Search For Displaced Leptons in $\sqrt{s}$ = 13.6 TeV pp Collisions with the ATLAS Detector

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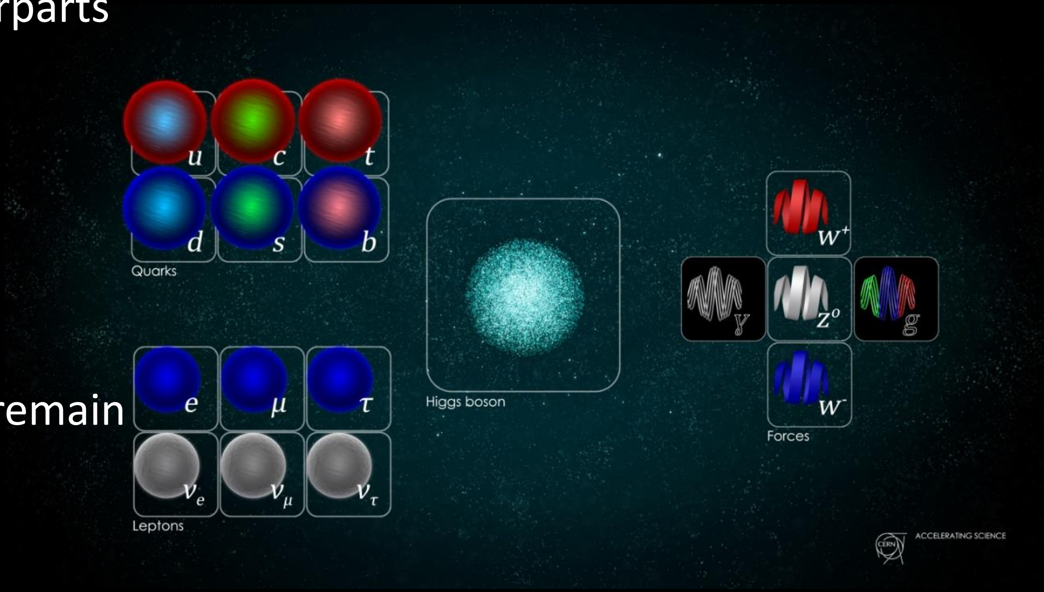
2023 REU PROGRAM AT COLUMBIA UNIVERSITY – NEVIS LABS

Outline

The Standard Model

The Standard Model (SM) is a well-tested theory that best characterizes the interactions between fundamental particles and three of the four fundamental forces; however, it is incomplete.

- Fermions – matter particles with spin ½
  - Quarks
  - Leptons
    - Electron, muon, tau + electrically neutral counterparts (neutrinos)
- Bosons – force mediators with integer spin
  - Gluons: Strong Force, spin 1
  - Photon: Electromagnetic Force, spin 1
  - W and Z Boson: Weak Force, spin 1
  - Higgs Boson: imparts mass to particles, spin 0
- Phenomena such as the dark matter, and "grand unification" remain a mystery!

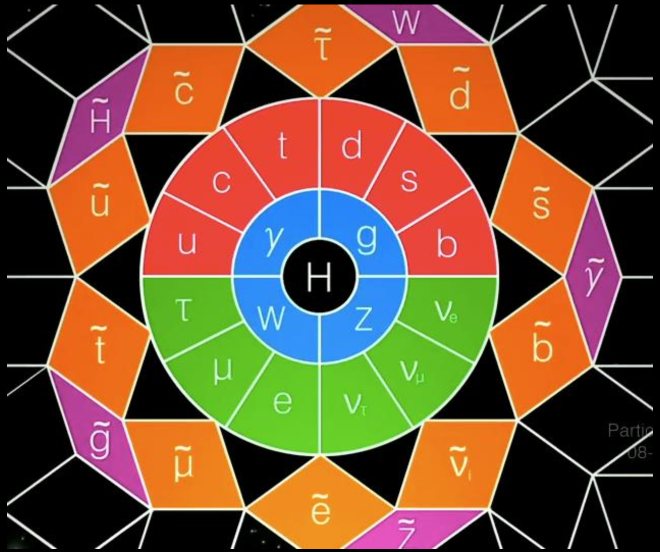


Supersymmetry

Supersymmetry (SUSY) is a hypothesized extension of the Standard Model most notable for proposing well-motivated dark matter candidates and presenting an elegant connection, or “unification” fundamental forces

A spin symmetry:

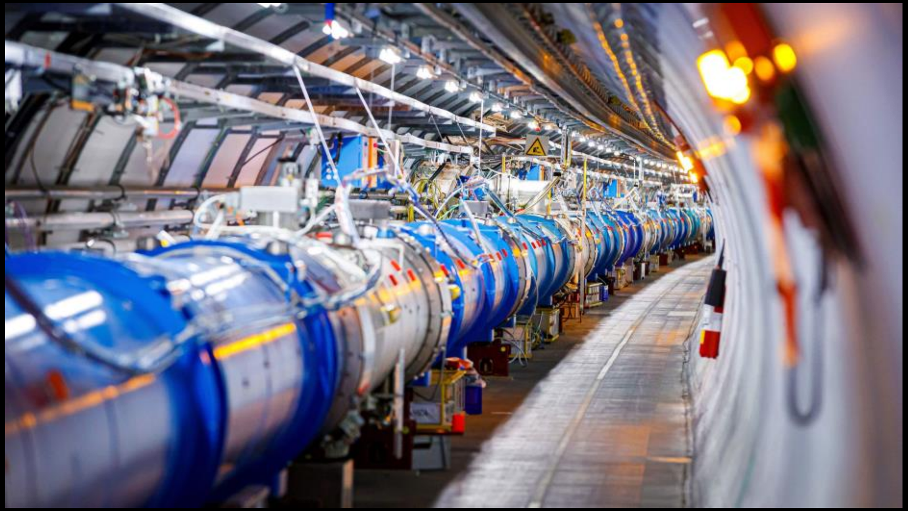
- Predicts each standard model particle has a nearly identical super-symmetric particle partner – differs by spin value
    - Fermions have boson “superpartners” with spin 0, bosons have fermion “superpartners” with spin ½
- A Broken symmetry…
    - Observed phenomena have shown electron is the lightest spin ½ particle
    - Indicates SUSY particles are likely heavy than their SM partners
- In R-parity conservation models, the lightest SUSY particle (LSP) is stable and neutral, thus acting as a great dark matter candidate
- SUSY manifestations at high energies lead to the unification of the strong, weak, and electromagnetic force



The Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and highest-energy particle accelerator. The primary focus of the LHC is to use high-energy collisions to "probe" answers about the most fundamental particles of our universe.

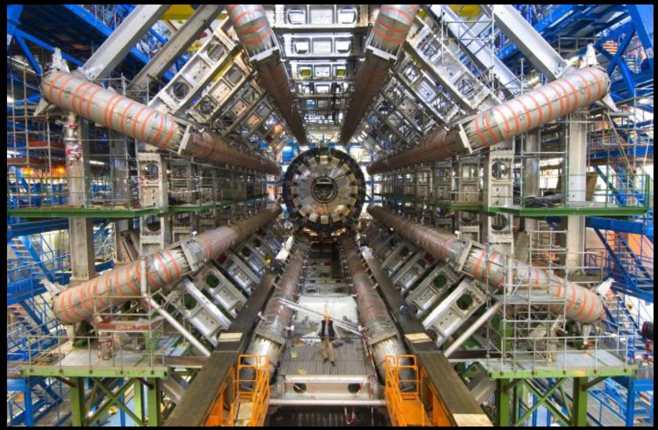
- The LHC operates in a 27 km loop
- Accelerates hadrons, specifically protons and heavy ions
- Superconducting magnets guide the trajectory of the particles
- There are four main experiments of the LHC, including:
    - ATLAS
    - CMS
    - ALICE
    - LHCb

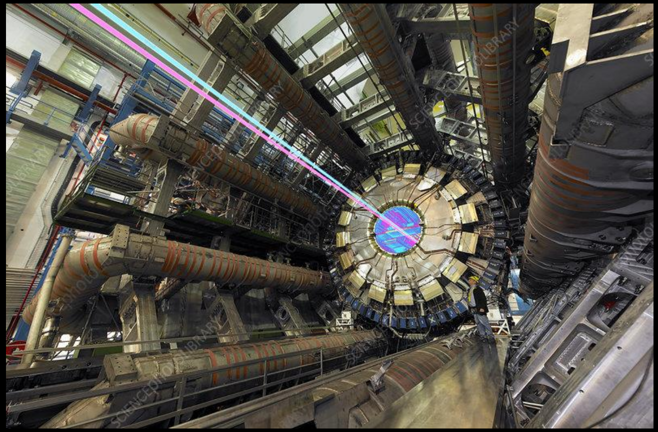


The ATLAS Detector

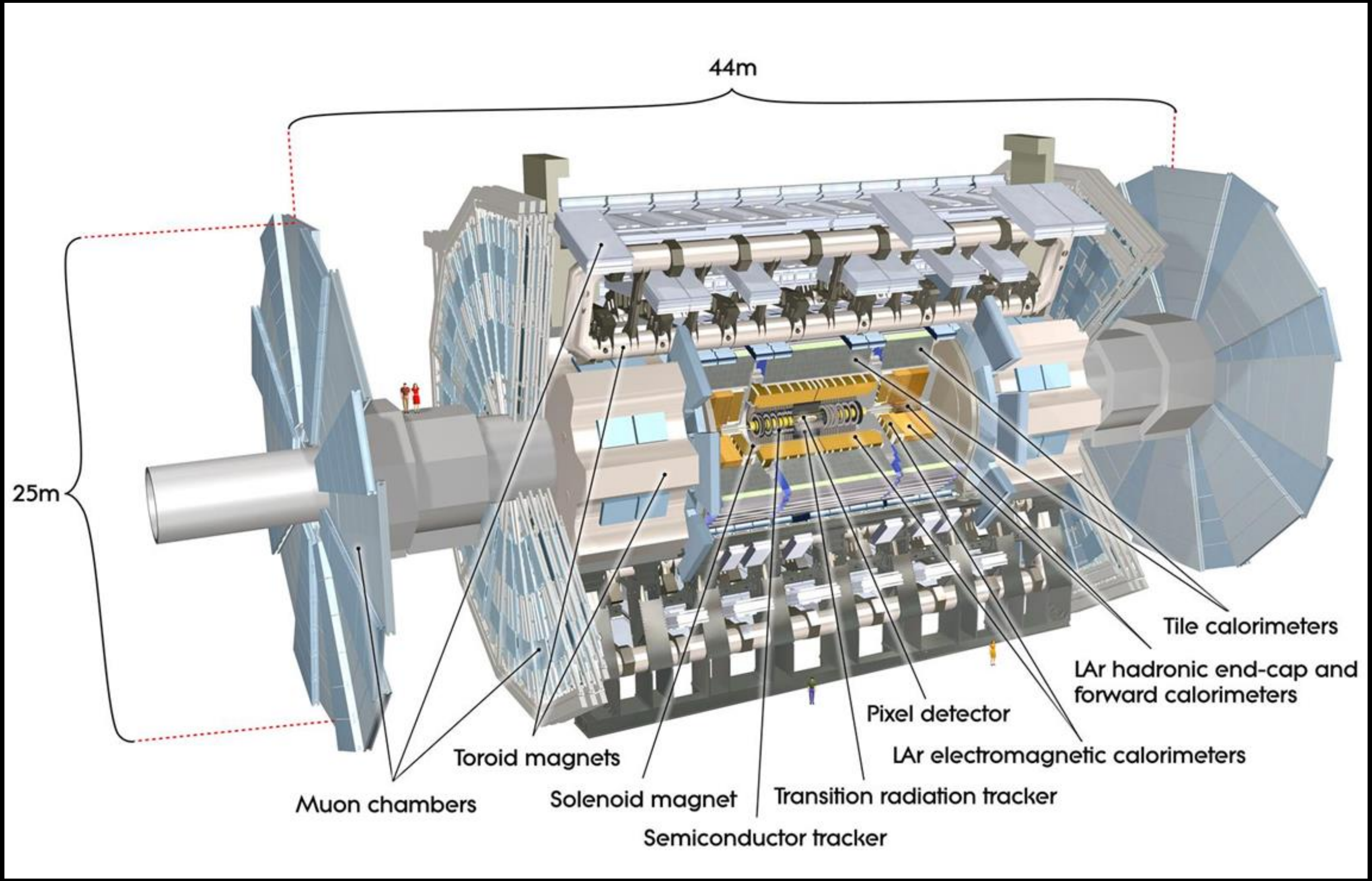
ATLAS is a general-purpose detector with uses ranging from precision measurements of the Higgs Boson mass to searches for beyond-standard model (BSM) physics.

- ATLAS: A Toroidal LHC ApparatuS
- Four Major Subsystems:
    - Inner Detector:
        - Closest subsystem to initial particle collision. Measures direction, momentum, and charge (of electrically-charged particles)
    - Calorimeters
        - Measures energy of particles passing through the detector.
        - Liquid Argon (LAr) Calorimeter – electrons and photons
        - Tile Hadronic Calorimeter – hadrons
    - Muon Detector:
        - Measures momentum of muons
    - Magnet System:
        - Modifies the trajectories of charged particles through the usage of solenoidal and toroidal superconducting magnet systems.





The ATLAS Detector



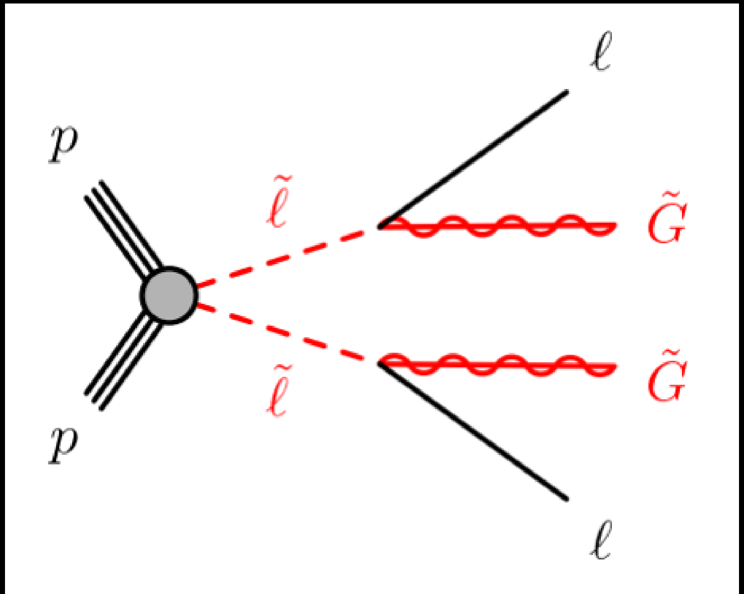
Outline

1. Introduction
   a) The Standard Model
   b) Supersymmetry
   c) Instrumentation
2. The Search For Displaced Leptons
   a) Motivation
   b) BDT Introduction
   c) 1eBDT
   d) 2eBDT
3. Event Level vs Object Level Tagger BDT
   a) 1eBDT on a 2e Signal Region
   b) Efficiency Comparisons
   c) Visuals
4. Conclusions and Next Steps

Search for Displaced Leptons: Motivation

We search for displaced leptons with specific characteristics as potential indicators of long-lived SUSY particles. Long-lived particles (LLPs) are features of many SUSY models and can travel partway through the detector before decaying, resulting in a displaced/delayed lepton.

- We choose a benchmark Gauge-Mediated Supersymmetry Breaking (GMSB) model in which:
    - A long-lived (lifetime time between 1 ps and 100 ns) slepton to be pair produced from the initial proton-proton collision
    - Slepton can travel partway through the detector before decaying
    - Decay products of this slepton are an undetectable gravitino and a displaced lepton
        - The Columbia effort is focused on the case where the slepton is a selectron, therefore an electron decay product is the object of our search



Feynman Diagram of the pair-produced sleptons from the initial proton-proton collision and their decay into a displaced lepton and a gravitino

Signal Regions

The electrons we are searching for are displaced, meaning the ATLAS detector does not always reconstruct displaced electrons as electrons. We need to consider each signal region a displaced lepton might be reconstructed as.

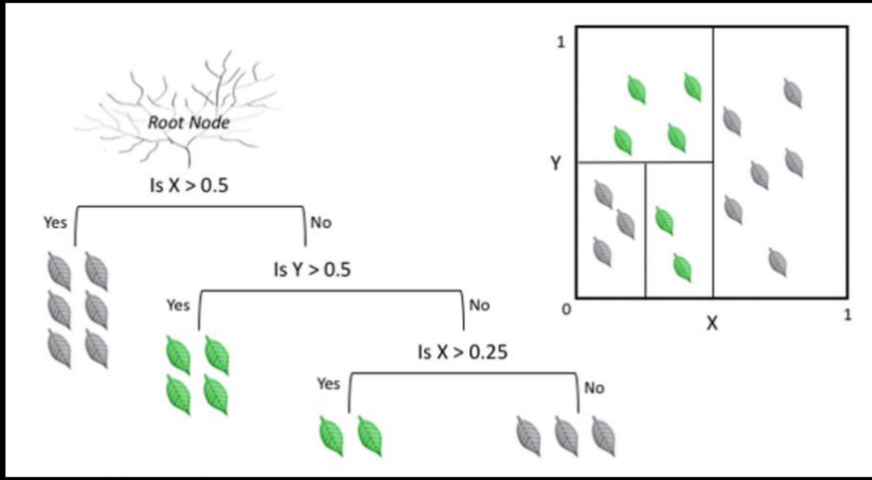
- Five potential final states that could indicate the decay products of a SUSY particle
    - 1 electron (1e), 1 photon (1γ), 2 electrons (2e), 2 photons (2γ), and 1 photon and 1 election (eγ)

- The BDTs implemented in this analysis are used in the 1e and 2e signal regions

BDT Introduction

Boosted decision trees (BDTs) are a type of machine learning algorithm that classifies events based on known parameters (input variables) and signal/background classes.

- Takes the form of a rooted binary tree when considering two class labels (i.e., signal and background)
- Boosting
    - Optimizes BDT performance and increases stability
    - At a high level, boosting uses classification errors from previously tested trees to improve the performance of a new decision tree
- Cross Validation
    - Classification analyses consist of a training and testing phase
    - Cross-validation ensures these events are independent – i.e., not testing our tree on events it has been trained over
    - Our BDT uses k-fold cross validation

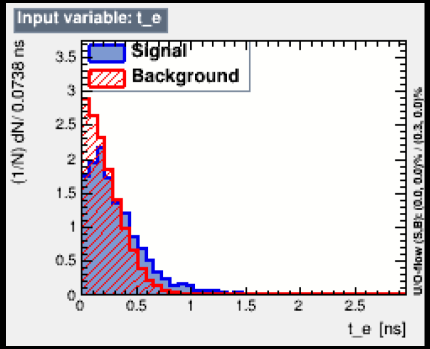


Animation of a generic decision tree algorithm. X and Y are input variables, and conditions applied to nodes are used to split the set of elements.

BDT Preselection

The data used in this classification analysis comes from Run 3 ATLAS data taken in 2022 and from Monte-Carlo generated signal events. This analysis looks at 2 signal regions of interest and makes cuts on the inputs, so we consider only relevant data. However, compared to Run 2 cuts, these cuts are very agnostic.

- Control Region: electron time of arrival < 0
  - Used to blind data
  - Ensures we are looking at a region of space with very few expected signal events



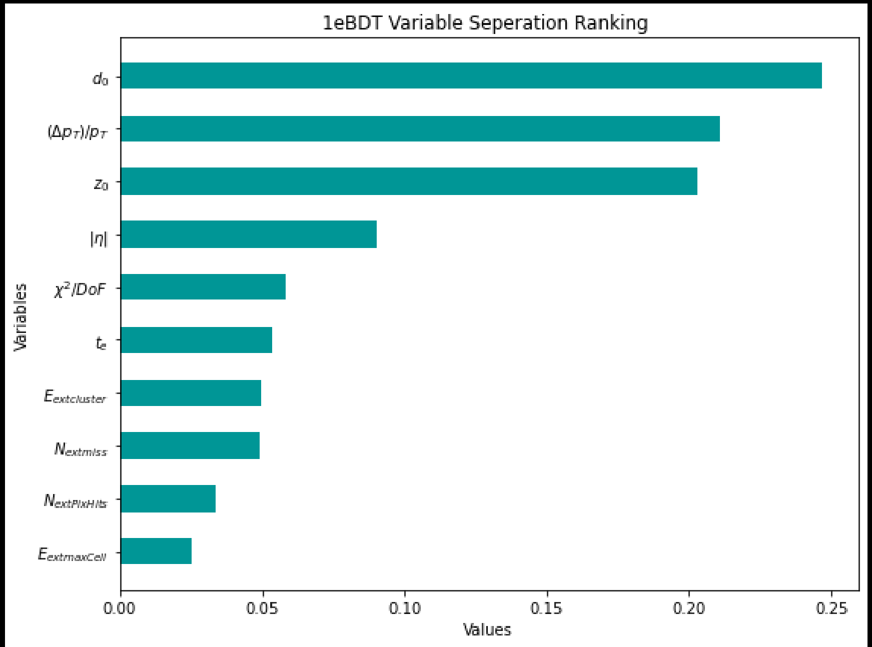
- Signal MC:
  - Lifetimes: 1ps – 30ns
  - Masses: 200GeV-900GeV
  - For each signal region: p_T + trigger cuts (e30LRT), η cuts (excludes crack values), ID and isolation cuts, veto on W mass, truth matched

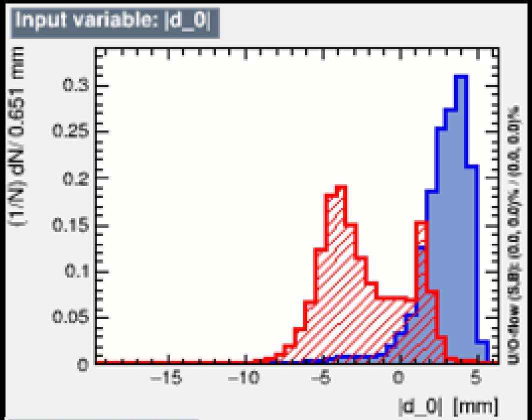
Key	
e30LRT	Large Radius Tracking - trigger implemented in Run 3 – reconstructs displaced/delayed electrons
1e (2e) m_T < 60 GeV (80 GeV) **OR** m_T > 100 GeV (100 GeV)	Used to ignore W Boson decays that also produce electrons with missing m_T
ID and Isolation Cuts	Modified Loose ID; doesn't include cuts on variables such as d_0 or pix hit

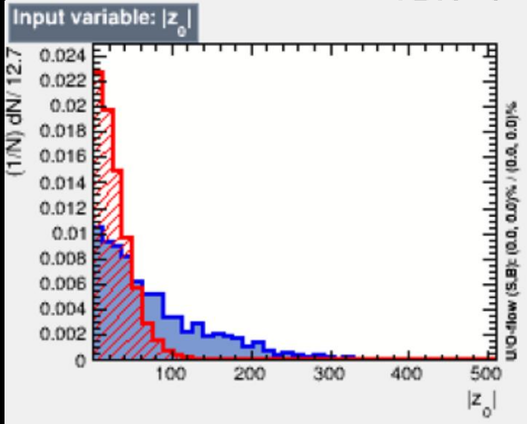
1eBDT – Inputs

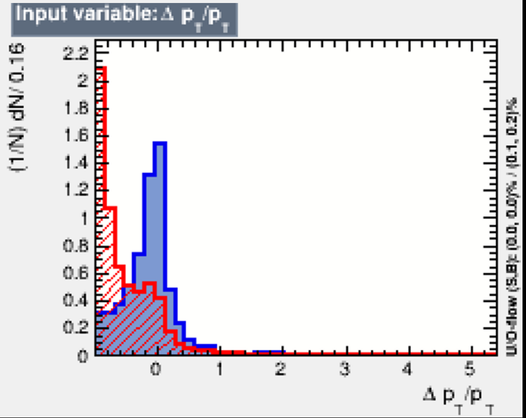
BDT ranks variables by their separation:

- Separation - $s/\sqrt{b}$
  - s → signal events left after split
  - b → background events left after split









d_0: Distance of closest approach from extrapolated electron track to the primary vertex in the longitudinal plane

z_0: Distance of closest approach from extrapolated electron track to the primary vertex in the transverse plane

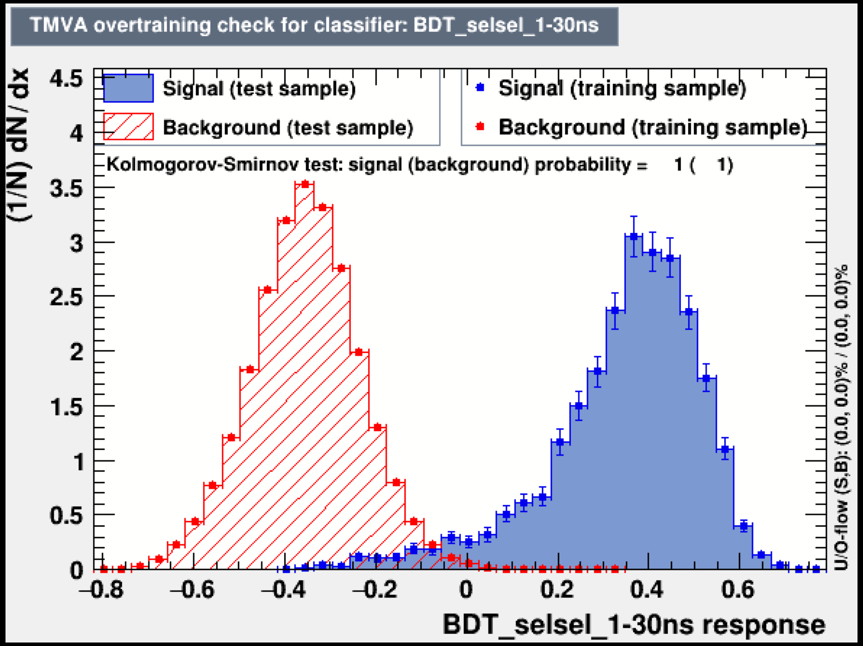
p_T: momentum of the transverse plane

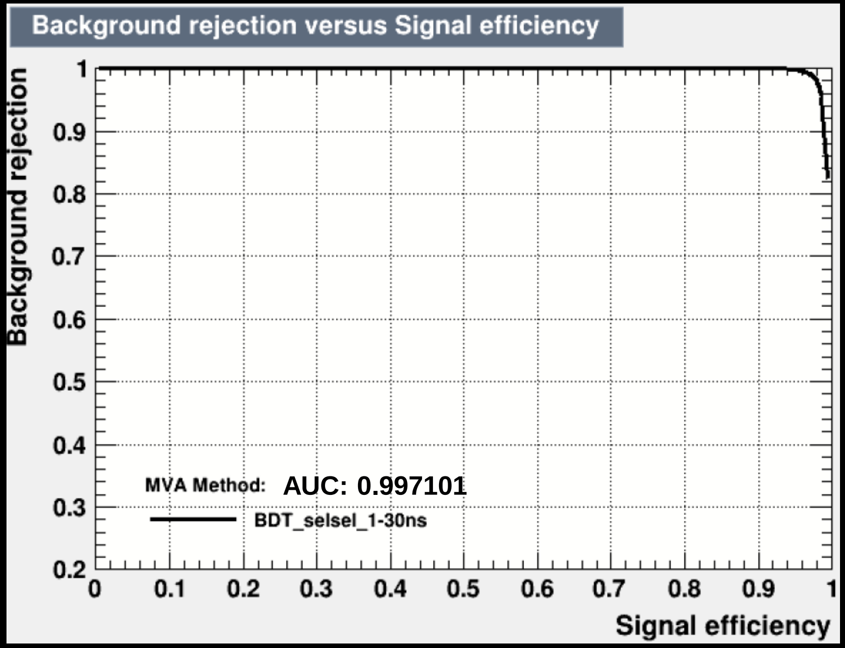
$\frac{p_{T,track} - p_{T,cluster}}{p_{T,cluster}}$: Percent difference between transverse momentum of the electron track and electron shower in the calorimeter

1eBDT – Output Plots

These plots summarize the strength of the BDT. Less overlap between the red and blue curves, and a larger area under the black curve = better BDT.

- Output Plot (Left):
  - Uses BDT "weights" to give a score regarding how signal-like an event is
- Receiver Operating Characteristic (ROC) Plot (Right):
  - Representation of a binary classifier
  - Plots true positive rate against false positive rate → signal efficiency vs background rejection

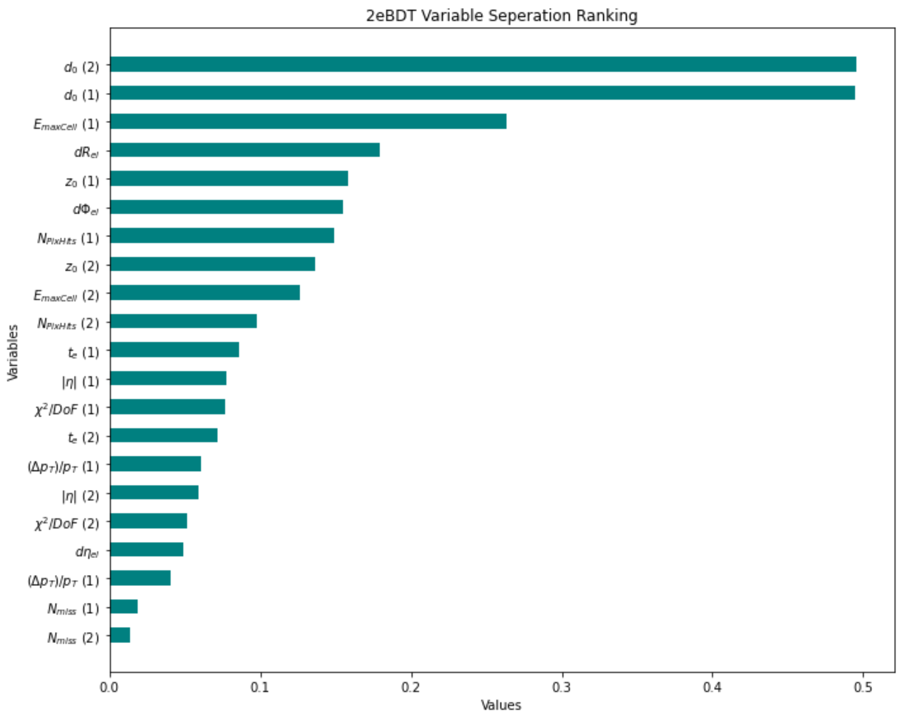


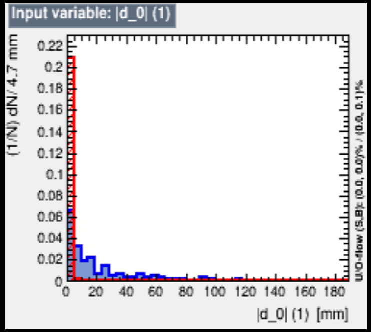


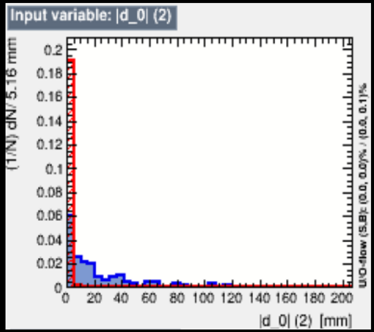
2eBDT – Inputs

Corresponding ranking plot for the 2eBDT:

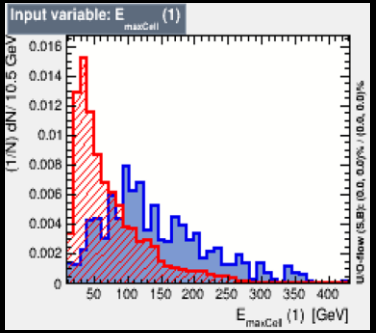
- New BDT created for the 2e signal region
- All variables applied in 1eBDT applied here – for leading and subleading electron
- Also add correlation variables: dR, dPhi, dη



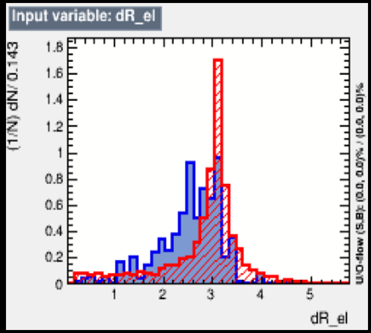




$d_0(1)$ $d_0(2)$ highly ranked – similar to the 1eBDT



$E_{maxCell}$: Energy deposited in the calorimeter cell that received the most energy from this electron.



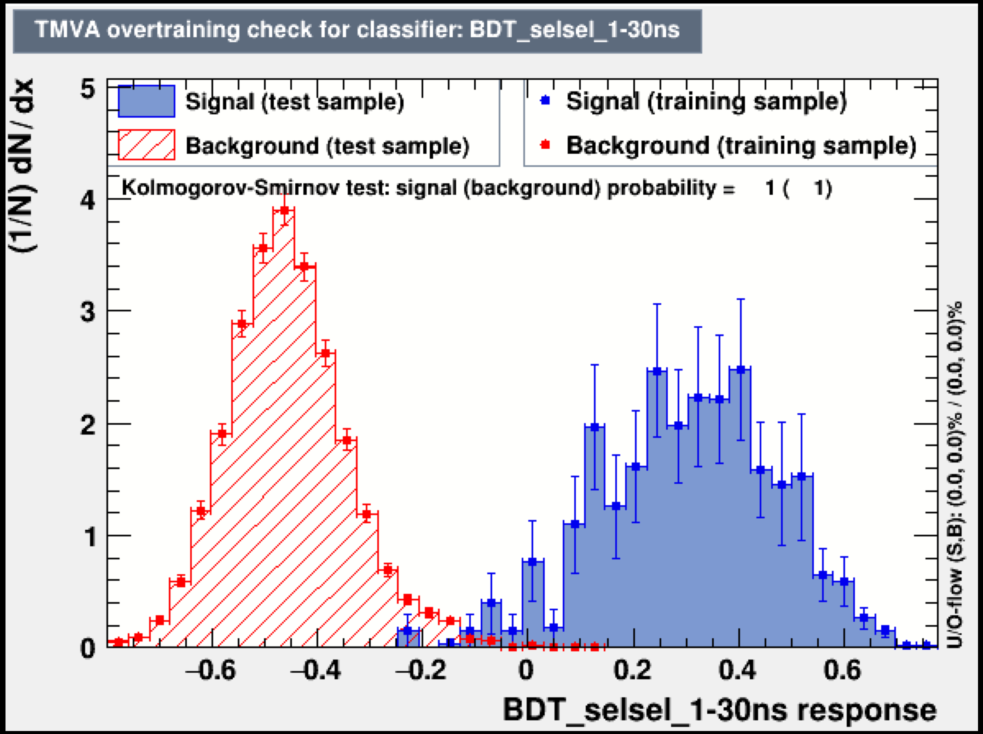
dR_{el}: $\sqrt{(d\phi)^2 + (d\eta)^2}$

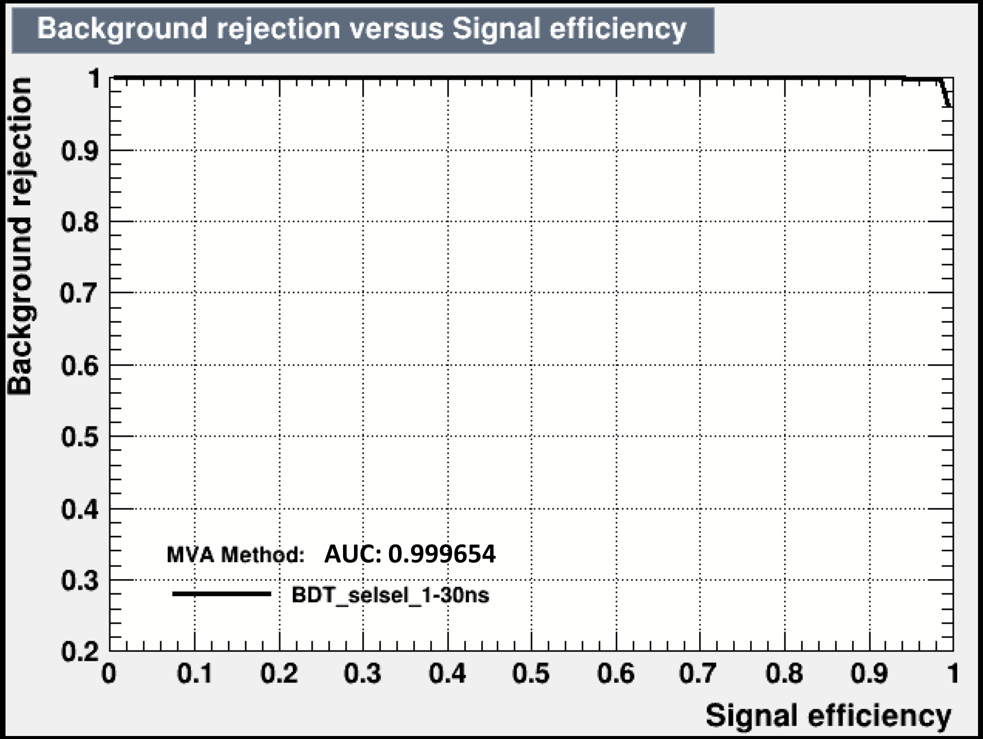
ϕ: angle in transverse plane

η: Pseudorapidity, a spatial coordinate that specifies the angle of a particle relative to the beam axis. Defined as $-\ln(\tan\frac{\theta}{2})$

2eBDT – Output Plots

Corresponding output plots for the 2eBDT weights.





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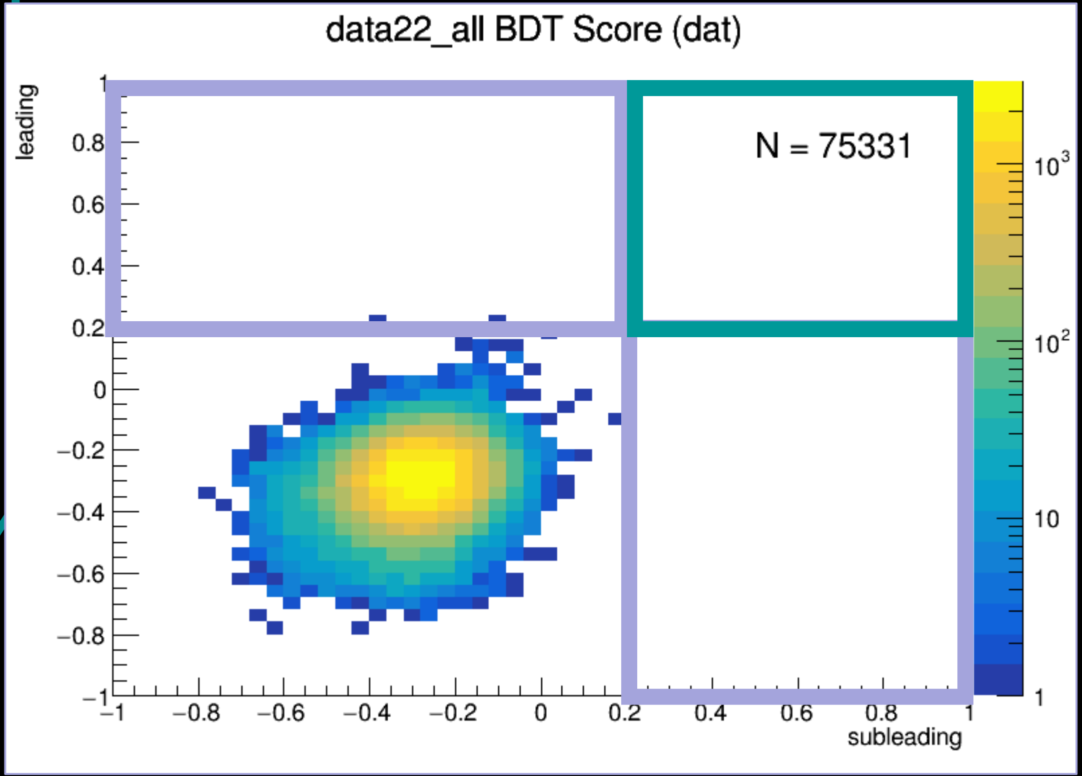
Event Level vs Object Tagger BDTs

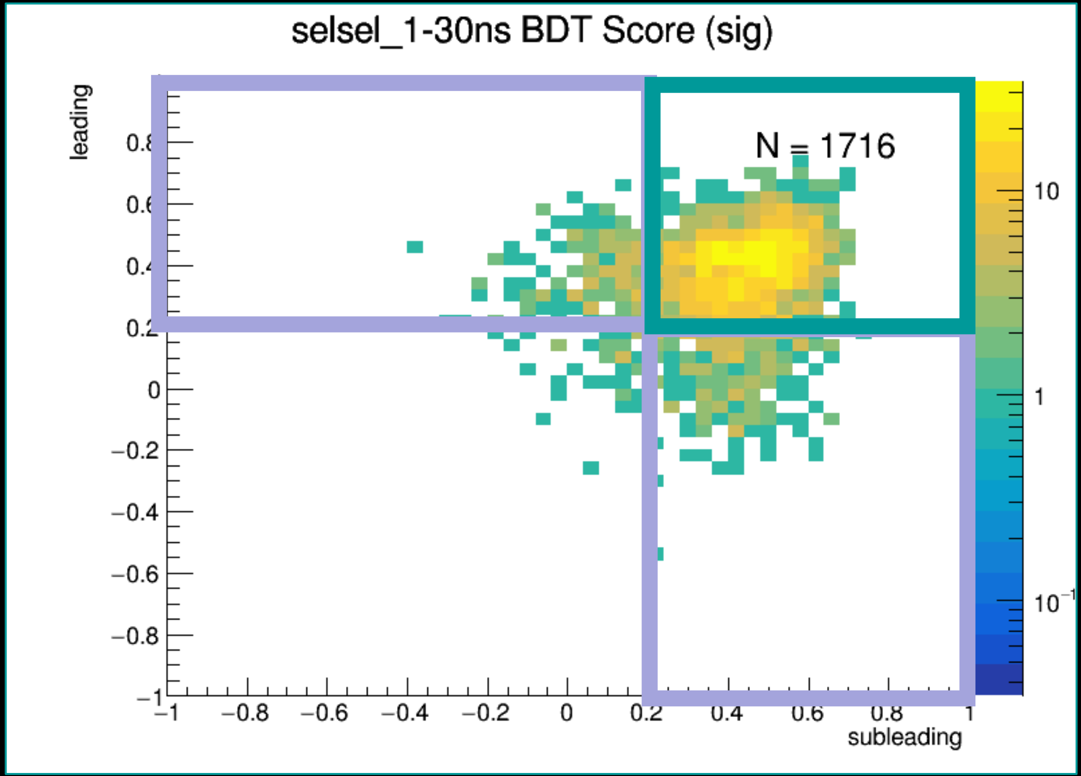
Before we had a BDT specific to the object's topology – this requires more knowledge about variables such as the opening angle between electrons, differences in $p_{T,}$ etc. An object-level BDT is more model-independent and uses generic electron characteristics to classify an event as displaced.

- In the BDTs shown previously (specifically the 2eBDT), we needed to know that our signal definitively belonged to the 2e signal region → BDT has fewer use cases
- A more useful BDT could score electrons in various event topologies (electron + electron, electron + photon, electron + muon, electron +jet, single electron)
- We started the implementation of an object tagger BDT by applying the 1eBDT twice in our 2e signal region
  - This means the 1eBDT checks if the leading electron is displaced, and then checks if the subleading electron is displaced
- In "object tagger" BDTs we use fewer inputs to differentiate between signal and CR data

	BDT Type	Total	Remaining	Efficiency	$\frac{s}{\sqrt{b}}$
Signal	2x1eBDT (both electrons displaced)	362.4	361.2	0.99	3.19
Background	2x1eBDT (both electrons displaced)	17162	12810	0.75	
Signal	2eBDT (event-level)	362.4	359.5	0.99	7.89
Background	2eBDT (event-level)	17162	2080	0.12	
Signal	2x1eBDT (at least one displaced electron)	362.4	359.7	0.99	12.31
Background	2x1eBDT (at least one displaced electron)	17162	853	0.049	

A Visual Representation





Teal: 2x1eBDT (both electrons displaced)
Lavender: 2x1eBDT (at least one electron displaced)

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Conclusions and Next Steps

✓ Created baseline BDTs for both the 1e and 2e regions
✓ Compared event-level BDTs to a displaced object “tagger” BDT

Conclusion: By requiring at least one electron to be “tagged” as displaced, we find that the object-level BDT is the more appropriate classifier for the displaced leptons analysis.

Next Steps:

- Hyperparameter optimization for the BDTs :
  - Boosting type (AdaBoost vs Gradient Boosting)
  - Tree depth, number of trees used in boosting, Node Size, etc.
- Apply BDT to look for signal in unblinded data
  - A process shape fit
- 1eBDT output scores potentially used as the main discrimination variable in the 1e (and maybe 2e, eγ) regions!

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Special Thanks to:

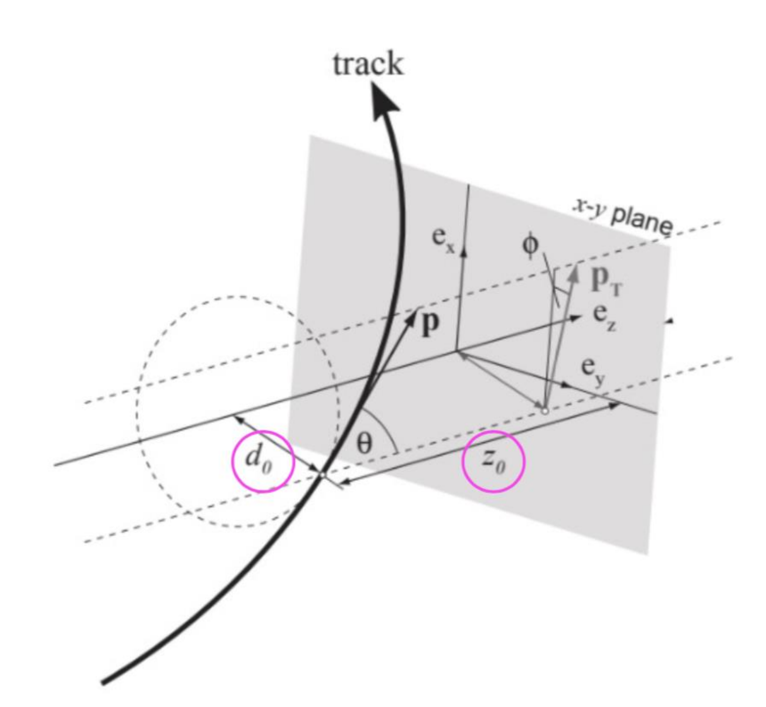
- The ATLAS Collaboration and the Columbia ATLAS group
- My fellow REUs who I’m glad I have gotten to know over the past 10 weeks
- Everyone at Nevis who made this REU possible, with special thanks to John, Georgia, and Amy
- The National Science Foundation (NSF) for funding this research under Grant No. PHY/1950431

BACKUP

BDT Inputs

Here we list and define the variables that we use to train the BDT

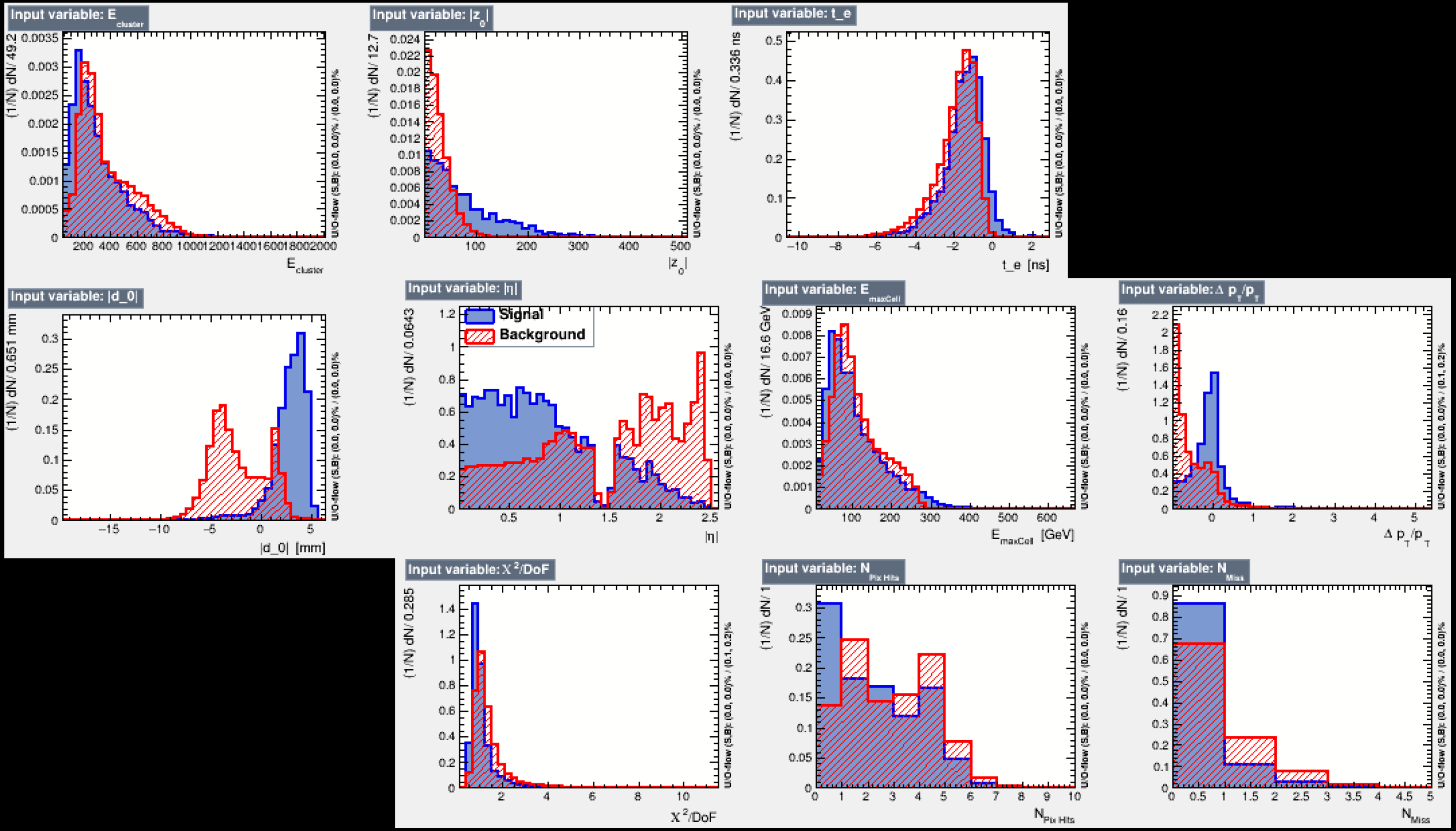
- η: Pseudorapidity, a spatial coordinate that specifies the angle of a particle relative to the beam axis Defined as $-\ln(\tan\frac{\theta}{2})$
- $E_{maxCell}$: Energy deposited in the calorimeter cell that received the most energy from this electron.
- p_T: momentum of the transverse plane
- $\frac{p_{T,track} - p_{T,cluster}}{p_{T,cluster}}$: Percent difference between transverse momentum of the electron
- track and electron shower in the calorimeter
- χ^2 /Dof: Goodness of fit parameter for electron track form fit to the hits that form the track divided by the parameter degrees of freedom.
- N_{pix}: Number of hits in the pixel layers crossed by the electron track.
- N_{miss}: Number of pixel layers with no hits after the electron track's first hit.
- $E_{cluster}$: Energy deposited by the electron in the calorimeter
- d_0: Distance of closest approach from extrapolated electron track to the primary vertex in the longitudinal plane
- $t_{electron}$: Electron time of arrival at calorimeter
- z_0: Distance of closest approach from extrapolated electron track to the primary vertex in the transverse plane



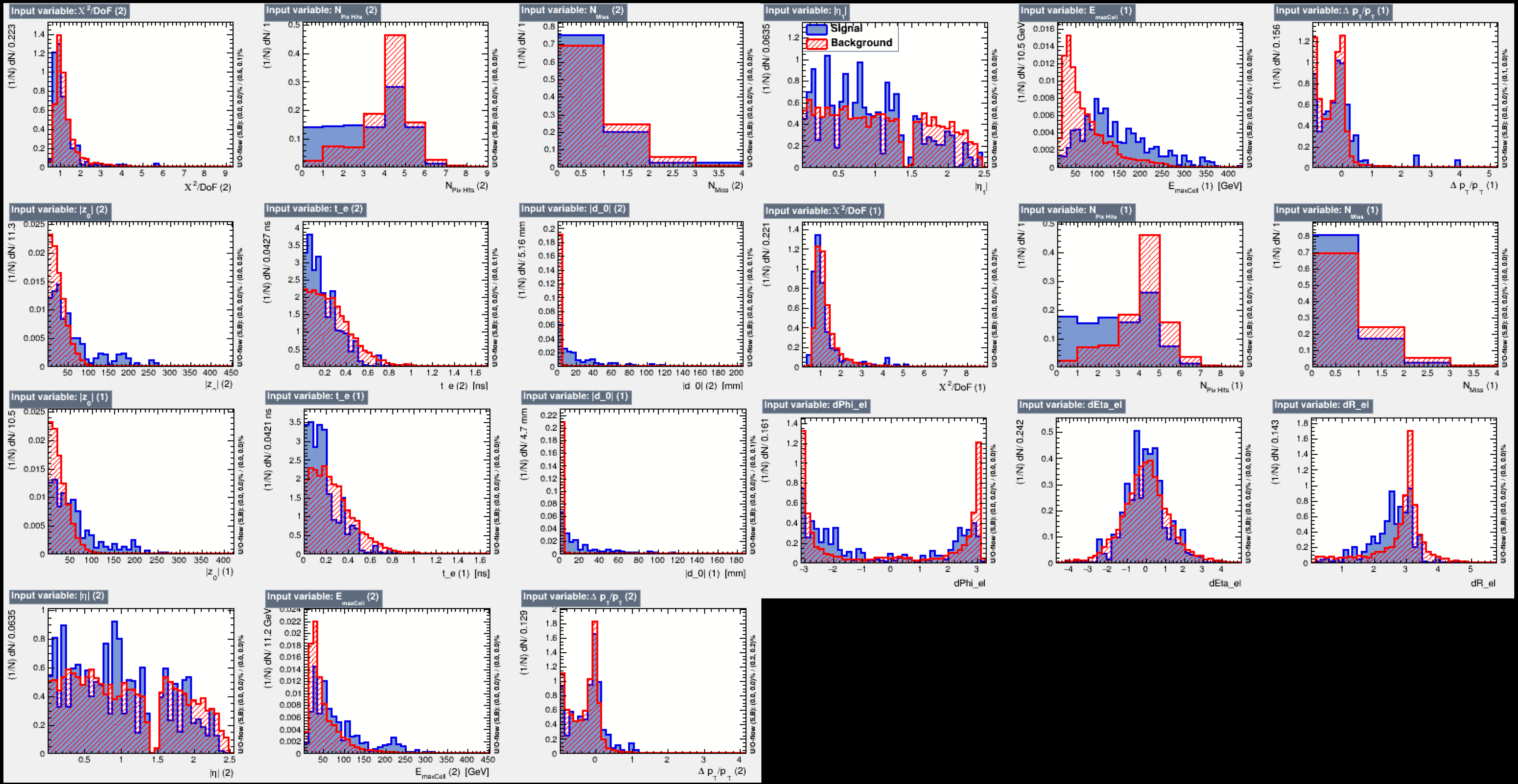
Representation of z_0, d_0 and p_T (transverse momentum)

1eBDT - Input Plots

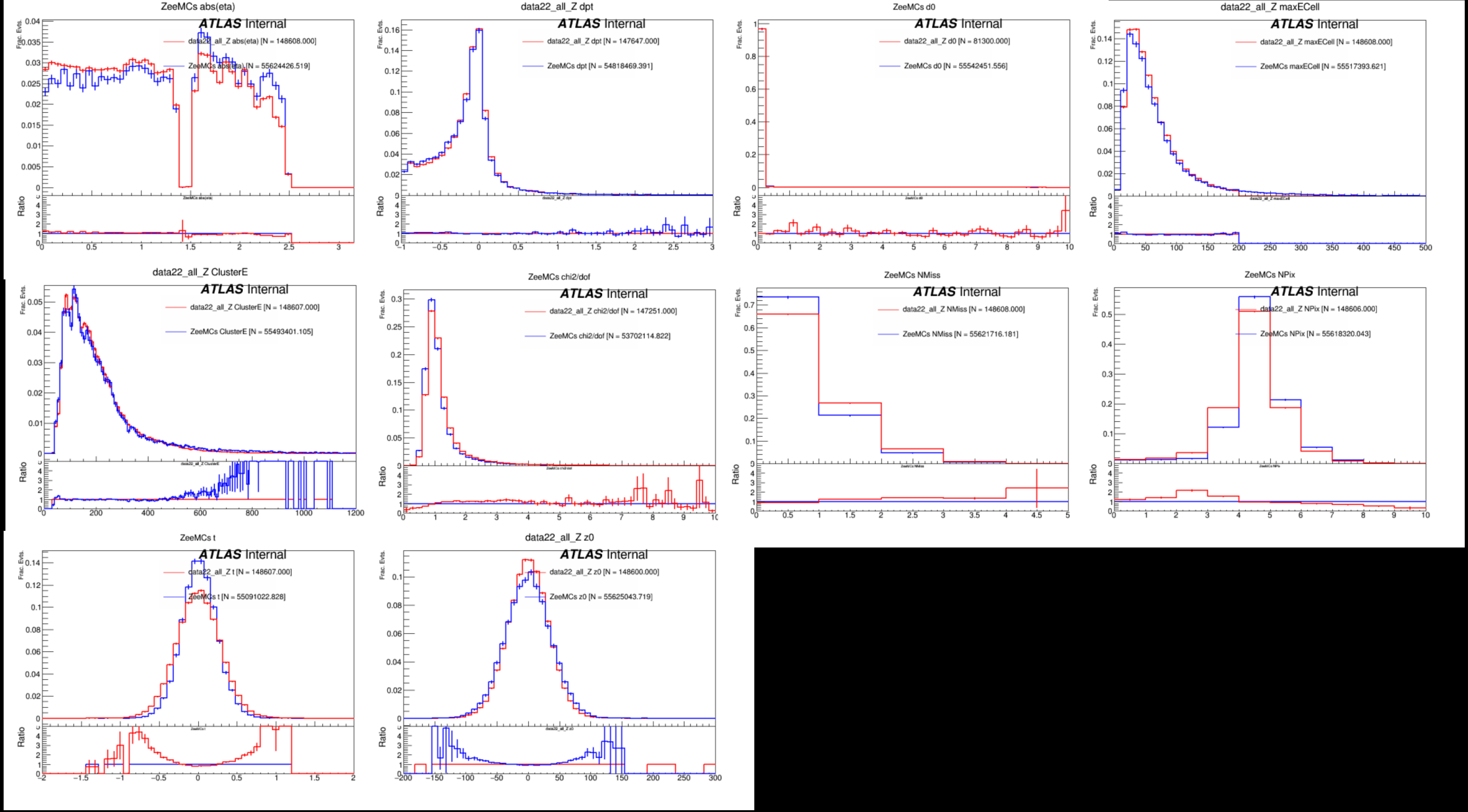
Rank	Variable	Separation ($\frac{s}{\sqrt{b}}$)
1	d_0	6.38×10^{-1}
2	$\frac{\Delta p_T}{p_T}$	2.47×10^{-1}
3	z_0	2.11×10^{-1}
4	$\|\eta\|$	2.03×10^{-1}
5	$\frac{\chi^2}{DoF}$	9.01×10^{-2}
6	t_e	5.82×10^{-2}
7	$E_{cluster}$	5.36×10^{-2}
8	N_{miss}	4.96×10^{-2}
9	$N_{Pix\ Hits}$	4.90×10^{-2}
10	$E_{maxCell}$	3.39×10^{-2}



2eBDT - Input Plots



2x1eBDT Weights Applied to Zee MC (Leading)



2x1eBDT Weights Applied to Zee MC (Subleading)