Automating Boosted Decision Tree Analyses With

MInOS

(Machine Intelligent Optimization of Significance)

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Pheno 2021
May 24-26
PITT PACC / Zoom

TM

Please See Physics Application Talk by Students Alyssa Horne and Marcus Snedecker on 5/25

What is MInOS?

- MInOS is 3rd in a trilogy of tools for automated collider analyses
- AEACuS computes statistics, applies cuts, and sorts channels
- RHADAMANTHUS generates 1- and 2-dimensional histograms
- All play nicely with MadGraph/MadEvent, Pythia, & Delphes
- Control is provided by simple reusable card files
- Installation is trivial (Perl/Python) with minimal dependencies
- Download today with quick-start examples:
  - `https://github.com/joelwwalker/AEACuS`

What does MInOS do?

- MInOS automates BDT Machine Learning in a Collider Context
- It reads event features computed by AEACuS
- It correctly combines distinct / over-sampled MC by cross section
- It trains for optimal Signal/BG discrimination (XGBoost backend)
- It facilitates ensemble training against distinct BGs with merging
- It generates density, significance, feature importance, & ROC plots (MatPlotLib backend) from validation data (1/3 by default)
- It lets Pheno Projects skip overhead & get answers QUICKLY

What is a BDT?

- Boosted Decision Trees are a type of Supervised Machine Learning
- "Hypothesis **Boosting**" is a technique for combining a number of "weak learners" (here shallow **Decision Trees**) into a "strong learner"
- Each tree separates signal (class 1) from background (class 0) via successive forks at selected split points on one data feature at a time
- Each terminal leaf carries a score, totaled over trees for a result on (0,1)
- Later trees focus on misclassifications from earlier trees (boosting!)

Why BDTs for Physics?

- Binary classification problems (Signal vs. Background) are common
- We want to maximize discrimination power
- We want to eliminate bias and work efficiently
- We want to incorporate domain knowledge & expertise
- We want to understand what the machine learning learned

BDTs balance POWER with TRANSPARENCY

How is MInOS Set Up?

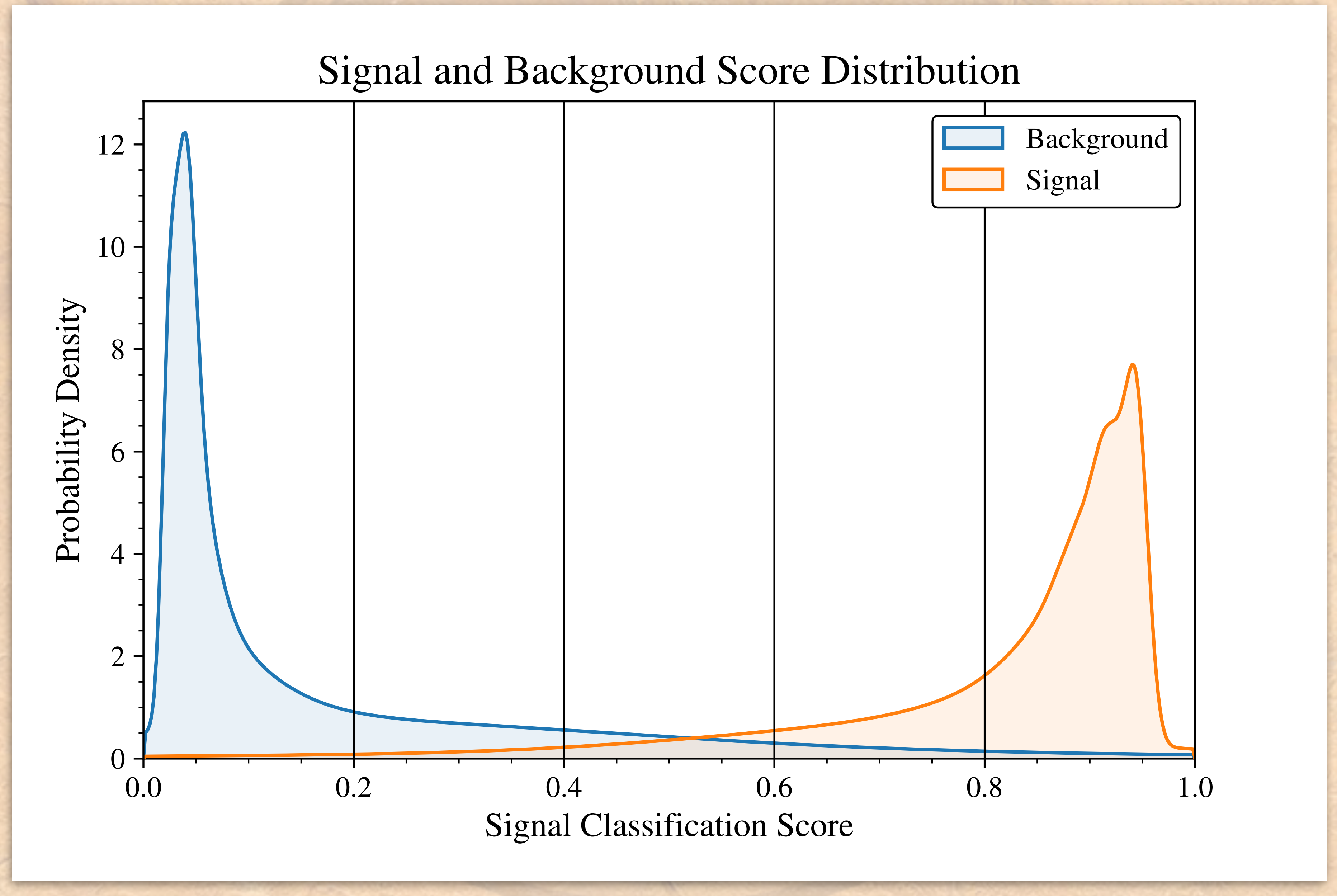
```
# Construct Data Sets From Files
MIN_DAT_001 = DIR:"./Cuts", FIL:["TTBarJJ_*"]
MIN_DAT_002 = DIR:"./Cuts", FIL:["ZZJJ_*","AZJJ_*","WZJJ_*","WWJJ_*"]
MIN_DAT_003 = DIR:"./Cuts", FIL:"llJJJ_*"
MIN_DAT_101 = DIR:"./Cuts", FIL:"MulMulJJ_sl_110_n1_50_*"

# Specify training features for inclusion (Channel 000 is for defaults)
MIN_CHN_000 = INC:[
        MAS_001,MAS_003,PTM_001,PTM_002,PTM_003,ETA_001,ETA_002,ETA_003,
        MET_000,MHT_000,MEF_000,TTM_001,CTS_001,ATM_001,ATM_002,
        MDP_001,MDP_002,MDP_003,ODP_001,ODP_002,ODP_004,
        VAR_001,VAR_002,VAR_004,VAR_011,VAR_012,VAR_013,VAR_021 ]

# Construct Channels from Data Sets
MIN_CHN_001 = DAT:[001,002,003], LBL:0
MIN_CHN_101 = DAT:101, LBL:1
# Construct Training from Channels
MIN_TRN_001 = CHN:[001,101]

# Apply Secondary Event Selections Before Training
MIN_ESC_001 = KEY:MAS_001, CUT:[101,81] # Z-Window Cut
MIN_ESC_002 = KEY:MET_000, CUT:75 # Require MET > 75 GeV
MIN_CHN_011 = DAT:[001,002,003], LBL:0, ESC:[+001,+002]
MIN_CHN_111 = DAT:101, LBL:1, ESC:[+001,+002]
MIN_TRN_011 = CHN:[011,111]
```

Card File from EXAMPLE_5 in GitHub Package

How is MInOS Run?

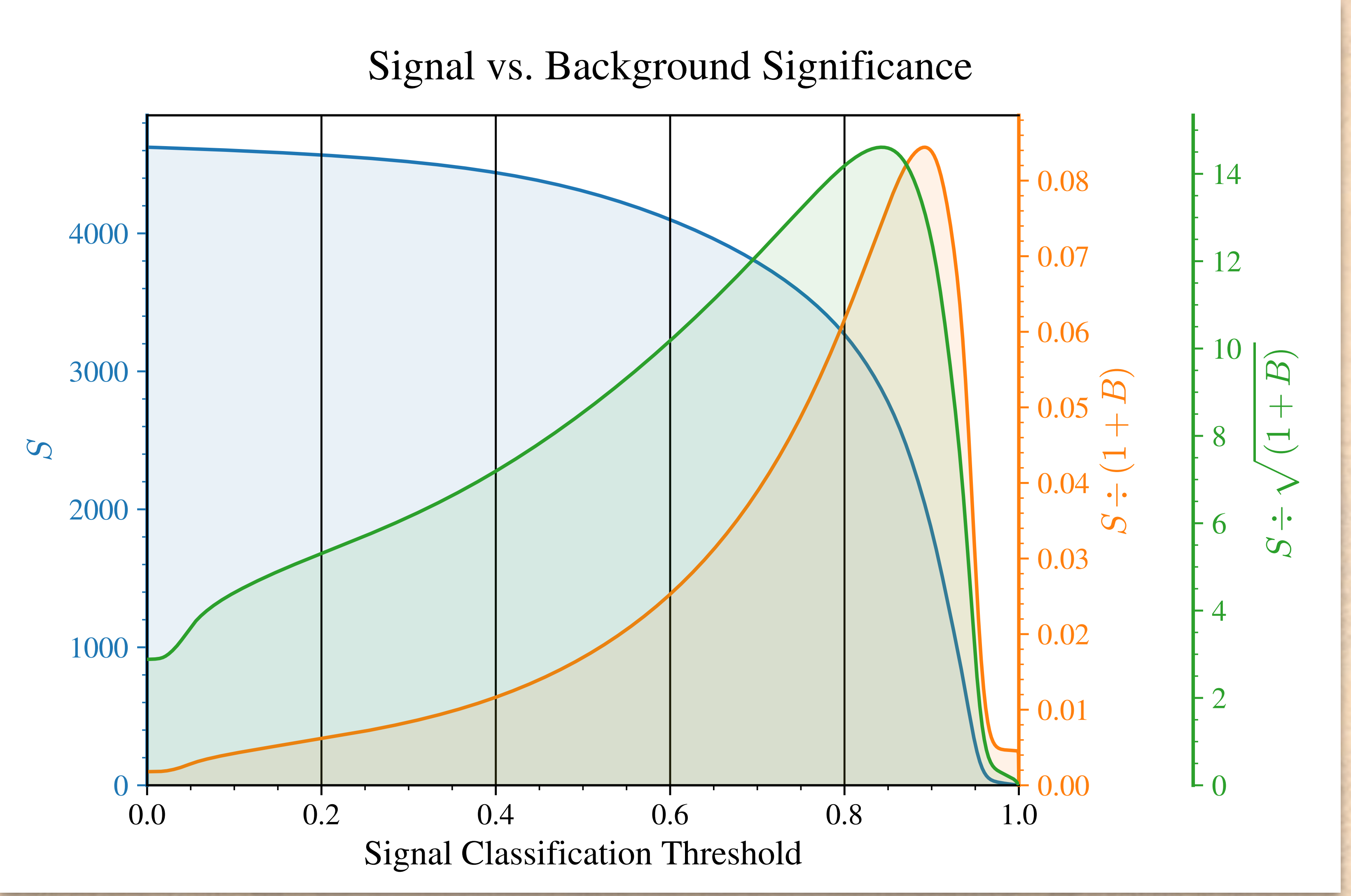
- Run simply as: "`./minos.pl`"
- The card file is located, indicated .cut files are accessed and merged, requested features are extracted with weights, training is initiated, and plots are generated and stored
- Note that the current release is BETA 0.1, and several switches and parameters are temporarily hard-coded (you can still rewrite them)

MInOS Output



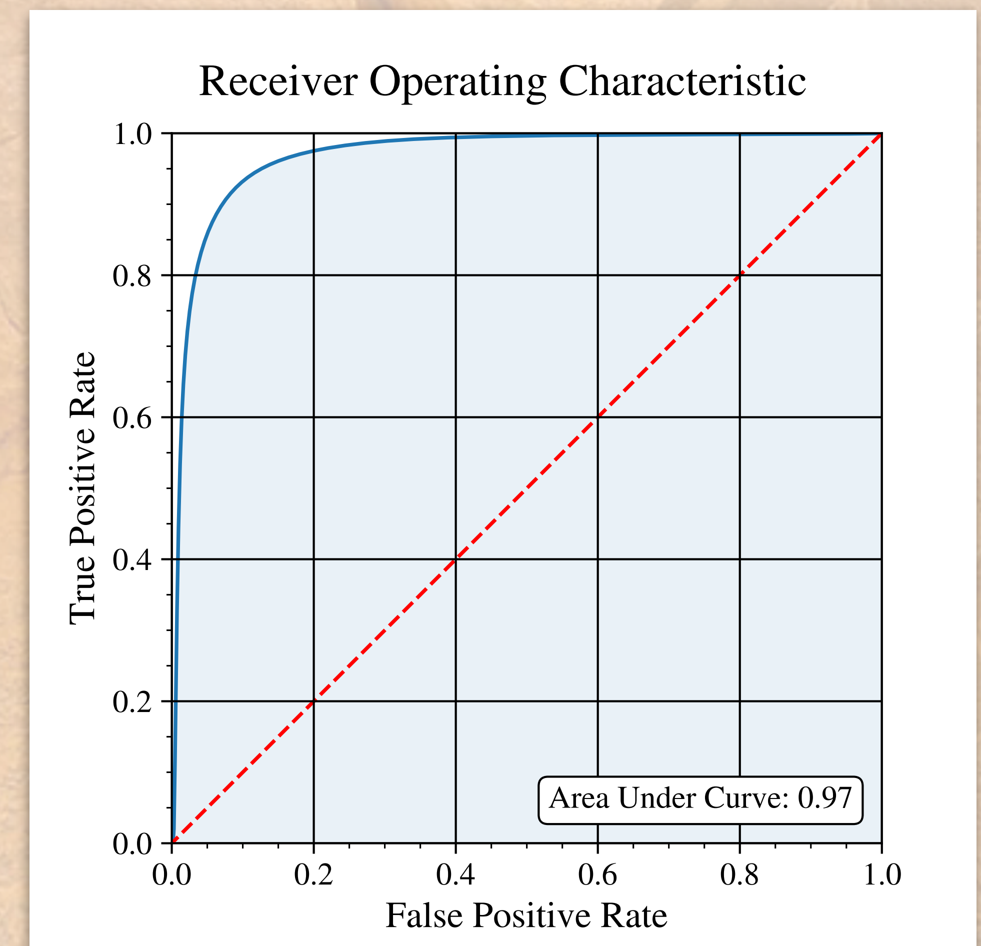
- Signal & Background Probability Density Visualizes Separation

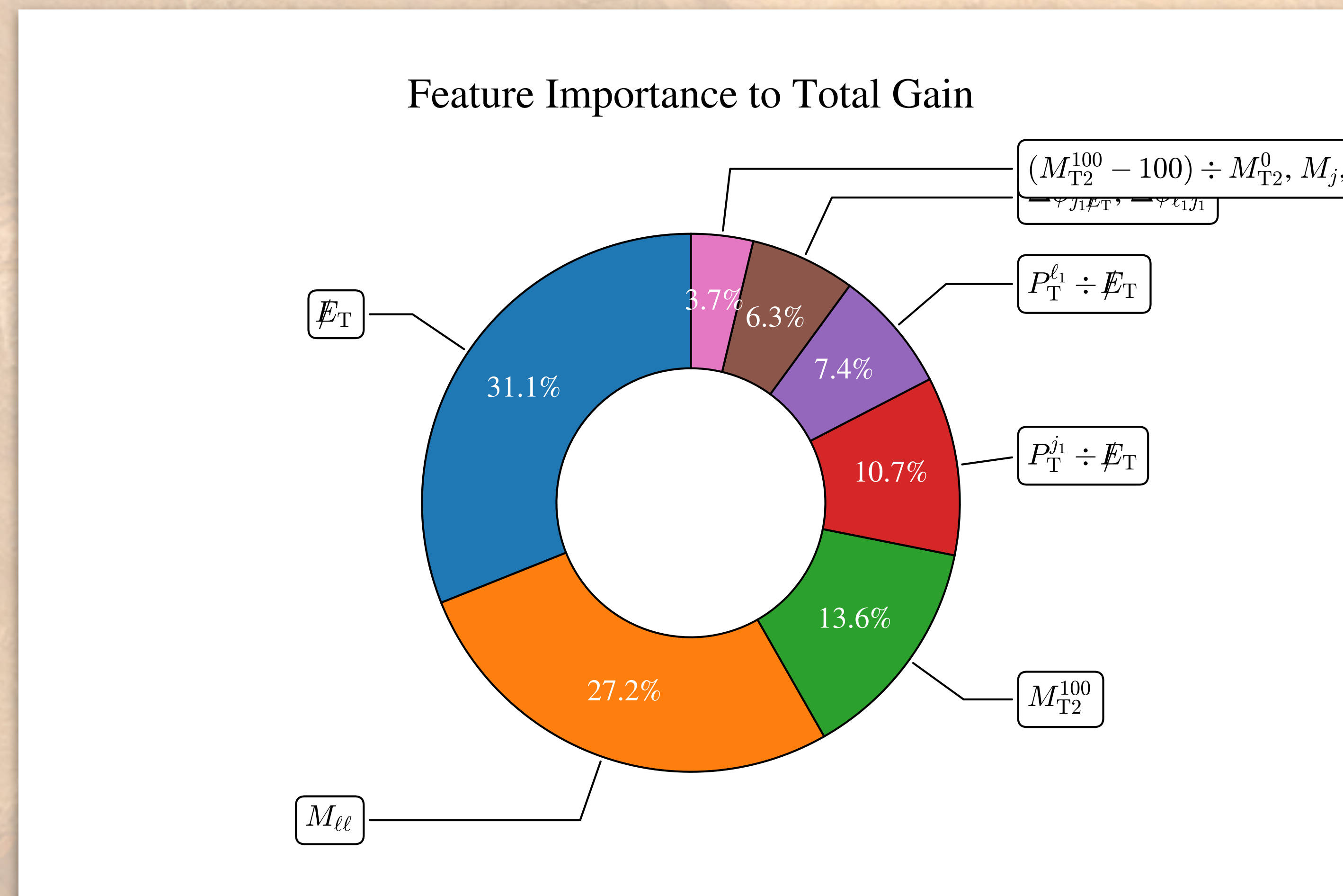
MInOS Output



- Survival fraction of S, B as a function of the classification threshold are used to show achievable significance (at specified luminosity)

MInOS Output





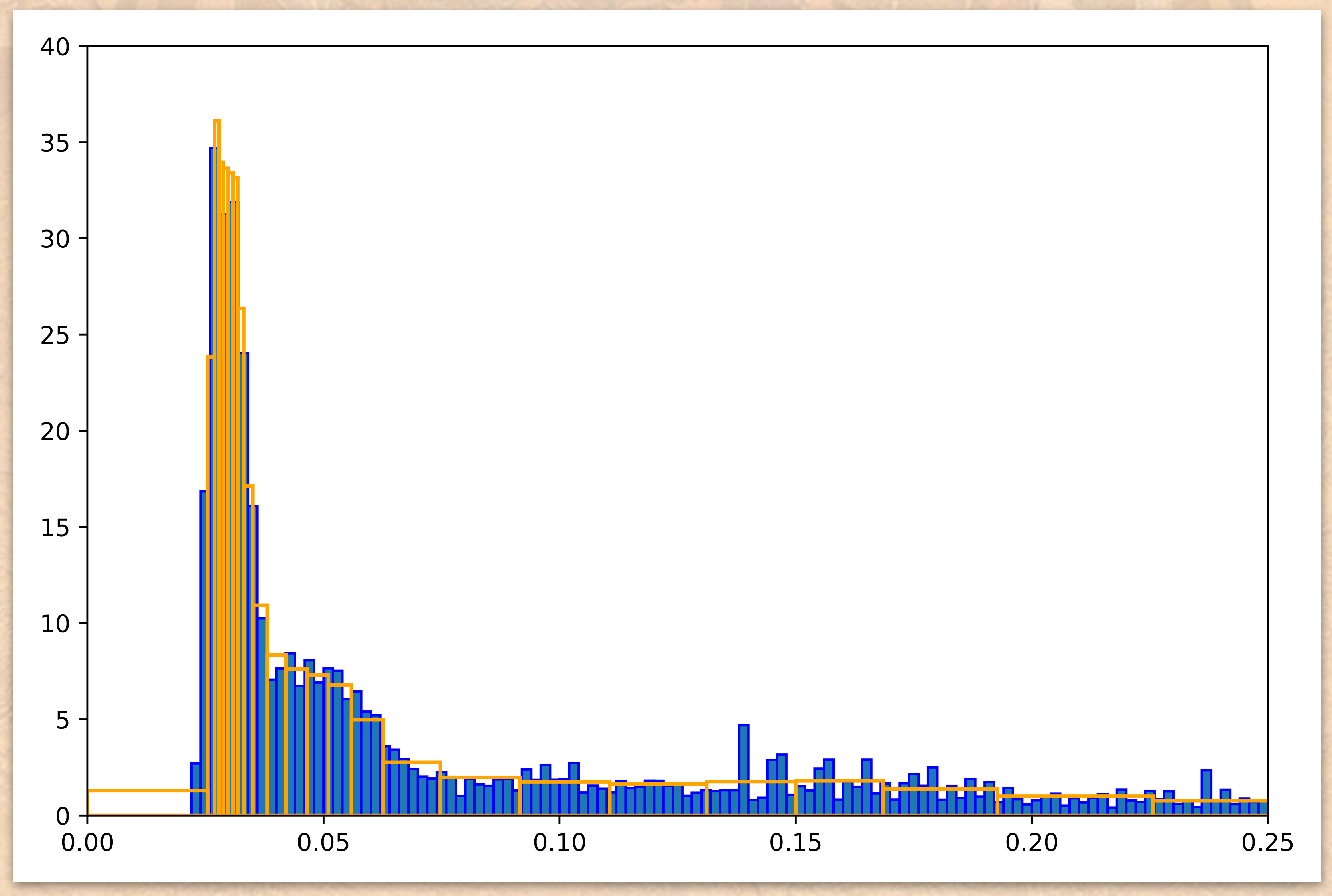
- The ROC curve is a standard metric of S/B separability
- A feature importance chart clarifies what is going on inside the BDT

Data Smoothing

- The statistical population of events grows sparse with harder cuts
- Smoothing may better approximate the reality of continuum data
- Naive interpolation (e.g. cubic spline) can induce unphysical artifacts
- We want to retain sharpness where clustering is real while washing out jitter where statistical event densities are low
- A proprietary multi-step solution is adopted to meet these goals

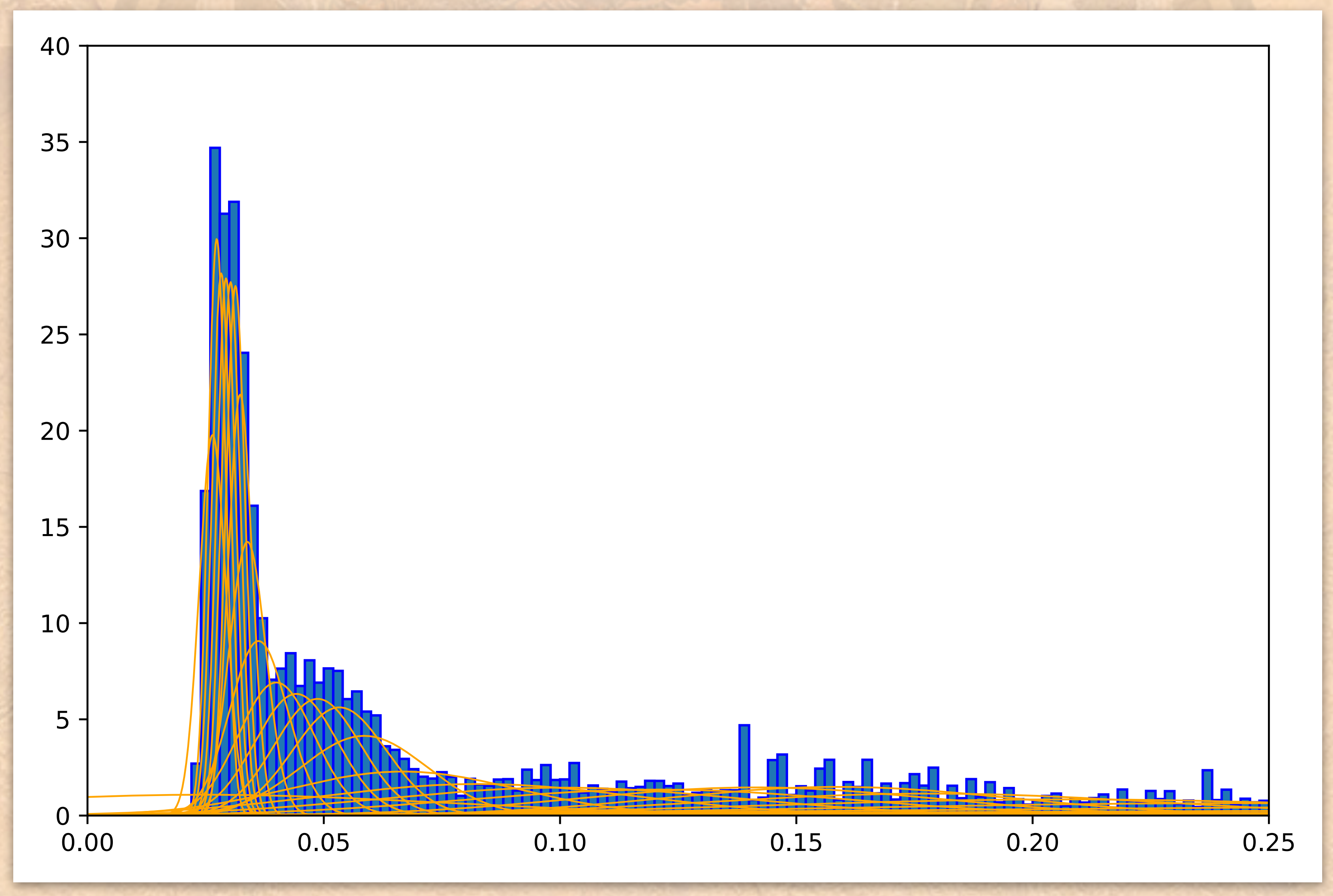
Data Smoothing

- First, we do variable-width binning with equal areas (cross sections)



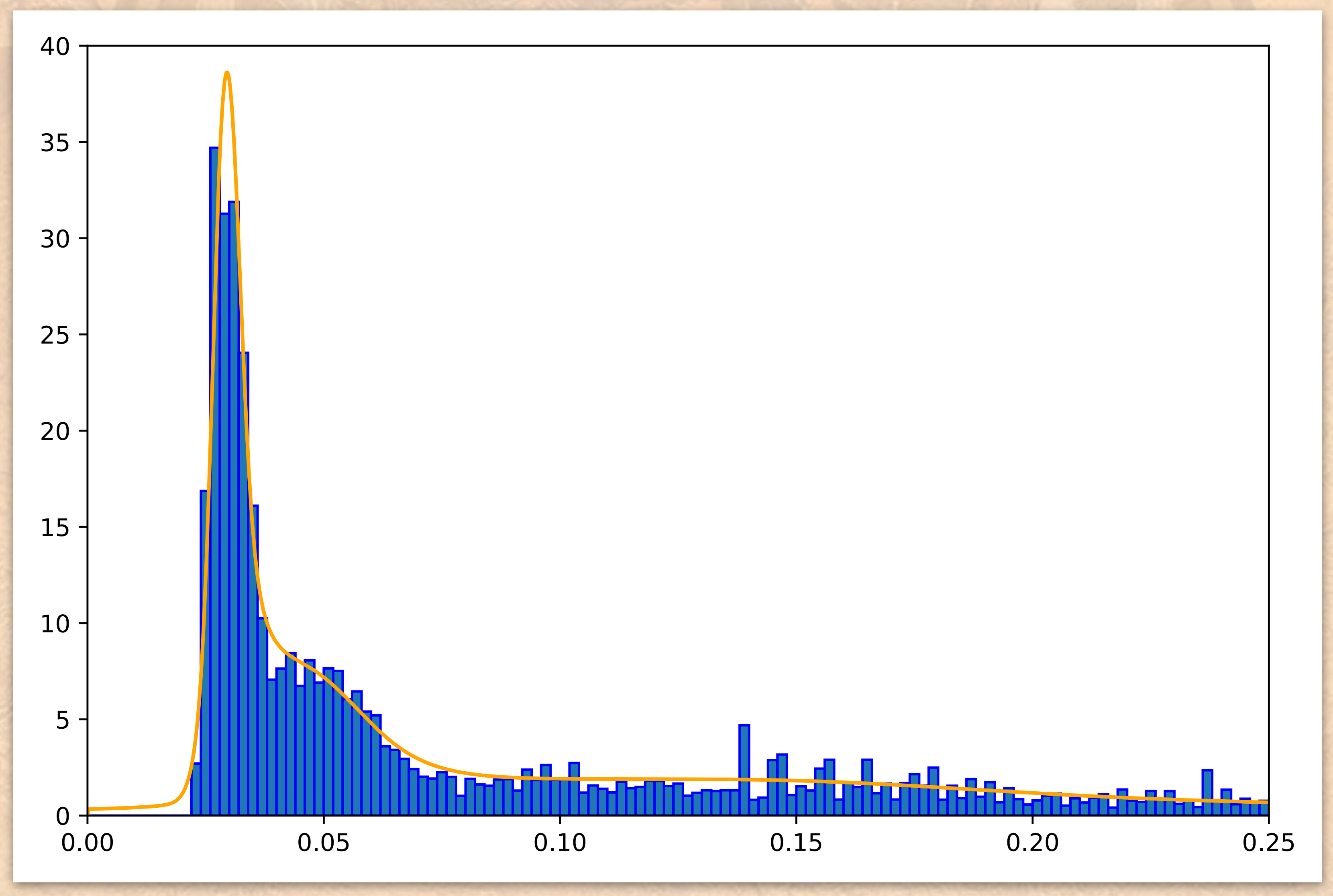
Data Smoothing

- Then, we populate narrow fixed bins via Gaussians ∝ prior widths



Data Smoothing

- Finally, we sum and scale to generate a smooth density of area one



What is XGBoost?

- XGBoost (Extreme Gradient Boosting) by Tianqi Chen is a popular, innovative, widely available, and very fast BDT implementation
- Trees are built "greedily" (no backtracking), with the splitting feature, splitting value, and leaf score selected to optimize an objective $\mathscr{L}$
- This is guided by first (gradient) and second (Hessian) derivatives of the loss-function with respect to the class estimator of the nth object

$$g_n \equiv \frac{\partial \mathcal{L}_L}{\partial \hat{y}_n}$$

$$h_n \equiv \frac{\partial^2 \mathcal{L}_L}{\partial \hat{y}_n^2}$$

$$\delta \mathcal{L}_L \simeq \sum_{n=1}^{N} \left\{ g_n \delta \hat{y}_n + h_n \frac{\delta \hat{y}_n^2}{2} \right\}$$

$$\partial(\delta \mathcal{L}) / \partial(\delta \hat{y}_n) = 0,$$

$$\delta_0 \hat{y}_n = -g_n / h_n$$

$$(-\delta_0 \mathcal{L}_L) \simeq \textstyle\sum_n g_n^2 / (2 h_n)$$

XGBoost Details

- It is not possible to correct misclassifications per event.
- Rather, events with common features flow similarly through the decision tree, and "vote" for the score carried by their destination node
- The max $-(\delta_0 \mathscr{L})$ split is selected
- "Regulators" limit overtraining

$$G_\ell \equiv \sum_{n=1}^{N} g_n \times \delta_{\ell,\ell'(\vec{x}_n)}$$

$$H_\ell \equiv \sum_{n=1}^{N} h_n \times \delta_{\ell,\ell'(\vec{x}_n)}$$

$$\mathcal{L}_\Omega = \gamma L + \alpha \sum_{\ell=1}^{L} |s_\ell| + \lambda \sum_{\ell=1}^{L} \frac{s_\ell^2}{2}$$

$$\delta\mathcal{L} \simeq \sum_{\ell=1}^{L} \left\{ \gamma + \alpha |s_\ell| + G_\ell s_\ell + (H_\ell + \lambda) \frac{s_\ell^2}{2} \right\}$$

$$s_0^\ell = - \frac{G_\ell \pm \alpha}{H_\ell + \lambda}$$

$$(-\delta_0 \mathcal{L}) \simeq \sum_{\substack{\ell=1 \\ (|G_\ell| > \alpha)}}^{L} \left\{ \frac{(G_\ell \pm \alpha)^2}{2\,(H_\ell + \lambda)} - \gamma \right\}$$

Binary Logistic Regression

- The simplest objective is the Mean-Square Error
- MInOS uses a binary logistic objective, yielding continuous classification scores on 0 to 1

$$\mathcal{L}_L = \sum_{n=1}^{N} \frac{(y_n - \hat{y}_n)^2}{2}$$

$$g_n \equiv \frac{\partial \mathcal{L}_L}{\partial \hat{y}_n} = (\hat{y}_n - y_n)$$

$$h_n \equiv \frac{\partial^2 \mathcal{L}_L}{\partial \hat{y}_n^2} = 1$$

"logistic" function $\quad p = \dfrac{1}{1+e^{-y}} \quad \in \{0, 1/2, 1\}$

"logit" function $\quad y = \ln\left(\dfrac{p}{1-p}\right) \quad \in \{-\infty, 0, +\infty\}$

$$\mathcal{L}_L = -\sum_{n=1}^{N} \left\{ p_n \ln(\hat{p}_n) + (1-p_n)\ln(1-\hat{p}_n) \right\}$$

$$\begin{aligned} g_n \equiv \frac{\partial \mathcal{L}_L}{\partial \hat{y}_n} &= \frac{\partial \mathcal{L}_L}{\partial \hat{p}_n} \times \frac{\partial \hat{p}_n}{\partial \hat{y}_n} \\ &= -p_n \times (1-\hat{p}_n) + \hat{p}_n \times (1-p_n) \\ &= \hat{p}_n - p_n \end{aligned}$$

$$\begin{aligned} h_n \equiv \frac{\partial^2 \mathcal{L}_L}{\partial \hat{y}_n^2} &= \left(\frac{\partial^2 \mathcal{L}_L}{\partial \hat{y}_n \partial \hat{p}_n} = 1 \right) \times \frac{\partial \hat{p}_n}{\partial \hat{y}_n} \\ &= \hat{p}_n \times (1-\hat{p}_n) \end{aligned}$$

Note on Tuning / Weights

- A number of hyper-parameters, including the objective-level regulators γ, α, and λ are available to confront "Bias-Variance" issues
- In short, one must not add complexity without benefit (like χ^2/DOF)
- XGBoost also allows specification of maximal tree depth and count, with handles for "early stopping" or "pruning" when learning slows
- MInOS balances data sets sent for training by separately normalizing the signal and background cross section to unity
- This stabilizes optimal numerical values of various hyper parameters, eliminates tension between intensive / extensive scaling, and induces a natural $\mathcal{O}(1)$ scale for the gradient, Hessian, and regulators

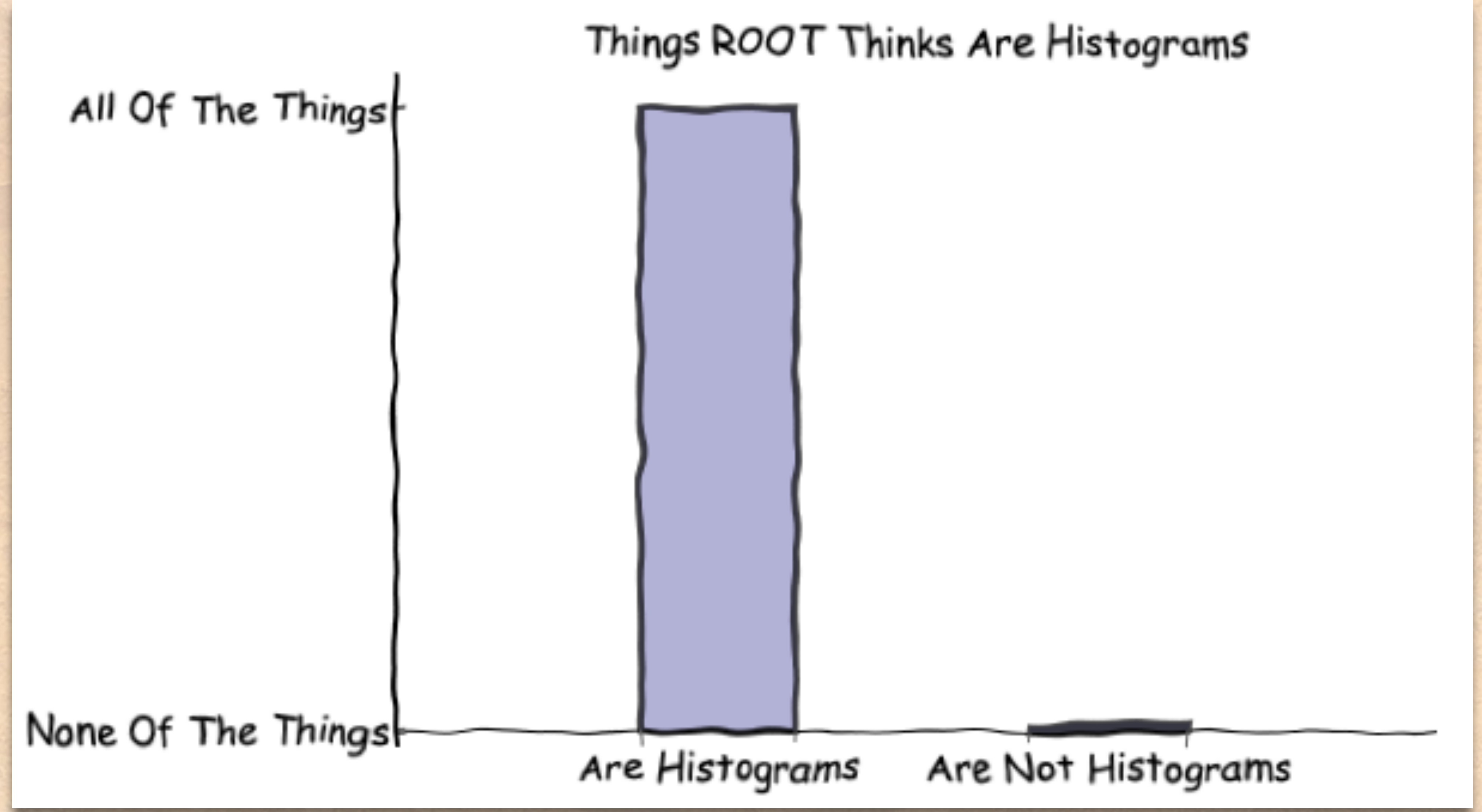
Physics Application

- MInOS was co-developed with a first physics application
- Please see 5/25 talk “Searching For Soft Leptons in Compressed Spectra with a BDT” by Alyssa Horne & Marcus Snedecker
    - with Dutta, Ghosh, Kumar, Sandick, & Stengel

TAKEAWAYS:

- BDTs can substantially improve results over hand-selected 1-D cuts
- Pre-application of “known” cuts lets the BDT focus on subtleties
- Ensemble training vs. distinct BG types is better than merged training

Thank You!



Things ROOT Thinks Are Histograms
All Of The Things
None Of The Things
Are Histograms
Are Not Histograms

“ Then spake Zeus: … ‘The cases are now indeed judged ill and it is because … many … who have wicked souls are clad in fair bodies and ancestry and wealth, and … the judges are confounded …, having their own soul muffled in the veil of eyes and ears and the whole body. …They must be stripped bare of all those things …, beholding with very soul the very soul of each immediately. … [I] have appointed sons of my own to be judges; two from Asia, **Minos** and **Rhadamanthus**, and one from Europe, **Aeacus**. These … shall give judgement in the meadow at the dividing of the road, whence are the two ways leading, one to the Isles of the Blest …, and the other to Tartaros.’ ”

– Plato, *Gorgias* (trans. Lamb)

Cutting with

AEACuS

(Algorithmic Event Arbiter and CUt Selector)

& Plotting with

RHADAMANTHUS

(Recursively Heuristic Analysis, Display, And MANipulation: The Histogram Utility Suite)

Joel W. Walker
Sam Houston State University

SUSY 2019
Texas A&M Corpus Christi
May 20-24, 2019

Students: Kebur Fantahun, B. Ash Fernando, Nicolle Schachtner, Trenton Voth, Jesse Cantu, & William Ellsworth
Sample plots from work also with: Dutta, Gao, Kumar, Li, Maxin, Nanopoulos, Sandick, Sinha, Stengel

Guiding Principles:

- It is important to separate WHAT from HOW
- It is important to document UNAMBIGOUSLY
- It is important to streamline REPRODUCTION

Language Vs. Framework

AEACuS is BOTH and it is FACTORIZABLE

- The AEACuS meta language is an ideal mechanism for large experiments (CMS/ATLAS) & small phenomenology groups to unambiguously propagate an approximate rendering of internal event selection strategies
- The AEACuS software tool is an ideal agent for the rapid and uniform projection of sophisticated event cut workflows onto new physics models

"Dogfooding"

- AEACuS and RHADAManTHUS are fully WORKING CODE
- They have been ITERATIVELY EVOLVED during several years of REAL WORLD USE on LHC Pheno studies
- This has grown flexibility & forced incorporation of several features that would have been difficult to anticipate in a single design cycle

Unified Work Flow

- **MadGraph (+ Others):** Matrix Element Generation
- **MadEvent (+ Others):** Hard Scattering Simulation
- **Pythia (+ Others):** Showering and Hadronization
- **DELPHES:** Detector Simulation
  (DEtector Level PHysics Emulation System)
- **AEACUS:** Statistics Computation & Cut Selection
- **RHADAMANTHUS:** Graphical Event Analysis

Package Notes

- AEACuS and RHADAMANTHUS are written in Perl
- All Perl scripts are self contained - no libraries or installation
- RHADAMANTHUS calls the public Python MatPlotLib library
- Control is provided by simple reusable card files
- Directory structure is: "./Events" for input .lhco event files, "./Cards" for input cards, "./Cuts" & "./Plots" for output
- Cut with AEACuS: "`./aeacus.pl card_name event_name cross_section`"
- Plot with RHADAMANTHUS: "`./rhadamanthus.pl card_name`"

AEACuS (Goals)

- Automate model recast comparison against LHC data
- Replicate most current search strategies for new physics
- Embody lightweight, consumer-level, standalone design
- Decouple specific usage from general functionality
- Render event cut strategies compactly & unambiguously
- Merge power & flexibility with uniformity & simplicity
- Decouple phenomenology from software maintenance

AEACuS (Function)

- Reads from standardized LHCO format input
- Filters kinematics, geometry, isolation, charge & flavor
- Dilepton pair assembly (by like/unlike charge & flavor)
- Jet (Re)clustering (KT, C/A, Anti-KT) & Hemispheres (Lund, etc.)
- Missing E_T, scalar H_T, effective & invariant mass, ratios & products
- Transverse mass, 1- & 2-step asymmetric M_{T2} (with combinatorics), Tri-jet mass, α_T, Razor & α_R, Dilepton Z-balance, Lepton W-projection, $\Delta\phi$ (& biased $\Delta\phi^*$), Shape Variables (thrust & minor, spheri[o]city, F), + MORE
- Arbitrary user-described combinations of computable statistics
- **The AEACuS LANGUAGE for event description exists independently of the AEACuS event analyzer, similar in spirit to the LHADA program**

Cut Card Example

```
# 1412.0618 MT2 Han/Liu
# 1409.7058 Baer, Mustafayev, Tata

*** Object Reconstruction ****

# Bound pseudo-rapidity magnitude and transverse momentum
OBJ_ELE = PRM:[0,2.5], PTM:7
OBJ_MUO = PRM:[0,2.5], PTM:7
OBJ_TAU = PRM:[0,2.5], CUT:[0,0] # Tau veto
OBJ_JET = PTM:20, PRM:[0,4.5]

OBJ_JET_001 = SRC:+000, PTM:30, CUT:[1,1] # Monojet
OBJ_JET_002 = SRC:+001, PTM:100, PRM:[0,2.5], CUT:1 # Jet is hard
OBJ_JET_003 = SRC:+000, HFT:1, PRM:[0,2.5], CUT:[0,0] # B-veto

# Find OSSF Dilepton with smallest mass
OBJ_LEP_001 = SRC:+000, SET:[DIL,-1,+1,0,UNDEF], CUT:2
# Report mass of that dilepton
OBJ_LEP_002 = SRC:+001, EFF:SUM, OUT:MAS_001
# Report p_T of leading lepton
OBJ_LEP_003 = SRC:+001, CUT:[1,UNDEF,-1], OUT:PTM_001
# Report p_T of sub-leading lepton
OBJ_LEP_004 = SRC:[+001,-003], OUT:PTM_002
*** Global Event Selection / Statistics Computation ***

# Cut on MET
EVT_MET = CUT:100
# Compute DiTau mass statistic
EVT_TTM_001 = LEP:001, JET:001, OUT:1
# Compute generalized MT2
EVT_ATM_001 = MET:000, MOD:[GEN,LEP_003,LEP_004,150,150], OUT:1
# Compute delta-phi angle between MET and the leptons
EVT_MDP_001 = MET:000, LEP:003, OUT:1
EVT_MDP_002 = MET:000, LEP:004, OUT:1
# Compute delta-R and delta-phi between the leptons
EVT_ODR_001 = LEP:001, OUT:1
EVT_ODP_001 = LEP:001, OUT:1
```

- Define hierarchical groupings of Jets & Leptons to set event topology w/ inclusion "+" and exclusion "-"
- Filter on sign, flavor, b-tags, etc.
- [Min,Max] brackets set bounds
- The "SET" command calls a variety of subroutines (e.g. dilepton) to extract a subset of input objects
- The "EFF" command is similar, but returns a transformed object, e.g. a vector sum or reclustered jets

Cut Card Example

```
# 1412.0618 MT2 Han/Liu
# 1409.7058 Baer, Mustafayev, Tata

*** Object Reconstruction ****

# Bound pseudo-rapidity magnitude and transverse momentum
OBJ_ELE = PRM:[0,2.5], PTM:7
OBJ_MUO = PRM:[0,2.5], PTM:7
OBJ_TAU = PRM:[0,2.5], CUT:[0,0] # Tau veto
OBJ_JET = PTM:20, PRM:[0,4.5]

OBJ_JET_001 = SRC:+000, PTM:30, CUT:[1,1] # Monojet
OBJ_JET_002 = SRC:+001, PTM:100, PRM:[0,2.5], CUT:1 # Jet is hard
OBJ_JET_003 = SRC:+000, HFT:1, PRM:[0,2.5], CUT:[0,0] # B-veto

# Find OSSF Dilepton with smallest mass
OBJ_LEP_001 = SRC:+000, SET:[DIL,-1,+1,0,UNDEF], CUT:2
# Report mass of that dilepton
OBJ_LEP_002 = SRC:+001, EFF:SUM, OUT:MAS_001
# Report p_T of leading lepton
OBJ_LEP_003 = SRC:+001, CUT:[1,UNDEF,-1], OUT:PTM_001
# Report p_T of sub-leading lepton
OBJ_LEP_004 = SRC:[+001,-003], OUT:PTM_002

*** Global Event Selection / Statistics Computation ***

# Cut on MET
EVT_MET = CUT:100
# Compute DiTau mass statistic
EVT_TTM_001 = LEP:001, JET:001, OUT:1
# Compute generalized MT2
EVT_ATM_001 = MET:000, MOD:[GEN,LEP_003,LEP_004,150,150], OUT:1
# Compute delta-phi angle between MET and the leptons
EVT_MDP_001 = MET:000, LEP:003, OUT:1
EVT_MDP_002 = MET:000, LEP:004, OUT:1
# Compute delta-R and delta-phi between the leptons
EVT_ODR_001 = LEP:001, OUT:1
EVT_ODP_001 = LEP:001, OUT:1
```

- Compute statistics associated with referenced groups of kinematic objects, or with the event as a whole
- Computed statistics may be used downstream for channel sorting or plotting

Advanced Features

```
# CMS 1405.7570
# Electroweak SUSY with decays to l,W,Z,H
# With students Fantahun, Fernando, Schachtner

*** Object Reconstruction ****
OBJ_ELE = PTM:10, PRM:[0.0,2.4]
OBJ_MUO = PTM:10, PRM:[0.0,2.4]
OBJ_TAU = PTM:20, PRM:[0.0,2.4]
OBJ_JET = PTM:30, PRM:[0.0,2.5]

OBJ_LEP_001 = SRC:+000, EMT:+3, CUT:[0,1] # zero or one tau
OBJ_LEP_002 = SRC:+000, CUT:[3,3] # exactly 3 of e, mu, tau
OBJ_LEP_003 = SRC:+002, PTM:20, CUT:1 # out of the 3 leptons, one >20 Gev

OBJ_JET_002 = SRC:+000, HFT:1, CUT:[0,0] # veto bjets

OBJ_LEP_004 = SRC:+002, EMT:-3, SET:[DIL,-1,0,50,UNDEF], CUT:0 # OSAF e/mu near 50 GeV
OBJ_LEP_005 = SRC:+004, EFF:SUM, OUT:MAS_001 # mass of the dilepton pair
OBJ_LEP_006 = SRC:[+002,-004], CUT:[1,UNDEF,-1] # remaining lepton

OBJ_LEP_007 = SRC:+000, EMT:-3, CUT:[1,UNDEF,-1] # harder of non-taus
OBJ_LEP_008 = SRC:[+001,+007], SET:[DIL,-1,0], CUT:0 # tau OSAF 1
OBJ_LEP_009 = SRC:+008, EFF:SUM, OUT:MAS_002 # mass of the dilepton pair

OBJ_LEP_010 = SRC:[+000,-007], EMT:-3, CUT:[1,UNDEF,-1] # softer of non-taus
OBJ_LEP_011 = SRC:[+001,+010], SET:[DIL,-1,0], CUT:0 # tau OSAF 2
OBJ_LEP_012 = SRC:+011, EFF:SUM, OUT:MAS_003 # mass of the dilepton pair

OBJ_LEP_013 = SRC:+002, SET:[DIL,-1,+1,91.2,UNDEF], CUT:0 # OSSF close to Z

*** Global Event Selection ****
EVT_MET = CUT:50
# Transverse masses of unmerged lepton with MET
EVT_OTM_001 = LEP:006, MET:000, OUT:1
EVT_OTM_002 = LEP:010, MET:000, OUT:1
EVT_OTM_003 = LEP:007, MET:000, OUT:1
# Find the reconstructed M_LL
# closest to simulation of visible system for Z -> ditau
# 50 GeV for ditau -> e/mu or 60 GeV if one tau is hadronic
EVT_VAR_001 = KEY:{
        IFE( LES( ABS( IFE(DEF($3),$3,$2) - 60 ), ABS($1-50)), IFE(DEF($3),$3,$2), $1 ),
        MAS_001,MAS_002,MAS_003}, OUT:1
# Select corresponding transverse mass of MET + 3rd lepton system
EVT_VAR_002 = KEY:{
        IFE( LES( ABS( IFE(DEF($3),$3,$2) - 60 ), ABS($1-50)), IFE(DEF($3),$6,$5), $4 ),
        MAS_001,MAS_002,MAS_003,OTM_001,OTM_002,OTM_003}, OUT:1
```

- This example replicates a sophisticated CMS SUSY study for recasting
- LEP_004 holds the e/mu opposite sign / any flavor dilepton closest to 50 GeV
- LEP_007/010 combine a tau with either of the other e/mu
- In each case, the mass of the dilepton and the transverse mass (OTM) of the 3rd lepton with the MET is computed
- An OSSF dilepton closest to the Z is also reconstructed (13)

Advanced Features

```
# CMS 1405.7570
# Electroweak SUSY with decays to l,W,Z,H
# With students Fantahun, Fernando, Schachtner

*** Object Reconstruction ****
OBJ_ELE = PTM:10, PRM:[0.0,2.4]
OBJ_MUO = PTM:10, PRM:[0.0,2.4]
OBJ_TAU = PTM:20, PRM:[0.0,2.4]
OBJ_JET = PTM:30, PRM:[0.0,2.5]

OBJ_LEP_001 = SRC:+000, EMT:+3, CUT:[0,1] # zero or one tau
OBJ_LEP_002 = SRC:+000, CUT:[3,3] # exactly 3 of e, mu, tau
OBJ_LEP_003 = SRC:+002, PTM:20, CUT:1 # out of the 3 leptons, one >20 Gev

OBJ_JET_002 = SRC:+000, HFT:1, CUT:[0,0] # veto bjets

OBJ_LEP_004 = SRC:+002, EMT:-3, SET:[DIL,-1,0,50,UNDEF], CUT:0 # OSAF e/mu near 50 GeV
OBJ_LEP_005 = SRC:+004, EFF:SUM, OUT:MAS_001 # mass of the dilepton pair
OBJ_LEP_006 = SRC:[+002,-004], CUT:[1,UNDEF,-1] # remaining lepton

OBJ_LEP_007 = SRC:+000, EMT:-3, CUT:[1,UNDEF,-1] # harder of non-taus
OBJ_LEP_008 = SRC:[+001,+007], SET:[DIL,-1,0], CUT:0 # tau OSAF 1
OBJ_LEP_009 = SRC:+008, EFF:SUM, OUT:MAS_002 # mass of the dilepton pair

OBJ_LEP_010 = SRC:[+000,-007], EMT:-3, CUT:[1,UNDEF,-1] # softer of non-taus
OBJ_LEP_011 = SRC:[+001,+010], SET:[DIL,-1,0], CUT:0 # tau OSAF 2
OBJ_LEP_012 = SRC:+011, EFF:SUM, OUT:MAS_003 # mass of the dilepton pair

OBJ_LEP_013 = SRC:+002, SET:[DIL,-1,+1,91.2,UNDEF], CUT:0 # OSSF close to Z

*** Global Event Selection ****
EVT_MET = CUT:50
# Transverse masses of unmerged lepton with MET
EVT_OTM_001 = LEP:006, MET:000, OUT:1
EVT_OTM_002 = LEP:010, MET:000, OUT:1
EVT_OTM_003 = LEP:007, MET:000, OUT:1
# Find the reconstructed M_LL
# closest to simulation of visible system for Z -> ditau
# 50 GeV for ditau -> e/mu or 60 GeV if one tau is hadronic
EVT_VAR_001 = KEY:{
        IFE( LES( ABS( IFE(DEF($3),$3,$2) - 60 ), ABS($1-50)), IFE(DEF($3),$3,$2), $1 ),
        MAS_001,MAS_002,MAS_003}, OUT:1
# Select corresponding transverse mass of MET + 3rd lepton system
EVT_VAR_002 = KEY:{
        IFE( LES( ABS( IFE(DEF($3),$3,$2) - 60 ), ABS($1-50)), IFE(DEF($3),$6,$5), $4 ),
        MAS_001,MAS_002,MAS_003,OTM_001,OTM_002,OTM_003}, OUT:1
```

- Search targets 3-lepton final states with mixed OS e/μ and a hadronic tau
- Simulation: Z -> τ τ visible mass ~50 GeV for e/μ or ~60 GeV when a τ goes hadronic
- The τ is guaranteed to be OS with one of the e or μ
- A custom variable takes mass of the defined OS system closest to the sim. target
- The associated 3rd body transverse mass is stored too

Regions / Channels

```
*** Event Channel Filtering ***
CUT_ESC_001 = KEY:LEP_001, CUT:[0,0] # Tau Veto
CUT_ESC_002 = KEY:LEP_004, CUT:[2,2] # Force 2 OSAF elec/muon
CUT_ESC_004 = KEY:LEP_013, CUT:[2,2] # Force 2 OSSF

# missing energy
CUT_ESC_031 = KEY:MET_000, CUT:[50,100]
CUT_ESC_032 = KEY:MET_000, CUT:[100,150]
CUT_ESC_033 = KEY:MET_000, CUT:[150,200]
CUT_ESC_034 = KEY:MET_000, CUT:200

# invariant mass
CUT_ESC_511 = KEY:VAR_001, CUT:[0,100]
CUT_ESC_512 = KEY:VAR_001, CUT:100

# transverse mass
CUT_ESC_521 = KEY:VAR_002, CUT:[0,120]
CUT_ESC_522 = KEY:VAR_002, CUT:[120,160]
CUT_ESC_523 = KEY:VAR_002, CUT:160
```

```
# TABLE 13, 1405.7570
# Opposite sign mixed e/mu pair plus a hadronic tau
# from 0 to 100 GeV Invariant Mass
CUT_CHN_301 = ESC:[+511,+521,+031,-001,+002,-004]
CUT_CHN_302 = ESC:[+511,+521,+032,-001,+002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]

002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
002,-004]
```

- Event selection cuts are "registered" for disjoint parameter regions
- For example, we define here a tau-veto, an OSAF and an OSSF sorting condition
- These cuts are NOT YET APPLIED, but only DEFINED

Regions / Channels

```
*** Event Channel Filtering ***
CUT_ESC_001 = KEY:LEP_001, CUT:[0,0] # Tau Veto
CUT_ESC_002 = KEY:LEP_004, CUT:[2,2] # Force 2 OSAF elec/muon
CUT_ESC_004 = KEY:LEP_013, CUT:[2,2] # Force 2 OSSF
```

- Many channels are defined very simply by subscribing to various cuts, without recomputation (fast)
- A minus sign inverts the cut
- here, we force a tau, and a MIXED (not SF) e/μ OS dilepton
- We then bin into channels on MET, invariant mass, and transverse mass

```
# TABLE 13, 1405.7570
# Opposite sign mixed e/mu pair plus a hadronic tau
# from 0 to 100 GeV Invariant Mass
CUT_CHN_301 = ESC:[+511,+521,+031,-001,+002,-004]
CUT_CHN_302 = ESC:[+511,+521,+032,-001,+002,-004]
CUT_CHN_303 = ESC:[+511,+521,+033,-001,+002,-004]
CUT_CHN_304 = ESC:[+511,+521,+034,-001,+002,-004]
CUT_CHN_311 = ESC:[+511,+522,+031,-001,+002,-004]
CUT_CHN_312 = ESC:[+511,+522,+032,-001,+002,-004]
CUT_CHN_313 = ESC:[+511,+522,+033,-001,+002,-004]
CUT_CHN_314 = ESC:[+511,+522,+034,-001,+002,-004]
CUT_CHN_321 = ESC:[+511,+523,+031,-001,+002,-004]
CUT_CHN_322 = ESC:[+511,+523,+032,-001,+002,-004]
CUT_CHN_323 = ESC:[+511,+523,+033,-001,+002,-004]
CUT_CHN_324 = ESC:[+511,+523,+034,-001,+002,-004]
# Greater than 100 GeV Invariant Mass
CUT_CHN_331 = ESC:[+512,+521,+031,-001,+002,-004]
CUT_CHN_332 = ESC:[+512,+521,+032,-001,+002,-004]
CUT_CHN_333 = ESC:[+512,+521,+033,-001,+002,-004]
CUT_CHN_334 = ESC:[+512,+521,+034,-001,+002,-004]
CUT_CHN_341 = ESC:[+512,+522,+031,-001,+002,-004]
CUT_CHN_342 = ESC:[+512,+522,+032,-001,+002,-004]
CUT_CHN_343 = ESC:[+512,+522,+033,-001,+002,-004]
CUT_CHN_344 = ESC:[+512,+522,+034,-001,+002,-004]
CUT_CHN_351 = ESC:[+512,+523,+031,-001,+002,-004]
CUT_CHN_352 = ESC:[+512,+523,+032,-001,+002,-004]
CUT_CHN_353 = ESC:[+512,+523,+033,-001,+002,-004]
CUT_CHN_354 = ESC:[+512,+523,+034,-001,+002,-004]
```

AEACuS Output

1000000 EVENTS PROCESSED IN TOTAL

5.316e-02 PB EVENT CROSS SECTION YIELDS 1.881e+07 PER PB LUMINOSITY

RESCALING BY 5.316e-04 TO TARGET LUMINOSITY OF 1.000e+04 PER PB

5.316e+02 SCALED EVENTS SURVIVE ALL CUTS WITH AN EFFECTIVE CROSS SECTION OF 5.316e-02 PB

000.000 % OF EVENTS CUT

CUT ID	% CUT	% SOLO
LEP_001	000.000	000.000
LEP_002	000.000	000.000
LEP_003	000.000	000.000
LEP_004	000.000	000.000
LEP_005	000.000	000.000
JET_000	000.000	000.000
JET_001	000.000	000.000
JET_002	000.000	000.000
JET_003	000.000	000.000
JET_004	000.000	000.000
JET_005	000.000	000.000
JET_006	000.000	000.000
JET_007	000.000	000.000
JET_008	000.000	000.000
JET_009	000.000	000.000
JET_010	000.000	000.000

INDIVIDUAL PASSING EVENT STATISTICS

EVENT_#	LEP_001	LEP_002	LEP_003	LEP_004	LEP_005	JET_000	JET_001	JET_002	JET_003	JET_004	JET_005	JET_006	JET_007	JET_008	JET_009	JET_010	PTM_001	PTM_002	MET_000	OIM_001	OIM_002	ODR_001	ODR_002	MDP_001
0003160	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	36.6	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0005003	4	0	3	0	1	2	1	1	0	2	0	0	0	0	0	0	76.1	72.2	173.0	UNDEF	UNDEF	UNDEF	UNDEF	1.834
0005115	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	37.6	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0005211	4	0	3	0	0	2	1	1	0	2	0	0	0	0	0	0	94.6	82.0	77.9	UNDEF	UNDEF	UNDEF	UNDEF	1.425
0007055	4	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	31.1	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0007418	4	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	104.3	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0008111	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	125.0	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0008333	4	0	4	0	1	1	1	0	0	1	0	0	0	0	0	0	36.4	UNDEF	27.7	UNDEF	UNDEF	UNDEF	UNDEF	0.175
0009493	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	111.8	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0009898	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	83.2	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010023	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	108.3	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010092	4	0	4	0	1	2	1	1	0	2	0	0	0	0	0	0	88.6	36.9	105.7	UNDEF	UNDEF	UNDEF	UNDEF	1.028
0010131	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	127.7	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0010219	4	0	4	0	1	2	1	0	0	1	0	0	0	0	0	1	79.0	UNDEF	46.5	UNDEF	UNDEF	UNDEF	UNDEF	2.291
0011575	4	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	93.9	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF
0013805	4	0	4	0	1	2	1	1	0	2	0	0	0	0	0	0	123.5	36.5	92.3	UNDEF	UNDEF	UNDEF	UNDEF	1.640
0015150	4	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	UNDEF	UNDEF	60.7	UNDEF	UNDEF	UNDEF	UNDEF	UNDEF

- Output is a set of tables reporting requested statistics & cut fractions
- It is often convenient to make no cuts at the lowest level, but only to compute
- Names such as "JET_001" have no invariant meaning - they are defined in a card_file

RHADAMANTHUS

(Recursively Heuristic Analysis, Display, And MANipulation:
The Histogram Utility Suite)

- Heuristic *adjective* \hyü-'ris-tik\ (www.merriam-webster.com)

  : using experience to learn and improve :

  involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods <*heuristic* techniques> <a *heuristic* assumption>; *also* : of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance <a *heuristic* computer program>

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_CHN_001 = DAT:[001,002,003], KEY:MET_000

PLT_HST_001 =
        IFB:300,
        CHN:001,
        LFT:0, RGT:1000, SPN:25,
        MIN:0.001, MAX:UNDEF,
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"
```

- Data Sets are built out of groups of ".cut" files from AEACuS
- Wildcards "*" are allowed to match multiple files
- Cross-sections are imported automatically
- Files with common trailing digits (name_NNN.cut) are averaged
- Files with unique names are summed

```
             "$t\overline{t}+$ 0-2 Jets",
             "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
             "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
      OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_CHN_001 = DAT:[001,002,003], KEY:MET_000
```

- Channels are built out of groups of datasets
- The plotting key refers to a statistic computed by AEACuS

```
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

Plot Card Example

- Histograms are built out of groups of channels
- Line continuation is indicated simply by indentation
- The luminosity may be specified in "IPB", "IFB", "IAB", etc.

```
PLT_HST_001 =
        IFB:300,
        CHN:001,
        LFT:0, RGT:1000, SPN:25,
        MIN:0.001, MAX:UNDEF,
        SUM:-1, NRM:0, AVG:3,
```

- By default, events are oversampled and scaled down to the target luminosity
- There is a warning on scale factors < 1
- Optionally specify trim at exact luminosity "IFB:[300,-1]"
- Bins are specified by "LFT" = left, "RGT" = right, "SPN" = bin span
- Optionally "BNS" = number of bins may be used instead of one prior
- "MIN" and "MAX" provide optional manual limits on range

Plot Card Example

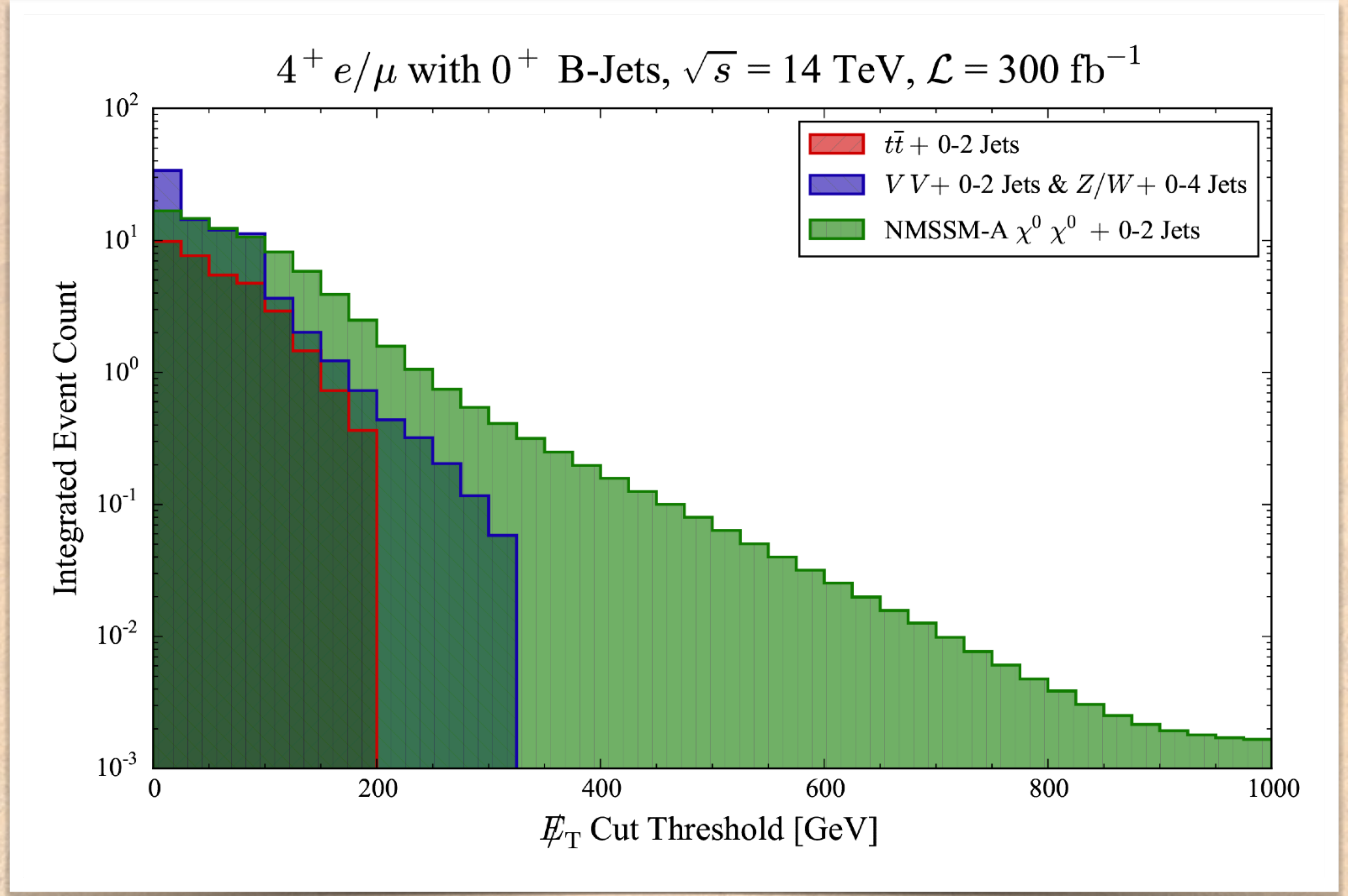
```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
```

- SUM +/- 1 compound bin counts to the right/left for threshold plots
- NRM facilitates normalization as for shape plots
- AVG engages bin smoothing with preservation of integrated counts
- LOG = 1/0 enables/disables logarithmic dependent axis

```
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$ with $0^+$ B-Jets, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[
                "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_0b_4l_300", FMT:"PDF"
```

- Inline LaTeX is used to input formulas for title, axis labels, and legends
- Several preconfigured notations are accessible via shorthand
- Available vector output formats include publication quality “EPS” & “PDF”
- Optionally specify intermediate Python source output “FMT:[PDF,1]”

Sample Plot Output

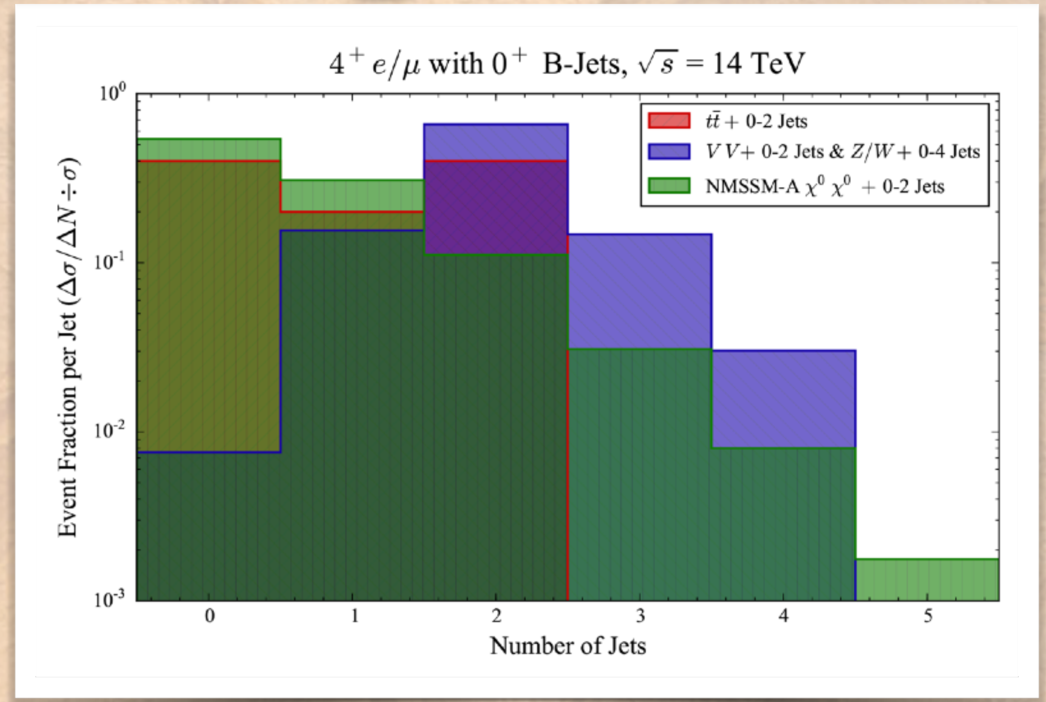


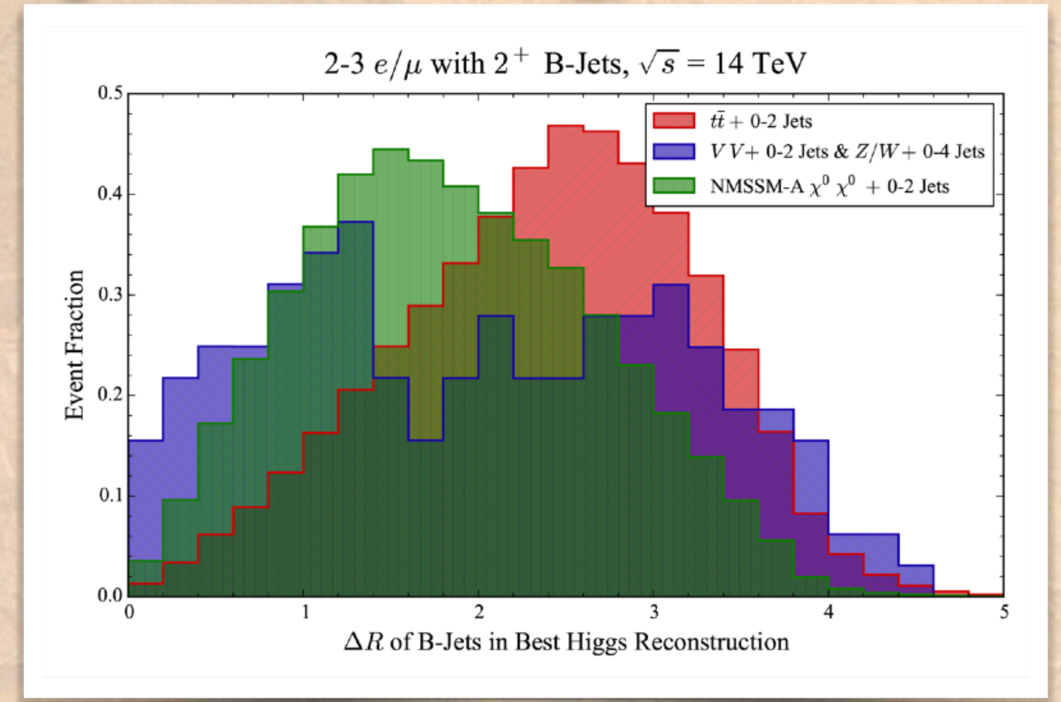
Optimize By Shape

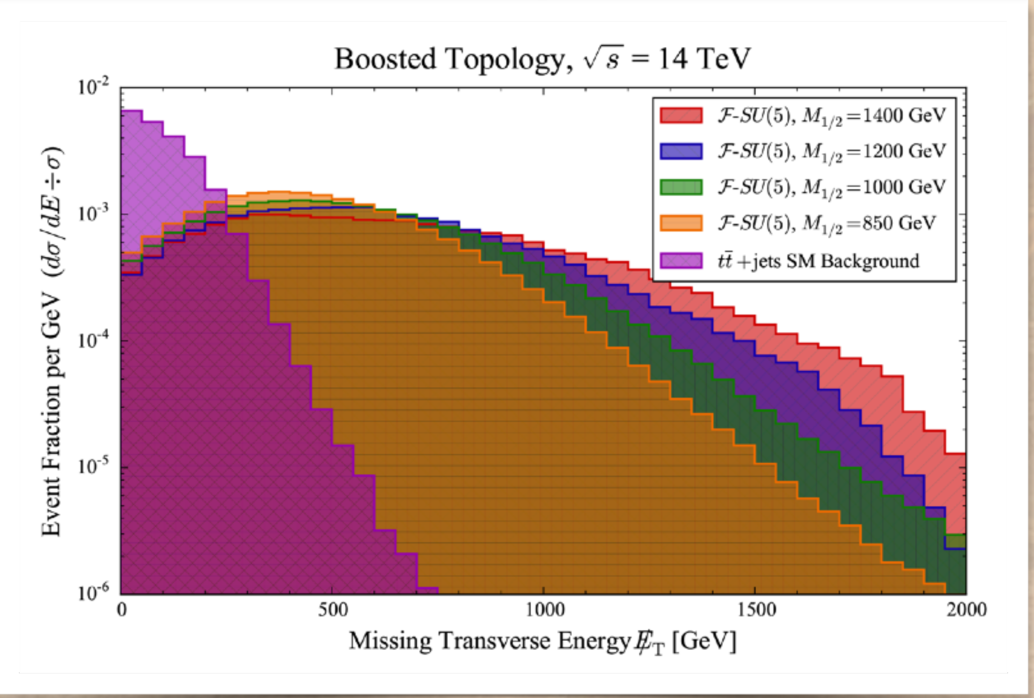
```
PLT_DAT_001 = DIR:"./Cuts", FIL:"Forward:BG:MEG:TTBAR_*"
PLT_DAT_002 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:850_*"
PLT_DAT_003 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1000_*"
PLT_DAT_004 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1200_*"
PLT_DAT_005 = DIR:"./Cuts", FIL:"Forward:FSU5_VBF_25:1400_*"

PLT_CHN_

PLT_HST_

         LFT:0, RGT:2000, SPN:50,
         MIN:0.000001, MAX:UNDEF,
         SUM:0, NRM:1, AVG:3,
         LOG:1, LOC:0, CLR:0,
         TTL:"Boosted Topology, <RTS> = 14 TeV",
         LBL:[    "Missing Transverse Energy <MET> [GeV]",
                  "Event Fraction per GeV  (<DEF>)" ],
         LGD:[    "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1400$ GeV",
                  "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1200$ GeV",
                  "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV",
                  "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 850$ GeV",
                  "$t\overline{t}+$jets SM Background" ],
         OUT:"./Plots", NAM:"met_shape_boosted_30", FMT:"PDF"
```

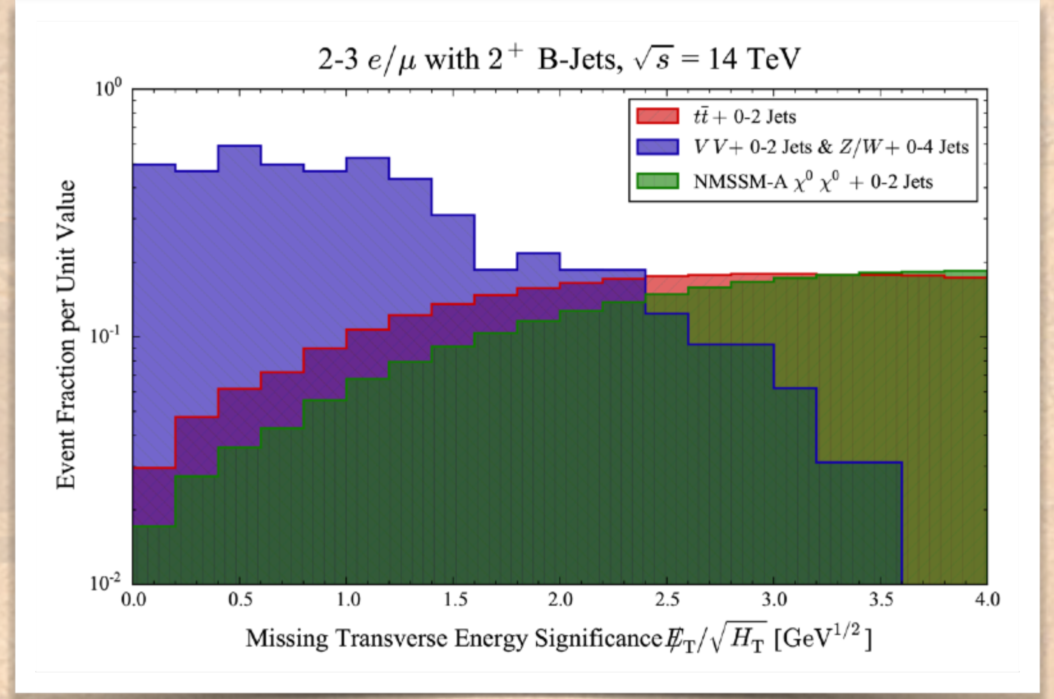
- **Shape plots are unit normalized**
- **They identify HOW to cut, e.g. threshold min/max vs. window**

Optimize By Shape









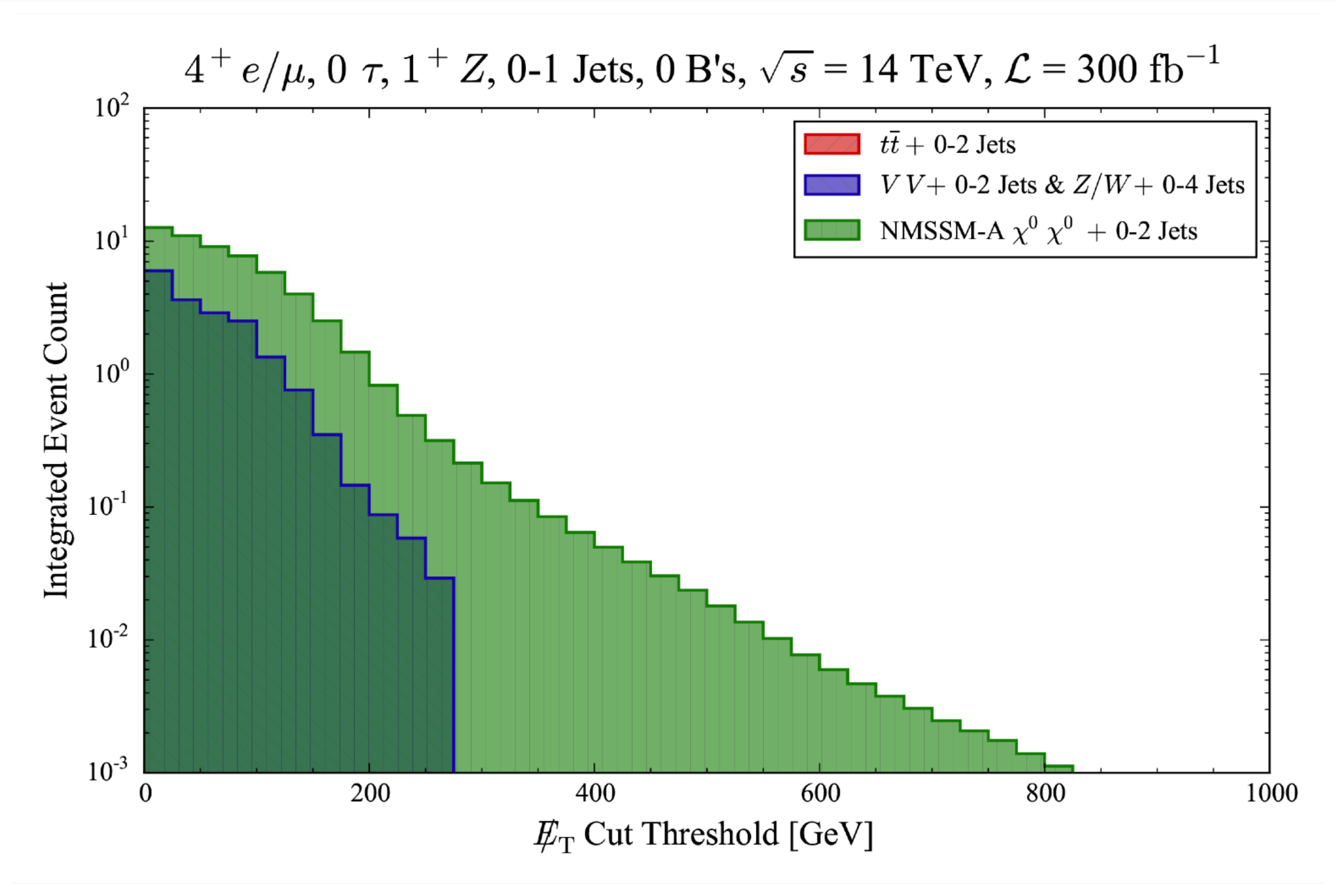
Apply Selection Cuts

```
PLT_DAT_001 = DIR:"./M3/0b_4l", FIL:"BG:MEG:TTBAR*"
PLT_DAT_002 = DIR:"./M3/0b_4l", FIL:["BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_003 = DIR:"./M3/0b_4l", FIL:"NMSSM:A:NMSSM*"

PLT_ESC_001 = KEY:LEP_002, CUT:[0,0]  # Veto Taus
PLT_ESC_002 = KEY:LEP_005, CUT:1      # Force 1 Lepton pair in Z Window
PLT_ESC_003 = KEY:JET_000, CUT:[0,1]  # Veto 2+ Jets
PLT_ESC_004 = KEY:JET_003, CUT:[0,0]  # Veto B's

PLT_CHN_003 = DAT:[001,002,003], KEY:MET_000, ESC:[+001,+002,+003,+004]
```

- Event Selection Cuts (ESC) are registered by AEACus key and range
- Channels may subscribe to any number of registered cuts

```
        SUM:-1, NRM:0, AVG:3,
        LOG:1, LOC:0, CLR:0,
        TTL:"$4^+e/\mu$, $0\,\tau$, $1^+Z$, 0-1 Jets, 0 B's, <RTS> = 14 TeV, <LUM> = 300 <IFB>",
        LBL:["<MET> Cut Threshold [GeV]","Integrated Event Count"],
        LGD:[   "$t\overline{t}+$ 0-2 Jets",
                "$V\,V+$ 0-2 Jets & $Z/W+$ 0-4 Jets",
                "NMSSM-A $\chi^0 \chi^0+$ 0-2 Jets" ],
        OUT:"./Plots", NAM:"event_count_MET_OPT_0b_4l_300", FMT:"PDF"
```

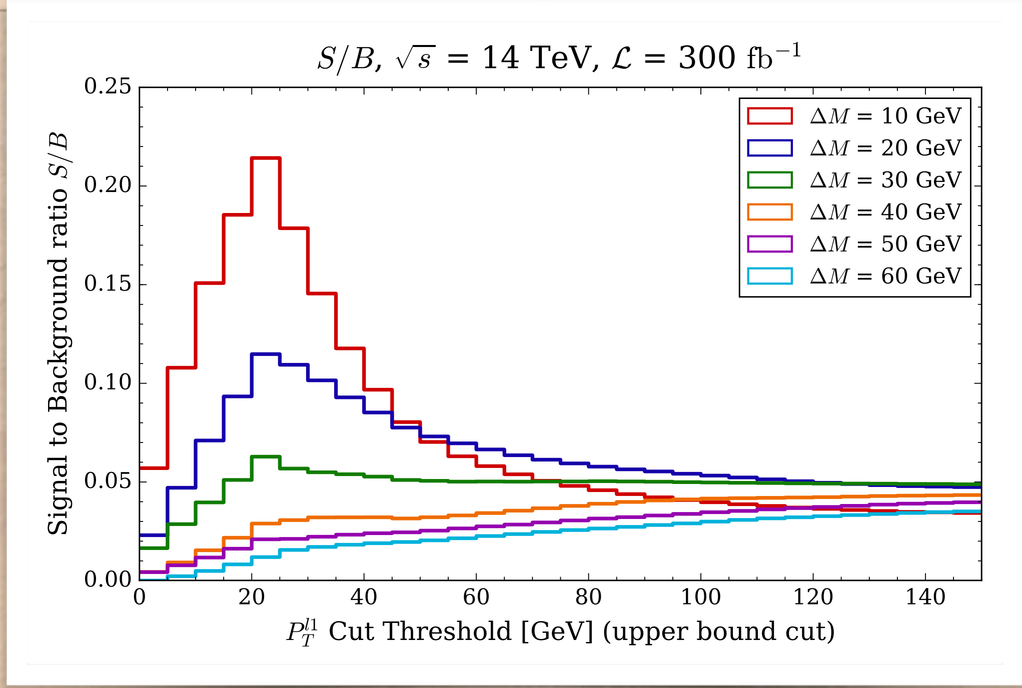
Optimized Plot Output

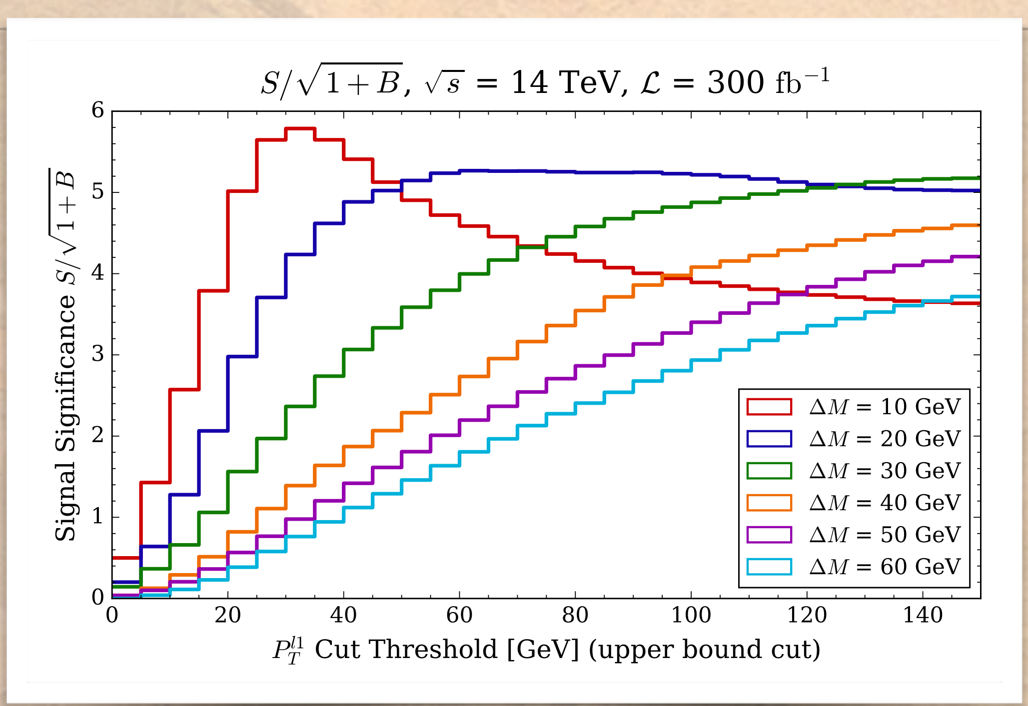


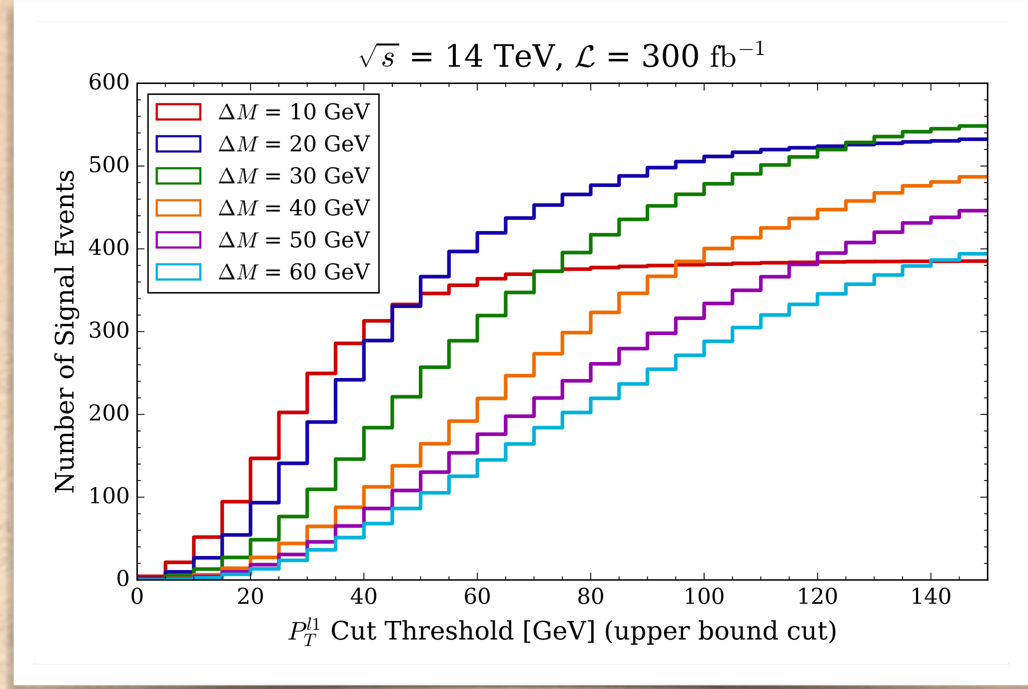
Transform Bin Channels

- User-defined functions of binned channels are allowed for specification of the dependent plotting variable
- Internal histogram object transparently applies the specified functional transformation bin-by-bin
- Channels with multiple data sets iterate automatically
- Single data sets expand to match large dimensionalities

Transform Bin Channels







- This is useful for taking arbitrary functions of merged channels, e.g. S/1+B, S/√1+B
- Useful for answering the question “WHERE to cut?”

Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_LSD", FIL:"Jets:BG:MEG:TTBAR_*"
PLT_DAT_002 = DIR:"./Cuts_LSD", FIL:"Jets:FSU5_VBF_25:850_*"
```

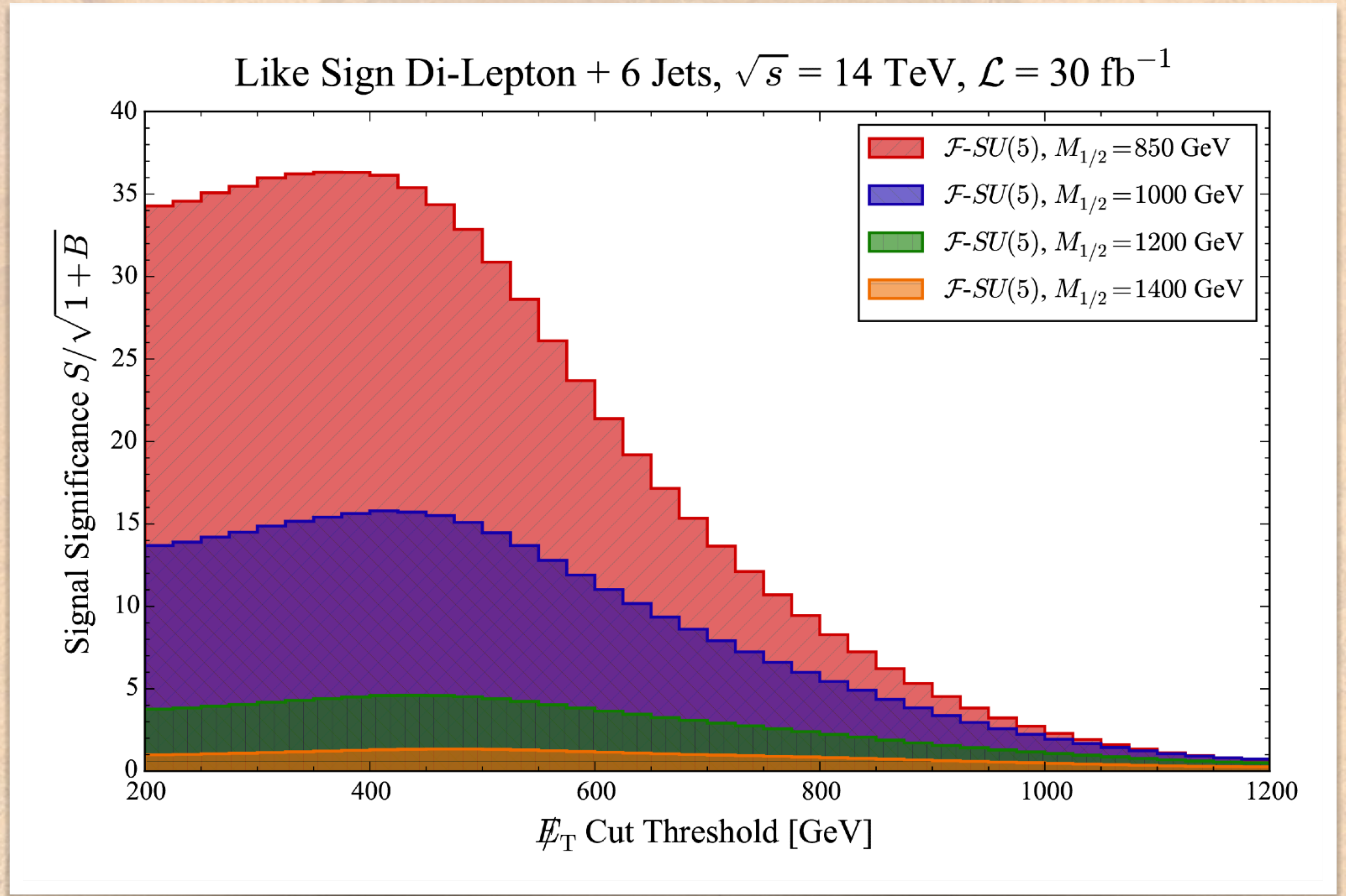
- Signal significance is computed here by combining Signal & BG
- Signal and BG use same key and subscribe to identical event selection cuts
- The single BG Channel is expanded to match four Signal Channels

```
        # One-dimensional background channel
PLT_CHN_001 = DAT:[001], KEY:MET_000, ESC:[+001,+002,+003,+004,+005]
        # Four-dimensional signal channel
PLT_CHN_002 = DAT:[002,003,004,005], KEY:MET_000, ESC:[+001,+002,+003,+004,+005]

PLT_HST_002 =
        CHN:{$2/SRT(1+$1),001,002},
        LFT:200, RGT:1200, SPN:25, BNS:UNDEF,
        MAX:UNDEF,
        SUM:-1, NRM:0, PER:UNDEF, AVG:3,
```

- For a lower bound threshold plot, integrate “SUM” from the left “-1”

```
        "Signal Significance <SIB>" ],
        LGD:[   "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 850$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1200$ GeV",
                "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1400$ GeV" ],
        OUT:"./Plots", NAM:"met_sig_LSD_30", FMT:"PDF"
```

Transform Bin Channels



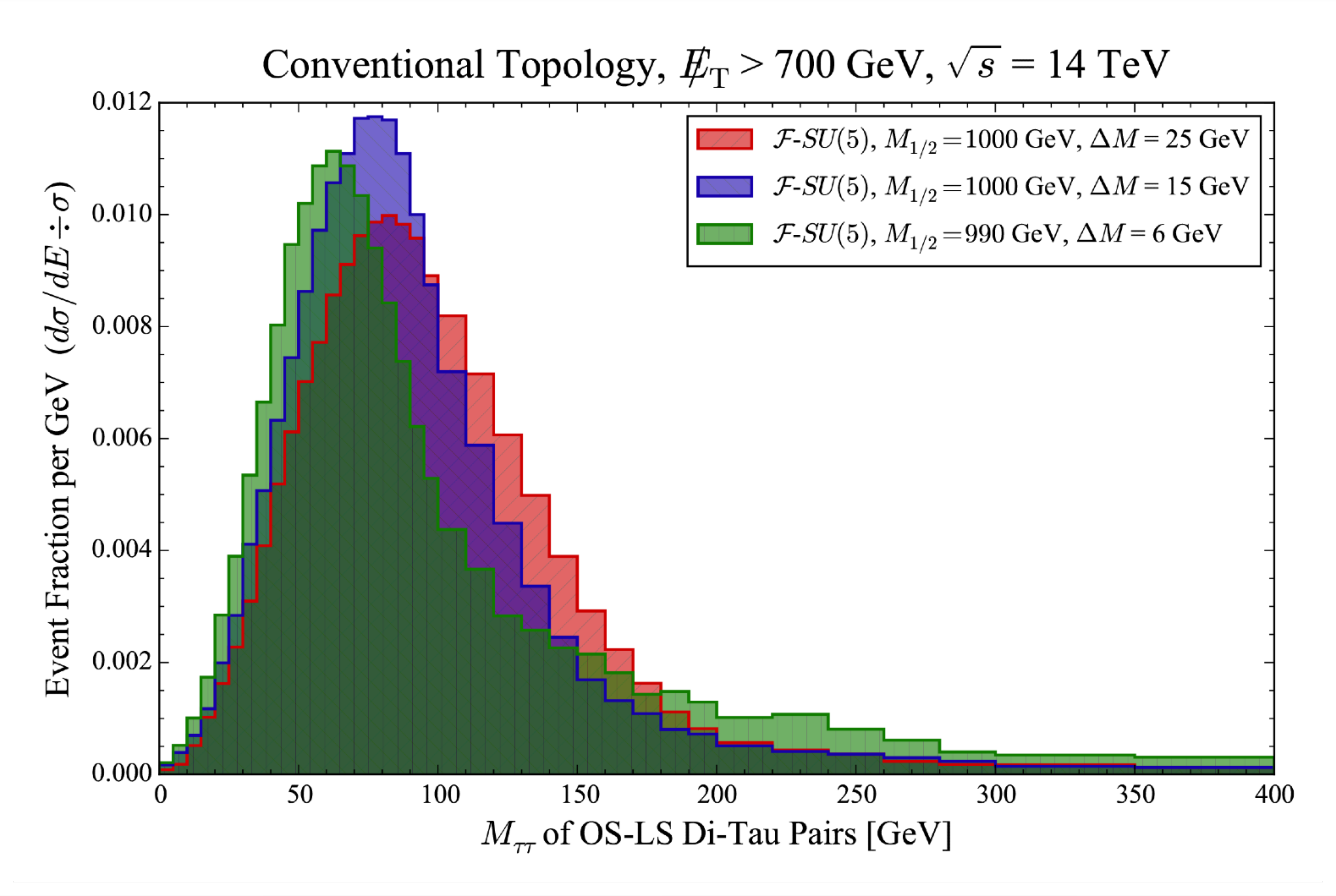
Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_25:1000_*"
PLT_DAT_002 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_15:1000_*"
PLT_DAT_003 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_6:990_*"

PLT_ESC_001 = KEY:PTM_001, CUT:400    # Leading P_T Cut
PLT_ESC_002 = KEY:PTM_002, CUT:200    # Sub-leading P_T Cut
PLT_ESC_003 = KEY:MET_000, CUT:700    # MET Cut
PLT_ESC_004 = KEY:DIL_001, CUT:1      # Same Sign Dilepton
PLT_ESC_005 = KEY:DIL_002, CUT:1      # Opposite Sign Dilepton

PLT_CHN_001 = DAT:[001,002,003], KEY:OIM_001, ESC:[+001,+002,+003,+004]
PLT_CHN_002 = DAT:[001,002,003], KEY:OIM_001, ESC:[+001,+002,+003,+005]

PLT_HST_001 =
        IFB:UNDEF,
        CHN:{($2-$1),001,002},
```

- Opposite- minus Like-Sign dilepton counts are binned on invariant mass
- The signal is compared to itself, subscribing to different selection cuts
- The operation is repeated over each of three registered data sets
- There is an internal limiter ensuring positive semi-def bin values

```
        OUT:"./Plots", NAM:"mtt_OS-LS_shape_DeltaM", FMT:"PDF"
```

Transform Bin Channels



Transform Bin Channels

```
PLT_DAT_001 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_25:1000_*"
PLT_DAT_002 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_15:1000_*"
PLT_DAT_003 = DIR:"./Cuts_MT2", FIL:"Central:FSU5_VBF_6:990_*"

PLT_ESC_001 = KEY:PTM_001, CUT:400    # Leading P_T Cut
```

- This example also demonstrates variable width binning
- Counts in wide bins are automatically scaled to preserve axis units
- The bin smoothing width “AVG” is independent for each data set

```
PLT_HST_001 =
        IFB:UNDEF,
        CHN:{($2-$1),001,002},
        LFT:0, RGT:[100,200,300,400], SPN:[5,10,20,50]
        MIN:0.0, MAX:UNDEF,
        SUM:0, NRM:1, AVG:[3,3,4],
        LOG:0, LOC:0, CLR:0,
        TTL:"Conventional Topology,  <MET> > 700 GeV, <RTS> = 14 TeV",
        LBL:[    "$M_{\tau \tau}$ of OS-LS Di-Tau Pairs [GeV]",
                 "Event Fraction per GeV  (<DEF>)" ],
        LGD:[    "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV, $\Delta M$ = 25 GeV",
                 "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 1000$ GeV, $\Delta M$ = 15 GeV",
                 "$\mathcal{F}$-$SU(5)$, $M_{1/2} = 990$ GeV, $\Delta M$ = 6 GeV" ],
        OUT:"./Plots", NAM:"mtt_OS-LS_shape_DeltaM", FMT:"PDF"
```

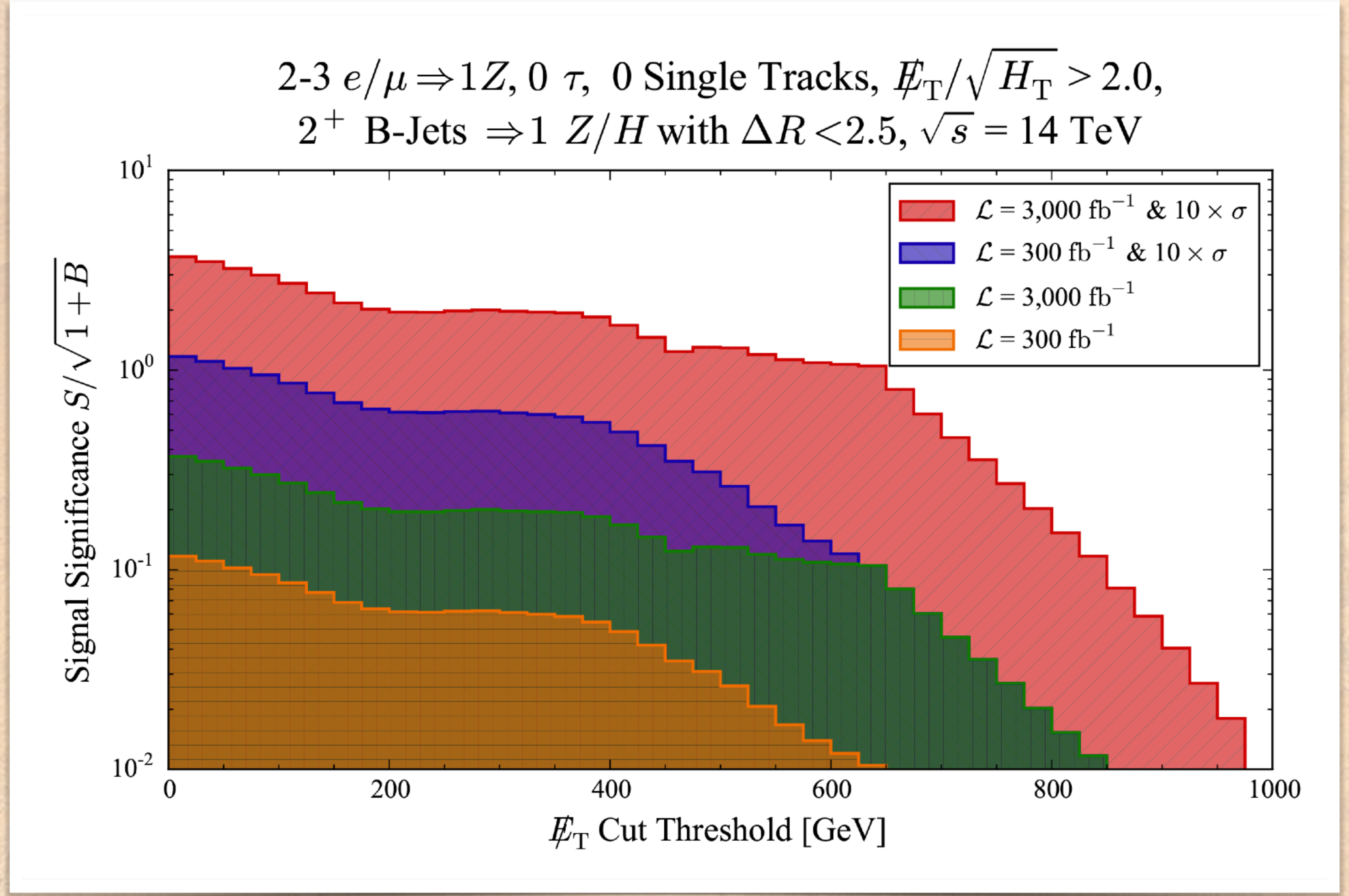
Transform Bin Channels

```
PLT_DAT_001 = DIR:"./M3/2b_2l",
        FIL:["BG:MEG:TTBAR*","BG:MEG:VVJJ*","BG:MEG:ZJJJJ*","BG:MEG:WJJJJ*"]
PLT_DAT_002 = DIR:"./M3/2b_2l", FIL:"NMSSM:A:NMSSM*"

PLT_ESC_001 = KEY:LEP_002, CUT:[0,0] # Veto Taus
PLT_ESC_002 = KEY:JET_007, CUT:1 # Force 1 B-Jet pair in Z/H Window
PLT_ESC_003 = KEY:LEP_005, CUT:1 # Force 1 Lepton pair in Z Window
PLT_ESC_004 = KEY:JET_010, CUT:[0,0] # Veto Single Track Jets
PLT_ESC_005 = KEY:ODR_001, CUT:[0,2.5] # Best Higgs Delta R < 2.5
PLT_ESC_006 = KEY:RHR_001, CUT:[2.0] # Met/root(HT) > 2

PLT_CHN_001 = DAT:001, KEY:MET_000, ESC:[+001,+002,+003,+004,+005,+006]
PLT_CHN_002 = DAT:002, KEY:MET_000, ESC:[+001,+002,+003,+004,+005,+006]

PLT_HST_001 =
        IFB:300,
        CHN:[  {100*$2/SRT(1+10*$1),001,002},
               {10*$2/SRT(1+$1),001,002},
               {10*$2/SRT(1+10*$1),001,002},
               {$2/SRT(1+$1),001,002} ],
        LFT:0, RCT:1000, SPN:2b
```

- Signal significance is again computed by combining Signal & BG Channels
- In this case the same channel is compared at two luminosity scale factors (1x,10x) and two cross section scale factors (1x,10x)

```
               "<LUM> = 3,000 <IFB>",
               "<LUM> = 300 <IFB>" ],
        OUT:"./Plots", NAM:"event_count_MET_OPT_sig_2b_2l_300", FMT:"PDF"
```

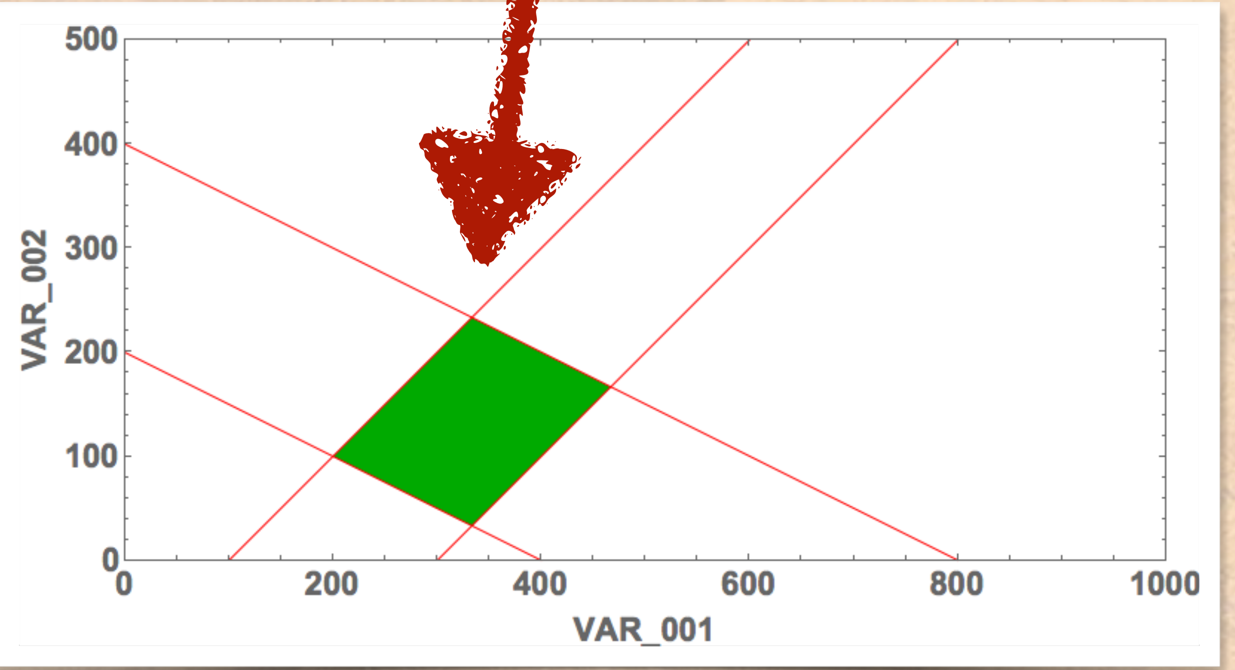
Transform Bin Channels



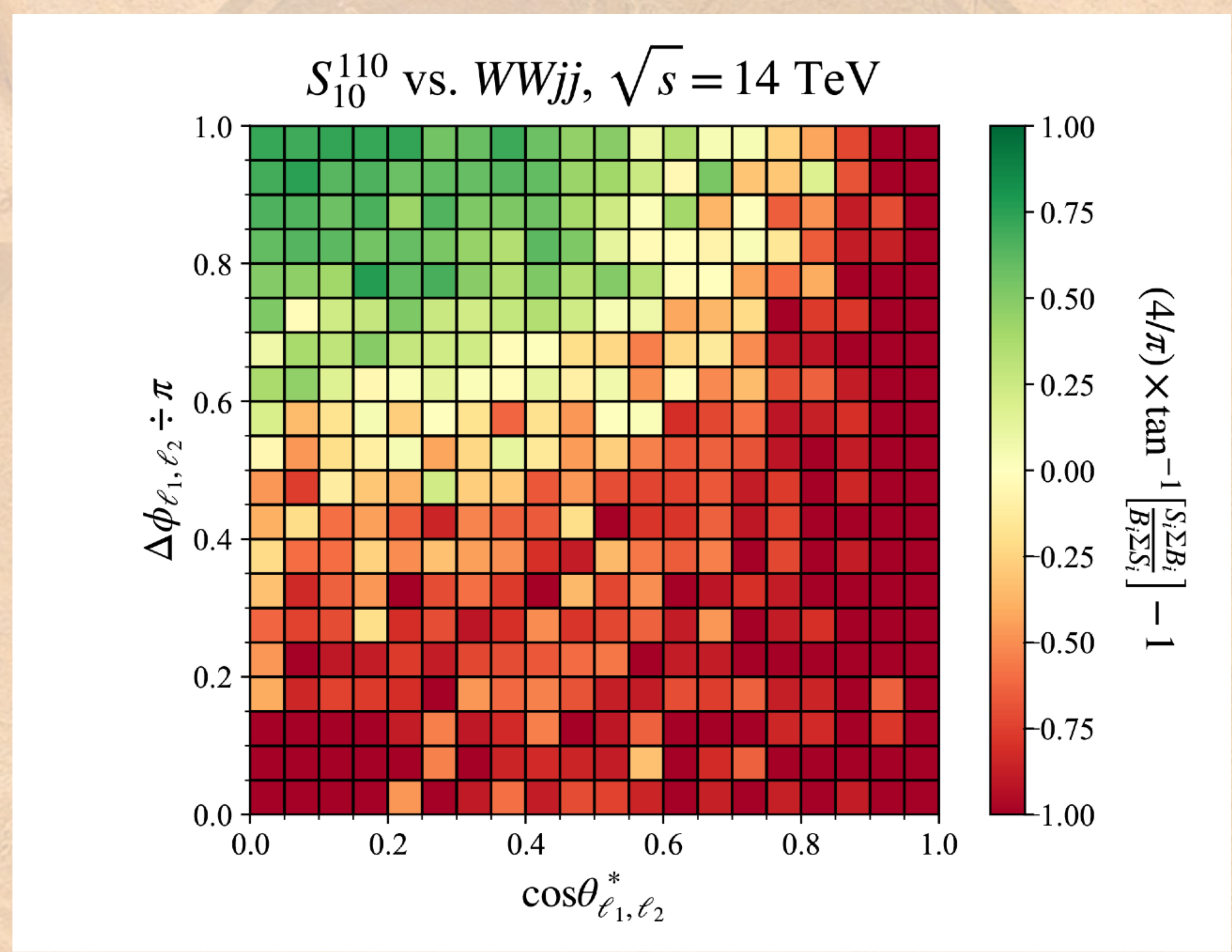
Transform Event Keys

```
        # Azimuthal Separation of two 4-vectors in range 0 to Pi
PLT_CHN_001 = DAT:[001,002,003], KEY:{PI()-ABS(PI()-ABS($2-$1)),PHI_001,PHI_002}

        # Compound rhomboid selection region in two variables
PLT_ESC_001 = KEY:{$2-$1,VAR_001,VAR_002}, CUT:[-300,-100]
PLT_ESC_002 = KEY:{$2+$1/2,VAR_001,VAR_002}, CUT:[200,400]
```

- User-defined compound functions of event keys are allowed for event selection and for specification of the independent plotting variable
- Available functions include basic arithmetic, trigonometry, roots, powers, logarithms, exponentials, min, max, integer, modulus, and average



2-D Histograms



2-D Histograms

```
    # Data sets are built from collections of files
DAT_001 = DIR:"./Cuts", FIL:"sl_110_n1_100_S14_001"
DAT_002 = DIR:"./Cuts", FIL:"S14_BG_WWJJ_*"

    # Event channels are built from Data sets,
    # referencing a pair (x then y) of keys,
    # which may be functionally transformed
    # using the curly-bracket notation
CHN_001 = DAT:001, KEY:[CTS_001,{$1/PIE(),ODP_001}]
CHN_002 = DAT:002, KEY:[CTS_001,{$1/PIE(),ODP_001}]

    # Two-dimensional histograms are built from
```

- **Channels are built out of a 2-D ARRAY of KEYS**
- **You can define multiple channels in order to combine them in some way**

```
    # pairwise vectorized inputs.  A second input
    # to the title key references the colorbar.
H2D_001 =
CHN:{(4/PIE()*ATN($1,$2)-1),001,002},
LFT:0, RGT:1, BNS:20, NRM:-1, MIN:-1, MAX:+1,
TTL:["$S_{10}^{110}$ vs. $WWjj$, $\sqrt{s} = 14$ TeV",
    "$(4/\pi) \times \tan^{-1}\left[\frac{S_i \Sigma B_i}{B_i \Sigma S_i}\right]-1$
LBL:["$\cos \theta^*_{ \ell_1,\ell_2}$", "$\Delta \phi_{\ell_1,\ell_2} \div \pi$"],
NAM:"H2D_CST_ODP"
```

2-D Histograms

```
   # Data sets are built from collections of files
DAT_001 = DIR:"./Cuts", FIL:"sl_110_n1_100_S14_001"
DAT_002 = DIR:"./Cuts", FIL:"S14_BG_WWJJ_*"
```

- **Ultimately, use a SINGLE 2-Dimensional Channel for plotting**
- **LFT/RGT can be arrays if different x-y ranges are required**
- **MIN/MAX are now the range of “z” values**

```
   # Two-dimensional histograms are built from
   # a single two-dimensional event channel,
   # which may represent a cell-by-cell functional
   # transformation of one or more basic channels.
   # Binning specifications and axis labels accept
   # pairwise vectorized inputs.  A second input
   # to the title key references the colorbar.
H2D_001 =
CHN:{(4/PIE()*ATN($1,$2)-1),001,002},
LFT:0, RGT:1, BNS:20, NRM:-1, MIN:-1, MAX:+1,
TTL:["$S_{10}^{110}$ vs. $WWjj$, $\sqrt{s} = 14$ TeV",
    "$(4/\pi) \times \tan^{-1}\left[\frac{S_i \Sigma B_i}{B_i \Sigma S_i}\right]-1$
LBL:["$\cos \theta^*_{ \ell_1,\ell_2}$", "$\Delta \phi_{\ell_1,\ell_2} \div \pi$"],
NAM:"H2D_CST_ODP"
```

AEACuS &
RHADAMANTHUS

- The joint package is now ready to use, available at GitHub
- https://github.com/joelwwalker/AEACuS
- There are four simple EXAMPLES to get started
- Please contact author directly: `jwalker@shsu.edu`
- Full documentation is pending
- If you are interested in teaming up, borrowing features, building a recast library, or doing validations, please Let Me Know!