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Search for electroweakinos with the ATLAS detector

Thesis submitted for a doctoral degree in physics
at the faculty of physics of the
Ludwig-Maximilians University
Munich, Germany

Submitted by Eric Schanet, born in Luxembourg
on May 4th, 2021

Supported by the Luxembourg National Research Fund (FNR) (13562317)

Part I

Fundamental concepts

Part II

The 1-lepton analysis

Chapter 7

Systematic uncertainties

Several sources of systematic uncertainties need to be considered in the following. As laid out in chapter 3, they enter the likelihood as nuisance parameters and can be interpreted as a loss of information on the signal strength parameter. In the following, they are separated into experimental uncertainties, arising for example from finite detector resolution, and theoretical uncertainties due to modelling of the physics processes during simulation.

7.1 Experimental uncertainties

Experimental uncertainties arise from the methods used to reconstruct, identify and calibrate the physics objects used in the 1ℓ search. They are evaluated using up and down variations provided either as variational weights[†] in the case of efficiency uncertainties, or as additional variational MC datasets derived by re-executing the entire object reconstruction pipeline with varied parameters.

7.1.1 Pile-up reweighting and luminosity

The MC simulated events used in the 1ℓ search were largely already generated before the full Run 2 dataset was recorded, and therefore before the full pile-up distribution in data was known. For this reason, the number of average interactions μ per bunch crossing in MC is in general not identical to that in data, necessitating a correction procedure in MC [252]. In order to account for differences in the measured inelastic pp cross section [253] and the one obtained from MC simulation, a scale factor of 1.03 is applied before the correction procedure. The uncertainty on the pile-up correction is evaluated by varying the data scale factor by ± 0.04 and deriving variational pile-up weights.

As detailed in section 2.1.2, the total integrated luminosity relies on the measurement of the bunch luminosity, which, in turn, needs precise measurements of the visible inelastic cross section σ_{vis} , as well as the visible pile-up parameter μ_{vis} . Uncertainties on the measurement of the total recorded luminosity are dominated by the uncertainties on σ_{vis} that is measured during special van der Meer (vdM) scans. For the full Run 2 dataset, an overall luminosity uncertainty of $\pm 1.7\%$, is considered for all MC processes not normalised to data using a control region, derived using the methods described in Ref. [113].

[†] See section 4.3.1 for a discussion on the use of weights in Monte Carlo (MC) events.

7.1.2 Triggers

All selections considered in the analysis apply a minimum requirement of $E_T^{\text{miss}} > 240$ GeV, thus targeting a region where the E_T^{miss} triggers are fully efficient (cf. section 4.7). For this reason, no trigger scale factors and associated uncertainties are needed. Instead, only a 2% normalisation uncertainty, correlated over all bins, is considered to cover differences between the trigger plateaus due to MC statistical uncertainties.

7.1.3 Leptons

Uncertainties on electrons arise primarily from energy scale and resolution measurements [219, 221]. They are assumed to be fully correlated in η and are summed in quadrature, resulting in one nuisance parameter for the energy scale and one for the resolution. Uncertainties on muons arise from calibrations of the muon momentum scale and resolution, and are evaluated using variations in the smearing of the inner detector and muon spectrometer tracks as well as the momentum scale, resulting in a total of five Gaussian-constrained nuisance parameters entering the likelihood [222]. Additional lepton-related uncertainties, considered in the following, originate from measurements of the reconstruction, identification and isolation efficiencies. In the case of muons, two more uncertainties, arising from track-to-vertex association and bad muon identification efficiencies, are considered.

7.1.4 Jets

The calibration of the jets to the absolute jet energy scale (JES) is subject to uncertainties arising from, e.g., the *in situ* measurements, pile-up effects or flavour-dependence [227]. They are encoded in a large set of 125 parameters, the full detail of which offers far greater statistical precision than needed for the 1ℓ search. As the majority of the parameters (a total of 98) stems from *in situ* measurements, an eigenvector decomposition is performed on the covariance matrix of these components [254], allowing to determine the 15 principal orthogonal components (including a residual term adding the remaining terms in quadrature), with minimal loss in bin-by-bin correlation information. Five additional parameters, evaluating uncertainties arising from *in situ* η -intercalibrations of forward jets with respect to central jets, are kept separate due to their two-dimensional dependence on p_T and η [227]. Effects from pile-up are described by four additional nuisance parameters. Uncertainties arising from differing detector responses to gluon- and quark-initiated jets as well as flavour-related differences are accounted for by two more nuisance parameters. Uncertainties on jets that are not contained in the calorimeters and *punch-through* into the muon spectrometer are evaluated with an additional parameter. A last parameter encodes the uncertainties arising from the calibration of MC samples reconstructed using ATLFast-II instead of the full GEANT4-based detector simulation.

Systematic uncertainties on the jet energy resolution (JER) arise from measured differences between data and MC simulation, noise from pile-up, and *in situ* measurements of the jet p_T imbalance. A similar eigenvector decomposition as for part of the JES uncertainties is used, reducing the set of nuisance parameters considered in the following to 13 [227]. Finally, uncertainties related to the efficiency of jet vertex tagging are evaluated using a weight systematic.

7.1.5 Flavour tagging

Uncertainties on the flavour tagging efficiency originate from modelling uncertainties and uncertainties on the reconstruction of physics objects. Similar to the JER and JES uncertainties, the full set of nuisance parameters, that would in principle need to be included in order to consider the full bin-by-bin correlations and p_T and η dependence of the flavour-tagging uncertainties, is reduced to a more manageable size using an eigenvector decomposition. This leads to a total of five nuisance parameters encoding uncertainties on the b -tagging efficiency, the c-jet and light-jet mis-tagging rate, and the extrapolation to high- p_T jets [233, 234].

7.1.6 Missing transverse energy

The uncertainties on E_T^{miss} are evaluated using the systematic variations of all calibrated objects as inputs to the E_T^{miss} calculation. Additional uncertainties arise from the calculation of the track soft term. In the following, uncertainties on the soft term scale and resolution are considered, resulting in one nuisance parameter for the soft term scale and two nuisance parameters—corresponding to the perpendicular and parallel components—for the soft term resolution uncertainties. All track soft term uncertainties are derived by comparing MC simulation to $Z \rightarrow \mu\mu$ events [235].

7.2 Theoretical uncertainties

As discussed in section 2.2.8, due to finite order calculations, the different steps of the MC simulation generally introduce a certain number of unphysical scales and parameters. In order to quantify the uncertainties arising from the ad-hoc values of these, the MC simulation generally needs to be re-run with systematically varied parameter values. Since varied MC simulation parameters affect the event kinematics even before reconstruction and calibration, it is computationally very expensive to produce a full set of variations for each MC simulated dataset used in the nominal analysis.

In the following, different approaches are used to derive the theory uncertainties. For some of the variational MC datasets, the full MC simulation chain was run with reduced statistics. For others, alternative MC datasets, produced with a different set of MC generators and tunes, were available. For others still, variations were already processed during the initial MC simulation of the nominal sample and subsequently stored as variational weights. Finally, some of the variational MC datasets were simulated at MC truth-level, i.e. skipping the detector simulation. The latter approach was used especially in the case of Supersymmetry (SUSY) signal samples, where the impact of the full detector simulation compared to truth-level comparisons is expected to be small in the context of theory uncertainties. Additionally, a full simulation of MC datasets for all parameter variations and all signal points considered, would be computationally unfeasible.

For background processes that are normalised to data in a dedicated control region (CR), the theory uncertainties are evaluated on the transfer factors. For a process p , a control region CR_i , and a destination region R_j , the transfer factor reads

$$f_p(\text{CR}_i \rightarrow \text{R}_j) = \frac{N_p^{\text{MC}}(\text{R}_j)}{N_p^{\text{MC}}(\text{CR}_i)}, \quad (7.1)$$

where $N_p^{\text{MC}}(R_j)$ and $N_p^{\text{MC}}(\text{CR}_i)$ are the expected event rates for the process p in CR_i and R_j , respectively. The systematic uncertainty on the transfer factor is then given by

$$\Delta f_p^{\text{syst}} = \frac{f_p^{\text{variation}}}{f_p^{\text{nominal}}} - 1, \quad (7.2)$$

with $f_p^{\text{variation}}$ and f_p^{nominal} the transfer factors from the variational and nominal samples, respectively. If the MC datasets used for deriving the variational and nominal transfer factors are statistically independent, a statistical component of the uncertainty is derived using the individual statistical uncertainties on the background estimate,

$$\Delta f_p^{\text{stat}} = (\Delta f_p^{\text{syst}} + 1) \sqrt{\sum_{n \in N} \left(\frac{\sigma_n}{n}\right)^2}, \quad (7.3)$$

where n runs over the set of expected event rates and σ_n is the absolute MC statistical uncertainty associated to each expected event rate n . In the following, the control region used to evaluate the uncertainties on the transfer factors is taken to be the sum of all CRs introduced in section 6.2.

For backgrounds directly estimated from MC simulation, the systematic uncertainty on the expected event rate in each region R_i is given by

$$\Delta n_p^{\text{syst}}(R_i) = \frac{n_p^{\text{syst}}(R_i) n_p^{\text{nominal}}(P)}{n_p^{\text{nominal}}(R_i) n_p^{\text{syst}}(P)} - 1, \quad (7.4)$$

where the region P is a so-called *loose preselection* with minimal analysis selection criteria, used for normalisation of the event rates to be compared. If not otherwise indicated, the loose preselection used for normalisation requires exactly one isolated lepton, 2–3 jets of which at least one is b -tagged, $E_T^{\text{miss}} > 220$ GeV and $m_T > 50$ GeV.

Apart from the hard scattering and parton showering uncertainties on top processes, all other theoretical uncertainties enter the likelihood as asymmetric correlated shape uncertainties. The hard scattering and parton showering uncertainties on top processes described below are estimated using MC generator comparisons.

7.2.1 Background

$t\bar{t}$ and single top

Theory uncertainties on the estimate of $t\bar{t}$ and single top processes arise for example from the simulation of the hard scattering between the interacting partons. These are evaluated by comparing the estimates from the nominal MC datasets generated using POWHEG-Box [199] and PYTHIA8 [193] with those from alternative datasets generated using MADGRAPH_AMC@NLO [190, 191] and PYTHIA8. Uncertainties resulting from the hadronisation and fragmentation scheme chosen in PYTHIA8 are estimated through a comparison to a MC dataset generated using POWHEG and HERWIG++ [255]. Uncertainties arising from initial state radiation are evaluated at full reconstruction level by varying up and down by a factor of two the unphysical renormalisation μ_R and factorisation μ_F scales as well as the parameters controlling

the parton showering and the matching with the matrix elements [256]. Likewise, uncertainties arising from the simulation of final state radiation are estimated by varying the effective coupling α_s^{FSR} [256].

Uncertainties also originate from the parton distribution function (PDF) set used during generation of the nominal MC dataset. As detailed in table 4.1, the NNPDF 3.0 NLO set is used for the simulation of both $t\bar{t}$ and single top processes. An envelope around the variational expected event rates, obtained from the NNPDF 3.0 NLO uncertainties, is used to compute an uncertainty on the transfer factor.

Beyond leading order (LO) single top production diagrams, interference appears between Wt and $t\bar{t}$ production. Two approaches are commonly used to try and isolate the Wt channel: diagram removal and diagram subtraction [257]. While the former removes all diagrams in the next-to-leading order (NLO) Wt amplitude that are doubly resonant, i.e. that involve an intermediate top quark which can be on-shell, the latter introduces subtraction terms in the NLO Wt cross section cancelling the $t\bar{t}$ contribution [257]. As the diagram removal scheme is used for estimating the event rate of the Wt channel in the analysis, a comparison with an estimation using the diagram subtraction scheme allows to derive an uncertainty associated to the interference.

$W/Z + \text{jets}$

For $W/Z + \text{jets}$ processes, simulated using SHERPA 2.2.1 [145, 202], four different unphysical scales can be varied in order to evaluate uncertainties on the modelling. The renormalisation μ_R and factorisation μ_F scales are both varied independently and together up and down by a factor of two, resulting in a total of seven combined variations. Three envelopes are determined from varying only μ_R , only μ_F or μ_R and μ_F together, allowing to determine three separate uncertainties. The CKKW matrix element and parton shower matching scheme also uses an unphysical scale for determining the overlap between jets from the matrix elements and the parton showers. The nominal value of 20 GeV for the merging scale is varied to 30 GeV and 15 GeV for the up and down systematic variations, respectively. Finally, the scale used for resummation of soft gluon emission μ_{QSF} is varied up and down by a factor of two, and the effect on the expected event rates is determined.

An additional uncertainty arises from the choice of PDF set used for simulating $W/Z + \text{jets}$. It is evaluated by propagating the PDF error set (containing slightly different parameterisations of the PDF) to the analysis observables. Uncertainties due to the choice of the strong coupling constant $\alpha_s(m_Z) = 0.118$ for fitting the PDFs are estimated by comparing with variations using $\alpha_s(m_Z) = 0.119$ and $\alpha_s(m_Z) = 0.117$, and are added in quadrature to the PDF uncertainty.

As the $Z + \text{jets}$ process is not normalised to data in a dedicated CR but to its nominal Standard Model (SM) cross section, an additional normalisation uncertainty corresponding to the theoretical uncertainty on the cross section is considered.

Other backgrounds

For diboson, multiboson and $t\bar{t} + V$ processes, uncertainties arising from the unphysical scales μ_F , μ_R as well as μ_{QSF} and the matrix element and parton shower matching scale are considered using the same prescription described above for the $W/Z + \text{jets}$ processes. For these three processes as well as for the other minor backgrounds $V + h$ and $t\bar{t} + h$, additional uncertainties on the SM cross sections used for normalisation are taken into account.

7.2.2 Signal

Theoretical uncertainties on the SUSY signal processes arise from the unphysical factorisation, renormalisation and CKKW-L matrix element and parton shower merging scales. These are evaluated using a similar procedure as for background processes, varying the different scales up and down by a factor of two and comparing the expected signal rates. An additional uncertainty on parton showering originating from the chosen PYTHIA8 tune is estimated by varying up and down the value chosen for α_s^{ISR} .

As detailed in section 4.3.2, the cross sections of electroweakino pair production are calculated using RESUMMINO. Theoretical uncertainties on the cross sections are considered in the following, but do not enter the statistical fit procedure as nuisance parameter. Instead, in addition to the set of observed CL_s values using the nominal cross section, two additional variational sets are derived using signal cross sections fixed at their $\pm 1\sigma$ variations. This allows to draw a cross section uncertainties band on the observed exclusion contour.

Due to the large number of MC samples, all theory uncertainties on SUSY signal processes are evaluated at MC truth-level only. As the validation regions (VRs) typically have relatively low signal contamination and thus low signal MC statistics available for evaluating theory uncertainties, requirements on observables with negligible impact on the shapes of the theoretical uncertainties are relaxed. In the on-peak VRs, the requirements relaxed are $m_T > 60$ GeV and $E_T^{\text{miss}} > 140$ GeV. The same relaxed selection is applied in signal regions (SRs) in cases where the MC statistical uncertainties are too high for a reliable estimation of the theoretical uncertainties. In the off-peak VRs, the requirements relaxed are $m_T > 60$ GeV, $E_T^{\text{miss}} > 60$ GeV and $m_{\text{CT}} > 60$ GeV. Overall, the theoretical uncertainties on the expected signal rate range from about 10% in phase space regions with large mass splitting to about 25% in regions with small mass splittings.

7.3 Impact on signal regions

Table 7.1 shows a breakdown of the dominant systematic uncertainties on the background prediction in the SRs, obtained after a background-only fit in the CRs with subsequent extrapolation to the SRs. The total uncertainties in the SRs amount to 15% in SR-LM and increases to 25% in SR-MM and 34% in SR-HM. Theoretical uncertainties give the largest contribution to the total uncertainties. For SR-LM, the largest uncertainties, amounting to 10% of the total background estimate, originate from the $t\bar{t}$ parton shower uncertainties. For SR-MM (SR-HM), the single top generator uncertainties are the largest ones with 10% (21%) of the total background estimate. Theoretical uncertainties on W + jets and other minor backgrounds have only small to negligible effects. The experimental uncertainties in general have less impact on the total uncertainties than the theoretical ones, with the largest experimental uncertainties contributing only 5–10%, depending on the SR. The dominant experimental uncertainties arise from the JES and JER, as well as from E_T^{miss} modelling and pile-up effects. The MC statistical uncertainties contribute 5–18%, depending on the signal region.

Table 7.1: Breakdown of the dominant systematic uncertainties on the background estimates in the various exclusion signal regions (m_{CT} bins summed up). As the individual uncertainties can be correlated, they do not necessarily add up in quadrature to the total background uncertainties. The percentages show the size of the uncertainties relative to the total expected background. Table adapted from Ref. [185].

Signal Region	SR-LM	SR-MM	SR-HM
Total background expectation	27	8.6	8.1
Total uncertainty	± 4 [15%]	± 2.2 [25%]	± 2.7 [34%]
Theoretical systematic uncertainties			
$t\bar{t}$	± 2.6 [10%]	± 0.6 [7%]	± 0.33 [4%]
Single top	± 0.8 [2.7%]	± 1.1 [12%]	± 1.9 [23%]
W +jets	± 0.23 [0.9%]	± 0.07 [0.8%]	± 0.19 [2.3%]
Other backgrounds	± 0.13 [0.5%]	± 0.15 [1.7%]	± 0.08 [1.0%]
MC statistical uncertainties			
MC statistics	± 1.7 [6%]	± 1.1 [13%]	± 1.2 [14%]
Uncertainties in the background normalisation			
Normalisation of dominant backgrounds	± 1.3 [5%]	± 1.6 [18%]	± 1.3 [16%]
Experimental systematic uncertainties			
$E_{\text{T}}^{\text{miss}}$ /JVT/pile-up/trigger	± 1.8 [7%]	± 0.4 [4%]	± 0.4 [5%]
Jet energy resolution	± 1.6 [6%]	± 0.5 [6%]	± 0.4 [5%]
b -tagging	± 1.1 [4%]	± 0.29 [3.4%]	± 0.13 [1.5%]
Jet energy scale	± 0.9 [3.2%]	± 0.9 [10%]	± 0.29 [4%]
Lepton uncertainties	± 0.32 [1.2%]	± 0.09 [1.0%]	± 0.19 [2.3%]

Part III

Reinterpretation

Part IV

Summary and Outlook

Part V

Appendices

Appendix A

Additional analysis material

This appendix provides additional analysis material for the 1ℓ search presented in part II of this thesis.

A.1 Kinematic distributions

Figure A.1 illustrates the dependence of the distributions of relevant kinematic observables on the electroweakino mass scale and the mass difference between $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. In the plots on the left column of fig. A.1, only $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$ is varied while $m(\tilde{\chi}_1^0)$ is kept to be massless. On the right-hand side of fig. A.1, $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$ is fixed at 450 GeV, while $m(\tilde{\chi}_1^0)$ is varied. As can be observed, model points with increasing $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ mass show increasing values in kinematic observables like E_T^{miss} , m_T , m_{CT} and the p_T of the lepton. Model points with increasingly small electroweakino mass differences tend to exhibit less E_T^{miss} and overall softer objects (as e.g. more events with leptons with relatively low p_T).

A.2 Signal region optimisation

A.2.1 Raw results from N -dimensional scan

Figure A.2 shows the results of the N -dimensional cut scan for all benchmark signal points considered. As in chapter 5, three different uncertainty configurations are used for computing the significance Z_B , and all values are computed for the two statistically independent subsets of the MC datasets used during the N -dimensional scan. This approach allows to gauge the impact of statistical fluctuations on the cut combinations tested.

By choosing a well-performing cut combination for each benchmark point, the optimised selections in figs. A.3 to A.8 are found after a round of $N-1$ plots. As discussed in section 5.2.2 the optimal cut combinations for each benchmark signal point are consolidated into multiple signal regions designed to be sensitive to different kinematic regions of the model parameter space.

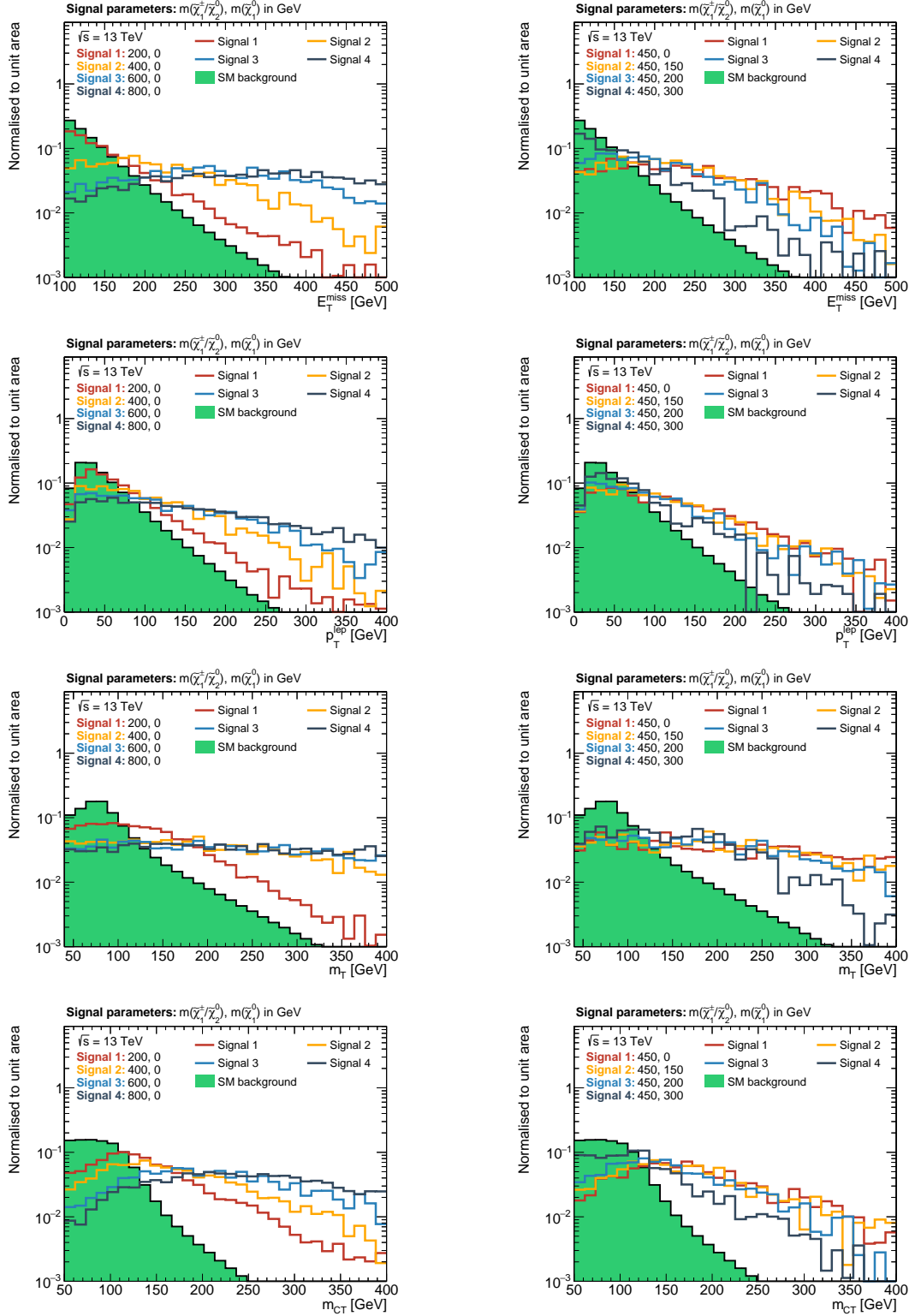


Figure A.1: Dependence of some of the kinematic observables on the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ mass scale (left) and $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0 - \tilde{\chi}_1^0$ mass differences (right). The simulated SM backgrounds are stacked on top of each other and summarised in a single ‘SM’ histogram. Distributions from exemplary signal models with the quoted mass parameters are overlaid. In order to emphasise the shape differences, both total background and signal distributions are normalised to unity. A preselection requiring a lepton, at least two jets and $E_T^{\text{miss}} > 100$ GeV is applied.

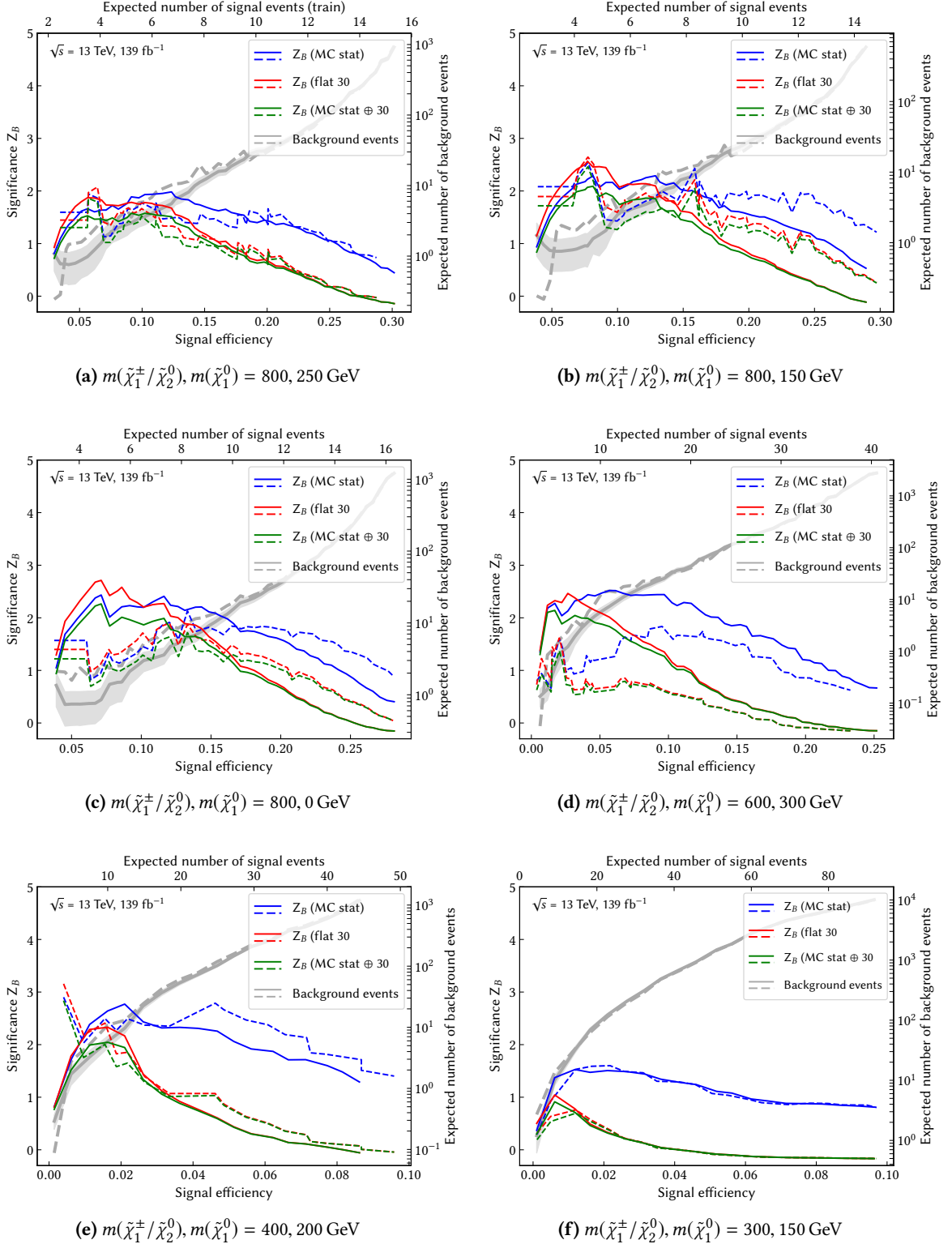


Figure A.2: Results of the N -dimensional cut scan for all benchmark points. The binomial discovery significance Z_B is plotted against the signal efficiency for varying uncertainty configurations. Additionally, the expected SM background rates are shown, including statistical uncertainties for one of the two statistically independent samples (shaded area). The solid and dashed lines represent the two statistically independent subsets that the MC datasets are split into.

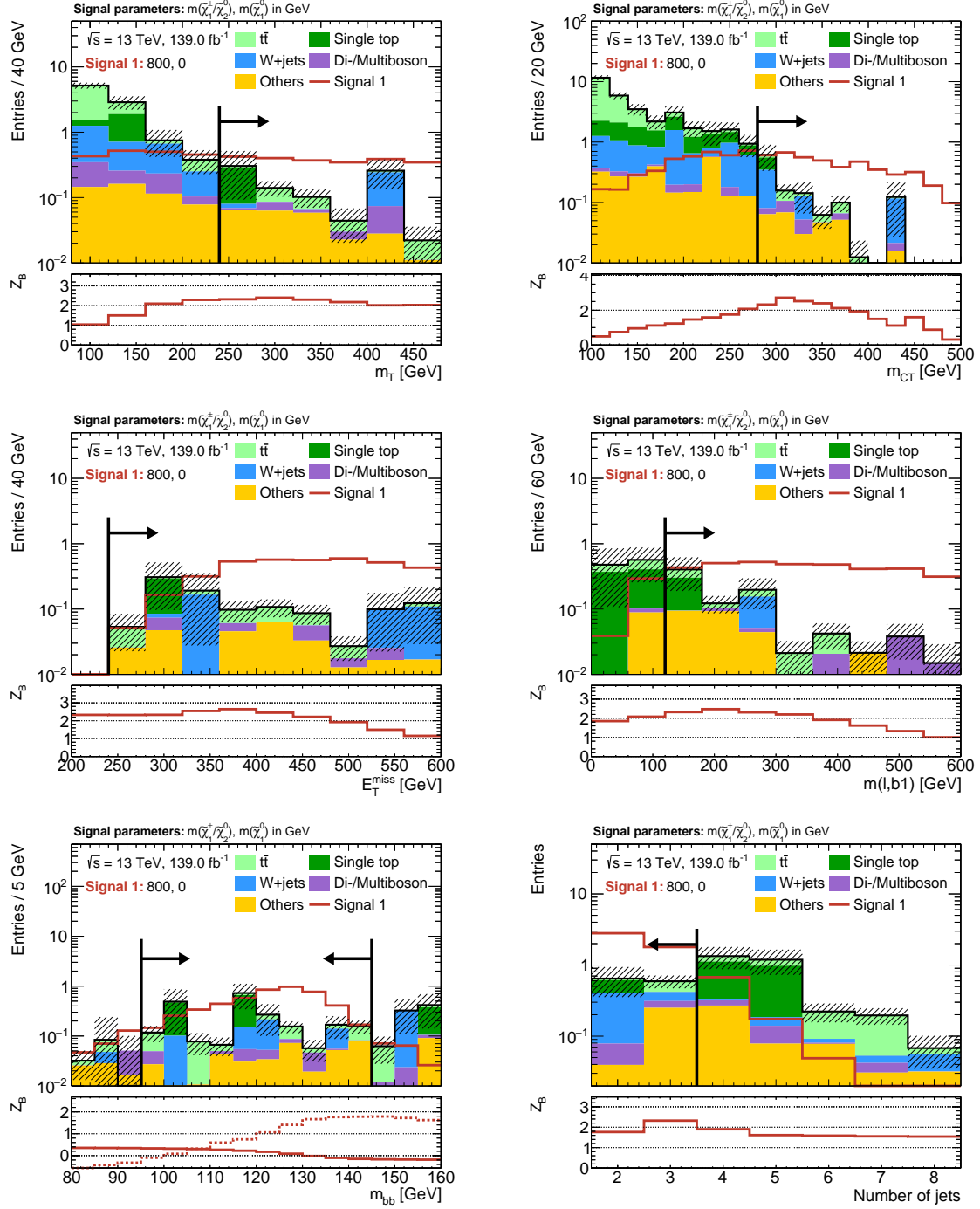


Figure A.3: $N-1$ plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (800 \text{ GeV}, 0 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

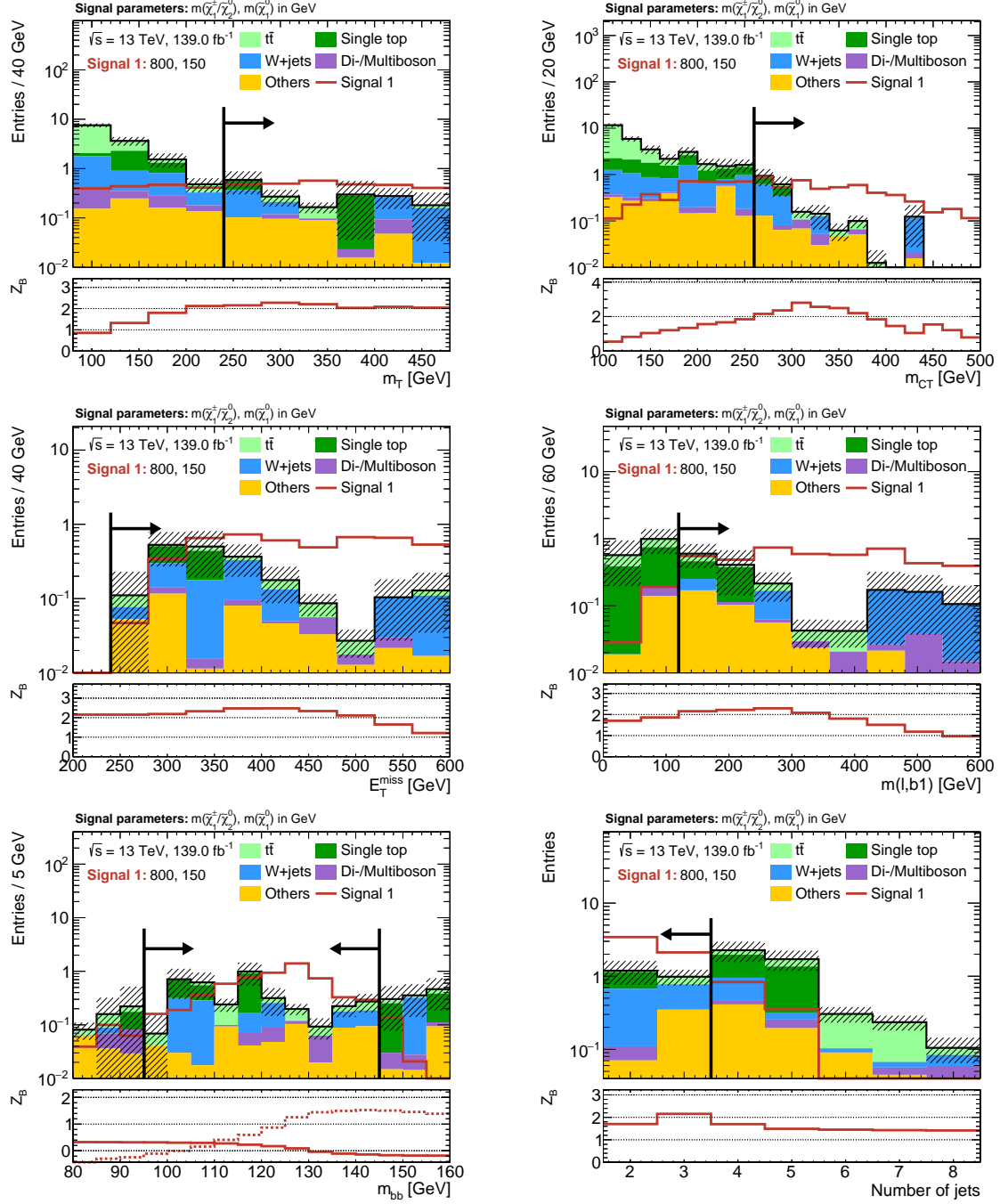


Figure A.4: N-1 plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (800 \text{ GeV}, 150 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

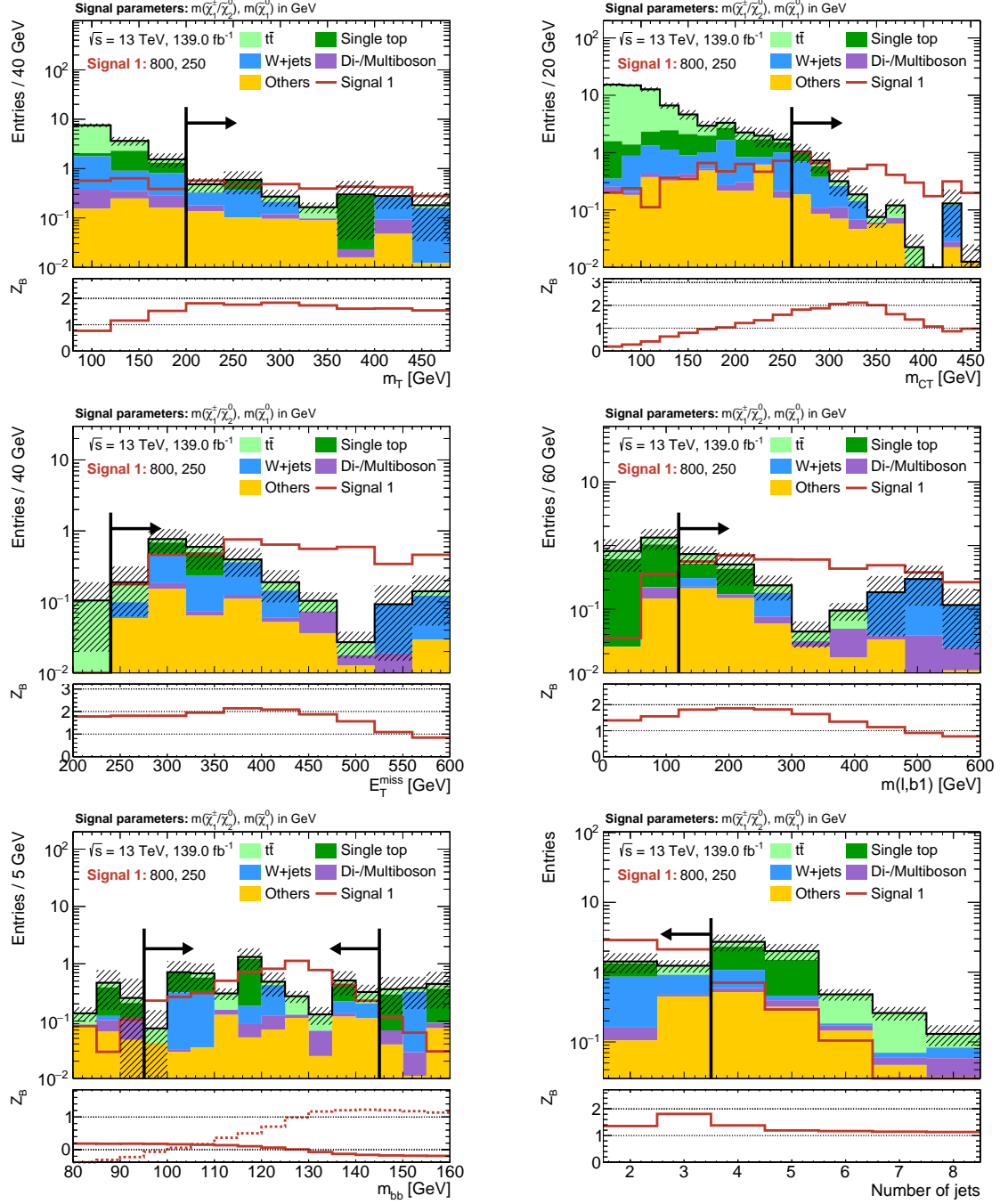


Figure A.5: $N-1$ plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (800 \text{ GeV}, 250 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

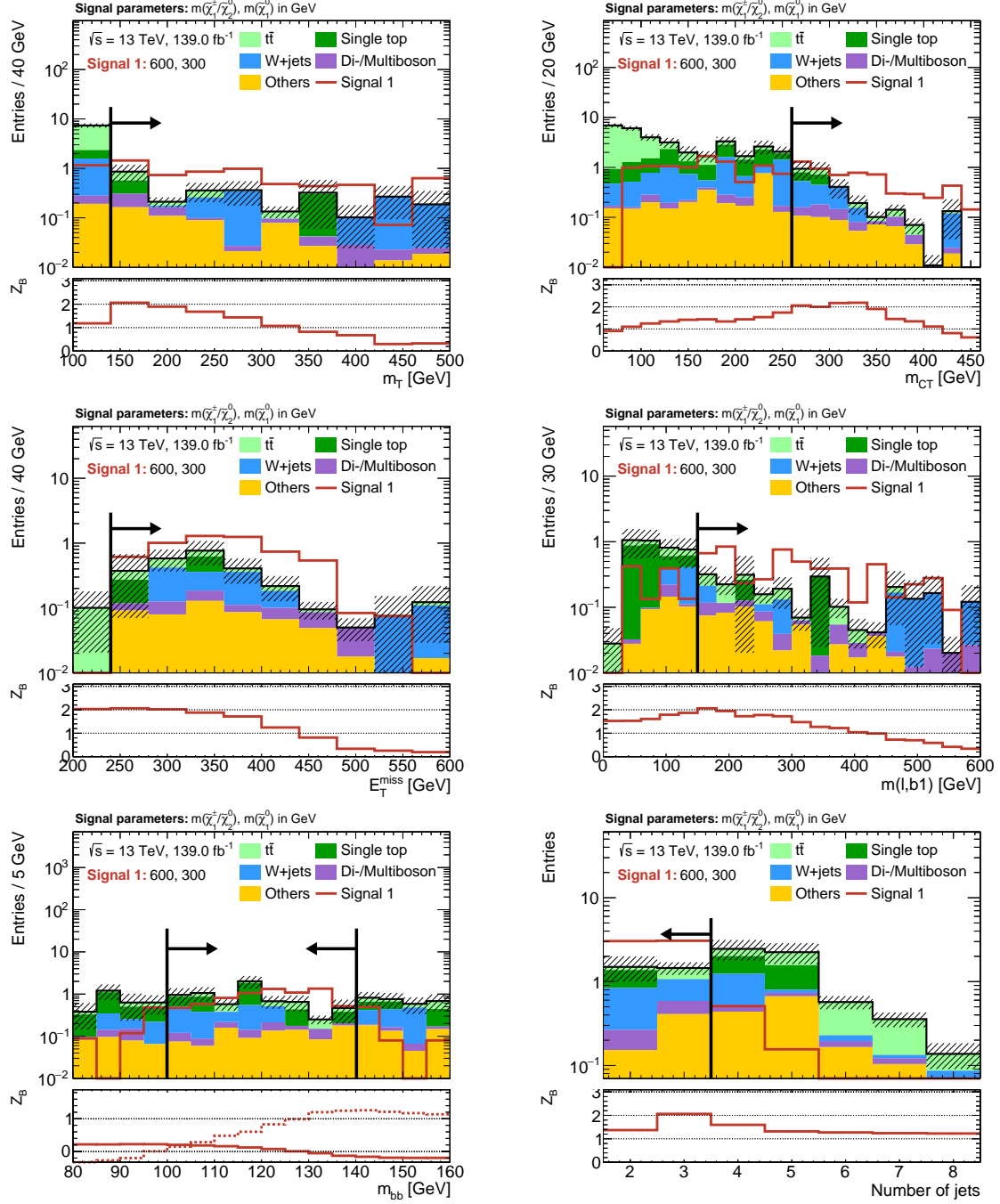


Figure A.6: $N-1$ plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (600 \text{ GeV}, 300 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

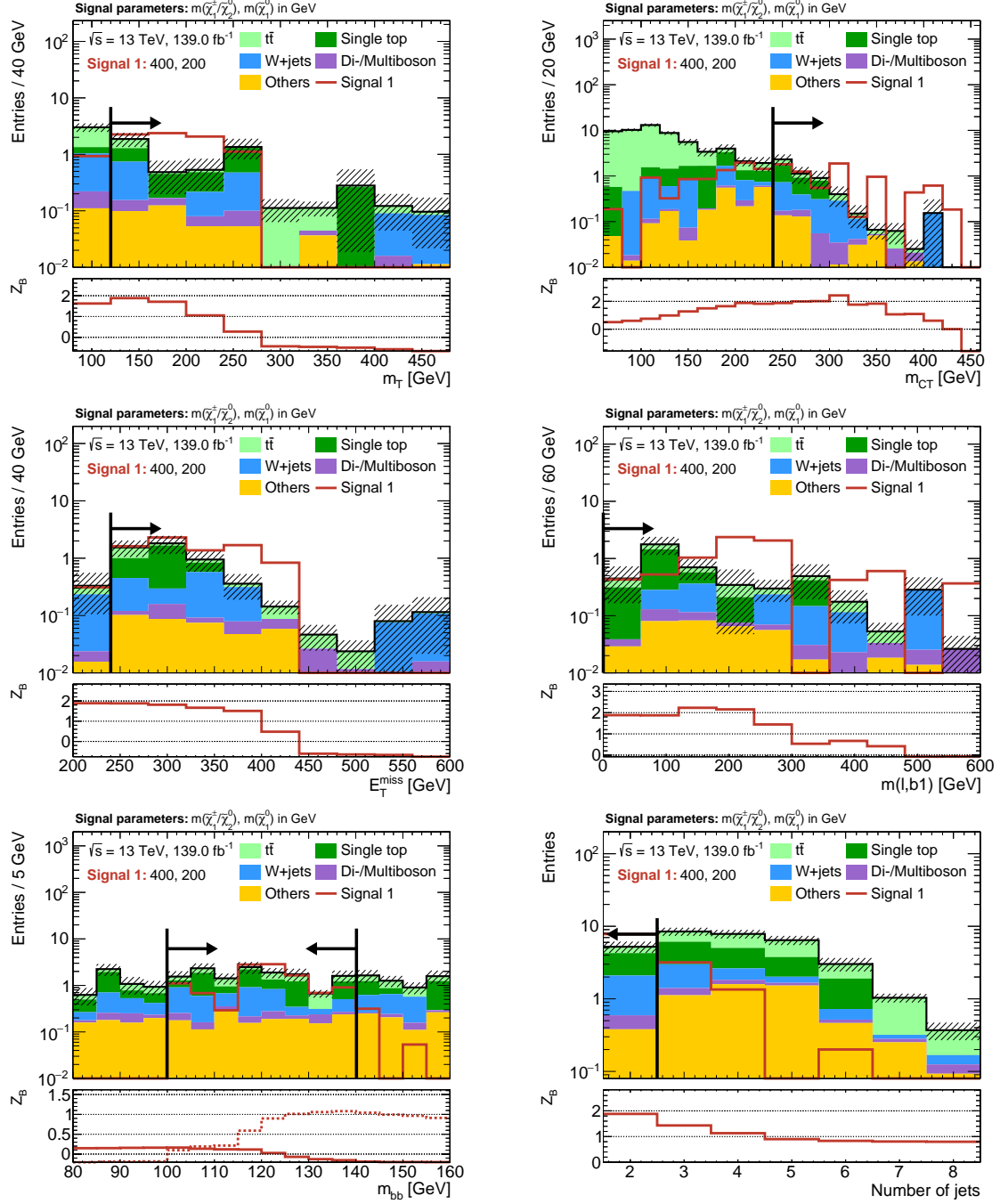


Figure A.7: N-1 plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (400 \text{ GeV}, 200 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

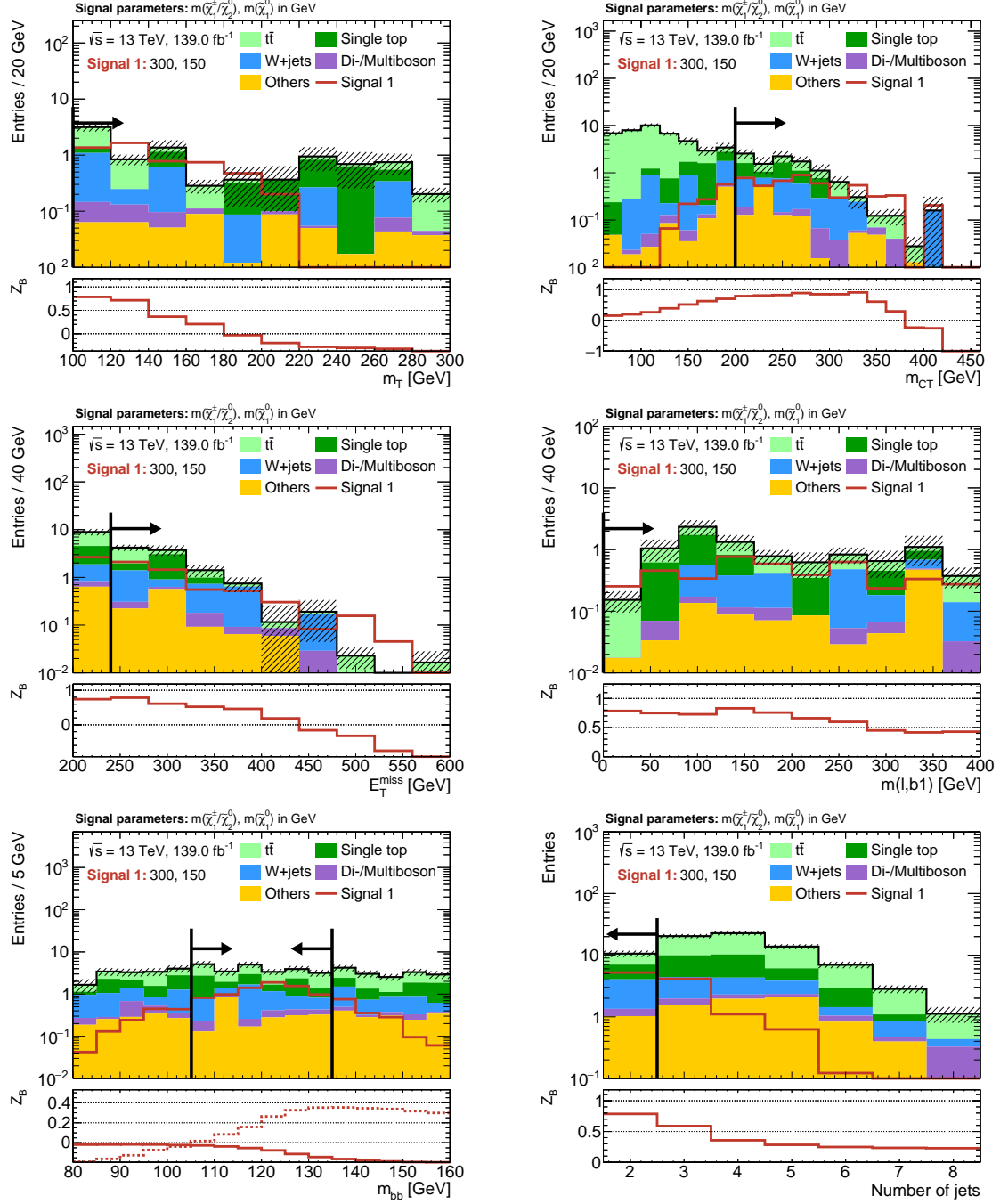


Figure A.8: $N-1$ plots for the chosen cut combination for the $(m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)) = (300 \text{ GeV}, 150 \text{ GeV})$ signal point. The shaded region includes MC statistical as well as 30% systematic uncertainties (added in quadrature) on the background. The significance is computed using the binomial discovery significance using the uncertainty on the background.

A.2.2 Impact of $m_{\ell b_1}$

As discussed in section 4.6, the distribution of $m_{\ell b_1}$ has a kinematic endpoint at about 153 GeV for $t\bar{t}$ and single top production events where the lepton and leading b -jet originate from the same top quark decay. In the SUSY processes considered, $m_{\ell b_1}$ depends on the mass-scale of the electroweakinos pair-produced, and thus offers especially good discriminative power in the high electroweakino mass regime targeted by SR-HM.

Figure A.9 illustrates the impact of adding a requirement of $m_{\ell b_1} > 120$ GeV in SR-HM, revealing a noticeable increase in sensitivity towards high electroweakino masses. Studies have shown that the addition of $m_{\ell b_1} > 120$ GeV to the remaining signal regions does not improve the sensitivity further.

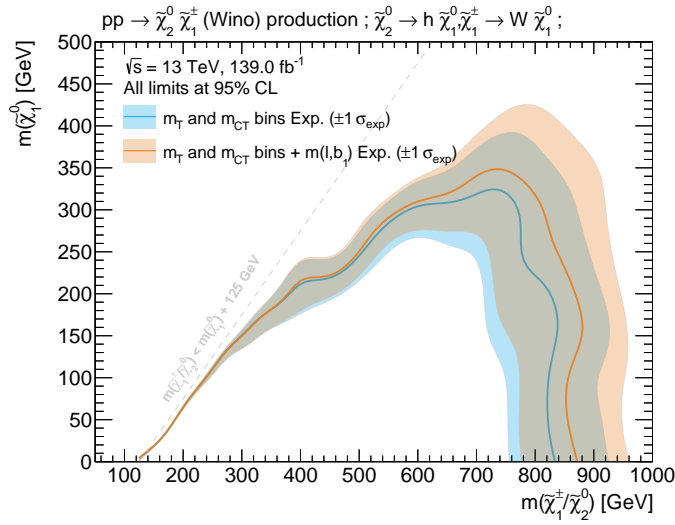


Figure A.9: Comparison of different shape-fit configurations, illustrating the sensitivity increase achieved through a requirement on high $m_{\ell b_1}$ values in SR-HM on top of the two-dimensional shape-fit in m_T and m_{CT} . All exclusion limits shown are expected limits at 95% CL, using MC statistical and 30% systematic uncertainties. Background estimation in the signal regions is taken directly from MC for all SM backgrounds.

A.3 Background estimation

The signal contamination in all validation regions is shown in fig. A.10. In the VR-off regions the maximum signal contamination is found to be about 7%–13%, depending on the requirement on m_T . In the VR-on regions, the maximum signal contamination amounts to about 5%–14%, depending again on the m_T -bin.

A.4 Summary of results of ATLAS searches for SUSY

Figure A.11 provides a comprehensive summary of current results of ATLAS searches for SUSY. The limits on the sparticle masses set by different searches in various models and signatures are given.

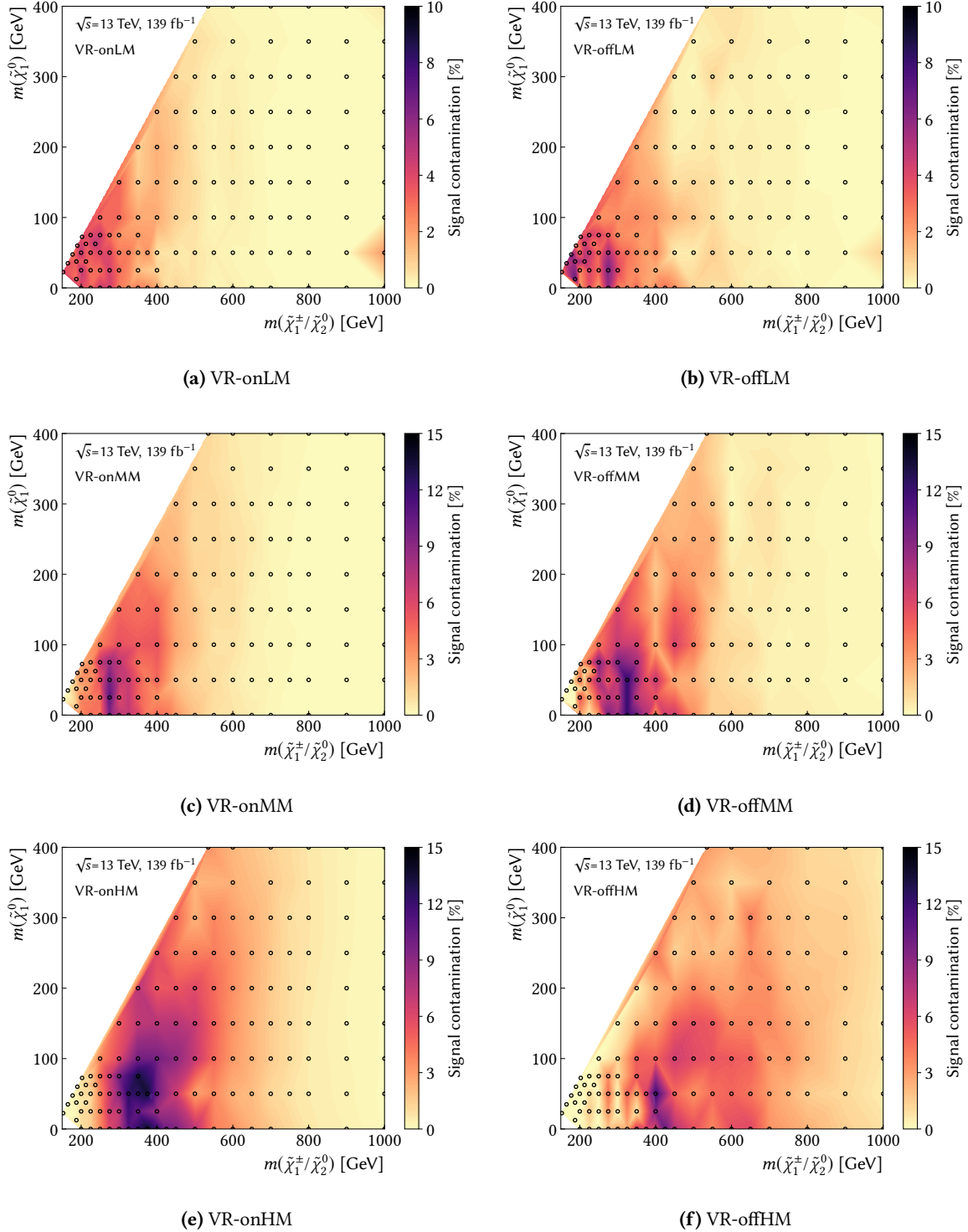
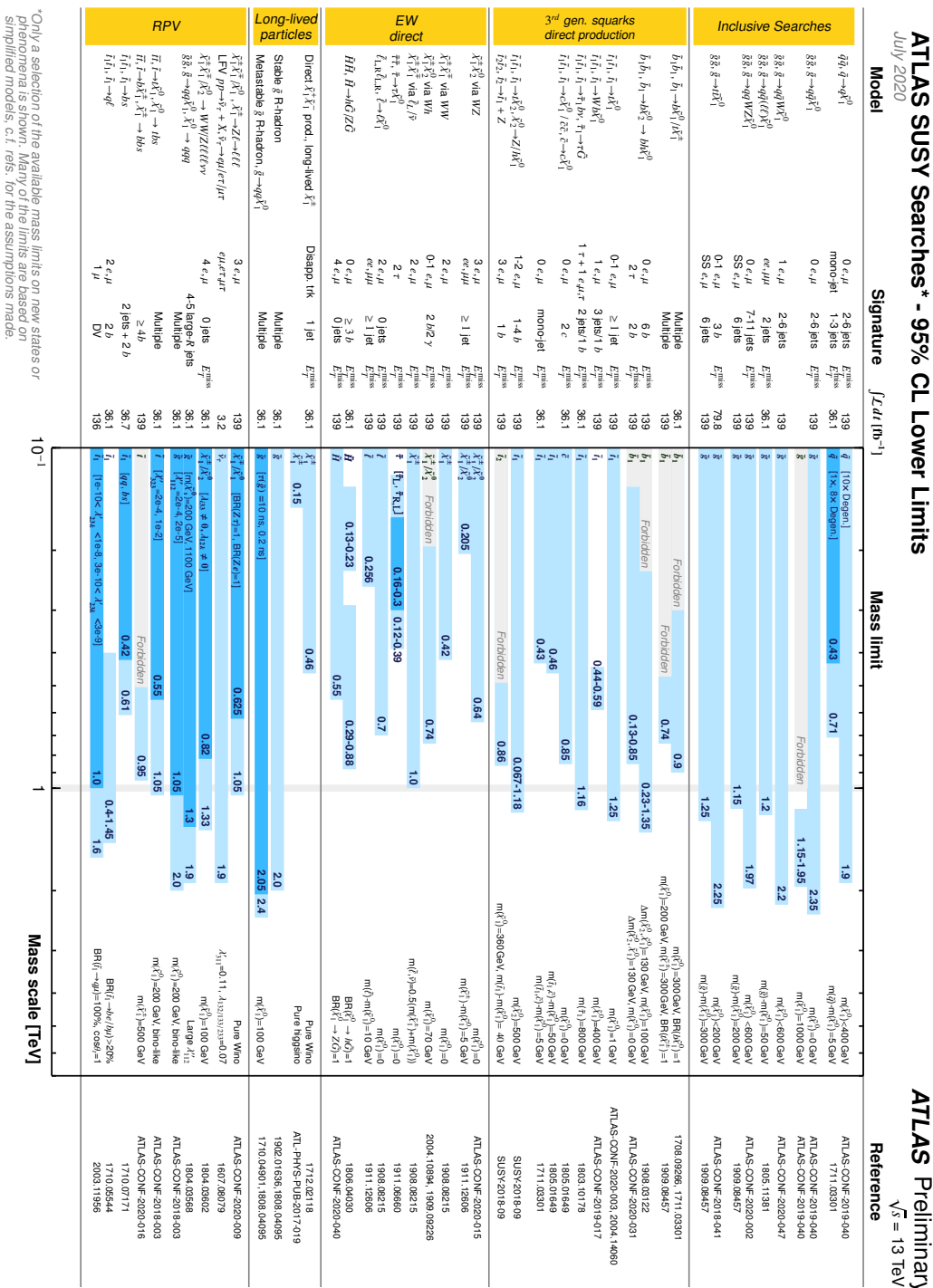


Figure A.10: Signal contamination (shown on the z -axis) for all VRs throughout the signal grid. The space between the signal points (indicated by the black circles) is interpolated using Delaunay triangles.

Figure A.11: Summary of the results of ATLAS searches for SUSY. A representative selection of the available search results is shown. Results are given with respect to the nominal cross section. In some cases additional dependencies are indicated by darker bands showing different model parameters. Figure adapted from Ref. [258].



Abbreviations

CR control region. [109–112](#)

JER jet energy resolution. [108](#), [109](#), [112](#)

JES jet energy scale. [108](#), [109](#), [112](#)

LO leading order. [111](#)

MC Monte Carlo. [107–112](#), [179](#), [181–188](#)

NLO next-to-leading order. [111](#)

PDF parton distribution function. [111](#)

SM Standard Model. [111](#), [180](#), [181](#), [188](#)

SR signal region. [112](#)

SUSY Supersymmetry. [109](#), [112](#), [188–190](#)

vdM van der Meer. [107](#)

VR validation region. [112](#), [189](#)

Bibliography

- [1] ATLAS Collaboration, “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, [arXiv:1207.7214 \[hep-ex\]](#).
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Phys. Lett. B* **716** (2012) 30, [arXiv:1207.7235 \[hep-ex\]](#).
- [3] I. C. Brock and T. Schorner-Sadenius, *Physics at the terascale*. Wiley, Weinheim, 2011. <https://cds.cern.ch/record/1354959>.
- [4] 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>.
- [5] S. P. Martin, “A Supersymmetry primer,” [arXiv:hep-ph/9709356v7 \[hep-ph\]](#). [Adv. Ser. Direct. High Energy Phys.18,1(1998)].
- [6] 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 \[hep-ph\]](#).
- [7] L. Brown, *The Birth of particle physics*. Cambridge University Press, Cambridge Cambridgeshire New York, 1986.
- [8] 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 \[physics.atom-ph\]](#).
- [9] Particle Data 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>.
- [10] Super-Kamiokande Collaboration, “Evidence for oscillation of atmospheric neutrinos,” *Phys. Rev. Lett.* **81** (1998) 1562–1567, [arXiv:hep-ex/9807003 \[hep-ex\]](#).
- [11] Z. Maki, M. Nakagawa, and S. Sakata, “Remarks on the unified model of elementary particles,” *Prog. Theor. Phys.* **28** (1962) 870–880. [,34(1962)].
- [12] 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>.
- [13] M. Kobayashi and T. Maskawa, “CP Violation in the Renormalizable Theory of Weak Interaction,” *Prog. Theor. Phys.* **49** (1973) 652–657.
- [14] E. Noether and M. A. Tavel, “Invariant variation problems,” [arXiv:physics/0503066](#).
- [15] 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>.

- [16] 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>.
- [17] 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>.
- [18] 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>.
- [19] 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>.
- [20] 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>.
- [21] K. G. Wilson, "Confinement of quarks," *Phys. Rev. D* **10** (Oct, 1974) 2445–2459. <https://link.aps.org/doi/10.1103/PhysRevD.10.2445>.
- [22] T. DeGrand and C. DeTar, *Lattice Methods for Quantum Chromodynamics*. World Scientific, Singapore, 2006. <https://cds.cern.ch/record/1055545>.
- [23] S. L. Glashow, "Partial-symmetries of weak interactions," *Nuclear Physics* **22** no. 4, (1961) 579 – 588. <http://www.sciencedirect.com/science/article/pii/0029558261904692>.
- [24] S. Weinberg, "A model of leptons," *Phys. Rev. Lett.* **19** (Nov, 1967) 1264–1266. <https://link.aps.org/doi/10.1103/PhysRevLett.19.1264>.
- [25] 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>.
- [26] C. S. Wu, E. Ambler, R. W. Hayward, *et al.*, "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>.
- [27] 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>.
- [28] 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>.
- [29] 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>.
- [30] 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>.
- [31] 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>.
- [32] 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>.
- [33] Y. Nambu, "Quasiparticles and Gauge Invariance in the Theory of Superconductivity," *Phys. Rev.* **117** (1960) 648–663. [,132(1960)].
- [34] J. Goldstone, "Field Theories with Superconductor Solutions," *Nuovo Cim.* **19** (1961) 154–164.

- [35] 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 \[hep-ph\]](#).
- [36] 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>.
- [37] G. L. Kane, *The supersymmetric world : the beginnings of the theory*. World Scientific, Singapore River Edge, NJ, 2000.
- [38] F. Zwicky, “Die Rotverschiebung von extragalaktischen Nebeln,” *Helv. Phys. Acta* **6** (1933) 110–127. <https://cds.cern.ch/record/437297>.
- [39] 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.
- [40] G. Bertone, D. Hooper, and J. Silk, “Particle dark matter: Evidence, candidates and constraints,” *Phys. Rept.* **405** (2005) 279–390, [arXiv:hep-ph/0404175](#).
- [41] D. Clowe, M. Bradac, A. H. Gonzalez, *et al.*, “A direct empirical proof of the existence of dark matter,” *Astrophys. J.* **648** (2006) L109–L113, [arXiv:astro-ph/0608407 \[astro-ph\]](#).
- [42] A. Taylor, S. Dye, T. J. Broadhurst, *et al.*, “Gravitational lens magnification and the mass of abell 1689,” *Astrophys. J.* **501** (1998) 539, [arXiv:astro-ph/9801158](#).
- [43] 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](#).
- [44] G. F. Smoot *et al.*, “Structure in the COBE Differential Microwave Radiometer First-Year Maps,” *ApJS* **396** (September, 1992) L1.
- [45] WMAP Collaboration, “Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results,” *ApJS* **208** no. 2, (October, 2013) 20, [arXiv:1212.5225 \[astro-ph.CO\]](#).
- [46] WMAP Collaboration, “Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results,” *ApJS* **208** no. 2, (October, 2013) 19, [arXiv:1212.5226 \[astro-ph.CO\]](#).
- [47] Planck Collaboration, “Planck 2018 results. I. Overview and the cosmological legacy of Planck,” *Astron. Astrophys.* **641** (2020) A1, [arXiv:1807.06205 \[astro-ph.CO\]](#).
- [48] A. Liddle, *An introduction to modern cosmology; 3rd ed.* Wiley, Chichester, Mar, 2015. <https://cds.cern.ch/record/1976476>.
- [49] Planck Collaboration, “Planck 2018 results. VI. Cosmological parameters,” *Astron. Astrophys.* **641** (2020) A6, [arXiv:1807.06209 \[astro-ph.CO\]](#).
- [50] 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>.
- [51] I. Aitchison, *Supersymmetry in Particle Physics. An Elementary Introduction*. Cambridge University Press, Cambridge, 2007.
- [52] Muon g-2 Collaboration, “Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL,” *Phys. Rev. D* **73** (2006) 072003, [arXiv:hep-ex/0602035](#).
- [53] H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events*. Cambridge University Press, 2006.

- [54] T. Aoyama *et al.*, “The anomalous magnetic moment of the muon in the Standard Model,” *Phys. Rept.* **887** (2020) 1–166, [arXiv:2006.04822 \[hep-ph\]](#).
- [55] Muon g-2 Collaboration, “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm,” *Phys. Rev. Lett.* **126** no. 14, (2021) 141801, [arXiv:2104.03281 \[hep-ex\]](#).
- [56] 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](#).
- [57] 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](#).
- [58] 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>.
- [59] R. Haag, J. T. Lopuszanski, and M. Sohnius, “All Possible Generators of Supersymmetries of the s Matrix,” *Nucl. Phys.* **B88** (1975) 257. [257(1974)].
- [60] J. Wess and B. Zumino, “Supergauge transformations in four dimensions,” *Nucl. Phys. B* **70** (1974) 39.
- [61] 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>.
- [62] S. Dimopoulos and D. W. Sutter, “The Supersymmetric flavor problem,” *Nucl. Phys. B* **452** (1995) 496–512, [arXiv:hep-ph/9504415](#).
- [63] MEG Collaboration, T. Mori, “Final Results of the MEG Experiment,” *Nuovo Cim. C* **39** no. 4, (2017) 325, [arXiv:1606.08168 \[hep-ex\]](#).
- [64] H. P. Nilles, “Supersymmetry, Supergravity and Particle Physics,” *Phys. Rept.* **110** (1984) 1–162.
- [65] 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>.
- [66] J. L. Feng, A. Rajaraman, and F. Takayama, “Superweakly interacting massive particles,” *Phys. Rev. Lett.* **91** (2003) 011302, [arXiv:hep-ph/0302215](#).
- [67] S. Y. Choi, J. Kalinowski, G. A. Moortgat-Pick, and P. M. Zerwas, “Analysis of the neutralino system in supersymmetric theories,” *Eur. Phys. J. C* **22** (2001) 563–579, [arXiv:hep-ph/0108117](#). [Addendum: *Eur.Phys.J.C* 23, 769–772 (2002)].
- [68] Super-Kamiokande Collaboration, “Search for proton decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ in 0.31 megaton-years exposure of the Super-Kamiokande water Cherenkov detector,” *Phys. Rev. D* **95** no. 1, (2017) 012004, [arXiv:1610.03597 \[hep-ex\]](#).
- [69] 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](#).
- [70] J. R. Ellis, J. Hagelin, D. V. Nanopoulos, *et al.*, “Supersymmetric Relics from the Big Bang,” *Nucl. Phys. B* **238** (1984) 453–476.
- [71] D. O. Caldwell, R. M. Eisberg, D. M. Grumm, *et al.*, “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>.
- [72] M. Mori, M. M. Nojiri, K. S. Hirata, *et al.*, “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>.

- [73] 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](#).
- [74] 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](#).
- [75] 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>.
- [76] J. Alwall, P. Schuster, and N. Toro, “Simplified Models for a First Characterization of New Physics at the LHC,” *Phys. Rev. D* **79** (2009) 075020, [arXiv:0810.3921 \[hep-ph\]](#).
- [77] L. N. P. W. Group, “Simplified Models for LHC New Physics Searches,” *J. Phys. G* **39** (2012) 105005, [arXiv:1105.2838 \[hep-ph\]](#).
- [78] 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 \[hep-ph\]](#).
- [79] F. Ambrogio, S. Kraml, S. Kulkarni, *et al.*, “On the coverage of the pMSSM by simplified model results,” *Eur. Phys. J. C* **78** no. 3, (2018) 215, [arXiv:1707.09036 \[hep-ph\]](#).
- [80] 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 \[hep-ph\]](#).
- [81] W. Beenakker, C. Borschensky, M. Krämer, *et al.*, “NNLL-fast: predictions for coloured supersymmetric particle production at the LHC with threshold and Coulomb resummation,” *JHEP* **12** (2016) 133, [arXiv:1607.07741 \[hep-ph\]](#).
- [82] M. Beneke, M. Czakon, P. Falgari, *et al.*, “Threshold expansion of the $gg(q\bar{q}) \rightarrow Q\bar{Q} + X$ cross section at $\mathcal{O}(\alpha_s^4)$,” *Phys. Lett. B* **690** (2010) 483, [arXiv:0911.5166 \[hep-ph\]](#).
- [83] 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 \[hep-ph\]](#).
- [84] 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 \[hep-ph\]](#).
- [85] J. Fiaschi and M. Klasen, “Slepton pair production at the LHC in NLO+NLL with resummation-improved parton densities,” *JHEP* **03** (2018) 094, [arXiv:1801.10357 \[hep-ph\]](#).
- [86] 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 \[hep-ex\]](#).
- [87] 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 \[hep-ex\]](#).
- [88] 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.
- [89] CMS Collaboration, “Summary plot moriond 2017,” https://twiki.cern.ch/twiki/pub/CMSPublic/SUSYSummary2017/Moriond2017_BarPlot.pdf, 2017.

- [90] 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.
- [91] ATLAS Collaboration, “Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector,” *Phys. Rev. D* **101** (2020) 052005, [arXiv:1911.12606 \[hep-ex\]](#).
- [92] ATLAS Collaboration, “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 \[hep-ex\]](#).
- [93] CMS Collaboration, “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 \[hep-ex\]](#).
- [94] A. Buckley, “PySLHA: a Pythonic interface to SUSY Les Houches Accord data,” *Eur. Phys. J. C* **75** no. 10, (2015) 467, [arXiv:1305.4194 \[hep-ph\]](#).
- [95] CERN, “About cern.” <https://home.cern/about>. Accessed: 2021-01-21.
- [96] CERN, “CERN Annual report 2019,” tech. rep., CERN, Geneva, 2020. <https://cds.cern.ch/record/2723123>.
- [97] O. S. Bruning, P. Collier, P. Lebrun, *et al.*, *LHC Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2004. <https://cds.cern.ch/record/782076>.
- [98] 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.
- [99] 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).
- [100] R. Scrivens, M. Kronberger, D. Kuchler, *et al.*, “Overview of the status and developments on primary ion sources at CERN*,”. <https://cds.cern.ch/record/1382102>.
- [101] M. Vretenar, J. Vollaie, R. Scrivens, *et al.*, *Linac4 design report*, vol. 6 of *CERN Yellow Reports: Monographs*. CERN, Geneva, 2020. <https://cds.cern.ch/record/2736208>.
- [102] E. Mobs, “The CERN accelerator complex - 2019. Complexe des accélérateurs du CERN - 2019,”. <https://cds.cern.ch/record/2684277>. General Photo.
- [103] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider,” *JINST* **3** (2008) S08003.
- [104] CMS Collaboration, “The CMS Experiment at the CERN LHC,” *JINST* **3** (2008) S08004.
- [105] ALICE Collaboration, “The ALICE experiment at the CERN LHC,” *JINST* **3** (2008) S08002.
- [106] LHCb Collaboration, “The LHCb Detector at the LHC,” *JINST* **3** (2008) S08005.
- [107] TOTEM Collaboration, “The TOTEM experiment at the CERN Large Hadron Collider,” *JINST* **3** (2008) S08007.
- [108] LHCf Collaboration, “Technical design report of the LHCf experiment: Measurement of photons and neutral pions in the very forward region of LHC,”.
- [109] MoEDAL Collaboration, “Technical Design Report of the MoEDAL Experiment,”.
- [110] ATLAS Collaboration, “ATLAS Public Results - Luminosity Public Results Run 2,”. <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>. Accessed: 2021-01-17.

- [111] ATLAS Collaboration, Z. Marshall, “Simulation of Pile-up in the ATLAS Experiment,” *J. Phys. Conf. Ser.* **513** (2014) 022024.
- [112] “First beam in the LHC - accelerating science,” <https://home.cern/news/news/accelerators/record-luminosity-well-done-lhc>. Accessed: 2021-01-10.
- [113] ATLAS 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>.
- [114] ATLAS Collaboration, “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](https://arxiv.org/abs/1608.03953) [hep-ex].
- [115] G. Avoni, M. Bruschi, G. Cabras, *et al.*, “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>.
- [116] 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>.
- [117] 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>.
- [118] M. Bajko *et al.*, “Report of the Task Force on the Incident of 19th September 2008 at the LHC,” Tech. Rep. LHC-PROJECT-Report-1168. CERN-LHC-PROJECT-Report-1168, CERN, Geneva, Mar, 2009. <https://cds.cern.ch/record/1168025>.
- [119] “New schedule for CERN’s accelerators and experiments,” <https://home.cern/news/press-release/cern/first-beam-lhc-accelerating-science>. Accessed: 2021-01-10.
- [120] ATLAS Collaboration, “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](https://arxiv.org/abs/1101.2185) [hep-ex].
- [121] ATLAS Collaboration, “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, (Feb, 2013) 2518. 27 p. <https://cds.cern.ch/record/1517411>.
- [122] “Record luminosity: well done LHC,” <https://home.cern/news/news/accelerators/new-schedule-cerns-accelerators-and-experiments>. Accessed: 2021-01-10.
- [123] CERN, “New schedule for CERN’s accelerators and experiments,” November, 2020. <https://home.cern/news/news/accelerators/new-schedule-cerns-accelerators-and-experiments>. Accessed: 2021-03-12.
- [124] A. G., B. A. I., B. O., *et al.*, *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>.
- [125] J. Pequeno, “Computer generated image of the whole ATLAS detector.” Mar, 2008.
- [126] ATLAS Collaboration, “ATLAS: Detector and physics performance technical design report. Volume 1,”.
- [127] J. Pequeno, “Computer generated image of the ATLAS inner detector.” Mar, 2008.

- [128] ATLAS 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.
- [129] ATLAS IBL Collaboration, “Production and Integration of the ATLAS Insertable B-Layer,” *JINST* **13** no. 05, (2018) T05008, [arXiv:1803.00844](https://arxiv.org/abs/1803.00844) [physics.ins-det].
- [130] 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>.
- [131] 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** no. 11, (2019) 970, [arXiv:1907.05120](https://arxiv.org/abs/1907.05120) [hep-ex].
- [132] ATLAS Collaboration, “Particle Identification Performance of the ATLAS Transition Radiation Tracker.” ATLAS-CONF-2011-128, 2011. <https://cds.cern.ch/record/1383793>.
- [133] J. Pequeno, “Computer Generated image of the ATLAS calorimeter.” Mar, 2008.
- [134] J. Pequeno, “Computer generated image of the ATLAS Muons subsystem.” Mar, 2008.
- [135] S. Lee, M. Livan, and R. Wigmans, “Dual-Readout Calorimetry,” *Rev. Mod. Phys.* **90** no. 2, (Dec, 2017) 025002. 40 p. <https://cds.cern.ch/record/2637852>. 44 pages, 53 figures, accepted for publication in Review of Modern Physics.
- [136] 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>.
- [137] S. Abdel Khalek *et al.*, “The ALFA Roman Pot Detectors of ATLAS,” *JINST* **11** no. 11, (2016) P11013, [arXiv:1609.00249](https://arxiv.org/abs/1609.00249) [physics.ins-det].
- [138] U. Amaldi, G. Cocconi, A. Diddens, *et al.*, “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>.
- [139] L. Adamczyk, E. Banaś, A. Brandt, *et al.*, “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>.
- [140] ATLAS Collaboration, A. R. Martínez, “The Run-2 ATLAS Trigger System,” *J. Phys. Conf. Ser.* **762** no. 1, (2016) 012003.
- [141] ATLAS Collaboration, *ATLAS level-1 trigger: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 1998. <https://cds.cern.ch/record/381429>.
- [142] ATLAS Collaboration, “Operation of the ATLAS trigger system in Run 2,” *JINST* **15** no. 10, (2020) P10004, [arXiv:2007.12539](https://arxiv.org/abs/2007.12539) [physics.ins-det].
- [143] ATLAS Collaboration, P. Jenni, M. Nèssi, 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>.
- [144] ATLAS Collaboration, “The ATLAS Simulation Infrastructure,” *Eur. Phys. J. C* **70** (2010) 823–874, [arXiv:1005.4568](https://arxiv.org/abs/1005.4568) [physics.ins-det].
- [145] T. Gleisberg, S. Hoeche, F. Krauss, *et al.*, “Event generation with SHERPA 1.1,” *JHEP* **02** (2009) 007, [arXiv:0811.4622](https://arxiv.org/abs/0811.4622) [hep-ph].

- [146] A. Buckley *et al.*, “General-purpose event generators for LHC physics,” *Phys. Rept.* **504** (2011) 145–233, [arXiv:1101.2599 \[hep-ph\]](#).
- [147] V. N. Gribov and L. N. Lipatov, “Deep inelastic $e p$ scattering in perturbation theory,” *Sov. J. Nucl. Phys.* **15** (1972) 438–450.
- [148] J. Blumlein, T. Doyle, F. Hautmann, *et al.*, “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](#).
- [149] A. Buckley, J. Ferrando, S. Lloyd, *et al.*, “LHAPDF6: parton density access in the LHC precision era,” *Eur. Phys. J. C* **75** (2015) 132, [arXiv:1412.7420 \[hep-ph\]](#).
- [150] M. Bengtsson and T. Sjostrand, “Coherent Parton Showers Versus Matrix Elements: Implications of PETRA - PEP Data,” *Phys. Lett. B* **185** (1987) 435.
- [151] S. Catani, F. Krauss, R. Kuhn, and B. R. Webber, “QCD matrix elements + parton showers,” *JHEP* **11** (2001) 063, [arXiv:hep-ph/0109231](#).
- [152] L. Lonnblad, “Correcting the color dipole cascade model with fixed order matrix elements,” *JHEP* **05** (2002) 046, [arXiv:hep-ph/0112284](#).
- [153] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjostrand, “Parton Fragmentation and String Dynamics,” *Phys. Rept.* **97** (1983) 31–145.
- [154] B. Andersson, *The Lund Model*. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 1998.
- [155] D. Amati and G. Veneziano, “Preconfinement as a Property of Perturbative QCD,” *Phys. Lett. B* **83** (1979) 87–92.
- [156] 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>.
- [157] M. Dobbs and J. B. Hansen, “The HepMC C++ Monte Carlo event record for High Energy Physics,” *Comput. Phys. Commun.* **134** (2001) 41–46.
- [158] GEANT4 Collaboration, “GEANT4: A Simulation toolkit,” *Nucl. Instrum. Meth. A* **506** (2003) 250–303.
- [159] ATLAS 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>.
- [160] K. Cranmer, “Practical Statistics for the LHC,” in *2011 European School of High-Energy Physics*, pp. 267–308. 2014. [arXiv:1503.07622 \[physics.data-an\]](#).
- [161] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics,” *Eur. Phys. J. C* **71** (2011) 1554, [arXiv:1007.1727 \[physics.data-an\]](#). [Erratum: *Eur. Phys. J.*C73,2501(2013)].
- [162] 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>.
- [163] ROOT Collaboration, K. Cranmer, G. Lewis, L. Moneta, *et al.*, “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>.

- [164] W. Verkerke and D. P. Kirkby, “The RooFit toolkit for data modeling,” *eConf* **C0303241** (2003) MOLT007, [arXiv:physics/0306116](https://arxiv.org/abs/physics/0306116) [physics]. [,186(2003)].
- [165] 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>.
- [166] L. Moneta, K. Belasco, K. S. Cranmer, *et al.*, “The RooStats Project,” *PoS* **ACAT2010** (2010) 057, [arXiv:1009.1003](https://arxiv.org/abs/1009.1003) [physics.data-an].
- [167] R. Brun and F. Rademakers, “ROOT: An object oriented data analysis framework,” *Nucl. Instrum. Meth. A* **389** (1997) 81–86.
- [168] 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>.
- [169] M. Baak, G. J. Besjes, D. Côte, A. Koutsman, J. Lorenz, D. Short, “HistFitter software framework for statistical data analysis,” *Eur. Phys. J. C* **75** (2015) 153, [arXiv:1410.1280](https://arxiv.org/abs/1410.1280) [hep-ex].
- [170] 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>.
- [171] L. Heinrich, M. Feickert, and G. Stark, “pyhf: v0.6.0,” Version 0.6.0. <https://github.com/scikit-hep/pyhf>.
- [172] C. R. Harris, K. J. Millman, S. J. van der Walt, *et al.*, “Array programming with NumPy,” *Nature* **585** no. 7825, (Sept., 2020) 357–362. <https://doi.org/10.1038/s41586-020-2649-2>.
- [173] A. Paszke, S. Gross, F. Massa, *et al.*, “Pytorch: An imperative style, high-performance deep learning library,” in *Advances in Neural Information Processing Systems* 32, H. Wallach, H. Larochelle, A. Beygelzimer, *et al.*, eds., pp. 8024–8035. Curran Associates, Inc., 2019. <http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf>.
- [174] M. Abadi, A. Agarwal, P. Barham, *et al.*, “TensorFlow: Large-scale machine learning on heterogeneous systems,” 2015. <https://www.tensorflow.org/>. Software available from tensorflow.org.
- [175] J. Bradbury, R. Frostig, P. Hawkins, *et al.*, “JAX: composable transformations of Python+NumPy programs,” Version 0.1.46, 2018. <http://github.com/google/jax>.
- [176] 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>.
- [177] 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>.
- [178] 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](https://arxiv.org/abs/1307.2487) [hep-ex].
- [179] A. L. Read, “Presentation of search results: the CL_S technique,” *J. Phys. G* **28** (2002) 2693.
- [180] 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](https://arxiv.org/abs/physics/0702156) [physics.data-an].

- [181] K. Cranmer, “Statistical challenges for searches for new physics at the LHC,” in *Statistical Problems in Particle Physics, Astrophysics and Cosmology (PHYSTAT 05): Proceedings, Oxford, UK, September 12–15, 2005*, pp. 112–123. 2005. [arXiv:physics/0511028](https://arxiv.org/abs/physics/0511028) [[physics.data-an](#)]. http://www.physics.ox.ac.uk/phystat05/proceedings/files//Cranmer_LHCStatisticalChallenges.ps.
- [182] 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](https://arxiv.org/abs/1501.07110) [[hep-ex](#)].
- [183] 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](https://arxiv.org/abs/1812.09432) [[hep-ex](#)].
- [184] 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](https://arxiv.org/abs/1706.09933) [[hep-ex](#)].
- [185] 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](https://arxiv.org/abs/1909.09226) [[hep-ex](#)].
- [186] 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>.
- [187] 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>.
- [188] ATLAS Collaboration, “ATLAS simulation of boson plus jets processes in Run 2.” ATL-PHYS-PUB-2017-006, 2017. <https://cds.cern.ch/record/2261937>.
- [189] ATLAS Collaboration, “Multi-Boson Simulation for 13 TeV ATLAS Analyses.” ATL-PHYS-PUB-2017-005, 2017. <https://cds.cern.ch/record/2261933>.
- [190] J. Alwall, R. Frederix, S. Frixione, *et al.*, “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](https://arxiv.org/abs/1405.0301) [[hep-ph](#)].
- [191] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO,” *JHEP* **12** (2012) 061, [arXiv:1209.6215](https://arxiv.org/abs/1209.6215) [[hep-ph](#)].
- [192] “Parton distributions with LHC data,” *Nucl. Phys. B* **867** (2013) 244, [arXiv:1207.1303](https://arxiv.org/abs/1207.1303) [[hep-ph](#)].
- [193] T. Sjöstrand, S. Ask, J. R. Christiansen, *et al.*, “An Introduction to PYTHIA 8.2,” *Comput. Phys. Commun.* **191** (2015) 159–177, [arXiv:1410.3012](https://arxiv.org/abs/1410.3012) [[hep-ph](#)].
- [194] ATLAS Collaboration, “ATLAS Pythia 8 tunes to 7 TeV data.” ATL-PHYS-PUB-2014-021, 2014. <https://cds.cern.ch/record/1966419>.
- [195] L. Lönnblad and S. Prestel, “Matching tree-level matrix elements with interleaved showers,” *JHEP* **03** (2012) 019, [arXiv:1109.4829](https://arxiv.org/abs/1109.4829) [[hep-ph](#)].
- [196] D. J. Lange, “The EvtGen particle decay simulation package,” *Nucl. Instrum. Meth. A* **462** (2001) 152.
- [197] 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>.

- [198] 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 \[hep-ph\]](#).
- [199] 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 \[hep-ph\]](#).
- [200] 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 \[hep-ph\]](#).
- [201] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms,” *JHEP* **11** (2004) 040, [arXiv:hep-ph/0409146](#).
- [202] E. Bothmann *et al.*, “Event generation with Sherpa 2.2,” *SciPost Phys.* **7** no. 3, (2019) 034, [arXiv:1905.09127 \[hep-ph\]](#).
- [203] NNPDF Collaboration, “Parton distributions for the LHC run II,” *JHEP* **04** (2015) 040, [arXiv:1410.8849 \[hep-ph\]](#).
- [204] 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 \[hep-ph\]](#).
- [205] M. Cacciari, M. Czakon, M. Mangano, *et al.*, “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 \[hep-ph\]](#).
- [206] P. Kant, O. M. Kind, T. Kintscher, *et al.*, “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 \[hep-ph\]](#).
- [207] 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 \[hep-ph\]](#).
- [208] J. M. Campbell and R. K. Ellis, “ $t\bar{t}W^{+-}$ production and decay at NLO,” *JHEP* **07** (2012) 052, [arXiv:1204.5678 \[hep-ph\]](#).
- [209] 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 \[hep-ph\]](#).
- [210] 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 \[hep-ph\]](#).
- [211] LHC Higgs Cross Section Working Group Collaboration, “Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector,” [arXiv:1610.07922 \[hep-ph\]](#).
- [212] 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>.
- [213] 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 \[hep-ex\]](#).
- [214] 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>.
- [215] T. Cornelissen, M. Elsing, I. Gavrilenko, *et al.*, “The new ATLAS track reconstruction (NEWT),” *J. Phys.: Conf. Ser.* **119** (2008) 032014. <https://cds.cern.ch/record/1176900>.

- [216] 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>.
- [217] 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 \[hep-ex\]](#).
- [218] 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 \[hep-ex\]](#).
- [219] 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 \[hep-ex\]](#).
- [220] 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 \[hep-ex\]](#).
- [221] ATLAS Collaboration, “Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **79** (2019) 639, [arXiv:1902.04655 \[hep-ex\]](#).
- [222] ATLAS Collaboration, “Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV,” *Eur. Phys. J. C* **76** (2016) 292, [arXiv:1603.05598 \[hep-ex\]](#).
- [223] 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 \[hep-ex\]](#).
- [224] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm,” *JHEP* **04** (2008) 063, [arXiv:0802.1189 \[hep-ph\]](#).
- [225] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual,” *Eur. Phys. J. C* **72** (2012) 1896, [arXiv:1111.6097 \[hep-ph\]](#).
- [226] 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\(2006\)](#)].
- [227] ATLAS Collaboration, “Jet energy scale and resolution measured in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” [arXiv:2007.02645 \[hep-ex\]](#).
- [228] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas,” *Phys. Lett. B* **659** (2008) 119–126, [arXiv:0707.1378 \[hep-ph\]](#).
- [229] ATLAS Collaboration, “Jet energy measurement with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 7$ TeV,” *Eur. Phys. J. C* **73** (2013) 2304, [arXiv:1112.6426 \[hep-ex\]](#).
- [230] ATLAS Collaboration, “Determination of jet calibration and energy resolution in proton–proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector,” [arXiv:1910.04482 \[hep-ex\]](#).
- [231] ATLAS Collaboration, “Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector,” *Eur. Phys. J. C* **76** (2016) 581, [arXiv:1510.03823 \[hep-ex\]](#).
- [232] 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>.

- [233] 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 \[hep-ex\]](#).
- [234] 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 \[hep-ex\]](#).
- [235] 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 \[hep-ex\]](#).
- [236] ATLAS Collaboration, “ $E_{\text{T}}^{\text{miss}}$ 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>.
- [237] 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>.
- [238] M. Cacciari, G. P. Salam, and G. Soyez, “The Catchment Area of Jets,” *JHEP* **04** (2008) 005, [arXiv:0802.1188 \[hep-ph\]](#).
- [239] UA1 Collaboration, “Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV,” *Phys. Lett. B* **122** (1983) 103–116.
- [240] 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>.
- [241] U. Baur, “Measuring the W boson mass at hadron colliders,” in *Mini-Workshop on Electroweak Precision Data and the Higgs Mass.* 4, 2003. [arXiv:hep-ph/0304266](#).
- [242] J. Smith, W. L. van Neerven, and J. A. M. Vermaseren, “The Transverse Mass and Width of the W Boson,” *Phys. Rev. Lett.* **50** (1983) 1738.
- [243] D. R. Tovey, “On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders,” *JHEP* **04** (2008) 034, [arXiv:0802.2879 \[hep-ph\]](#).
- [244] G. Polesello and D. R. Tovey, “Supersymmetric particle mass measurement with the boost-corrected contraverse mass,” *JHEP* **03** (2010) 030, [arXiv:0910.0174 \[hep-ph\]](#).
- [245] ATLAS Collaboration, “Performance of the missing transverse momentum triggers for the ATLAS detector during Run-2 data taking,” *JHEP* **08** (2020) 080, [arXiv:2005.09554 \[hep-ex\]](#).
- [246] ATLAS Collaboration, “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 \[hep-ex\]](#).
- [247] ATLAS Collaboration, “ATLAS data quality operations and performance for 2015–2018 data-taking,” *JINST* **15** (2020) P04003, [arXiv:1911.04632 \[physics.ins-det\]](#).
- [248] 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>.
- [249] N. Hartmann, “ahoi.” <https://gitlab.com/nikoladze/ahoi>, 2018.
- [250] 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>.

- [251] A. Roodman, “Blind analysis in particle physics,” *eConf* **C030908** (2003) TUIT001, [arXiv:physics/0312102](#).
- [252] W. Buttinger, “Using Event Weights to account for differences in Instantaneous Luminosity and Trigger Prescale in Monte Carlo and Data,” tech. rep., CERN, Geneva, May, 2015. <https://cds.cern.ch/record/2014726>.
- [253] ATLAS Collaboration, “Measurement of the Inelastic Proton–Proton Cross Section at $\sqrt{s} = 13$ TeV with the ATLAS Detector at the LHC,” *Phys. Rev. Lett.* **117** (2016) 182002, [arXiv:1606.02625 \[hep-ex\]](#).
- [254] 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>.
- [255] J. Bellm *et al.*, “Herwig 7.0/Herwig++ 3.0 release note,” *Eur. Phys. J.* **C76** no. 4, (2016) 196, [arXiv:1512.01178 \[hep-ph\]](#).
- [256] 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>.
- [257] S. Frixione, E. Laenen, P. Motylinski, *et al.*, “Single-top hadroproduction in association with a W boson,” *JHEP* **07** (2008) 029, [arXiv:0805.3067 \[hep-ph\]](#).
- [258] ATLAS Collaboration, “SUSY July 2020 Summary Plot Update,” Tech. Rep. ATL-PHYS-PUB-2020-020, CERN, Geneva, Jul, 2020. <http://cds.cern.ch/record/2725258>.
- [259] CMS Collaboration, “Search for chargino-neutralino production in final states with a Higgs boson and a W boson,” Tech. Rep. CMS-PAS-SUS-20-003, CERN, Geneva, 2021. <https://cds.cern.ch/record/2758360>.
- [260] ATLAS Collaboration, “Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector,” *Eur. Phys. J. C* **80** (2020) 123, [arXiv:1908.08215 \[hep-ex\]](#).
- [261] G. Apollinari, I. Béjar Alonso, O. Brüning, *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2015. <https://cds.cern.ch/record/2116337>.
- [262] X. Chen, S. Dallmeier-Tiessen, R. Dasler, *et al.*, “Open is not enough,” *Nature Physics* **15** no. 2, (Feb, 2019) 113–119. <https://doi.org/10.1038/s41567-018-0342-2>.
- [263] 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 \[hep-ph\]](#).
- [264] 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>.
- [265] K. Cranmer and I. Yavin, “RECAST: Extending the Impact of Existing Analyses,” *JHEP* **04** (2011) 038, [arXiv:1010.2506 \[hep-ex\]](#).
- [266] D. Dercks, N. Desai, J. S. Kim, *et al.*, “CheckMATE 2: From the model to the limit,” *Comput. Phys. Commun.* **221** (2017) 383–418, [arXiv:1611.09856 \[hep-ph\]](#).
- [267] M. Drees, H. Dreiner, D. Schmeier, *et al.*, “CheckMATE: Confronting your Favourite New Physics Model with LHC Data,” *Comput. Phys. Commun.* **187** (2015) 227–265, [arXiv:1312.2591 \[hep-ph\]](#).

- [268] 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 \[hep-ph\]](#).
- [269] 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 \[hep-ex\]](#).
- [270] ATLAS Collaboration, “Simpleanalysis,” <https://gitlab.cern.ch/atlas-sa/simple-analysis>, 2021.
- [271] S. Ovyin, X. Rouby, and V. Lemaitre, “DELPHES, a framework for fast simulation of a generic collider experiment,” [arXiv:0903.2225 \[hep-ph\]](#).
- [272] A. Buckley, J. Butterworth, D. Grellscheid, *et al.*, “Rivet user manual,” *Comput. Phys. Commun.* **184** (2013) 2803–2819, [arXiv:1003.0694 \[hep-ph\]](#).
- [273] A. Buckley, D. Kar, and K. Nordström, “Fast simulation of detector effects in Rivet,” *SciPost Phys.* **8** (2020) 025, [arXiv:1910.01637 \[hep-ph\]](#).
- [274] S. Kraml, S. Kulkarni, U. Laa, *et al.*, “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 \[hep-ph\]](#).
- [275] F. Ambrogio, S. Kraml, S. Kulkarni, *et al.*, “SModels v1.1 user manual: Improving simplified model constraints with efficiency maps,” *Comput. Phys. Commun.* **227** (2018) 72–98, [arXiv:1701.06586 \[hep-ph\]](#).
- [276] 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>.
- [277] ATLAS Collaboration, “1lbb-likelihoods-hepdata.tar.gz,” 2020. <https://www.hepdata.net/record/resource/1408476?view=true>.
- [278] G. Alguero, S. Kraml, and W. Waltenberger, “A SModelS interface for pyhf likelihoods,” [arXiv:2009.01809 \[hep-ph\]](#).
- [279] 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.
- [280] 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 \[hep-ph\]](#).
- [281] 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 \[cs.DC\]](#).
- [282] R. Chard, Y. Babuji, Z. Li, *et al.*, “funcx: A federated function serving fabric for science,” ACM, Jun, 2020. <http://dx.doi.org/10.1145/3369583.3392683>.
- [283] D. Merkel, “Docker: Lightweight linux containers for consistent development and deployment,” *Linux J.* **2014** no. 239, (Mar., 2014) .
- [284] 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>.
- [285] 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 \[physics.data-an\]](#).

- [286] E. R. Gansner and S. C. North, “An open graph visualization system and its applications to software engineering,” *SOFTWARE - PRACTICE AND EXPERIENCE* **30** no. 11, (2000) 1203–1233.
- [287] E. R. Gansner, Y. Koren, and S. North, “Graph drawing by stress majorization,” in *Graph Drawing*, J. Pach, ed., pp. 239–250. Springer Berlin Heidelberg, Berlin, Heidelberg, 2005.
- [288] ATLAS Collaboration, “Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton–proton collision data,” *JINST* **14** (2019) P03017, [arXiv:1812.03848 \[hep-ex\]](#).
- [289] Schanet, Eric, “simplify,” Version 0.1.5. <https://github.com/eschanet/simplify>.
- [290] Schanet, Eric, “SUSY-2019-08 simplified likelihood,” Version 0.0.1. https://github.com/eschanet/simplify/blob/master/examples/ANA-SUSY-2019-08/simplify_BkgOnly.json.
- [291] P. C. Bryan and M. Nottingham, “Javascript object notation (json) patch,” Version RFC 6902, Apr, 2013. <https://www.rfc-editor.org/rfc/rfc6902.txt>.
- [292] ATLAS Collaboration, “Search for direct stau production in events with two hadronic τ -leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector,” *Phys. Rev. D* **101** (2020) 032009, [arXiv:1911.06660 \[hep-ex\]](#).
- [293] 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 \[hep-ex\]](#).
- [294] 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](#).
- [295] 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 \[hep-ph\]](#).
- [296] 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](#).
- [297] H. Bahl, T. Hahn, S. Heinemeyer, *et al.*, “Precision calculations in the MSSM Higgs-boson sector with FeynHiggs 2.14,” *Comput. Phys. Commun.* **249** (2020) 107099, [arXiv:1811.09073 \[hep-ph\]](#).
- [298] T. Hahn, S. Heinemeyer, W. Hollik, *et al.*, “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 \[hep-ph\]](#).
- [299] B. C. Allanach, “SOFTSUSY: a program for calculating supersymmetric spectra,” *Comput. Phys. Commun.* **143** (2002) 305–331, [arXiv:hep-ph/0104145 \[hep-ph\]](#).
- [300] 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](#).
- [301] 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 \[hep-ph\]](#).
- [302] 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://www.cn.cern.ch/mspira/prospino/>.

- [303] W. Beenakker, M. Klasen, M. Kramer, *et al.*, “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)].
- [304] ATLAS Collaboration, “Search for long-lived charginos based on a disappearing-track signature using 136 fb⁻¹ of *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2021-015, CERN, Geneva, Mar, 2021. <https://cds.cern.ch/record/2759676>.
- [305] 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 \[hep-ph\]](#).
- [306] M. E. Cabrera, J. A. Casas, A. Delgado, *et al.*, “Naturalness of MSSM dark matter,” *JHEP* **08** (2016) 058, [arXiv:1604.02102 \[hep-ph\]](#).
- [307] N. Arkani-Hamed, G. L. Kane, J. Thaler, and L.-T. Wang, “Supersymmetry and the LHC inverse problem,” *JHEP* **08** (2006) 070, [arXiv:hep-ph/0512190](#).
- [308] S. Amari, *Differential-Geometrical Methods in Statistics*. Springer New York, New York, NY, 1985.
- [309] J. Brehmer, K. Cranmer, F. Kling, and T. Plehn, “Better Higgs boson measurements through information geometry,” *Phys. Rev. D* **95** no. 7, (2017) 073002, [arXiv:1612.05261 \[hep-ph\]](#).