Reinterpreting the results of the LHC with \textsc{MadAnalysis 5}: uncertainties and higher-luminosity estimates

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Abstract. The \textsc{MadAnalysis 5} framework can be used to assess the potential of various LHC analyses for unraveling any specific new physics signal. We present an extension of the LHC reinterpretation capabilities of the programme allowing for the inclusion of theoretical and systematical uncertainties on the signal in the reinterpretation procedure. We have implemented extra methods dedicated to the extrapolation of the impact of a given analysis to higher luminosities, including various options for the treatment of the errors. As an application, we consider a simplified new physics model in which the Standard Model is supplemented by a gluino and a neutralino and investigate the effect of the errors on current bounds and the corresponding high-luminosity LHC expectation. We show that uncertainties could in particular degrade the bounds by several hundreds of GeV when considering 3000 fb\textsuperscript{−1} of future LHC data.

1 Introduction

The discovery of the Higgs boson has accomplished one of the long awaited objectives of the LHC physics programme and confirmed our understanding of the fundamental laws of nature. However, the concrete realisation of the electroweak symmetry breaking mechanism remains unexplained and no evidence for physics beyond the Standard Model (SM), whose existence is motivated by the SM theoretical inconsistencies and limitations, has emerged from data. There are two classes of possible explanations as to why the associated new particles and/or interactions have escaped detection so far. The first one is that the new states are too heavy and/or the new interactions too feeble to be observed with present collider reaches. Alternatively, new particles may be hiding just around the corner, but lie in a specific configuration (like being organised in a compressed spectrum) that renders their discovery challenging. The possible observation of any new phenomena therefore is the foremost goal of the future LHC runs, including in particular the LHC Run 3, to be started in two years, and the high-luminosity operations planned to begin in half a decade.

In order to investigate whether new physics could be present in existing data, several groups have developed and maintained public software dedicated to the reinterpretation of the results at the LHC \cite{1–5}. In practice, these tools rely on predictions detailing how the different signal regions of given LHC analyses are populated to derive the potential of these searches for its observation. However, signal uncertainties are in general ignored in this procedure, although they could sometimes lead to incorrect interpretations \cite{6}. Moreover, with the limits on the masses of any hypothetical particle being pushed to higher and higher scales, the theoretical uncertainties related with the new physics signals can sometimes be quite severe, in particular if the associated scale and Bjorken-$x$ value lead to probing the parton densities in a regime in which they are poorly constrained \cite{7}.

In addition, it would be valuable to get estimates of the capabilities of the future runs of the LHC with respect to a given signal, possibly on the basis of the interpretation of the results of existing analyses of current data. Predictions in which the signal and the background are naively scaled up could hence be useful to obtain an initial guidance on the reach of future collider setups within new physics parameter spaces.

In this paper, we present an extension of the recasting capabilities of the \textsc{MadAnalysis 5} platform \cite{3,8} so that signal theoretical and systematics uncertainties could be included in the recasting procedure. Moreover, we show how the reinterpretation results, with uncertainties included, could be correctly extrapolated to different luminosities to get insight on the sensitivity of the future LHC data on given signals.

In order to illustrate how to make use of these new features within a concrete case, we consider a simplified model inspired by the Minimal Supersymmetric Standard Model (MSSM) in which the SM is complemented by a

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gluino and a neutralino, all other superpartners being assumed heavy and decoupled. We reinterpret the results of an ATLAS search [9] for the signal obtained in the production of a pair of gluinos decaying into jets and missing energy, carried away by neutralinos in 36 fb$^{-1}$ of LHC data. We investigate the impact of the theory errors on the derived bounds at the nominal luminosity of the search, and extrapolate the findings to estimate the outcome of a similar search analysing 300 and 3000 fb$^{-1}$ of LHC data.

The rest of this paper is organised as follows. We discuss the details of the recasting capabilities of MadAnalysis 5 in section 2, focusing not only on the new features that have been implemented in the context of this work, but also on how the code should be used for LHC recasting. We then apply it to extracting gluino and neutralino mass limits in section 3 for various luminosities of LHC data, and conclude in section 4.

2 LHC recasting with MadAnalysis 5

The MadAnalysis 5 package [10,11] is a framework dedicated to new physics phenomenology. Whilst the first aim of the programme was to facilitate the design and the implementation of analyses targeting a given collider signal of physics beyond the Standard Model, and how to unravel it from the background, more recently it has been extended by LHC reinterpretation capabilities [3,8]. This feature allows the user to derive the sensitivity of the LHC to any collider signal obtained by matching hard-scattering matrix elements with parton showers, based on the ensemble of analyses that have implemented in the MadAnalysis 5 public analysis database (PAD) [3].

For each of these analyses, the code simulates the experimental strategies (which includes both the simulation of the detector response and the selection) to predict the number of signal events that should populate the analysis signal regions. It then compares the results with both data and the SM expectation, so that conclusive statements could be drawn. As in all recasting codes relying on the same method [2,4,5], the uncertainty on the signal is ignored although it could be relevant [7].

With the release of MadAnalysis 5 version v1.8, the user has now the possibility to deal with various classes of signal uncertainties and to extrapolate any reinterpretation result to higher luminosities. This section documents all these new functionalities. Section 2.1 briefly summarises how to install MadAnalysis 5, get the code running and download a local copy of its public analysis database. Section 2.2 details how the code can be used to reinterpret the results of a specific LHC analysis. A more extensive and longer version of this information on MadAnalysis 5 installation and running procedures can be found in ref. [8]. Section 2.3 is dedicated to the new methods that have been developed in the context of this work, and which are available from MadAnalysis 5 version v1.8 onwards. We also introduce in this section several new optional features that can be used for the design of the analysis.

One such file accompanies each analysis of the database and contains information on the observation and the SM expectation of the different analysis signal regions. In section 2.4, we describe the corresponding modifications of the output format relevant for a recasting run of MadAnalysis 5.

2.1 Prerequisites and installation

MadAnalysis 5 is compatible with most recent Unix-based operating systems, and requires the GNU G++ or Clang compiler, a Python 2.7 installation (or more recent, but not a Python 3 one) and GMAKE. In order for the recasting functionalities to be enabled, the user must ensure that the SciPy library is present, as it allows for limit computations, and that the Delphes 3 package [12] is locally available within the MadAnalysis 5 installation. The latter, which requires the ROOT framework [13] and the FastJet programme [14], is internally called by MadAnalysis 5 to deal with the simulation of the response of the LHC detectors and to reconstruct the events. Moreover, reading compressed event files can only be performed if the ZLIB library is available.

The latest version of MadAnalysis 5 can be downloaded from LaunchPad\textsuperscript{2}, where it is provided as a tarball named $\texttt{ma5_v\textsuperscript{xxx}.tgz}$, that contains all MadAnalysis 5 source files ($\texttt{\langle xxx \rangle}$ standing for the version number). After unpacking the tarball, the code can be started by issuing in a shell

```
./bin/ma5 -R
```

where the $\texttt{-R}$ options enforces the $\texttt{reco}$ mode of MadAnalysis 5, that is relevant for LHC recasting. The programme begins with checking the presence of all mandatory packages and determining which of the optional packages are available. The MadAnalysis 5 command-line interface is then initialised and the user is prompted to type in commands.

In the case where any of the ZLIB or Delphes 3 package would not be found by MadAnalysis 5, they can be installed locally by typing, directly in the MadAnalysis 5 interpreter,

```
install zlib
install delphes
```

Whilst ROOT can in principle be installed similarly, we recommend the user to handle this manually, following the instructions available on the ROOT website\textsuperscript{3}. Furthermore, all existing and validated recast LHC analyses in the MadAnalysis 5 framework can be locally downloaded by typing in,

```
install PAD
install PADFOrMA5tune
```

The second command triggers the installation of older implemented analyses, that requires a (now disfavoured) MA5tune version of Delphes 3. The latter can be installed by typing, in the MadAnalysis 5 shell,

\textsuperscript{2}launchpad.net/madanalysis5
\textsuperscript{3}root.cern.ch

\footnote{madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase}
install delphesForMA5tune

2.2 Recasting LHC analyses with MadAnalysis 5

In this section, we rely on a generic example in which a user aims to estimate the sensitivity of a specific LHC analysis to a given signal with MadAnalysis 5. The analysis consists of one of the analyses available from the PAD and the signal is described by simulated events collected into a file that we call `events.hepmc.gz`. Such an event file includes the simulation of the considered hard-scattering process matched with parton showers, as well as the hadronisation of the final-state partons present in each of the showered events.

As mentioned above, MadAnalysis 5 has to be started in the reco mode,

```
./bin/ma5 -R
```

In a first step, the recasting mode of the programme has to be enabled and the event file, physically located at `<path-to-events.hepmc.gz>` on the user system, has to be imported. This is achieved by issuing the commands

```
set main.recast = on
import <path-to-events.hepmc.gz> as <label>
```

The second command defines a dataset identified by the label `<label>` that here solely includes the imported sample. Several event files can be imported and collected either under a unique dataset (by using the same `<label>` for each call to the `import` command) or split into different datasets (by employing different labels). When studying the signal under consideration, MadAnalysis 5 will run over all defined datasets and imported event files.

In addition, the user can activate the storage of the ROOT file(s) generated by DELPHES 3 by issuing the command

```
set main.recast.store_root = <status>
```

where `<status>` can take the True or False value, and directly provide a predefined recasting card (available on the system at `<path-to-a-card>`), through

```
set main.recast.card_path = <path-to-a-card>
```

In the case where no card is provided, MadAnalysis 5 creates a consistent new card with one entry for each of the available analyses. Such an entry is of the form

```
<tag> <type> <switch> <detector> # <comment>
```

The `<tag>` label corresponds to the filename of the C++ code associated with the considered analysis (located in the Build/SampleAnalyzer/User/Analyzer subdirectory of the PAD installation in tools/PAD), the `<type>` label indicates whether the PADForMA5tune (v1.1) or PAD (v1.2) recasting infrastructure should be used and the `<switch>` tag (to be set to on or off) drives whether the analysis has to be recast. The name of the DELPHES 3 card to use (see the Input/Cards subdirectory of the PAD installation) is passed as `<detector>`, and `<comment>` consists of an optional comment (usually briefly describing the analysis).

The run is finally started by typing in the interpreter,

```
submit
```

Firstly, MadAnalysis 5 simulates the detector impact on the input events, for each of the necessary DELPHES 3 cards according to the analyses that have been switched on in the recasting card. Next, the code derives how the different signal regions are populated by the signal events and finally computes, by means of the CL$_s$ prescription [15], the corresponding exclusion limits, signal region by signal region. This is achieved by a comparison of the results with the information on the SM background and data available from the different info files shipped with the PAD.

The output information is collected into a folder named `ANALYSIS_X`, where X stands for the next available positive integer (in terms of non-existing directories). On top of basic details about the run itself, this folder contains the recasting results that are located in the `ANALYSIS_X/Output` folder. The latter includes the CLs_output_summary.dat file that concisely summarises all the results of the run. A more extensive version of these results can be found in the set of subfolders named after the labels of the imported datasets. The `CLs_output_summary.dat` file contains one line for each signal region of each reinterpreted analysis, and this for each of the datasets under consideration. Each of these lines follows the format

```
<set> <tag> <SR> <exp> <obs> || <eff> <stat>
```

where the `<set>` and `<tag>` elements respectively consist in the names of the dataset and analysis relevant for the considered line of the output file. The `<SR>` entry relates to one of the analysis signal regions, the exact name being the one defined in the analysis C++ source code. The `<exp>` and `<obs>` quantities are the expected and observed cross-section values for which the signal modelled by the events stored within the dataset `<set>` is excluded by the signal region `<SR>` of the analysis `<tag>` at the 95% confidence level. In the former case, the code makes use of the SM expectation to predict the number of events populating the signal region `<SR>`, whilst in the latter case, data is used. Finally, the `<eff>` and `<stat>` entries respectively refer to the corresponding selection efficiency and the associated statistical error.

The user has the option to specify the cross section corresponding to the investigated signal by issuing, in the MadAnalysis 5 interpreter,

```
set <label>.xsection = <value>
```

prior to the call to the `submit` command. Following this syntax, `<label>` stands for one of the labels of the considered datasets and `<value>` for the associated cross-section value, in pb. In this case, the confidence level at which the analysed signal is excluded is included in the output summary file (before the double vertical line).

The Output folder additionally contains a specific subfolder for each of the defined datasets. Such a directory contains a file named `CLs_output.dat` that includes the same information as in the `CLs_output_summary.dat` file, following the same syntax, but restricted to a specific dataset. A second file encoded into the SAF format [10] and named `<label>.saf` (<label> being the dataset name)
contains general information on the dataset organised according to an XML-like structure. The latter relies on three classes of elements, namely <SampleGlobalInfo>, <FileInfo> and <SampleDetailedInfo>. The first of these contains general information on the dataset, such as its cross section ($xsec$), the associated error ($xsec\_err$), the number of events (nev) or the sum of the positive and negative event weights ($\text{sum}_w^+$ and $\text{sum}_w^-$). The corresponding entry in the output file would read

```xml
<SampleGlobalInfo>
  # xsec xsec_error nev sum_w+ sum_w-
  ...
</SampleGlobalInfo>
```

where the numerical values have been omitted for clarity. The <FileInfo> element sequentially provides the paths to the different event files included in the dataset, while detailed information on each file is provided within the <SampleDetailedInfo> XML root element, in a similar manner as for the sample global information (with one line for each file).

Furthermore, the dataset output directory includes a RecEvents folder dedicated to the storage of DELPHES 3 output files (one file for each considered detector parameterisation), provided that the corresponding option has been turned on (see above), as well as one folder for each of the recast analyses. Each of these folders contains one SAF file listing all signal regions implemented in the associated analysis, as well as two subfolders Cutflows and Histograms. The former includes one SAF file for each signal region, and the latter a single file named histos.saf.

A cutflow is organised through XML-like elements, <InitialCounter> and <Counter> being used for the initial number of events and the results of each selection cut respectively. As depicted by the example below, in which all numbers have been omitted for clarity,

```xml
<Counter>
  "my_cut_name" # 1st cut
  .... .... # nentries
  .... .... # sum of weights
  .... .... # sum of weights^2
</Counter>
```

any of such elements includes a cut name as defined in the analysis C++ file (first line), the number of events passing the cut (second line), the weighted number of events passing the cut (third line) and the sum of the squared weights of all events passing the cut (last line). Moreover, the first (second) column refers to the positively-weighted (negatively-weighted) events only.

Histograms are all collected into the file histos.saf, that is also organised according to an XML-like structure relying on several <Histo> elements. Each of these corresponds to one of the histograms implemented in the analysis. A <Histo> element includes the definition of the histogram (provided within the <Description> element), general statistics (as part of the <Statistics> element) and the histogram data itself (within the <Data> element). The description of a histogram schematically reads

```xml
<Description>
  "name"
  # nbins xmin xmax
  ...
</Description>
```

and is self-explanatory, all numbers having been replaced by dots. This moreover shows that a given histogram can be associated with several signal regions, provided they are indistinguishable at the moment the histogram is filled. Statistics are typically given as

```xml
<Statistics>
  ...
  ...
  ...
  ...
  # Defined regions
  ...
  # Region nr. 1
  ...
  # Region nr. 2
</Statistics>
```

which include information about the number of entries, the weighted number of entries, the variance, etc. Moreover, the contributions of the positively-weighted and negatively-weighted events are again split and provided within the first and second column respectively. The values of each bin are finally available from the <Data> element,

```xml
<Data>
  ...
  ...
  # underflow
  ...
  ...
  # bin 1 / 15
  ...
  ...
  # bin 15 / 15
  ...
  ...
  # overflow
</Data>
```

where all bin values are omitted and the two columns respectively refer to events with positive (first column) and negative (second column) weights. The underflow and overflow bins are also included.

To close this section, we detail below how limits on a given signal are derived by MADANALYSIS 5, using the CL$_s$ prescription. The output file generated by the code contains three numbers associated with those limits, the expected and observed cross sections excluded at the 95% confidence level, $\sigma_{\text{exp}}$ and $\sigma_{\text{obs}}$, as well as the confidence level at which the input signal is excluded. Those numbers are extracted on the basis of the information available from the .info file, shipped with each recast analysis and that contains, for each signal region, the number of expected SM events $n_b$, the associated error $\Delta n_b$ and the observed number of events populating the signal region $n_{\text{obs}}$. As said above, starting from the input event file, MADANALYSIS 5 simulates the response of the LHC detector, applies the analysis selection, and estimates how the different signal regions are populated. In this way, for each signal region, the number of signal events $n_s$ is known.
This enables the computation of the background-only and signal-plus-background probabilities $p_b$ and $p_b+s$ and to further derive the related CLs exclusion. In practice, the code considers a number of toy experiments (the default being 100000 that can be changed by issuing, in the MADANALYSIS 5 interpreter, similarly to the cross section associated with a given dataset (see section 2.2),

where $<\text{value}>$ stands for the desired number of toy experiments. For each toy experiment, the expected number of background events $N_b$ is randomly chosen assuming that its distribution is Gaussian, with a mean $n_b$ and a width $\Delta n_b$. The corresponding probability density thus reads

$$f(N_b|n_b, \Delta n_b) = \frac{\exp\left\{ \frac{-(N_b-n_b)^2}{2\Delta n_b^2} \right\}}{\sqrt{2\pi} \Delta n_b}.$$  

(1)

Imposing $N_b > 0$, the actual number of background events $\hat{N}_b$ is randomly generated from the Poisson distribution

$$f(\hat{N}_b|N_b) = \frac{N_b^{\hat{N}_b} e^{-N_b}}{\hat{N}_b!}.$$  

(2)

Accounting for the observation of $n_{\text{obs}}$ events, $p_b$ is defined as the percentile of score associated with $\hat{N}_b \leq n_{\text{obs}}$, which consists in the probability for the background to fluctuate as low as $n_{\text{obs}}$.

The signal-plus-background probability $p_b+s$ is computed similarly, assuming that the actual number of signal-plus-background events $\hat{N}_b + \hat{N}_s$ follows a Poisson distribution of parameter $n_s + \hat{N}_b$ (after imposing this time that $\hat{N}_b + n_s > 0$). The resulting CLs exclusion is then derived as

$$\text{CL}_s = \max\left(0, 1 - \frac{p_b+s}{p_b}\right).$$  

(3)

and $\sigma_{\text{obs}}^{s}$ is calculated as above in a case where the number of signal events $n_s$ is kept free. From the (derived) knowledge of the analysis selection efficiencies, MADANALYSIS 5 can extract the upper allowed cross section value for which the signal is not excluded, i.e. $\sigma_{\text{obs}}^{s}$. The expected cross section excluded at the 95% confidence level, $\sigma_{\text{obs}}^{95}$, is obtained by replacing $n_{\text{obs}}$ by $n_b$ in the above calculations.

2.3 Including signal uncertainties and extrapolation to higher luminosities

In the procedure described in the previous section, any error on the signal is ignored, both concerning the usual theory uncertainties (scale variations, parton densities) and the systematics, mostly stemming from more experimental aspects. In particular, with the constantly growing mass bounds on hypothetical new particles, the scale entering the relevant hard-scattering processes is larger and larger, so that theoretical errors could start to impact the derived limits in an important and non-negligible manner.

Starting from version v1.8 onwards, MADANALYSIS 5 offers the user a way to account for both the theoretical and systematical errors on the signal when a limit calculation is performed. The scale and parton density (PDF) uncertainties can be entered, within the MADANALYSIS 5 interpreter, similarly to the cross section associated with a given dataset (see section 2.2),

$$\text{set } <\text{label}>.xsection = <xsec_val>$$

$$\text{set } <\text{label}>.scale_variation = <scale>$$

$$\text{set } <\text{label}>.pdf_variation = <pdf>$$

where $<\text{value}>$ stands for the label defining the signal dataset. In this case, the signal cross section $\sigma_s$ is provided through the $xsection$ attribute of the dataset, as described in the previous section, while the scale and parton density uncertainties $\Delta\sigma_{\text{scale}}$ and $\Delta\sigma_{\text{pdf}}$ are given through the $scale_variation$ and $pdf_variation$ attributes. The errors are symmetric with respect to the central value $\sigma_s$ and their value (given by $<\text{scale}>$ and $<\text{pdf}>$ in the above example) must be inputted as the absolute values of the relative errors on the cross section (i.e. as positive floating-point numbers). Asymmetric errors can also be provided, the upper and lower uncertainties being independently fixed by issuing, in the MADANALYSIS 5 interpreter,

$$\text{set } <\text{label}>.scale_up_variation = <scale_up>$$

$$\text{set } <\text{label}>.scale_down_variation = <scale_dn>$$

$$\text{set } <\text{label}>.pdf_up_variation = <pdf_up>$$

$$\text{set } <\text{label}>.pdf_down_variation = <pdf_dn>$$

Each error is again provided as a positive floating-point number and refers to the relative error on the cross section, in absolute value. On top of the computation of the confidence level at which the signal is excluded, MADANALYSIS 5 additionally calculates the CLs variation band associated with the scale uncertainties, as well as with the total theory uncertainties where both the scale and PDF contributions to the total error are added linearly. Such a behaviour can however be modified by issuing, in the interpreter

$$\text{set main.recast.TError_combination = <value>}$$

where $<\text{value}>$ can be set either to quadratic (the theory errors are added quadratically) or linear (default, the theory errors are added linearly). The CLs band is then derived by allowing the signal cross section to vary within its error band, deriving the associated spread on $p_b+s$.

The user can also specify one or more values for the level of systematics on the signal. This is achieved by issuing, in the command line interface,

$$\text{set main.recast.add.systematics = <syst>}$$

This command can be reissued as many times as needed, MADANALYSIS 5 taking care of the limit calculation for each entered value independently. The level of systematics $<\text{syst}>$ has to be given either as a floating-point number lying in the $[0,1]$ range, or as a pair of floating-point numbers lying in the same interval. In the former case, the error is symmetric with respect to the central value $\sigma_s$, whilst in the latter case, it is asymmetric with the first value being associated with the upper error and the second one with the lower error.
In addition, we have also extended the code so that naive extrapolations for a different luminosity $L_{\text{new}}$ could be performed. This is achieved by typing, in the interpreter,

```
set main.recast.add.extrapolated_luminosity \n  = <lumi>
```

Once again, the user has the possibility to reissue the command several times, so that the extrapolation will be performed for each luminosity $<\text{lumi}>$ independently (where the value has to be provided in fb$^{-1}$). Those extrapolations assume that the signal and background selection efficiencies of a given region in a specific analysis are identical to those corresponding to the reference luminosity $L_0$ initially considered. In this framework, the extrapolated number of background events $n_{b,\text{new}}$ is related to $n_b$ (the number of background events expected for the reference luminosity $L_0$) as

$$n_{b,\text{new}} = n_b \frac{L_{\text{new}}}{L_0}.$$  

(4)

On the other hand, the associated uncertainties, $\Delta n_{b,\text{new}}$, are derived from the relation

$$\Delta n_{b,\text{new}} = \Delta n_{b,\text{syst}} \frac{L_{\text{new}}}{L_0} + \Delta n_{b,\text{stat}} \sqrt{\frac{L_{\text{new}}}{L_0}},$$  

(5)

where the statistics and systematics components are added in quadrature. The systematics are extrapolated linearly, whilst the statistical uncertainties assume that the event counts follow a Poisson distribution. Such an extrapolation of the background error requires an access to the details of the background uncertainties. This is however not achievable within the XML info file format dedicated to the transfer of the background and data information to MadAnalysis 5 [3]. We therefore introduce two new XML elements to this format, namely deltanb_stat and deltanb_syst. These offer the user the option to implement his/her info file by either providing a unique combined value for the uncertainties (via the standard deltanb XML element) or by splitting them into their statistical and systematical components (via a joint use of the new deltanb_stat and deltanb_syst XML elements). In this way, a region element could be either implemented according to the old syntax, as in the schematic example below (with all numbers omitted),

```
<region type="signal" id="Region name">
  <nobs> ... </nobs>
  <nb> ... </nb>
  <deltanb> ... </deltanb>
</region>
```

or following the new syntax, which would then read

```
<region type="signal" id="Region name">
  <nobs> ... </nobs>
  <nb> ... </nb>
  <deltanb_stat> ... </deltanb_stat>
  <deltanb_syst> ... </deltanb_syst>
</region>
```

Whilst the usage of the new syntax is encouraged, this new possibility for embedding the error information strongly depends on how the background uncertainties are provided in the experimental analysis notes. For this reason, as well as for backward-compatibility, MadAnalysis 5 supports both choices. If only a global error is provided, the user can freely choose how to scale the error (linearly or in a Poisson way), by typing in the interpreter,

```
set main.recast.error_extrapolation = <value>
```

where $<value>$ has to be set either to linear or to sqrt. Finally, all extrapolations are based on expectations and not on observations, so that $n_{\text{obs}}$ will be effectively replaced by the corresponding SM expectation $n_b$.

### 2.4 Output format

MadAnalysis 5 propagates the information on the impact of the uncertainties all through the output file, which is then written in a format slightly extending the one presented in section 2.2. Starting with the summary file CLS_output_summary.dat, each line (corresponding to a given signal region of a given analysis) is now followed by information schematically written as

```
Scale var. band    ... ...
TH error band      ... ...
+<1lv_up>%, -<1lv_dn>% syst ... ...
```

The uncertainties on the exclusion stemming from scale variations are given in the first line, which is trivially omitted if the corresponding information on the signal cross section is not provided by the user. In the second line, MadAnalysis 5 adds either quadratically or linearly (according to the choice of the user) all theory errors, such a line being written only if at least one source of theory uncertainties is provided by the user. Finally, if the user inputted one or more options for the level of systematics, MadAnalysis 5 computes the band resulting from the combination of all errors and writes it into the output file (one line for each choice of level of systematics). In the above snippet, the user fixed an asymmetric level of systematics (for the sake of the example) indicated by the `<1lv_up>` and `<1lv_dn>` tags.

In cases where the band would have a vanishing size, the uncertainty information is not written to the output file. This could be due either to negligibly small uncertainties, to the fact that for the considered region, the signal is excluded regardless the level of systematics (at the 100% confidence level), or to the region not targeting the signal at all (the corresponding selection efficiency being close to zero).

The CLS_output.dat dataset-specific files present in the output subdirectory associated with each imported dataset all contain similar modifications. In case of extrapolations to different luminosities, copies of this file named CLS_output_lumi_<$\text{lumi}>$.dat are provided for each desired luminosity $<\text{lumi}>$. 

```
``
3 Gluino and neutralino mass limits

To illustrate the usage of the new functionalities of MADAnalysis 5 introduced in the previous section, we perform several calculations in the context of a simplified model inspired by the MSSM. In this framework, all superpartners are heavy and decoupled, with the exception of the gluino \( \tilde{g} \) and the lightest neutralino \( \tilde{\chi}_1^0 \), taken to be bino-like. Any given benchmark is thus defined by two parameters, namely the gluino and the neutralino masses \( m_{\tilde{g}} \) and \( m_{\tilde{\chi}_1^0} \). Such a new physics setup can typically manifest itself at the LHC through a signature made of a large hadronic activity and missing transverse energy. As shown by the schematic Feynman diagram of figure 1, such a signature originates from the production of a pair of gluinos, each of them promptly decaying into two jets and a neutralino (via virtual squark contributions).

We study the sensitivity of the LHC and its higher-luminosity upgrades to this signal by analysing state-of-the-art Monte Carlo simulations achieved by means of the MG5_AMC framework (version 2.6.6) [17], using the MSSM-NLO model implementation developed in ref. [7]. Hard-scattering matrix elements are generated at the next-to-leading-order (NLO) accuracy in QCD and convoluted with the NLO set of NNPDF 3.0 parton densities [18], as provided by the LHAPDF interface [19]. The gluino leading-order (LO) decays are handled with the MadSpin [20] and MadWidth [21] packages. The resulting NLO matrix elements are then matched with PYTHIA parton showers and hadronisation (version 8.240) [22], following the MC@NLO method [23]. Our predictions include theoretical uncertainties stemming from the independent variations of the renormalisation and factorisation scales by a factor of two up and down relatively to the central scale, taken as half the sum of the transverse masses of the final-state particles, as well as from the parton densities extracted following the recommendations of ref. [24].

In the upper panel of figure 2, we present the total LO and NLO gluino pair-production cross section for gluino masses ranging from 1 to 3 TeV, the error bars being associated with the quadratic sum of the scale and PDF uncertainties. The cross section central value is found to vary within the 100–0.001 fb range when the gluino mass varies from 1 to 3 TeV, so that at least tens of gluino events could be expected even for a very heavy gluino benchmark at a high-luminosity upgrade of the LHC. With the second and third panels of the figure, we emphasise the significant reduction of the scale uncertainties at NLO by depicting the LO and NLO scale uncertainty bands respectively, the \( K_{LO} \) and \( K_{NLO} \) quantities, presented in the two subfigures, these being the LO and NLO cross sections normalised to the LO central value. Such better control in the theoretical predictions is one of the main motivations for relying on NLO simulations instead of on LO ones. In the lower panel of figure 2, we focus on the PDF uncertainties associated with the total rates and present the \( K_{PDF} \) quantity where the NLO result (with its PDF error band) is again shown relatively to the LO central result. We omit the corresponding LO curve, as it is similar to the NLO one, the same PDF set being used both at LO and NLO in order to avoid having to deal with the poor-quality LO NNPDF 3.0 fit [18]. Whilst the uncertainties are under good control over most of the probed mass range, the poor PDF constraints in the large Bjorken-\( x \) regime lead to predictions plagued by sizeable uncertainties for gluino heavier than about 2.6–2.7 TeV. Finally, our results show that the NLO \( K \)-factor \( K_{NLO} \) is of about 1.6–1.7, a typical value for a strong supersymmetric production process, and features a significant gluino mass dependence. The latter originates from the quark-antiquark contributions.

**Fig. 1.** Generic Feynman diagram associated with the production and decay of a pair of gluinos in the considered MSSM-inspired simplified model. The figure has been produced with the help of the JAXODRAW package [16].

**Fig. 2.** Total LO (red) and NLO (blue) cross sections (upper panel) and \( K \)-factors (three lower panels, where the results are normalised to the LO central value) for gluino pair-production, at a centre-of-mass energy of \( \sqrt{s} = 13 \) TeV. In the upper panel, the error bands correspond to the quadratic sum of the scale and PDF uncertainties, whilst in the second and third panels, respectively, they refer to the scale uncertainties on the LO and NLO predictions. The last panel focuses on the PDF errors.
Our results are presented in figure 3 in the form of exclusion contours in the \((m_{\tilde{g}}, m_{\tilde{\chi}_0})\) mass plane, to which we supplement the values of the signal cross section that are excluded at the 95% confidence level through a colour code. We compare our predictions (the solid red line) with the official ATLAS results, extracted using the MadAnalysis 5 framework [26] (solid red) with the ATLAS results as originating from the \(M_{\text{eff}}\)-based signal region yielding the best expectation. ATLAS simulations are based on calculations at the LO accuracy in which samples of events describing final states featuring up to two extra jets are merged [28]. Moreover, the ATLAS results are normalised to NLO predictions matched with the resummation of threshold logarithms at the next-to-leading logarithmic accuracy [29]. This differs from our setup both at the level of the differential distributions, as we model the properties of the second radiation jet solely at the level of the parton showers, and at the level of the total rates that are evaluated at the NLO matched with parton showers (NLO+PS) accuracy. This consequently results in MadAnalysis 5 limits slightly weaker than the ATLAS ones by about 10%, especially in the light neutralino mass regime.

In addition, we assess the impact of the scale and PDF errors on the exclusion contours derived with NLO+PS predictions, the scale uncertainty band being shown on figure 3 as a dotted contour, and the combined scale and parton density uncertainty band as a dashed contour. It turns out that the uncertainties on the signal impacts the gluino mass limits by about 50 GeV, the effect being mostly dominated by scale variations. The reach of the considered ATLAS-SUSY-2016-07 analysis concerns gluino masses smaller than about 1.8 TeV. This corresponds to a mass range where the uncertainty on the predictions is dominated by the scale variations, as shown in figure 2. The latter indeed shows that the PDF errors (lower panel of the figure) are at the level of a few percent for \(m_{\tilde{g}} < 1.8\) TeV, the parton density fits being under a very good control for the corresponding Bjorken-\(x\) values.

In order to estimate the reach of this ATLAS supersymmetry search in the context of the future runs of the LHC, we make use of the framework detailed in section 2.3 to extrapolate the results to 300 fb\(^{-1}\) and 3000 fb\(^{-1}\). As the ATLAS note of ref. [9] does not include detailed and separate information on the systematical and statistical components of the uncertainties associated with the SM expectation in each signal region, we consider the two implemented options for their extrapolation to higher luminosities. More conservative, a linear extrapolation assumes that the error on the SM background is mostly dominated by its systematical component and scales proportionally to the luminosity (see the first term in eq. (5)). More aggressive, an extrapolation in which the error scales proportionally to the square root of the luminosity (second term of eq. (5)) considers that the background uncertainties are mainly of a statistical origin. The second option hence naively leads to a more important gain in sensitivity for higher luminosities, by definition.

The results are presented in figure 4, first, by scaling the background uncertainties linearly to the luminosity (left panel), and second, by scaling them proportionally to the square root of the luminosity (right panel). In all cases, we moreover assess the impact of the theory errors, the scale and PDF uncertainties being combined quadratically.

For an extrapolation to 300 fb\(^{-1}\) (upper subfigures), the gluino mass limits are pushed to 2.1 – 2.2 TeV for
Fig. 4. Expected constraints on the gluino-neutralino simplified model under consideration, represented as 95% confidence level exclusion contours in the $(m_{\tilde{g}}, m_{\tilde{\chi}^0_1})$ plane. We present the exclusions derived by extrapolating with MadAnalysis 5 the expectation of the ATLAS-SUSY-2016-07 analysis for 36 fb$^{-1}$ of LHC collisions to 300 fb$^{-1}$ (upper) and 3000 fb$^{-1}$ (lower). In the left panel, we extrapolate the uncertainties on the background linearly (i.e. the errors are assumed to be dominated by the systematics) while in the right panel, we extrapolate them proportionally to the square root of the luminosity (i.e. the errors are assumed to be dominated by statistics). The colour scheme represents the cross section value excluded at the 95% confidence level for each mass configuration.

A light bino-like neutralino with $m_{\tilde{\chi}^0_1} \lesssim 500$ GeV. The 36 fb$^{-1}$ exclusion is then found to be improved by about 15–20% (or 300–400 GeV). For such a mass range, the error on the theoretical predictions is still dominated by the scale variations (see figure 2) and only mildly impacts the exclusion, the effects reaching a level of about 5%. Such a small effect on a mass limit is related to the behaviour of the cross section with the increasing gluino mass, that is only reduced by a factor of a few. Comparing the left and right upper figures, one can assess the impact of the different treatment for the extrapolation of the background uncertainties. In the parameter space region under discussion, the impact is mild, reaching roughly a level of about 5% on the gluino mass limit. Such a small effect originates from the small resulting difference on the background error, that is 3 times smaller in the more aggressive case. Correspondingly, this allows us to gain a factor of 3 in cross section, or equivalently a few hundreds of GeV in terms of a mass reach.

For more compressed scenarios in which the neutralino is heavier ($m_{\tilde{\chi}^0_1} \gtrsim 800$ GeV) and the gluino lighter ($m_{\tilde{g}} \in [1, 1.7]$ TeV), the treatment of the background extrapolation has a quite severe impact on the bounds on the neutralino mass. A more conservative linear extrapolation of the background error does not yield any significant change comparatively to the 36 fb$^{-1}$ case, neutralinos lighter than about 800 GeV being excluded. However, treating more aggressively the background uncertainties as being purely statistical, leads to an important increase in the bounds, neutralino masses ranging up to about 1 TeV becoming reachable. In those configurations, the spectra are more compressed and therefore more complicated to probe than for split configurations, consequently to the fact that the signal regions are less populated by the supersymmetry...
signals. A more precisely known background (with a relatively smaller uncertainty) is therefore crucial for being able to draw conclusive statements. As found in our results, any improvement, as little it is, can have a large impact.

In the lower subfigures, we present the results of an extrapolation to 3000 fb$^{-1}$. All above-described effects are emphasised to a larger extent. The differences in the treatment of the background uncertainties corresponding to knowing the background more accurately indeed involve a factor of 10 in precision. A more interesting aspect concerns the theoretical predictions themselves that turn out to be known less and less precisely consequently to large parton density uncertainties. The limits indeed enter a regime in which large Bjorken-$x$ are probed, which corresponds to PDF uncertainties contributing significantly to the total theory error. A better knowledge of the parton densities at large $x$ and large scale is thus mandatory to keep our capacity to probe new physics in this regime.

We have verified that the obtained bounds were compatible with the naive extrapolations performed by the COller REach$^4$ platform that extracts naive limits of a given collider setup with respect to the reach of a second collider setup, rescaling the results of the later by ratio of partonic luminosities. For instance, an 1.8 TeV gluino excluded with 36 fb$^{-1}$ of LHC collisions would correspond to a 2.4 – 2.7 TeV exclusion at 300 fb$^{-1}$. This is in fair agreement with our findings, after accounting for the fact that COller REach uses the NNPDF 2.3 set of parton densities [30], a set of parton distribution functions whose fit only includes 2010 and 2011 LHC data, so that important differences are expected, particularly in the large-$x$ regime.

In figure 5, we make use of the MadAnalysis 5 infrastructure to estimate, for various benchmark points, the luminosity $L_{95}$ that is required to exclude the scenario at the 95% confidence level. We still consider the ATLAS-SUSY-2016-07 analysis, fix the neutralino mass to $m_{\tilde{\chi}_1^0} = 50$ GeV, and let the gluino mass vary. We compute $L_{95}$ for two choices of systematics on the signal (combined in both cases with the theory errors quadratically), namely 10% (dotted line) and 20% (dashed line), and compare the predictions with the central value where the signal is perfectly known (solid line). In those calculations, we scale the error on the background proportionally to the square root of the luminosity, as if it was mainly dominated by its statistical component. Our analysis first shows that light gluinos with masses smaller than about 1.5 TeV can be excluded with a luminosity $L_{95}$ included with a luminosity of about 10 fb$^{-1}$, as confirmed by the early Run 2 ATLAS search of ref. [31] that consists of the 3.2 fb$^{-1}$ version of the ATLAS-SUSY-2016-07 analysis. The steep fall of the cross section with an increasing gluino mass moreover implies that the high-luminosity LHC reach of the analysis under consideration will be limited to gluinos of about 2.5 TeV, a bound that could be reduced by about 10% if the systematics on the signal are of about 10–20%. This order of magnitude has been found to agree with older ATLAS estimates [32].

4 collider-reach.web.cern.ch/collider-reach

4 Conclusion

We have presented new features of the MadAnalysis 5 package that improve the recasting functionalities of the programme. These features focus on two aspects.

First, we have designed a way to include the uncertainties on the signal when the code is used to reinterpret given LHC results in different theoretical contexts. Theory errors on the total signal production cross section induced by scale and PDF variations can be propagated through the reinterpretation procedure. This results in an uncertainty band attached to the confidence level at which a given signal is excluded. In addition, the user has the option to provide information on the systematic uncertainties on the signal. With the existence of new physics masses being pushed to higher and higher scales, keeping track of error information on the signal becomes mandatory, especially for what concerns the theoretical uncertainties, which can be significant for beyond the Standard Model physics signals involving heavy particles.

Second, we have implemented a new option allowing the user to extrapolate the constraining power of any specific analysis to a different luminosity, assuming a naive scaling of the signal and background selection efficiencies. Several options are available for the treatment of the background uncertainties, depending on the information provided by the experimental collaborations for the analyses under consideration. If information on the statistical and systematical components of the uncertainties is available separately, signal region by signal region, MadAnalysis 5 can use it to scale them up accordingly, i.e. proportionally
to the square root of the luminosity and linearly to the luminosity for the statistical and systematical uncertainties respectively. In contrast, if such a detailed information is absent, the user is offered the choice to treat the total error as being dominated either by statistics or by systematics.

We have illustrated the usage of these new MadAnalysis 5 features by considering the production of a pair of gluinos that each decay into jets and missing transverse momentum. As an example, we have considered, as a theoretical framework, a simplified model inspired by the MSSM, in which only the gluino and the lightest neutralino are light enough to be reachable at the LHC. We have investigated the potential of an ATLAS search for supersymmetry with $36 \, \text{fb}^{-1}$ of LHC data that relies on the effective mass variable and on the presence of a large amount of missing transverse energy. We have reproduced to a good approximation the ATLAS results at the nominal luminosity of the analysis and compared our extrapolations at higher luminosities with those obtained either through the more naive approach of the ColliderREACH platform, or to publicly available ATLAS estimates for the high-luminosity runs of the LHC. Fair agreement has been found.

Our results moreover emphasise the importance of embedding the uncertainties on the signal. In the considered example, this could degrade the expected bounds by about 10 – 20%, especially as a consequence of the large theory errors originating from the poor PDF fit constraints at large Bjorken-$x$. Such a regime is indeed relevant for new physics configuration still allowed by current data and that involves the production of massive particles lying in the multi-TeV mass range.

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