Using Machine Learning Techniques for Data Quality Monitoring at CMS Experiment

by

Guillermo A. Fidalgo Rodríguez

A thesis presented for the degree of

BACHELLOR’S OF SCIENCE??

in

Physics

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2018

Approved by:

______________________________ ____________________
Sudhir Malik, Ph.D. Date
President, Graduate Committee

______________________________ ____________________
Héctor Méndez, Ph.D. Date
Member, Graduate Committee

______________________________ ____________________
Samuel Santana Colón, Ph.D. Date
Member, Graduate Committee

______________________________ ____________________
Rafael A. Rámos, Ph.D. Date
Chairperson of the Department

Abstract

The Data Quality Monitoring (DQM) of CMS is a key asset to deliver high-quality data for physics analysis and it is used both in the online and offline environment. The current paradigm of the quality assessment is labor intensive and it is based on the scrutiny of a large number of histograms by detector experts comparing them with a reference. This project aims at applying recent progress in Machine Learning techniques to the automation of the DQM scrutiny. In particular the use of convolutional neural networks to spot problems in the acquired data is presented with particular attention to semi-supervised models (e.g. autoencoders) to define a classification strategy that doesn't assume previous knowledge of failure modes. Real data from the hadron calorimeter of CMS are used to demonstrate the effectiveness of the proposed approach.

Keywords: [DQM, online, offline, Machine Learning]

Acknowledgments

I wish to thank United States State Department and University of Michigan for providing the opportunity to work abroad at CERN during the 2018 Winter Semester. I also wish to thank CERN staff, CMS Experiment , Texas Tech University, and the University of Puerto Rico at Mayagüez, with special thanks to Dr. Federico de Guio for his local mentorship and Dr. Nural Akchurin, and Dr. Sudhir Malik for their guidance. A very special thanks to Dr. Jean Krisch for accepting me for this great research opportunity and Dr. Steven Goldfarb for being a wonderful host and overall local guidance at CERN.

List of Figures

Contents

Chapter 1

Introduction

The work for this thesis was performed at CERN on CMS Experiment. CERN stands for European Organization for Nuclear Research. It was founded in 1954 and is located at the Franco-Swiss border near Geneva. At CERN, physicists and engineers are probing the fundamental structure of the universe. They use the world's largest and most complex scientific instruments to study the basic constituents of matter – the fundamental particles. The instruments used at CERN are purpose-built particle accelerators and detectors. Accelerators boost beams of particles to high energies before the beams are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions. The accelerator at CERN is called the Large Hadron Collider (LHC), the largest machine ever built by humans and it collides particles (protons) at close to the speed of light. The process gives the physicists clues about how the particles interact, and provides insights into the fundamental laws of nature. Seven experiments at the LHC use detectors to analyze particles produced by proton-proton collisions. The biggest of these experiments, ATLAS and CMS, use general-purpose detectors designed to study the fundamental nature of matter and fundamental forces and to look for new physics or evidence of particles that are beyond the Standard Model. Having two independently designed detectors is vital for cross-confirmation of any new discoveries made. The other two major detectors ALICE and LHCb, respectively, study a state of matter that was present just moments after the Big Bang and preponderance of matter than antimatter. Each experiment does important research that is key to understanding the universe that surrounds and makes us.

Chapter 2 presents a basic description of the Large Hadron Collider and CMS Detector

?? gives a brief motivation

?? is dedicated to a study optimizing

?? ptimated.

?? details an improvarger production cross-section than Z+jets process used before.

The conclusions and results of each chapter are presented in the corresponding chapter.

This thesis work has been presented at several internal meetings of the CMS Experiment and at the following international meetings and conferences:

1. **Andrés Abreu** gave a talk "***Estimation of the Z Invisible Background for Searches for Supersymmetry in the All-Hadronic Channel***" at "APS April 2018: American Physical Society April Meeting 2018, 14-17 Apr 2018", Columbus, OH

2. **Andrés Abreu** gave a talk "***Phase-2 Pixel upgrade simulations***" at the "USLUA Annual meeting: 2017 US LHC Users Association Meeting, 1-3 Nov 2017", Fermilab, Batavia, IL

Chapter 2

The CMS Experiment

The Compact Muon Solenoid (CMS) detector is a general purpose particle detector designed to investigate various physical phenomena concerning the SM and beyond it, such as Supersymmetry, Extra Dimensions and Dark Matter. As its name implies, the detector is a solenoid which is constructed around a superconducting magnet capable of producing a magnetic field of 3.8 T. The magnetic coil is 13m long with an inner diameter of 6m, making it the largest superconducting magnet ever constructed. The CMS detector itself is 21m long with a diameter of 15m and it has a weight of approximately 14,000 tons. The CMS experiment is one of the largest scientific collaborations in the history of mankind with over 4,000 participants from 42 countries and 182 institutions. CMS is located at one of these points and it essentially acts as a giant super highspeed camera that makes 3D images of the collisions that are produced at a rate of 40 MHz (40 million times per second). The detector has an onion-like structure to capture all the particles that are produced in these high energy collisions most of them being unstable and decaying further to stable particles that are detected. CMS detector was designed with the following features (as shown in Figure 2.1) :

1. A **magnet** with large bending power and high performance muon detector for good muon identification and momentum resolution over a wide range of momenta and angles.

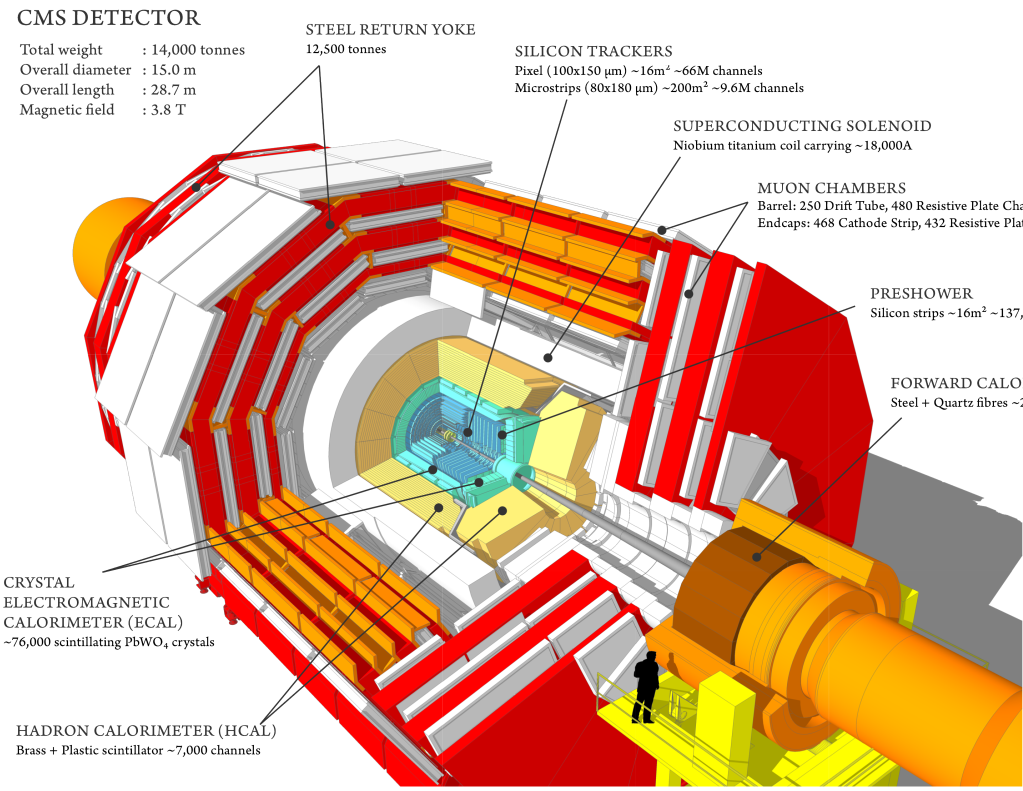

Figure 2.1: CMS Detector

2. An **inner tracking system** capable of high reconstruction efficiency and momentum resolution requiring **pixel detectors** close to the interaction region.

3. An **electromagnetic calorimeter** able to provide good electromagnetic energy resolution and a high isolation efficiency for photons and leptons.

4. A **hadron calorimeter** capable of providing precise missing-transverse-energy and dijet-mass resolution.

A property from these particles that is exploited is their charge. Normally, particles produced in collisions travel in a straight line, but in the presence of a magnetic field, their paths are skewed and curved. Except the muon system, the rest of the subdetectors lie inside a 3.8 Tesla magnetic field . Due to the magnetic field the trajectory of charged particle produced in the collisions gets curved (as shown in Figure **??**) and one can calculate the particle's momentum and know the type of charge on the particle. The Tracking devices are responsible for drawing the trajectory of the particles by using a

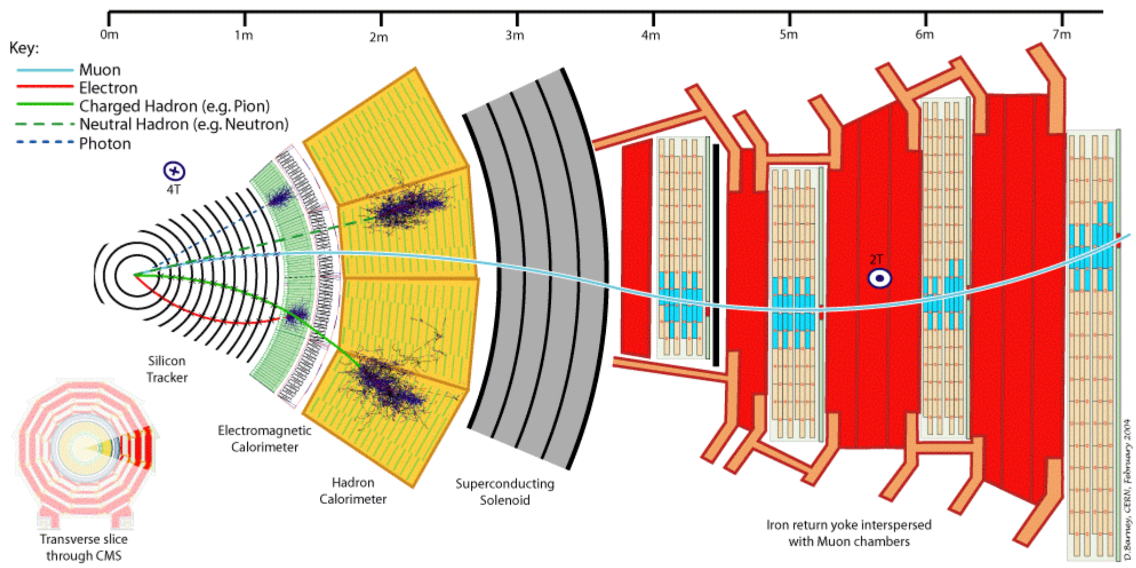

Figure 2.2: The trajectory of a particle traveling through the layers of the detector leaving behind a it's signature footprint

computer program that reconstructs the path by using electrical signals that are left by the particle as they move. The Calorimeters measure the energy of particles that pass through them by absorbing their energy with the intent of stopping them. The particle identification detectors work by detecting radiation emitted by charged particles and using this information they can measure the speed, momentum, and mass of a particle. After the information is put together to make the "snapshot" of the collision one looks for results that do not fit the current theories or models in order to look for new physics.

2.1 Supersymmetric extension of the Standard Model

The supersymmetry theories are based on a symmetry between fermions and bosons. It is similar to solving the 'electron mass hierarchy problem' in quantum mechanics, where the number of particles is doubled: in addition to the electron, there is also a positron. The virtual electron–positron contributions solved the problem of electrons having a small mass by smearing out the electric charge. Supersymmetry is an analogous theory where once again the set of particles is doubled, and in doing so the loop contributions of one particle to the Higgs are cancelled by the loop contributions of its super-partner. It extends space-time symmetry since it relates matter particles to force particles. It relates particles with different spins but the same gauge charges.Figure ??

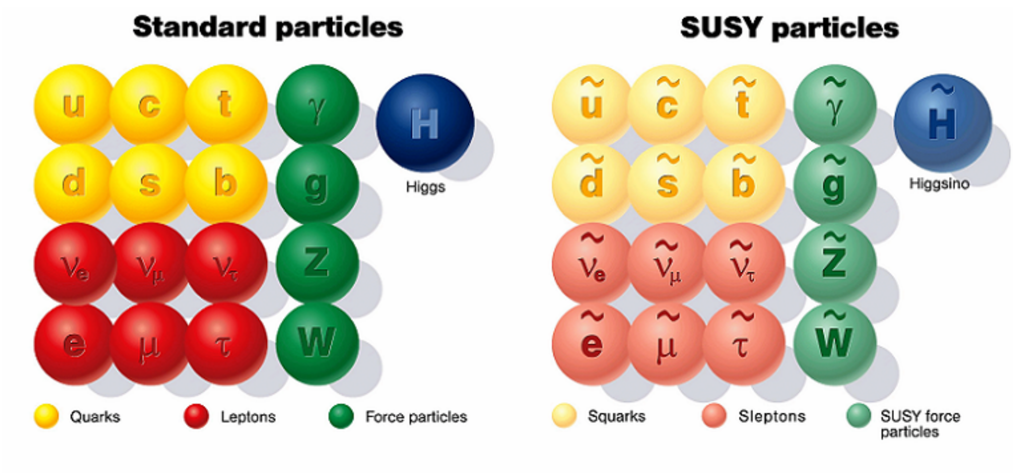

Figure 2.3: Schematic representation of the Standard Model particles with the added SUSY particles.

The gluon (QCD) has a fermionic partner, the gluino. Similarly, the spin 1 gauge bosons W+, W0, W- and B^0 have their counterparts, called winos and binos, that, after electroweak symmetry breaking, mix to give the mass eigenstate Z^0 and γ, and the zino and photino respectively. For every lepton/quark there is a bosonic partner (i.e. a scalar slepton/squark). There are three families for each of the quark and lepton supermultiplets. The left-handed and right-handed pieces of the squarks and sleptons are two separate components, as in the corresponding SM sector. The Higgs doublet is extended by another doublet leading to other Higgs boson particles (Higgsinos).

Even though supersymmetry solves many problems in particle physics, it also poses new problems. If these new particles had the same mass as their counterparts in the standard model, we would have already observed them. Since none of these particles have been found yet, SUSY must be a broken symmetry. What makes superpartners heavier than ordinary particles? Why are superpartners so well hidden in rare phenomena? This arbitrary mass spectrum for the superpartners would have effects that are far too large in rare processes that change the flavor of particles. There must be some special reason why such effects are well hidden. How do we extract information on the mechanism of supersymmetry breaking? How does supersymmetry impact cosmology? Is the lightest supersymmetric partner what really composes Dark Matter? Different mechanisms have been suggested on how this symmetry is broken and have led to different phenomenological scenarios like the minimal supergravity model (mSUGRA) [9, 10], the gauge-mediated supersymmetry breaking (GMSB) [11–13] model or R-parity [14, 15]. A discussion of mSUGRA and GMSB is beyond the scope of this dissertation. R-parity is a new symmetry that has been added to the minimal supersymmetry scenario which prevents the violation of the leptonic and baryonic numbers. All SM fields have even R-parity, while SUSY particles have odd R-parity. The most obvious experimental constraint comes from the non-observation of proton decay [16], which would violate both baryonic and leptonic number conservation. Due to R-parity every interaction vertex in the theory involves an even number of sparticles, meaning that they must be pair-produced. The decay chains of the produced particles are characterized by the presence of one stable particle, generically called the Lightest Supersymmetric Particle (LSP), that may account for all the dark matter in the Universe. However, in other models, like the R-parity violating SUSY this may not apply. In other scenarios, those LSP can be regarded as vanishing mass and may not be enough to satisfy the dark matter in the Universe.

2.1.1 Simplified Models Approach to Supersymmetry

Simplified models [17] are a new approach for characterizing LHC supersymmetry results. In a simplified model only a few new particles and a single decay topology are introduced, and hence these models are easy to constrain. Traditionally, testing a particle physics theory against experimental results requires calculating what the theory predicts in an experimental situation using a particle accelerator detector. This translates into computing: the masses of new particles, their decay widths, their branching ratios and production cross-sections. This information is subsequently used in Monte Carlo simulations of passage of proton-proton collisions products and their decays through the CMS detector. This is done under the hypothesis that the theory is true. The simulated data is analyzed just like the actual experimental data resulting from proton-proton collisions.

The theoretical and the experimental results can then be compared. Though conceptually uncomplicated it requires access to the experimental data, and the step of simulating the detector response requires intimate knowledge of the CMS detector by theorist community. It is also restrictive being model/theory dependent. The CMS collaboration, like ATLAS, does not share experimental details but only the final results via publications. The Simplified Model approach circumvents this issue by presenting results on very simple phenomenological models instead of a specific model, such as the constrained MSSM (cMSSM) [18]. Each simplified models encompasses a specific phenomenological feature that is common to many different theories. A limited set of hypothetical particles and decay chains are introduced to produce a given topological signature. The amplitudes describing the production and decays of these particles are parametrized in terms of the particle masses and their branching ratios to daughter particles. This makes the analysis of simplified models less model dependent. The Simplified Models assume that a particular decay signature can be realized without specifying the exact mechanism, offering the possibility to overcome small branching ratios. Some Simplified Models with their corresponding production and decay modes are shown in the Table 2.1. We have used T2tt, T1tttt, T1ttbb, T5tttt and T5ttcc models in analysis in this thesis. Some of these topologies are further discussed in more detail in **??**, since they correspond to some of the signals for SUSY in the treated analysis.

Model name	Production mode	Decay	Visibility
T1	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to q\bar{q}\widetilde{\chi}_{LSP}$	All-Hadronic
T2	$\widetilde{q}\,\widetilde{q}^{\,*}$	$\widetilde{q} \to q\widetilde{\chi}_{LSP}$	All-Hadronic
T5zz	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to q\bar{q}\widetilde{\chi}^0_2, \widetilde{\chi}^0_2 \to Z\widetilde{\chi}_{LSP}$	All-Hadronic Opposite-Sign Dileptons Multileptons
T3w	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to q\bar{q}\widetilde{\chi}_{LSP}$ $\widetilde{g} \to q\bar{q}\widetilde{\chi}^{\pm}_1, \widetilde{\chi}^{\pm}_1 \to W^{\pm}\widetilde{\chi}_{LSP}$	Single Lepton + Jets
T5lnu	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to q\bar{q}\widetilde{\chi}^{\pm}_1, \widetilde{\chi}^{\pm}_1 \to \ell\nu\widetilde{\chi}_{LSP}$	Same-Sign Dileptons
T3lh	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to q\bar{q}\widetilde{\chi}_{LSP}$ $\widetilde{g} \to q\bar{q}\widetilde{\chi}^0_2, \widetilde{\chi}^0_2 \to \ell^+\ell^-\widetilde{\chi}_{LSP}$	Opposite-Sign Dileptons
T1bbbb	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to b\bar{b}\widetilde{\chi}_{LSP}$	All-Hadronic (b)
T1tttt	$\widetilde{g}\widetilde{g}$	$\widetilde{g} \to t\bar{t}\widetilde{\chi}_{LSP}$	All-Hadronic (b) Single Lepton + Jets (b) Same-Sign Dileptons (b) Inclusive (b)
T2bb	$\widetilde{b}\,\widetilde{b}^*$	$\widetilde{b} \to b\widetilde{\chi}_{LSP}$	All-Hadronic (b)
T6ttww	$\widetilde{b}\,\widetilde{b}^*$	$\widetilde{b} \to t\widetilde{\chi}^-, \widetilde{\chi}^- \to W^-\widetilde{\chi}_{LSP}$	Same-Sign Dileptons (b)
T2tt	$\widetilde{t}\,\widetilde{t}^*$	$\widetilde{t} \to t\widetilde{\chi}_{LSP}$	All-Hadronic (b)

Table 2.1: Some Simplified Models with their corresponding production and decay modes.

Appendix A

Appendix Title

Appendix B

References

[1] C. Lefevre, "The CERN accelerator complex. Complexe des accelerateurs du CERN." Available on the CERN document server, Dec 2008.

[2] T. Sakuma and T. McCauley, "Detector and Event Visualization with SketchUp at the CMS Experiment," *J. Phys. Conf. Ser.*, vol. 513, p. 022032, 2014. doi:10.1088/1742-6596/513/2/022032.

[3] S. Spannagel, *CMS Pixel Detector Upgrade and Top Quark Pole Mass Determination*, vol. 27. Springer, 2017. doi:10.1007/978-3-319-58880-3.

[4] CMS Collaboration, "CMS Physics Technical Design Report Volume 1: Detector Performance and Software," Technical Design Report CERN-LHCC-2006-001, CERN (2006).

[5] CMS Collaboration, "The CMS Experiment at the CERN LHC," *JINST*, vol. 3, p. S08004, 2008. doi:10.1088/1748-0221/3/08/S08004.

[6] CMS Collaboration, "Performance of the CMS Hadron Calorimeter with Cosmic Ray Muons and LHC Beam Data," *JINST*, vol. 5, p. T03012, 2010. doi:10.1088/1748-0221/5/03/T03012.

[7] J. Nielsen, "Fundamentals of LHC Experiments," in *Proceedings, Theoretical Advanced Study Institute in Elementary Particle Physics (TASI 2010). String Theory*

and Its Applications: From meV to the Planck Scale: Boulder, Colorado, USA, June 1-25, 2010, pp. 127–152, 2011. arXiv:1106.2516.

[8] C. Borschensky, M. Kramer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn, and X. Portell, "Squark and gluino production cross sections in pp collisions at $\sqrt{s}$ = 13, 14, 33 and 100 TeV," *Eur. Phys. J.*, vol. C74, no. 12, p. 3174, 2014. doi:10.1140/epjc/s10052-014-3174-y.

[9] S. Ferrara, R. Kallosh, A. Linde, and M. Porrati, "Minimal Supergravity Models of Inflation," *Phys. Rev.*, vol. D88, no. 8, p. 085038, 2013. doi:10.1103/PhysRevD.88.085038.

[10] A. B. Lahanas and D. V. Nanopoulos, "The Road to No Scale Supergravity," *Phys. Rept.*, vol. 145, p. 1, 1987. doi:10.1016/0370-1573(87)90034-2.

[11] G. F. Giudice and R. Rattazzi, "Theories with gauge mediated supersymmetry breaking," *Phys. Rept.*, vol. 322, pp. 419–499, 1999. doi:10.1016/S0370-1573(99)00042-3.

[12] S. P. Martin and J. D. Wells, "Implications of gauge-mediated supersymmetry breaking with vector-like quarks and a 125 GeV Higgs boson," *Phys. Rev.*, vol. D86, p. 035017, 2012. doi:10.1103/PhysRevD.86.035017.

[13] R. Barbieri and G. F. Giudice, "Upper Bounds on Supersymmetric Particle Masses," *Nucl. Phys.*, vol. B306, pp. 63–76, 1988. doi:10.1016/0550-3213(88)90171-X.

[14] R. Barbieri *et al.*, "R-parity violating supersymmetry," *Phys. Rept.*, vol. 420, pp. 1–202, 2005. doi:10.1016/j.physrep.2005.08.006.

[15] D. Dercks, H. Dreiner, M. E. Krauss, T. Opferkuch, and A. Reinert, "R-Parity Violation at the LHC," *Eur. Phys. J.*, vol. C77, no. 12, p. 856, 2017. doi:10.1140/epjc/s10052-017-5414-4.

[16] P. Langacker, "Grand Unified Theories and Proton Decay," *Phys. Rept.*, vol. 72, p. 185, 1981. doi:10.1016/0370-1573(81)90059-4.

[17] CMS Collaboration, "Interpretation of Searches for Supersymmetry with simplified Models," *Phys. Rev.*, vol. D88, no. 5, p. 052017, 2013. doi:10.1103/PhysRevD.88.052017.

[18] P. Bechtle *et al.*, "Killing the cMSSM softly," *PoS*, vol. EPS-HEP2015, p. 139, 2015. doi:10.22323/1.234.0139.

[19] L. Evans and P. Bryant, "LHC Machine," *JINST*, vol. 3, p. S08001, 2008. doi:10.1088/1748-0221/3/08/S08001.

[20] R. Rosenfeld, "Physics Beyond the Standard Model," in *Proceedings, 8th CERN–Latin-American School of High-Energy Physics (CLASHEP2015): Ibarra, Ecuador, March 05-17, 2015*, pp. 159–164, 2016. doi:10.5170/CERN-2016-005.159.

[21] N. Doble, L. Gatignon, K. Hübner, and E. Wilson, *The Super Proton Synchrotron (SPS): A Tale of Two Lives*, pp. 135–177. World Scientific Publishing Co, 2017.

[22] ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST*, vol. 3, p. S08003, 2008. doi:10.1088/1748-0221/3/08/S08003.

[23] LHCb Collaboration, "The LHCb Detector at the LHC," *JINST*, vol. 3, p. S08005, 2008. doi:10.1088/1748-0221/3/08/S08005.

[24] K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC," *JINST*, vol. 3, p. S08002, 2008. doi:10.1088/1748-0221/3/08/S08002.

[25] K. Garrett and G. Duda, "Dark Matter: A Primer," *Adv. Astron.*, vol. 2011, p. 968283, 2011. doi:10.1155/2011/968283.

[26] R. C. G. Landim, *Dark Sector Cosmology*. PhD thesis, Sao Paulo U., 2017. arXiv:1702.06024.

[27] K. W. Bell *et al.*, "Vacuum phototriodes for the CMS electromagnetic calorimeter endcap," *IEEE Trans. Nucl. Sci.*, vol. 51, pp. 2284–2287, 2004. doi:10.1109/TNS.2004.836053.

[28] H. Bichsel, D. E. Groom, and S. R. Klein, "Passage of particles through matter," 2004.

[29] CMS Collaboration, "Alignment of the CMS Muon System with Cosmic-Ray and Beam-Halo Muons," *JINST*, vol. 5, p. T03020, 2010. doi:10.1088/1748-0221/5/03/T03020.

[30] "Muon Detectors." `http://cms.web.cern.ch/news/muon-detectors`. Accessed: 2018-04-08.

[31] A. Tapper and D. Acosta, "CMS Technical Design Report for the Level-1 Trigger Upgrade," 2013.

[32] W. Adam *et al.*, "The CMS high level trigger," *Eur. Phys. J.*, vol. C46, pp. 605–667, 2006. doi:10.1140/epjc/s2006-02495-8.

[33] F. Beaudette, *The CMS Particle Flow Algorithm*, 2013.

[34] A. K. Nayak, "Reconstruction of physics objects in the CMS detector," *PoS*, vol. CHARGED2012, p. 010, 2012.

[35] CMS Collaboration, "CMS: The computing project. Technical design report," Technical Design Report CERN-LHCC-2005-023, CERN (2005).

[36] R. Brun and F. Rademakers, "ROOT: An object oriented data analysis framework," *Nucl. Instrum. Meth.*, vol. A389, pp. 81–86, 1997. doi:10.1016/S0168-9002(97)00048-X.

[37] M. Lipinski, "The Phase-1 upgrade of the CMS pixel detector," *JINST*, vol. 12, no. 07, p. C07009, 2017. doi:10.1088/1748-0221/12/07/C07009.

[38] G. Apollinari, I. Bejar Alonso, O. Bruning, M. Lamont, and L. Rossi, "High-Luminosity Large Hadron Collider (HL-LHC) : Preliminary Design Report," 2015. doi:10.5170/CERN-2015-005.

[39] D. Contardo, M. Klute, J. Mans, L. Silvestris, and J. Butler, “Technical Proposal for the Phase-II Upgrade of the CMS Detector,” 2015. CMS-TDR-15-02.

[40] J. Pilot, “Future of the CMS Muon System: Upgrades and Aging,” *PoS*, vol. ICHEP2016, p. 281, 2016. doi:10.22323/1.282.0281.

[41] K. Klein, “The Phase-2 Upgrade of the CMS Tracker,” 2017. CMS-TDR-014.

[42] S. Mersi, “Phase-2 Upgrade of the CMS Tracker,” *Nucl. Part. Phys. Proc.*, vol. 273-275, pp. 1034–1041, 2016. doi:10.1016/j.nuclphysbps.2015.09.162.

[43] C. Foudas, A. Rose, J. Jones, and G. Hall, “A Study for a tracking trigger at first level for CMS at SLHC,” in *Proceedings, eleventh Workshop on Electronics for LHC and Future Experiments, Heidelberg, Germany, 12-16 September 2005*, p. 90, 2005. arXiv:physics/0510227.

[44] N. De Maio, G. Bianchi, S. Martina, Z. Drasal, G. Hugo, and S. Mersi. http://tklayout.web.cern.ch.

[45] CMS Collaboration, “Search for supersymmetry in proton-proton collisions at 13 tev using identified top quarks,” *Phys. Rev. D*, vol. 97, p. 012007, Jan 2018. doi:10.1103/PhysRevD.97.012007.

[46] H. E. Haber and L. Stephenson Haskins, “Supersymmetric Theory and Models,” in *Theoretical Advanced Study Institute in Elementary Particle Physics: Anticipating the Next Discoveries in Particle Physics (TASI 2016) Boulder, CO, USA, June 6-July 1, 2016*, 2017. arXiv:1712.05926.

[47] M. Cacciari, G. P. Salam, and G. Soyez, “The Anti-k(t) jet clustering algorithm,” *JHEP*, vol. 04, p. 063, 2008. doi:10.1088/1126-6708/2008/04/063.

[48] CMS Collaboration, “A Cambridge-Aachen (C-A) based Jet Algorithm for boosted top-jet tagging,” 2009.

[49] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft Drop,” *JHEP*, vol. 05, p. 146, 2014. doi:10.1007/JHEP05(2014)146.

[50] L. Breiman, “Random Forests,” *Machine Learning*, vol. 45, no. 1, pp. 5–32, 2001. doi:10.1023/A:1010933404324.

[51] T. Junk, “Confidence level computation for combining searches with small statistics,” *Nucl. Instrum. Meth.*, vol. A434, pp. 435–443, 1999. doi:10.1016/S0168-9002(99)00498-2.

[52] A. L. Read, “Presentation of search results: The CL(s) technique,” *J. Phys.*, vol. G28, pp. 2693–2704, 2002. [,11(2002)], doi:10.1088/0954-3899/28/10/313.

[53] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics,” *Eur. Phys. J.*, vol. C71, p. 1554, 2011. [Erratum: Eur. Phys. J.C73,2501(2013)], doi:10.1140/epjc/s10052-013-2501-z.

[54] CMS Collaboration, “CMS Luminosity Measurements for the 2016 Data Taking Period,” Tech. Rep. CMS-PAS-LUM-17-001, CERN, Geneva, 2017. CMS-PAS-LUM-17-001.

[55] CMS Collaboration, “Comparison of the Z/γ^* + jets to γ + jets cross sections in pp collisions at $\sqrt{s} = 8$ TeV,” *JHEP*, vol. 10, p. 128, 2015. [Erratum: JHEP04,010(2016)], doi:10.1007/JHEP04(2016)010, doi:10.1007/JHEP10(2015)128.

[56] CMS Collaboration, “Search for supersymmetry in the multijet and missing transverse momentum final state in pp collisions at 13 TeV,” *Phys. Lett.*, vol. B758, pp. 152–180, 2016. doi:10.1016/j.physletb.2016.05.002.

[57] CMS Collaboration, “Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV,” *Phys. Rev.*, vol. D96, no. 3, p. 032003, 2017. doi:10.1103/PhysRevD.96.032003.

[58] "Data-Driven Estimation of the Invisible Z Background to the SUSY MET Plus Jets Search," 2009. CMS-PAS-SUS-08-002.

[59] F. Micheli, "Cut Based Photon ID for Run 2." `https://twiki.cern.ch/twiki/bin/viewauth/CMS/CutBasedPhotonIdentificationRun2`. Accessed: 2018-01-27.

[60] J. Berryhill, "Electron Detection at CMS." The Egamma Physics Object Group, 2009. ppt.

[61] CMS Collaboration, "Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at sqrt(s) = 8 TeV," *JINST*, vol. 10, no. 08, p. P08010, 2015. doi:10.1088/1748-0221/10/08/P08010.

[62] A. M. Sirunyan *et al.*, "Particle-flow reconstruction and global event description with the CMS detector," *JINST*, vol. 12, no. 10, p. P10003, 2017. doi:10.1088/1748-0221/12/10/P10003.

[63] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaitre, A. Mertens, and M. Selvaggi, "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," *JHEP*, vol. 02, p. 057, 2014. doi:10.1007/JHEP02(2014)057.

[64] M. Klasen, C. Klein-Bosing, and H. Poppenborg, "Prompt photon production and photon-jet correlations at the LHC," *JHEP*, vol. 03, p. 081, 2018. doi:10.1007/JHEP03(2018)081.

[65] S. Folgueras, "Baseline muon selections for Run-II." `https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideMuonIdRun2`. Accessed: 2018-05-13.

[66] CMS Collaboration, "Measurement of the Z/gamma*+jets/photon+jets cross section ratio in pp collisions at sqrt(s)=8 TeV," 2014. CMS-PAS-SMP-14-005.