Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results

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Abstract

We present a draft set of recommendations for the presentation of LHC results on searches for new physics, which are aimed at providing a more efficient flow of scientific information between the experimental collaborations and the rest of the high energy physics community, and facilitating the interpretation of the results in a wide class of models. Implementing these recommendations would aid the full exploitation of the physics potential of the LHC.

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1. INTRODUCTION

The LHC has very successfully begun to explore the TeV energy scale, and will be the energy frontier machine for the foreseeable future. There are high hopes for groundbreaking discoveries shedding light on electroweak symmetry breaking (be it via the Higgs mechanism or some other new dynamics) and new physics beyond the Standard Model (SM) of electroweak and strong interactions. It is of highest priority to our community to exploit fully the physics potential of the LHC. As part of this exploitation, the interpretation of LHC searches in the contexts of different new physics scenarios is crucial, in order to unravel the correct new physics model and determine its parameters.

To this end, the ATLAS and CMS collaborations are providing detailed results of searches in many different channels, see [1, 2]. Moreover, the search groups interpret their results in the contexts of the most popular new physics scenarios—regarding supersymmetry (SUSY), for instance, within the constrained minimal supersymmetric standard model, CMSSM. In addition, some analyses present constraints for Simplified Models[1] designed as an effective-Lagrangian description of a small number of new particles. Compilations of all the public results are available at [1, 2]. However, there exists such a vast variety of SUSY and non-SUSY models, that clearly a broad effort involving non-collaboration groups is required in order to carry out a sufficiently wide range of interpretation studies.

In this spirit, the published LHC results based on the first fb^{-1} of data were used to confront scenarios including the CMSSM in [4, 5, 6], the non-universal-Higgs-mass (NUHM1) model in [5], minimal anomaly mediation (mAMSB) in [7], and general gauge mediation in [8, 9]. Furthermore, interpretations within the phenomenological MSSM (pMSSM) were made in [10, 11], combining results from leptonic and hadronic search channels. Related to the question of naturalness, the limits that the 1 fb^{-1} searches pose on light stops, gluinos and/or light higgsinos were investigated in [12, 13, 14], and implications of compressed SUSY spectra were analyzed in [15].

Non-supersymmetric models have also been examined with regard to their consistency with the LHC data. For example, the 1 fb^{-1} LHC searches resulting in one lepton and missing transverse momentum were confronted with the predictions of the minimal universal extra dimensions model in [16]. Similar non-collaboration efforts to interpret Higgs searches are also underway. In particular the recent tantalizing hints of a Higgs boson with a mass around 125 GeV [17, 18] have been stimulating interpretation efforts in a large variety of scenarios.

These examples illustrate the community interest in the LHC experimental results, whose exploitation will be most efficient if all the necessary information is provided. In this report we therefore put forward a set of recommendations for the presentation of LHC results aimed at optimizing the scientific return. While many of the experimental publications already implement several of the basic recommendations we will make, we wish to work towards an agreement on a common standard. Also, as we will see, the sum of our recommendations goes substantially beyond current practice.

We note that implementing these recommendations will be useful not only for non-collaboration groups or individuals performing (re-)interpretation studies; a common standard will also greatly facilitate the comparison and combination of analyses within and across the LHC collaborations.

2. GUIDING PRINCIPLES

As mentioned, it is our purpose here to provide a set of recommendations that could act as guidelines to the experimental collaborations for presenting the LHC results in a form that would be most useful to the community at large, and that would help to maximize the scientific output of the LHC. Our recommendations are intended to respect the property rights of the collaborations and be concrete, practical and clear, as well as not being burdensome for the scientists performing the experimental analyses. With this in mind, our recommendations are guided by the following principles:

- *What* has been observed should be clear to a non-collaboration colleague.

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[1] This approach has a long heritage. For a recent paper advocating it see e.g. [3].

- *How* it has been observed should be clear to a non-collaboration colleague.
- An interested non-collaboration colleague should be able to use and (re-)interpret results without the need to take up the time of collaboration insiders.

The latter principle implies that all ingredients (e.g., data, experimental systematics, cuts, procedures and so forth) in the analysis should be completely and unambiguously specified. We are not, of course, arguing that scientific discourse either within a collaboration or between collaboration members and those outside should be curtailed. On the contrary, this is vital to maintain the intellectual vibrancy of the field, and our suggestions are intended to make this more efficient and to reduce the burden on collaboration members.

To this aim, we think it useful to distinguish between experimental results and their interpretation. We suggest that the term *experimental result* be used exclusively to mean the empirical outcome, such as an event count or the measurement of some physical quantity. The experimental results themselves should be independent of any hypothesized new physics model. The term *interpretation* is the act of comparing the experimental results to model predictions. If full details of the experimental results employed for a given interpretation are readily available, their interpretation in different new physics models becomes possible. While the design of an analysis may have been inspired or guided by a specific physics model, ideally, the experimental results themselves should be independent of any such model so that the results can, in principle, be subject to different interpretations.

We also emphasize that it is important for the legacy of the LHC that its experimental results can be used in the future, even after the LHC has shut down and the collaborations have been disbanded. A coherent strategy for data preservation and re-use is discussed in [19].

These considerations, along with the principles listed above, have guided the recommendations in this document. We note again that many of these recommendations are already implemented in experimental analyses and publications: we hope that this document will facilitate discussions of—and serve as a guide for—best practice.

3. RECOMMENDATIONS

In the following we discuss our recommendations, which we present in four broad categories: analysis description, detector modeling, analysis dissemination and analysis design. Moreover, we include some recommendations regarding the interpretation of the results. Where appropriate, we split our recommendations into options:

(a) "crucial" (mandatory) recommendations, defined as actions that we believe should be undertaken, following revision motivated by feedback from the experiments, and

(b), (c) "desirable steps", i.e. actions that would help, but whose implementation is recognized as either being controversial, and thus needing more debate, or requiring major efforts and a longer timescale.

Recommendations without such sub-division are understood as "crucial".

3.1 Analysis Description

As noted above, our guiding principle is that an interested non-collaboration colleague should be provided with all of the necessary information that is needed to use published results without having to consult collaboration insiders (although it may be wise to do so anyway). We thus recommend that the collaborations provide as clear and explicit a description of the analyses in publications as possible. Basic object definitions—for example, what constitutes an isolated electron—should be specified, so that the analysis may be reliably reproduced. Definitions of the important variables for the analysis should be precisely stated, because different definitions or conventions may exist for selection variables such as $E_T^{\rm miss}$, $m_{\rm eff}$, H_T, M_{T2}, α_T. One way to validate the completeness and clarity of the descriptions would be to encourage collaboration colleagues not involved in the details of a specific analysis to try to reproduce approximately the results that the collaboration intends to publish.

It is crucial that the analysis description provides sufficient information to validate an implementation of the analysis by users. In this regard, providing *cutflows*, i.e., the number of events obtained after each stage of the event selection for a given data or Monte Carlo (MC) event set, would provide valuable assistance. Since non-collaboration colleagues do not have access to the experimental data, nor the MC event set simulated with an official collaboration detector simulation, they do not have direct means to perform an exact, one-to-one synchronization and validation. It would help substantially to adopt the common practice of providing cutflows for a set of MC events, as well as experimental data, for a physics process that can be easily reproduced. Relevant information defining these MC events, e.g. the underlying physics model and processes, and the details of tools used in pre-detector event generation, including version information, should be specified. We note that guidelines for using event generators already exist in `MCNET` [20], see also [21], and we endorse these guidelines.

Access to all this necessary information will be facilitated if it is tabulated, rather then described in the text. If limits on publication length do not allow the inclusion of all relevant information in the publication itself, the remaining details could be provided as *auxiliary information* alongside the publication. It would further greatly help to provide the relevant information in figures (coordinates of points in a graph, events in a histogram, etc.) in a digital form that is easily readable, e.g., as lists of numbers, as self-contained functions or as `ROOT` objects, etc. We thus summarize

> **Recommendation 1a:** *Provide a clear, explicit description of the analysis in publications. In particular, the most crucial information such as basic object definitions and event selection should be clearly displayed in the publications, preferably in tabular form, and kinematic variables utilised should be unambiguously defined. Further information necessary to reproduce the analysis should be provided on a suitable common platform.*

We note that it is already common practice in ATLAS and CMS to provide useful auxiliary information on the CERN document sever (`CDS`), `HEPdata` [22] and/or collaboration twiki pages [1, 2]. The ultimate goal should be to store all analysis information systematically in a common public archive based, e.g., at CERN. This brings us to

> **Recommendation 1b:** *Provide a common analysis database where all the experimental results are stored together with all necessary information about the analyses, including well-encapsulated functions, such as multivariate analysis (MVA) functions if they are needed.*

3.2 Detector Modeling

A) Efficiency maps: Analyses often use different definitions of analysis objects. For example, the definition of a candidate electron in one analysis may use a different definition of isolation than in another, or one analysis may use a cut on an MVA function to define an electron candidate while another applies cuts to multiple measured quantities. A well-understood way to shield a potential analyst from unnecessary complexity is to provide efficiency maps for each candidate object. Indeed experiments do provide efficiency maps along with some analyses, and we strongly encourage this practice. For a reliable use of efficiency maps,

- the definition of the object for which an efficiency is provided, e.g. an offline isolated electron, missing energy trigger, etc.,
- the definition of the efficiency, e.g. in which fiducial volume, or after which cuts an efficiency is defined,
- the final state topology for which an efficiency is defined

should be given precisely. Furthermore, it is very helpful if the efficiencies are presented in formats that can be implemented easily, such as lists of numbers or mathematical functions or standard digitized forms that are easy to interface with simulators or analysis codes. We thus arrive at

> **Recommendation 2a:** *Provide histograms or functional forms of efficiency maps wherever possible in the auxiliary information, along with precise definitions of the efficiencies, and preferably provide them in standard electronic forms that can easily be interfaced with simulation or analysis software.*

B) Public fast detector simulation: A fast detector simulation provides an approximate mapping from the pre-detector data to the post-reconstruction data. While publicly available fast detector simulations like `PGS` [23] or `DELPHES` [24] perform quite well and are generally found to reproduce ATLAS and CMS results with reasonable precision—in particular with the above-mentioned efficiency maps implemented—it would be helpful for the community to have access to public, fast detector simulations endorsed and maintained by the LHC experimental collaborations.

> **Recommendation 2b:** *Provide and maintain a public simulator developed by the collaboration, or provide official support of an existing one. The public simulator would provide the mapping from the pre-detector data to the post-reconstruction data.*

Within the currently available public fast detector simulators, there is typically a file called a 'detector card' defining some physical properties of the experiment. Often the jet definition must be changed within the detector card, and so different analyses from the same experiment would still require changes. However, modulo these analysis-dependent definitions, it should be possible for the experimental collaborations to examine and validate detector cards for one of the fast detector simulations by tuning them with data. A first approach to Recommendation 2b could thus be in the form of a detector card of an approximate, publicly available fast detector simulation. This would provide some quality assurance, although it would probably still be wise for users to validate their analysis against that of the experiment.

3.3 Analysis dissemination

A) Basic requirements: It is extremely important that all the crucial numbers regarding experimental results be summarized in a clear, concise, yet complete manner, preferably in tables. Experimental publications routinely provide these numbers, nevertheless here we encourage the maintenance of this good practice and list the minimum required information.

> **Recommendation 3a:** *Provide all crucial numbers regarding the results of the analysis, preferably in tabulated form in the publication itself. Further relevant information, like fit functions or distributions, should be provided as auxiliary material.*

In the case of a single-bin counting experiment these numbers include:

- D — the number of observed events in the signal region,
- δS — the systematic error on the expected number of signal events across the parameter space of the new physics model considered,
- B — the background estimate,
- δB — the estimated background uncertainty,
- $\mathcal{L}$ — the integrated luminosity estimate, and
- $\delta\mathcal{L}$ — the integrated luminosity uncertainty.

If the background estimate is the result of extrapolating from a control region (e.g, from a side-band) to the signal region, the following should also be provided (perhaps in the auxiliary information):

- Q — the observed number of events in the control region
- Q' — the expected number of events in the control region from simulations and its uncertainty
- k — the ratio of expected background in the control region to the expected background in the signal region. If the uncertainty δk on k is not negligible, it should also be included.

In the case of a multi-bin analysis, the above numbers should be given for each bin.

An important complication to address is how to account for systematic uncertainties. For the single-bin analysis, numbers should be reported with and without the inclusion of systematic uncertainties. The same holds for theoretical uncertainties of various types: it would be useful if the experiments also provided results obtained without the inclusion of the theoretical uncertainties for well-specified theoretical inputs (such as parton distribution functions (PDFs), top mass, etc.). In particular, since theoretical uncertainties are not static, this has the advantage of facilitating their re-assessment at a later stage in a straight-forward manner. Systematic uncertainties on the signal, δS, should be given separately for detector specific sources, and for SM theory uncertainties, such as PDFs. The systematic uncertainty stemming purely from the calculation of the signal model prediction should be left out.

Whilst this method suffices for a single-bin analysis, it is not adequate for multiple-bin analyses, because it does not account for statistical dependencies between bins. One way to account for the lowest-order statistical dependencies, i.e., linear correlations, is to provide the correlation matrix. However, this approach breaks down if the uncertainties are large or if errors are highly asymmetric.

Since it is common practice to include systematic uncertainties by integrating over systematic parameters, we include the following recommendation, which provides a straightforward way to perform this integration (or to profile).

> **Addendum to 3a:** *For multi-bin results, provide an ensemble of sets of the numbers B, δB, $\mathcal{L}$, $\delta\mathcal{L}$, Q, k, etc in the auxiliary information. These would be created by sampling from the various experiment-specific systematic effects, such as the jet energy scale, jet energy resolution, etc. Systematic uncertainties external to the experiment, such as PDF uncertainties, need not be included because they induce correlations across measurements.*

B) The full likelihood: The statistical model of an analysis provides the complete mathematical description of that analysis. The statistical model, through the probability density $p(o|x)$, relates the observed quantities o to the parameters x, describing the prediction in a model-independent way. By definition, the likelihood for a given set of theoretical model parameters x is the probability density over the observables o evaluated at their observed values O. (For clarity, we denote observed quantities, e.g. O, by upper case symbols and parameters, e.g. o, x, by lower case symbols.)

The likelihood is the appropriate starting point for any detailed interpretation of experimental results. However, many published analyses use likelihoods implicitly rather than explicitly. One problem with using likelihoods implicitly (for example, when results are expressed as $O \pm \delta O$) is that possible non-Gaussian tails are ignored. If the uncertainties are small this is not an issue. However, if the uncertainties are large the likelihood should be modelled explicitly. Given the likelihood, all the standard statistical approaches are available for extracting information from it. We therefore suggest the following.

> **Recommendation 3b:** *Provide a mathematical description of the <u>final</u> likelihood function in which experimental data and parameters are clearly distinguished, either in the publication or the auxiliary information.*

Often, likelihood functions are constructed in several steps involving several hierarchies of fitted functions. Here, we define the <u>final</u> likelihood function as the last step in this process: it may be expressed in terms of an integral or maximisation over the product of several (possibly fitted) functions, which may be Gaussian or Poisson distributed, for example.

It would also be very useful and practical if the likelihood was provided in addition in a digital form. There already exists a generic, unified framework, `RooStats` [25], currently adapted by many LHC analyses, which allows to model the probability density functions and likelihoods required as an input for any statistical inference technique, and also provides a set of major statistical techniques as `c++` classes with coherent interfaces to the statistical model. Publication of likelihoods in a systematic fashion under a standard digital format would also make combination of results much more feasible.

> **Recommendation 3c:** *Additionally provide an digitized implementation of the likelihood that is consistent with the mathematical description.*

We also note at this point that the `RECAST` [26] project would allow one to obtain the signal contribution to the likelihood for an arbitrary theoretical model, thus allowing one to build a higher-level framework for analysis re-interpretation.

3.4 Interpretation of experimental results

So far our recommendations concern generally the presentation of experimental results, irrespective of whether they report a signal or are used to set limits. Let us now turn to the interpretation of these results, the presentation of confidence intervals, parameter inference and limit setting.

Many different forms of experimental limits exist. Commonly, one-sided limits are derived in the absence of a signal observation, as is currently the case, but this will switch to two-sided limits (constraints) in case of a discovery. These limits may be quoted in various different schemes (such as Feldman-Cousins, CL_s, etc). It is crucial that the limit setting procedure be explicitly defined in order to permit an informed comparison of the quoted confidence level.

The *shape* (steepness) of the confidence level is essential information, e.g., for analyses that combine different experimental searches. It is therefore important that constraints are shown at several, rather than just one, confidence levels. Moreover, for the correct statistical interpretation, the expected constraints should be given in addition to the observed ones. Of course the optimum would be to here, too, implement recommendation 3b and publish the full likelihoods.

Regarding uncertainties, as mentioned earlier, it would be useful if confidence intervals were (also) presented for fixed input PDF's and other theoretical input, all explicitly tabulated. Moreover, when the interpretation of the experimental results is done in a "model-independent" way in terms of $\sigma \times \mathrm{BR} \times \mathrm{acceptance}$, the modeling of the acceptance should be precisely described. We sum this up as

> **Recommendation 4:** *In the interpretation of experimental results, preferably provide the final likelihood function (following 3b or 3c), or provide a grid of confidence levels over the parameter space. The expected constraints should be given in addition to the observed ones, and whatever sensitivity measure is applied must be be precisely defined. Modeling of the acceptance needs to be precisely described.*

Note that Recommendation 4 in principle applies to any (re-)interpretation study, irrespective of whether it is done by an LHC collaboration or by non-collaboration groups.

As an aside we note that when conducting searches for supersymmetry or other new physics, experimental collaborations often use grids of models for which signal cross-sections, acceptances, efficiencies, and exclusions are evaluated, and then used to set limits by interpolation. It would be useful if these grid models were documented and fully specified in terms of model inputs, spectrum information (e.g., SLHA files), predicted signal cross-sections, acceptance×efficiency after selections and cuts, etc.. Also, since the tools provided by theorists constantly evolve, it is useful to document which tools and versions thereof have been used.

3.5 Higgs Searches

Given the special role of Higgs searches, we make a specific and separate recommendation for them. Higgs bosons are searched for in many different possible topologies, each of which are predicted to be present at some level, dictated by Higgs branching ratios in the Standard Model or other new physics models. Many Higgs searches may be interpreted within the Standard Model itself, but both the branching ratios and the production cross-sections and distributions (and indeed the number of Higgs particles) may differ in new physics models. For this reason, it is important to include the channel-by-channel information in the primary Higgs search papers. Of course this does not preclude an additional combination of channels assuming some model, e.g., the Standard Model.

> **Recommendation 5:** *For Higgs searches, provide all relevant information on a channel-by-channel basis.*

Many publications on Higgs searches are already consistent with this recommendation in that constraints for individual production/decay modes are presented. The procedure of doing so as a function of the Higgs mass is crucial, especially in the context of multiple Higgs boson models. Indeed different Higgs models weight various possible production mechanism and decay distributions differently.

Note also that in order to make the channel-by-channel data available for an analysis of the Higgs sector of (nearly any) arbitrary model, it is important that in addition to the observed data also the expected sensitivity be reported for each channel. This permits the selection of the potentially strongest search channel, as well as to retain the correct statistical interpretation of, e.g., 95% C.L. exclusion bounds [27]. Finally, in setting limits or analyzing positive signals it is crucial to give details of acceptance systematics related thereto. These aspects are covered by Recommendation 4. Needless to say, all the other Recommendations also apply.

3.6 Exclusive Analysis Design

It is a common approach to confront a new physics model with multiple analyses. In such cases, a likelihood is assigned to each analysis separately, and then all likelihoods are combined. This combination is typically easy only if the statistical data from each analysis are independent: then, one may combine the analyses by simply taking the product of all likelihoods. The correlations that may arise in the systematic errors can be dealt with by following the addendum to Recommendation 3a. We realize that it is not possible to build an experimental search program that consists fully of disjoint analyses, and understand that avoiding overlaps between various inclusive analyses, e.g., those based on complicated kinematic variables, is far from trivial. Our recommendation applies to simpler cases, e.g. when building analyses based on simple variables like object multiplicity, or when defining different search regions in a single analysis. It intends to emphasize that more information is typically available in the combination of multiple disjoint analyses than via a single analysis.

> **Recommendation 6:** *When relevant, design analyses and signal regions that are based on disjoint sets of events.*

4. Executive Summary of Recommendations

We here summarize our recommendations. We remind the reader that whenever we split into several steps, options **(a)** should be understood as "crucial" recommendations, while **(b), (c)** are "desirable steps". When no options are given, the recommendation is to be regarded as "crucial". For completeness we also note that the ordering of recommendations 1–6 does *not* imply prioritizing.

1. (a) Provide a clear, explicit description of the analysis in publications. In particular, the most crucial information such as basic object definitions and event selection should be clearly displayed in the publications, preferably in tabular form, and kinematic variables utilised should be unambiguously defined. Further information necessary to reproduce the analysis should be provided on a suitable common platform.

   (b) Provide a common analysis database where all the experimental results are stored together with all necessary information about the analyses, including well-encapsulated functions, such as multivariate analysis (MVA) functions if they are needed.

2. (a) Provide histograms or functional forms of efficiency maps wherever possible in the auxiliary information, along with precise definitions of the efficiencies, and preferably provide them in standard electronic forms that can easily be interfaced with simulation or analysis software.

   (b) Provide and maintain a public simulator developed by the collaboration, or provide official support of an existing one. The public simulator would provide the mapping from the pre-detector data to the post-reconstruction data.

3. (a) Provide all crucial numbers regarding the results of the analysis, preferably in tabulated form in the publication itself. Further relevant information, like fit functions or distributions, should be provided as auxiliary material.
   Addendum:
   For multi-bin results, provide an ensemble of sets of the numbers B, δB, $\mathcal{L}$, $\delta\mathcal{L}$, Q, k, etc in the auxiliary information. These would be created by sampling from the various experiment-specific systematic effects, such as the jet energy scale, jet energy resolution, etc. Systematic uncertainties external to the experiment, such as PDF uncertainties, need not be included because they induce correlations across measurements.

   (b) Provide a mathematical description of the final likelihood function in which experimental data and parameters are clearly distinguished, either in the publication or the auxiliary information.

   (c) Additionally provide an digitized implementation of the likelihood that is consistent with the mathematical description.

4. In the interpretation of experimental results, preferably provide the final likelihood function (following 3b or 3c), or provide a grid of confidence levels over the parameter space. The expected constraints should be given in addition to the observed ones, and whatever sensitivity measure is applied must be be precisely defined. Modeling of the acceptance needs to be precisely described.

5. For Higgs searches, provide all relevant information on a channel-by-channel basis.

6. When relevant, design analyses and signal regions that are based on disjoint sets of events.

5. CONCLUSIONS

The present document presents an initial set of recommendations, intended to serve as a basis for further discussion and refinement. We hope to achieve these refinements in a dedicated miniworkshop involving the ATLAS and CMS search groups, such that the recommendations might be adopted by the experimental collaborations for the presentation of 2012 search and Higgs results.

The added value for the experiments, and the whole HEP community, in providing "open-access" information on the experimental results consist in a faster and more precise feedback on implications of these results for a broad range of theoretical scenarios that, in turn, will serve as crucial input in the choice of the best research directions in the near future, at the LHC, and in the longer term. The tools needed to provide extended experimental information will require some dedicated efforts in terms of resources and manpower, to be supported by both the experimental and the theory communities. Practical solutions on the implementation of these tools will also be addressed in the miniworkshop and in subsequent venues (e.g. within the Les Houches PhysTeV 2013 Workshop).

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