AEACuS: A Tool for Implementing Generic Data Selection Cuts

Joel W. Walker
Sam Houston State University

Introduction: In this document, operation and functionality of the fully-featured selection cut software package AEACuS (formerly developed as CutLHCO [1, 2]) will be demonstrated in the context of two real-world physics studies pioneered by the ATLAS and CMS experimental collaborations. The purpose of this program, which has been freely released into the public domain under the terms of the GNU General Public License [3], is the implementation of generic data selection cuts on Monte-Carlo collider-detector simulated event specification files in the standardized *.lhco* format. The program name, as with Delphes [4] or Pythia [5], references an element of Greek myth that runs thematically parallel to the program's function — the judges Minos, Rhadamanthus and Aeacus, sons of Zeus, are said in this tradition to weigh the fate of souls departing the mortal sphere. It is also an acronym, standing for Algorithmic Event Arbiter and CUt Selector. The full AEACuS 3.2 distribution (consisting of the main processing script, some instructions for running cuts, a reference test case, and card files describing many dozens of active LHC search channels) is available for download from the author's personal website [2]. A more traditional, though somewhat out of date (certain new functionality is omitted, and a few keywords have been reassigned) user's guide is available at the *arXiv.org* [1] repository.

Selection cuts are most often implemented by the major detector collaborations within the Root [6] data analysis framework. However, it would appear that there remains room within the Monte Carlo collider-detector simulation ecology for development of light-weight consumer-level event selection tools that embody the analogous role with respect to Root [6] that PGS4 [7] and Delphes [4] play with respect to Geant4 [8]. In particular, high energy theorists and phenomenologists, who operate with much smaller reserves of human and computational resources than the major experimental collaborations, but who are likewise able to tolerate certain analytical approximations that may be unacceptable in the experimental context, frequently have need to (*i*) test a preferred toy model against current experimental results, or (*ii*) optimize the suggested selection cut regime for discovery of a given toy model signature; It is essential that these functions be performed with great speed and efficiency, while also maintaining reasonable precision and accuracy. Parallel efforts to fill this operational niche include the MadAnalysis5 [9] package available for integration with the MadGraph [10] software family, and Mathematica notebook based solutions such as the original Chameleon [11] package and various extensions based upon it. A key advantage of the AEACuS platform is the extreme ease with which it may be integrated into any standard Unix-based analysis installation — in fact, it is designed to seamlessly attach to the end of the standard MadGraph, MadEvent, Pythia, PGS4/Delphes chain. The AEACuS program consists of a single Perl script, which references no external libraries, and is fully self-contained. No installation procedure is necessary, as Perl is an interpreted language. The executable source code, along with support directories for holding control cards, input *.lhco* event files, and output event statistics, are simply placed into a suitable location on the host file system, and are then immediately deployable.

The processing of an input event begins with an "object reconstruction" phase that is designed to enforce minimum data quality characteristics for groups of leptons and jets, in terms of characteristics including their kinematics, geometry, isolation and proximity to other objects, multiplicity, flavor tagging, and charge. Dileptons may be grouped by like/unlike sign and/or flavor, jet topologies associated with the vector boson fusion event topology may be identified, and groups of jets may be reclustered according to the KT, Cambridge/Aachen, or Anti-KT prescriptions. Classified particle groups may be subsequently dereferenced by a numerical identifier during the program's

```
1  ****** cut_card.dat 3.0 ******
2  * ATLAS Jets and Lepton (3J1L)
3  * ATLAS-CONF-2012-041
4  *** Object Reconstruction ****
5  OBJ_ALL = PRM:[0.0,4.9]
6  OBJ_ELE = PTM:10, PRM:[0.0,2.47]
7  OBJ_MUO = PTM:10, PRM:[0.0,2.4]
8  OBJ_LEP_001 = SRC:+000, EMT:+1, PTM:25
9  OBJ_LEP_002 = SRC:+000, EMT:+2, PTM:20
10 OBJ_JET_002 = SRC:+000, CMP:+001, PTM:20, PRM:[0.0,4.5], CDR:0.2
11 OBJ_LEP_003 = SRC:[+001,+002], CMP:+002, CDR:0.4, CUT:[1,1]
12 OBJ_JET_003 = SRC:+002, PTM:25, PRM:[0.0,2.5], CUT:3
13 OBJ_LEP_004 = SRC:[+000,-003], EMT:-3, CUT:[0,0]
14 OBJ_JET_004 = SRC:+003, CUT:[3,UNDEF,-1]
15 OBJ_JET_005 = SRC:+003, PTM:80, CUT:[0,3]
16 OBJ_JET_006 = SRC:+005, PTM:100, CUT:1
17 ****** Event Selection *******
18 EVT_MET = CUT:250
19 EVT_MHT_001 = LEP:003, JET:004
20 EVT_MEF_001 = MET:000, MHT:001
21 EVT_REF_001 = NUM:000, DEN:001, CUT:0.3
22 EVT_LTM_001 = LEP:003, MET:000, CUT:100
23 EVT_MHT_002 = LEP:003, JET:003
24 EVT_MEF_002 = MET:000, MHT:002, CUT:1200
25 ******************************
```

```
1  ****** cut_card.dat 3.0 ******
2  * CMS Razor ELE Box (SR6)
3  * CMS PAS SUS-12-005
4  *** Object Reconstruction ****
5  OBJ_ELE = PRM:[1.566,1.422]
6  OBJ_MUO = PRM:[0.0,2.4]
7  OBJ_LEP = EMT:-3, PTM:10, PRM:[0.0,2.5]
8  OBJ_JET = PTM:60, PRM:[0.0,3.0]
9  OBJ_LEP_001 = SRC:+000, EMT:+1
10 OBJ_LEP_002 = SRC:+000, EMT:+2
11 OBJ_LEP_003 = SRC:+002, ETR:[0.00,0.27], PRM:[0.0,2.1]
12 # OBJ_LEP_004 = SRC:+003, PTM:12, CUT:[0,0]
13 # OBJ_LEP_005 = SRC:+001, PTM:20, CUT:[0,0], ANY:004
14 OBJ_LEP_006 = SRC:+003, CUT:[0,0]
15 OBJ_LEP_007 = SRC:+002, PTM:15, CUT:[0,0]
16 OBJ_LEP_008 = SRC:+002, CUT:[0,1], ANY:[006,007]
17 # OBJ_LEP_009 = SRC:+001, PTM:20, CUT:[0,0]
18 OBJ_LEP_010 = SRC:+001, CUT:[0,1], ANY:009
19 OBJ_LEP_011 = SRC:+003, PTM:12, CUT:[0,0]
20 OBJ_LEP_012 = SRC:+001, PTM:20, CUT:1
21 ****** Event Selection *******
22 EVT_JRM_001 = LEP:000, JET:000, CUT:[450,1000]
23 EVT_ALR_001 = LEP:000, JET:000, MET:000, CUT:[0.30,0.50]
24 ******************************
```

FIG. 1: ATLAS Jets and Isolated Lepton Search [12] & CMS Razor Variable SUSY Search [28, 29]

event selection phase, for testing against various discovery statistics designed to isolate new physics. Analysis continues with a second "event selection" processing phase, which is dedicated to isolating global signatures of new physics that may become apparent when the event is contemplated as a unified entity. 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. Available options include all of the standard dimensionful transverse statistics, namely the missing transverse energy $\not{E}_{\rm T}$, the scalar transverse energy sum $H_{\rm T}$, and the transverse effective mass $M_{\rm T}^{\rm eff}$, as well as common rational and difference signal discriminants, such as $(\not{E}_{\rm T}^{\rm A}/\not{E}_{\rm T}^{\rm B})$, $(\not{E}_{\rm T}^{\rm A}/\sqrt{[H_{\rm T}^{\rm B}]})$, $(\not{E}_{\rm T}^{\rm A}/M_{\rm T}^{\rm eff\,B})$, and $|\vec{\not{P}}_{\rm T}^{\rm B} - \vec{\not{P}}_{\rm T}^{\rm A}|$. A number of specialized discovery statistics employed by CMS and ATLAS are likewise replicated, including the transverse mass $M_{\rm T}^{\ell,\not{E}}$ [12–15], $M_{\rm T2}^{j,j}$ (the "s-transverse mass") [16, 17] with Lund hemisphere reconstruction [5, 18], and its asymmetric one- and two-step variants $\widetilde{M}_{\rm T2}$ with associated handling of combinatorics [19–24], the tri-jet invariant mass M_{jjj} [19, 25, 26], the jet and dilepton-Z transverse energy balance $\Delta E_{\rm T}^{j,\ell\ell}$ [27], the razor variables $M_{\rm TR}$ and $M_{\rm R}$ and their dimensionless squared ratio $\alpha_{\rm R}$ [28–30], the $\alpha_{\rm T}$ ratio [31–34], the angular difference $\Delta\phi_{j,\not{E}}$ [35], the "biased" azimuthal difference $\Delta\phi^{*}_{j,\not{E}}$ [32], the lepton W-projection $L_{\rm P}$ [15, 36, 37], and the transverse thrust $T_{\perp}$, thrust minor $T_{\rm M}$, transverse sphericity $S_{\perp}$, transverse sphere$O$city $S_{\widetilde{\perp}}$, and F-parameter event shape variables [38–44].

Unified Control Language: The described generality of function is must be made accessible by a highly adaptable, uniform, intuitive, and extremely simple control interface. A vital element of the AEACuS package is the meta language invented to compactly deliver processing instructions via a single input card file. A pair of example card files are presented in FIG 1, which respectively model an ATLAS SUSY search in the jets plus isolated lepton signature [12], and a CMS SUSY search employing the Razor variables [28, 29].

The first card exhibited in FIG 1 corresponds to a multi-level selection employed by the ATLAS collaboration to search for SUSY in final states with jets, missing transverse momentum, and a single isolated lepton [12]. Object reconstruction begins in line (5) by enforcing a primary upper limit on the pseudo-rapidity magnitude $|\eta| \leq 4.9$ of all input objects. The light lepton (electron,muon) populations are then filtered according to transverse momentum $P_{\rm T} \geq 10$ GeV and pseudo-rapidity $|\eta| \leq (2.47, 2.40)$. 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 $P_{\rm T} \geq 20$ GeV and $|\eta| \leq 4.5$ 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 $P_{\rm T} \geq 25$ GeV and $|\eta| \leq 2.5$ 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 "`-1`" 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 $P_{\rm T} \geq 80$ 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 $P_{\rm T} \geq 100$ GeV threshold. Event selection begins in line (18) by placing a lower bound on the inclusive missing energy $\not\!\!E_{\rm T}^{\rm all} \geq 250$ GeV. Next, an indexed scalar transverse energy sum specification $H_{\rm T}^{\ell,3{\rm jet}}$ 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 $M_{\rm T}^{\rm eff}$ specification is established as a sum of the prior two quantities. Subsequently, a limit $\not\!\!E_{\rm T}^{\rm all}/(\not\!\!E_{\rm T}^{\rm all} + H_{\rm T}^{\ell,3{\rm jet}}) \geq 0.3$ is placed on the corresponding missing energy to effective mass ratio. Proceeding, a cut $M_{\rm T}^{\ell,\not E} \geq 100$ 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 $H_{\rm T}^{\ell,{\rm jets}}$ is defined that incorporates the lepton and all jets (not only the leading 3) within the $P_{\rm T} \geq 25$ GeV and $|\eta| \leq 2.5$ reconstruction from line (12). Finally, a lower bound is imposed on the effective mass $(\not\!\!E_{\rm T}^{\rm all} + H_{\rm T}^{\ell,{\rm jets}}) \geq 1,200$ GeV formed by combining the previous scalar sum with the event missing energy.

The second card exhibited in FIG 1 corresponds to a CMS search for SUSY using the Razor variables [28, 29]; Additional information on the active lepton reconstruction strategy and isolation requirements may be found in Ref. [45]. This selection strategy hierarchically divides the 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 sequestered 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. [29]. Object reconstruction begins in line (5) with the exclusion of electrons located within the pseudo-rapidity 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 pseudo-rapidity 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 $450 \text{ GeV} \leq M_R^{j,j} \leq 1000$ GeV and $0.30 \leq \alpha_R^{j,j} \leq 0.50$ that is sourced from the inclusive missing transverse energy and the full retained classifications of leptons and jets.

Afterword: It is suggested that the AEACuS card file language represents an ideal mechanism for the CMS and ATLAS collaborations (as well as smaller phenomenology groups), either in print or as ancillary electronic content, to compactly and unambiguously communicate a reasonably approximated rendering of their internally applied data selection cuts to the broader community of high energy physicists, facilitating the rapid, uniform, and reproducible reinterpretation of experimental (or Monte Carlo) results in the context of a wide variety of specific models of new physics. It is emphasized that the AEACuS control meta language specification, and the promise of bringing automation to parallel analyses, may be entirely decoupled, both conceptually and physically, from the correspondingly named software for implementation of selection cuts on *.lhco* Monte Carlo collider-detector event files.

References Cited

[1] J. W. Walker, "CutLHCO: A Consumer-Level Tool for Implementing Generic Collider Data Selection Cuts in the Search for New Physics," (2012), Accepted to Computer Physics Communications D, pending minor revision, 1207.3383.

[2] J. W. Walker, "AEACuS 3.2," (2014), URL `http://www.joelwalker.net/code/aeacus.tar.gz`.

[3] "GNU General Public License, Version 3," (2007), URL `http://www.gnu.org/licenses/gpl.html`.

[4] S. Ovyn, X. Rouby, and V. Lemaitre, "DELPHES, a framework for fast simulation of a generic collider experiment," (2009), 0903.2225.

[5] T. Sjostrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 Physics and Manual," JHEP **05**, 026 (2006), hep-ph/0603175.

[6] R. Brun and F. Rademakers, "ROOT: An object oriented data analysis framework," Nucl.Instrum.Meth. **A389**, 81 (1997).

[7] J. Conway et al., "PGS4: Pretty Good (Detector) Simulation," (2009), URL http://www.physics.ucdavis.edu/~conway/research/.
[8] S. Agostinelli et al. (GEANT4), "GEANT4: A Simulation toolkit," Nucl.Instrum.Meth. **A506**, 250 (2003).
[9] E. Conte, B. Fuks, and G. Serret, "MadAnalysis 5, a user-friendly framework for collider phenomenology," (2012), 1206.1599.
[10] J. Alwall et al., "MadGraph/MadEvent v4: The New Web Generation," JHEP **09**, 028 (2007), 0706.2334.
[11] "LHC Olympics Wiki," (2007), URL http://www.jthaler.net/olympicswiki/.
[12] ATLAS, "Further search for supersymmetry at $\sqrt{s} = 7$ TeV in final states with jets, missing transverse momentum and one isolated lepton," (2012), ATLAS-CONF-2012-041.
[13] "Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in final states with missing transverse momentum, b-jets and one lepton with the ATLAS detector," (2011), ATLAS-CONF-2011-130.
[14] G. Aad et al. (ATLAS Collaboration), "Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in $\sqrt{s} = 7$ TeV pp collisions using 1 fb^{-1} of ATLAS data," Phys.Rev. **D85**, 012006 (2012), 1109.6606.
[15] "Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in events with a single lepton, jets, and missing transverse momentum," (2011), CMS PAS SUS-11-015.
[16] "Search for Supersymmetry in hadronic Final states using M_{T2} with the CMS detector at $\sqrt{s} = 7$ TeV," (2012), CMS PAS SUS-12-002.
[17] C. Lester and D. Summers, "Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders," Phys.Lett. **B463**, 99 (1999), hep-ph/9906349.
[18] G. Bayatian et al. (CMS Collaboration), "CMS technical design report, volume II: Physics performance," J.Phys.G **G34**, 995 (2007).
[19] "Search for direct top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions using 21 fb^{-1} of ATLAS data," (2013), ATLAS-CONF-2013-037.
[20] H.-C. Cheng and Z. Han, "Minimal Kinematic Constraints and m_{T2}," JHEP **0812**, 063 (2008), 0810.5178.
[21] A. J. Barr, B. Gripaios, and C. G. Lester, "Transverse masses and kinematic constraints: from the boundary to the crease," JHEP **0911**, 096 (2009), 0908.3779.
[22] P. Konar, K. Kong, K. T. Matchev, and M. Park, "Dark Matter Particle Spectroscopy at the LHC: Generalizing M_{T2} to Asymmetric Event Topologies," JHEP **1004**, 086 (2010), 0911.4126.
[23] Y. Bai, H.-C. Cheng, J. Gallicchio, and J. Gu, "Stop the Top Background of the Stop Search," JHEP **1207**, 110 (2012), 1203.4813.
[24] Y. Bai, H.-C. Cheng, J. Gallicchio, and J. Gu, "A Toolkit of the Stop Search via the Chargino Decay," (2013), 1304.3148.
[25] "Search for direct top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 7$ TeV pp collisions using 4.7 fb^{-1} of ATLAS data," (2012), ATLAS-CONF-2012-073.
[26] "Search for direct top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions using 13.0 fb^{-1} of ATLAS data," (2012), ATLAS-CONF-2012-166, URL http://cdsweb.cern.ch.
[27] S. Chatrchyan et al. (CMS Collaboration), "Search for physics beyond the standard model in events with a Z boson, jets, and missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV," Phys. Lett. B **716**, 260 (2012), 1204.3774.
[28] S. Chatrchyan et al. (CMS Collaboration), "Inclusive search for squarks and gluinos in pp collisions at $\sqrt{s} = 7$ TeV," (2011), 1107.1279.
[29] "Search for Supersymmetry with the Razor Variables," (2012), CMS PAS SUS-12-005.
[30] C. Rogan, "Kinematical variables towards new dynamics at the LHC," (2010), 1006.2727.
[31] "SUSY searches with dijet events," (2008), CMS PAS SUS-08-005.
[32] "Search strategy for exclusive multi-jet events from supersymmetry at CMS," (2009), CMS PAS SUS-09-001.
[33] "Search for supersymmetry in all-hadronic events with $\alpha_{\rm T}$," (2011), CMS PAS SUS-11-003.
[34] L. Randall and D. Tucker-Smith, "Dijet Searches for Supersymmetry at the LHC," Phys.Rev.Lett. **101**,

221803 (2008), 0806.1049.

[35] "Search for squarks and gluinos with the ATLAS detector using final states with jets and missing transverse momentum and 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV proton-proton collision data," (2012), ATLAS-CONF-2012-033, 1208.0949.

[36] S. Chatrchyan et al. (CMS Collaboration), "Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC," Phys.Rev.Lett. **107**, 021802 (2011), 1104.3829.

[37] "Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in events with a single lepton, jets, and missing transverse momentum," (2012), CMS PAS SUS-12-010.

[38] G. Aad et al. (ATLAS Collaboration), "Measurement of event shapes at large momentum transfer with the ATLAS detector in *pp* collisions at $\sqrt{s} = 7$ TeV," Eur.Phys.J. **C72**, 2211 (2012), 1206.2135.

[39] G. Aad et al. (ATLAS Collaboration), "Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector," Phys.Rev. **D88**, 032004 (2013), 1207.6915.

[40] V. Khachatryan et al. (CMS Collaboration), "First Measurement of Hadronic Event Shapes in *pp* Collisions at $\sqrt{(s)} = 7$ TeV," Phys.Lett. **B699**, 48 (2011), 1102.0068.

[41] A. Banfi, G. P. Salam, and G. Zanderighi, "Resummed event shapes at hadron - hadron colliders," JHEP **0408**, 062 (2004), hep-ph/0407287.

[42] A. Banfi, G. P. Salam, and G. Zanderighi, "Phenomenology of event shapes at hadron colliders," JHEP **1006**, 038 (2010), 1001.4082.

[43] M. Guchait and D. Sengupta, "Searches for Supersymmetry at the LHC with 7 TeV energy," (2011), 1102.4785.

[44] R. M. Chatterjee, M. Guchait, and D. Sengupta, "Probing Supersymmetry using Event Shape variables at 8 TeV LHC," Phys.Rev. **D86**, 075014 (2012), 1206.5770.

[45] "Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV," (2010), CMS PAS EWK-10-002.