Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

Dark Matter And Super Symmetry: Exploring And Explaining The Universe With Simulations At The LHC

Oliver Gutsche

Scientific Computing Division
Fermi National Accelerator Laboratory
P.O.Box 500
Batavia, IL, 60510, USA

ABSTRACT

The Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, is one of the largest machines on this planet. It is built to smash protons into each other at unprecedented energies to reveal the fundamental constituents of our universe. The 4 detectors at the LHC record multi-Petabyte datasets every year. The scientific analysis of this data requires equally large simulation datasets of the collisions based on the theory of particle physics, the Standard Model. The goal is to verify the validity of the Standard Model or of theories that extend the Model like the concepts of Super Symmetry and an explanation of Dark Matter. I will give an overview of the nature of simulations needed to discover new particles like the Higgs Boson in 2012, and review the different areas where simulations are indispensable: from the actual recording of the collisions to the extraction of scientific results to the conceptual design of improvements to the LHC and its experiments.

1 INTRODUCTION

High Energy Physics (HEP) strives to develop a detailed mathematical understanding of nature at the smallest elementary level. Its science is based on the interplay between the theory framework that describes elementary particles and elementary forces between them; and the experimental detection of particles and measurements of their interactions. It calls for probing nature at ever increasing detail to unlock the last mysteries of our universe.

The theory of particle physics is called the Standard Model and describes the universe through 12 particles and their anti-particles, and 4 fundamental forces represented by their own force particles. Particles are called fermions and have half-integer spins (one of fundamental properties or quantum numbers of particles) and respect the Pauli exclusion principle (not two particles can be identical in all their quantum numbers). There are 12 fermions, separated into 6 leptons (electron, electron neutrino, muon, muon neutrino, tau, tau neutrino), and 6 quarks (up, down, charm, strange, bottom, top). The hydrogen atom consists of an electron orbiting a proton, which consist of 2 up and 1 down quark.

Force particles are bosons with integer spin and describe the fundamental forces: the electro-magnetic force represented by the photon, the weak force represented by the W and Z bosons, the strong force represented by the gluon, and gravitation which is the least known fundamental force and believed to be represented by the graviton, but this is not yet proven.

The Standard Model uses the principles of Quantum Field Theory to mathematically describe particles and their interactions. Today, the Standard Model is very successful in describing matter and their interactions. It took many years and numerous experiments to develop and veify the theory. Although it is therotically self-consistent, it cannot describe gravitation, account for the accelerating expansion of the universe, and cannot incorporate that neutrinos have mass, as proved through the detection of neutrino oscillations. Therefore the field of particle physics is very active in understanding these topics and improve and enhance the Standard Model. The goal is to develop an all-encompassing theory.

2 SIMULATION

The rules of particle physics are governed by quantum physics. Therefore description and predictions of particle physics interactions and phenomena have to deal with probablities and sufficiently large statistics to make meaningful statements. For the experiment, this means that only particle interactions that have been observed in sufficient numbers can be compared to theoretical predictions. Fortunately, experiments are mostly event driven. Individual particle interactions, may they be collisions or otherwise produced, can be treated individually. This makes particle physics a highly parallelizable science.

2.1 EVENT SIMULATION

The empirical calculation of a particle interaction is only possible in approximation and is called event simulation. The problem of describing mathematically a simple collision of two particles producing a different set of two particles at the first and most basic order can be calculated simply by calculating the exchange of a force particle. First one calculates the interaction of the two incoming particles with the force particle (first vertex) and then the interaction of the same force particle with the outgoing second set of two particles (second vertex). But higher order corrections can play a significant role in calculating this collision. There are two kinds of higher order corrections that are important.

The first is extending the number of particles and force particles that are produced and exchanged between the first and second vertex. In particle physics speak, the number of vertices is increased and therefore the order of the calculation increases. The more orders are calculated, the closer the approximation of the calculation to the truth. The first order is called the ”leading order (LO)” and the next following orders are called ”next-to-leader order (NLO)” and ”next-to-next-to-leading order (NNLO)”. NNLO calculations are currently state-of-the-art in particle physics.

The second kind of higher order correction is harder to approximate. These corrections have to do with additional force particles radiated from the incoming and outgoing particles and therefore changing the calculation from above. As there are many possibilities to radiate extra particles with a wide range of possible kinematical parameters (energy, momentum to name a few), a precise or even mathematical approximation is very difficult. Particle physics uses Monte Carlo techniques to tackle these problems. A sufficiently large number of interactions is calculated starting from a randum number seed. Every simulated interaction is using a different randum number seed. The random number is used to choose the composition of the empirical calculation up to the order specified, meaning it chooses randomly how many vertices need to be calculated and what the internal kinematical parameters of these vertices are. Then the random number is used to determine if and how particles are radiated and this is included in the calculation as well. Probability density functions are used to constrain the possibilities that can be chosen. These functions are determined by theory confirmed by experiment or by experiment directly.

The sufficiently large statistics of these simulated interactions allows to make statistically significant statements about the interaction of interest, including kinematic distributions of the final state, through averaging the results. Sufficiently large statistics means that we are covering the phase space of allowed configurations sufficiently that on average we get the correct result.

2.2 DETECTOR SIMULATION

To verify or even extend the theory, experiments and the comparison of experimental results with theoretical predictions are needed. The event simulation step described in Sec. 2.1 is not directly comparable with a potential experimental setup. This is because we can only very few of the particles of the Standard Model produce, control and measure.

Of the leptons, only the electron and muon are stable and observable. The tau is decaying into electrons or muons very quickly and the neutrinos are so weakly interacting that neutrino physics is its own branch in particle physics. The quarks are not observable individually at all. Governed by the strong force and a concept called confinement, quarks can only be observed in 2 or 3 quark bound states. 3 quark bound states are called baryons and the most prominent examples are protons and neutrons. 2 quark bound states are called mesons. Because we also cannot control the initial state of a particle interaction to all extend. We can collide for example protons with protons, which means two 3-quark states are colliding, giving multiple possibilities how a certain quark quark ineraction can be produced. Also these effects can be simulated using Monte Carlo techniques.

The same effect that binds quarks in mesons and baryons also governs the constitution of the final state of an interaction. Because individual quarks cannot exist on their own, quarks that are produced in an interaction hadronize by collecting additional quarks from the vaccum (spontaneous quark anti-quark production following $E = mc\,2$) or from neigbouring quarks in the final state of the interaction. Hadronization is described as well with the help of Monte Carlo techniques using underlying models and theories. The same is true for particles that fragment or decay while transversing a detector material.

Detectors are made of matter and detect particles by interacting with them. Dtectors can consists of a gas that is ionized by particles, or a plastic that produces light when a particle transverses the material, or a semi-conductor in which a current can be measured when a particle is passing through. In simulation, we know the final state of an interaction. We encapsulated all theories and models to describe the enegry depositions of particles in material in a single package that is generally used, also outside particle physics, called Geant. Geant simulates the energy deposition of a particle in material, depending on the type of material, the amount of material and the three-dimensional cmoposition of various materials that make up a detector or detector system.

The last part of the detector simulation step is to translate the energy depositions of the particles simulated by Geant into electrical signals of the used detectors and detector systems. After this step, a simulated interaction and an experimentally measured interaction are equivalent can be treated the same in the following.

2.3 RECONSTRUCTION

The current understanding of nature in the form of the Standard Model is very advanced. New discoveries or improvements require higher and higher energies in the final state of the produced particle interaction. This requires that particle accelerators are becoming more advanced but also more difficult and costly to build and operate. To maximize the variety of investigations of the produced collisions, a complete capture of the final state of the collisions is required. Complicated detector systems that close to hermetically surround the collision regions are built. Different detector techniques are used to measure different aspects of the final states of the collisions. Charged particle tracks are measured with tracking detectors closests to the interaction region. Particle tracks give momentum and direction of charged particles, if the tracking detectors are situated in a magnetif field. Calorimeters are arranged outside the tracking detectors to measure the energy of particles. Muons are very minimally interacting with material. Special muon detectors outside the calorimeters are built to detect the muons.

Software is used to translate the signals and location of the detectors into reconstructed objects that describe particles or jets of particles. Only at this stage, a comparison to simulation can be done and physics results can be extracted.

3 LARGE HADRON COLLIDER AND THE CMS EXPERIMENT

The Large Hadron Collider (LHC) (Evans and Bryant 2008) is the current highest energy particle collider in the world. It accelerates protons to 6.5 TeV energy in two circular evacuated beampipes. The beams of protons are brought to collision in 4 points around the almost 17 miles circumference ring. The interaction rate in a single collision point is 40 MHz. Each of the 4 collision points is instrumented with a large particle physics detector system, two multi-purpose detectors and one detector for heavy quark physics and heavy ion physics each. The two multi-purpose detectors have the same physics program but using different detector technology and analysis strategies. This is needed to cross-check results because a second machine of this size would be too expensive to build. In the following, we will concentrate on ond of the two multi-purpose detectors.

The CMS collaboration built, maintains and operates the CMS detector. CMS stands for ”Compact Muon Solenoid”, describing the main feature of the compact architecture of the detector system and the emphasis on muon detection. In the innermost layer surrounding the coliision region, a silicon pixel detector is detecting charged particle trajectories. Pixel detectors are like a three-dimensional array of digital camera CMOS chips specifically manufactures to withstand the high data rates and radiation backgrounds from particle collisions of the LHC. Pixel detectors have a very good spatial resultion, needed to detect individual particles which have not yet moved apart significantly while traveling outwards after the collision. The pixel tracker is surrounded by a silicon strip tracker which has a more course resolution but covers a lot more volume. Surrounding the tracking systems is the electro-magnetic calorimeter built from lead-tungsten crystals. The crystals are transparent and produce light proportional to the energy of a passing particle. Completing the calorimetry is the hadronic calorimeter, a sandwich of brass and scintillators to stop hadrons and to measure the penetration depth which is proportional of the energy of the hadrons. The tracking and calorimeter systems are surrounded by a superconducting solenoid producing a magnetic field of 3.8T. With its solenoid size of 6 times 13 meters, it is the largest and most powerful magnet of its kind. Completing the CMS detector is the muon detector system surrounding the magnet instrumenting its return yoke.

Not all collisions of the 40 MHz collision rate are being recorded and saved for analysis. Most of the collisions can be identified quickly as un-interesting events where the physics is well understood. Also the total data rate and subsequent data volume would be about 1 PB every minute if all of the collisions are recorded. CMS uses a 2 level trigger system to identify collisions for physics analysis. The first level is implemented in custom-made electronics and reduces the data rate to 100 KHz. All detector components have buffers to allow the level 1 decision to be taken within 3 micro-seconds. For selected events, the signals of all detector components are read out and combined into a single event, which is then passed on to the high level trigger. The high level trigger consists of a dedicated compute farm at the detector pit that performs a streamlined version of the full event reconstruction. The high level triger compute farm is dimensioned to sustain an output rate of 1 kHz and an average reconstruction time per event of 200 milliseconds, currently amounting to 22k compute cores. A trigger decision is taken according to the reconstructed information and the events are sent for offline processing, storage and analysis.

Simulations are used in all stages of designing and maintaining the trigger. Starting from the physics program, first and high level trigger selections are designed to maximize interesting events that have the potential to improve the Standard Model or find new physics not yet described by the Standard Model. These selections are then optimized to fit within the latencies of the trigger levels and the timing is checked. Constant feedback from the actual data recording is needed to improve the trigger simulation and the event selection for physics.

4 PHYSICS WITH THE CMS EXPERIMENT

There are two main thrusts in particle physics, improving the Standard Model and its predictive power and finding physics that is not yet described by the Standard Model. The latter category of physics Beyond the Standard Model (BSM) would allow to solve question about the composition of the universe and the existence of the concept of the grand unified theory (GUT). It is known from cosmological observations that the universe consists only to about 4% of ordinary matter as the Standard Model describes. About 20% is assumed to be Dark Matter, matter that does not interact electr-magnetically, and about 75% is assumed to be Dark Energy. Dark Matter particles would be invisible and therefore not detectable in particle physics detectors. But theories predict that at LHC collision energies, Dark Matter particles can be produced under certain circumstances and would manifest themselves in deviations from the Standard Model. The same is true for the concept of Supersymmetry, which doubles the elementary particles to give every particle its super-partner. Supersymmetry would solve the fine-tuning problem in the Standard Model and would also allow for all three forces, electr-magnetic, weak and strong, to unify at high energies and be described by the same simple mathematical construct. This would bring us closer to the Grand Unified Theory of particle physics. Supersymmetric particles would also be a good candidate for Dark Matter.

In all cases the comparison of exeprimental observation to the preductions of the Standard Model are crucial to find deviations. These deviations can then be interpreted in the context of theoretical models like Dark Matter or Supersymmetry and probabilities can be assigned to deviation being compatible with certain theories.

In the case of the Higgs Boson discovery in 2012, theory predicted a number of final states where the new particle was most likely to be found. One of them was the 4-lepton final state. Measuring 4-lepton events and indentifying and supressing as much as possible already known interactions predicted by the Standard Model, a peak was discovered that could not be explained by the Standard Model. But adding a Higgs Boson with a mass of about 125 GeV allowed the data to be described by the simulation. The statistical significance of the description exceeded 5 sigma and the signal qualified for the discovery of a Higgs Boson at 125 GeV. Simulations played a crucial role in this discovery.

5 The FUTURE: HIGH-LUMINOSITY LHC

ACKNOWLEDGMENTS

Place the acknowledgments section, if needed, after the main text, but before any appendices and the references. The section heading is not numbered. These instructions are adapted from instructions that have been updated and improved by proceedings editors and several other individuals, who are too numerous to name separately (our apologies, but it is necessary), since the first set of instructions were written by Barry Nelson for the 1991 WSC.

REFERENCES

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AUTHOR BIOGRAPHIES

Oliver Gutsche is a staff scientist at the Fermi National Accelerator Laboratory and member of the CMS collaboration of 2,500 physicists, which is operating one of the 4 detectors at the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. After the Higgs Boson discovery in 2012, his research is focusing on new physics beyond the established theory of particle physics called the Standard Model, especially in the areas of Super Symmetry and Dark Matter. In his role as Assistant Head of the Scientific Computing Division, Dr. Gutsche coordinates the computing needs of the High Energy, Neutrino and Muon Particle Physics experiments at the laboratory. He has intimate knowledge of the large scale computing solutions used for the LHC experiments to analyze multi-Petabyte size datasets on distributed computing infrastructures of many 100,000 cores, having architected many of the used systems and leading the computing operations team of CMS during the first running period of the LHC. His email address is gutsche@fnal.gov.