Suche nach Elektroweakinos mit dem ATLAS Detektor

Ludwig-Maximilians-Universität München
Fakultät für Physik

Dissertation

Eric Schanet

April 2021

Supervisor: PD Dr. Jeanette Lorenz

Abstract

Despite the success of the Standard Model of Particle Physics, a number of hints suggest the existence of new physics beyond the scope of phenomena that can be explained in the theoretical framework of the Standard Model. One class of theories that could be able to explain some of the open questions of the Standard Model is Supersymmetry. It introduces supersymmetric partners to each of the Standard Model particles and could for example provide a candidate for Dark Matter.

This thesis presents a search for electroweak production of supersymmetric particles in events with one lepton, missing transverse momentum and a Higgs boson decaying into two b-jets. The search uses $139\,\mathrm{fb}^{-1}$ of proton–proton collision data at a centre-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$ recorded by the ATLAS detector. A two-dimensional shape-fit is introduced in order to achieve sensitivity to a large variety of kinematic regimes. No significant deviation from the Standard Model predictions are seen in data in any of the search regions. The results are subsequently interpreted in a simplified model for electroweakino pair-production. Lightest chargino and next-to-lightest neutralino masses of $740\,\mathrm{GeV}$ ($600\,\mathrm{GeV}$) can be excluded for lightest neutralino masses of $\lesssim 100\,\mathrm{GeV}$ ($\approx 250\,\mathrm{GeV}$), significantly improving the limits set by previous ATLAS searches for Supersymmetry.

Given that today's particle physics experiments are not easily reproducible and a large number of phenomenologically viable models for physics beyond the Standard Model exist, special focus is put on the reusability and reinterpretability of the search. The full likelihood of the search is made publicly available and a fully reusable implementation of the search using containerised workflows parameterised job templates is provided. In light of conceptually interesting but computationally challenging reinterpretations in high-dimensional parameter spaces, a method for generically approximating the likelihoods of searches for Supersymmetry is introduced and validated. Using this approach, a reinterpretation of the search in a class of more complete supersymmetric models is performed and its results are discussed.

Zusammenfassung

Obwohl das Standardmodell der Teilchenphysik eine außerordentlich erfolgreiche Theorie darstellt, weisen einige Beobachtungen auf die Existenz neuer Physik jenseits dessen was im Rahmen des Standardmodells erklärt werden kann hin. Supersymmetrie ist der Oberbegriff für eine Klasse von Theorien, die einige der offenen Fragen des Standardmodells erklären könnte. Sie sagt die Existenz von supersymmetrischen Partnern für jedes Teilchen des Standardmodells voraus und könnte, unter anderem, einen Teilchenkandidaten für dunkle Materie liefern.

Diese Arbeit stellt eine Suche nach supersymmetrischen Teilchen die über die elektroschwache Wechselwirkung paar-produziert werden vor. Die Suche untersucht Endzustände mit einem Lepton, fehlender Transversalenergie und einem Higgs Boson welches in zwei b-Jets zerfällt. Insgesamt werden $139\,\mathrm{fb}^{-1}$ an Daten aus Proton-Proton Kollisionen berücksichtigt, welche mit dem ATLAS Detektor bei einer Schwerpunktsenergie von $\sqrt{s} = 13\,\mathrm{TeV}$ im Run 2 des Large Hadron Colliders aufgezeichnet wurden. Ein zwei-dimensionaler Shape-Fit wird eingeführt um hohe Sensitivität zu möglichst vielen kinematischen Bereichen im Parameterraum zu gewährleisten. Keine signifikante Abweichung von den Standardmodellvorhersagen wird in den Daten beobachtet. Die Ergebnisse werden deshalb in einem vereinfachten Modell für Paar-Produktion von Elektroweakinos interpretiert. Leichteste Charginos und zweitleichteste Neutralinos mit Massen bis zu $740\,\mathrm{GeV}$ ($600\,\mathrm{GeV}$) können für leichteste Neutralino Massen von $\lesssim 100\,\mathrm{GeV}$ ($\approx 250\,\mathrm{GeV}$) ausgeschlossen werden. Die Ausschlussgrenzen vorheriger ATLAS Suchen nach Supersymmetrie werden signifikant verbessert.

Da heutige Teilchenphysik-Experimente aufgrund ihrer Komplexität und Größenordnung nicht trivial reproduzierbar sind, gleichzeitig aber eine Vielzahl an Modellen für Physik jenseits des Standardmodells existiert, wird ein besonderes Augenmerk auf die technische Durchführbarkeit gelegt, die Suche zu in neuen Modellen zu interpretieren. Das volle statistische Modell der Suche wird veröffentlicht und eine vollständig reproduzierbare Implementierung der Suche anhand Container-Technologie und parametrisierter Job-Vorlagen wird diskutiert. Mit Hinblick auf rechenintensive Reinterpretationen in hoch-dimensionalen Parameterräumen wird eine Methode eingeführt um die statistischen Modelle von Suchen nach Supersymmetrie generisch zu approximieren. Mit Hilfe dieser Methode wird schlussendlich eine Reinterpretation der Suche in einer Klasse von realistischen supersymmetrischen Modellen durchgeführt und deren Ergebnisse diskutiert.

Introduction

Particle physics studies the fundamental constituents and interactions of matter with the goal of uncovering the laws of nature that ultimately govern the most fundamental building blocks of the universe. Over the course of more than a century, fundamental physics has continuously pushed the intellectual frontier to new realms, reaching ever-smaller length-scales on which the fundamental interactions of the building blocks of matter can be understood. The resulting theoretical framework, the Standard Model of Particle Physics (SM), provides answers to some of the deepest questions that can be asked about the universe and is the most fundamental—experimentally confirmed—description of nature known to date.

Particle physics finds itself, however, at an interesting crossroad. On the hand, the SM is extraordinarily successful in describing nature at its smallest scales and—with the discovery of the Higgs boson in 2012—has recently been completed. Through various particle physics experiments, the precision and predictive power of the SM has been tested to an unprecedented level, finding no significant deviations in experimental data. On the other hand, however, various cosmological and astrophysical observations are putting increasing pressure on the SM. Although the existence of dark matter (DM) is nowadays well-established, it cannot be suitably described within the theoretical framework of the SM. It has become increasingly clear, that the SM is an effective theory and thus only an approximation to a more fundamental theory of nature.

A plethora of theories aiming to explain the shortcomings of the SM exist. One class of such theories is Supersymmetry (SUSY), extending the SM by associating supersymmetric partners to the SM particles. SUSY could, for example, be able to provide a candidate particle for DM or serve as a basis for a coherent theory describing all four known fundamental forces. Up until the discovery of the Higgs boson, particle physics was in a state of *symbiosis* where the theory and experimental communities showed each other where to look and what to think about next. Particle physics always had a clear pathway to follow: validate and complete the SM. This is, however, no longer the case and experimental particle physics faces an era where a large number of models for physics beyond the Standard Model (BSM) that need to be investigated are constantly being devised by the theory community with no clear indication on where to start looking.

Although theoretical arguments suggest supersymmetric particles could exist at the energies accessible with the Large Hadron Collider (LHC), no such particles have been found so far. Up until recently, searches for SUSY have however mostly focused on the production of the supersymmetric partners of quarks and gluons through the strong interaction. With the second run of the LHC recently come to an end, an unprecedented amount of collision data has been recorded by the LHC experiments and is available for physics analysis. This allows to search for supersymmetric particles produced through the electroweak interaction that have previously not been accessible due to their low theoretical production rates compared to those produced through the strong interaction.

Due to their complexity and lifetimes approaching half a century, experiments like the ATLAS detector at the LHC severely challenge the scientific method as they are in general not easily repeatable. This precarious situation, coupled with the ever-changing landscape of promising BSM models developed by the theory community, requires efforts to not only preserve searches for BSM physics, but make them fully re-usable in the context of new, promising BSM models.

This thesis presents a search for the supersymmetric partners of the SM Higgs and gauge bosons, collectively referred to as *electroweakinos*. The search uses $139\,\mathrm{fb}^{-1}$ of proton–proton collision data recorded at a centre-of-mass energy of $13\,\mathrm{TeV}$ using the ATLAS detector. The search is embedded in a larger effort within the ATLAS collaboration searching for SUSY using a variety of theoretical models. The thesis is divided into four main parts. In part I, the fundamental concepts necessary for the remainder of the thesis are presented. This includes a theoretical introduction to the SM and SUSY, followed by a description of the experimental setup, concluding with a discussion of the statistical concepts used. Part II introduces the aforementioned search for electroweakinos and discusses its results using $139\,\mathrm{fb}^{-1}$ of data recorded by ATLAS. In part III, preservation and re-usability efforts are presented, aiming to significantly increase the scientific impact of the search by making it readily available to re-interpretation efforts inside as well as outside of the ATLAS collaboration. Additionally, a method for approximating the statistical models of SUSY searches is introduced and discussed, followed by a re-interpretation in a high-dimensional parameter space containing complex SUSY scenarios. Finally, the thesis concludes with a brief summary in part IV.

Part I

Fundamental concepts

Part II

The 1-lepton analysis

Part III

Reinterpretation

Part IV

Summary and Outlook

Chapter 12

Conclusions

This thesis presented a search for direct production of electroweakinos in events with one lepton, missing transverse momentum and a Higgs boson decaying into two b-jets. The full dataset LHC Run 2 dataset of $139\,\mathrm{fb}^{-1}$ of pp collisions recorded at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector was analysed. The search targets a simplified $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production model with subsequent decays into W and Higgs bosons together with two $\tilde{\chi}_1^0$. Branching fractions of 100% are assumed in each branch. While the two $\tilde{\chi}_1^0$ completely escape the detector, resulting in significant amounts of missing transverse momentum that can be triggered on, the search targets a W boson decay into a lepton–neutrino pair and a Higgs boson decay into a b-jet pair.

The b-jet pair offers a powerful discriminative handle as its invariant mass, $m_{b\bar{b}}$, shows a characteristic peak around the Higgs boson mass. In order to achieve sensitivity to a maximum variety of kinematic regimes, nine search regions are defined, optimised using a dedicated optimisation procedure. All search regions are situated on the Higgs boson mass peak and are designed to be mutually exclusive through their requirements on the transverse mass, m_{T}, and the contransverse mass, m_{CT}. A single likelihood is constructed, statistically combining all search regions into a two-dimensional shape-fit that exploits the varying shapes of the SUSY signal and SM background processes. Contributions from SM background processes in the search regions are estimated either using dedicated control regions and transfer factors, or directly from Monte Carlo (MC) simulation normalised to their theoretical cross section. A combined likelihood containing terms for all control and signal regions including all systematic uncertainties considered was constructed and fit to data.

No significant excess was found in any of the search regions, and hence limits on the model parameters are set. Due to the introduction of the two-dimensional shape-fit and the unprecedented amount of $139\,\mathrm{fb}^{-1}$ of data analysed, the limits set by previous searches targeting the same simplified model can be significantly extended. For a light lightest supersymmetric particle (LSP), $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses up to $740\,\mathrm{GeV}$ can be excluded at 95% CL. In the case of a heavier LSP with $m(\tilde{\chi}_1^0) \approx 250\,\mathrm{GeV}$, the limits on the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses weaken to about $600\,\mathrm{GeV}$. At the time of writing, the limits obtained by this search represent the most stringent constraints on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production set by ATLAS in the context of the simplified model considered [243].

The absence of physics beyond the Standard Model in the full Run 2 dataset of the LHC in the search presented herein, is in line with the results of other SUSY searches performed by ATLAS. The existence of gluinos and squarks at the TeV-scale was already severely challenged by the end of Run 1 of the LHC. Due to the large integrated luminosity available through the full Run 2 dataset and the improved analysis techniques and strategies developed over the last years, the typically weaker limits on electroweakinos and sleptons are also significantly increasing and in some cases approach the 1 TeV mark.

Given these constraints, one might be tempted to discard the existence of SUSY at the LHC altogether. Such conclusions would, however, be drawn much too early. On the one hand, only a fraction of the total integrated luminosity the LHC is designed to deliver is available. By the end of the its lifetime (including the high-luminosity upgrade), a projected amount of $3000\,\mathrm{fb}^{-1}$ [244] will have been delivered to the particle physics experiments by the LHC. A multitude of supersymmetric models not accessible with the full Run 2 dataset using today's analyses will only come into reach in the coming years of the LHC. On the other hand, and more importantly in the context of this thesis, most limits derived by SUSY searches assume specific simplified models and are thus only valid in the context of models satisfying the respective simplified model assumptions. In any realistic SUSY scenario, assumptions like 100% branching fractions or only a small set of supersymmetric particles not kinematically decoupled are most likely not exactly fulfilled. Thus, the quoted simplified model limits can in general not be trivially interpreted as the true underlying constraint on the respective parameter of a more realistic SUSY scenario. The true constraints on supersymmetric model parameters will in general be weaker than the limits frequently quoted.

Due to the rapidly changing landscape of models for physics beyond the SM, and the limited scope of parameter limits quoted by the experiments, re-interpretations of searches for supersymmetry are highly desirable and see significant interest from both the experimental as well as theory communities. With this in mind, the search for SUSY presented herein was implemented to be fully re-usable and re-interpretable in the light of new BSM models. This is achieved using a cyber-infrastructure called Recast [247], relying on containerised workflows orchestrating parametrised job templates. Additionally, the full likelihood of the search was made publicly available in `JSON` format, allowing it to be incorporated in re-interpretation efforts like SModelS [256, 257] and MadAnalysis5 [262, 263].

Large-scale re-interpretations using high-dimensional parameter spaces are especially interesting as they include complex SUSY models producing more realistic scenarios than the usual simplified models. Such re-interpretations are, however, computationally extremely challenging and require approximations to make them computationally feasible. In this thesis, a method to generically approximate the full likelihoods of SUSY searches was introduced and validated using a selection of ATLAS SUSY searches. The search previously presented was then re-interpreted in the phenomenological Minimal Supersymmetric Standard Model (pMSSM), a 19-dimensional parameter space containing realistic SUSY scenarios. Due to the assumption of 100% branching fractions not being satisfied in many more realistic SUSY scenarios, the sensitivity of the 1ℓ search was found to be significantly reduced but a small fraction of models could still be excluded. The impact of the 1ℓ search on electroweakino masses was investigated, revealing some sensitivity to $\tilde{\chi}_2^{\pm}\tilde{\chi}_2^0$ production in addition to sensitivity towards models phenomenologically close to the simplified model initially considered. The impact of the 1ℓ search on the DM relic density was also investigated. While no conclusive statement could be made for models with a bino-like $\tilde{\chi}_1^0$ due to the limited number of such models sampled in the relevant parameter space, some models with a wino-like $\tilde{\chi}_1^0$ with the right relic density could be excluded.

Although hopes of quickly finding supersymmetric particles with the LHC have not materialised, there is still a possibility of finding hints for physics beyond the SM with LHC experiments. Considerable regions of the parameter space of realistic SUSY scenarios are still largely unconstrained and offer ample space for SUSY to hide in. In order to provide a comprehensive overview of the constrained parameter space, it is crucial to design searches for Supersymmetry to be systematically re-interpretable, especially in light of complete and realistic SUSY scenarios. Searches for BSM physics are the tools that shine a light on the otherwise dark landscape that are the parameter spaces of BSM theories. Allowing these tools to be re-usable significantly increases the area of parameter space they can shine a light onto.

Part V

Appendix

Abbreviations

BSM beyond the Standard Model. 1, 2, 170, 171

DM dark matter. 1, 170

LHC Large Hadron Collider. 1, 2, 169–171

LSP lightest supersymmetric particle. 169

MC Monte Carlo. 169

pMSSM phenomenological Minimal Supersymmetric Standard Model. 170

SM Standard Model of Particle Physics. 1, 2, 169–171

SUSY Supersymmetry. 1, 2, 169–171

Bibliography

[1] I. C. Brock and T. Schorner-Sadenius, *Physics at the terascale*. Wiley, Weinheim, 2011. https://cds.cern.ch/record/1354959.

[2] M. E. Peskin and D. V. Schroeder, *An Introduction to quantum field theory*. Addison-Wesley, Reading, USA, 1995. http://www.slac.stanford.edu/~mpeskin/QFT.html.

[3] S. P. Martin, "A Supersymmetry primer," `arXiv:hep-ph/9709356 [hep-ph]`. [Adv. Ser. Direct. High Energy Phys.18,1(1998)].

[4] M. Bustamante, L. Cieri, and J. Ellis, "Beyond the Standard Model for Montaneros," in *5th CERN - Latin American School of High-Energy Physics*. 11, 2009. `arXiv:0911.4409 [hep-ph]`.

[5] L. Brown, *The Birth of particle physics*. Cambridge University Press, Cambridge Cambridgeshire New York, 1986.

[6] P. J. Mohr, D. B. Newell, and B. N. Taylor, "CODATA Recommended Values of the Fundamental Physical Constants: 2014," *Rev. Mod. Phys.* **88** no. 3, (2016) 035009, `arXiv:1507.07956 [physics.atom-ph]`.

[7] P. D. Group, "Review of Particle Physics," *Progress of Theoretical and Experimental Physics* **2020** no. 8, (08, 2020) , `https://academic.oup.com/ptep/article-pdf/2020/8/083C01/34673722/ptaa104.pdf`. https://doi.org/10.1093/ptep/ptaa104. 083C01.

[8] **Super-Kamiokande** Collaboration, Y. Fukuda *et al.*, "Evidence for oscillation of atmospheric neutrinos," *Phys. Rev. Lett.* **81** (1998) 1562–1567, `arXiv:hep-ex/9807003 [hep-ex]`.

[9] Z. Maki, M. Nakagawa, and S. Sakata, "Remarks on the unified model of elementary particles," *Prog. Theor. Phys.* **28** (1962) 870–880. [,34(1962)].

[10] N. Cabibbo, "Unitary symmetry and leptonic decays," *Phys. Rev. Lett.* **10** (Jun, 1963) 531–533. https://link.aps.org/doi/10.1103/PhysRevLett.10.531.

[11] M. Kobayashi and T. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interaction," *Prog. Theor. Phys.* **49** (1973) 652–657.

[12] E. Noether and M. A. Tavel, "Invariant variation problems," `arXiv:physics/0503066`.

[13] J. C. Ward, "An identity in quantum electrodynamics," *Phys. Rev.* **78** (Apr, 1950) 182–182. https://link.aps.org/doi/10.1103/PhysRev.78.182.

[14] Y. Takahashi, "On the generalized ward identity," *Il Nuovo Cimento (1955-1965)* **6** no. 2, (Aug, 1957) 371–375. https://doi.org/10.1007/BF02832514.

[15] G. 'tHooft, "Renormalization of massless yang-mills fields," *Nuclear Physics B* **33** no. 1, (1971) 173 – 199. http://www.sciencedirect.com/science/article/pii/0550321371903956.

[16] J. Taylor, "Ward identities and charge renormalization of the yang-mills field," *Nuclear Physics B* **33** no. 2, (1971) 436 – 444. http://www.sciencedirect.com/science/article/pii/0550321371902975.

[17] A. A. Slavnov, "Ward identities in gauge theories," *Theoretical and Mathematical Physics* **10** no. 2, (Feb, 1972) 99–104. https://doi.org/10.1007/BF01090719.

[18] C. N. Yang and R. L. Mills, "Conservation of isotopic spin and isotopic gauge invariance," *Phys. Rev.* **96** (Oct, 1954) 191–195. https://link.aps.org/doi/10.1103/PhysRev.96.191.

[19] K. G. Wilson, "Confinement of quarks," *Phys. Rev. D* **10** (Oct, 1974) 2445–2459. https://link.aps.org/doi/10.1103/PhysRevD.10.2445.

[20] T. DeGrand and C. DeTar, *Lattice Methods for Quantum Chromodynamics*. World Scientific, Singapore, 2006. https://cds.cern.ch/record/1055545.

[21] S. L. Glashow, "Partial-symmetries of weak interactions," *Nuclear Physics* **22** no. 4, (1961) 579 – 588. http://www.sciencedirect.com/science/article/pii/0029558261904692.

[22] S. Weinberg, "A model of leptons," *Phys. Rev. Lett.* **19** (Nov, 1967) 1264–1266. https://link.aps.org/doi/10.1103/PhysRevLett.19.1264.

[23] A. Salam and J. C. Ward, "Weak and electromagnetic interactions," *Il Nuovo Cimento (1955-1965)* **11** no. 4, (Feb, 1959) 568–577. https://doi.org/10.1007/BF02726525.

[24] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, "Experimental test of parity conservation in beta decay," *Phys. Rev.* **105** (Feb, 1957) 1413–1415. https://link.aps.org/doi/10.1103/PhysRev.105.1413.

[25] M. Gell-Mann, "The interpretation of the new particles as displaced charge multiplets," *Il Nuovo Cimento (1955-1965)* **4** no. 2, (Apr, 1956) 848–866. https://doi.org/10.1007/BF02748000.

[26] K. Nishijima, "Charge Independence Theory of V Particles*," *Progress of Theoretical Physics* **13** no. 3, (03, 1955) 285–304, `https://academic.oup.com/ptp/article-pdf/13/3/285/5425869/13-3-285.pdf`. https://doi.org/10.1143/PTP.13.285.

[27] T. Nakano and K. Nishijima, "Charge Independence for V-particles*," *Progress of Theoretical Physics* **10** no. 5, (11, 1953) 581–582, `https://academic.oup.com/ptp/article-pdf/10/5/581/5364926/10-5-581.pdf`. https://doi.org/10.1143/PTP.10.581.

[28] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons," *Phys. Rev. Lett.* **13** (Aug, 1964) 321–323. https://link.aps.org/doi/10.1103/PhysRevLett.13.321.

[29] P. W. Higgs, "Broken symmetries and the masses of gauge bosons," *Phys. Rev. Lett.* **13** (Oct, 1964) 508–509. https://link.aps.org/doi/10.1103/PhysRevLett.13.508.

[30] P. W. Higgs, "Spontaneous symmetry breakdown without massless bosons," *Phys. Rev.* **145** (May, 1966) 1156–1163. https://link.aps.org/doi/10.1103/PhysRev.145.1156.

[31] Y. Nambu, "Quasiparticles and Gauge Invariance in the Theory of Superconductivity," *Phys. Rev.* **117** (1960) 648–663. [,132(1960)].

[32] J. Goldstone, "Field Theories with Superconductor Solutions," *Nuovo Cim.* **19** (1961) 154–164.

[33] V. Brdar, A. J. Helmboldt, S. Iwamoto, and K. Schmitz, "Type-I Seesaw as the Common Origin of Neutrino Mass, Baryon Asymmetry, and the Electroweak Scale," *Phys. Rev. D* **100** (2019) 075029, `arXiv:1905.12634 [hep-ph]`.

[34] G. 't Hooft and M. Veltman, "Regularization and renormalization of gauge fields," *Nuclear Physics B* **44** no. 1, (1972) 189 – 213. http://www.sciencedirect.com/science/article/pii/0550321372902799.

[35] F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln," *Helv. Phys. Acta* **6** (1933) 110–127. https://cds.cern.ch/record/437297.

[36] V. C. Rubin and W. K. Ford, Jr., "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions," *Astrophys. J.* **159** (1970) 379–403.

[37] G. Bertone, D. Hooper, and J. Silk, "Particle dark matter: Evidence, candidates and constraints," *Phys. Rept.* **405** (2005) 279–390, `arXiv:hep-ph/0404175`.

[38] D. Clowe, M. Bradac, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, "A direct empirical proof of the existence of dark matter," *Astrophys. J.* **648** (2006) L109–L113, `arXiv:astro-ph/0608407 [astro-ph]`.

[39] A. Taylor, S. Dye, T. J. Broadhurst, N. Benitez, and E. van Kampen, "Gravitational lens magnification and the mass of abell 1689," *Astrophys. J.* **501** (1998) 539, `arXiv:astro-ph/9801158`.

[40] C. Bennett *et al.*, "Four year COBE DMR cosmic microwave background observations: Maps and basic results," *Astrophys. J. Lett.* **464** (1996) L1–L4, `arXiv:astro-ph/9601067`.

[41] G. F. Smoot *et al.*, "Structure in the COBE Differential Microwave Radiometer First-Year Maps," *ApJS* **396** (September, 1992) L1.

[42] **WMAP** Collaboration, "Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results," *ApJS* **208** no. 2, (October, 2013) 20, `arXiv:1212.5225 [astro-ph.CO]`.

[43] **WMAP** Collaboration, "Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results," *ApJS* **208** no. 2, (October, 2013) 19, `arXiv:1212.5226 [astro-ph.CO]`.

[44] **Planck** Collaboration, "Planck 2018 results. I. Overview and the cosmological legacy of Planck," *Astron. Astrophys.* **641** (2020) A1, `arXiv:1807.06205 [astro-ph.CO]`.

[45] A. Liddle, *An introduction to modern cosmology; 3rd ed.* Wiley, Chichester, Mar, 2015. https://cds.cern.ch/record/1976476.

[46] **Planck** Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astron. Astrophys.* **641** (2020) A6, `arXiv:1807.06209 [astro-ph.CO]`.

[47] H. Georgi and S. L. Glashow, “Unity of all elementary-particle forces,” *Phys. Rev. Lett.* **32** (Feb, 1974) 438–441. https://link.aps.org/doi/10.1103/PhysRevLett.32.438.

[48] I. Aitchison, *Supersymmetry in Particle Physics. An Elementary Introduction*. Cambridge University Press, Cambridge, 2007.

[49] **Muon g-2** Collaboration, G. Bennett *et al.*, “Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL,” *Phys. Rev. D* **73** (2006) 072003, arXiv:hep-ex/0602035.

[50] H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events*. Cambridge University Press, 2006.

[51] A. Czarnecki and W. J. Marciano, “The Muon anomalous magnetic moment: A Harbinger for 'new physics',” *Phys. Rev. D* **64** (2001) 013014, arXiv:hep-ph/0102122.

[52] J. L. Feng and K. T. Matchev, “Supersymmetry and the anomalous magnetic moment of the muon,” *Phys. Rev. Lett.* **86** (2001) 3480–3483, arXiv:hep-ph/0102146.

[53] S. Coleman and J. Mandula, “All possible symmetries of the s matrix,” *Phys. Rev.* **159** (Jul, 1967) 1251–1256. https://link.aps.org/doi/10.1103/PhysRev.159.1251.

[54] R. Haag, J. T. Lopuszanski, and M. Sohnius, “All Possible Generators of Supersymmetries of the s Matrix,” *Nucl. Phys.* **B88** (1975) 257. [,257(1974)].

[55] J. Wess and B. Zumino, “Supergauge transformations in four dimensions,” *Nuclear Physics B* **70** no. 1, (1974) 39 – 50. http://www.sciencedirect.com/science/article/pii/0550321374903551.

[56] H. Georgi and S. L. Glashow, “Gauge theories without anomalies,” *Phys. Rev. D* **6** (Jul, 1972) 429–431. https://link.aps.org/doi/10.1103/PhysRevD.6.429.

[57] S. Dimopoulos and D. W. Sutter, “The Supersymmetric flavor problem,” *Nucl. Phys. B* **452** (1995) 496–512, arXiv:hep-ph/9504415.

[58] **MEG** Collaboration, T. Mori, “Final Results of the MEG Experiment,” *Nuovo Cim. C* **39** no. 4, (2017) 325, arXiv:1606.08168 [hep-ex].

[59] H. P. Nilles, “Supersymmetry, Supergravity and Particle Physics,” *Phys. Rept.* **110** (1984) 1–162.

[60] A. Lahanas and D. Nanopoulos, “The road to no-scale supergravity,” *Physics Reports* **145** no. 1, (1987) 1 – 139. http://www.sciencedirect.com/science/article/pii/0370157387900342.

[61] J. L. Feng, A. Rajaraman, and F. Takayama, “Superweakly interacting massive particles,” *Phys. Rev. Lett.* **91** (2003) 011302, arXiv:hep-ph/0302215.

[62] **Super-Kamiokande** Collaboration, K. Abe *et al.*, “Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ in 0.31 megaton-years exposure of the Super-Kamiokande water Cherenkov detector,” *Phys. Rev.* **D95** no. 1, (2017) 012004, arXiv:1610.03597 [hep-ex].

[63] J. R. Ellis, “Beyond the standard model for hill walkers,” in *1998 European School of High-Energy Physics*, pp. 133–196. 8, 1998. arXiv:hep-ph/9812235.

[64] J. R. Ellis, J. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, "Supersymmetric Relics from the Big Bang," *Nucl. Phys. B* **238** (1984) 453–476.

[65] D. O. Caldwell, R. M. Eisberg, D. M. Grumm, M. S. Witherell, B. Sadoulet, F. S. Goulding, and A. R. Smith, "Laboratory limits on galactic cold dark matter," *Phys. Rev. Lett.* **61** (Aug, 1988) 510–513. https://link.aps.org/doi/10.1103/PhysRevLett.61.510.

[66] M. Mori, M. M. Nojiri, K. S. Hirata, K. Kihara, Y. Oyama, A. Suzuki, K. Takahashi, M. Yamada, H. Takei, M. Koga, K. Miyano, H. Miyata, Y. Fukuda, T. Hayakawa, K. Inoue, T. Ishida, T. Kajita, Y. Koshio, M. Nakahata, K. Nakamura, A. Sakai, N. Sato, M. Shiozawa, J. Suzuki, Y. Suzuki, Y. Totsuka, M. Koshiba, K. Nishijima, T. Kajimura, T. Suda, A. T. Suzuki, T. Hara, Y. Nagashima, M. Takita, H. Yokoyama, A. Yoshimoto, K. Kaneyuki, Y. Takeuchi, T. Tanimori, S. Tasaka, and K. Nishikawa, "Search for neutralino dark matter heavier than the w boson at kamiokande," *Phys. Rev. D* **48** (Dec, 1993) 5505–5518. https://link.aps.org/doi/10.1103/PhysRevD.48.5505.

[67] **CDMS** Collaboration, D. S. Akerib *et al.*, "Exclusion limits on the WIMP-nucleon cross section from the first run of the Cryogenic Dark Matter Search in the Soudan Underground Laboratory," *Phys. Rev. D* **72** (2005) 052009, `arXiv:astro-ph/0507190`.

[68] A. Djouadi, J.-L. Kneur, and G. Moultaka, "SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM," *Comput. Phys. Commun.* **176** (2007) 426–455, `arXiv:hep-ph/0211331`.

[69] C. F. Berger, J. S. Gainer, J. L. Hewett, and T. G. Rizzo, "Supersymmetry without prejudice," *Journal of High Energy Physics* **2009** no. 02, (Feb, 2009) 023–023. http://dx.doi.org/10.1088/1126-6708/2009/02/023.

[70] J. Alwall, P. Schuster, and N. Toro, "Simplified Models for a First Characterization of New Physics at the LHC," *Phys. Rev.* **D79** (2009) 075020, `arXiv:0810.3921 [hep-ph]`.

[71] **LHC New Physics Working Group** Collaboration, D. Alves, "Simplified Models for LHC New Physics Searches," *J. Phys.* **G39** (2012) 105005, `arXiv:1105.2838 [hep-ph]`.

[72] D. S. Alves, E. Izaguirre, and J. G. Wacker, "Where the Sidewalk Ends: Jets and Missing Energy Search Strategies for the 7 TeV LHC," *JHEP* **10** (2011) 012, `arXiv:1102.5338 [hep-ph]`.

[73] F. Ambrogi, S. Kraml, S. Kulkarni, U. Laa, A. Lessa, and W. Waltenberger, "On the coverage of the pMSSM by simplified model results," *Eur. Phys. J. C* **78** no. 3, (2018) 215, `arXiv:1707.09036 [hep-ph]`.

[74] O. Buchmueller and J. Marrouche, "Universal mass limits on gluino and third-generation squarks in the context of Natural-like SUSY spectra," *Int. J. Mod. Phys. A* **29** no. 06, (2014) 1450032, `arXiv:1304.2185 [hep-ph]`.

[75] **ATLAS** Collaboration, M. Aaboud *et al.*, "Dark matter interpretations of ATLAS searches for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV proton-proton collisions," *JHEP* **09** (2016) 175, `arXiv:1608.00872 [hep-ex]`.

[76] **ATLAS** Collaboration, "Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM," *JHEP* **10** (2015) 134, `arXiv:1508.06608 [hep-ex]`.

[77] **ATLAS** Collaboration, "Mass reach of the atlas searches for supersymmetry." https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-020/fig_23.png, 2020.

[78] **CMS** Collaboration, "Summary plot moriond 2017." https://twiki.cern.ch/twiki/pub/CMSPublic/SUSYSummary2017/Moriond2017_BarPlot.pdf, 2017.

[79] L. S. W. Group, "Notes lepsusywg/02-04.1 and lepsusywg/01-03.1." http://lepsusy.web.cern.ch/lepsusy/, 2004. Accessed: 2021-02-11.

[80] **ATLAS** Collaboration, G. Aad *et al.*, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Phys. Lett. B* **716** (2012) 1–29, arXiv:1207.7214 [hep-ex].

[81] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," *Phys. Lett. B* **716** (2012) 30–61, arXiv:1207.7235 [hep-ex].

[82] CERN, "About cern." https://home.cern/about. Accessed: 2021-01-21.

[83] CERN, "CERN Annual report 2019," tech. rep., CERN, Geneva, 2020. https://cds.cern.ch/record/2723123.

[84] O. S. Bruning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2004. https://cds.cern.ch/record/782076.

[85] M. Blewett and N. Vogt-Nilsen, "Proceedings of the 8th international conference on high-energy accelerators, cern 1971. conference held at geneva, 20–24 september 1971.," tech. rep., 1971, 1971.

[86] L. R. Evans and P. Bryant, "LHC Machine," *JINST* **3** (2008) S08001. 164 p. http://cds.cern.ch/record/1129806. This report is an abridged version of the LHC Design Report (CERN-2004-003).

[87] R. Scrivens, M. Kronberger, D. Küchler, J. Lettry, C. Mastrostefano, O. Midttun, M. O'Neil, H. Pereira, and C. Schmitzer, "Overview of the status and developments on primary ion sources at CERN*,". https://cds.cern.ch/record/1382102.

[88] M. Vretenar, J. Vollaire, R. Scrivens, C. Rossi, F. Roncarolo, S. Ramberger, U. Raich, B. Puccio, D. Nisbet, R. Mompo, S. Mathot, C. Martin, L. A. Lopez-Hernandez, A. Lombardi, J. Lettry, J. B. Lallement, I. Kozsar, J. Hansen, F. Gerigk, A. Funken, J. F. Fuchs, N. Dos Santos, M. Calviani, M. Buzio, O. Brunner, Y. Body, P. Baudrenghien, J. Bauche, and T. Zickler, *Linac4 design report*, vol. 6 of *CERN Yellow Reports: Monographs*. CERN, Geneva, 2020. https://cds.cern.ch/record/2736208.

[89] E. Mobs, "The CERN accelerator complex - 2019. Complexe des accélérateurs du CERN - 2019,". https://cds.cern.ch/record/2684277. General Photo.

[90] **ATLAS** Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST* **3** (2008) S08003.

[91] **CMS** Collaboration, S. Chatrchyan *et al.*, "The CMS Experiment at the CERN LHC," *JINST* **3** (2008) S08004.

[92] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC," *JINST* **3** (2008) S08002.

[93] **LHCb** Collaboration, J. Alves, A.Augusto *et al.*, "The LHCb Detector at the LHC," *JINST* **3** (2008) S08005.

[94] **TOTEM** Collaboration, G. Anelli *et al.*, "The TOTEM experiment at the CERN Large Hadron Collider," *JINST* **3** (2008) S08007.

[95] **LHCf** Collaboration, O. Adriani *et al.*, "Technical design report of the LHCf experiment: Measurement of photons and neutral pions in the very forward region of LHC,".

[96] **MoEDAL** Collaboration, J. Pinfold *et al.*, "Technical Design Report of the MoEDAL Experiment,".

[97] **ATLAS** Collaboration, "ATLAS Public Results - Luminosity Public Results Run 2,". https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2. Accessed: 2021-01-17.

[98] **ATLAS** Collaboration, Z. Marshall, "Simulation of Pile-up in the ATLAS Experiment," *J. Phys. Conf. Ser.* **513** (2014) 022024.

[99] "First beam in the LHC - accelerating science,". https://home.cern/news/news/accelerators/record-luminosity-well-done-lhc. Accessed: 2021-01-10.

[100] **ATLAS Collaboration** Collaboration, "Luminosity determination in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC," Tech. Rep. ATLAS-CONF-2019-021, CERN, Geneva, Jun, 2019. https://cds.cern.ch/record/2677054.

[101] **ATLAS** Collaboration, M. Aaboud *et al.*, "Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC," *Eur. Phys. J. C* **76** no. 12, (2016) 653, `arXiv:1608.03953 [hep-ex]`.

[102] G. Avoni, M. Bruschi, G. Cabras, D. Caforio, N. Dehghanian, A. Floderus, B. Giacobbe, F. Giannuzzi, F. Giorgi, P. Grafström, V. Hedberg, F. L. Manghi, S. Meneghini, J. Pinfold, E. Richards, C. Sbarra, N. S. Cesari, A. Sbrizzi, R. Soluk, G. Ucchielli, S. Valentinetti, O. Viazlo, M. Villa, C. Vittori, R. Vuillermet, and A. Zoccoli, "The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS," *Journal of Instrumentation* **13** no. 07, (Jul, 2018) P07017–P07017. https://doi.org/10.1088/1748-0221/13/07/p07017.

[103] S. van der Meer, "Calibration of the effective beam height in the ISR," Tech. Rep. CERN-ISR-PO-68-31. ISR-PO-68-31, CERN, Geneva, 1968. https://cds.cern.ch/record/296752.

[104] P. Grafström and W. Kozanecki, "Luminosity determination at proton colliders," *Progress in Particle and Nuclear Physics* **81** (2015) 97 – 148. http://www.sciencedirect.com/science/article/pii/S0146641014000878.

[105] "New schedule for CERN's accelerators and experiments,". https://home.cern/news/press-release/cern/first-beam-lhc-accelerating-science. Accessed: 2021-01-10.

[106] **ATLAS** Collaboration, G. Aad *et al.*, "Luminosity Determination in *pp* Collisions at $\sqrt{s} = 7$ TeV Using the ATLAS Detector at the LHC," *Eur. Phys. J. C* **71** (2011) 1630, arXiv:1101.2185 [hep-ex].

[107] **ATLAS Collaboration** Collaboration, G. Aad *et al.*, "Improved luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC. Improved luminosity determination in pp collisions at sqrt(s) = 7 TeV using the ATLAS detector at the LHC," *Eur. Phys. J. C* **73** no. CERN-PH-EP-2013-026. CERN-PH-EP-2013-026, (Feb, 2013) 2518. 27 p. https://cds.cern.ch/record/1517411. Comments: 26 pages plus author list (39 pages total), 17 figures, 9 tables, submitted to EPJC, All figures are available at <a href=.

[108] "Record luminosity: well done LHC,". https://home.cern/news/news/accelerators/new-schedule-cerns-accelerators-and-experiments. Accessed: 2021-01-10.

[109] A. G., B. A. I., B. O., F. P., L. M., R. L., and T. L., *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN Yellow Reports: Monographs. CERN, Geneva, 2017. https://cds.cern.ch/record/2284929.

[110] J. Pequenao, "Computer generated image of the whole ATLAS detector." Mar, 2008.

[111] **ATLAS** Collaboration, "ATLAS: Detector and physics performance technical design report. Volume 1,".

[112] J. Pequenao, "Computer generated image of the ATLAS inner detector." Mar, 2008.

[113] **ATLAS Collaboration** Collaboration, K. Potamianos, "The upgraded Pixel detector and the commissioning of the Inner Detector tracking of the ATLAS experiment for Run-2 at the Large Hadron Collider," Tech. Rep. ATL-PHYS-PROC-2016-104, CERN, Geneva, Aug, 2016. https://cds.cern.ch/record/2209070. 15 pages, EPS-HEP 2015 Proceedings.

[114] **ATLAS IBL** Collaboration, B. Abbott *et al.*, "Production and Integration of the ATLAS Insertable B-Layer," *JINST* **13** no. 05, (2018) T05008, arXiv:1803.00844 [physics.ins-det].

[115] **ATLAS** Collaboration, "ATLAS Insertable B-Layer Technical Design Report," Tech. Rep. CERN-LHCC-2010-013. ATLAS-TDR-19, Sep, 2010. http://cds.cern.ch/record/1291633.

[116] **ATLAS** Collaboration, G. Aad *et al.*, "ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV," *Eur. Phys. J. C* **79** no. 11, (2019) 970, arXiv:1907.05120 [hep-ex].

[117] ATLAS Collaboration, "Particle Identification Performance of the ATLAS Transition Radiation Tracker." ATLAS-CONF-2011-128, 2011. https://cds.cern.ch/record/1383793.

[118] J. Pequenao, "Computer Generated image of the ATLAS calorimeter." Mar, 2008.

[119] J. Pequenao, "Computer generated image of the ATLAS Muons subsystem." Mar, 2008.

[120] S. Lee, M. Livan, and R. Wigmans, "Dual-Readout Calorimetry," *Rev. Mod. Phys.* **90** no. arXiv:1712.05494. 2, (Dec, 2017) 025002. 40 p. https://cds.cern.ch/record/2637852. 44 pages, 53 figures, accepted for publication in Review of Modern Physics.

[121] M. Leite, "Performance of the ATLAS Zero Degree Calorimeter," Tech. Rep. ATL-FWD-PROC-2013-001, CERN, Geneva, Nov, 2013. https://cds.cern.ch/record/1628749.

[122] S. Abdel Khalek *et al.*, "The ALFA Roman Pot Detectors of ATLAS," *JINST* **11** no. 11, (2016) P11013, `arXiv:1609.00249 [physics.ins-det]`.

[123] U. Amaldi, G. Cocconi, A. Diddens, R. Dobinson, J. Dorenbosch, W. Duinker, D. Gustavson, J. Meyer, K. Potter, A. Wetherell, A. Baroncelli, and C. Bosio, "The real part of the forward proton proton scattering amplitude measured at the cern intersecting storage rings," *Physics Letters B* **66** no. 4, (1977) 390 – 394. http://www.sciencedirect.com/science/article/pii/0370269377900223.

[124] L. Adamczyk, E. Banaś, A. Brandt, M. Bruschi, S. Grinstein, J. Lange, M. Rijssenbeek, P. Sicho, R. Staszewski, T. Sykora, M. Trzebiński, J. Chwastowski, and K. Korcyl, "Technical Design Report for the ATLAS Forward Proton Detector," Tech. Rep. CERN-LHCC-2015-009. ATLAS-TDR-024, May, 2015. https://cds.cern.ch/record/2017378.

[125] **ATLAS** Collaboration, A. R. Martínez, "The Run-2 ATLAS Trigger System," *J. Phys. Conf. Ser.* **762** no. 1, (2016) 012003.

[126] **ATLAS Collaboration** Collaboration, *ATLAS level-1 trigger: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 1998. https://cds.cern.ch/record/381429.

[127] **ATLAS** Collaboration, G. Aad *et al.*, "Operation of the ATLAS trigger system in Run 2," *JINST* **15** no. 10, (2020) P10004, `arXiv:2007.12539 [physics.ins-det]`.

[128] **ATLAS Collaboration** Collaboration, P. Jenni, M. Nessi, M. Nordberg, and K. Smith, *ATLAS high-level trigger, data-acquisition and controls: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 2003. https://cds.cern.ch/record/616089.

[129] **ATLAS** Collaboration, G. Aad *et al.*, "The ATLAS Simulation Infrastructure," *Eur. Phys. J. C* **70** (2010) 823–874, `arXiv:1005.4568 [physics.ins-det]`.

[130] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert, and J. Winter, "Event generation with SHERPA 1.1," *JHEP* **02** (2009) 007, `arXiv:0811.4622 [hep-ph]`.

[131] A. Buckley *et al.*, "General-purpose event generators for LHC physics," *Phys. Rept.* **504** (2011) 145–233, `arXiv:1101.2599 [hep-ph]`.

[132] V. N. Gribov and L. N. Lipatov, "Deep inelastic e p scattering in perturbation theory," *Sov. J. Nucl. Phys.* **15** (1972) 438–450.

[133] J. Blumlein, T. Doyle, F. Hautmann, M. Klein, and A. Vogt, "Structure functions in deep inelastic scattering at HERA," in *Workshop on Future Physics at HERA (To be followed by meetings 7-9 Feb and 30-31 May 1996 at DESY)*. 9, 1996. `arXiv:hep-ph/9609425`.

[134] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, "LHAPDF6: parton density access in the LHC precision era," *Eur. Phys. J. C* **75** (2015) 132, `arXiv:1412.7420 [hep-ph]`.

[135] M. Bengtsson and T. Sjostrand, "Coherent Parton Showers Versus Matrix Elements: Implications of PETRA - PEP Data," *Phys. Lett. B* **185** (1987) 435.

[136] S. Catani, F. Krauss, R. Kuhn, and B. R. Webber, "QCD matrix elements + parton showers," *JHEP* **11** (2001) 063, `arXiv:hep-ph/0109231`.

[137] L. Lonnblad, "Correcting the color dipole cascade model with fixed order matrix elements," *JHEP* **05** (2002) 046, `arXiv:hep-ph/0112284`.

[138] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjostrand, "Parton Fragmentation and String Dynamics," *Phys. Rept.* **97** (1983) 31–145.

[139] B. Andersson, *The Lund Model*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 1998.

[140] D. Amati and G. Veneziano, "Preconfinement as a Property of Perturbative QCD," *Phys. Lett. B* **83** (1979) 87–92.

[141] D. Yennie, S. Frautschi, and H. Suura, "The infrared divergence phenomena and high-energy processes," *Annals of Physics* **13** no. 3, (1961) 379–452. https://www.sciencedirect.com/science/article/pii/0003491661901518.

[142] M. Dobbs and J. B. Hansen, "The HepMC C++ Monte Carlo event record for High Energy Physics," *Comput. Phys. Commun.* **134** (2001) 41–46.

[143] **GEANT4** Collaboration, S. Agostinelli *et al.*, "GEANT4: A Simulation toolkit," *Nucl. Instrum. Meth.* **A506** (2003) 250–303.

[144] **ATLAS Collaboration** Collaboration, "The new Fast Calorimeter Simulation in ATLAS," Tech. Rep. ATL-SOFT-PUB-2018-002, CERN, Geneva, Jul, 2018. https://cds.cern.ch/record/2630434.

[145] K. Cranmer, "Practical Statistics for the LHC," in *2011 European School of High-Energy Physics*, pp. 267–308. 2014. `arXiv:1503.07622 [physics.data-an]`.

[146] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics," *Eur. Phys. J.* **C71** (2011) 1554, `arXiv:1007.1727 [physics.data-an]`. [Erratum: Eur. Phys. J.C73,2501(2013)].

[147] ATLAS Collaboration, "Reproduction searches for new physics with the ATLAS experiment through publication of full statistical likelihoods." ATL-PHYS-PUB-2019-029, 2019. https://cds.cern.ch/record/2684863.

[148] **ROOT Collaboration** Collaboration, K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, "HistFactory: A tool for creating statistical models for use with RooFit and RooStats," Tech. Rep. CERN-OPEN-2012-016, New York U., New York, Jan, 2012. https://cds.cern.ch/record/1456844.

[149] W. Verkerke and D. P. Kirkby, "The RooFit toolkit for data modeling," *eConf* **C0303241** (2003) MOLT007, `arXiv:physics/0306116 [physics]`. [,186(2003)].

[150] L. Moneta, K. Belasco, K. S. Cranmer, S. Kreiss, A. Lazzaro, D. Piparo, G. Schott, W. Verkerke, and M. Wolf, "The RooStats Project," *PoS* **ACAT2010** (2010) 057, `arXiv:1009.1003 [physics.data-an]`.

[151] F. James and M. Roos, "MINUIT: a system for function minimization and analysis of the parameter errors and corrections," *Comput. Phys. Commun.* **10** no. CERN-DD-75-20, (Jul, 1975) 343–367. 38 p. https://cds.cern.ch/record/310399.

[152] R. Brun and F. Rademakers, "ROOT: An object oriented data analysis framework," *Nucl. Instrum. Meth.* **A389** (1997) 81–86.

[153] I. Antcheva *et al.*, "Root — a c++ framework for petabyte data storage, statistical analysis and visualization," *Computer Physics Communications* **182** no. 6, (2011) 1384 – 1385. http://www.sciencedirect.com/science/article/pii/S0010465511000701.

[154] M. Baak, G. J. Besjes, D. Côte, A. Koutsman, J. Lorenz, and D. Short, "HistFitter software framework for statistical data analysis," *Eur. Phys. J.* **C75** (2015) 153, arXiv:1410.1280 [hep-ex].

[155] L. Heinrich, M. Feickert, G. Stark, and K. Cranmer, "pyhf: pure-python implementation of histfactory statistical models," *Journal of Open Source Software* **6** no. 58, (2021) 2823. https://doi.org/10.21105/joss.02823.

[156] L. Heinrich, M. Feickert, and G. Stark, "pyhf: v0.6.0." https://github.com/scikit-hep/pyhf.

[157] C. R. Harris, K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, J. Taylor, S. Berg, N. J. Smith, R. Kern, M. Picus, S. Hoyer, M. H. van Kerkwijk, M. Brett, A. Haldane, J. F. del R'ıo, M. Wiebe, P. Peterson, P. G'erard-Marchant, K. Sheppard, T. Reddy, W. Weckesser, H. Abbasi, C. Gohlke, and T. E. Oliphant, "Array programming with NumPy," *Nature* **585** no. 7825, (Sept., 2020) 357–362. https://doi.org/10.1038/s41586-020-2649-2.

[158] A. Paszke, S. Gross, F. Massa, A. Lerer, J. Bradbury, G. Chanan, T. Killeen, Z. Lin, N. Gimelshein, L. Antiga, A. Desmaison, A. Kopf, E. Yang, Z. DeVito, M. Raison, A. Tejani, S. Chilamkurthy, B. Steiner, L. Fang, J. Bai, and S. Chintala, "Pytorch: An imperative style, high-performance deep learning library," in *Advances in Neural Information Processing Systems 32*, H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox, and R. Garnett, eds., pp. 8024–8035. Curran Associates, Inc., 2019. http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf.

[159] M. Abadi, A. Agarwal, P. Barham, E. Brevdo, Z. Chen, C. Citro, G. S. Corrado, A. Davis, J. Dean, M. Devin, S. Ghemawat, I. Goodfellow, A. Harp, G. Irving, M. Isard, Y. Jia, R. Jozefowicz, L. Kaiser, M. Kudlur, J. Levenberg, D. Mané, R. Monga, S. Moore, D. Murray, C. Olah, M. Schuster, J. Shlens, B. Steiner, I. Sutskever, K. Talwar, P. Tucker, V. Vanhoucke, V. Vasudevan, F. Viégas, O. Vinyals, P. Warden, M. Wattenberg, M. Wicke, Y. Yu, and X. Zheng, "TensorFlow: Large-scale machine learning on heterogeneous systems," 2015. https://www.tensorflow.org/. Software available from tensorflow.org.

[160] J. Bradbury, R. Frostig, P. Hawkins, M. J. Johnson, C. Leary, D. Maclaurin, and S. Wanderman-Milne, "JAX: composable transformations of Python+NumPy programs," 2018. http://github.com/google/jax.

[161] S. S. Wilks, "The large-sample distribution of the likelihood ratio for testing composite hypotheses," *Ann. Math. Statist.* **9** no. 1, (03, 1938) 60–62. https://doi.org/10.1214/aoms/1177732360.

[162] A. Wald, "Tests of statistical hypotheses concerning several parameters when the number of observations is large," *Transactions of the American Mathematical Society* **54** no. 3, (1943) 426–482. https://doi.org/10.1090/S0002-9947-1943-0012401-3.

[163] G. Cowan, "Statistics for Searches at the LHC," in *69th Scottish Universities Summer School in Physics: LHC Physics*, pp. 321–355. 7, 2013. arXiv:1307.2487 [hep-ex].

[164] A. L. Read, "Presentation of search results: the CL_S technique," *J. Phys. G* **28** (2002) 2693.

[165] R. D. Cousins, J. T. Linnemann, and J. Tucker, "Evaluation of three methods for calculating statistical significance when incorporating a systematic uncertainty into a test of the background-only hypothesis for a Poisson process," *Nucl. Instrum. Meth. A* **595** no. 2, (2008) 480, arXiv:physics/0702156 [physics.data-an].

[166] K. CRANMER, "Statistical challenges for searches for new physics at the lhc," *Statistical Problems in Particle Physics, Astrophysics and Cosmology* (May, 2006) . http://dx.doi.org/10.1142/9781860948985_0026.

[167] ATLAS Collaboration, "Search for direct pair production of a chargino and a neutralino decaying to the 125 GeV Higgs boson in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector," *Eur. Phys. J. C* **75** (2015) 208, arXiv:1501.07110 [hep-ex].

[168] ATLAS Collaboration, "Search for chargino and neutralino production in final states with a Higgs boson and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector," *Phys. Rev. D* **100** (2019) 012006, arXiv:1812.09432 [hep-ex].

[169] CMS Collaboration, "Search for electroweak production of charginos and neutralinos in WH events in proton–proton collisions at $\sqrt{s} = 13$ TeV," *JHEP* **11** (2017) 029, arXiv:1706.09933 [hep-ex].

[170] ATLAS Collaboration, "Search for direct production of electroweakinos in final states with one lepton, missing transverse momentum and a Higgs boson decaying into two b-jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *Eur. Phys. J. C* **80** (2020) 691, arXiv:1909.09226 [hep-ex].

[171] ATLAS Collaboration, "Improvements in $t\bar{t}$ modelling using NLO+PS Monte Carlo generators for Run 2." ATL-PHYS-PUB-2018-009, 2018. https://cds.cern.ch/record/2630327.

[172] ATLAS Collaboration, "Modelling of the $t\bar{t}H$ and $t\bar{t}V(V = W, Z)$ processes for $\sqrt{s} = 13$ TeV ATLAS analyses." ATL-PHYS-PUB-2016-005, 2016. https://cds.cern.ch/record/2120826.

[173] ATLAS Collaboration, "ATLAS simulation of boson plus jets processes in Run 2." ATL-PHYS-PUB-2017-006, 2017. https://cds.cern.ch/record/2261937.

[174] ATLAS Collaboration, "Multi-Boson Simulation for 13 TeV ATLAS Analyses." ATL-PHYS-PUB-2017-005, 2017. https://cds.cern.ch/record/2261933.

[175] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," *JHEP* **07** (2014) 079, arXiv:1405.0301 [hep-ph].

[176] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO," *JHEP* **12** (2012) 061, arXiv:1209.6215 [hep-ph].

[177] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, "An Introduction to PYTHIA 8.2," *Comput. Phys. Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph].

[178] L. Lönnblad and S. Prestel, "Matching tree-level matrix elements with interleaved showers," *JHEP* **03** (2012) 019, arXiv:1109.4829 [hep-ph].

[179] R. D. Ball *et al.*, "Parton distributions with LHC data," *Nucl. Phys. B* **867** (2013) 244, arXiv:1207.1303 [hep-ph].

[180] ATLAS Collaboration, "ATLAS Pythia 8 tunes to 7 TeV data." ATL-PHYS-PUB-2014-021, 2014. https://cds.cern.ch/record/1966419.

[181] D. J. Lange, "The EvtGen particle decay simulation package," *Nucl. Instrum. Meth. A* **462** (2001) 152.

[182] ATLAS Collaboration, "The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model." ATL-PHYS-PUB-2016-017, 2016. https://cds.cern.ch/record/2206965.

[183] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, "Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO," *Eur. Phys. J. C* **73** (2013) 2480, arXiv:1304.0790 [hep-ph].

[184] J. Fiaschi and M. Klasen, "Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II," *Phys. Rev. D* **98** no. 5, (2018) 055014, arXiv:1805.11322 [hep-ph].

[185] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, "Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV," *JHEP* **10** (2012) 081, arXiv:1207.2159 [hep-ph].

[186] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX," *JHEP* **06** (2010) 043, arXiv:1002.2581 [hep-ph].

[187] S. Frixione, P. Nason, and G. Ridolfi, "A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction," *JHEP* **09** (2007) 126, arXiv:0707.3088 [hep-ph].

[188] P. Nason, "A New method for combining NLO QCD with shower Monte Carlo algorithms," *JHEP* **11** (2004) 040, arXiv:hep-ph/0409146.

[189] E. Bothmann *et al.*, "Event generation with Sherpa 2.2," *SciPost Phys.* **7** no. 3, (2019) 034, arXiv:1905.09127 [hep-ph].

[190] S. Höche, F. Krauss, S. Schumann, and F. Siegert, "QCD matrix elements and truncated showers," *JHEP* **05** (2009) 053, arXiv:0903.1219 [hep-ph].

[191] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, "QCD matrix elements + parton showers. The NLO case," *JHEP* **04** (2013) 027, arXiv:1207.5030 [hep-ph].

[192] **NNPDF** Collaboration, R. D. Ball *et al.*, "Parton distributions for the LHC run II," *JHEP* **04** (2015) 040, arXiv:1410.8849 [hep-ph].

[193] ATLAS Collaboration, "Example ATLAS tunes of Pythia8, Pythia6 and Powheg to an observable sensitive to Z boson transverse momentum." ATL-PHYS-PUB-2013-017, 2013. https://cds.cern.ch/record/1629317.

[194] M. Czakon and A. Mitov, "Top++: A program for the calculation of the top-pair cross-section at hadron colliders," *Comput. Phys. Commun.* **185** (2014) 2930, arXiv:1112.5675 [hep-ph].

[195] M. Cacciari, M. Czakon, M. Mangano, A. Mitov, and P. Nason, "Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation," *Phys. Lett. B* **710** (2012) 612–622, arXiv:1111.5869 [hep-ph].

[196] P. Kant, O. M. Kind, T. Kintscher, T. Lohse, T. Martini, S. Mölbitz, P. Rieck, and P. Uwer, "HatHor for single top-quark production: Updated predictions and uncertainty estimates for single top-quark production in hadronic collisions," *Comput. Phys. Commun.* **191** (2015) 74–89, arXiv:1406.4403 [hep-ph].

[197] N. Kidonakis, "Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-," *Phys. Rev. D* **82** (2010) 054018, arXiv:1005.4451 [hep-ph].

[198] J. M. Campbell and R. K. Ellis, "$t\bar{t}W^{+-}$ production and decay at NLO," *JHEP* **07** (2012) 052, arXiv:1204.5678 [hep-ph].

[199] A. Lazopoulos, T. McElmurry, K. Melnikov, and F. Petriello, "Next-to-leading order QCD corrections to $t\bar{t}Z$ production at the LHC," *Phys. Lett. B* **666** (2008) 62–65, arXiv:0804.2220 [hep-ph].

[200] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, "FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order," arXiv:1011.3540 [hep-ph].

[201] **LHC Higgs Cross Section Working Group** Collaboration, D. de Florian *et al.*, "Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector," arXiv:1610.07922 [hep-ph].

[202] ATLAS Collaboration, "Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2," *Eur. Phys. J. C* **77** (2017) 673, arXiv:1704.07983 [hep-ex].

[203] R. Frühwirth, "Application of Kalman filtering to track and vertex fitting," *Nucl. Instrum. Methods Phys. Res., A* **262** no. HEPHY-PUB-503, (Jun, 1987) 444. 19 p. https://cds.cern.ch/record/178627.

[204] T. Cornelissen, M. Elsing, I. Gavrilenko, W. Liebig, E. Moyse, and A. Salzburger, "The new ATLAS track reconstruction (NEWT)," *J. Phys.: Conf. Ser.* **119** (2008) 032014. https://cds.cern.ch/record/1176900.

[205] ATLAS Collaboration, "Vertex Reconstruction Performance of the ATLAS Detector at $\sqrt{s} = 13$ TeV." ATL-PHYS-PUB-2015-026, 2015. https://cds.cern.ch/record/2037717.

[206] ATLAS Collaboration, "Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC," *Eur. Phys. J. C* **77** (2017) 332, arXiv:1611.10235 [hep-ex].

[207] ATLAS Collaboration, "Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1," *Eur. Phys. J. C* **77** (2017) 490, arXiv:1603.02934 [hep-ex].

[208] ATLAS Collaboration, "Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data," *JINST* **14** (2019) P12006, arXiv:1908.00005 [hep-ex].

[209] ATLAS Collaboration, "Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016," *Eur. Phys. J. C* **79** (2019) 205, arXiv:1810.05087 [hep-ex].

[210] ATLAS Collaboration, "Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$," *Eur. Phys. J. C* **79** (2019) 639, arXiv:1902.04655 [hep-ex].

[211] ATLAS Collaboration, "Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$," *Eur. Phys. J. C* **76** (2016) 292, arXiv:1603.05598 [hep-ex].

[212] **ATLAS** Collaboration, "Muon reconstruction and identification efficiency in ATLAS using the full Run 2 *pp* collision data set at $\sqrt{s} = 13$ TeV," arXiv:2012.00578 [hep-ex].

[213] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm," *JHEP* **04** (2008) 063, arXiv:0802.1189 [hep-ph].

[214] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual," *Eur. Phys. J. C* **72** (2012) 1896, arXiv:1111.6097 [hep-ph].

[215] M. Cacciari, "FastJet: A Code for fast k_t clustering, and more," in *Deep inelastic scattering. Proceedings, 14th International Workshop, DIS 2006, Tsukuba, Japan, April 20-24, 2006*, pp. 487–490. 2006. arXiv:hep-ph/0607071 [hep-ph]. [,125(2006)].

[216] **ATLAS** Collaboration, G. Aad *et al.*, "Jet energy scale and resolution measured in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," arXiv:2007.02645 [hep-ex].

[217] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas," *Phys. Lett. B* **659** (2008) 119–126, arXiv:0707.1378 [hep-ph].

[218] ATLAS Collaboration, "Jet energy measurement with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$," *Eur. Phys. J. C* **73** (2013) 2304, arXiv:1112.6426 [hep-ex].

[219] ATLAS Collaboration, "Determination of jet calibration and energy resolution in proton–proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ using the ATLAS detector," arXiv:1910.04482 [hep-ex].

[220] ATLAS Collaboration, "Performance of pile-up mitigation techniques for jets in *pp* collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ using the ATLAS detector," *Eur. Phys. J. C* **76** (2016) 581, arXiv:1510.03823 [hep-ex].

[221] ATLAS Collaboration, "Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run." ATL-PHYS-PUB-2017-013, 2017. https://cds.cern.ch/record/2273281.

[222] ATLAS Collaboration, "ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV," *Eur. Phys. J. C* **79** (2019) 970, arXiv:1907.05120 [hep-ex].

[223] ATLAS Collaboration, "Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV," *JHEP* **08** (2018) 089, arXiv:1805.01845 [hep-ex].

[224] ATLAS Collaboration, "Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV," *Eur. Phys. J. C* **78** (2018) 903, arXiv:1802.08168 [hep-ex].

[225] **ATLAS Collaboration** Collaboration, "$E_{\mathrm{T}}^{\mathrm{miss}}$ performance in the ATLAS detector using 2015-2016 LHC p-p collisions," Tech. Rep. ATLAS-CONF-2018-023, CERN, Geneva, Jun, 2018. http://cds.cern.ch/record/2625233.

[226] D. Adams *et al.*, "Recommendations of the Physics Objects and Analysis Harmonisation Study Groups 2014," Tech. Rep. ATL-PHYS-INT-2014-018, CERN, Geneva, Jul, 2014. https://cds.cern.ch/record/1743654.

[227] M. Cacciari, G. P. Salam, and G. Soyez, "The Catchment Area of Jets," *JHEP* **04** (2008) 005, arXiv:0802.1188 [hep-ph].

[228] **UA1** Collaboration, G. Arnison *et al.*, "Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV," *Phys. Lett. B* **122** (1983) 103–116.

[229] **Aachen-Annecy-Birmingham-CERN-Helsinki-London(QMC)-Paris(CdF)-Riverside-Rome-Rutherford-Saclay(CEN)-Vienna** Collaboration, G. Arnison *et al.*, "Further evidence for charged intermediate vector bosons at the SPS collider," *Phys. Lett. B* **129** no. CERN-EP-83-111, (Jun, 1985) 273–282. 17 p. https://cds.cern.ch/record/163856.

[230] D. R. Tovey, "On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders," *JHEP* **04** (2008) 034, arXiv:0802.2879 [hep-ph].

[231] G. Polesello and D. R. Tovey, "Supersymmetric particle mass measurement with the boost-corrected contransverse mass," *JHEP* **03** (2010) 030, arXiv:0910.0174 [hep-ph].

[232] **ATLAS** Collaboration, G. Aad *et al.*, "Performance of the missing transverse momentum triggers for the ATLAS detector during Run-2 data taking," *JHEP* **08** (2020) 080, arXiv:2005.09554 [hep-ex].

[233] **ATLAS** Collaboration, G. Aad *et al.*, "Performance of algorithms that reconstruct missing transverse momentum in $\sqrt{s} = 8$ TeV proton-proton collisions in the ATLAS detector," *Eur. Phys. J. C* **77** no. 4, (2017) 241, arXiv:1609.09324 [hep-ex].

[234] ATLAS Collaboration, "ATLAS data quality operations and performance for 2015–2018 data-taking," *JINST* **15** (2020) P04003, arXiv:1911.04632 [physics.ins-det].

[235] ATLAS Collaboration, "Selection of jets produced in 13 TeV proton–proton collisions with the ATLAS detector." ATLAS-CONF-2015-029, 2015. https://cds.cern.ch/record/2037702.

[236] N. Hartmann, "ahoi." https://gitlab.com/nikoladze/ahoi, 2018.

[237] **ATLAS** Collaboration, "Object-based missing transverse momentum significance in the ATLAS detector," Tech. Rep. ATLAS-CONF-2018-038, CERN, Geneva, Jul, 2018. https://cds.cern.ch/record/2630948.

[238] A. Roodman, "Blind analysis in particle physics," *eConf* **C030908** (2003) TUIT001, arXiv:physics/0312102.

[239] ATLAS Collaboration, "A method for the construction of strongly reduced representations of ATLAS experimental uncertainties and the application thereof to the jet energy scale." ATL-PHYS-PUB-2015-014, 2015. https://cds.cern.ch/record/2037436.

[240] J. Bellm *et al.*, "Herwig 7.0/Herwig++ 3.0 release note," *Eur. Phys. J.* **C76** no. 4, (2016) 196, arXiv:1512.01178 [hep-ph].

[241] ATLAS Collaboration, "Simulation of top-quark production for the ATLAS experiment at $\sqrt{s} = 13$ TeV." ATL-PHYS-PUB-2016-004, 2016. https://cds.cern.ch/record/2120417.

[242] S. Frixione, E. Laenen, P. Motylinski, C. White, and B. R. Webber, "Single-top hadroproduction in association with a W boson," *JHEP* **07** (2008) 029, arXiv:0805.3067 [hep-ph].

[243] **ATLAS Collaboration** Collaboration, "SUSY July 2020 Summary Plot Update," Tech. Rep. ATL-PHYS-PUB-2020-020, CERN, Geneva, Jul, 2020. http://cds.cern.ch/record/2725258.

[244] G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, and L. Rossi, *High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2015. https://cds.cern.ch/record/2116337.

[245] **LHC Reinterpretation Forum** Collaboration, W. Abdallah *et al.*, "Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2," *SciPost Phys.* **9** no. 2, (2020) 022, arXiv:2003.07868 [hep-ph].

[246] ATLAS Collaboration, "RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two b-quarks." ATL-PHYS-PUB-2019-032, 2019. https://cds.cern.ch/record/2686290.

[247] K. Cranmer and I. Yavin, "RECAST: Extending the Impact of Existing Analyses," *JHEP* **04** (2011) 038, arXiv:1010.2506 [hep-ex].

[248] S. Ovyn, X. Rouby, and V. Lemaitre, "DELPHES, a framework for fast simulation of a generic collider experiment," arXiv:0903.2225 [hep-ph].

[249] A. Buckley, J. Butterworth, D. Grellscheid, H. Hoeth, L. Lonnblad, J. Monk, H. Schulz, and F. Siegert, "Rivet user manual," *Comput. Phys. Commun.* **184** (2013) 2803–2819, arXiv:1003.0694 [hep-ph].

[250] A. Buckley, D. Kar, and K. Nordström, "Fast simulation of detector effects in Rivet," *SciPost Phys.* **8** (2020) 025, arXiv:1910.01637 [hep-ph].

[251] D. Dercks, N. Desai, J. S. Kim, K. Rolbiecki, J. Tattersall, and T. Weber, "CheckMATE 2: From the model to the limit," *Comput. Phys. Commun.* **221** (2017) 383–418, arXiv:1611.09856 [hep-ph].

[252] M. Drees, H. Dreiner, D. Schmeier, J. Tattersall, and J. S. Kim, "CheckMATE: Confronting your Favourite New Physics Model with LHC Data," *Comput. Phys. Commun.* **187** (2015) 227–265, arXiv:1312.2591 [hep-ph].

[253] E. Conte, B. Fuks, and G. Serret, “MadAnalysis 5, A User-Friendly Framework for Collider Phenomenology,” *Comput. Phys. Commun.* **184** (2013) 222–256, arXiv:1206.1599 [hep-ph].

[254] E. Maguire, L. Heinrich, and G. Watt, “HEPData: a repository for high energy physics data,” *J. Phys. Conf. Ser.* **898** no. 10, (2017) 102006, arXiv:1704.05473 [hep-ex].

[255] **ATLAS** Collaboration, “Simpleanalysis.” https://gitlab.cern.ch/atlas-sa/simple-analysis, 2021.

[256] S. Kraml, S. Kulkarni, U. Laa, A. Lessa, W. Magerl, D. Proschofsky-Spindler, and W. Waltenberger, “SModelS: a tool for interpreting simplified-model results from the LHC and its application to supersymmetry,” *Eur. Phys. J. C* **74** (2014) 2868, arXiv:1312.4175 [hep-ph].

[257] F. Ambrogi, S. Kraml, S. Kulkarni, U. Laa, A. Lessa, V. Magerl, J. Sonneveld, M. Traub, and W. Waltenberger, “SModelS v1.1 user manual: Improving simplified model constraints with efficiency maps,” *Comput. Phys. Commun.* **227** (2018) 72–98, arXiv:1701.06586 [hep-ph].

[258] **ATLAS** Collaboration, “Search for direct production of electroweakinos in final states with one lepton, missing transverse momentum and a higgs boson decaying into two b-jets in pp collisions at $\sqrt{s} = 13$ tev with the atlas detector,” 2021. https://www.hepdata.net/record/ins1755298?version=4.

[259] **LHC Reinterpretation Forum** Collaboration, W. Abdallah *et al.*, “Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2,” *SciPost Phys.* **9** no. 2, (2020) 022, arXiv:2003.07868 [hep-ph].

[260] **ATLAS** Collaboration, “1lbb-likelihoods-hepdata.tar.gz,” 2020. https://www.hepdata.net/record/resource/1408476?view=true.

[261] G. Alguero, S. Kraml, and W. Waltenberger, “A SModelS interface for pyhf likelihoods,” arXiv:2009.01809 [hep-ph].

[262] M. D. Goodsell, “Implementation of the ATLAS-SUSY-2019-08 analysis in the MadAnalysis 5 framework (electroweakinos with a Higgs decay into a $b\bar{b}$ pair, one lepton and missing transverse energy; 139 fb^{-1}),” *Mod. Phys. Lett. A* **36** no. 01, (2021) 2141006.

[263] J. Y. Araz *et al.*, “Proceedings of the second MadAnalysis 5 workshop on LHC recasting in Korea,” *Mod. Phys. Lett. A* **36** no. 01, (2021) 2102001, arXiv:2101.02245 [hep-ph].

[264] M. Feickert, L. Heinrich, G. Stark, and B. Galewsky, “Distributed statistical inference with pyhf enabled through funcX,” in *25th International Conference on Computing in High-Energy and Nuclear Physics*. 3, 2021. arXiv:2103.02182 [cs.DC].

[265] R. Chard, Y. Babuji, Z. Li, T. Skluzacek, A. Woodard, B. Blaiszik, I. Foster, and K. Chard, “funcx: A federated function serving fabric for science,” ACM, Jun, 2020. http://dx.doi.org/10.1145/3369583.3392683.

[266] D. Merkel, “Docker: Lightweight linux containers for consistent development and deployment,” *Linux J.* **2014** no. 239, (Mar., 2014) .

[267] S. Binet and B. Couturier, “docker & HEP: Containerization of applications for development, distribution and preservation,” *J. Phys.: Conf. Ser.* **664** no. 2, (2015) 022007. 8 p. https://cds.cern.ch/record/2134524.

[268] K. Cranmer and L. Heinrich, "Yadage and Packtivity - analysis preservation using parametrized workflows," *J. Phys. Conf. Ser.* **898** no. 10, (2017) 102019, arXiv:1706.01878 [physics.data-an].

[269] ATLAS Collaboration, "Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM," *JHEP* **10** (2015) 134, arXiv:1508.06608 [hep-ex].

[270] ATLAS Collaboration, "Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s} = 13\,\text{TeV}$ pp collisions with the ATLAS detector," *Phys. Rev. D* **101** (2020) 052005, arXiv:1911.12606 [hep-ex].

[271] ATLAS Collaboration, "Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s} = 13\,\text{TeV}$ pp collisions using the ATLAS detector," *Eur. Phys. J. C* **80** (2020) 123, arXiv:1908.08215 [hep-ex].

[272] ATLAS Collaboration, "Search for direct stau production in events with two hadronic τ-leptons in $\sqrt{s} = 13\,\text{TeV}$ pp collisions with the ATLAS detector," *Phys. Rev. D* **101** (2020) 032009, arXiv:1911.06660 [hep-ex].

[273] ATLAS Collaboration, "Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets and missing transverse momentum," *JHEP* **12** (2019) 060, arXiv:1908.03122 [hep-ex].

[274] W. Porod, "SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders," *Comput. Phys. Commun.* **153** (2003) 275–315, arXiv:hep-ph/0301101.

[275] W. Porod and F. Staub, "SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM," *Comput. Phys. Commun.* **183** (2012) 2458–2469, arXiv:1104.1573 [hep-ph].

[276] S. Heinemeyer, W. Hollik, and G. Weiglein, "FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM," *Comput. Phys. Commun.* **124** (2000) 76–89, arXiv:hep-ph/9812320.

[277] H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, S. Paßehr, H. Rzehak, and G. Weiglein, "Precision calculations in the MSSM Higgs-boson sector with FeynHiggs 2.14," *Comput. Phys. Commun.* **249** (2020) 107099, arXiv:1811.09073 [hep-ph].

[278] T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, "High-Precision Predictions for the Light CP -Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model," *Phys. Rev. Lett.* **112** no. 14, (2014) 141801, arXiv:1312.4937 [hep-ph].

[279] B. C. Allanach, "SOFTSUSY: a program for calculating supersymmetric spectra," *Comput. Phys. Commun.* **143** (2002) 305–331, arXiv:hep-ph/0104145 [hep-ph].

[280] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, "MicrOMEGAs 2.0: A Program to calculate the relic density of dark matter in a generic model," *Comput. Phys. Commun.* **176** (2007) 367–382, arXiv:hep-ph/0607059.

[281] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, "micrOMEGAs: A Tool for dark matter studies," *Nuovo Cim. C* **033N2** (2010) 111–116, arXiv:1005.4133 [hep-ph].

[282] F. Mahmoudi, "SuperIso v2.3: A Program for calculating flavor physics observables in Supersymmetry," *Comput. Phys. Commun.* **180** (2009) 1579–1613, arXiv:0808.3144 [hep-ph].

[283] W. Beenakker, R. Hopker, and M. Spira, "PROSPINO: A Program for the Production of Supersymmetric Particles in Next-to-leading Order QCD," Tech. Rep. hep-ph/9611232, Nov, 1996. https://cds.cern.ch/record/314229. 12 pages, latex, no figures, Complete postscript file and FORTRAN source codes available from http://wwwcn.cern.ch/ mspira/prospino/.

[284] W. Beenakker, M. Klasen, M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, "The Production of charginos / neutralinos and sleptons at hadron colliders," *Phys. Rev. Lett.* **83** (1999) 3780–3783, arXiv:hep-ph/9906298. [Erratum: Phys.Rev.Lett. 100, 029901 (2008)].

[285] A. Arbey, M. Battaglia, and F. Mahmoudi, "Higgs Production in Neutralino Decays in the MSSM - The LHC and a Future e^+e^- Collider," *Eur. Phys. J. C* **75** no. 3, (2015) 108, arXiv:1212.6865 [hep-ph].

[286] M. E. Cabrera, J. A. Casas, A. Delgado, S. Robles, and R. Ruiz de Austri, "Naturalness of MSSM dark matter," *JHEP* **08** (2016) 058, arXiv:1604.02102 [hep-ph].