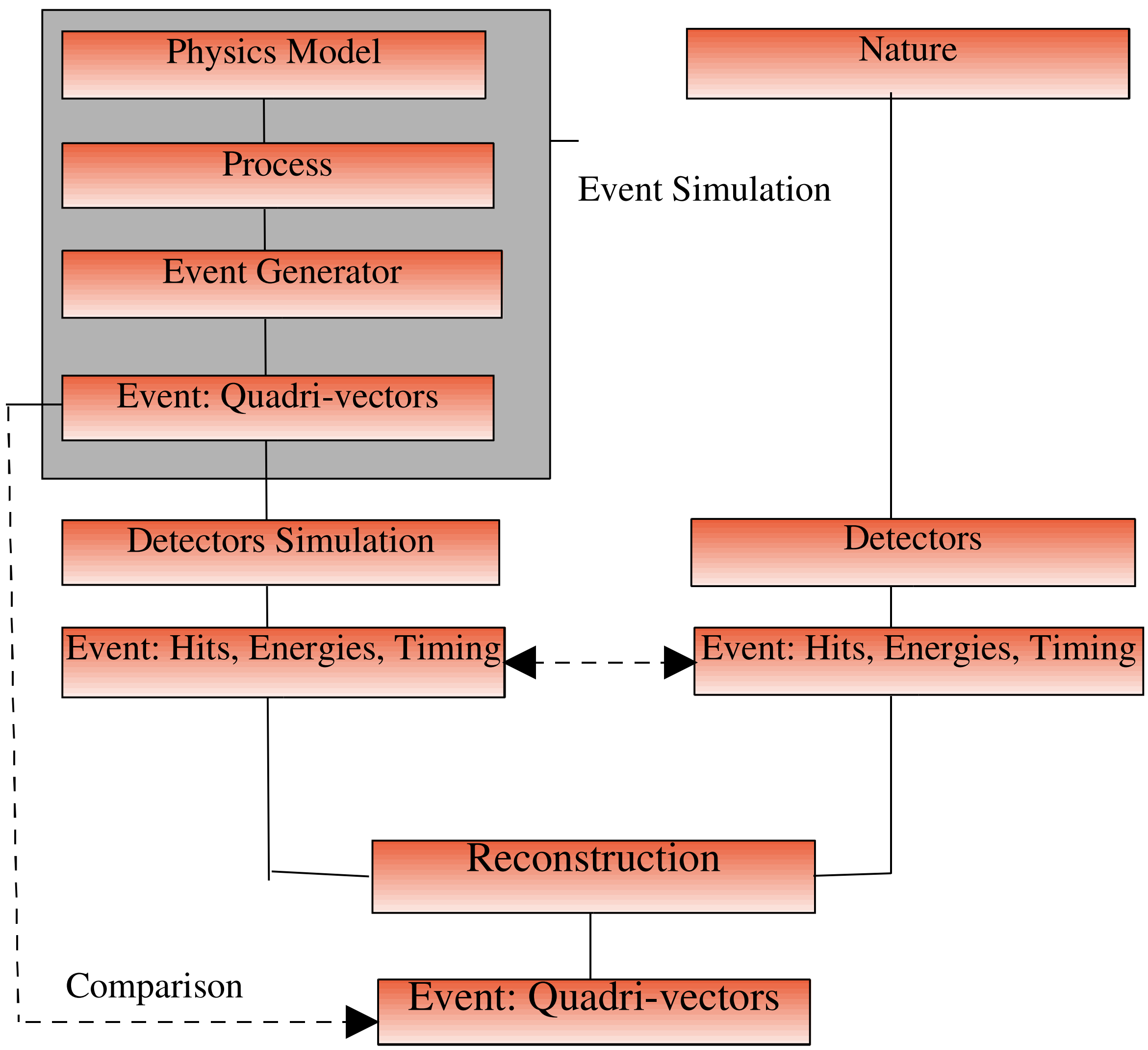


Figure 2: Basic Steps in simulation and data analysis.

## 3. Shortcomings of the Standard Model

The Standard Model does not solve all questions posed to us by nature, and therefore our current understanding of the universe is incomplete. These questions include the question of the origin of mass. We do not yet fully understand why elementary particles have mass, and why their masses differ. Studies at LHC will improve our understanding of gravity which is not explained by the Standard Model.

There is also the question of antimatter. Matter and antimatter are perfect opposites; for each of the basic particles of matter, there exists an antiparticle, with many properties such as electric charge reversed. An electron, for example, has negative charge, whilst its antiparticle, positron, has a positive charge. When matter and antimatter meet, they "annihilate" (mutually destroy each other), and their energy reappears as photons or other particle-antiparticle pairs.
Scientists believe that when the Universe originated, about 15 billions years ago, equal amounts of matter and antimatter were created. In today's Universe though, there is almost no antimatter around (beside production in high energy physics collisions). All of it seems to have disappeared, leaving behind questions: where did the antimatter go? Why did the antimatter not completely annihilate the matter, leaving only energy (photons) in the Universe? This imbalance may be due to the fact that antimatter and matter may not be perfect reflections of each other.

Also there has been extensive evidence of existence of dark matter that we cannot see because it does not interact electromagnetically. The mismatch between the mass required to provide the derived gravitational potential with the observed mass cannot be explained.

## 4. Higgs Theory

The question of origin of mass may be answered by Higgs theory, an idea within the framework of the Standard Model. A British physicist, Peter Higgs, postulated the Higgs theory in the 1960’s. According to Higgs theory, the whole of space is filled with a 'Higgs field', and by interacting with this field, particles acquire their masses. Particles, which interact strongly with the Higgs field, are heavy, whilst those, which interact weakly, are light. The Higgs field has at least one particle associated with it, the Higgs boson. Particles obtain their masses through Higgs mechanism. As particles move through the Higgs field, they cluster around as they interact with the Higgs particle. As the clustering increases, movement decreases and other particles experience difficulty in passing through.

However, there are enormous theoretical difficulties applying the framework of Quantum Field Theory (which Standard Model is an example of) to Higgs. To predict the masses of elementary particles in Quantum Field Theory, the so-called Quantum correction have to be taken into account. The calculated mass of the Higgs Boson is infinite, which is obviously not possible. [5, 7]

## 5. Supersymmetry

There has been much attempt to unify the four fundamental forces into a 'Grand Unified Theory'. A very popular idea suggested by the unification of the forces is called supersymmetry (SUSY). SUSY predicts that for each known particle there is a 'supersymmetric' partner (fig 3).

Particles, in addition to mass and electric charge, have another important property called intrinsic angular momentum (spin). In relation to spin, particles obey two types of statistics. Elements with integer spin (1, 2, 3 etc) are called bosons and they obey Bose-Einstein statistics e.g. lasers. Elements with half integer spin (1/2, 3/2, 5/2 etc) are called fermions and they obey Fermi-Dirac statistics e.g. shell structure of atoms. From angular momentum formalism, it turns out that Quantum Mechanical wave functions for the system of fermions is antisymmetric while systems of bosons have symmetric wave functions. Quantum corrections to Higgs mass from fermions are of opposite sign to those from bosons. Therefore there would be an elegant resolution to the infinite quantum corrections problem if each particle had an identical partner (same mass, same electric charge and so on) with intrinsic angular momentum obeying different statistics. That is, if each fermion had a boson partner and vice versa, quantum corrections divergency would cancel to zero.

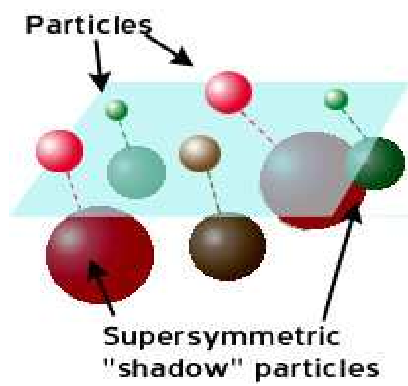


Figure 3: Idea of having Supersymmetric partners.

## 6. Large Hadron Collider (LHC)

Elementary particles are extremely tiny, and to be able to detect them and to study their properties, scientists need very special tools. They need elementary particle accelerators, huge machines able to speed up particles to very high energies before smashing them into other particles. Around the points where the collision occurs, scientists build experiments that allow them to observe and study the collisions. These are instruments made of several kinds of particle detectors. By accelerating and smashing particles, physicists can identify their components or create new particles, revealing the nature of the interactions between them.

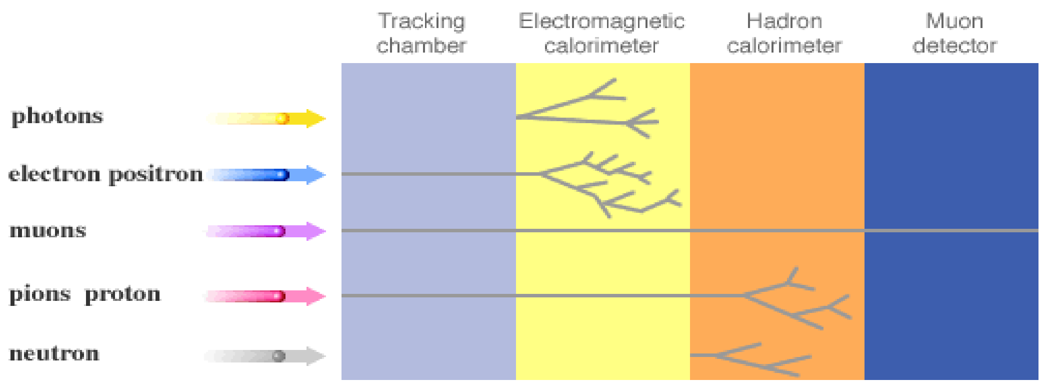


Figure 4: Particle pathways in the Detector Chambers

During the last few decades, many experiments have been designed and carried out to help us answer these questions about fundamental properties of matter and the origin of mass. At present, as mentioned earlier, construction of the Large Hadron Collider (LHC) is being carried out at CERN in Switzerland. The LHC is a particle accelerator which will be the most powerful instrument ever built to investigate on particle properties. At the LHC, two proton beams will be made to collide at certain points. The LHC is designed to recreate the conditions prevailing just after the 'big bang', thereby providing optimum conditions for observing the Higgs boson and SUSY particles if they exist. The dominant mechanism of Higgs production is gluon fusion which are abundant within protons. The LHC will also serve as a very good 'antimatter mirror' to help compare matter and antimatter. [2]

To keep the LHC's proton beams on track requires stronger magnetic fields than ever been used before. This is achieved using superconductive magnets. Superconductivity is the ability of certain materials to conduct electricity almost without resistance or energy loss, usually at very low temperatures. The LHC will operate at about 300 degrees below room temperature. Because the LHC will accelerate two beams moving in opposite directions, it is really two accelerators in one. The LHC will be built in the same tunnel as CERN's Large Electron Positron collider (LEP).

There will be four experiments at the LHC, with huge detectors, which will study the effects of the beam collisions. LHC will also have the most intense beams and the highest energy of all similar experiments. Collisions will happen so fast (800 million times a second) that particles from one collision will often be traveling through the detector when the next collision happens. Often, however, proton collisions would not yield formation of other particles.

Understanding what happens in these collisions is the key to the LHC's success. The four experiments are ATLAS, CMS, ALICE and LHCb. Atlas and CMS will be two general-purpose detectors dedicated to the search for new physics. LHCb is being designed for precision studies of hadrons containing b quarks, in particular looking for CP violation in the b sector, and ALICE will analyze heavy ion collisions and study the properties of quark-gluon plasma, recently discovered at CERN and BNL. [2]

## 7. Detector Mechanism

For each recorded collision, which is called an event, a physicist's goal is to count, trace and characterize all the different particles that were produced and fully reconstruct the process. As mentioned earlier, scientists require particle detectors for this purpose. These consist of many different pieces of equipment, each one able to recognize and measure a special set of particle properties, such as charge, mass and energy. [1]

Tracking chambers (figure 4), for instance, make the path of an electrically charged particle directly visible. The trajectories' of each particle give a lot of useful information, especially if the detector is placed inside a magnetic field: the charge of the particle, for instance, will be obvious since particles with positive electric charge will bend one way and those with negative charge will bend the opposite way. Also the momentum of the particle can be determined: very high momentum particles travel in almost straight lines; low momentum particles make tight spirals. However, more information is necessary to understand the collision and usually tracking devices are complemented by calorimeters. Calorimeters stop and fully absorb most of the particles, providing a measurement of their energy. Muons and neutrinos are often the only particles capable of escaping calorimeters. Muons can hardly be stopped, but at least they can be identified: special muon detectors are located outside the calorimeter, and only muons can emerge and leave a track there. Neutrinos, by contrast, escape and don't even leave a track, going through all the detectors undetected. However, as they are the only known particles that can escape, their presence can be inferred from an imbalance of the initial and final energies of the event.

## 8. Event Generation and Detector Simulation

Assembling all the pieces of information from each track of the detector, physicists can fully characterize each particle, and by arranging all the tracks coming from a collision, they can reconstruct the event with great precision.

Physics modeling, first step in event simulation, is based on material evaluation of probabilities associated with the studied process. Cross-sections, namely event rates, can hence be calculated for any selected process. Event generation produces random events following the statistical distribution deduced from the differential cross-sections.
For a given hard scattering process, the basic steps are as follows: generation of the “Feyman diagrams” involved in the process, construction of the “matrix element” expression which, after being integrated over the phase space, provides the total and different cross-sections in a particular model or theory. Finally, events are randomly generated according to the full differential cross-section as a set of four energy-momentum vectors each associated with one of the final particles. Quarks and gluons do not exist in bare form need to be grouped by 2 or 3 in hadrons. This is called hadronization. ATLAS Monte Carlo simulations have evolved to a point where all known physical processes involving the interaction between particles and matter are included in the simulation.

The subsequent interactions of each particle of a generated event with the various detectors are finely simulated leading to 'raw data' similar to the detector output for real data events. Each part of the detector is represented by a volume so that at any point in time, during the propagation of a particle inside the detector, a pointer gives the type of material the particle is transversing. An interaction with matter can then be triggered according to the known fundamental laws. For example, if the particle is an electron, this can be an ionization or the emission of a photon. Whether the particle is inside of an active part of a detector or not, the contribution will or will not be added to the detector's final signal. So, by following each particle's trajectories inside the detector, the simulation package estimates the energy depositions and timing information (fig 2). These hits are the same for real and simulated data. From all the detector data pieces, it reconstructs the full event and rebuilds the original interaction. By comparing the original simulated events and those that have been reconstructed, one can estimate the accuracy of simulation and the acceptance of the detectors. By comparing the real and simulated data, one can check the validity of the underlying physics model. In principle, any difference between the simulated and the experimental data might signal some new physics, not predicted by the SM: a physics discovery.

At Pittsburgh we carried out simulations on Higgs decay to two photons. Higgs boson decays into two photons at masses less than 150 GeV. This decay channel is very rare. The branching ratio is very small (~ $10^{-3}$) (fig 5). However this channel is expected to be promising due to the excellent resolution of photon energy measurement. [6]
The H--> $\gamma\gamma$ decay has to be observed above a large background of irreducible photon-photon background. The invariant mass distribution of the photon-photon background will vary smoothly across the mass range from 80-120 GeV. A Higgs particle could be discovered as a slight bump on top of a well-understood background.

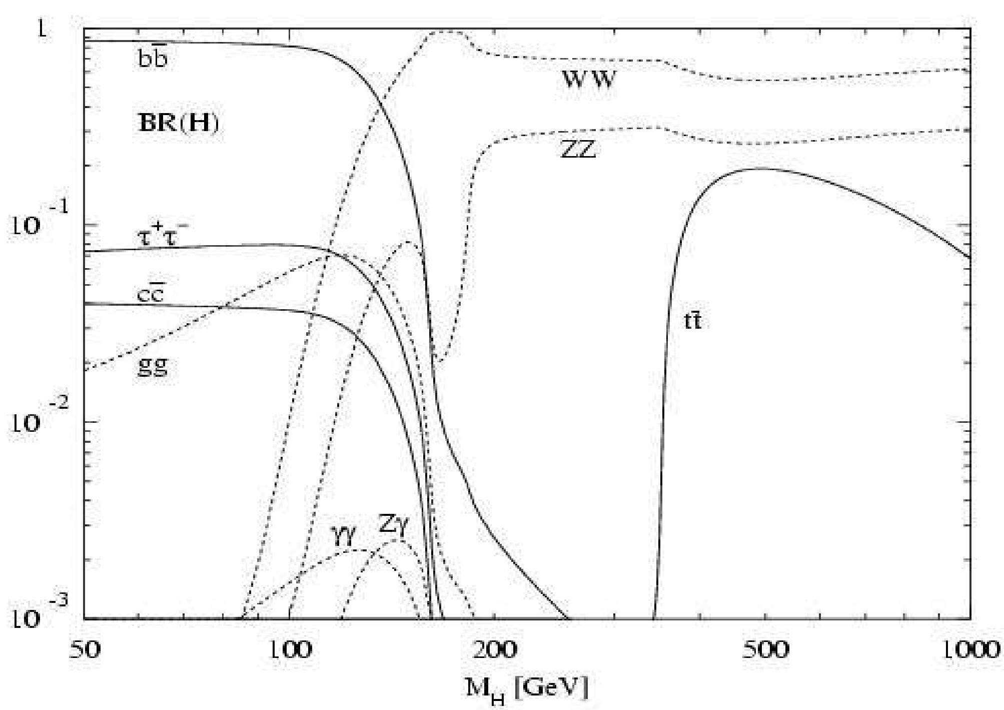


Figure 5: Higgs branching ratios

By specifying event generator parameters, we select certain Higgs production and decay mechanisms. We study light Standard Higgs production via gluon fusion (gg--> $h^0$ ), $Z^0Z^0$ fusion ($f_if_j$ --> $f_i f_j h^0$) and $W^+W^-$ fusion ($f_if_j$ --> $f_kf_lh^0$) ( where f represent fermions). (fig 6).

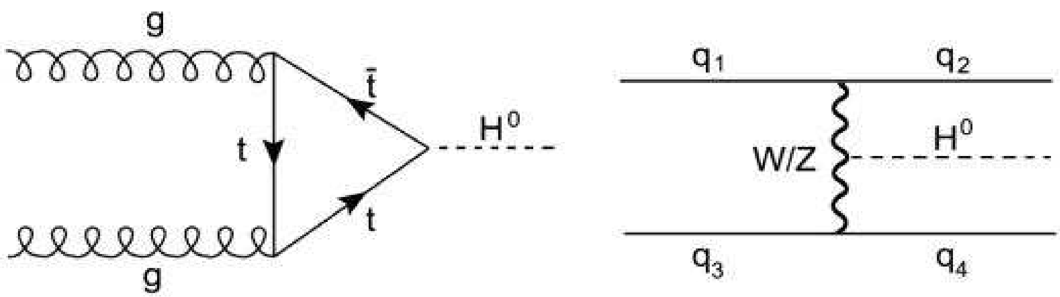


Figure 6 Higgs Production at LHC

Such Higgs would dominantly decay into particles, which are difficult to detect directly. Therefore we must search for Higgs in its decay to stable particles, for example to two photons ($h^0$ --> $\gamma\,\gamma$) (fig 7). The decay is possible through loop processes with either fermions or bosons in the loop.

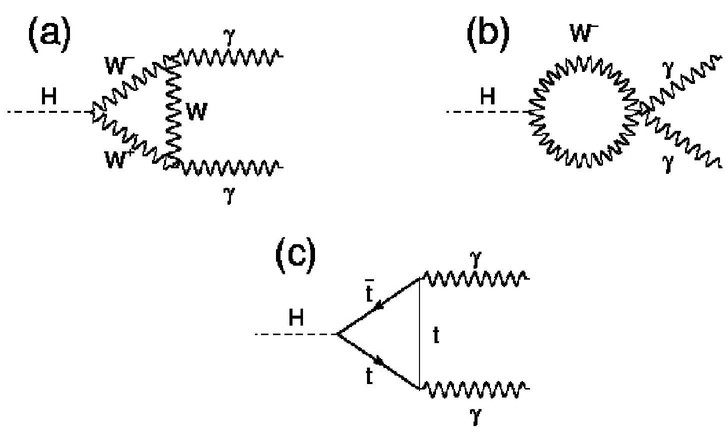


Figure 7: Higgs decay into two photons

Figures 7(a) and 7(c) above, are included in the extended Standard Model. Figure 7(b) includes some characteristics of a SUSY model.

Reconstruction involves calculating invariant mass of photon pairs using the well-known formulas of special relativity.

$$(mc^2)^2 = E^2 - (pc)^2$$

$$m^2 = E^2 - p^2 \quad (c=1)$$

$$m^2 = ( E_1+E_2 )^2 - |( \overline{p_1} + \overline{p_2} )|^2$$

Hence
mass = $\sqrt{}$ ( (Energy of isolated photons)$^2$ - ( X momentum of isolated photons)$^2$ - ( Y momentum of isolated photons)$^2$ - ( Z momentum of isolated photons$^2$) )

In the mass spectrum plot, Higgs should appear as a peak at $m_H$. Direct observation of Higgs would be a direct confirmation of the Higgs theory. Higgs must be observed with a signal larger than five times the error of the background to qualify for a discovery.
That is

Significance, $S = \dfrac{N_S}{\sqrt{N_B}}$ (a simplified definition)

where
$N_S$ = Number of Signal Events
$N_B$ = Number of Background Events.

if $S > 5$ then one can claim a discovery according to the standards accepted among high-energy physics community.

Optimizing two factors can maximize significance, S. First, detectors with better resolution have higher probability to find a signal. Secondly, luminosity is an important factor since number of events increases with luminosity.
An example of how significance is affected by these factors is outlined below.

Let us take two situations with luminosity $L_1$ and $L_2$

$L_1$ $N_S = 40$ => $S = \dfrac{40}{\sqrt{100}} = 4$

$N_B = 100$

$L_2$ where $L_2 = 100\,L_1$

$N_S = 4000$ => $S = \dfrac{4000}{\sqrt{10000}} = \underline{40}$ => DISCOVERY!!!

$N_B = 10000$

Figure 8 below shows how detector resolution would compare to Higgs intrinsic width,

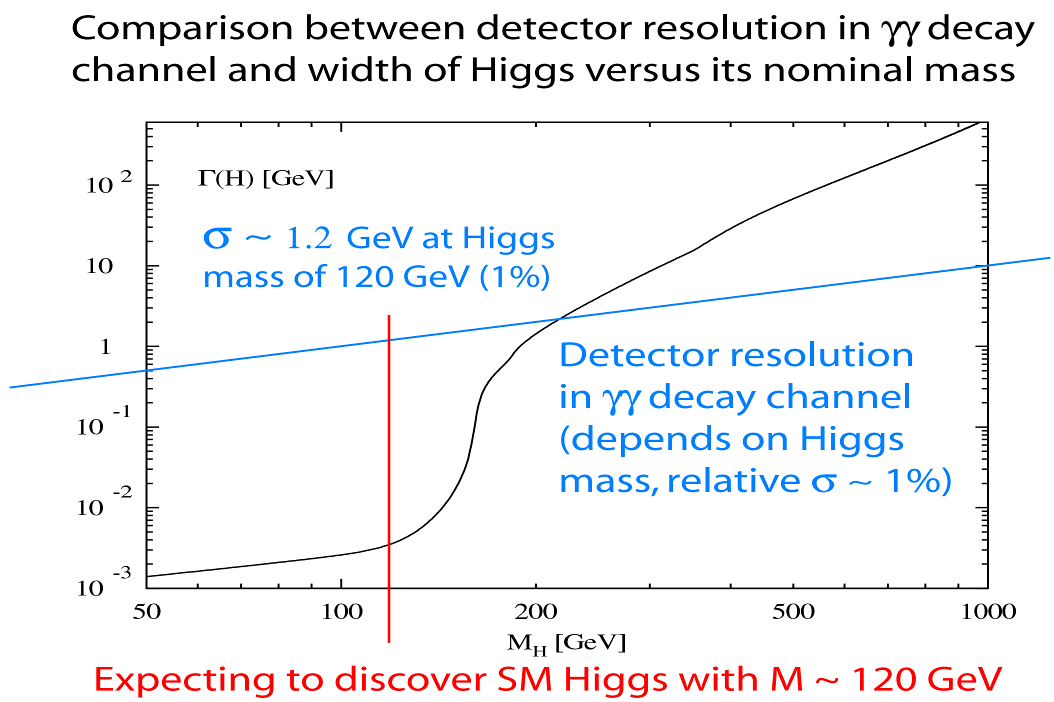


Figure 8: Higgs width compared to detector resolution

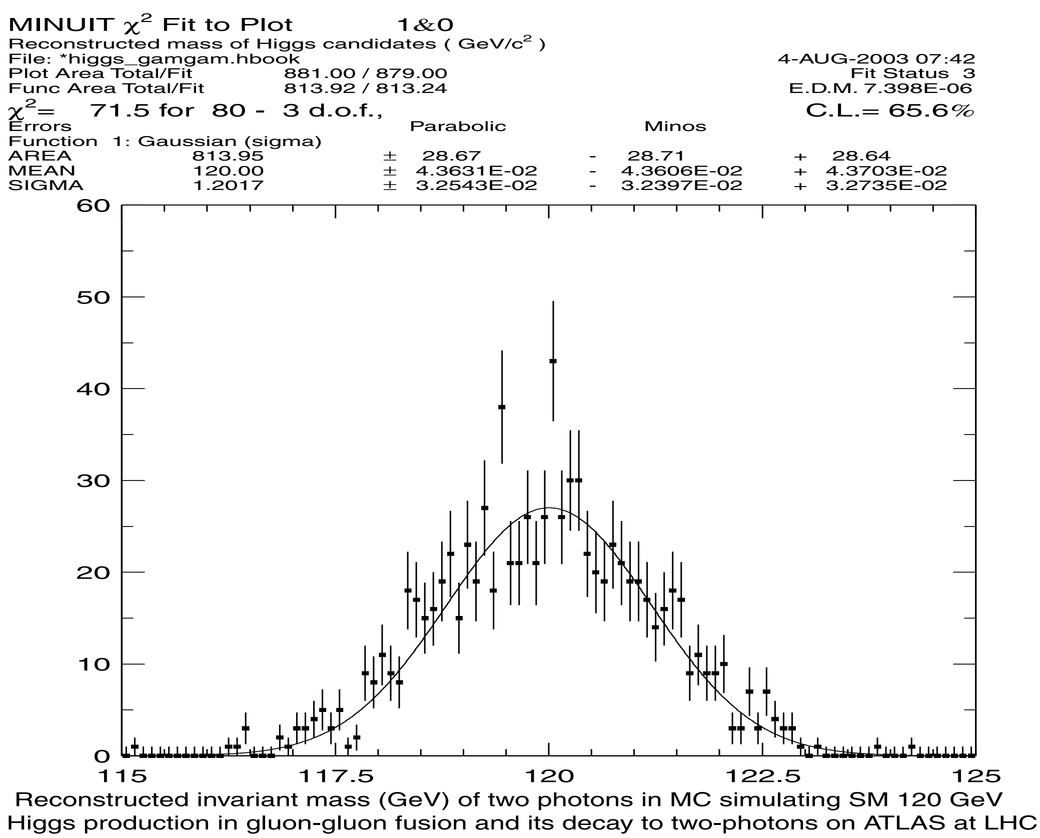


Figure 9: Reconstructed Invariant mass of two photons

Simulations on Blind Analysis Exercise were performed along with Dr. Savinov. In the Blind Analysis Exercise, half a million events were generated with some new physics embedded in it. Monte Carlo information was blanked out and Atlas physicists were asked to find this new physics to try and explore analysis strategies in preparation for real data from the detector.

We first started by searching for a possible Higgs candidate by looking at invariant masses of some of its possible decay products. Plots of masses of two photons, electrons and muons were created. Reconstructed invariant mass of two photons did not have any visible Higgs production. Only small peaks over the background were visible, which were most probably resolution effects of the detector. (figure 9)

Plots of reconstructed invariant masses of two electrons and two muons did not yield any Higgs production either, but there was a clear peak around 90 GeV, which meant that a Z boson was being formed.

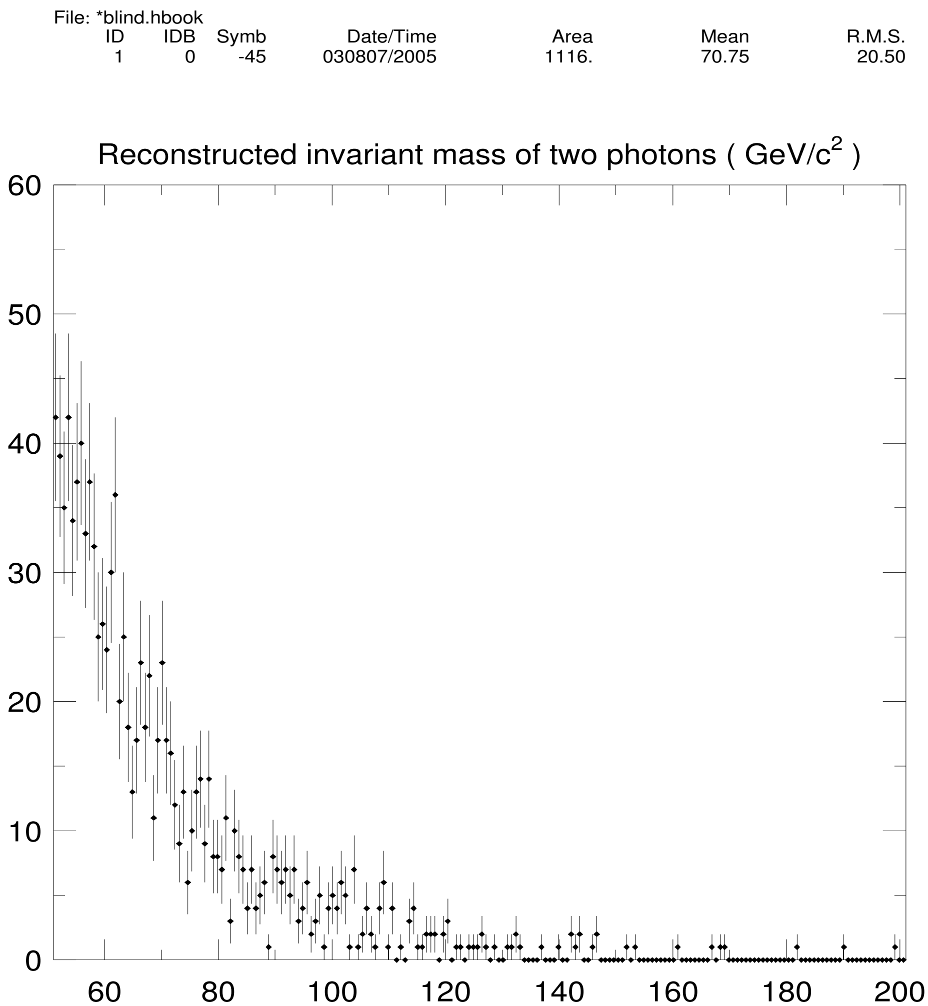


Figure 10 : Reconstructed Invariant mass of two photons (blind analysis sample)

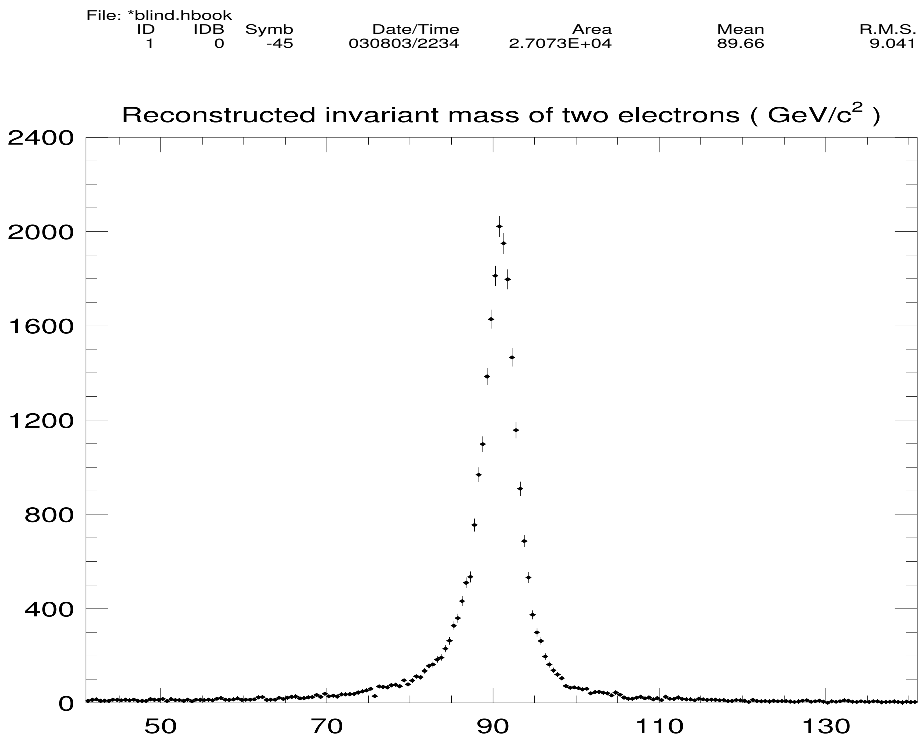


Figure 11 : Reconstructed Invariant mass of two electrons (blind analysis sample)

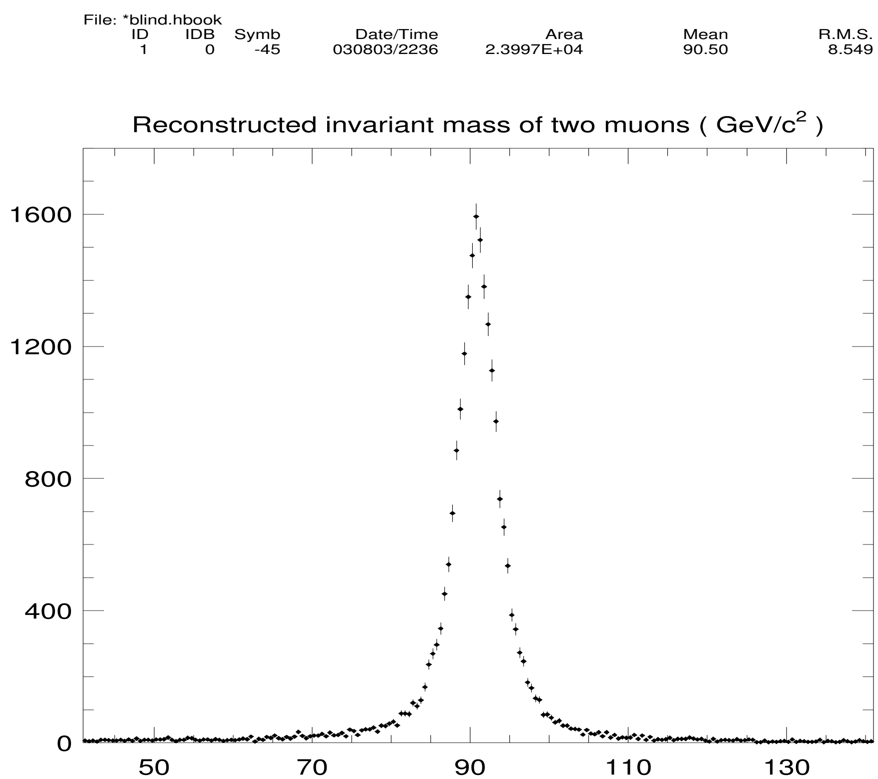


Figure 12 : Reconstructed Invariant mass of two muons (blind analysis sample)

## 9. Future Work

There is now an environment at the University of Pittsburgh to carry out simulations using the various packages available. More refined simulations on Higgs two-photon decay can be carried out in preparation for the real data.


## Acknowledgments

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[8] Jean-Paul Guillard, PYTHA miniguide, http://wwwlapp.in2p3.fr/Pythia.


## Appendix

Please refer to

http://atlas-physics.phyast.pitt.edu/~cernlib
http://atlas-physics.phyast.pitt.edu/~atlas

for installation procedures of simulation packages CERNlib, PAW, ROOT, MN_FIT, ATLFAST and Athena and general information on their usage.