CutLHCO: A Consumer-Level Tool for Implementing Generic Collider Data Selection Cuts in the Search for New Physics

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A new computer program named CutLHCO is introduced, whose function is the implementation of generic data selection cuts on collider event specification files in the standardized .lhco format. This software is intended to fill an open market niche for a lightweight yet flexible "consumer-level" alternative to the Root data analysis framework. The primary envisioned application is as a filter on output produced by the PGS4 and Delphes detector simulations, which are themselves lightweight alternatives to the Geant4 based solutions favored by the large LHC experiments. All process control instructions are provided via a compact and powerful card file input syntax that efficiently facilitates the reasonable approximation of most event selection strategies and specialized discovery statistics commonly employed by the CMS and ATLAS collaborations. The structure, function, invocation and usage of the most recent CutLHCO 2.0 program version are documented thoroughly, including a detailed deconstruction of several example card file specifications. The associated software is simultaneously being made available for free public download.

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I. INTRODUCTION AND MOTIVATION

A. Monte Carlo Event Generation

In order to make a tangible connection between the abstraction of a given theoretical construct and the actuality of detailed collider level observations, a sophisticated and reliable mechanism of simulation is essential. However, the gulf separating the theoretical inception from the experimental inquest of a physical model can be quite wide. The spanning of this great divide can be logically partitioned into four distinct steps, each of which may be sequentially effected via widely established public computer code.

The initial computational task consists of generating low order Feynman diagrams that may link the incoming beam to the desired range of hard scattering intermediate states. The resulting matrix elements are subsequently fed into a secondary processing phase for appropriate kinematic scaling and an implicit all-order resummation of the leading order transition into batches of Monte Carlo simulated parton level scattering events. In the case that the more precise but computationally demanding matrix element calculation is extended to include radiation by higher order diagrams (as is increasingly advisable outside the soft, collinear secondary emission regime), a one-to-one matching algorithm must also be applied to preclude the double counting of states. Programs popularly employed to facilitate this intricate sequence of calculations include Alpgen [1] and the MadGraph/MadEvent [2, 3] suite.

The third tier of processing, which handles the cascaded fragmentation and hadronization of the parton level events into final state showers of photons, leptons and mixed jets, is the domain of programs such as Pythia [4], Herwig [5] and Sherpa [6]. Finally, though, a veil of obfuscation must be drawn across the detailed omniscience of the initial three steps, replicating the limits on information and vulnerability to error of a physical detector environment. Options available for this fourth processing phase include the industrial strength Geant4 [7] simulation toolkit favored by the major ATLAS and CMS detector collaborations at the Large Hadron Collider (LHC), and also lighter-weight consumer-level tools such as PGS4 [8] and Delphes [9].

B. The Need for Data Selection Cuts

The output produced by the utilities just described is not, however, directly suitable either for human consumption or for the efficient discernment of signal from background. For these purposes, a fifth processing phase is required - one that is sensitive to the extraordinary delicacy of the modern high energy experimental condition. It is an environment in which known processes, sufficiently well understood to be relegated to subservience as calibration, will, by their definition as the easier target, comprise a noise floor that tends to swamp any candidate indication of new physics. The severe synchrotron radiation limits on light particles has moreover forced circular ring collider probes at the energy frontier to abandon the clean kinematic consumption of elemental electron-positron pairs for the muddled partial interactions of strongly bound quark-gluon composites. Any given set of final states, even assuming perfect efficiency in measurement, and admitting the inevitable evanes-
ence of the neutrino, will correspond to an immeasurable large amalgam of unobservable internal processes. The stochastic variation inherent in quantum interactions will create false excesses and shortfalls in production which both mask and masquerade as the sought post Standard Model (SM) contributions. In this environment, discovery is only as certain as the aggregate of statistics, fastidiously extracted from the tails of event distribution tails, accumulated with the laborious passage of time.

The most incisive tool in the particle physicist’s arsenal for the clearing away of these myriad obstacles is a savagely application of the data selection cut. Simply put, it is necessary to isolate, or select, potential outcomes that are accessible to the desired signal, but inaccessible to, or at least substantially unlikely for, the competing background. It may actually be beneficial to discard even a large quantity of signal events from regions of phase space that are background dominated, in favor of a smaller quantity of retained events of an unusual character that may be uniquely differentiated. Additional layers of selection filtering may typically be applied to eliminate faked signals attributable to the persistent incompleteness and occasional fallibility of detector measurements. Careful tailoring of the cuts to the sought signal may readily account for orders of magnitude of relative signal enhancement, and great effort is thus expended in this pursuit, commensurate with the weight of potential benefit that the cuts employed may leverage against the great cost and effort of the project at large.

C. A New Selection Cut Tool

Selection cuts are most often implemented by the major detector collaborations within the ROOT [10] data analysis framework. However, it would appear that there remains room within the Monte Carlo collider-detector simulation ecology for development of lightweight consumer-level event selection tools that embody the analogous role with respect to ROOT that PGS4 [8] and DELPHES [9] play with respect to GEANT4 [6]. Parallel efforts to fill this niche include the MADANALYSIS5 [11] package available for integration with the MADGRAPH [3] software family, and MATHEMATICA notebook based solutions such as the original CHAMELEON [12] package and various extensions based upon it. During the course of an extensive phenomenological study with colleagues Nanopoulos, Li and Maxin of a particle physics model named $F$-$SU(5)$ [13, 14], it proved beneficial to develop and refine a proprietary software solution for the implementation of desired cuts, and the counting and compilation of the associated net statistics, in order to facilitate a clear and testable description of the experimental profile that our preferred model might present at the LHC. A documentation of the resulting PERT program, named CutLHCO for its operation on event files in the standardized .lhco output format that may be produced natively by both PGS4 [8] and DELPHES [9], is the object of the present article.

The CutLHCO program has evolved organically during extensive private use over more than a year’s time for the rapid prototyping and application of generic selection cut criteria against Monte Carlo collider-detector event simulation data. Development under the real-world pressure exerted by a need to carefully model a substantial (and growing) variety of actual selection strategies from the ATLAS and CMS collaborations has resulted in an extremely flexible and powerful analysis framework that is capable of addressing the majority of leading contemporary use cases. To cope with this extreme generality of function, the user interface syntax has necessarily been driven toward an extremely simple and intuitive form, with all processing instructions compactly delivered via a single input card file. A recently established plateau in stability and sophistication has presented an apt occasion for wider release of the associated package into the public domain under the terms of the GNU General Public License [17], in conjunction with assignment of the 2.0 versioning designation. The full CutLHCO 2.0 distribution is available for download from the author’s personal website [18], where it shall be updated as new versions become available. The main program is also included as an ancillary file “anc/cut_lhco.pl” with this document’s electronic source at the arXiv.org repository.

II. PROGRAM STRUCTURE AND FUNCTION

Operation of the CutLHCO program may be subdivided into three basic phases consisting of the reading of an event specification in the .lhco format (II A), the filtering and reconstruction of basic physics objects (II B), and the selection of event subsets consistent with specific global signatures (II C). An explicit deconstruction of the user syntax required to control these various operational phases will be provided subsequently in Section (III), whereas the primary purpose of the present discussion is a higher-level introduction to the logic, organization and physical underpinnings of the available program functionality. As such, it may also serve more generically as a gentle contemporary review of the broad science and art of the collider data selection cut.

A. The .lhco Object Format Input

The processing cycle of a CutLHCO program instance begins with the reading in of an .lhco format event specification file, which reasonably approximates the most critical aspects of object substructure that are knowable for a given collision within a modern high energy detector environment [12]. The physical geometry of such a particle detector generally includes an inner system of silicon pixel track finders with extraordinarily fine timing and position resolution surrounded by a network of calorimeters designed to separately absorb energy through elec-
tromagnetic and hadronic interactions; intense magnetic fields curve the paths of charged particles to facilitate a
determination of the charge-to-mass ratio, and a supplementary outer gas detector may be employed that special-
izes in the identification of muons, whose calorimeter depositions are generally weak. An astute integration of the raw data collected by the various detector sub-
systems allows for the segregation of key particle species with high confidence based upon various mutual tracking and calorimeter signatures, and also for the efficient handling of beam pile-up conditions, multiple source interactions, intrusion from cosmic rays, and secondary vertex displacement (a key marker of heavy flavor physics).

While still substantially less detailed than the cor-
responding Root [10] object classification, the .lhco format
data subset represents a reasonable compromise be-
tween precision and ease of use. The event constituents
are combined into high-level physics objects consisting of
photons, leptons (with specified flavor), and recon-
structed hadronic jet clusters. These objects are de-
scribed one per line in plain text, each with a variety of standard geometrical and kinematic parameters pro-
vided in a reader-friendly fixed column layout. All dimen-
sionful quantities are given in GeV-scaled natural units.

Some degree of isolation filtering and cross-cleaning is
typically applied prior to assembly of the high level ob-
jects. It is likewise typical that decays in-flight of the
tau have already been handled at a higher level of the
analysis hierarchy, and that tau leptons reported by the
event specification are thus only the subset deduced from
a hadronic signature within the daughter product. While
it is usually possible to additionally restrict the . lhco file
content to events passing various triggering criteria, it
may be preferable to revert to only level-0 triggering in
the detector simulation, so that all event selection activ-
ity may be globally encapsulated as an exclusive domain
of theCutLHCO program.

In addition to the object type, each line of data in-
cludes an additional seven pieces of information, plus
two dummy columns reserved for future expansion of the
format. The first four serve as a one-to-one proxy for
the energy-momentum 4-vector of the object, translated
into the traditional language of collider physicists. The
pseudo-rapidity, defined as follows, is a pure function of
the zenith angle θ, as measured from the instantaneous ẑ
direction of travel of the counterclockwise beam element.

\[ \eta \equiv -\ln \tan(\theta/2) \]  

Forward (or backward) scattering correspond to η equals
plus (or minus) infinity, while η = 0 is an entirely trans-
verse scattering event. The angle φ is simply the usual
azimuthal angle, measuring orientation around the beam
axis. The transverse momentum \( P_T \) gives the magnitude of the 3-vector momentum \( \vec{P} \) projection that is perpen-
dicular to the beamline.

\[ P_T \equiv \sqrt{P_x^2 + P_y^2} \]  

The final parcel of kinematic data is the object invari-
ant mass \( M \), which is especially important for jets rep-
resenting the composition of several lower level physical
objects. In particular, it should be recalled that the 4-
vector sum of individually massless objects may easily
acquire an energy-momentum imbalance that manifests
as a non-negligible mass-square in the invariant product.

\[ P_\mu P^\mu \equiv E^2 - \vec{P} \cdot \vec{P} = M^2 \]  

The given data may readily be inverted back into a stan-
dard 4-vector form for internal use.

\[
\begin{align*}
\vec{P} &\equiv \left\{ P_T \cos \phi, P_T \sin \phi, P_T \sec \eta \left( 2 \tan^{-1} e^{-\eta} \right) \right\} \\
E &\equiv \sqrt{\vec{P} \cdot \vec{P} + M^2} \\
P_\mu &\equiv \left\{ E, \vec{P} \right\}
\end{align*}
\]

It is also useful to define a quantity \( \Delta R \) derived from
the pairwise kinematic descriptions of two objects that
gives a fairly scaled measure of their relativistic “angular separation”, in radians.

\[ \Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]  

The final three active data columns contain additional
information of a non-kinematic variety, and may perform
multiple duty by context. One column is reserved to in-
dicate the number of identified tracks associated with the
object. For charged leptons, the sign of the track count
distinguishes particles from anti-particles. For hadron-
ically reconstructed taus, the track magnitude will be
either 1 or 3. For jets, it is a positive number or zero.

The next column is used to indicate whether a given jet
has been tagged for heavy quark flavor content (usually
a b, but also sometimes c). For muons, this column is
appropriated instead to provide the numeric identity of
the jet most adjacent to the muon track. It is often the case that this information will already have
been employed by a muon cleaning script at a higher
level in the processing chain to remerge poorly isolated
muons with a parent jet cluster. If this has occurred, the
appropriate jet kinematics will have been adjusted and
the track count incremented for each assimilated muon;
additionally, the integer appearing after the decimal in
the jet track count will reflect the number of such occur-
rences. The last data column provides the object’s energy
deposition ratio into the hadronic and electromagnetic
calorimeters. For present purposes, it is useful to recast
this ratio as an electromagnetic fraction (cf. Ref. [19]).

\[ \xi \equiv \left( 1 + E_{\text{had}}/E_{\text{em}} \right)^{-1} \]  

Excessively large values (\( \xi \sim 1 \)) may indicate that a given
jet (especially one outside the pseudo-rapidity bounds
|\( \eta \| \sim 3 \) where leptons and photons are typically explic-
itly classified) is actually an electron or a photon rather
than a hadronic object. For muons, this column contains a decimal number, where the digits to the left of the decimal indicate the amount of transverse momentum carried by adjacent tracks $P^\text{adj}_T$ within a $\Delta R \leq 0.4$ cone around the muon track, and the digits to the right of (and including) the decimal give a fraction representing the transverse calorimeter energy $E^\text{cal}_T$ (i.e., the energy deposition reduced by a trigonometric factor for an angular orientation) within an inclusive three-by-three cell array surrounding the muon track divided by the muon transverse momentum. Again, this information is likely to have already been fed into a higher level processing phase dedicated to muon isolation cleaning, prior to invocation of the CutLHCO script. For internal use, a composite transverse energy-momentum isolation ratio (cf. Ref. [20]) is defined as follows.

$$\zeta = \left( \frac{P^\text{adj}_T + E^\text{cal}_T}{P_T} \right)$$  \hspace{1cm} (7)

Subsequent to the itemization of constituent physics objects, the .hco format specifies a final line to report the composite calorimeter based event missing transverse energy $E^\text{cal}_T$. This is, again, primarily a calorimeter based statistic, which is supplemented by additional kinematical extrapolations with aid of the muon detection subsystem. In words, this quantity measures the magnitude of the vector sum over directed calorimeter energy deposits, trigonometrically reduced to reflect only components transverse to the beamline. The imbalance reflected by a substantial $E^\text{cal}_T$ residue indicates that weakly interacting particles may have escaped the detector. In addition to the calorimeter estimate for the missing energy vector magnitude, an angular orientation in the transverse plane is also provided; to be more precise, this orientation actually represents the angular negation of the described vector sum, i.e., the directionality of the missing energy deposition whose inclusion would close the overall sum to the expected zero magnitude. The topic of missing energy will be revisited in Subsection (II.C), where the native .hco calorimeter based estimate will be contrasted to track based estimates computable directly within CutLHCO.

### B. Object Reconstruction

After reading the relevant content from the .hco input file, the CutLHCO program initiates an event processing phase that may be broadly labeled as “object reconstruction”, according to controls specified by the user in a card file. The basic purpose of the object reconstruction is to enforce minimum data quality characteristics for groups of leptons and jets, in terms of their kinematics, geometry, proximity to other objects and multiplicity. Classified particle groups may be subsequently dereferenced by a numerical identifier during the program’s event selection phase, for testing against various discovery statistics designed to isolate new physics. Elements of the card file syntax that are organically encountered during this dialog on the object reconstruction procedure will be denoted by **Typewriter** font for future reference.

The principal object grouping OBJ_ALL is, as the name suggests, applied universally during the initial read access of all input physics objects. It takes only two parameters, namely a global specification of the acceptable boundaries on each object’s transverse momentum magnitude $P_T$ (PTM) and pseudo-rapidity magnitude $|\eta|$ (PRM). Objects failing this primary filtering are permanently discarded from the event. Next, a set of instructions OBJ_PHO is processed for the handling of photon type objects. In addition to the standard PTM and PRM filters, two additional parameters are made available. The CUT parameter specifies the acceptable range of acceptable photon counts after application of the previously described filters, as a minimum and maximum; noncompliance with the specified limits causes the event to be rejected, or cut, as a whole. The JET parameter specifies how individual photon candidates that fail the filtering specification are to be handled; a value of “+1” indicates that these objects should be reclassified as jets, whereas the default behavior “0” is simply to discard them. The initial separation of the charged leptons proceeds in a very similar manner, as controlled by individual object specifications OBJ_LEP ($\ell$, OBJ_MUO ($\mu$), and OBJ_TAU ($\tau$) for each generation. The only universal operational distinction is the addition of an additional parameter SGN for controlling the lepton charge; values of “+1” and “-1” act to retain only the indicated sign grouping, whereas the default behavior “0” makes no distinction between particles and antiparticles. For muons there are two additional specifications, PTC and ETR, respectively describing the allowed range of transverse momentum $P^\text{adj}_T$ in GeV carried by tracks within a $\Delta R \leq 0.4$ cone of adjacency to the muon, and the allowed range of dimensionless values taken by the transverse energy-momentum isolation ratio $\zeta$ of Eq. (7).

From this point forward, the outer control structures refer to the leptons only as a unified class. The object reconstruction OBJ_LEP governs the content of the zeroth combined lepton classification, which constitutes also the default starting point of all latter groupings. Although the leptons are consolidated, finely grained control over inclusion and exclusion by flavor is retained by the addition of a new parameter, EMT. This parameter can take the values “+1”, “+2” or “+3” to specify the inclusion only of electrons, muons or taus, respectively, whereas the default behavior “0” retains all lepton flavors. However, negative values “-1”, “-2” or “-3” are also allowed, and are interpreted instead as an exclusion of the given flavor index; in practice, the value of “-3”, which selects both electrons and muons for retention, is particularly useful. The SGN, PTM, PRM and CUT parameters carry over in the expected manner, but reclassification under the JET flag is no longer permitted. The PTC and ETR tags are also retained, but affect only the muonic object subset.

The hadronic jets are treated very similarly to the unified lepton classifications, although there are distinctions
in the available filtering options. The object reconstruction OBJ_JET governs the zeroth level jet assembly, which will again constitute the default starting point for all subsequent groupings. The PTM, PRM and CUT parameters are supplemented by four additional control specifications unique to the jets. The parameter HFT indicates whether jets are required to possess a heavy flavor tag. A value of “1” indicates that loose tagging is sufficient, while a value of “2” enforces the stricter tight tagging criterion; the default setting “0” enforces no requirements on heavy flavor content. The parameter FEN specifies a range of acceptable values for the dimensionless electromagnetic fraction $\xi$ of Eq. (6). The tags TRK and MUD indicate the allowed range of counts, respectively, for individual object tracks associated with the jet, and poorly isolated muons integrated into the jet by a prior cleaning phase.

The real power and flexibility of the CutLHCO object reconstruction specification comes from the ability to iteratively define a practically unlimited number of additional lepton and jet classification levels. These go by the control structure tags OBJ_LEP_N and OBJ_JET_N, where N is positive integer between “1” and “999”. These specifications are processed in numerical sequence, and may refer for sourcing and comparison back to any previously defined specification with a lower valued index. Five new parameter keys are introduced, in addition to the full set of retained OBJ_LEP and OBJ_JET inputs, to regulate this data network. The most important is the source SRC, which specifies the initial company of objects that are to be filtered. Indices provided for the lepton (jet) source parameter refer to previously defined lepton (jet) groups. Multiple index values may be listed, and the union of all lepton or jet objects (as the case may be) included within any of the referenced groups is assembled into the source for the current object reconstruction; negative integers are also allowed, and have the effect of vetoing the inclusion of all objects present within any group so referenced. The default value “0” adopts all objects within the zeroth lepton or jet classification as the current source set. A functionally similar parameter key CMP is available for isolating a complementary set of oppositely typed objects (leptons refer now to jets, and vice versa) against which a comparative filtering of objects may be applied. Each of the CMP and SRC inputs is accompanied by a corresponding parameter (CDR or SDR) specifying the acceptable range of Eq. (5). $\Delta R$ displacements between passed objects and either the external complementary object set or the (otherwise successful elements of the) internal source object set.

Finally, the ANY tag allows for multiple lepton or jet specifications to be joined by the logical construct “or” rather than the default “and”. The accepted input is a list of previously defined (lower valued) reconstruction indices of the same lepton or jet variety as the host, with the effect that the linked set of selections is passed as a whole if any single member (including the host) passes. This is particularly useful for constructing the logical negation of a compound statement, according to the identity $\text{not}(A \text{ and } B) \equiv (\text{not } A) \text{ or } (\text{not } B)$. In particular, tiered classifications may be constructed that retain only events failing at least one of the criteria simultaneously required for admission into a prior tier.

The final category of object reconstruction groupings OBJ_DIL_N facilitates the identification of dilepton object pairs. There is no default zeroth classification in this case, and the integer N again ranges between “1” and “999”. There are four new parameter specifications particular to the dilepton groupings, in addition to a CUT on the number of surviving pairs. Firstly, LEP specifies a single integer index corresponding to a previously defined source lepton grouping. Since the dileptons represent an independent data set, processed after all lepton classifications are complete, the selected index does not have to be less than N. The zeroth lepton set “0” is an acceptable specification, but is not a default. Next, DLS specifies the target dilepton sign classification. Allowed values are “+1” for same-sign pairs only, “-1” for opposite-sign pairs only and the default value of “0” to allow all combinations. A similar specification DLF restricts dilepton flavor mixing, where a value of “1” allows only matching flavors to be paired, and the default value of “0” imposes no flavor restrictions. Lastly, the specification DMI provides the acceptable range of the dilepton mass invariant $M_{\ell,\ell}$ in GeV, where the invariant mass $M_{A,B}$ is defined generically for any pair of objects A and B as follows.

\[
M_{A,B} = \sqrt{(P_{A\mu} + P_{B\mu}) (P_{A\mu}^* + P_{B\mu}^*)} \\
= \sqrt{M_A^2 + M_B^2 + 2 E_A E_B - P_A \cdot P_B} \\
\frac{\lim_{M_A=M_B=0} \Rightarrow 2 |P_A||P_B| (1 - \cos \Delta \phi_{B,A})}{(8)}
\]

A massless limit for the individual leptons is generally a fair approximation in the present case, but is not enforced by the program.

C. Event Selection

Following the reconstruction of component physics objects into groups satisfying various data quality and counting requirements, the CutLHCO program proceeds on with the second half of its analysis duties, which may be summarized under the heading of “event selection”. This processing phase is dedicated to isolating global signatures of new physics that may become apparent when the event is contemplated as a unified entity. In particular, various discovery statistics, either optimized for sensitivity to missing energy and exotic decay configurations or biased against false triggers and energy mismeasurement, are evaluated under projection of the previously indexed objects. Elements of the card file syntax that are organically encountered as a part of this dialog on the event selection procedure will be denoted by *Typewriter* font for future reference.
Selection Tier 1

Three elementary (but not fully independent) statistics are presently considered to comprise the first event selection tier, each of which provides a distinct perspective on the basic transverse kinematics of the collision event. The notion of transverse variables has been broached already in Subsection (IA), but their ubiquity of application in the event selection process now comes front and center. The driving motivation for adoption of this perspective is the simple reality that the detector cannot be sensitive to particle flow down the beamline. Moreover, since the initial portion of longitudinal momentum carried by the interfering “parton” constituents in a hadron collision cannot be ascertained, an imbalance in the detected momentum sum can only be established in the beam-transverse plane, where the net conserved momentum may be safely approximated as zero. This projection bestows an intrinsic kinematic incompleteness on the transverse variables, by dint of which they will generically tend to indicate new physics via a termination point rather than a peak. Beyond this inherent loss of information, there are other obstacles that additionally complicate the direct interpretation of transverse statistics. As an important case in point, it is useful to consider the following definition of the transverse energy of a single particle.

\[ E_T \equiv \sqrt{M^2 + \vec{P}_T \cdot \vec{P}_T} = \sqrt{E^2 - P^2_T} \]
\[ \lim_{M \to 0} |\vec{P}_T| \]  

(9)

Firstly, note that the characteristic Lorentz transformation response associated with energy as a time-like four-vector component has been corrupted through a quadratic reduction (while retaining the same invariant mass \( M \)) by the longitudinal momentum. However, this is not necessarily a detrimental exchange; in particular, the transverse energy \( E_T \) has acquired by trade the interesting new property of invariance under the subset of Lorentz transformations corresponding to longitudinal boosts. This is not a fundamental invariance of the type garnered by the mass \( M \) in Eq. (4) from contraction under the Lorentz metric, but rather an “accidental” byproduct of the quiescence of \( \vec{P}_T \) (which lacks time-like and longitudinal spatial components) under orthogonally directed space-time rotations; nevertheless, it is a very useful property that may be leveraged in interesting ways to link relative frames of reference along the beamline. Secondly, the mutual transverse energy \( E_{T}^{A,B} \) of two summed four-vector constituents \( A \) and \( B \) is not equivalent to the simple sum of individual transverse energies.

\[ E_{T}^{A,B} \equiv E_A^T + E_B^T \]
\[ \vec{P}_{T}^{A,B} \equiv \vec{P}_T^A + \vec{P}_T^B \]
\[ E_{T}^{A,B} \equiv \sqrt{(M^{A,B})^2 + (|\vec{P}_{T}^{A,B}|)^2} \neq E_A^T + E_B^T \]  

(10)

In this sense, the transverse energy adds more like a mass than like an energy-momentum four-vector component.

\( \mathcal{E}_T \): The first, and arguably the most vital, of the dimensionful transverse statistics to be modeled for event analysis by the CutLHCO program is the missing transverse energy \( \mathcal{E}_T \). The inclusive calorimeter based estimate \( \mathcal{E}_T^{\text{cal}} \) of this quantity described in Subsection (IA) is accessed through the selector tag \( \text{EVTLHCO} \), and is accompanied by only a single control parameter, namely an optional \( \text{cut} \) in GeV. However, in addition to this intrinsically available statistic, substantial flexibility is provided to the user to craft transverse momentum \( \vec{P}_T \) track enhanced \( \mathcal{E}_T \) variations as follows, which may call upon preferred subsets of the event’s physics objects.

\[ \vec{P}_T \equiv -1 \times \sum_{i=1}^{N} (P_{iT}^x \cos \phi_i \hat{x} + P_{iT}^y \sin \phi_i \hat{y}) \]
\[ \mathcal{E}_T \equiv |\vec{P}_T| = |\vec{P}_T| \left\{ \lim_{M \to 0} \right\} \]
\[ \mathcal{E}_T^{A,B} \equiv \left| \vec{P}_T^{A,B} = \vec{P}_T^A + \vec{P}_T^B \right| \neq E_A^T + E_B^T \]  

(11)

Keeping with the previous verbal definition of \( \mathcal{E}_T^{\text{cal}} \), \( \mathcal{E}_T \) is the magnitude of the vector negation of the sum over the transverse momentum \( \vec{P}_T \) carried by \( N \) individually reconstructed objects. As before, it represents the unaccounted contribution required in order to balance the open polygonal vector sum of visible transverse momenta to the nominally expected net value of zero. The composite missing transverse energy \( \mathcal{E}_T^{A,B} \) adds like the composite visible transverse energy in Eq. (10) and is equal in magnitude to the mass-exclusive portion of that statistic, given that the missing transverse momentum vector \( \vec{P}_T \) is the simple inverse of the visible transverse momentum vector \( \vec{P}_T \). To recapitulate, the merit of this statistic lies in the fact that key indicators of new physics, particularly the SUSY neutralino \( \tilde{\chi} \) dark matter candidate, may interact only weakly and are expected to yield a missing energy signature upon escape from the detector.

It is in some circles conventional to distinguish estimates of this quantity that are augmented by data from the tracking subsystems as “missing transverse momentum”, while the term “missing transverse energy” is reserved for estimates based dominantly on directed calorimeter deposition; one may even occasionally see a hybrid notation that superimposes a vector symbol onto the slashed energy. Instead, given that there is no unambiguous method for assigning a non-zero invariant mass \( M \) to any underlying physics objects that may escape the detector network, the presently adopted practice will be to designate all such vectorial space-like transverse imbalances as \( \vec{P}_T \), and all corresponding time-like three-vector magnitudes as \( E_T \), resolving ambiguity as to the measurement origination by addition of the superscript “cal” when applicable. However, determination of a mass to be associated with the missing transverse energy remains a physically relevant issue, which is driven by the practicality that escaping particles are frequently expected to be produced in pairs that may be entirely kinematically decoupled from each other by intervening steps in the decay.
cascade, implying that a substantial portion of the unseen tracks associated with the true missing momentum vector may internally cancel in the observable sum. In fact, this dilemma forms the motivation for certain of the specialized discovery statistics to be introduced shortly as the third event selection tier.

The zeroth incarnation of the missing transverse energy \( E_T \) to be computed internally is labeled for input purposes as \( \text{EVT\_MET} \), and includes the tracks of all constituents of the event that survive the primary \( \text{OBJ\_ALL} \) classification. It is made available for reference to latter selectors by default, with no need for specific invocation by the user. Again, an optional \( \text{CUT} \) may be specified in GeV. Additional indexed \( \text{EVT\_MET\_N} \) selectors, with \( N \) an integer in the range “1” to “999”, are provided for evaluation of the missing transverse energy carried by various object subsets. Two additional parameter specifications, \( \text{LEP} \) and \( \text{JET} \), allow sourcing from previously defined \( \text{OBJ\_LEP\_N} \) and \( \text{OBJ\_JET\_N} \) object reconstructions. At least one of these inputs must be set equal to a single integer back-reference \( N \); a value of “0” is allowed, but is not a default. The missing energy event statistics may themselves be made available for back-reference by their integer index to the \( \text{MET} \) parameter of subsequent selector definitions, with \( \text{EVT\_MET} \) taking the implicit valuation of \( N = \text{“0”} \). As a special case, the calorimeter based estimate \( \text{EVT\_CAL} \) is also automatically made available, under the index assignment \( N = \text{“-1”} \). The directional characteristics of each computed missing transverse energy statistic are retained internally for reference by future selectors. \( H_T \): A second event selector of great importance is the scalar sum on transverse energy \( H_T \), which is defined as follows and indicated programmatically as \( \text{EVT\_MHT} \).

\[
H_T = \sum_{i=1}^{N} E_T^i \quad \lim_{M_i=0} \Rightarrow \sum_{i=1}^{N} \left| \frac{P_T^i}{H_T^i} \right|
\]

A massless limit is imposed by default, but may be overridden by setting the \( \text{MAS} \) parameter to “1”. The key distinction between \( H_T \) and the missing transverse energy (in the massless limit) is that the absolute value is applied prior to the summation rather than after, so that vector cancellation is avoided. As such, this statistic is instead representative of the net energy carried by the visible event constituents. In fact, it represents precisely the massive transverse longitudinal scalar possessing the property of linear composition that eludes the transverse energy as defined by Eq. (10).

\[
H_T^{A,B} \equiv H_T^A + H_T^B
\]

In this sense, the massive limit might be considered somewhat more deeply consistent, insomuch as the desired associative property may be disrupted by compound alternation of mass-zeroing with four-vector summation. As before, \( H_T \) is automatically computed for all primary event objects in the zeroth incarnation, and an optional \( \text{CUT} \) is allowed on the result in GeV. Likewise, indexed \( \text{EVT\_MHT\_N} \) \( H_T \) selectors are available as before for treating \( \text{LEP} \) and \( \text{JET} \) object subsets.

\( M_T^{\text{eff}} \): The missing and visible energy magnitudes are combined in a third selector called the transverse effective mass \( M_T^{\text{eff}} \), which is defined as the following simple sum, and indicated programmatically as \( \text{EVT\_MEF} \).

\[
M_T^{\text{eff}} = E_T + H_T
\]

Once again, \( M_T^{\text{eff}} \) is automatically computed for all primary event objects, with a single optional parameter \( \text{CUT} \). Additional indexed \( \text{EVT\_MEF\_N} M_T^{\text{eff}} \) selectors are likewise provided as before, but the supplemental parameter specifications are different in this case. Since \( M_T^{\text{eff}} \) will be considered as a dependent construction based upon \( E_T \) and \( H_T \), the available inputs are instead \( \text{MET} \) and \( \text{MHT} \), each of which must specify an integer back-reference \( N \) to a previously defined incarnation of \( \text{EVT\_MET\_N} \) or \( \text{EVT\_MHT\_N} \); a value of “0” is allowed in either case, but is not a default.

Selection Tier 2

A second tier of derivative event selectors is constituted from various comparative combinations of the three previously defined statistics. No default analysis is performed in these cases, and an index \( N \) in the usual “1” to “999” range is always explicitly specified. The first such statistic, \( \text{EVT\_RET\_N} \), consists of the dimensionless comparison \( (E_T^N/E_T^D) \) of two missing energy magnitudes. This quantity might be used, for example, to protect against the danger that reinclusion of discarded soft or high pseudo-rapidity jets could substantively alter the observed momentum imbalance. Back-references to a pair of previously defined missing energy indices must be provided to the inputs \( \text{NUM} \) and \( \text{DEN} \), for use in the numerator and denominator, respectively. The \( \text{CUT} \) specification accepts pure numerical values for evaluation against the computed ratio. A similar pair of selectors \( \text{EVT\_RHT\_N} \) and \( \text{EVT\_REF\_N} \) are provided for analysis of the ratios \( (E_T^N/|H_T^N|) \) and \( (E_T^N/M_T^{\text{effD}}) \), which instead reference the scalar momentum sum and effective mass in the denominator, respectively. The square root employed in the \( \text{EVT\_RHT\_N} \) example evinces the expected Gauss/Poisson fluctuation size, so that the statistic provides a metric for the relative significance of the missing energy magnitude. The former \( \text{NUM} \), \( \text{DEN} \) and \( \text{CUT} \) inputs extend in a straightforward manner to each of these latter two cases, although one should take note of the curious GeV\(^{1/2}\) units for the \( \text{EVT\_RHT\_N} \) selector output. The final statistic to be defined, \( \text{EVT\_DET\_N} \), represents the absolute vector difference \( |P_T^B - P_T^A| \) between two distinct population studies \( (A,B) \) of the missing transverse momentum. Its function, once again, is to protect against false indications of escaped particles. In addition to a \( \text{CUT} \) specification in GeV, two parameters, \( \text{ONE} \) and \( \text{TWO} \), are provided for specifying (in either order) a pair of back-references to previously defined missing energy indices in the usual manner.
Selection Tier 3

The third tier of provided event selectors represents a sampling of somewhat specialized statistics that are in contemporary use by the ATLAS and CMS collaborations. As with the second tier, no default computation is performed in these cases, and an index n in the usual “1” to “999” range is always to be explicitly specified. A robust variety of analyses are provided with the presently documented CUTFHCO 2.0 release, although the creation of additional subroutines to supplement the generality of this coverage represents a potentially active source of ongoing program development. The author welcomes useful suggestions for expansion in this regard, and encourages users who write their own program extensions to resubmit them for inclusion into the main program trunk.

$M_{T^{E}}$: The first specialized statistic to be discussed is the transverse mass $M_{T^{E}}$ computed for a leading lepton object reconstruction and the missing transverse momentum, which shall be denoted for programmatic purposes as EVT_LTM_N. This statistic has been employed frequently by the ATLAS collaboration [21–23], although essentially similar channels are also of interest to CMS [24]. For any two objects A and B, the transverse mass statistic is defined as follows [25]:

$$M_{T}^{A,B} \equiv \sqrt{\left(E_{T}^{A} + E_{T}^{B}\right)^{2} - \left(\vec{P}_{T}^{A} + \vec{P}_{T}^{B}\right)^{2}} = \sqrt{M_{A}^{2} + M_{B}^{2} + 2 \left(E_{T}^{A}E_{T}^{B} - \vec{P}_{T}^{A} \cdot \vec{P}_{T}^{B}\right)}$$

$$\lim_{M_{A}=M_{B}=0} \Rightarrow 2 |\vec{P}_{T}^{A}||\vec{P}_{T}^{B}| \left(1 - \cos \Delta \phi^{B,A}\right) (15)$$

Note that the referenced transverse energy $E_{T}$ of each constituent object is defined in a recursively consistent manner according to the prescription by Eq. (9). Also, the simple sum of individual transverse energies that is featured in the Eq. (14) definition mimics the $H_{T}^{A,B}$ prescription from Eq. (13) rather than the behavior of $E_{T}^{A,B}$ from Eq. (10). In fact, by inspection, the mismatch between these quantities is precisely also the mismatch between the pairwise invariant mass $M^{A,B}$ of Eq. (8) and its transverse variant $M_{T}^{A,B}$.

The $M_{T^{E}}$ transverse mass distribution will have an endpoint corresponding to the mass of the presumed common parent of the included lepton and missing energy candidate, as may be verified by noting that $M_{A,B}^{A,B} \leq M_{A,B}^{A,B}$. This potentially facilitates use as a tool for the detailed mass measurement of SUSY particles, although the key present utilization is simply as a discovery statistic, where a lower mass bound in the vicinity of 100 GeV is typically imposed. The transverse mass $M_{T}^{A,B}$ is distinguished as a Lorentz invariant under the subset of transformations consisting of longitudinal boosts for the same trivial reasons that the definition of $E_{T}$ from Eq. (9) was itself so recognized. An individually massless limit for both the lepton and missing transverse momentum is enforced in the present $M_{T^{E}}$ program implementation. The available control parameters include the usual CUT selector in GeV units, and index back-references for the included LEP object set (from which the leading lepton is extracted) and the counterpart MET vector.

$M_{T_{2}^{j}}$: A generalization of the previously described transverse mass statistic referred to as $M_{T_{2}^{j}}$ or the jet “s-transverse mass”, and which will be addressed programmatically as EVT_JSM_N, has been adopted by the CMS collaboration [20] in order to better treat the SUSY scenario where pairwise sparticle production leads to dual decay chains that each manifest a missing momentum signature. First introduced in Ref. [27], the s-transverse mass construction is based upon the observation that each such visible shower may be convolved with its affiliated contribution to the missing momentum to yield a transverse mass, as defined in Eq. (15), that is bounded above by the mass of the system’s parent particle. However, since only the unified missing transverse momentum vector $\vec{P}_{T}$ is experimentally available, further numerical analysis requires the specialization to a suitably optimized location in the distribution of this sum between the pair of missing momentum candidates. The $M_{T_{2}^{j}}$ prescription is to assume an equivalent structure for each decay chain, so that the larger of the two transverse masses may be used imply a lower bound on a common parent species, subsequent to minimization of that maximum value with respect to all consistent $\vec{P}_{T}$ partitions. If event pollution by upstream decays of the initial state prior to the targeted pair production can be neglected, the minimization may actually be performed analytically [28]. If the mass of the escaping particle species $\tilde{\chi}$ is additionally set equal to zero, the following simple expression is realized.

$$M_{T_{2}^{j}} = \sqrt{\Lambda_{T}^{2} + \left(\Lambda_{T}\right)^{2} - M_{A}^{2}M_{B}^{2}}$$

$$\lim_{M_{A}=M_{B}=0} \Rightarrow \sqrt{2 |\vec{P}_{T}^{A}||\vec{P}_{T}^{B}| \left(1 + \cos \Delta \phi^{B,A}\right)} (16)$$

Relative to Eq. (15), one immediately notices the curious emergence of a Euclidean signature for the inner product. This difference may be traced to the fact that $M_{T_{2}^{j}}$ employs two visible systems rather than a single visible system in conjunction with associated missing energy; escaping missing energy is expected to be antiparallel to its conjugate visible shower, inducing a phase shift by $\pi$ radians that effectively reverses the sign of the trigonometric factor. In order to apply the formula from Eq. (15), the reconstructed objects taken to constitute the dual visible systems must be specified; following the CMS lead [26], CUTFHCO computes the s-transverse mass $M_{T_{2}^{j}}$ of a pair of optimally separated pseudo-jets in the massless limit. The “event hemisphere reconstruction” procedure (cf. Ref. [29], Section 13.4) begins by establish-
ing a pair of pseudo-jet axis “seeds” consisting of the two individual massless jets that possess the largest relative 4-dimensional invariant mass. These axes $P_{j,j}^R$ are iteratively reconstructed as the 4-vector sum (with rezeroed mass) of all massless jets $P_{\mu}^B$ that are assigned to them in a given round by merit of the smaller Lund-inspired \cite{4} dimensionful distance measure $(E_A M_{A,B}^2)/(E_A + E_B)^2$.

The cycle terminates upon the retracing of a previously encountered hemisphere partitioning, which may (but does not necessarily) indicate convergence to a stable fixed point assignment of the pseudo-jet axes. Although originally introduced as tool for deducing the mass scale of decaying SUSY particles, the s-transverse mass (like the transverse mass itself) is currently enjoying service as a discovery statistic, with various tuned cutoff thresholds ranging from around 100 GeV up to about half a TeV \cite{20}. The available control parameters include only a \texttt{cut} selector in GeV units and an index back-reference to the included \texttt{jet} object set.

$\Delta E_T^{j,\ell\ell}$: The next specialized discovery statistic to be made available is the CMS jet and dilepton-Z transverse energy balance $\Delta E_T^{j,\ell\ell}$, which will be referenced by the tag \texttt{EVT_JZB_N}. Searches implementing this statistic are designed to target events featuring a leptonically decaying Z boson, which may be inferred by the signature of residual opposite sign electron or muon pairs. The production of Z bosons, in conjunction with jets and missing energy, is a potentially regular byproduct of SUSY transitions from a heavy to light neutralino mass state. Moreover, this selection naturally suppresses large portions of the SM event background, including the difficult QCD multijet component. Troublesome opposite-sign dilepton background competition persists from the dual leptonic decay of pair produced top quarks $t\bar{t}$, which may be obviated by leveraging the absence of flavor correlation in this process. The $\Delta E_T^{j,\ell\ell}$ statistic constitutes an active discriminant against interference from SM Z bosons plus initial state jet radiation by highlighting the kinematic correlation that may persist between the jet track momentum imbalance and the observed dilepton pair, if they indeed were borne of a common antecedent. It is formally defined as follows, employing a massless limit for each of the composite N-jet and dilepton objects.

\begin{equation}
\Delta E_T^{j,\ell\ell} \equiv |\sum_{j=1}^N P_{T,j}^j - |\sum_{\ell=1}^2 P_{T,\ell}^\ell| \\
\approx |\vec{P}_T + \vec{P}_{T,\ell}^{j,\ell\ell} - |\vec{P}_{T,\ell}^{j,\ell\ell}| \tag{17}
\end{equation}

The second line follows as a precise equality if the full missing momentum signal is attributable only to the dilepton and included jets. The unwanted background events are expected to be symmetrically balanced about the zero line of this statistic, with random fluctuations driven in either direction by faked missing energy. For the targeted SUSY events, directional collinearity between the Z boson and the escaping light neutralino will systematically bias $\Delta E_T^{j,\ell\ell}$ toward a positive value. The active signal region is typically restricted to that subset possessing a dilepton invariant mass $M^{\ell,\ell}$ (cf. Eq. [5]) within about 20 GeV of $M_Z$. Additionally, one generally requires the presence of at least three jets, to ensure decoupling between the orientation of potential momentum mismeasurements and the Z boson track. Along with a standard GeV \texttt{cut} selector, the user must specify back-reference indices for a pair of previously defined \texttt{jet} and \texttt{dil} object sets.

$M_R^{j,\beta}$ & $\alpha_R^{j,\beta}$: A trio of SUSY search statistics currently employed by the CMS collaboration \cite{31,32} are the razor variables $M_{TR}$ and $M_{RR}$, and their dimensionless squared ratio, denoted here as $\alpha_R$. Based upon a suggestion originally proffered in Ref. \cite{33}, the pair of massive razor quantities represent independent estimators, the former transverse and the latter longitudinally inclusive, of the scale $(m_{\tilde{q}}^2 - m_{\tilde{g}}^2)/m_{\tilde{q}}$ underlying compound SUSY event chains, where $m_{\tilde{q}}$ is the common mass of an initial hard squark or gluino pair production event and $m_{\tilde{g}}$ represents a pair of weakly interacting particles from the dual decay cascade that escape the detector unseen. In practice, the jet razor mass variable $M_R$, whose modeling is invoked by the tag \texttt{EVT_JRM_N}, may be available to isolate the scale of prospective new physics in conjunction with application of the $\alpha_R$ ratio, which is provided the independent identification tag \texttt{EVT_ALR_N}, as a “razor” discriminant against SM background competition, primarily from QCD di-jets. The $M_{TR}$ variable, which is dependent in this point of view, is not given its own access tag, although the corresponding numerical value may be easily reconstructed as needed from the other two. The razor statistics confront the same innate difficulty as the $M_{T,tt}^j$ s-transverse mass analysis, namely that the history of an event with a dual $\tilde{\chi}$ detection failure is essentially under-constrained by the residual visible particle content, generating fundamental ambiguity within any reconstruction effort. The strategy for surmounting this obstacle that is embodied by the razor analysis is based upon an approximation of the opaque center of mass and pairwise $\tilde{g}$ rest frames (which will be identical in the limit of pair-production at the kinematic threshold) via the expression of a transparent $\tilde{z}$-axis boost into the “razor frame”, wherein the visible center of mass energy may be estimated in terms of the explicit longitudinal invariant $M_R$ composed from observations projected solely out of the laboratory frame; the garnered longitudinal invariance protects the integrity of the $M_R$ distribution peak even if the boost into the true center of mass frame is non-trivial. Construction of the razor frame is initiated by partitioning all relevant physics objects into two massless pseudo-jets A and B representing the observable remnant of the putative SUSY pair production event. The historically favored methodology is replicated by election of the object partition that minimizes the sum of pseudo-jet invariant mass-squares. The jets are taken to be individually massless and, following their reassembly, the masses of each composite pseudo-jet are likewise zeroed by an appropriate compensation of the energy. The specific required longitudinal boost is then guaranteed to exist and is expressible as $\beta = (P_{A}^2 + P_{B}^2)/(E_A^2 + E_B^2)$, assuming
vanishing of the transverse initial state radiation component. The razor variables themselves are defined as follows.

\[ M_{\text{TR}}^{A,B} = \sqrt{\left\{ (|\vec{P}_T| + |\vec{P}_T^A|) - \frac{\vec{P}_T \cdot (\vec{P}_T^A + \vec{P}_T^B)}{2} \right\}/2} \]

\[ \frac{1}{2} \left( M_{\text{TR}}^{A,B} \right)^2 + \left( M_{\text{MET}}^{A,B} \right)^2 = \left( \frac{\vec{P}_T \cdot (\vec{P}_T^A + \vec{P}_T^B)}{2} \right)^2 \]

\[ \alpha_T = \left( \frac{M_{\text{TR}}}{M_{\text{MET}}} \right)^2 \] (18)

In the transverse razor mass, it should be noted that a legitimate missing momentum, even if constructed inclusively from the event at large, should be very nearly equal and opposite to the pseudo-jet vector sum, making the second term under the radical positive, and equal in magnitude to the missing energy squared. If the pseudo-jets are close to parallel, then each term in the sum will moreover be equal, and \( M_{\text{TR}}^{A,B} \) will take the scale of the missing energy as a whole. Conversely, if the pseudo-jets are back-to-back, as is increasingly likely for QCD di-jets, a partial cancellation will be exhibited, even in the presence of faked missing energy. If there is no missing energy signal at all, then \( M_{\text{TR}}^{A,B} \) will be identically zero.

The first term under the \( M_{\text{TR}}^{A,B} \) radical may be recognized as the Eq. (10) invariant mass-square of the merged visible pseudo-jet system, and the expression as a whole is identical to the definition of the transverse energy, as in Eqs. (17,10), for this same system. Since both mass estimators are designed to highlight the same underlying physical scale, the ratio \( \alpha_T \) should be expected to peak at order one for signal events; specifically accounting for "geometric" factors in the respective Eq. (15) definitions, the fact that \( M_{\text{TR}} \) (like all transverse statistics) identifies a kinematic endpoint, and a small relative Lorentz transformation factor \( \gamma \gtrsim 1 \), the signal peak will tend to occur closer to a value of 1/4. The SM QCD distribution will indeed peak at zero, allowing for a clear-cut excision of the encroaching background competition. The available control parameters for each of the individually addressable statistics includes a cut selector in GeV units and an index back-reference to the included LEP and JET object set; for \( \text{EVT}_{\text{ALT,N}} \) the user may additionally include a reference \( \text{MET} \) to the preferred missing transverse momentum, which will instead be rebuilt from the local lepton and jet content if an index is not provided.

\[ \alpha_T^{A,B} \]: A replication of the CMS \( \alpha_T \) ratio [19, 34, 35] is provided for use under the identification handle \( \text{EVT}_{\text{ALT,N}} \). This quantity was devised [36] to help distinguish actual missing transverse energy from detector mismeasurement. It is formally defined as follows, where \( H_T^{A,B} \) is the minimal positive difference that may be realized between the pair of \( H_T \) sums corresponding to a grouping of all included objects into two effective pseudo-jets A and B, when considering all such possible partitions; \( H_T^* \) is the lesser of \( H_T^A \) and \( H_T^B \).

\[ \alpha_T^{A,B} = \frac{H_T^{A,B}}{M_{\text{TR}}^{A,B}} \equiv \frac{H_T^{A,B} - \frac{(H_T^{A,B})^2}{2}}{\sqrt{\left( H_T^{A,B} \right)^2 - \left( \frac{(H_T^{A,B})^2}{2} \right)^2}} \]

If there is no mismeasurement or true missing energy, the value of \( \alpha_T^{A,B} \) will just be 1/2. For energy mismeasurements of otherwise anti-parallel pseudo-jet pairs, subtraction of the nonvanishing scalar difference \( \Delta H_T^{A,B} \) will tend to drive \( \alpha_T^{A,B} \) below the midline. In this case \( \Delta H_T = H_T^* \), but the squaring of the small (typically \( \ll 1 \)) factor in the denominator renders it less significant. Conversely, genuine missing energy, as manifest in the departure from pseudo-jet anti-parallelism, will imbalance the vector sum within \( E_T \) more so than the simple magnitude difference \( \Delta H_T \), tending to create a contrasting elevation in \( \alpha_T^{A,B} \) above one-half. In addition to a dimensionless \( \text{CUT} \) selector, the user may specify index back-references for the included JET object set, and the referenced \( \text{MET} \) and \( \text{MHT} \) values. The latter two quantities will be recomputed from the jet content itself if omitted. Additionally, the same \( \text{MAS} \) tag available to \( \text{MHT} \) itself is also available here to indicate a preference for the mass inclusive determination of \( H_T \). As an editorial aside, it has been observed by the author’s research collaboration [13, 14] that the \( \alpha_T \) statistic may become unsuitable in the soft, high multiplicity jet regime, as the large array of finely grained pseudo-jet permutations makes quite likely that a balanced scalar sum \( \Delta H_T \approx 0 \) might be achieved, creating an overall suppression of the final computed value.

\[ \Delta \phi_{j,E}^*: \] The next event selector to be discussed is a relatively simple angular difference statistic \( \Delta \phi_{j,E}^* \) employed by the ATLAS collaboration. It will be labeled \( \text{EVT}_{\text{MDP,N}} \), and is defined as follows.

\[ \Delta \phi_{j,E}^* \equiv \min_{j=1}^N \left\{ \phi \left( \vec{P}_{T} \right) - \phi \left( \vec{P}_{j}^* \right) \right\} \] (20)

To summarize, \( \Delta \phi_{j,E}^* \) simply isolates the minimal angular separation in the transverse plane between a set of \( N \) reconstructed objects and a fixed missing energy vector. It is designed to protect against spurious indications of missing energy associated with detector mismeasurement. The user may specify a \( \text{CUT} \) on the resulting 0 to \( \pi \) radian angle, as well as index back-references for the active JET object set and the static \( \text{MET} \) vector, the latter of which will be reconstructed from the included jets if omitted. To reduce the likelihood of randomly generating a dispositively small value for \( \Delta \phi_{j,E}^* \) Concurrently with a legitimate missing energy signal, this statistic is typically computed for no more than the four hardest jets.

\[ \Delta \phi_{j,E}^*: \] The final event selector to be modeled is a CMS statistic [19] that is quite similar to the just discussed angular difference \( \Delta \phi_{j,E}^* \), but with a somewhat
more complicated implementation. This “biased” azimuthal difference \(\Delta \phi_{j,\ell}^*\), is formally defined as follows, and will be associated with the program invocation tag \texttt{EVT\_BDP\_N}.

\[
\Delta \phi_{j,\ell}^* \equiv \min_{j=1}^{N} \left\{ \left| \phi \left( \vec{P}_T + \vec{P}_j \right) - \phi \left( \vec{P}_\ell \right) \right| \right\}
\] (21)

In words, \(\Delta \phi_{j,\ell}^*\) is the minimal value of the set of \(N\) angular separations in the transverse plane between each reconstructed object’s own momentum vector and the missing transverse momentum composed from all other objects. It is expressed as an angle in radians, in the range \(0\) to \(\pi\). Intuitively, it registers whether the elongation of a single momentum vector is capable of substantially repairing an imbalance in the missing transverse momentum. If a single jet mismeasurement is indeed dominantly responsible for a false missing energy signal, then \(\Delta \phi_{j,\ell}^*\) should register close to zero. In addition to an angular \texttt{CUT} selector in radians, the user may specify index back-references for the included \texttt{JET} object set, and the baseline \texttt{MET} vector. If the latter quantity is omitted, it will be recomputed from the jet content itself. This statistic may again suffer in the case of very high jet multiplicities; given a wide selection of randomly oriented jets, it becomes quite likely that the angular orientation of at least one such member might be sufficiently well azimuthally aligned with the true missing energy track that its rescaling could apparently rebalance the event.

III. PROGRAM INVOCATION AND USAGE

A. Card File Command Syntax

All object reconstruction and event selection operations available to the \texttt{CUTLHCO} program are controlled by command lines specified in an external card file. An overview of the logic and scope of the available functionality was provided previously, in Section \texttt{(II)}. Five exemplar cards from the dozens of working selection strategies accompanying the current program distribution \texttt{[18]} are documented in the forthcoming Section \texttt{[19]}, with a line-by-line textual deconstruction of the specific command formatting and intent provided in each case. A compact yet comprehensive synopsis of the command lexicon is provided in the Appendix. The purpose of the present section is a description of the uniform aspects of the card file command syntax and grammar.

Each processing instruction is placed on its own line in the card file and begins by invoking the name of an object reconstruction (\texttt{OBJ\_ABC\_N}) or event selection (\texttt{EVT\_ABC\_N}) identifier, where \texttt{ABC} represents a three character alphabetic code unique to each command family, and \texttt{N} is an integer within the range “0” to “999”. Omission of the integer \texttt{N} and the associated trailing underscore is functionally equivalent to a selection of 0. This zeroth integer specification is generally reserved for quantities that are automatically evaluated by the program, irrespective of user input, although it may still be possible to modify the default parameter configuration in these cases through an explicit reference. However, not all input tags provide a meaningful zeroth configuration, and, conversely, not all of those tag specifications that do automatically provide for a zeroth configuration additionally support multiple numerical versioning. Any lines of input that do not begin in the manner described are disregarded as comments. Likewise, the inclusion of a “#” hash symbol at the end of a valid input line is interpreted to initiate a comment enveloping all trailing content. The order in which lines are specified in the card file is not material to the sequence in which they are ultimately evaluated; the order of program execution is instead established by the fixed operations sequence described in Section \texttt{(II)}, and within that framework, whenever there might otherwise be ambiguities, by an ascending numerical sort on the associated numerical tags.

The parameter specification input for each command line is separated from the leading identifier name by an equals sign “=”. This parameter specification consists of a list of key and value pairs, individually joined by a colon “:”, and separated from adjacent pairs by a comma “,”. Each parameter key consists of a three character alphabetic string that uniquely specifies the role of the subsequently input value. The valid parameter specifications vary according to the specific object reconstruction or event selector context of each command identifier, as detailed in the document Appendix. The order in which a given command line’s parameter specifications are provided is a matter of the user’s discretion and has no impact on the logical flow of the selection algorithms. The value assigned to each key may consist of an integer or floating point number (including signed values), the character string “\texttt{UNDEF}” (to specify an undefined or null input), or a list consisting of elements drawn from the prior classes, individually separated by commas “,”, and enclosed in square brackets “[ ... ]”. The set of value inputs that may be considered valid or useful is, again, a function of the context provided by the active parameter key. Unspecified values default to “\texttt{UNDEF}”, or if the expected input is an integer to be chosen from a predefined list of options, the value “0”. Parameters designed to accept multiple inputs will treat an isolated value as the leading list element, with all other terms undefined; likewise, there is no penalty for enclosing a single expected input in square brackets, creating a list composed of a single entry.

A frequently employed value formatting idiom is the “[\texttt{Min,Max}]” pair, used to indicate a numeric range. So long as \(\texttt{Min} \leq \texttt{Max}\), the set of matched numbers simply consists of those values inclusively bounded by the specified range. An undefined value for \texttt{Min} is treated as indefinitely small, and an undefined value for \texttt{Max} is treated as indefinitely large. If no numerically valid limits are provided, then all values match. If the upper and lower boundaries are numerically equivalent, then only that single value matches. However, a subtle ad-
ditional functionality is accessed under the circumstance that $\text{Min} > \text{Max}$. In this case, a numerical match is achieved if the comparison value is either at least as large as $\text{Min}$ or at least as small as $\text{Max}$; in other words, the interval from $\text{Max}$ up to $\text{Min}$ is rejected, exclusive of the boundaries. Often, an additional instruction flag is accepted from the third position of the described value list, which may be used to indicate various processing preferences, according to context. The availability and function of this third input, whose uses include sorting objects that match the specified range criteria, terminating object matching upon an initial failure, and clipping the count of objects satisfying some independent selection, is efficiently summarized as part of the encompassing command specification reference provided as a document Appendix.

B. Running the Program

The CutLHCO “executable” is delivered as a single PERL script named cut_lhco.pl; to be more precise, since PERL is an “interpreted” language, this file serves both as the program source document and runtime portal. A benefit of this paradigm is inherent platform independence, making the CutLHCO program ready for immediate use, without the need for installation or compilation, on any computer with a reasonably modern perl environment; this should automatically include almost all systems in current service that run a Unix/Linux flavor variant, including Mac OS X, and free installations for Windows are also readily available on the web. The detailed instructions to follow will assume a Unix styled directory structure and command line shell.

The CutLHCO distribution package is available for download from the web [18], and is delivered as a tar-gzipped file bundle. To unpack the distribution, the user should run the commands “gunzip cut_lhco.tar.gz” and “tar -xf cut_lhco.tar” in sequence from the command line. The directory from which CutLHCO is called must possess two specific subdirectories named Events/ and Cards/, which will house, respectively, the .lhco format input files and the card files controlling the application of selection cuts. These directories are created automatically upon unpacking the program distribution as described. Users of the MADGRAPH [3] simulation environment will recognize this directory structure, which is in fact appropriated to streamline integration with that framework. At the user’s discretion, the main program file may likewise be grouped with any existing scripts and executables in a common bin/ subdirectory. Execution of the script can then be as simple as entering “./cut_lhco.pl”, or “./bin/cut_lhco.pl”, at the terminal window, as the case may be; however, there are several optional command-line parameters that the user may wish to subsequently specify, which shall now be described in the sequence of their usage. Any such instructions are typed directly after invocation of the program name, separated from it and from each other by an empty space; any parameter position may be effectively skipped by providing the value “UNDEF”.

The initial parameter input is associated with the filename that one wishes to process, and it takes a default value of “data”. Any processed output will ultimately be placed into a corresponding file named “Events/filename.cut”. The referenced input file must physically exist within the Events/ directory, either as “filename.lhco” or as “filename pys_events.lhco”. However, the latter scenario actually allows for two possible points of flexibility. A group of files within Events/ that follows the specified root name with an extra underscore and a positive integer, as may be produced by the MADGRAPH [3] helper script “multi_run”, will be treated as a family of batch jobs to be merged for analysis. Also, any matching files with a trailing extension of .gz will be automatically unpacked with the gunzip utility prior to subsequent processing. Additionally, the more simply named “filename.lhco” file will be created, and filled with the appropriate merged content. The next parameter input position is associated with the cardfile governing event selection, and has a default value of “cut_card”. The referenced file must likewise exist within the Cards/ directory, as “cardfile.dat”.

The third parameter position allows the user to specify a numerical cross section in pb for the physical processes under consideration. Specifying the negative cross-section value “-1” causes the program to search for a file named “filename python.log” (or the set of integrally labeled file variants) in the Events/ directory, from which the cross section will be dynamically extracted, along with a statistic for the fragmentation cut percentage. An unrecoverable error signal is issued if the expected file (or files) are not found. If multiple records are queried, the cross section and fragmentation cut values are averaged, with equal weight assigned to each individual file. The fourth position designates a target luminosity in pb$^{-1}$ to which the surviving event count should be scaled. Since this calculation is dependent upon a known cross section, the reading of this input is skipped unless the third parameter was defined and non-zero; if required but not defined, the luminosity target is set to a default of 1.0 pb$^{-1}$. The fifth and final input, which may actually shift into the fourth position as described, represents an integer variable for controlling the output of detailed event-by-event statistics. The default value “0” suppresses this output, while “1” enables it, and “2” additionally implements a resorting of the original event sequence by the numerical value of each data column, from left to right; this sorting process may take an appreciable amount of time for large quantities of surviving events with large multiplicities of statistics.

To provide a concrete initiation example, the command “./cut_lhco.pl ttbar cut_card_LHC 79.8 4500 1” will, given placement of the main executable within the working directory, cause a file named “ttbar.lhco” (or its permissible variants) within the Events/ directory to be processed according to the selection cut strategy de-
scribed in the file “Cards/cut_card_LHC.dat”, assuming a process cross-section of 79.8 pb, with results scaled up to a sample size of 4.5 fb$^{-1}$, and all event statistics reported but not sorted.

C. Program Output and Interpretation

The output .cut file described in the prior section provides a summary report of the CutLHCO runtime environment and any actionable statistics generated from the surviving events. It opens by stating the number of .lhco files merged during the process initiation (if there were multiple inputs), the total number N of events processed, the percentage of events failing fragmentation cuts (if harvested from the PYTHIA [4] log), the source event cross section $\sigma$ in pb and associated simulation luminosity $L = N/\sigma$ in pb$^{-1}$ (if available), and the target luminosity and associated event rescaling (if non-trivial). These particulars of the operational context are followed by a presentation of key results and analysis, beginning with the all-important scaled count of events surviving the selection cut regimen. Next, the percentage of events cut during the selection is tabulated, as a unified total and also as a statement of activity for each individually defined cut; the latter set of statistics is supplemented by the percentage tally of circumstances in which each specified cut constitutes a uniquely enforced rationale for event exclusion. Each object or event command providing a value for the “CUT” selector that is not functionally equivalent to “UNDEF” will be included in this report, referenced by its unique alphabetic identification code (omitting the “OBJ_” or “EVT_” prefix) and its numerical sequencing tag.

If a detailed itemization of results was specified during the program initiation, then each surviving event will be given a line in the output that inventories its response to each defined selection cut query. This is particularly useful for tabulating histogram reports in various discovery statistics, or for partitioning the counts of events satisfying subordinate selection conditions. It may also be usefully applied to optimization of the underlying selection strategy itself, facilitating the identification of inefficiencies or knees in the event distribution, potential advantages over (or novel tools for the suppression of) background, and selection redundancies or inefficiencies. To include a given output statistic in this report without actually imposing a cut, a trivial value should be provided for the CUT selector that is still technically defined, e.g. an inclusive lower bound of “0” for an inherently positive quantity such as $P_T$. A helper script histogram.pl is provided in the main directory of the CutLHCO distribution [18] that is well suited for this analysis task. This script concurrently processes all .cut format files within the Events/ subdirectory, and place the results into a file called “histogram.txt” in the working directory.

The histogramming script accepts up to six optional space-separated parameter inputs after the primary invocation “.histogram.pl”, and again permits the usage of “UNDEF” for reversion to system defaults. The first input should be the name of the event detail column heading from the relevant .cut files that the histogram should be based upon. The default behavior is a simple single-column histogram on the net event count; although this repeats raw information already provided in the underlying report, it may still be useful for rapidly assembling the counts of multiple event samples into a unified presentation. The second input is a numerical specification for the binning width; the default value of “0” indicates a single, inclusive bin. The next two inputs numerically specify the minimum and maximum cutoff values for inclusion in the histogram; the lower boundary defaults to “0”, and the upper boundary defaults to “UNDEF”, which is interpreted to be indefinitely large. The fifth input is a integer list selector for the numerical label that should be assigned to each bin; “0” (which is the default) labels each bin by its left-most (minimum, inclusive) value, while “1” substitutes reporting of the central bin value, and “2” instead calls for the right-most (maximum, excluded) boundary value. The last parameter input is a binary flag for governing the histogram output format; the default value of “0” produces standard tab-delimited text that is suitable for passing on to spreadsheet based statistics packages, while the alternate specification of “1” will yield a file employing the array input syntax favored by MATHEMATICA.

Additional helper scripts for interpreting the statistics of surviving groups of events and for automating the generation of supervisory shell scripts to shepherd the processing of large batches of parallel analyses are available to interested parties upon personal request. No public documentation currently exists for these tools, although the curious are welcome to explore and modify any provided code for adaptation to their own purposes, under the same terms [12] as the rest of the package. In general, the author is quite open to private inquiries, suggestions, and requests for support by potential CutLHCO users on any topic regarding application of this software to the physics analysis of collider data selection cuts.

IV. CARD FILE CASE STUDIES

The most efficient way to communicate a working vocabulary of CutLHCO commands to the potential user is probably by direct example. The general syntax tutorial from Section [11], along with the summary of available parameters in the document Appendix, are thus supplemented in the present section by five specific case studies of card files designed for the replication of actual LHC SUSY searches, three from the CMS collaboration, and two from ATLAS. The coded instruction sets are are transcribed in Typewriter font within individually boxed panels, and a line-by-line deconstruction of the event selection intent accompanies each such inset. A growing library of several dozens of additional LHC search card
files is provided along with the online program distribution package [13]. Users who create interesting new search cards are encouraged to submit them to the author for inclusion with future releases.

A. CMS Hadronic Multijet Search

The first card file scenario to be documented here represents a search by the CMS collaboration for SUSY signals in purely Hadronic multijet events [19, 35]. The procedure specified in the two CMS references differs in various minor details, and the provided card file thus represents something of a hybrid treatment. Following a point of some persistent interest to the author’s research collaboration [13, 14], a high jet multiplicity threshold requirement is enforced by the current card that does not appear in the original CMS sources. This example likewise omits a cut on the \( \alpha^{2j}_{\text{J}} \) statistic of Eq. (19), in keeping with the previously described difficulties facing application of that measure to extreme multijet content. The resulting selection is appropriate, for example, for comparison against the data plotted in Figure 1b of Ref. [33], which shows the event distribution per jet count, up to a maximum of 12, prior to application of the \( \alpha_{\text{J}} \) filter.

The object reconstruction begins in line (5) by discarding events that possess photons meeting a 25 GeV minimal threshold on the transverse momentum \( P_T \). Likewise, events with either electrons or muons carrying a \( P_T \) at or above 10 GeV are subsequently eliminated. The remaining object specifications are dedicated to the partitioning of hadronic jets. Line (8) prescribes a soft zeroth order cut of \( P_T \geq 30 \text{ GeV} \) on the transverse momentum of jets described in the input .\( \text{theo} \) event, which will be inherited by all subsequent groupings. A first positively indexed partition, sourced from the prior zeroth order designation, is created from the jet object subset possessing a harder transverse momentum selection of \( P_T \geq 50 \text{ GeV} \), and events are rejected that do not possess at least 9 such jets. A second subdivision further requires the presence of at least two leading hard jets with \( P_T \geq 100 \text{ GeV} \). The third jet reconstruction index extends this sequential processing of the object chain to require a pseudo-rapidity magnitude \( |\eta| \leq 2.5 \) for the leading jet; activation of the third position “stop” flag within the PRM parameter forces the clustering of objects to terminate upon the first selection failure (in descending \( P_T \) order), guaranteeing that a non-zero final count does indeed include the single hardest jet. The final two groupings in lines (12,13) are sourced retroactively from the previously defined \( P_T \geq 50 \text{ GeV} \) set in line (9), and further isolate jets with a pseudo-rapidity \( |\eta| \geq 3.0 \) or an electromagnetic fraction \( \xi \geq 0.9 \), rejecting the event as a whole if any such surviving objects are identified.

The event selection opens in lines (15,16) with missing transverse energy definitions for two source populations consisting, in turn, of all soft \( P_T \geq 30 \text{ GeV} \) jets and the harder \( P_T \geq 50 \text{ GeV} \) subset. The latter of these groupings, which is guaranteed from before to possess at least 9 objects with satisfactory \( \eta \) and \( \xi \) values, must yield a missing energy of at least 100 GeV for the event to continue. Subsequently, the same set of harder jets is checked for its scalar transverse momentum sum \( H_T \), where a minimal value of 375 GeV is required. Finally, an upper bound on the ratio of hard-to-soft jet missing energies \( (E^\text{hard}_T/E^\text{soft}_T) \leq 1.25 \) is imposed. If one wishes to reinstate the CMS \( \alpha^{2j}_{\text{J}} \geq 0.55 \) selection, this is easily accomplished by addition of the line “\( \text{EVT_ALL}=\text{JET}:001, \text{CUT:}:0.55 \)”.

B. ATLAS Hadronic Multijet Search

The second card file example to be presented represents a parallel search by the ATLAS collaboration for SUSY signals in purely Hadronic multijet events [38]. The specific selection strategy to be documented is referred to as “7j80”, in reference to the required jet count and transverse momentum per jet. Though targeting an essentially identical event profile to that just described, the mechanism of the adopted selections is distinct.
The object specification begins in line (5) with a global restriction on the pseudo-rapidity magnitude $|\eta| \leq 4.5$ that will be enforced on all subsequently inherited objects. The light lepton (electron, muon) populations are then filtered according to transverse momentum $P_T \geq (20,10)$ GeV and pseudo-rapidity $|\eta| \leq (2.47,2.40)$. Likewise, the zeroth jet classification is restricted to the object subset with $P_T \geq 20$ GeV and $|\eta| \leq 2.8$. In line (9) a lepton reconstruction is sourced from the individual merged lepton flavors, and filtered specifically to contain only electrons. The inherited jet object set is then compared against the prior electron grouping for angular proximity, and only those jets that are isolated by $\Delta R > 0.2$ radians from the nearest electron are retained. Next, a fresh assembly of leptons is gathered in line (11) that specifically exempts tau flavor content. It is evaluated for angular proximity against all jets surviving the filter defined previously in line (10), and the event is discarded as a whole if any well isolated leptons, having $\Delta R \geq 0.4$ with respect to all jets, persist. An intermediate transverse momentum cut of $P_T \geq 40$ GeV is then applied to the continued jets. Immediately following is a further hard classification of $P_T \geq 80$ GeV, which must be survived by at least 7 jets for the event to proceed.

The event selection phase initiated in line (15) is rather compact, firstly defining a scalar transverse momentum sum $H_T^{jets}$ for the intermediate jet classification, and secondly enforcing a relative significance boundary of $E_T^{all}/\sqrt{|H_T^{jets}|} \geq 4 \text{ GeV}^{1/2}$ on the missing transverse energy $E_T^{all}$ computed from all objects that were consistent with the primary pseudo-rapidity filter.

C. CMS Dilepton and B-Tagged Jet Search

The next selection card deconstruction confronts an intricate CMS search strategy formulated around the invariant mass of a same-sign, any-flavor dilepton pair, and requiring the presence of jets with heavy flavor tagging [39]. In particular, the example documents a region of the selection space referred to as “SRI”.

The object reconstruction begins in line (5) by dismissing electrons that are located within an angular dead region at the CMS barrel-endcap calorimeter seam corresponding to the pseudo-rapidity magnitude $1.422 < |\eta| < 1.566$ range. Next, there is a specification of the zeroth lepton object set that rejects intrusion by the tau, and places outer limits on the light flavor transverse momentum $P_T \geq 10$ GeV and pseudo-rapidity $|\eta| \leq 2.4$. Likewise, the zeroth jet classification, for which surviving events must provide at least two matching objects, is bounded by $P_T \geq 40$ GeV and $|\eta| \leq 2.5$. In lines (8,9) a pair of signed lepton groupings is sourced from the established zeroth order set, one entirely positive and one entirely negative, each of which caps the transverse momentum at $P_T \leq 20$ GeV. Three additional lepton partitions are then recursively defined by the selective veto of candidates from the zeroth sourcing pool that also appear within one or either of the signed intermediate $P_T$ pairs; the result is a group of softer negative $P_T \geq 10$ GeV leptons mixed with harder positive $P_T > 20$ GeV leptons, a similar group with precisely the reversed charge versus transverse momentum relationship, and a group of mixed sign leptons that all respect the harder $P_T > 20$ GeV classification. A single indexed jet partition is reduced from the zeroth classification in line (13) by specifying a loose selector on the heavy flavor tag, and events without at least 2 such tagged jets are are cut. The final three object reconstructions are of the dilepton variety. The first two reject events containing an opposite-sign same-flavor dilepton configuration that yields an invariant mass $M_{\ell,\ell}$, as in Eq. (8), within 15 GeV of $M_Z \simeq 91$ GeV, if at least one member of the pair is of the harder $P_T > 20$ GeV object variety. The final object specification line requires the presence of at least 1 same-sign any-flavor dilepton pair with an invariant mass $M_{\ell,\ell} \geq 8$ GeV, where each lepton is above the individual $P_T > 20$ GeV threshold.

The event selection phase prescribed in lines (18,19) is quite straightforward, consisting of a cut $E_T^{all} \geq 30$ GeV on the missing energy composed from all primary event objects, and a cut $H_T^{jets} \geq 80$ GeV on the scalar transverse momentum sum for the zeroth assembly of jets.

D. ATLAS Jets and Isolated Lepton Search

The second ATLAS collaboration card file scenario to be documented represents a multi-level selection employed to search for SUSY in final states with jets, missing transverse momentum, and a single isolated lepton [21]. An important role is played in this procedure by the transverse mass statistic of Eq. (15). The example provided corresponds specifically to the 3-jet selection sub-strategy. Most ATLAS SUSY searches share a common core of generic low-level object reconstruction filters, and the present card file specification does indeed bear several initial structural similarities to that featured in the previous ATLAS case study.
The object reconstruction begins in line (5) by enforcing a primary upper limit on the pseudo-rapidity magnitude |η| ≤ 4.9 of all input objects. The light lepton (electron, muon) populations are then filtered according to transverse momentum $P_T \geq 10$ GeV and pseudo-rapidity |η| ≤ (2.47, 2.40). In the next pair of lines a slightly harder variant of each of these two distinct lepton flavor populations is indexed relative to the implicit zeroth lepton composite, raising the lower limits on transverse momentum to 25 GeV and 20 GeV, respectively. An initial jet classification in line (10) is likewise sourced from its corresponding inclusive zeroth grouping, enforcing $P_T \geq 20$ GeV and |η| ≤ 4.5 limits, and rejecting objects that are poorly isolated ($\Delta R < 0.2$ radians) from members of the preceding electronic lepton partition defined in line (8). The electron and muon forks are subsequently rejoined into a unified object source for the next instruction line, which filters against a minimal isolation requirement of $\Delta R \geq 0.4$ radians from elements of the just established jet reconstruction, and rejects events that do not afford 1, and only 1, compliant object. After this, a slightly harder and substantially more central jet partition is sourced from its direct numerical predecessor, with $P_T \geq 25$ GeV and |η| ≤ 2.5 limits, requiring a minimum of three such jets for event continuation. Line (13) marks a final return to the leptonic analysis, prescribing a cut on events where any non-tau flavored object from the zeroth classification proved too soft, forward or poorly isolated to pass through the remainder of the described selection cascade. The last three object reconstruction commands are additional jet assembly protocols. Picking up where the prior jet selection left off, the first of these lines imposes a redundant lower bound of 3 on the surviving jet content, but sets a value of “-4” for the third position “clip” input to the CUT parameter, which prevents any jets beyond the minimally required count from appearing within the indexed object partition. The next instruction, which rejects events possessing more than 3 hard jets with $P_T \geq 80$ GeV, returns for its sourcing to the classification defined in line (12) rather than perpetuating the sequential filtering pattern; this discontinuity is essential, given that the immediately prior classification was capped at a 3 jet maximum. Resuming a stepwise object flow, the final jet specification requires the event to contain at least 1 jet meeting the $P_T \geq 100$ GeV threshold.

The event selection phase opens in line (18) by placing a lower bound on the inclusive missing energy $E_T^{miss} \geq 250$ GeV. Next, an indexed scalar transverse energy sum specification $H_T^{3\text{jet}}$ is created from back-references to the single surviving lepton and the capped partition of 3 jets, as defined in lines (11,14), respectively. Likewise, an indexed effective mass $M_{T2}^{eff}$ specification is established as a sum of the prior two quantities. Subsequently, a limit $E_T^{miss}/(E_T^{miss} + H_T^{3\text{jet}}) ≥ 0.3$ is placed on the corresponding missing energy to effective mass ratio. Proceeding on, a cut $M_{T2}^{eff} \geq 100$ GeV is instituted in line (22) on the transverse mass composed from the isolated lepton and the event missing momentum vector. In the next-to-final instruction, a more inclusive transverse energy sum $H_T^{4\text{jet}}$ is defined that incorporates the lepton and all jets (not only the leading 3) within the $P_T \geq 25$ GeV and |η| ≤ 2.5 reconstruction from line (12). Finally, a lower bound is imposed on the effective mass $(E_T^{miss} + H_T^{4\text{jet}}) ≥ 1.200$ GeV formed by combining the previous scalar sum with the event missing energy.

E. CMS Razor Variable Supersymmetry Search

The last card file scenario to be documented corresponds to a CMS search for SUSY using the razor variables [31][32]. Additional information on the active lepton reconstruction strategy and isolation requirements may be found in Ref. [20]. The selection strategy to
be highlighted hierarchically divides the harvested event content into one of several “boxes” according to the lepton (or dilepton) flavor content, or the lack thereof. To keep the various groupings disjoint, events satisfying the requirements of multiple boxes are uniquely sequenced upon their first match against an ordered sequence of clustered selection criteria. Conversely, the assignment of an event into one of the latter classification stages requires demonstrating that none of the prior available box qualifications were successfully matched. In general, each box will possess multiple positive attributes that must all be satisfied for inclusion of the event; therefore, a negation of this inclusion is facilitated by falsifying any single member of the composite list of properties. The required logic may be implemented within the card file description by application of the ANY parameter to link related filters.

The example provided corresponds specifically to signal region 6 of the single isolated electron box from Ref. [32]. The object reconstruction begins in line (5) with the exclusion of electrons located within the pseudorapidity range corresponding to the barrel-endcap detector gap. Next, muons are required to be contained within $|\eta| \leq 2.4$, and a combined electron-muon lepton classification is composed with transverse momentum $P_T \geq 10$ GeV and the slightly weaker pseudorapidity limit of $|\eta| \leq 2.5$. Similarly, the zeroth jet classification is defined with $P_T \geq 60$ GeV and $|\eta| \leq 3.0$. In lines (9-11) the electron and muon objects are reseparated, and a tightened muon object grouping is instantiated with an explicit bound on the transverse momentum isolation ratio $\zeta \leq 0.27$ and a more central track orientation $|\eta| \leq 2.1$. Lines (12,13) are the first content negation grouping to be tethered by the ANY keyword. The two members of this construct are actually made redundant by subsequent instructions, and, although their content is retained for pedagogical purposes, the leading comment markers # will suppress interpretation of the associated commands. In concert, events would be retained by this pair of instructions that lacked either a tight muon with $P_T \geq 12$ GeV or a hard electron with $P_T \geq 20$ GeV, both of which are mandated by the first box definition. The next three lines similarly retain events disqualified from inclusion in the second box, which is defined by the presence of at least one tight muon, at least one harder muon with $P_T \geq 15$ GeV, and at least two muons overall. Lines (17,18), one of which is again duplicative, would act collectively to exclude events that lack either a single electron with $P_T \geq 20$ GeV or two electrons overall. Line (19) constitutes a negation of the fourth lepton box criterion, namely the presence of at least one tight muon with $P_T \geq 12$ GeV. Since this is a precise duplication of line (12), which is logically coupled to line (13), there is no need to explicitly execute either of the prior tests. The final object reconstruction command grants otherwise successful events admission into the fifth leptonic box according to the presence of at least one hard electron with $P_T \geq 20$ GeV. Surviving objects will thus necessarily fail the test embodied in line (17), which may consequently be omitted from its cluster. The same holds true for line (13), although its action was already blocked for independent reasons.

The event selection phase prescribed in lines (22,23) of this card is quite simple, isolating a rectangular area of the razor plane with $450$ GeV $\leq M_{R}^{j,j} \leq 1000$ GeV and $0.30 \leq R_{j,j}^{L} \leq 0.50$ that is sourced from the inclusive missing transverse energy and the full retained classifications of leptons and jets.

V. AFTERWORD

A new computer program named CutLHCO has been introduced, whose function is the implementation of generic data selection cuts on collider event specification files in the standardized .lhco format. This software is intended to fill an open market niche for a lightweight yet flexible “consumer-level” alternative to the ROOT [10] data analysis framework. The primary envisioned application is as a filter on output produced by the PGS4 [9] and DELPHES [8] detector simulations, which are themselves lightweight alternatives to the GEANT4 [7] based solutions favored by the large LHC experiments. All process control instructions are provided via a compact and powerful card file input syntax that efficiently facilitates the reasonable approximation of most event selection strategies and specialized discovery statistics commonly employed by the CMS and ATLAS collaborations. The structure, function, invocation and usage of the most recent CutLHCO 2.0 program version has been documented thoroughly, including a detailed deconstruction of several example card file specifications. The associated software is now available for free public download [18].

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Appendix: Card File Specification Synopsis

********* Event Selection **********************

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