A framework to create customised LHC analyses within CheckMATE

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CheckMATE is a framework that allows the user to conveniently test simulated BSM physics events against current LHC data in order to derive exclusion limits. For this purpose, the data runs through a detector simulation and is then processed by a user chosen number of experimental analyses. These analyses are all defined by signal regions that can be compared to the experimental data with a multitude of statistical tools.

Due to the large and continuously growing number of experimental analyses available, users may quickly find themselves in the situation that the study they are particularly interested in has not (yet) been implemented officially into the CheckMATE framework. However, the code includes a rather simple framework to allow users to add new analyses on their own. This document serves as a guide to this.

In addition, CheckMATE serves as a powerful tool for testing and implementing new search strategies. To aid this process, many tools are included to allow a rapid prototyping of new analyses.

Website: [http://checkmate.hepforge.org/](http://checkmate.hepforge.org/)
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PROGRAM SUMMARY

Program Title: CheckMATE, AnalysisManager
Journal Reference:
Catalogue identifier:
Licensing provisions: none
Programming language: C++, Python
Computer: PC, Mac
Operating system: Linux, Mac OS
Keywords: Analysis, Confidence Limits, Monte Carlo, Detector Simulation, Delphes, ROOT, LHC
Classification: 11.9
External routines/libraries: ROOT, Python
Subprograms used: Delphes
Nature of problem: The LHC has delivered a wealth of new data that is now being analysed. Both ATLAS and CMS have performed many searches for new physics that theorists are eager to test their model against. However, tuning the detector simulations, understanding the particular analysis details and interpreting the results can be a tedious and repetitive task. Furthermore, new analyses are being constantly published by the experiments and might be not yet included in the official CheckMATE distribution.
Solution method: The AnalysisManager within CheckMATE framework allows user to easily include new experimental analyses as they are published by the collaborations. Furthermore, completely novel analyses can be designed and added by the user in order to test models at higher center-of-mass energy and/or luminosity.
Restrictions: Only a subset of available experimental results have been implemented.
Running time: The running time scales about linearly with the number of input events provided by the user. The detector simulation / analysis of 20000 events needs about 50s / 1s for a single core calculation on an Intel Core i5-3470 with 3.2 GHz and 8 GB RAM.

IMPORTANT NOTE

- Checkmate is built upon the tools and hard work of many people. If Checkmate is used in your publication it is extremely important that all of the following citations are included,
  - Delphes 3 [1].
  - FastJet [2, 3].
  - Anti-kt jet algorithm [4].
  - CLS prescription [5].
  - In analyses that use the $M_{T2}$ family of kinematical discriminants we use the Oxbridge Kinetics Library [6, 7] and the algorithm developed by Cheng and Han [8] which also includes the $M_{T2}^*$ variable [9].
  - In analyses that use the $M_{CT}$ family of kinematical discriminants we use MctLib [10, 11] which also includes the $M_{CT\perp}$ and $M_{CT\parallel}$ variables [12].
  - All experimental analyses that were used to set limits in the study.
  - The Monte Carlo event generator that was used.

I. INTRODUCTION

CheckMATE [13] is a tool that allows for the easy testing of new physics models against current LHC data. The fully validated version now contains 14 LHC analyses with over 100 separate signal regions. More analyses are being added all the time and the beta-version now contains over 30 finished analyses that have been validated over significant regions of the parameter space. Including these analyses means that CheckMATE contains over 300 separate signal regions and this list is growing continuously.

The tool is growing in popularity and many studies have now used CheckMATE to constrain both Supersymmetry SUSY (e.g. [14–16]) and other models of new physics (e.g. [17, 18]) that may be probed at the LHC. In addition, the tool can be used to fit excesses that could potentially be the first signs of new physics (e.g. [19]).
However CheckMATE is not only a tool to be used to re-interpret analyses that are already included in the program, it is also a powerful analysis environment for users to include other analyses or invent their own searches [20]. To this end, CheckMATE contains an AnalysisManager which makes the process of writing, testing and validating an analysis as easy as possible. In particular, the manager guides the user through the various choices of available final state objects, automatically writes an analysis template and calculates the various statistical measures required to define the sensitivity of a search. Many steps along this path are also significantly smoothed by extra features included in the CheckMATE package.

Whilst similar analysis tools already exist, CheckMATE is specifically designed for new physics searches at the LHC. The analysis framework is heavily influenced by the Rivet [21] program and shares the philosophy of using projections to define the particular final state objects of interest. However, the big difference is that whilst Rivet is designed to recast unfolded high energy analyses, CheckMATE includes the detector simulation Delphes [1] with a significantly improved ATLAS tuning [17]. Consequently, CheckMATE can reproduce new physics searches where a detector simulation is vital to accurately reproduce the experimental result. Additionally, the integrated statistics functionality allows exclusion and/or discovery regions to be easily found with minimal user input.

The MadAnalysis [22, 24] framework is another similar approach that also has an emphasis on new physics searches at the LHC. Since MadAnalysis also uses the Delphes detector simulation, work has now begun to improve the compatibility with CheckMATE so that the tools can be used interchangeably.

For budding LHC phenomenology analysis authors, the most attractive feature is the simplification CheckMATE achieves in the analysis writing procedure. Many different tunes of final state objects are available (e.g. ‘loose’, ‘medium’ and ‘tight’ electrons in case of ATLAS) while some objects even have the full multi-variate discriminant parametrised (e.g. b-jets) that automatically recalculate the fake rate depending on the efficiency required. Routines also exist for the automatic calculation of isolation variables where the user only has to specify the required parameters. Furthermore, many of the kinematical variables (e.g. $m_{T2}$, $d_{T}$, razor) used by the LHC collaborations are included. Additionally, since ROOT is fully integrated, the TLorentzVector class is available which allows the easy access and calculation of a huge number of 4-vector variables.

To help with creating, testing and validating the analyses, tools are included for the automatic calculation of cutflows and signal regions. The statistical evaluations required to assess the analysis are also implemented to assist the user at every point. Finally, if backgrounds and the corresponding errors are known, the experimental reach of the analysis to a particular model of new physics is also then calculated.

In this manual, we will guide the users through the list of steps necessary to add these skeletons to CheckMATE, how these skeletons have to be understood and what has to be done in order to fill them with proper content. In Section IV we introduce the main features of CheckMATE. Section III describes in detail the AnalysisManager module of CheckMATE and presents the main ingredients of analyses within CheckMATE. In Section IV we provide a detailed discussion of two analyses implemented in CheckMATE in order to familiarise the user with the analysis writing technique. This is followed by an example of a completely new analysis to test the discovery potential of a compressed SUSY scenario at the 14 TeV LHC. Finally we summarise in Section V.

II. OVERVIEW: THE ANALYSISMANAGER WITHIN CHECKMATE

In this section we briefly summarize CheckMATE’s main program flow and outline the procedure to add a new analysis to the existing framework. Detailed information on CheckMATE itself can be found in [13].

CheckMATE uses simulated event files and cross sections as input. Users have to provide these and list the analyses they want them to be tested against. The provided files are then fully automatically processed by the following 3-step procedure:

1. The embedded program Delphes takes the input events and applies a fast detector simulation. CheckMATE determines the settings required for Delphes based on the exact analyses chosen. This optimises the detector simulation by only requiring the final states objects needed for the particular analysis list.

2. The output of the simulation is quantified by applying a standalone C++ analysis program on the results. The final state objects of each event are tested to see if they fulfil the criteria of one or more of the signal regions defined within the analyses. For each of these signal regions, the total number of input events that pass the selection is evaluated and normalised to the given input cross section and luminosity.

3 The implementation of an improved CMS tuning is planned in the near future.
3. The predictions for all signal regions are compared to the stored experimental results in terms of the observed and expected number of events. This set of information is statistically combined to quantify the compatibility of the observation with the input model. CheckMATE then deduces whether the input model can be excluded or not to the 95 \% C.L.

In order to add a new analysis to this framework, CheckMATE requires various pieces of information and needs them stored in a well defined form at specific places in the code. The AnalysisManager offers a simple way to provide this information automatically to CheckMATE. It is already included in the official CheckMATE distribution and only has to be compiled explicitly, see Section IV. Users can simply use terminal commands to list, add, edit or remove analyses. In order to add an analysis, a sequence of questions has to be answered which collects the information that CheckMATE requires to setup the internal workings accordingly:

- Some general information (name of the author, name of the analysis, luminosity, \( \sqrt{s} \), ...) is gathered first to define the headers and names of all the respective files and to determine the normalisation of the event numbers.

- The properties of final state objects determined on the detector level (jet clustering algorithm, working point efficiencies for jet flavour tagging, lepton isolation criteria, ...) will later define the Delphes setup during the actual CheckMATE run as well as the available objects in the analysis code.

- Numbers (observed number of events, Standard Model expectation, ...) and names for all signal regions have to be defined by the user and are used in CheckMATE’s evaluation step. The user normally can take these directly from the corresponding experimental publication.

After this information is entered, the AnalysisManager will create all the internal files necessary to run the analysis within the normal CheckMATE framework. The user still has to define the actual analysis prescription in the form of a C++ code. For that purpose, a skeleton source code is provided which gives the user automatic access to all objects defined during the AnalysisManager step. Lots of additional predefined helper functions further reduce the effort to implement the analysis code. The call of a single function, \texttt{countSignalEvent(<SR>)}, is sufficient to trigger the CheckMATE evaluation routines. In the upcoming sections we will discuss the definitions and features of all these objects and functions in more detail.

III. FEATURES OF CHECKMATE ANALYSISMANAGER

As explained in the introduction, CheckMATE contains many novel features to make recasting or designing a new LHC analysis as simple as possible. In this section we introduce these features in detail while later sections give examples of how these are used in practice.

A. Final state objects and functions

Most of the reconstruction efficiencies for final state objects available in CheckMATE have been re-tuned according to ATLAS performance studies. In addition, new functionality has been included to allow a full reproduction of all the final state cuts currently implemented by the LHC experiments. Details of all the individual reconstruction efficiencies can be found in [13].

Electrons

All three of the current ATLAS electron definitions, loose, medium and tight, are available in CheckMATE and can be called in any analysis. They are different in terms of the reconstruction efficiency and these are implemented in terms of 2-dimensional look-up tables as a function of \( p_T \) and \( \eta \). A default loose isolation condition that requires the sum of calorimeter objects in a cone size of \( \Delta R = 0.2 \) not associated to the electron to be less than 0.2 of the electron \( p_T \) is always applied. If tighter and/or more complicated isolation conditions are required please see the specific isolation subsection below. Also, in the case of ATLAS, a retuned algorithm is present to smear the reconstructed electron momentum. For CMS, the default Delphes tunings for electrons are used.
Muons

The majority of ATLAS analyses currently use one of two muon reconstruction algorithms, ‘Combined’ and ‘Segment–Tagged’. The latter is usually used in combination with the first to maximise the muon efficiency and is hence called ‘Combined+Segment–Tagged’. Both definitions are implemented in CheckMATE as 2-dimensional look-up tables as a function of $\eta$ and $\phi$. Again, in the case of ATLAS, a retuned algorithm is present that accurately smears the reconstructed muon momentum. As for electrons, the default Delphes CMS tuning for muons is used.

Jets

Jets are reconstructed using either smeared calorimeter deposits in the case of ATLAS or particle flow information in the case of CMS. By default, the anti-$k_T$ algorithm implemented in FastJet \cite{2, 3} is chosen to cluster jets and the user only has to specify the cone size ($\Delta R$) required.

Taus

The tau reconstruction algorithm searches the event tree for the presence of a tau and, if the momentum vector determined from its visible decay products overlaps with a reconstructed jet, identifies the jet as a tau candidate. If not, it is considered a fake background candidate, for which different efficiencies are used. These jets are then further sub-divided into two categories, 1-prong or multi-prong depending on whether the jet contains exactly one or more reconstructed tracks. For each category CheckMATE has three different reconstruction algorithms (loose, medium and tight) parametrised as a function of $p_T$ and $\eta$ that the user can easily select. Currently only ATLAS parametrisations are available with CMS functions planned for a future release. For CMS analyses, the ATLAS parametrisations are used.

B-jets

The $b$-jet reconstruction function begins by first defining whether the jet overlaps with a $b$-quark. If not, it is checked whether there is overlap with a $c$-quark and if again there is no overlap, it is assumed that it only contains light quarks. All three types of jet have different probabilities to be tagged as a final state $b$-jet depending on the $p_T$ and $\eta$ of the jet.

A feature of CheckMATE is that the complete receiver operator curve (ROC) of the ATLAS multivariate $b$-tagger is implemented. Consequently the user can choose any particular $b$-tag reconstruction probability that they desire and CheckMATE will automatically adjust the probability that $c$-quarks or light jets fake a true $b$-quark. This feature is very useful since ATLAS uses widely different tagging points depending on the analysis of interest and the associated fake rates vary by orders of magnitude. Currently only ATLAS parametrisations are available but CMS functions are planned for a future release. For now, the tuned ATLAS parametrisations are used for CMS analyses with the assumption that for a given working point the deduced efficiency distributions are roughly equal.

Tracks and Calorimeter Cells

Although not routinely required for most analyses, all reconstructed tracks and calorimeter cells are available. This information can be used for example to develop more complicated isolation procedures than those already implemented (see Isolation below) or for custom jet algorithms. For the track reconstruction efficiency and momentum smearing we use the default Delphes parametrisation for both ATLAS and CMS. The same is also true for the calorimeter energy smearing.

Missing Energy

Missing energy is reconstructed from the the sum of the smeared calorimeter deposits in the case of ATLAS or the sum of the smeared particle flow objects in the case of CMS. In addition, to effectively parametrise additional QCD activity due to pile-up we also include an extra smearing factor on the missing energy that has been tuned to match
the ATLAS distributions, but is used for both ATLAS and CMS analyses: This smearing is done by adding a vector with uniformly random direction magnitude which follows a Gaussian distribution with width 20 GeV centred around 0. Due to the way Delphes treats final state muons, their contribution has to be added separately to the missing energy, as will be shown in the following Section.

Isolation

CheckMATE supplies routines that automatically calculate the various isolation conditions required by the LHC experiments for both muons and electrons. Firstly the user can specify whether the isolation is calculated with respect to the calorimeter or to reconstructed tracks. In addition, the option to calculate isolation as an absolute $p_T$ or as a fraction of the reconstructed lepton $p_T$ is available. For finer control, the thresholds that individual tracks or calorimeter cells are included in the isolation calculations can also be stated.

Whilst the above options allow reproduction of the vast majority of isolation variables used by the experiments we also remind the user that both the tracking and calorimeter information is available if more control is required.

Final state projections

In order to simplify the basic acceptance cuts required on final state objects, CheckMATE employs a projection based system that is very similar to the one pioneered by Rivet [21]. The idea is that a vector of final state objects is given to a function along with the the angular acceptance and minimum $p_T$. A vector of the objects that passed the cuts is returned and this avoids multiple loops over final state objects being needed in the analysis code. In addition, ATLAS often performs a cut on final state objects that fall into the transition region between the central and forward detectors and an optional projection for this area is included.

Overlap removal

Another commonly required routine for LHC analyses is the removal of overlapping final state objects. For example, since electrons deposit energy in the calorimeter they are also included in the jet algorithm and must be removed from the list of jets in order not to double count momentum. In addition many analyses also require an overlap removal between muons and jets as well. CheckMATE allows easy overlap removal where the user only has to state the cone size required for the operation, the object to be removed and the object to be kept.

B. Kinematical Variables

CheckMATE has access to both the Delphes kinematical variables and the TLorentzVector class from Root. The Delphes library contains many of the most used kinematical parameters, like transverse momentum, energy and pseudo-rapidity, as well as non-kinematical properties, for example electric charge. In addition the TLorentzVector class contains the full list of Lorentz variables and the possibility to calculate values from two separate vectors, e.g. relative angles.

CheckMATE also contains a number of popular LHC kinematical variables which are either hard-coded or sourced from other libraries (Oxbridge Kinetics Library [6–8] and MctLib [10, 11]). For a more detailed review of many of the variables that have now been developed for high energy physics please see [25].

- $M_T$ [26–30]: The transverse mass, $M_T$, allows for the reconstruction of a particle that decays semi-invisibly via an end-point in the kinematical distribution. We define,

\[ M_T^2 = m_{\text{invis}}^2 + 2 p_T^e p_T^\mu (1 - \cos \Delta \phi) , \]  

\[ (1) \]
where \( p^T_1 \) is the magnitude of the transverse momentum of the visible final state particle which is assumed to be massless. \( m_{\text{invis}} \) is the mass and \( \Delta \phi \) is the magnitude of the missing transverse energy of the invisible particle and \( \Delta \phi \) is the azimuthal angle between the visible final state particle and the missing energy vector.

\( M_T \) is most commonly used to identify and measure the leptonic decay modes of the \( W \) boson, \( W \to \ell \nu \) in which case both of the final state particles, lepton and neutrino, can be considered massless.

- **\( M_{T2} \)** [7]:
  In the case that an event contains two or more missing particles, an end-point in \( M_T \) to measure the decaying particle mass will no longer exist. This is true when we for example consider the production of two particles that both decay to a final state that contains an invisible particle. In addition, for new physics searches we are also often faced with the possibility that the masses of the invisible particles are unknown. If however the two invisible particles have the same mass, the space of possible momentum configurations is reduced and in fact can be numerically tested. To account for these scenarios, the \( M_{T2} \) variable was defined [7] which minimises over all possible partitions \( (p^T_1, p^T_2) \) of the vector missing energy \( (p^T) \) between the two decay chains,

\[
M_{T2}(m_\chi) = \min_{p^T_1 + p^T_2 = p^T} \left[ \max \{ M_T(p^T_1, p^T_1; m_\chi), M_T(p^T_2, p^T_2; m_\chi) \} \right].
\]

Here, \( p^T_1(2) \) is the vector transverse momentum of the visible final state particles, assumed to be massless, and \( m_\chi \) is the mass of the invisible particle, which may be unknown and set to some test value.

- **\( M_{T2}^{bl} \)** [9]:
  A popular variable to efficiently discriminate scalar top partners which decay into top quarks and an invisible particle from the SM top background at the LHC is \( M_{T2}^{bl} \). This is a modification of standard \( M_{T2} \) to an asymmetric case where a single lepton and two \( b \)-jets are reconstructed. The aim for \( M_{T2}^{bl} \) is to reconstruct the top-quark mass in di-leptonic top decays where one lepton fails to be reconstructed. Thus, the decay chain with a reconstructed lepton should evaluate \( M_{T2} \) with a massless neutrino, \( \nu_\ell \), while the other chain — assumed to be missing a lepton — should reconstruct the \( W \) mass, \( m_W \),

\[
M_{T2}^{bl} = \min_{p^T_1 + p^T_2 = p^T} \left[ \max \{ M_T(p^T_{b_1} + p^T_{1}, p^T_{1}; m_\nu), M_T(p^T_{b_2}, p^T_2; m_W) \} \right].
\]

Here, \( p^T_{b_1(2)} \) is the vector transverse momentum of the \( b \)-jets and \( p^T_1 \) is the vector transverse momentum of the lepton. Commonly, both combinations of the \( b \)-jet momentum with the lepton momentum are computed and the smallest resulting \( M_{T2}^{bl} \) is used.

- **\( M_{CT} \)** [10]:
  The \( M_T \) variable (Eq. 1) is invariant under Lorentz–boosts. More specifically, it is invariant under co-linear transverse boosts, i.e. if both particles are boosted by the same magnitude in the same transverse direction. A related observable called \( M_{CT} \),

\[
M_{CT}^2 = m_1^2 + m_2^2 + 2 (E^T_1 E^T_2 + p^T_1 \cdot p^T_2),
\]

can be defined, where the transverse energy is defined as, \( E^T = \sqrt{m^2 + |p^T|^2} \). Contrarily to \( M_T \), it is invariant under contra-linear transverse boosts, i.e. under boosts with equal magnitude but opposite direction in the transverse plane of the two final state particles. This is useful at a hadron collider since in the absence of initial state radiation (ISR), the production of a pair of equal mass particles will have equal back to back transverse boosts. Moreover, these boosts will be unknown if the parent particle decays to an invisible particle.

- **\( M_{CT+} \) and \( M_{CT-} \)** [12]:
  In event topologies that allow for the reliable determination of ISR, two one dimensional decompositions of
\( M_{CT} \) can be made. We first define the decomposition of the final state momentum vectors into the components, perpendicular and parallel, to the ISR transverse vector, \( U^T \),

\[
\begin{align*}
\mathbf{p}_{i}^{T_{\perp}} &= \frac{1}{|U^T|^2} (\mathbf{p}_i^T \cdot U^T) U^T, \\
\mathbf{p}_{i}^{T_{\parallel}} &= \mathbf{p}_i^T - \mathbf{p}_{i}^{T_{\perp}} = \frac{1}{|U^T|^2} U^T \times (\mathbf{p}_i^T \times U^T).
\end{align*}
\] (5) (6)

We can now define the one dimensional analogues of \( M_{CT} \),

\[
M_{CT_{\perp}} = m_1^2 + m_2^2 + 2 (E_{T_{\perp}1} E_{T_{\perp}2} + \mathbf{p}_{i}^{T_{\perp}1} \cdot \mathbf{p}_{i}^{T_{\perp}2}),
\] (7) \[ M_{CT_{||}} = m_1^2 + m_2^2 + 2 (E_{T_{||}1} E_{T_{||}2} + \mathbf{p}_{i}^{T_{||}1} \cdot \mathbf{p}_{i}^{T_{||}2}),
\] (8)

where we also define the corresponding energy decompositions,

\[
E_{i}^{T_{\perp}} = \sqrt{m_i^2 + |\mathbf{p}_{i}^{T_{\perp}}|^2}, \quad E_{i}^{T_{||}} = \sqrt{m_i^2 + |\mathbf{p}_{i}^{T_{||}}|^2}.
\] (9)

The perpendicular variable, \( M_{CT_{\perp}} \), has the useful property that it is transverse to the ISR and thus invariant under the magnitude of the ISR boost.

\( \alpha_T [31, 32] \): A substantial background to missing energy searches with jet final states are pure QCD events where one jet has a large mismeasurement. The mismeasurement can lead to a significant missing energy signal that could fake new physics with genuine missing energy and the variable \( \alpha_T \), was designed to guard against this. For a di-jet system the variable is defined as,

\[
\alpha_T = \frac{E_{T_{j2}}}{M_{T_{j}}},
\] (10)

where \( E_{T_{j2}} \) is the less energetic of the two jets and \( M_{T_{j}} \) the transverse mass of the di-jet system,

\[
M_{T_{j}} = \left( \sum_{i=1}^{2} E_{T_{j_i}} \right)^2 - \left( \sum_{i=1}^{2} p_{x_{j_i}} \right)^2 - \left( \sum_{i=1}^{2} p_{y_{j_i}} \right)^2.
\] (11) (12)

For a perfectly back to back di-jet system, \( \alpha_T = 0.5 \), but if one of the jets suffers a mismeasurement in energy the resulting \( \alpha_T \) will be lower. In contrast, signal like events that do not have a back to back topology but genuine missing energy can have values of \( \alpha_T > 0.5 \).

The variable is also generalised to multi-jet topologies,

\[
\alpha_T = \frac{H_T - \Delta H_T}{2 \sqrt{H_T^2 - \mathbb{H}_T^2}},
\] (13)

where,

\[
H_T = \sum_{i=1}^{n_{jet}} E_{T_{j_i}},
\] (14) \[ \mathbb{H}_T = \left| \sum_{i=1}^{n_{jet}} \mathbf{p}_{j_i}^T \right|.
\] (15)

\( \Delta H_T \) is found by forming two pseudo jets from all the reconstructed jets in the event. The combination is done by performing a scalar sum of the jet \( E_T \) and choosing the jet combination that minimises the absolute \( E_T \) difference (\( \Delta H_T \)) between the two.
- **Razor** [33–35]:

Another approach that has been designed to focus on the pair production of new states, e.g. scalar quark partners, that each decay into a visible and an invisible particle, e.g. a neutralino and a jet, has been called ‘razor’. Two dimensionful variables are defined,

\[
M_R = \sqrt{\left( |p_1| + |p_2| \right)^2 - \left( p_T^1 + p_T^2 \right)^2},
\]

\[
M_T^R = \frac{p_T^1 (p_T^1 + p_T^2) - p_T \cdot (p_T^1 + p_T^2)}{2}.
\]

(16)

(17)

where \(M_R\) is designed to peak at the mass scale of the new physics and \(M_T^R\) measures the transverse momentum imbalance. Combining the two values in a ratio,

\[
R = \frac{M_T^R}{M_R},
\]

(18)

one finds a variable that is expected to peak at \(R \sim 0.5\) for two body decays. In the Standard Model, both \(M_R\) and \(R\) are expected to fall smoothly and thus new physics can appear as a bump on a falling background.

As for \(\alpha_T\), the variable can be generalised to topologies that contain more than two visible final state particles by first performing a clustering. In this case, two ‘megajets’ are formed by summing the four-momentum of all combinations of final state jets and leptons. The combination that minimises the sum of the invariant masses of the two megajets is then chosen.

**C. Validation**

An extremely important step on the way to recasting an LHC analysis is validation in order to ensure that all kinematical cuts are implemented correctly. LHC analyses now routinely provide information for particular hypothetical signal models concerning the acceptance as each individual cut is applied in order. This information is vitally important when validating an analysis since it allows the acceptance of each individual cut to be checked.

In order to make the validation procedure as simple as possible, CheckMATE includes a specific syntax for recording cutflows that can then be easily checked against the experimental publication. The syntax simply replaces the call `countSignalEvent(<SR>)` with `countCutFlowEvent(<CF>)` and generates completely separate cutflow results that can be quickly modified and do not interfere with the defined signal regions.

**D. Evaluation statistics**

One of the most convenient features of CheckMATE is the evaluation of the number of signal events and the corresponding calculation of all of the statistics required to determine if a particular model is excluded at the LHC or not. In fact the easiest way of running CheckMATE simply leads to the result `excluded` or `allowed` depending on the number of signal events. More results and statistical variables are available for more advanced users. All of the above procedures are automatically evaluated for newly defined analyses with minimal user input required.

For the implementation of existing LHC analyses, the user simply has to provide the number of background events expected in a particular signal region, the associated error and the actual number of observed events. All the normal CheckMATE evaluation routines are then available automatically and work with both weighted and unweighted signal events.

In the case that the user is developing a new analysis, the Standard Model backgrounds must first be evaluated before the expected reach at the LHC can be calculated. For this the user simply runs CheckMATE as normal on the various backgrounds that are expected to contribute. The number of events normalised to cross-section is then evaluated by CheckMATE process by process for each signal region and simply summed to give the total background. Once this procedure is complete the analysis can then be used as normal.

In addition, since we inherit all of libraries contained within ROOT, any of the statistical functions and histogramming features are easily accessible for use within analyses.

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4 Depending on the analysis, this information can also be in the form of cross sections or simply Monte-Carlo event counts.
IV. PRACTICAL EXAMPLES

Often it is easiest to do a task oneself after one has seen it in a practical example. This is why in this section we will discuss the implementation of three practical examples in detail.

A. Example 1: Recasting a simple analysis step by step

In this part we will add an (already existing) analysis to the CheckMATE framework from the very first steps on. We assume that CheckMATE is already installed in the directory `<CM>`.

Running the Analysis Manager

If `<CM>/bin/AnalysisManager` does not yet exist, we run `make AnalysisManager` within `<CM>` to create it. Starting the AnalysisManager will open the introduction header and a first prompt:

```
/\ _ _ | _. _ |/_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _...```

What would you like to do?
- (l)ist all analyses,
- (a)dd a new analysis to CheckMATE,
- (e)dit analysis information,
- (r)emove an analysis from CheckMATE

Apparently we want to add something new, so we hit a:

This will collect all necessary information to create a full analysis and
Takes care for the creation and implementation of the source files into the code.
Please answer the following questions.
Attention: Your input is NOT saved before you answered all questions!

The first block of questions gathers some general information on the analysis. At the beginning, you are asked for your name and your email address. These are printed on the very first lines of the analysis code to make sure that the right author can be contacted in case something goes wrong.

1. General Information to build analysis
   Your Name (to declare the analysis author):
   Guybrush Threepwood
   Your Email:
   threepwood@pirates.arr

   Afterwards, some simple information on the analysis has to be provided. The name should be short but clear and should not contain any spaces, since this string defines the names for all analysis-specific files.

   Analysis Name:
   atlast_conf_2013_047X

   The one-line description is the one used when someone types 1 in the AnalysisManager. It can also be found in the file `list_of_analyses.dat`. The multiline description is printed on the top of every output file the respective analysis code creates:

   Description (short, one line): ATLAS, 0 leptons + 2-6 jets + etmiss
   Description (long, multiple lines, finish with empty line): ATLAS
   ATLAS-CONF-2013-047
   0 leptons, 2-6 jets, etmiss
   sqrt(s) = 8 TeV
   int(L) = 20.3 fb^-1

   \[5\] Note that we only added the letter X at the end of the analysis name to prevent the AnalysisManager from overwriting the already implemented `atlast_conf_2013_047` analysis data.
The luminosity is important for the correct normalisation of the analysis results:

Luminosity (in fb\(^{-1}\)):

20.3

At the end of this block, the AnalysisManager will ask you whether you want to provide control regions for the given analysis. If we choose “yes”, it will produce a second analysis source file which can be run separately from within CheckMATE. In our case, we are only interested in implementing signal regions and cutflows for which we do not need a second analysis file.

Do you plan to implement control regions to that analysis? [(y)es, (n)o]

n
Now we go more into the details of the analysis. As the next step, we have to list all signal regions the analysis provides. If we check out the actual analysis publication [36], we find five main signal regions A–E which sometimes are split into subregions L(loose), M(edium) or T(ight). We enter them one by one

2. Information on Signal Regions

List all signal regions (one per line, finish with an empty line):

AL
AM
BM
BT
CN
CT
D
EL
EN
ET

In our case, we implement an experimental study for which the experimental observation and Standard Model expectation are known. If we want to create a new analysis, see later sections, we will not know these and have to find and enter them later.

Is the SM expectation B known? [(y)es, (n)o]?

y

Now things become a little more involved: for each of the above signal regions, we have to provide a set of numbers to which CheckMATE can compare the model prediction. In its most simple form, this includes the observed number of events \(\text{obs}\) and the Standard Model expectation \(\text{bkg}\) including error \(\text{bkg}_{\text{err}}\). Sometimes, the background error is split up into a statistical and systematical error and sometimes the systematical error is given in asymmetrical ± form. The different input options also allow for the data to be given in all these different formats. In our example, Table 4 in ref. [36] gives us the minimal set: \(\text{obs}, \text{bkg}\) and \(\text{bkg}_{\text{err}}\).

Information: We are now going to ask you which numbers you want to provide for each signal region. The following items are possible:

- \(\text{obs}\): Observed number of events
- \(\text{bkg}\): Expected number of background events
- \(\text{bkg}_{\text{err}}\): Expected total error on \(\text{bkg}\)
- \(\text{bkg}_{\text{errp}}\): Expected total upper error (in case of asymmetric errors)
- \(\text{bkg}_{\text{errm}}\): Expected total lower error (in case of asymmetric errors)
- \(\text{bkg}_{\text{err_stat}}\): Expected statistical error on \(\text{bkg}\)
- \(\text{bkg}_{\text{err_sys}}\): Expected systematical error on \(\text{bkg}\)
- \(\text{bkg}_{\text{errp_sys}}\): Expected systematical upper error (in case of asymmetric errors)
- \(\text{bkg}_{\text{errm_sys}}\): Expected systematical lower error (in case of asymmetric errors)

Note that not all of these numbers have to be given (e.g. you don’t have to give the total error if you give the individual stat and sys contributions). However, there are some requirements, about which you will be warned if you don’t meet them (e.g. giving \(\text{xyz}_{\text{errp}}\) without \(\text{xyz}_{\text{errm}}\)). The standard, minimum set of information consists of \(\text{obs}, \text{bkg}\) and \(\text{bkg}_{\text{err}}\).

List all categories you want to supply (one per line)

- \(\text{obs}\)
- \(\text{bkg}\)
- \(\text{bkg}_{\text{err}}\)

The set of information you entered is valid.

The AnalysisManager would reject the input list if it was not complete: for example, if we entered only the statistical error \(\text{bkg}_{\text{stat}}\) but no systematical error.

Next, we have to enter the actual numbers for all the above categories for each and every one of the listed signal regions:
You now have to add the numbers for each of the given signal regions. Note that while you enter more numbers, the corresponding model independent 95\% confidence limits for the items you have already entered are calculated in the background.

AL

\begin{itemize}
\item \textbf{obs:} 5333
\item \textbf{bkg:} 4700
\item \textbf{bkg\_err:} 500
\end{itemize}

S95obs and S95exp values are calculated internally (progress: 0 / 2)

AM

\begin{itemize}
\item \textbf{obs:} 135
\item \textbf{bkg:} 122
\item \textbf{bkg\_err:} 18
\end{itemize}

S95obs and S95exp values are calculated internally (progress: 0 / 4)

ET

\begin{itemize}
\item \textbf{obs:} 5
\item \textbf{bkg:} 2.9
\item \textbf{bkg\_err:} 1.8
\end{itemize}

S95obs and S95exp values are calculated internally (progress: 3 / 20)

To allow for a fast statistical evaluation of the result in CheckMATE, it is convenient to first translate observation and expectation into a model independent upper limit on any new signal prediction S95. These numbers are calculated internally by the AnalysisManager. As this calculation takes some time, it is queued and calculated in the background while the user enters the detector related information.

The next set of questions are all about detector level objects:

3. Settings for Detector Simulation

3.1: Miscellaneous

To which experiment does the analysis correspond? [(A)TLAS, (C)CMS]

A

As a next step we have to enter information regarding lepton isolation criteria. Normally, these are defined within the experimental publications and are needed to distinguish signal leptons from leptons within jets. In our example, however, there are no signal leptons and therefore we do not require any particular isolation criteria for neither electrons, muons nor photons.

3.2: Electron Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]

n

3.3: Muon Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]

n

3.4: Photon Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]

n

Note that even though we entered no, internally there will always be a soft isolation condition that cannot be overwritten by the user and which is automatically applied on electrons, muons and photons. This ensures that objects that would not have been reconstructed due to overlapping detector activity are automatically removed internally.

We now continue with the definition of jets. Reference \[36\] tells us the exact properties we have to enter here:

3.5: Jets

Which dR cone radius do you want to use for the FastJet algorithm?

0.4

What is the minimum pt of a jet? [in GeV]

20

Do you need a separate, extra type of jet? [(y)es, (n)o]

n

The extra type of jet is needed in the rare case that a single analysis requires two different jet cone size, $\Delta R$, however it is not required in our example. The final questions relate to potential flavour tags we have to apply on jets. The given analysis considers $b$-tags with a reconstruction efficiency of 70\%. We therefore simply enter
Do you want to use b-tagging? [(y)es, (n)o]

(y)
b-Tagging 1:
What is the signal efficiency to tag a b-jet? [in %]

70

Do you need more b tags? [(y)es, (n)o]

(n)

Do you want to use tau-tagging? [(y)es, (n)o]

(n)

Depending on how quickly we entered the above information, the AnalysisManager either finished the internally started S95 calculations or will wait until these are complete. When the evaluation ends, the results are shown and should be briefly checked to make sure that all numbers are sensible.

All necessary information has been entered. Before the AnalysisManager can create all required files, the internal S95obs and S95exp calculations have to finish. The calculation should take 10s up to a minute per point.

... done!

Please check the below results for sanity. If anything looks suspicious, please contact the CheckMATE authors.

| obs   | bkg   | bkgerr | S95obs | S95exp |
|-------|-------|--------|--------|--------|
| 5333  | 4700  | 500    | 1400   | 985    |
| 135   | 122   | 18     | 50     | 40     |
| 29    | 33    | 7      | 14     | 17     |
| 4     | 2.4   | 1.4    | 6.9    | 5.8    |
| 228   | 210   | 40     | 87     | 79     |
| 0     | 1.6   | 1.4    | 3.0    | 3.4    |
| 18    | 15    | 5      | 15     | 13     |
| 166   | 113   | 21     | 90     | 54     |
| 41    | 30    | 8      | 28     | 21     |
| 5     | 2.9   | 1.8    | 8.2    | 6.6    |

(Press any key to continue)

Note that due to numerical effects, your results might differ from the numbers above. Comparing the calculated numbers to the ones in Ref. [36] tells us that the numbers are acceptable. Usually, the experimental numbers differ from the ones calculated by the AnalysisManager. This is mainly caused by different parametrisations of the background uncertainties, taking information on individual error sources into account to which CheckMATE does not have access. CheckMATE still prefers to calculate and use its own numbers as the exact same statistical routines for S95 are used for the proper CLs calculation in the CheckMATE evaluation routines such that the results of the two approaches are more consistent with each other.

We therefore accept the numbers and finish the AnalysisManager section:

- Variable values saved in /hdd/sandbox/managertest/data/atlas_conf_2013_047X.var.j
- Created source file /hdd/sandbox/managertest/tools/analysis/src/atlas_conf_2013_047X.cc
- Created header file /hdd/sandbox/managertest/tools/analysis/include/atlas_conf_2013_047X.h
- Updated Makefile
- Updated main source main.cc
- Reference file created
- List of analyses updated

Analysis atlas_conf_2013_047X has been added successfully!
Run ‘autoreconf; ./configure {parameters}; make’ to compile the new sources.
You can find the list ‘{parameters}’ you configured CheckMATE originally with at the beginning of the file ‘config.log’.

Looking at the Skeleton Code

The AnalysisManager is mainly responsible to gather all the information for the detector simulation and the statistical evaluation sections of CheckMATE. What is still left to do is to define the analysis code that is used to analyse the events the user provides. In this section we describe how to do this by continuing our example of atlas_conf_2013_047X. Note that the code we develop here differs slightly from the actual code implemented in CheckMATE since we, for the sake of understanding, change the order of some steps here and shorten the code where possible. It still gives the exact same results for the signal region tests though.

As the AnalysisManager has told us, source and header file for our analysis have already been created. These are already filled with skeleton code that properly compiles and embeds the analysis into the existing framework. What should concern us most is the source file which contains the actual analysis code. Every CheckMATE analysis contains three main functions.°

° The three-function structure is similar to the one used in the Rivet framework.
initialize(): This function is called once at the beginning of an analysis. It is therefore used to setup overall information, initialise variables and open files that are used throughout the analysis. By default, AnalysisManager data that is important for the analysis is already embedded.

```c++
#include "atlas_conf_2013_047X.h"
// AUTHOR: Guybrush Threepwood
// EMAIL: threewood@pirates.arr
void Atlas_conf_2013_047x::initialize() {
    setAnalysisName("atlas_conf_2013_047X");
    setInformation(""
        "# ATLAS"
        "# ATLAS-CONF-2013-047"
        "# 0 leptons, 2-6 jets, etmiss"
        "# sqrt(s) = 8 TeV"
        "# int(L) = 20.3 fb^-1"
    "");
    setLuminosity(20.3*units::INVFB);
    ignore("towers");
    ignore("tracks");
    bookSignalRegions("AL;AM;BM;BT;CM;CT;D;EL;EM;ET;");
}
```

The `setAnalysisName` and `setInformation` functions define human readable headers and the prefix of all analysis-related output files. `setLuminosity` is used to properly normalise the input to a physical number of events given the cross section the user provides in the CheckMATE input card. This number can be used to rescale the overall output, e.g. to take a global event-cleaning efficiency into account. `ignore` functions are for pure computing time optimisation reasons: they ignore information in the detector simulation to be read out if it is not required by the user. This is usually the case for calorimeter towers and tracker information which forms large datasets but which are rarely needed for the actual analysis. Finally `book` functions are defined for `SignalRegions` and `CutflowRegions`. These functions make sure that the respective `_signal.dat` and `_cutflow.dat` analysis output files contains numbers for each of the booked signal/cutflow regions. No matter in which order the signal regions are booked they will always be sorted alphabetically in the output.

analyze(): This function is the heart of any analysis: It is called once per event and contains the physics that is used to quantify the given data. Except for some comments and tips, this function does not contain any code yet and we will fill it in the next part of this tutorial.

finalize(): As the name suggests, this function is called once at the end of a given analysis. Usually this function is empty, however it can be used to e.g. free pointers that have been defined during `initialize` or to close some extra files that have been opened and filled before.

Now that we have understood the structure let us start to implement the analysis code.

Selection of Final State Objects

As the first step, we should define all the final state objects that we need and apply the appropriate kinematical cuts. The given analysis requires the following objects:

- missing energy
- electrons with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.47 \) that pass minimal selection criteria
- muons with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.4 \) reconstructed with combined data from tracker and muon spectrometer
- photons with \( p_T > 130 \text{ GeV} \) and \( |\eta| < 2.47 \) excluding \( 1.37 < |\eta| < 1.52 \) and
- jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.8 \).

In the code, all the above objects are already predefined and we just have to select the right kinematic range using the `filterPhaseSpace` function of the analysis base class:

```c++
void Atlas_conf_2013_047::analyze() {
    missingET->addMuons(muonsCombined);
    electronsLoose = filterPhaseSpace(electronsLoose, 10., -2.47, 2.47);
    muonsCombined = filterPhaseSpace(muonsCombined, 10., -2.4, 2.4);
    jets = filterPhaseSpace(jets, 20., -2.8, 2.8);
    photons = filterPhaseSpace(photons, 130., -2.47, 2.47, true);
}
```

Note that the actual source file includes many extra lines of explanatory comments which we have removed for this tutorial.
The missing energy vector does not a priori contain muon contributions as different analyses can have different definitions of the construction of the missing momentum vector. We therefore add the contribution of all reconstructed muons by using the `addMuons` function. Furthermore, the area $1.37 \leq |\eta| \leq 1.52$ is often excluded for objects reconstructed in the electromagnetic calorimeter. The `filterPhaseSpace` function therefore has an optional last parameter which — if set to `true` — ignores objects in exactly that region.

These objects are then tested against different overlap conditions. In our case, these are defined as follows:

1. First, any jet with $\Delta R(jet, e) < 0.2$ to a nearby electron is removed.
2. Then, any electron and any muon with $\Delta R(\ell, jet) < 0.4$ is removed.

Functions that take care of these removals are fortunately already available in the `AnalysisBase` class:

```cpp
jets = overlapRemoval(jets, electronsLoose, 0.2);
electronsLoose = overlapRemoval(electronsLoose, jets, 0.4);
musonsCombined = overlapRemoval(musonsCombined, jets, 0.4);
```

Beware that the order of these steps is crucial. Due to the setup of the detector simulation most electrons will also be reconstructed as jets. An overlap removal with respect to these two objects is therefore always necessary to avoid severe double counting issues.

### Event Selection

Now that we have finished the object reconstruction step, we can start checking whether a given event fulfils the criteria of the given analysis. In our example, we should ignore events with leptons and hard photons. This is done very easily by using the `return` statement which ends the current run of the `analyze()` function and hence effectively vetoes the currently processed event:

```cpp
if(!photons.empty() || !electronsLoose.empty() || !muonsCombined.empty())
    return;
```

We now start to look at the signal region criteria which are summarised in Table 1 in [36]. Firstly all signal regions require $E_T \geq 160$ GeV and at least two reconstructed jets. From these the leading jet must have a $p_T$ of least 130 GeV and the sub-leading jet $p_T > 60$ GeV. All objects in CheckMATE analyses have a $p_T$ member that can be directly accessed for this purpose:

```cpp
if(missingET->PT < 160.0)
    return;
if(jets.size() < 2 || jets[0]->PT < 130 || jets[1]->PT < 60)
    return;
```

Note that all object vectors are automatically sorted with respect to $p_T$ such that leading and sub-leading jet are simply the first and the second object in the `jet` vector.

Furthermore the angular separation of the missing momentum vector and the leading two jets must be at least 0.4. We make use of the `P4()` function of each object which returns the corresponding `TLorentzVector` object defined in `ROOT`. This class comes with a large list of procedures to calculate 4-momentum parameters like the $\Delta \phi$ separation we need:

```cpp
if (fabs(jets[0]->P4().DeltaPhi(missingET->P4())) < 0.4)
    return;
if(fabs(jets[1]->P4().DeltaPhi(missingET->P4())) < 0.4)
    return;
```

There are more constraints on further ‘hard jets’ with $p_T > 40$ GeV: If a third ‘hard jet’ exists, it has to pass the above criterion too. For some signal regions, an additional constraint is applied if extra jets appear in the event. Here the looser constraint that $\Delta \phi > 0.2$ is applied to the third jet onwards:

```cpp
std::vector<Jet*> hardjets = filterPhaseSpace(jets, 40., -2.8, 2.8);
bool validThirdJet = (hardjets.size() < 3 || fabs(hardjets[2]->P4().DeltaPhi(missingET->P4()))) > 0.4;
bool validMultiJet = validThirdJet;
for (int j = 2; j < hardjets.size(); j++) {
    if (fabs(hardjets[j]->P4().DeltaPhi(missingET->P4()))) < 0.2)
        validMultiJet = false;
}
```

---

8 Standard C++ vectors do not catch out-of-bound indices. Users therefore have to ensure semantically that `jets[1]` is only accessed if `jets` contains at least $i + 1$ members.
For our selection we need the ratio of $E_T$ to the total effective mass $m_{\text{eff}}(N_j)$ as well as to $\sqrt{H_T}$. $H_T$ is defined to be the scalar $p_T$ sum of of all jets with $p_T > 40$ GeV whereas $m_{\text{eff}}(N_j)$ is the scalar $p_T$ sum of the leading $N$ jets plus $E_T$. There is also a requirement on $m_{\text{eff}}(\text{incl}) := H_T + E_T$. We have to calculate these explicitly for all allowed number of jets.

```cpp
define HT = 0.;
for(int j = 0; j < hardjets.size(); j++)
    HT += hardjets[j]->PT;
define mEffincl = HT + missingET->PT;

define mEff2 = missingET->PT + jets[0]->PT + jets[1]->PT;
define rEff2 = missingET->PT/mEff2;

define mEff3 = 0;
if (jets.size() >= 3)
    mEff3 = mEff2 + jets[2]->PT;
define rEff3 = 0;
if (jets.size() >= 3)
    rEff3 = missingET->PT/mEff3;

define mEff4 = 0;
if (jets.size() >= 4)
    mEff4 = mEff3 + jets[3]->PT;
define rEff4 = 0;
if (jets.size() >= 4)
    rEff4 = missingET->PT/mEff4;

double rEffHT = missingET->PT/sqrt(HT);
```

The last requirement we have to check is that the momentum of the leading $N$ jets in a given signal region is larger than 60 GeV. For that we simply count the number of jets after cutting to the signal phase space:

```cpp
int nSignalJets = filterPhaseSpace(jets, 60., -2.8, 2.8).size();
```

With all these numbers at hand we can go ahead and check the various signal regions. Whenever an event passes the respective criteria, we just have to call the `countSignalEvent` function:

```cpp
if (validThirdJet) {
    if (nSignalJets >= 2 && rEff2 > 0.2 && mEffincl > 1000.)
        countSignalEvent("AL");
    if (nSignalJets >= 2 && rEffHT > 15. && mEffincl > 1600.)
        countSignalEvent("AM");
    if (nSignalJets >= 3 && rEff3 > 0.3 && mEffincl > 1800.)
        countSignalEvent("BM");
    if (nSignalJets >= 3 && rEff3 > 0.4 && mEffincl > 2200.)
        countSignalEvent("BT");
}
if (validMultiJet) {
    if (nSignalJets >= 4 && rEff4 > 0.25 && mEffincl > 1200.)
        countSignalEvent("CM");
    if (nSignalJets >= 4 && rEff4 > 0.25 && mEffincl > 2200.)
        countSignalEvent("CT");
    if (nSignalJets >= 5 && rEff5 > 0.2 && mEffincl > 1600.)
        countSignalEvent("DM");
    if (nSignalJets >= 5 && rEff5 > 0.2 && mEffincl > 2200.)
        countSignalEvent("DT");
    if (nSignalJets >= 6 && rEff6 > 0.15 && mEffincl > 1000.)
        countSignalEvent("EL");
    if (nSignalJets >= 6 && rEff6 > 0.2 && mEffincl > 1200.)
        countSignalEvent("EM");
    if (nSignalJets >= 6 && rEff6 > 0.25 && mEffincl > 1500.)
        countSignalEvent("ET");
}
```

With these lines, we are actually done. The full code is listed in Fig. [1]. CheckMATE then needs to be re-compiled with the following commands, `autoreconf`; `.configure {parameters}; make` within the CheckMATE main folder should compile the analysis and make it usable in the usual CheckMATE binary.

---

9 The authors are aware that the conditions could be formulated more concisely by using the ternary `?` operator, e.g.

```cpp
double mEff4 + jets.size() >= 4 ? mEff3 + jets[3]->PT : 0;
```
For this manual we however preferred to use the easier to read version using `if` that most users should be familiar with.
void Atlas_conf_2013_047x::analyze() {
  missingET->addMuons(muonsCombined);
  electronsLoose = filterPhaseSpace(electronsLoose, 10., -2.47, 2.47);
  muonsCombined = filterPhaseSpace(muonsCombined, 10., -2.4, 2.4);
  jets = filterPhaseSpace(jets, 20., -2.8, 2.8);
  photons = filterPhaseSpace(photons, 130., -2.47, 2.47, true);
  jets = overlapRemoval(jets, electronsLoose, 0.3);
  electronsLoose = overlapRemoval(electronsLoose, jets, 0.4);
  muonsCombined = overlapRemoval(muonsCombined, jets, 0.4);
  if(!photons.empty() || !electronsLoose.empty() || !muonsCombined.empty())
    return;
  if(missingET->PT < 160.0)
    return;
  if(jets.size() < 2 || jets[0]->PT < 130 || jets[1]->PT < 60)
    return;
  if(fabs(jets[0]->P4().DeltaPhi(missingET->P4())) < 0.4)
    return;
  if(fabs(jets[1]->P4().DeltaPhi(missingET->P4())) < 0.4)
    return;
  std::vector<Jet*> hardjets = filterPhaseSpace(jets, 40., -2.8, 2.8);
  bool validThirdJet = (hardjets.size() < 3 || fabs(hardjets[2]->P4().DeltaPhi(missingET->P4())) > 0.4);
  bool validMultiJet = validThirdJet;
  for (int j = 2; j < hardjets.size(); j++)
    if (fabs(hardjets[j]->P4().DeltaPhi(missingET->P4())) < 0.2)
      validMultiJet = false;
  HT = 0.;
  for(int j = 0; j < hardjets.size(); j++)
    HT += hardjets[j]->PT;
  mEffincl = HT + missingET->PT;
  mEff2 = missingET->PT + jets[0]->PT + jets[1]->PT;
  rEff2 = missingET->PT/mEff2;
  mEff3 = 0;
  if (jets.size() >= 3)
    mEff3 = mEff2 + jets[2]->PT;
  rEff3 = 0;
  if (jets.size() >= 3)
    rEff3 = missingET->PT/mEff3;
  mEff4 = 0;
  if (jets.size() >= 4)
    mEff4 = mEff3 + jets[3]->PT;
  rEff4 = 0;
  if (jets.size() >= 4)
    rEff4 = missingET->PT/mEff4;
  mEff5 = 0;
  if (jets.size() >= 5)
    mEff5 = mEff4 + jets[4]->PT;
  rEff5 = 0;
  if (jets.size() >= 5)
    rEff5 = missingET->PT/mEff5;
  mEff6 = 0;
  if (jets.size() >= 6)
    mEff6 = mEff5 + jets[5]->PT;
  rEff6 = 0;
  if (jets.size() >= 6)
    rEff6 = missingET->PT/mEff6;
  if (validThirdJet)
    if(nSignalJets >= 2 && rEff2 > 0.2 && mEffincl > 1000.)
      countSignalEvent("AL");
    if(nSignalJets >= 2 && rEffHT > 15. && mEffincl > 1600.)
      countSignalEvent("AM");
    if(nSignalJets >= 3 && rEff3 > 0.3 && mEffincl > 1800.)
      countSignalEvent("BM");
    if(nSignalJets >= 3 && rEff3 > 0.4 && mEffincl > 2200.)
      countSignalEvent("BT");
  if (validMultiJet)
    if(nSignalJets >= 4 && rEff4 > 0.25 && mEffincl > 1200.)
      countSignalEvent("CM");
    if(nSignalJets >= 4 && rEff4 > 0.25 && mEffincl > 2200.)
      countSignalEvent("CT");
    if(nSignalJets >= 5 && rEff5 > 0.2 && mEffincl > 1600.)
      countSignalEvent("DT");
    if(nSignalJets >= 5 && rEff5 > 0.25 && mEffincl > 1500.)
      countSignalEvent("EL");
    if(nSignalJets >= 6 && rEff6 > 0.2 && mEffincl > 1200.)
      countSignalEvent("DM");
    if(nSignalJets >= 6 && rEff6 > 0.25 && mEffincl > 1050.)
      countSignalEvent("EL");
  }
}

FIG. 1: Full source code of the simplified reimplementation of atlas_conf_2013_047 into CheckMATE.

B. Example 2: Recasting a more complicated analysis

The previous example was a rather simple search that did not contain many complicated features within the actual analysis code. In this example we want to consider another analysis with 3 leptons and large missing transverse momentum in the final state, atlas_1402_7029, see Ref. [37]. This analysis requires us to define specific isolation conditions for leptons, tag and \(\tau\) jets and use advanced kinematic variables. We will also implement some cutflow
steps to help track the signal efficiency when each cut is applied in turn.

Detector Setting in AnalysisManager

We run the AnalysisManager as usual and add all the necessary information, including the data for all 24 signal regions (we do not go into more detail here: This step is identical to the analysis before). When it comes to the detector simulation part, things become more involved now. The given analysis requires two specific electron isolation conditions: the first one needs the scalar sum of transverse momenta of tracks with $p_T > 0.4$ in the vicinity of $\Delta R \leq 0.3$ to the candidate be at most 16% of the transverse momentum of the electron.

A second condition checks the surrounding calorimeter cells in the same region to contain at most 18% of the candidate’s momentum. The $p_T^{\text{min}}$ of the considered cells is set to be 0.1 so that random cell noise is ignored.

That is all for the electrons. For the muons we also have a condition which is very similar to the first electron condition but with different numbers:

Photons are not needed in our analysis:
The analysis demands vetoes against jets that originated from $b$-quarks. For that, a $b$-tagging algorithm is used that is tuned to a working point signal efficiency of 80%. Furthermore, ‘medium’ $\tau$-tags are used to identify signal events. We therefore have to include these objects in the AnalysisManager:

### 3.5: Jets

Which dR cone radius do you want to use for the FastJet algorithm? 0.4

What is the minimum pt of a jet? [in GeV] 20.0

Do you need a separate, extra type of jet? [(y)es, (n)o] n

Do you want to use b-tagging? [(y)es, (n)o] y

b-Tagging 1:

What is the signal efficiency to tag a b-jet? [in %] 80

Do you need more b tags? [(y)es, (n)o] n

Do you want to use tau-tagging? [(y)es, (n)o] y

Note that when $\tau$-tagging is activated, all three working points ‘loose’, ‘medium’ and ‘tight’ are automatically tagged and available in the analyses. This step will finish the AnalysisManager part and create the analysis skeleton file as usual.

### Analysis: Setup

With all the parameters set, we can continue with the analysis code. Since we also want to check the cutflow of our analysis, we should book cutflow regions to make sure the _cutflow.dat file is produced at the end of a CheckMATE analysis run. For this we need to examine the initialize() function in our analysis skeleton file. Here all the signal regions we defined above are already booked:

```cpp
bookSignalRegions("SR0taua01;SR0taua02;SR0taua03;SR0taua04;SR0taua05;...
```

For cutflows we add a similar line with all the desired cutflow region names. In this tutorial, let us check the number of events we lose after the trigger, after the event selection and how many we get with 0, 1 or 2 $\tau$’s:

```cpp
bookCutflowRegions("CR0_All;CR1_Trigger;CR2_Selection;CR3_0Tau;CR3_1Tau;CR3_2Tau;"
```

Note that regions are automatically sorted alphabetically. We therefore constructed the names such that they will appear in logical order in the output file.

### Analysis: Event Cleaning

As before, we focus on the analyze() function in the analysis source file. We start with the definition of the interesting final state objects and the overlap removals, whose proper definitions can be found in.[37] Note that here we have to consider both ‘medium’ and ‘tight’ electrons, where the former are used for the event cleaning at the beginning and the latter are necessary for the signal region tests later. We also have to remove electrons that lie in the vicinity of each other, i.e. if two electrons are closer than $\Delta R = 0.1$, the one with lower energy should be removed. This is done using the same overlapRemoval() function as before, but now with only one particle vector parameter given.

```cpp
void Atlas_1402_7029::analyze() {
    missingET->addMuons(muonsCombined);
    electronsMedium = filterPhaseSpace(electronsMedium, 10., -2.47, 2.47, false);
    electronsTight = filterPhaseSpace(electronsTight, 10., -2.47, 2.47, false);
    muonsCombined = filterPhaseSpace(muonsCombined, 10., -2.4, 2.4);
    jets = filterPhaseSpace(jets, 20., -2.5, 2.5);
    electronsMedium = overlapRemoval(electronsMedium, 0.1);
    electronsTight = overlapRemoval(electronsTight, 0.1);
    jets = overlapRemoval(jets, electronsMedium, 0.2);
    electronsMedium = overlapRemoval(electronsMedium, jets, 0.4);
    electronsTight = overlapRemoval(electronsTight, jets, 0.4);
    muonsCombined = overlapRemoval(muonsCombined, jets, 0.4);
}
```

---

10 It should be noted that the implementation of the analysis we describe here slightly differs from the public version used in CheckMATE, as the public version considers more cutflows which sometimes require a different ordering.

11 Note that overlapRemoval(electronsMedium, electronsMedium, 0.1) must not be used: It will always return an empty list as each electron in the first vector finds an ‘overlapping’ $\Delta R = 0$ electron in the second vector, namely itself.
Next follows an analysis-specific ‘resonance removal’ which forces leptons that form opposite-sign same-flavour pairs with an invariant mass smaller than 12 GeV to be removed. We can do this using a simple double-loop. For electrons, we only need to test signal electrons (‘tight’) but they must not form an invariant mass pair with ‘medium’ electrons either. Since ‘tight’ electrons are a subset of ‘medium’ electrons this will also remove any pairs formed by two ‘tight’ electrons.

```cpp
std::vector<Electron*> noResonanceElecs;
for (int t = 0; t < electronsTight.size(); t++) {
    bool valid = true;
    for (int m = 0; m < electronsMedium.size(); m++) {
        if (electronsMedium[m]->Charge*electronsTight[t]->Charge > 0)
            continue;
        if ((electronsMedium[m]->P4() + electronsTight[t]->P4()).M() < 12.)
            valid = false;
    }
    if (valid)
        noResonanceElecs.push_back(electronsTight[t]);
}
```

We do the same for muons and store the cleaned vectors:

```cpp
std::vector<Muon*> noResonanceMuons;
for (int t = 0; t < muonsCombined.size(); t++) {
    bool valid = true;
    for (int m = 0; m < muonsCombined.size(); m++) {
        if (muonsCombined[m]->Charge*muonsCombined[t]->Charge > 0)
            continue;
        if ((muonsCombined[m]->P4() + muonsCombined[t]->P4()).M() < 12.)
            valid = false;
    }
    if (valid)
        noResonanceMuons.push_back(muonsCombined[t]);
}
electronsTight = noResonanceElecs;
muonsCombined = noResonanceMuons;
```

We further select our signal final state objects by applying our defined isolation conditions. Note that applying the function without any arguments will apply all stored conditions on the respective object, i.e. both conditions for the electron and the single condition for the muon:

```cpp
electronsTight = filterIsolation(electronsTight);
muonsCombined = filterIsolation(muonsCombined);
```

Let us now keep track of all events we start with in the cutflow:

```cpp
countCutflowEvent("CR0_All");
```

**Analysis: Event Trigger**

The next step tests if the event could have passed at least one of the applied trigger conditions. For the present analysis, various triggers with different momentum thresholds for the considered objects are tested. We do not consider any turn-on curves but simply apply a 100 % trigger efficiency if there are objects that pass the respective \( p_T \) \text{min} criteria:

```cpp
bool trigger = false;
if( electronsTight.size() > 0 && electronsTight[0]->PT > 25.)
    trigger = true;
else if( muonsCombined.size() > 0 && muonsCombined[0]->PT > 25.)
    trigger = true;
else if( electronsTight.size() > 1 && electronsTight[0]->PT > 14. && electronsTight[1]->PT > 14.)
    trigger = true;
else if( electronsTight.size() > 1 && electronsTight[0]->PT > 26. && electronsTight[1]->PT > 10.)
    trigger = true;
else if( muonsCombined.size() > 1 && muonsCombined[0]->PT > 14. && muonsCombined[1]->PT > 14.)
    trigger = true;
else if( electronsTight.size() > 1 && muonsCombined[0]->PT > 18. && muonsCombined[1]->PT > 10.)
    trigger = true;
else if( electronsTight.size() > 0 && muonsCombined.size() > 0 && electronsTight[0]->PT > 18. && muonsCombined[0]->PT > 18.)
    trigger = true;
if( !trigger )
    return;
```

Our cutflow should tell us how many events pass this stage:

```cpp
countCutflowEvent("CR1_Trigger");
```
Analysis: Event Selection

The present three lepton analysis considers signal regions with tau leptons and for that purpose we have to consider the jets that have been tagged as "medium" tau jets by using the checkTauTag function. It is important to note that tagged jets a priori do not have to pass conditions on the number and charge of reconstructed tracks. In the analysis we have to explicitly ensure this by testing the charge of the tested jets. Events then have to contain exactly three signal leptons (e, µ, τ) but not exactly three τ only:

```cpp
std::vector<Jet*> tauJets;
for(int j = 0; j < jets.size(); j++) {
    if( checkTauTag(jets[j], "medium") && fabs(jets[j]->Charge) == 1)
        tauJets.push_back(jets[j]);
}
if( ( electronsTight.size() + muonsCombined.size() + tauJets.size() ) != 3 )
    return;
if( electronsTight.size() + muonsCombined.size() == 0 )
    return;
```

Furthermore no \( b \)-jet should be present in the final state. We can test this by applying the checkBTag() function on a given jet candidate and, in our analysis, veto the event if any of these tests return true:

```cpp
for (int i = 0; i < jets.size(); i++) {
    if( checkBTag(jets[i]))
        return;
```

Again we want to know how many events pass all of the above cuts:

```cpp
countCutflowEvent("CR2_Selection");
```

Analysis: Signal Region Categorisation

We now start categorising the event into the different signal regions. From this point on we will often consider both electrons and muons on the same footing. In certain cases the same treatment will also be applied to taus. It would therefore be convenient if we combined all the three leptons into a common vector which we can use if the kinematical cut is flavour independent. Unfortunately, the three objects are described by different C++ classes and hence cannot be combined trivially. However, within the analysis code there is a new class FinalStateObject into which electrons, muons, jets and even the missing momentum vector can be transformed. We therefore define a vector of FinalStateObject objects and choose to fill it with the three different kinds of lepton we have in the final state.

```cpp
std::vector<FinalStateObject*> leptons;
for(int e = 0; e < electronsTight.size(); e++) {
    FinalStateObject* lep = newFinalStateObject(electronsTight[e]);
    leptons.push_back(lep);
}
for(int m = 0; m < muonsCombined.size(); m++) {
    FinalStateObject* lep = newFinalStateObject(muonsCombined[m]);
    leptons.push_back(lep);
}
for(int t = 0; t < tauJets.size(); t++) {
    FinalStateObject* lep = newFinalStateObject(tauJets[t]);
    leptons.push_back(lep);
}
```

Note that this ordering ensures that the tau objects always come last. With his vector we can easily test the further condition that all leptons have to be separated by at least \( \Delta R \geq 0.3 \), without distinguishing electrons, muons or tau-jets:

```cpp
if (leptons[0]->P4().DeltaR(leptons[1]->P4()) < 0.3)
    return;
if (leptons[0]->P4().DeltaR(leptons[2]->P4()) < 0.3)
    return;
if (leptons[1]->P4().DeltaR(leptons[2]->P4()) < 0.3)
    return;
```

The main difference between the signal region definitions is the number of tau jets in the final state. We will use our cutflow regions to check how many events in general have 0, 1 or 2 taus. Let us start with the definition of the two signal regions involving two tau jets:

```cpp
switch(tauJets.size()) {
    case 2:
        countCutflowEvent("CR3_2tau");
```
The first one of these, \texttt{SR2taua}, requires at least 50 GeV missing energy in the event. Furthermore, it tests the \( mT_2 \) variable, see [III] for more information. This variable requires two \texttt{TLorentzVectors} arguments, i.e. two four-momenta, and the mass of the invisible particle that is typically assumed to be 0, to reject SM background due to leptonic \( W \) decays. Signal region \texttt{SR2taua} then requires the maximum \( mT_2 \) out of all combinations of the three signal leptons to be at least 100 GeV. With our above universal \texttt{leptons} vector, this is a very easy exercise:

\begin{verbatim}
  double mT2_1 = mT2(leptons[0]->P4(), leptons[1]->P4(), 0.);
  double mT2_2 = mT2(leptons[0]->P4(), leptons[2]->P4(), 0.);
  double mT2_3 = mT2(leptons[1]->P4(), leptons[2]->P4(), 0.);
  double mT2max = std::max(std::max(mT2_1, mT2_2), mT2_3);
  if (missingET->PT > 50. && mT2max > 100)
    countSignalEvent("SR2taua");
\end{verbatim}

The other signal region, \texttt{SR2taub}, requires different total missing energy, an opposite sign tau pair with their scalar \( p_T \) sum to be larger than 110 GeV and their invariant mass to be between 70 GeV and 120 GeV:

\begin{verbatim}
  double mtautau = (tauJets[0]->P4()+tauJets[1]->P4()).M();
  double sumpt = tauJets[0]->PT + tauJets[1]->PT;
  if (missingET->PT > 60. && tauJets[0]->Charge*tauJets[1]->Charge < 0 && sumpt > 110. && mtautau > 70. && mtautau < 120.)
    countSignalEvent("SR2taub");
\end{verbatim}

We continue with the \( 1\tau \) signal region:

\begin{verbatim}
  break;
\end{verbatim}

\begin{verbatim}
  case 1: {
    countCutflowEvent("CR3_1tau");
\end{verbatim}

Here we have to find the \( \tau \) and light lepton invariant mass combination that lies closest to the Higgs boson mass and the invariant mass of the light lepton pair. Since the tau jet is always the third object in the \texttt{leptons} vector — caused by the order we filled it above — we know which combinations to test. The invariant mass is easily calculated using the \texttt{TLorentzVector} internal \texttt{M()} function:

\begin{verbatim}
  double mTL_1 = (leptons[0]->P4() + leptons[2]->P4()).M();
  double mTL_2 = (leptons[1]->P4() + leptons[2]->P4()).M();
  double mTL = fabs(mTL_1 - 125.) < fabs(mTL_2 - 125.) ? mTL_1 : mTL_2;
  double mLL = (leptons[0]->P4() + leptons[1]->P4()).M();
\end{verbatim}

The light leptons must have same charge and the event is vetoed if an electron pair reconstruct an invariant mass compatible with the \( Z \) boson:

\begin{verbatim}
  bool samesignl = (leptons[0]->Charge*leptons[1]->Charge > 0);
  bool zElectronVeto = (leptons[0]->Type == "electron" && leptons[1]->Type == "electron" && mLL > 81.2 && mLL < 101.2);
\end{verbatim}

Lastly, these combine with requirements on the missing transverse momentum and the transverse momenta of the light leptons:

\begin{verbatim}
  double sumpt = leptons[0]->PT + leptons[1]->PT;
  if (missingET->PT > 50. && leptons[0]->PT > 30. && leptons[1]->PT > 30. && sumpt > 70. && mTL < 120. && samesign && !zElectronVeto)
    countSignalEvent("SR1tau");
    break;
\end{verbatim}

\begin{verbatim}
  case 0: {
    countCutflowEvent("CR3_0tau");
\end{verbatim}

For this signal region, we first have to check if there is a same-flavour opposite-sign (SFOS) pair.

\begin{verbatim}
  bool sfos = false;
  double msfos = -1E10;
  if (leptons[0]->Charge * leptons[1]->Charge < 0 && leptons[0]->Type == leptons[1]->Type)
    sfos = true;
  else if (leptons[0]->Charge * leptons[2]->Charge < 0 && leptons[0]->Type == leptons[2]->Type)
    sfos = true;
  else if (leptons[2]->Charge * leptons[1]->Charge < 0 && leptons[2]->Type == leptons[1]->Type)
    sfos = true;
\end{verbatim}

Let us now continue with the test of \texttt{SR0taub} which requires no SFOS pair. In that case, we have to require that there is at least one lepton of different flavour (OF) and that the product of all charges is negative. We then have to find the OF combination which yields the smallest relative polar angle \( \Delta \Phi \). Note that our construction has produced a \texttt{leptons} vector of either of the four possibilities \( eee, e\mu, e\mu \) or \( \mu\mu \) so one does not have to test all combinations to find OF pairs:

\begin{verbatim}
  bool sfos = false;
  double msfos = -1E10;
  if (leptons[0]->Charge * leptons[1]->Charge < 0 && leptons[0]->Type == leptons[1]->Type)
    sfos = true;
  else if (leptons[0]->Charge * leptons[2]->Charge < 0 && leptons[0]->Type == leptons[2]->Type)
    sfos = true;
  else if (leptons[2]->Charge * leptons[1]->Charge < 0 && leptons[2]->Type == leptons[1]->Type)
    sfos = true;
\end{verbatim}
if (!sfos && leptons[0]->Type != leptons[2]->Type && fabs(leptons[0]->Charge + leptons[1]->Charge + leptons[2]->Charge) == 1) {
    double deltaPhi1 = fabs(leptons[0]->P4().DeltaPhi(leptons[2]->P4()));
    double deltaPhi2 = 0;
    if (leptons[0]->Type != leptons[1]->Type)
        deltaPhi2 = fabs(leptons[0]->P4().DeltaPhi(leptons[1]->P4()));
    else
        deltaPhi2 = fabs(leptons[1]->P4().DeltaPhi(leptons[2]->P4()));
    double mindeltaPhi = std::min(deltaPhi1, deltaPhi2);
    if(missingET->PT > 50. && leptons[0]->PT > 20. && leptons[1]->PT > 20. && leptons[2]->PT > 20. && mindeltaPhi <= 1.0)
        countSignalEvent("SR0taub");
}

For the SFOS signal region we have to find the SFOS combination with invariant mass closest to the Z boson. We need this invariant mass and the transverse mass of the remaining lepton:

else if(sfos) {
    double msfos = -1E10;
    double mTthird = 0;
    if (leptons[0]->Charge * leptons[1]->Charge < 0 && leptons[0]->Type == leptons[1]->Type) {
        double minv = (leptons[0]->P4() + leptons[1]->P4()).M();
        if (fabs(minv - 92.) < fabs(msfos - 92.)) {
            msfos = minv;
            mTthird = mT(leptons[2]->P4(), missingET->P4());
        }
    }
    if (leptons[0]->Charge * leptons[2]->Charge < 0 && leptons[0]->Type == leptons[2]->Type) {
        double minv = (leptons[0]->P4() + leptons[2]->P4()).M();
        if (fabs(minv - 92.) < fabs(msfos - 92.)) {
            msfos = minv;
            mTthird = mT(leptons[1]->P4(), missingET->P4());
        }
    }
    else if (leptons[2]->Charge * leptons[1]->Charge < 0 && leptons[2]->Type == leptons[1]->Type){
        double minv = (leptons[2]->P4() + leptons[1]->P4()).M();
        if (fabs(minv - 92.) < fabs(msfos - 92.)) {
            msfos = minv;
            mTthird = mT(leptons[0]->P4(), missingET->P4());
        }
    }
}

Lastly, some signal regions specifically veto if the three lepton invariant mass lies within the Z boson mass window:

double m3l = (leptons[0]->P4() + leptons[1]->P4() + leptons[2]->P4()).M();

The analysis ends with a binning of missing energy, msfos and mTthird

if (12. < msfos && msfos < 40) {
    if (0. <= mTthird && mTthird < 80) {
        if (50. <= missingET->PT && missingET->PT < 90.)
            countSignalEvent("SR0tau01");
        else if (90. <= missingET->PT)
            countSignalEvent("SR0tau02");
    } else if (80. <= mTthird ) {
...

Analysis Testing

To check the implementation of our analysis, let us run CheckMATE on a simple model that is also analysed within [37]: a simplified supersymmetric scenario with direct production of the lightest chargino and the second lightest neutralino, both with mass $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = 625$ GeV. These both decay into the lightest neutralino with mass $m_{\tilde{\chi}_1^0} = 375$ GeV and two leptons via an intermediate slepton with mass $m_{\tilde{\ell}} = 500$ GeV. By charge conservation this will lead to an odd number of charged leptons in the final state and is consequently a good candidate for our underlying three lepton study. We take the corresponding slha spectrum file [38, 39] and use Prospino [40, 41] to calculate the production cross section to be $\sigma \approx 2.893$ pb. We then use Herwig++ [42] to generate events and analyse these with CheckMATE using the following input parameter card:

## General Options

[Mandatory Parameters]
Name: My_Trilepton_Run
Analyses: atlas_1402_7029X

## Process Information (Each new process `X` must start with `[X]`)  
(Simplified)
XSect: 2.893 FB
XSectErr: 0 FB
Events: /hdd/data/validation/trileptons/exclusion_A/mC1N2_625_0_mN1_375_0.hepmc
Looking at the `/analysis/` sub-folder within the results directory reveals the desired `000_atlas_1402_7029X_cutflow.dat` and `000_atlas_1402_7029X_signal.dat` files we booked in our analysis code. The cutflow file tells us the number of events remaining after each selection step in our analysis.

```plaintext
# ATLAS
# 3 leptons
# tutorial

Inputfile: /tutorial/results/My_Trilepton_Run/delphes/000_delphes.root
XSect: 2.893 fb
Error: 0 fb
MCEvents: 10000
SumOfWeights: 10000
SumOfWeights2: 10000
NormEvents: 58.7279

| Cut         | Sum_W | Sum_W2 | Acc   | N_Norm |
|-------------|-------|--------|-------|--------|
| CR0_All     | 10000 | 10000  | 1     | 58.7279|
| CR1_Trigger | 7448  | 7448   | 0.7448| 43.7405|
| CR2_Selection| 1647  | 1647   | 0.1647| 9.67249|
| CR3_0Tau    | 1306  | 1306   | 0.1306| 7.66986|
| CR3_1Tau    | 272   | 272    | 0.0272| 1.5974 |
| CR3_2Tau    | 69    | 69     | 0.0069| 0.405223|
```

Furthermore we can check the numbers for each signal region:

```plaintext
# ATLAS
# 3 leptons
# tutorial

Inputfile: /hdd/sandbox/trileptonupdate/results/My_Trilepton_Run/delphes/000_delphes.root
XSect: 2.893 fb
Error: 0 fb
MCEvents: 10000
SumOfWeights: 10000
SumOfWeights2: 10000
NormEvents: 58.7279

| SR          | Sum_W | Sum_W2 | Acc   | N_Norm |
|-------------|-------|--------|-------|--------|
| SR0taua01   | 1     | 1      | 0.0001| 0.00587279|
| SR0taua02   | 4     | 4      | 0.0004| 0.0234912 |
| SR0taua03   | 4     | 4      | 0.0004| 0.0234912 |
| [...]       |       |        |       |         |
| SR0taub     | 4     | 4      | 0.0004| 0.0234912 |
| SR1tau      | 20    | 20     | 0.002 | 0.117456 |
| SR2taua     | 38    | 38     | 0.0038| 0.223166 |
| SR2taub     | 11    | 11     | 0.0011| 0.0646607|
```

Finally, CheckMATE tells us `Result: Allowed, Result for r: r_max = 0.36209`. One might be surprised if one compares to Fig. 7a in [37] in which the exact same point lies very close to the exclusion line. However, the discrepancy is to be expected as CheckMATE only considers the most sensitive signal region whereas within [37], sensitivities of various signal regions are combined using correlations to which CheckMATE does not have access. It is therefore reasonable that CheckMATE returns a weaker limit which is however still close to the nominal limit.

C. Example 3: Inventing a completely new analysis

So far, we have discussed the implementation of current experimental collider studies. In this section, we want to implement a completely new analysis, a monojet search at 14 TeV with an integrated luminosity of 100 fb$^{-1}$. The monojet analysis at 14 TeV is based on Ref. [43] but with additional signal regions accommodating harder transverse momentum cuts on the leading jet and stricter cuts on missing transverse energy.

We run the AnalysisManager and enter the general information as previously described. We call our analysis:

```plaintext
Analysis Name: atlas_monojet_at_14_tev
```

We define five signal regions:

```
12 Note that if you do the same, you will find slightly different numbers due to finite Monte Carlo statistics.
```
2. Information on Signal Regions

List all signal regions (one per line, finish with an empty line):

- M1
- M2
- M3
- M4
- M5

We now have to provide the background numbers for each signal region. However, these numbers are evidently not known at this stage, so we choose no.

Is the SM expectation B known? [(y)es, (n)o]?

n

The AnalysisManager will display the following message:

Signal regions are registered but without any numbers associated to them.

IMPORTANT: The analysis will be created and can then be used like any other analysis. CheckMATE will skip the model exclusion tests as long as the expectation is not known. You can e.g. use CheckMATE on background samples to estimate B and dB. As soon as you know these numbers, run the AnalysisManager again and use the (e)dit feature to add them.

Press key to continue!

We will simulate the dominant Standard Model backgrounds and enter the background numbers for all signal regions later, because for that we have to write the analysis first. In the next step we have to define all detector level objects as discussed in the previous examples.

3. Settings for Detector Simulation

3.1: Miscellaneous

To which experiment does the analysis correspond? [(A)TLAS, (C)MS]?

A

3.2: Electron Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]?

n

3.3: Muon Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]?

y

Isolation 1:

Which objects should be considered for isolation? [(t)rack, (c)alo objects]?

t

What is the minimum pt of a surrounding object to be used for isolation? [in GeV]?

1.0

What is the dR used for isolation?

0.2

Is there an absolute or a relative upper limit for the surrounding pt? [(a)bolute, (r)elative]?

a

What is the maximum surrounding pt used for isolation [in GeV]?

1.8

Do you need more isolation criteria? [(y)es, (n)o]?

n

3.4: Photon Isolation

Do you need any particular isolation criterion? [(y)es, (n)o]?

n

3.5: Jets

Which dR cone radius do you want to use for the FastJet algorithm?

0.4

What is the minimum pt of a jet? [in GeV]?

20.0

Do you need a separate, extra type of jet? [(y)es, (n)o]?

n

Do you want to use b-tagging? [(y)es, (n)o]?

n

Do you want to use tau-tagging? [(y)es, (n)o]?

n

After answering the remaining questions of the AnalysisManager, the source and header files are generated. Everything is now set by the AnalysisManager and we start to write the analysis code.

We want to select events satisfying the following trigger condition and kinematic cuts. First, we apply an online trigger condition with $E_T > 80$ GeV and assume a flat trigger efficiency of 100%. All events are required to have $E_T > 150$ GeV and the leading jet must satisfy $p_T > 150$ GeV and $|\eta| < 2.8$. Events with isolated electrons (muons) with $p_T > 20$ ( $p_T > 10$ GeV) are rejected. We also veto events if there are more than three jets with $p_T > 30$ GeV and $|\eta| < 2.8$. In order to reduce the QCD background, we require an azimuthal separation between the jets and the missing transverse momentum vector: $\Delta \phi (\text{jet}, \mathbf{p}_T^{\text{miss}}) > 0.4$. Finally, we choose the following set of cuts to define our signal regions.
• M1: $E_T > 220$ GeV and $p_T^{\text{leading jet}} > 280$ GeV
• M2: $E_T > 340$ GeV and $p_T^{\text{leading jet}} > 340$ GeV
• M3: $E_T > 450$ GeV and $p_T^{\text{leading jet}} > 450$ GeV
• M4: $E_T > 500$ GeV and $p_T^{\text{leading jet}} > 500$ GeV
• M5: $E_T > 550$ GeV and $p_T^{\text{leading jet}} > 550$ GeV

We now have all the information to write the analysis code. Since we have already discussed two examples, we just present the full analysis code without discussing it in detail.

```c
#include "atlas_monojet_at_14_tev.h"

void Atlas_monojet_at_14_tev::initialize() {
  setAnalysisName("atlas_monojet_at_14_tev");
  setInformation("@#targets generic ATLAS monojet studies
  @#14 TeV, 100/fb
  ");
  setLuminosity(100.0*units::INVFB);
  ignore("towers"); // These won't read tower or track information from the
  ignore("tracks"); // Delphes output branches to save computing time.
  bookSignalRegions("M1;M2;M3;M4;M5;*");
}
```
After having implemented the monojet analysis code, we have to determine the expected numbers of Standard Model background events for all signal regions. Firstly, we briefly discuss the major backgrounds to the monojet signal. The $Z(\rightarrow \nu \bar{\nu}) + j$ is the dominant irreducible background. In general, $W(\rightarrow \ell \nu) + j$ is a non-negligible background even though it contains one charged lepton ($\ell = e^\pm, \mu^\pm$). However, if the charged lepton is not reconstructed, it will have similar final states as the monojet signature. The hadronic $\tau$ decays of $W + j$ production also yield a sizeable contribution to the background of the monojet signal. The $t\bar{t}$ background happens to be relatively small and consequently we will omit it for simplicity as well as the other sub-dominant backgrounds. We have simulated the $Z + j$ and $W + j$ samples with the MC event generator Sherpa [44] using leading order matrix elements for up to 3 partons and using massive $b/c$ quarks with the CTEQ10 parton distribution functions [45]. Our background estimate is given in Table I. Now we have to provide our background numbers for each signal region from Table I to CheckMATE. We again call the AnalysisManager but this time choose the (e)dit analysis information option.
TABLE I: Number of expected background events for all signal regions. Only statistical errors are included. All numbers are normalized to 100 fb$^{-1}$ at $\sqrt{s} = 14$ TeV.

| Signal Region | M1                  | M2                  | M3                  | M4                  | M5                  |
|---------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| SM prediction | 733900 ± 4860        | 197501 ± 2592       | 51776 ± 1231        | 18461 ± 640         | 7477 ± 364          |

What would you like to do?
- (l) ist all analyses,
- (a) dd a new analysis to CheckMATE,
- (e) dit analysis information,
- (r) emove an analysis from CheckMATE

You can now edit or update some of the information for a given analysis.
Enter the identifier of the analysis you want to edit:
   atlas_monojet_at_14_tev

Analysis atlas_monojet_at_14_tev successfully read in.

Do you want to...
   ...list all defined entries? (l)
   ...restart the detector settings questions? (d)
   ...enter signal region numbers for observation and background? (n)

We choose n and enter the number of observed events (which for a hypothetical analysis will be the same as the expected background), expected background events and the error of the background events for each signal region. The AnalysisManager will then calculate the model independent upper limits.

We are now in the position to perform studies with our new analysis and as an example we choose to apply our implementation to a simple supersymmetric scenario. We consider direct production of scalar top quark (stop) pairs in association with one jet [46]. We assume that the stops decay into a charm quark and the lightest neutralino with a branching ratio of 100%. If the mass splitting between the stop and the neutralino is very small, the charm jets cannot be reconstructed and hence our signal is a single highly energetic jet recoiling against missing momentum. We choose a benchmark point with $m_{\tilde{t}_1} = 400$ GeV and $m_{\tilde{\chi}^0_1} = 350$ GeV. We calculate the cross section with Prospino [41] and obtain $\sigma = 2.15$ pb. The events are generated as a matched sample $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* + j$ with Madgraph [47] and the showering is done with Pythia [48]. Analysing our resulting event file with CheckMATE, we obtain a r-value of 0.32 for M1 which is determined to be the most sensitive signal region. Consequently we conclude that the parameter point is expected to be allowed in this analysis after 100 fb$^{-1}$ at LHC-14.

D. Auxiliary Information

The following functionalities might also be useful for the user in certain scenarios, which is why we list them separately here without reference to a particular example:

File Booking

The CheckMATE internal files _signal.dat are automatically put into the globally chosen output directory with individual prefixes for each analysis and each separate input file. Sometimes a user might want to store extra information that is determined during the analysis, as an example kinematical distributions in order to draw histograms, in separate files. CheckMATE provides simple to use functions that create these files in the same manner as the _signal.dat files, i.e. into the user–chosen output directory with individual prefixes.

To do this, the user should use the bookFile(filename, noHeader) function within the initialize() part of the analysis code (similarly to bookSignalRegions): this will create a file with the correct prefix before filename in the CheckMATE output directory. If one wants to create a text file and wants general analysis information to automatically be written to the top of that file, noHeader should be set to false, otherwise true. The function returns an integer number, which should always be stored by the user in a variable, for example int iFile = bookFile("hist.txt", false);

Then, fNamees[iFile] can be used to get the absolute path to the file, which can e.g. be used to book histograms via ROOT (see ROOT documentation for more information on ROOT histogramming).

---

13 The r-value is defined as the number of expected signal events divided by the expected 95% C.L. value.
Alternatively, one can write text information directly into the file by using `fStreams[iFile]` for example as follows:

```cpp
fStreams[iFile] << "I have a jet with pt " << jet[0]->PT << std::endl;
```

If `iFile` is defined as a member of the analysis class, the above code can be used in all three functions `initialize()`, `analyze()`, `finalize()`.

### Random Numbers

If random numbers have to be used, `rand()/(RAND_MAX+1.)` should be used to get a uniformly distributed random number between 0 and 1. The reason to use `rand()` and not e.g. ROOT based random number generators is that CheckMATE has a parameter to fix the random seed of a run. This fixed seed only applies for the `rand()` function. As a fixed seed should lead to completely deterministic results, one should avoid using any other random number generator.

### V. SUMMARY

We have introduced the AnalysisManager of CheckMATE that allows for the easy implementation of new analyses, either invented by user or following experimental searches. The program guides the user through the numerous choices possible for final state objects, simplifying many of the complicated LHC definitions. In order to aid the actual coding of analyses, many useful, routinely performed functions are included. Additionally, a suite of common LHC kinematical variables are also implemented. Finally, all the statistical variables already available in CheckMATE can be calculated automatically.

CheckMATE can be downloaded from:

[http://checkmate.hepforge.org/](http://checkmate.hepforge.org/)

Detailed program documentation can be found at:

[http://checkmate.hepforge.org/documentation/index.html](http://checkmate.hepforge.org/documentation/index.html)

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[36] “Search for squarks and gluinos with the atlas detector in final states with jets and missing transverse momentum and 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV proton-proton collision data,” Tech. Rep. ATLAS-CONF-2013-047, CERN, Geneva, May 2013.

[37] G. Aad et al., “Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in $\sqrt{s} = 8$TeV $pp$ collisions with the ATLAS detector,” JHEP, vol. 1404, p. 169, 2014.

[38] P. Z. Skands, B. Allanach, H. Baer, C. Balazs, G. Belanger, et al., “SUSY Les Houches accord: Interfacing SUSY spectrum calculators, decay packages, and event generators,” JHEP, vol. 0407, p. 036, 2004.

[39] B. Allanach, C. Balazs, G. Belanger, M. Bernhardt, F. Boudjema, et al., “SUSY Les Houches Accord 2,” Comput.Phys.Commun., vol. 180, pp. 8–25, 2009.

[40] W. Beenakker, M. Klasen, M. Kramer, T. Plehn, M. Spira, et al., “The Production of charginos / neutralinos and sleptons at hadron colliders,” Phys.Rev.Lett., vol. 83, pp. 3780–3783, 1999.

[41] W. Beenakker, R. Hopker, and M. Spira, “PROSPINO: A Program for the production of supersymmetric particles in next-to-leading order QCD,” 1996.

[42] M. Bahr, S. Gieseke, M. Gigg, D. Grellscheid, K. Hamilton, et al., “Herwig++ Physics and Manual,” Eur.Phys.J., vol. C58, pp. 639–707, 2008.

[43] G. Aad et al., “Search for pair-produced third-generation squarks decaying via charm quarks or in compressed supersymmetric scenarios in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” Phys.Rev., vol. D90, no. 5, p. 052008, 2014.

[44] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, et al., “Event generation with SHERPA 1.1,” JHEP, vol. 0902, p. 007, 2009.

[45] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, et al., “New parton distributions for collider physics,” Phys.Rev., vol. D82, p. 074024, 2010.

[46] M. Drees, M. Hanussek, and J. S. Kim, “Light Stop Searches at the LHC with Monojet Events,” Phys.Rev., vol. D86, p. 035024, 2012.

[47] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, “MadGraph 5 : Going Beyond,” JHEP, vol. 1106, p. 128, 2011.

[48] T. Sjostrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 Physics and Manual,” JHEP, vol. 0605, p. 026, 2006.