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# **A Deep Learning Approach to Differential Measurements of Higgs - Top Interactions in Multilepton Final States**

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The ATLAS Collaboration

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6 Several theories Beyond the Standard Model modify the momentum spectrum of the Higgs  
7 Boson, without significantly altering the overall rate of Higgs produced from top quark pairs.  
8 A differential measurement of the Higgs transverse momentum provides a way to search for  
9 these effects at the LHC. Because of the challenges inherent to reconstructing the Higgs in  
10 multilepton final states, a deep learning approach is used to predict the momentum spectrum  
11 of the Higgs for events where the Higgs Boson is produced from top quark pairs and decays  
12 to final states that include multiple leptons. The regressed Higgs  $p_T$  is fit to data for events  
13 with two or three leptons in the final state, and estimates of the sensitivity to variations in the  
14 Higgs  $p_T$  spectrum are given.

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**93 Part I****94 Introduction****95 1 Introduction**

96 Particle physics is an attempt to describe the fundamental building blocks of the universe and  
97 their interactions. The Standard Model (SM) - our best current theory of fundamental particle  
98 physics - does a remarkable job of that. All known fundamental particles and (almost) all of the  
99 forces underlying their interactions can be explained by the SM, and the predictions from this  
100 theory agree with experiment to an incredibly precise degree. This is especially true since the  
101 Higgs Boson, the last piece of the SM predicted decades before, was finally discovered at the  
102 Large Hadron Collider (LHC) in 2012.

103 Despite the success of the SM, there remains significant work to be done. For one, the  
104 SM is incomplete: it fails to provide a description of gravity, to give an explanation for the  
105 observation of Dark Matter, or to provide a mechanism for neutrinos to gain mass. Further, a  
106 Higgs Boson with a mass of around 125 GeV, as observed at the LHC, gives rise to what is  
107 known a hierarchy problem - such a low mass Higgs requires a seemingly unnatural level of “fine  
108 tuning” that is unexplained by the SM.

109 A promising avenue for addressing these problems is to study the properties of the Higgs  
110 Boson and the way it interacts with other particles, in part simply because these interactions

111 have not been measured before. Its interactions with the Top Quark are a particularly promising  
112 place to look. Because the Higgs Field is responsible for allowing particle to acquire mass, the  
113 strength of a particle's interaction with the Higgs Boson is proportional to its mass. As the most  
114 massive of the fundamental particles, the Top Quark has the strongest coupling to the Higgs  
115 Boson, meaning any new physics in the Higgs sector is likely to present itself most prominently  
116 in its interaction with the Top Quark.

117 These interactions can be measured by directly by studying the production of a Higgs  
118 Boson in association with a pair of Top Quarks ( $t\bar{t}H$ ). While studies have been done measuring  
119 the overall rate of  $t\bar{t}H$  production, there are several theories of physics Beyond the Standard  
120 Model (BSM) that would affect the kinematics of  $t\bar{t}H$  production without altering its overall  
121 rate. This dissertation attempts to make a differential measurement of the kinematics of the  
122 Higgs Boson in  $t\bar{t}H$  events in order to search for these BSM effects.

123 An Effective Field Theory model can be used to model the low energy effects of high  
124 energy physics.

125 The proton-proton collision data collected by the ATLAS detector at the LHC from 2015-  
126 2018 provides the opportunity to make this measurement for the first time. The unprecedented  
127 energy achieved by the LHC during this period greatly increase the rate at which  $t\bar{t}H$  events are  
128 produced, and the large amount of data collected provides the necessary statistics for a differential  
129 measurement to be performed.

130 A study of  $t\bar{t}H$  events with multiple leptons in the final state is performed, using  $139 \text{ fb}^{-1}$

131 of data from proton-proton collisions at an energy  $\sqrt{s} = 13$  TeV collected by the ATLAS detector  
132 from 2015-2018. Events are separated into channels based on the number of light leptons in the  
133 final state - either two same-sign leptons, or three leptons. A deep neural network is used to  
134 reconstruct the momentum of the Higgs Boson in each event. This momentum spectrum is fit to  
135 data for each analysis channel, the result of which is used to place limits on BSM effects.

136 This dissertation begins with a brief explanation of the SM, its limitations, and the theor-  
137 etical motivation behind this work. This is followed by a description of the LHC and the ATLAS  
138 detector. The analysis strategy is then described, and the results are presented. Finally, the results  
139 of the study are summarized in the conclusion.

## 140 Part II

### 141 Theoretical Motivation

#### 142 2 The Standard Model and the Higgs Boson

143 The Standard Model of particle physics (SM) is a Quantum Field Theory (QFT) describing the  
144 known fundamental particles and their interactions. It accounts for three of the four known  
145 fundamental force - electromagnetism, the weak nuclear force, and the strong nuclear force, but  
146 not gravity. Further, the SM describes a mechanism for combining the weak and electromagnetic  
147 forces into a singular interaction, known as the electroweak force. It is a non-Abelian gauge

<sup>148</sup> theory, invariant under the Lie Group  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ , where C refers to color

<sup>149</sup> charge, L, the helicity of the particle, and Y, the hypercharge.

<sup>150</sup> **2.1 The Forces and Particles of the Standard Model**

<sup>151</sup> The SM particles, summarized in figure 2.1, can be classified into two general categories based

<sup>152</sup> on their spin: fermions, and bosons.

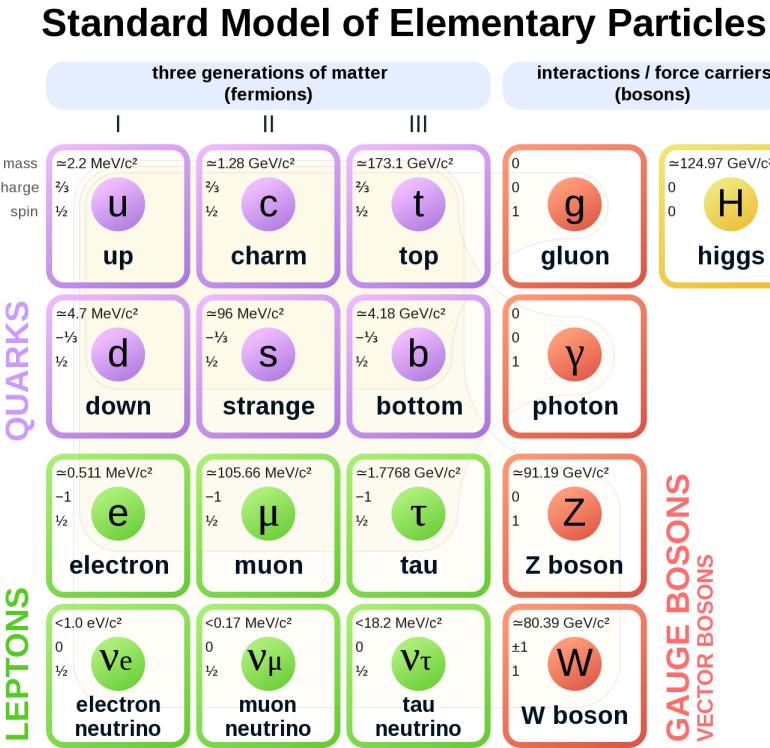


Figure 2.1: A summary of the particles of the Standard Model, including their mass, charge and spin, with the fermions listed on the left, and the bosons on the right. []

<sup>153</sup> Fermions are particles with  $\frac{1}{2}$ -integer spin, which according to the spin-statistics theorem,

<sup>154</sup> causes them to comply with the Pauli-exclusion principle []. They can be separated into two

155 groups, leptons and quarks, each of which consist of three generations of particles with increasing  
 156 mass.

157 Leptons are fermions interact via the electroweak force, but not the strong force. The three  
 158 generation of leptons consist of the electron and electron neutrino, the muon and muon neutrino,  
 159 the tau and tau neutrino. The quarks, which do interact via the strong force - which is to say they  
 160 have color charge - in addition to the electroweak force. The three generations include the up  
 161 and down quarks, the strange and charm quarks, and the top and bottom quarks. Each of these  
 162 generations form left-handed doublets invariant under SU(2) transformations. For the leptons  
 163 these doublets are:

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}_L, \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}_L, \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}_L \quad (2.1)$$

164 And for the quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} s \\ c \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L \quad (2.2)$$

165 For both leptons and quarks, the heavier generations can decay into the lighter generation  
 166 of particles, while the first generation does not decay. Hence, ordinary matter generally consists  
 167 of this first generation of fermions - electrons, up quarks, and down quarks. Each of these  
 168 fermions has a corresponding anti-particle, which has an equal mass as its partner but opposite

<sup>169</sup> charge. The fermions acquire their mass via the Higgs Mechanism, except for the neutrinos,

<sup>170</sup> whose mass has been experimentally confirmed but is not accounted for in the SM.

<sup>171</sup> Bosons, by contrast, have integer spin, and are therefore unconstrained by the Pauli-

<sup>172</sup> exclusion principle. The SM includes two kinds of bosons: Gauge bosons, which are spin-1

<sup>173</sup> particles that mediate the interactions between the fermions, and a single scalar, i.e. spin-0,

<sup>174</sup> particle - the Higgs Boson. Of the gauge bosons, the  $W^+$ ,  $W^-$  and  $Z$  bosons - which are the

<sup>175</sup> mass eigenstates of the electroweak bosons - mediate the weak interaction, while the photon

<sup>176</sup> mediates the electric force, and the gluon mediates the strong force.

## <sup>177</sup> 2.2 The Higgs Mechanism

<sup>178</sup> A key feature of the SM is the gauge invariance of its Lagrangian. However, any terms added to

<sup>179</sup> the Lagrangian giving mass to the the gauge bosons would violate the underlying symmetry of

<sup>180</sup> the theory. This presents a clear problem with the theory: The experimental observation that the

<sup>181</sup>  $W$  and  $Z$  bosons have mass seems to contradict the basic structure of the SM.

<sup>182</sup> Rather than abandoning gauge invariance, an alternative way for particles to acquire mass

<sup>183</sup> beyond adding a simple mass term to the Lagrangian was theorized by Higgs, Englert and Brout

<sup>184</sup> in 1964 []. This procedure for introducing masses for the gauge bosons while preserving local

<sup>185</sup> gauge invariance, known as the Higgs mechanism, was incorporated into the electroweak theory

<sup>186</sup> by Weinberg in 1967 [].

<sup>187</sup> **2.2.1 The Higgs Field**

<sup>188</sup> The Higgs mechanism introduces a complex scalar  $SU(2)$  doublet,  $\Phi$ , with the form:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_L \quad (2.3)$$

<sup>189</sup> This field introduces a scalar potential to the Lagrangian of the form:

$$V(\Phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda (|\Phi^\dagger \Phi|)^2 \quad (2.4)$$

<sup>190</sup> Where  $\mu$  and  $\lambda$  are free parameters of the new field. This represents the most general  
<sup>191</sup> potential allowed while preserving  $SU(2)_L$  invariance and renormalizability. In the case that  
<sup>192</sup>  $\mu^2 < 0$ , this potential takes the form shown in figure 2.2.

<sup>193</sup> The significant feature of this potential is that its minimum does not occur for a value of  
<sup>194</sup>  $\Phi = 0$ . Instead, it is minimized when  $|\Phi^\dagger \Phi| = -\mu^2/\lambda$ . This means that in its ground state, the  
<sup>195</sup> Higgs field takes on a non-zero value - referred to as a vacuum expectation value (VEV). So while  
<sup>196</sup> the Higgs potential is globally symmetric, about the minimum this symmetry is broken. Since

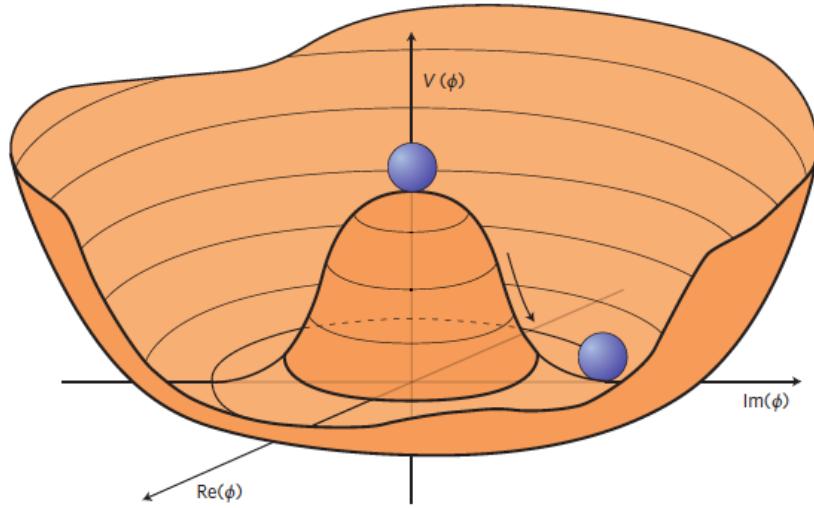


Figure 2.2: The value of the Higgs potential,  $V(\Phi)$  as a function of  $\Phi$ , for the case that  $\mu^2 < 0$  [].

<sub>197</sub> the minimum is determined only by  $\Phi^\dagger \Phi$ , there is some ambiguity in the particular definition of  
<sub>198</sub> the VEV, but it is generally represented as

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.5)$$

<sub>199</sub> The full value of  $\Phi$  can be written as

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H/\sqrt{2} \end{pmatrix} \quad (2.6)$$

<sub>200</sub> with  $v$  being the value of the VEV, and  $H$  being the real value of the scalar field.

201 **2.2.2 Electroweak Symmetry Breaking**

202 The Electroweak (EWK) interaction is described in the SM by a  $SU(2)_L \otimes U(1)_Y$  gauge theory.  
 203 This theory predicts three  $SU(2)_L$  gauge boson,  $W_\mu^1, W_\mu^2, W_\mu^3$ , and a single  $U(1)_Y$  gauge boson,  
 204  $B_\mu$ . The couplings of these bosons to the Higgs field show up in the kinetic terms of the scalar  
 205 field  $\Phi$  in the Lagrangian:

$$(D_\mu \Phi)^\dagger (D^\mu \Phi) = |(\partial_\mu - \frac{ig}{2} W_\mu^a \sigma^a - \frac{ig'}{2} B_\mu Y) \phi|^2 \quad (2.7)$$

206 Here  $D_\mu$  represents the covariant derivative required to preserve gauge invariance,  $g$  and  
 207  $g'$  represent coupling constant of the gauge bosons,  $\sigma^a$  denotes the Pauli matrices of  $SU(2)$ ,  
 208 and  $Y$  represents the hypercharge of  $U(1)$ . The terms in this interaction which contribute to the  
 209 masses of the gauge bosons can be written as:

$$\frac{1}{2}(0, v)(\frac{g}{2} W_\mu^a \sigma^a - \frac{g'}{2} B_\mu)^2 \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.8)$$

210 Expanding these terms into the mass eigenstates of the electroweak interaction yields four  
 211 physical gauge bosons, two charged and two neutral, which are linear combinations of the fields

<sup>212</sup>  $W_\mu^1, W_\mu^2, W_\mu^3$ , and  $B_\mu$ :

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}(W_\mu^1 \pm iW_\mu^2) \\ Z^\mu &= \frac{1}{\sqrt{(g^2 + g'^2)}}(-g'B_\mu + gW_\mu^3) \\ A^\mu &= \frac{1}{\sqrt{(g^2 + g'^2)}}(gB_\mu + g'W_\mu^3) \end{aligned} \tag{2.9}$$

<sup>213</sup> And the masses of these fields are given by:

$$\begin{aligned} M_W^2 &= \frac{1}{4}g^2v^2 \\ M_Z^2 &= \frac{1}{4}(g^2 + g'^2)v^2 \\ M_A^2 &= 0 \end{aligned} \tag{2.10}$$

<sup>214</sup> This produces exactly the particles we observe - three massive gauge bosons and a single  
<sup>215</sup> massless photon. The massless photon represents the portion of the gauge symmetry, a single  
<sup>216</sup>  $U(1)$  of the electromagnetic force, that remains unbroken by the VEV.

<sup>217</sup> Interactions with the Higgs field also lead to the generation of the fermion masses, which  
<sup>218</sup> in the Lagrangian take the form:

$$-\lambda_\psi(\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi^\dagger \psi_L) \tag{2.11}$$

219 After symmetry breaking has occurred and  $\phi$  has taken on the value of the VEV as written  
 220 in equation 2.5, the mass terms for the fermions become  $\lambda_\psi v$ . Written this way, the fermion  
 221 masses are proportional to their Yukawa coupling to the VEV,  $\lambda_\psi$ .

222 Based on the equation 2.6, an additional mass term,  $\mu^2 H^2$  arises from the potential  $V(\Phi)$ .  
 223 This term can be understood as an excitation of the Higgs field, a scalar boson with mass  $M_H = \mu$ .  
 224 This is the Higgs boson, which comes about as a natural prediction of electroweak symmetry  
 225 breaking.

226 The fermion's Yukawa coupling to the VEV take the same form as the fermion's coupling  
 227 to the Higgs boson -  $\lambda_\psi$ . Therefore, the strength of a fermion's interaction with the Higgs is  
 228 directly proportional to its mass. We now have a model that predicts a Higgs boson with mass  
 229  $M_H = \mu$ , which interacts with the fermions with coupling strength  $\lambda_\psi$ . Because  $\mu$  and  $\lambda_\psi$  are  
 230 free parameters of the theory, the mass of the Higgs boson and its interactions with the fermions  
 231 must be measured experimentally.

### 232 2.3 Limitations of the Standard Model

233 While the SM has great predictive power, there are still several experimental observations that the  
 234 SM fails to explain. For example, the SM predicts neutrinos to be massless, despite experimental  
 235 observation to the contrary.

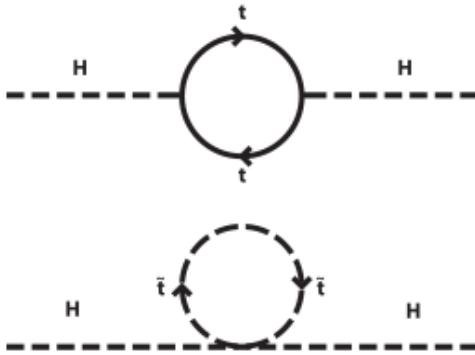


Figure 2.3: Above diagram is the leading order correction to the Higgs mass via a top quark loop, and below is the stop squark loop, coming from a supersymmetric extension of the SM, that provides a potential cancellation of the top diagram [6].

### <sup>236</sup> 3 Effective Field Theory in $t\bar{t}H$ Production

<sup>237</sup> Higher dimension operators are a common way to paramaterize the effects of physics at very  
<sup>238</sup> high energies into

#### <sup>239</sup> 3.1 Extensions to the Higgs Sector

#### <sup>240</sup> 3.2 Six Dimensional Operators

<sup>241</sup> While the SM has been tested to great precision, particularly at the LHC, it is generally accepted  
<sup>242</sup> that it is only valid up to a certain energy scale. It is assumed that above a certain energy, at the  
<sup>243</sup> scale where something like a Grand Unified Theory (GUT) or quantum gravity become relevant,  
<sup>244</sup> the SM will not be applicable.

---

**Part III****246 The LHC and the ATLAS Detector****247 4 The LHC**

248 The Large Hadron Collider (LHC) is a particle accelerator consisting of a 27 km ring, designed  
249 to collide protons at high energy. Located outside of Geneva, Switzerland and buried about 100  
250 m underground, it consists of a ring of superconducting magnets which are used to accelerate  
251 opposing beams of protons - or lead ions - which collide at the center of one of the various  
252 detectors located around the LHC ring which record the result of these collisions. These  
253 detectors include two general purpose detectors, ATLAS and CMS, which are designed to make  
254 precision measurements of a broad range of physics phenomenon, and two more specialized  
255 experiments, LHCb and ALICE, which are optimized to study b-quarks and heavy-ion physics,  
256 respectively.

257 The LHC first began running in 2009 at a proton-proton center of mass energy of  $\sqrt{s} = 8$   
258 TeV. It operated at this energy from 2009 to 2012, known as Run 1, and data collected during  
259 this period was used in discovering the Higgs Boson. The LHC began running again in 2015,  
260 and collected data at an increased energy of  $\sqrt{s} = 13$  TeV until 2018, a period referred to as Run  
261 2.

262 The LHC consists of a chain of accelerators, which accelerate the protons to higher and

higher energies until they are injected into the main ring. This process is summarized in figure 4.1. Protons extracted from a tank of ionized hydrogen are fed into a linear accelerator, LINAC2, where they reach an energy of 50 MeV. From there, they enter a series of three separate circular accelerators, before being injected into the main accelerator ring at an energy of 450 GeV. Within the main ring protons are separated into two separate beams moving in opposite directions, and their energy is increased to their full collision energy. Radiofrequency cavities are used to accelerate these particles and sort them into bunches. From 2015-2018, these bunches consisted of around 100 billion protons each with an energy of 6.5 TeV per proton, which collided at a rate of 40 MHz, or every 25 ns.

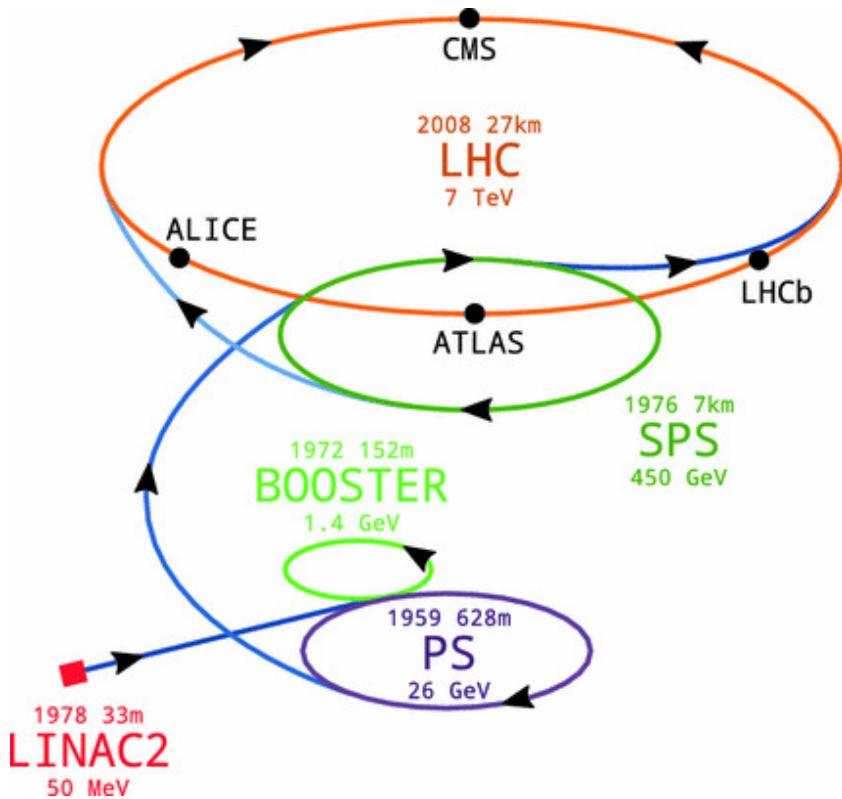


Figure 4.1: A summary of the accelerator chain used to feed protons into the LHC [].

272 Because these proton bunches consist of a large number of particles, each bunch crossing  
 273 consists of not just one, but several direct proton-proton collisions. The number of interactions  
 274 that occur per bunch crossing,  $\mu$ , is known as pileup. During Run 2, the average pileup for bunch  
 275 crossings was around  $\langle \mu \rangle = 35$ , with values typically ranging between 10 and 70.

276 The amount of data collected by the LHC is measured in terms of luminosity, which is the  
 277 ratio of the number of events detected per unit time,  $\frac{dN}{dt}$ , and the interaction cross-section,  $\sigma$ .

$$\mathcal{L} = \frac{1}{\sigma} \frac{dN}{dt} \quad (4.1)$$

278 The design luminosity of the LHC is  $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ , however the LHC has achieved a  
 279 luminosity of over  $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ . The total luminosity is then this instantaneous luminosity  
 280 integrated over time.

$$\mathcal{L}_{\text{int}} = \int \mathcal{L} dt \quad (4.2)$$

281 The integrated luminosity collected by the ATLAS detector as of the end of 2018 is around  
 282  $140 \text{ fb}^{-1}$ , exceeding the expected integrated luminosity of  $100 \text{ fb}^{-1}$ .

## 283 5 The ATLAS Detector

284 ATLAS (a not terribly natural acronym for “A Toroidal LHC Apparatus”) is a general purpose  
 285 detector designed to maximize the detection efficiency of all physics objects, including leptons,  
 286 jets, and photons. This means it is capable of measuring all SM particles, with the exception of  
 287 neutrinos, the presence of which can be inferred based on missing transverse momentum. The  
 288 detector measures 44 m long, and 25 m tall.

289 The ATLAS detector consists of multiple layers, each of which serves a different purpose  
 290 in reconstructing collisions. At the very center of the detector is the interaction point where the  
 291 proton beams of the LHC collide.

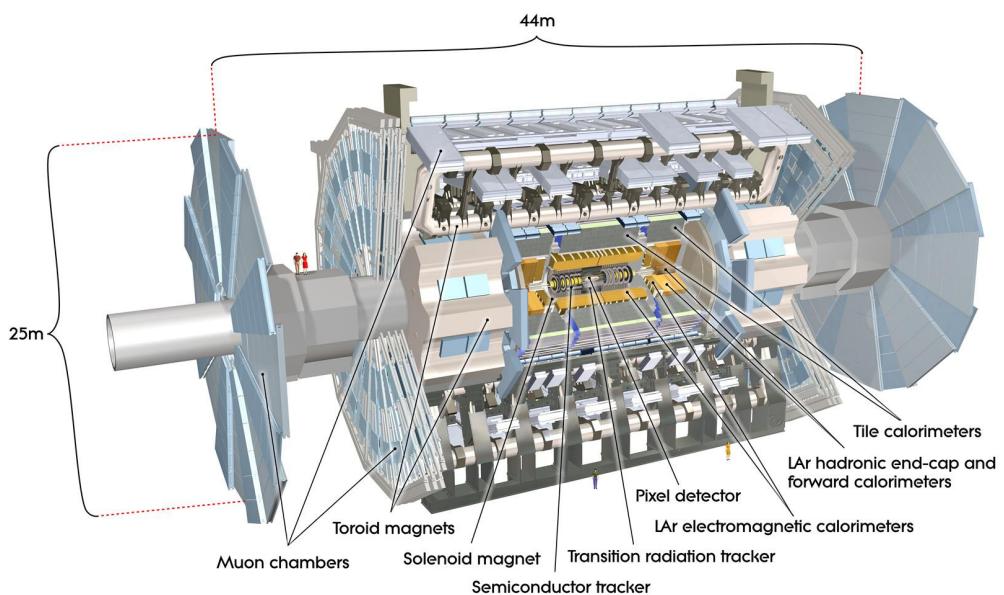


Figure 5.1: Cutaway view of the ATLAS detector, with labels of its major components [].

292 **5.1 Inner Detector**

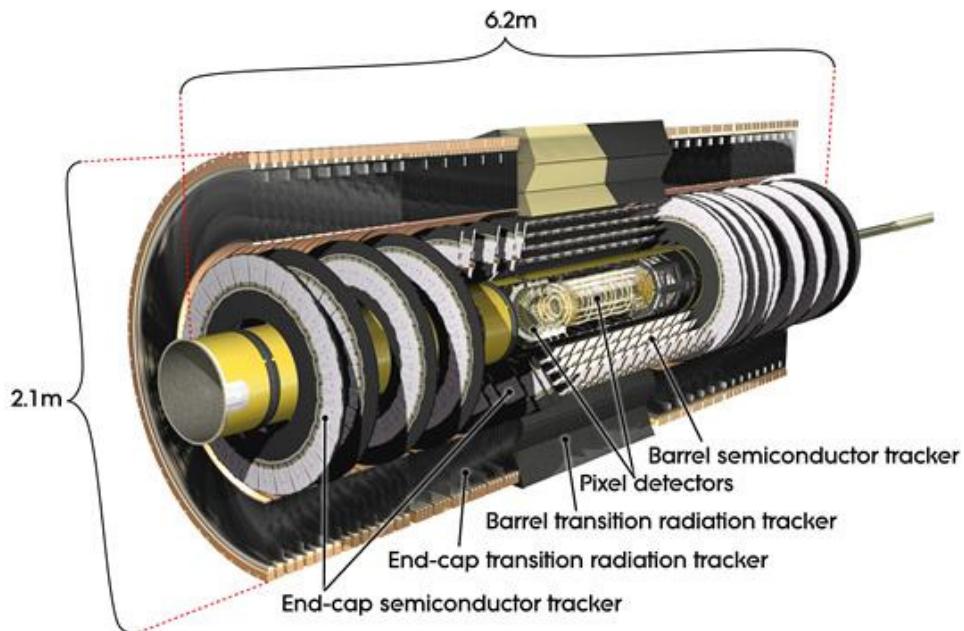


Figure 5.2: Cutaway view of the Inner Detector [].

293 Just surrounding the interaction point is the Inner Detector, designed to track the path  
294 of charged particles moving through the detector. An inner solenoid surrounding the Innder  
295 Detector is used to produces a magnetic field of 2 T. This large magnetic field causes the path  
296 of charged particles moving through the Inner Detector to bend. Because this magnetic field is  
297 uniform and well known, it can be used in conjunction with the curvature of a particles path to  
298 measure its charge and momentum.

299 The Inner Detector consists of three components - the Pixel Detector, the Semi-Conductor  
300 Tracker (SCT), and the Transition Radiation Tracker (TRT). The Pixel Detector is the innermost  
301 of these, beginning just 33.25 mm away from the beam line. It consists of three silicon layers

302 along the barrel, as well as three endcap layers, covering a range of  $|\eta| < 2.5$ .

303 The Semiconductor Tracker (SCT) is similar to the Pixel detector, but uses long strips  
 304 rather than small pixel to cover a larger spatial area.

305 **5.2 Calorimeters**

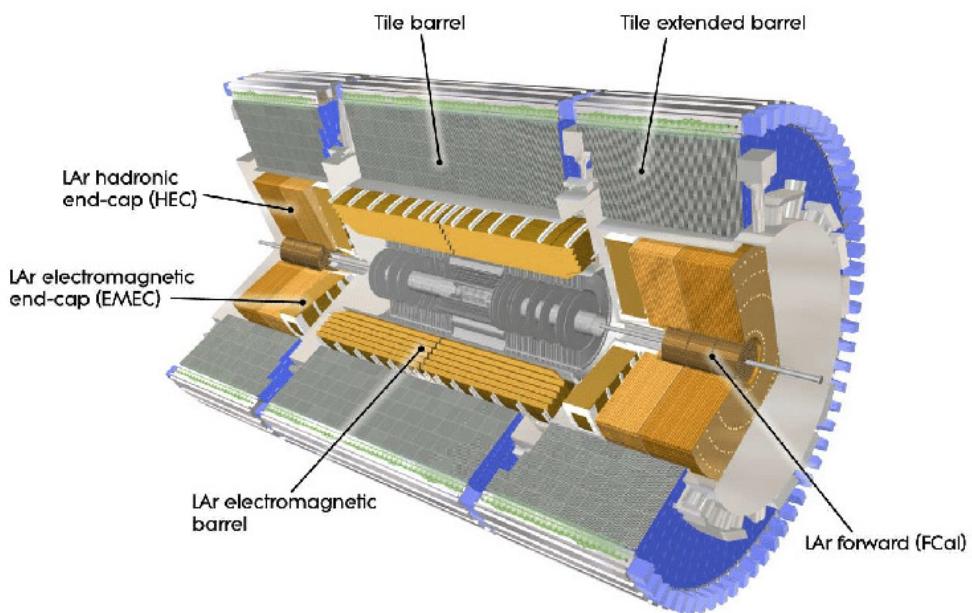


Figure 5.3: Cutaway view of the calorimeter system of the ATLAS detector [].

306 Situated outside the Inner Detector are two concentric calorimeters. The inner calorimeter  
 307 uses liquid argon (LAr) to measure energy of particles that interact electromagnetically, which  
 308 includes photons and any charged particle. The LAr calorimeter is made of heavy metals,  
 309 primarily lead and copper, which causes electromagnetically interacting particles to shower,  
 310 depositing their energy in the detector. The showering of the high energy particles that pass

311 through calorimeter cause the liquid argon to ionize, and the ionized electrons are detected by  
312 electronic readouts. The LAr calorimeter consists of around 180,000 readout channels.

313       The outer calorimeter measures the energy from particles that pass through the EM calor-  
314 imeter, and measures the energy of particles that interact via the strong force. This is primarily  
315 hadrons. It is composed of steel plates to cause hadronic showering and scintillating tiles as the  
316 active material. The signals from the hadronic calorimeter are read out by photomultiplier tubes  
317 (PMTs).

318       **5.3 Muon Spectrometer**

319       Because muons are heavier than electrons and photons, and do not interact via the strong force,  
320 they generally pass through the detector without being stopped by the calorimeters. The outermost  
321 components of the detector are designed specifically to measure the energy and momentum of  
322 muons produced in the LHC. The muon spectrometer consists of tracking and triggering system.  
323 It extends from the outside of the calorimeter system, about a 4.25 m radius from the beam line,  
324 to a radius of 11 m. This large detector system is necessary to accurately measure the momentum  
325 of muons, which is essential not only for measurements involving the muons themselves, but also  
326 to accurately estimate the missing energy in each event.

327       Two large toroidal magnets within the muon system generate a large magnetic field which  
328 covers an area 26 m long with a radius of 10 m. Because the area covered by this magnet system  
329 is so large, a uniform magnetic field like the one produced in the Inner Detector is impractical.

330 Instead, the magnetic field that exists in the muon spectrometer ranges between 2 T and 8 T, and  
331 is much less uniform. The path of the muons passing through the spectrometer is bent by this  
332 field, allowing their charge to be determined.

333 1200 tracking chambers are placed in the muon system in order to precisely measure the  
334 tracks of muons with high spatial resolution.

335 **5.4 Trigger System**

336 Because of the high collision rate and large amount of data collected by the various subdetectors,  
337 ATLAS produces far more data than can actually be stored. Each event produces around 25 Mb  
338 of raw data, which multiplied by the bunch crossing rate of 40 MHz, comes out to around a  
339 petabyte of data every second. The information from every event cannot practically be stored,  
340 therefore a sophisticated trigger system is employed in real time to determine whether events are  
341 sufficiently interesting to be worth storing.

342 The trigger system in ATLAS involves multiple levels, each of which select out which  
343 events move on to the next level of scrutiny. The level-1 trigger uses hardware information from  
344 the calorimeters and muon spectrometer to select events that contain candidates for particles  
345 commonly used in analysis, such as energetic leptons and jets. The level-1 trigger reduces the  
346 rate of events from 40 MHz to around 100 kHz.

347 Events that pass the level-1 trigger move to the High-Level Trigger (HLT). The HLT takes  
 348 place outside of the detector in software, and looks for properties such as a large amount of  
 349 missing transverse energy, well defined leptons, and multiple high energy jets. Events that pass  
 350 the HLT are stored and used for analysis. Because the specifics of the HLT are determined by  
 351 software rather than hardware, the thresholds can be changed throughout the run of the detector  
 352 in response to run conditions such as changes to pileup and luminosity. After the HLT is applied,  
 353 the event rate is reduced to around 1000 per second, which are recorded for analysis.

## 354 **Part IV**

### 355 **Search for Dimension-Six Operators**

#### 356 **6 Data and Monte Carlo Samples**

357 For both data and Monte Carlo (MC) simulations, samples were prepared in the `xAOD` format,  
 358 which was used to produce a `xAOD` based on the `HIGG8D1` derivation framework. This framework  
 359 was designed for the main  $t\bar{t}H$  multi-lepton analysis. Because this analysis targets events with  
 360 multiple light leptons, as well as tau hadrons, this framework skims the dataset of any events that  
 361 do not meet at least one of the following requirements:

- 362 • at least two light leptons within a range  $|\eta| < 2.6$ , with leading lepton  $p_T > 15$  GeV and  
 363 subleading lepton  $p_T > 5$  GeV

- at least one light lepton with  $p_T > 15 \text{ GeV}$  within a range  $|\eta| < 2.6$ , and at least two hadronic taus with  $p_T > 15 \text{ GeV}$ .

366 Samples were then generated from these HIGG8D1 derivations using a modified version of  
367 AnalysisBase version 21.2.127.

368 6.1 Data Samples

369 The study uses proton-proton collision data collected by the ATLAS detector from 2015 through  
370 2018, which represents an integrated luminosity of  $139 \text{ fb}^{-1}$  and an energy of  $\sqrt{s} = 13 \text{ TeV}$ . All  
371 data used in this analysis was included in one the following Good Run Lists:

- data15\_13TeV.periodAllYear\_DetStatus-v79-repro20-02\_DQDefects-00-02-02  
\_PHYS\_StandardGRL\_All\_Good\_25ns.xml
  - data16\_13TeV.periodAllYear\_DetStatus-v88-pro20-21\_DQDefects-00-02-04  
\_PHYS\_StandardGRL\_All\_Good\_25ns.xml
  - data17\_13TeV.periodAllYear\_DetStatus-v97-pro21-13\_Unknown\_PHYS\_StandardGRL  
\_All\_Good\_25ns\_Triggerno17e33prim.xml
  - data18\_13TeV.periodAllYear\_DetStatus-v102-pro22-04\_Unknown\_PHYS\_StandardGRL  
\_All\_Good\_25ns\_Triggerno17e33prim.xml

380 **6.2 Monte Carlo Samples**

381 Several Monte Carlo (MC) generators were used to simulate both signal and background pro-  
382 cesses. For all of these, the effects of the ATLAS detector are simulated in Geant4. The specific  
383 event generator used for each of these MC samples is listed in table 1.

Table 1: The configurations used for event generation of signal and background processes, including the event generator, matrix element (ME) order, parton shower algorithm, and parton distribution function (PDF).

Process	Event generator	ME order	Parton Shower	PDF
ttH	MG5_AMC (MG5_AMC)	NLO (NLO)	PYTHIA 8 (HERWIG++)	NNPDF 3.0 NLO [ <a href="#">Ball:2014uwa</a> ] (CT10 [ <a href="#">ct10</a> ])
t̄W	MG5_AMC (SHERPA 2.1.1)	NLO (LO multileg)	PYTHIA 8 (SHERPA)	NNPDF 3.0 NLO (NNPDF 3.0 NLO)
t̄t(Z/γ* → ll)	MG5_AMC	NLO	PYTHIA 8	NNPDF 3.0 NLO
VV	SHERPA 2.2.2	MEPS NLO	SHERPA	CT10
t̄t	POWHEG-BOX v2 [ <a href="#">powhegtt</a> ]	NLO	PYTHIA 8	NNPDF 3.0 NLO
t̄tγ	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
tZ	MG5_AMC	LO	PYTHIA 6	CTEQ6L1
tHqb	MG5_AMC	LO	PYTHIA 8	CT10
tHW	MG5_AMC (SHERPA 2.1.1)	NLO (LO multileg)	HERWIG++ (SHERPA)	CT10 (NNPDF 3.0 NLO)
tWZ	MG5_AMC	NLO	PYTHIA 8	NNPDF 2.3 LO
t̄t̄t, t̄t̄t̄t	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
t̄tW+W-	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
s-, t-channel, Wt single top	POWHEG-BOX v1 [ <a href="#">powhegstp</a> ]	NLO	PYTHIA 6	CT10
qqVV, VVV				
Z → l+l-	SHERPA 2.2.1	MEPS NLO	SHERPA	NNPDF 3.0 NLO

384 **7 Object Reconstruction**

385 All analysis channels considered in this note share a common object selection for leptons and  
386 jets, as well as a shared trigger selection.

387 **7.1 Trigger Requirements**

388 Events are required to be selected by dilepton triggers, as summarized in table 2.

Dilepton triggers (2015)	
$\mu\mu$ (asymm.)	HLT_mu18_mu8noL1
$ee$ (symm.)	HLT_2e12_lhloose_L12EM10VH
$e\mu, \mu e$ ( $\sim$ symm.)	HLT_e17_lhloose_mu14
Dilepton triggers (2016)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
$ee$ (symm.)	HLT_2e17_lhvloose_nod0
$e\mu, \mu e$ ( $\sim$ symm.)	HLT_e17_lhloose_nod0_mu14
Dilepton triggers (2017)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
$ee$ (symm.)	HLT_2e24_lhvloose_nod0
$e\mu, \mu e$ ( $\sim$ symm.)	HLT_e17_lhloose_nod0_mu14
Dilepton triggers (2018)	
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
$ee$ (symm.)	HLT_2e24_lhvloose_nod0
$e\mu, \mu e$ ( $\sim$ symm.)	HLT_e17_lhloose_nod0_mu14

Table 2: List of lowest  $p_T$ -threshold, un-prescaled dilepton triggers used for 2015-2018 data taking.

389 **7.2 Light Leptons**

390 Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter that  
391 are associated with charged particle tracks reconstructed in the inner detector [**ATLAS-CONF-2016-024**].  
392 Electron candidates are required to have  $p_T > 10$  GeV and  $|\eta_{\text{cluster}}| < 2.47$ . Candidates in the  
393 transition region between different electromagnetic calorimeter components,  $1.37 < |\eta_{\text{cluster}}| <$   
394 1.52, are rejected. A multivariate likelihood discriminant combining shower shape and track

395 information is used to distinguish prompt electrons from nonprompt leptons, such as those  
396 originating from hadronic showers.

397 To further reduce the non-prompt contribution, the track of each electron is required to  
398 originate from the primary vertex; requirements are imposed on the transverse impact parameter  
399 significance ( $|d_0|/\sigma_{d_0}$ ) and the longitudinal impact parameter ( $|\Delta z_0 \sin \theta_\ell|$ ), as shown in table  
400 ??.

401 Muon candidates are reconstructed by combining inner detector tracks with track segments  
402 or full tracks in the muon spectrometer [**PERF-2014-05**]. Muon candidates are required to have  
403  $p_T > 10$  GeV and  $|\eta| < 2.5$ . All leptons are required to be isolated, and pass a non-prompt BDT  
404 selection described in detail in [**ttH\_paper**].

### 405 7.3 Jets

406 Jets are reconstructed from calibrated topological clusters built from energy deposits in the  
407 calorimeters [**ATL-PHYS-PUB-2015-015**], using the anti- $k_t$  algorithm with a radius parameter  
408  $R = 0.4$ . Jets with energy contributions likely arising from noise or detector effects are removed  
409 from consideration [**ATLAS-CONF-2015-029**], and only jets satisfying  $p_T > 25$  GeV and  
410  $|\eta| < 2.5$  are used in this analysis. For jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$ , a jet-track  
411 association algorithm is used to confirm that the jet originates from the selected primary vertex,  
412 in order to reject jets arising from pileup collisions [**PERF-2014-03**].

<sup>413</sup> **7.4 Missing Transverse Energy**

<sup>414</sup> Because all  $t\bar{t}H - ML$  channels considered include multiple neutrinos, missing transverse  
<sup>415</sup> energy ( $E_T^{\text{miss}}$ ) is present in each event. The missing transverse momentum vector is defined as  
<sup>416</sup> the inverse of the sum of the transverse momenta of all reconstructed physics objects as well  
<sup>417</sup> as remaining unclustered energy, the latter of which is estimated from low- $p_T$  tracks associated  
<sup>418</sup> with the primary vertex but not assigned to a hard object [ATL-PHYS-PUB-2015-027].

<sup>419</sup> **8 Higgs Momentum Reconstruction**

<sup>420</sup> Reconstructing the momentum of the Higgs boson is a particular challenge for channels with  
<sup>421</sup> leptons in the final state: Because all channels include at least two neutrinos in the final state, the  
<sup>422</sup> Higgs can never be fully reconstructed. However, the momentum spectrum can be well predicted  
<sup>423</sup> by a neural network when provided with the four-vectors of the Higgs Boson decay products, as  
<sup>424</sup> shown in section 8.1. With this in mind, several layers of MVAs are used to reconstruction the  
<sup>425</sup> Higgs momentum.

<sup>426</sup> The first layer is a model designed to select which jets are most likely to be the b-jets  
<sup>427</sup> that came from the top decay, detailed in section 8.2. As described in section 8.3, the kinematics  
<sup>428</sup> of these jets are fed into the second layer, which is designed to identify the decay products of  
<sup>429</sup> the Higgs Boson itself. The kinematics of these particles are then fed into yet another neural-

430 network, which predicts the momentum of the Higgs (8.4). MVAs are also used in the analysis  
431 to determine the decay of the Higgs boson in the 3l channel (8.5).

432 For all of these models, the Keras neural network framework, with Tensorflow as the  
433 backend, is used, and the number of hidden layers and nodes are determined using grid search  
434 optimization. Each neural network uses the LeakyReLU activation function, a learning rate  
435 of 0.01, and the Adam optimization algorithm, as alternatives are found to either decrease or  
436 have no impact on performance. Batch normalization is applied after each layer. For the  
437 classification algorithms (b-jet matching, Higgs reconstruction, and 3l decay identification)  
438 binary-cross entropy is used as the loss function, while the  $p_T$  reconstruction algorithm uses  
439 MSE.

440 The specific inputs features used for each model are arrived at through a process of trial  
441 and error - features considered potentially useful are tried, and those that are found to increase  
442 performance are included. While each model includes a relatively large number of features,  
443 some using upwards of 30, this inclusive approach is found to maximize the performance of each  
444 model while decreasing the variance compared to a reduced number of inputs. Each input feature  
445 is validated by comparing MC simulations to  $80 \text{ fb}^{-1}$  of data, as shown in the sections below.

## 446 8.1 Decay Candidate Reconstruction

447 Machine Learning algorithms are trained to identify the decay products of the Higgs Boson  
448 using MC simulations of  $t\bar{t}H$  events. These include light leptons and jets. Reconstructed

449 physics objects are matched to truth level particles, in order to identify the parents of these  
450 reconstructed objects. The kinematics of the decay product candidates as well as event level  
451 variables are used as inputs.

452 Leptons considered as possible Higgs and top decay candidates are required to pass the  
453 selection described in section 7.2. For jets, however, it is found that a large fraction that originate  
454 from either the top decay or the Higgs decay fall outside the selection described in section 7.3.  
455 Specifically, jets from the Higgs decay tend to be soft, with 32% having  $p_T < 25$  GeV. Therefore  
456 jets with  $p_T < 15$  GeV are considered as possible candidates in the models described below. By  
457 contrast, less than 5% of the jets originating from the Higgs fall below this  $p_T$ . The jets are found  
458 to be well modeled even down to this low  $p_T$  threshold, as shown in section 9.1. The impact of  
459 using different  $p_T$  selection for the jet candidates is considered in detail in section ???. As they  
460 are expected to originate from the primary vertex, jets are also required to pass a JVT cut.

## 461 8.2 b-jet Identification

462 Including the kinematics of the b-jets that originate from the top decay is found to improve the  
463 identification of the Higgs decay products, and improve the accuracy with which the Higgs  
464 momentum can be reconstructed. Because these b-jets are reconstructed by the detector with  
465 high efficiency (just over 90% of the time), and can be identified relatively consistently, the first  
466 step in reconstructing the Higgs is selecting the b-jets from the top decay.

467        Exactly two b-jets are expected in the final state of  $t\bar{t}H - ML$  events. However, in both  
 468        the 3l and 2lSS channels, only one or more b-tagged jets are required (where the 70% DL1r b-tag  
 469        working point is used). Therefore, for events which have exactly one, or more than two, b-tagged  
 470        jets, deciding which combination of jets correspond to the top decay is non-trivial. Further,  
 471        events with 1 b-tagged jet represent just over half of all  $t\bar{t}H - ML$  events. Of those, both b-jets  
 472        are reconstructed by the detector 75% of the time. Therefore, rather than adjusting the selection  
 473        to require exactly 2 b-tagged jets, and losing more than half of the signal events, a neural network  
 474        is used to predict which pair of jets is most likely to correspond to truth b-jets.

475        Once the network is trained, all possible pairings of jets are fed into the model, and the pair  
 476        of jets with the highest output score are taken to be b-jets in successive steps of the analysis.

### 477        8.2.1 2lSS Channel

478        For the 2lSS channel, the input features shown in table 3 are used for training. Here  $j_0$  and  $j_1$   
 479        are the two jet candidates, while  $l_0$  and  $l_1$  are the two leptons in the event, ordered by  $p_T$ . jet  
 480        DL1r is an integer corresponding to the calibrated b-tagging working points reached by each jet,  
 481        where 5 represents the tightest working point and 1 represents the loosest. The variables nJets  
 482        DL1r 60% and nJets DL1r 85% represent the number of jets in the event passing the 60% and  
 483        85% b-tag working points, respectively.

484        As there are far more incorrect combinations than correct ones, by a factor of more than  
 485        20:1, the training set is resampled to reduce the fraction of incorrect combinations. A random

jet $p_T$ 0	jet $p_T$ 1	Lepton $p_T$ 0
Lepton $p_T$ 1	jet $\eta$ 0	jet $\eta$ 1
$\Delta R(j_0)(j_1)$	$M(j_0 j_1)$	$\Delta R(l_0)(j_0)$
$\Delta R(l_0)(j_1)$	$\Delta R(l_1)(j_0)$	$\Delta R(l_1)(j_1)$
$M(l_0 j_0)$	$M(l_0 j_1)$	$M(l_1 j_0)$
$M(l_1 j_1)$	jet DL1r 0	jet DL1r 1
nJets OR DL1r 85	nJets OR DL1r 60	$\Delta R(j_0 l_0)(j_1 l_1)$
$\Delta R(j_0 l_1)(j_1 l_0)$	$p_T(j_0 j_1 l_0 l_1 E_T^{\text{miss}})$	$M(j_0 j_1 l_0 l_1 E_T^{\text{miss}})$
$\Delta\phi(j_0)(E_T^{\text{miss}})$	$\Delta\phi(j_1)(E_T^{\text{miss}})$	HT jets
nJets	$E_T^{\text{miss}}$	

Table 3: Input features used in the 2ISS b-jet identification algorithm

486 sample of 5 million incorrect entries are used for training, along with close 1 million correct  
 487 entries. 10% of the dataset is set aside for testing, leaving around 5 million datapoints for  
 488 training.

489 The difference between the distributions for a few of these features for the correct(i.e.  
 490 both jets are truth b-jets), and incorrect combinations are shown in figure 8.1. The correct and  
 491 incorrect contributions are scaled to the same integral, so as to better demonstrate the differences  
 492 in the distributions.

493 The modeling of these inputs is validated against data, with figure 8.2 showing good  
 494 general agreement between data and MC. Plots for the complete list of features can found in  
 495 section A.

496 Based on the results of grid search evaluation, the optimal architecture is found to include  
 497 5 hidden layers with 40 nodes each. No regularizer or dropout is added to the network, as  
 498 overfitting is found to not be an issue. The output score distribution as well as the ROC curve for

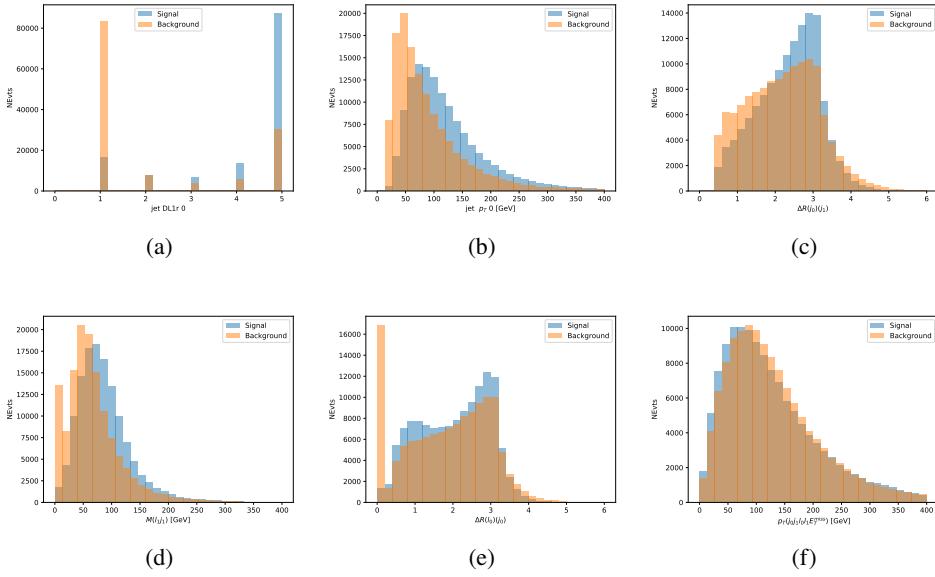


Figure 8.1: Input features for top2lSS training. The signal in blue represents events where both jet candidates are truth b-jets from top decays, and the orange is all other combinations. Scaled to the same number of events.

499 the trained model are shown in figure 8.2.1. The model is found to identify the correct pairing  
500 of jets for 73% of 2lSS signal events on test data.

501 For point of comparison, a naïve approach to identify b-jets is used as well: The two jets  
502 which pass the highest DL1r b-tag working point are assumed to be the b-jets from the top decay.  
503 In the case that multiple jets meet the same b-tag working point, the jet with higher  $p_T$  is used.  
504 This method identifies the correct jet pair 65% of the time.

505 The accuracy of the model for different values of n-bjets, compared to this naive approach,  
506 is shown in table 4.

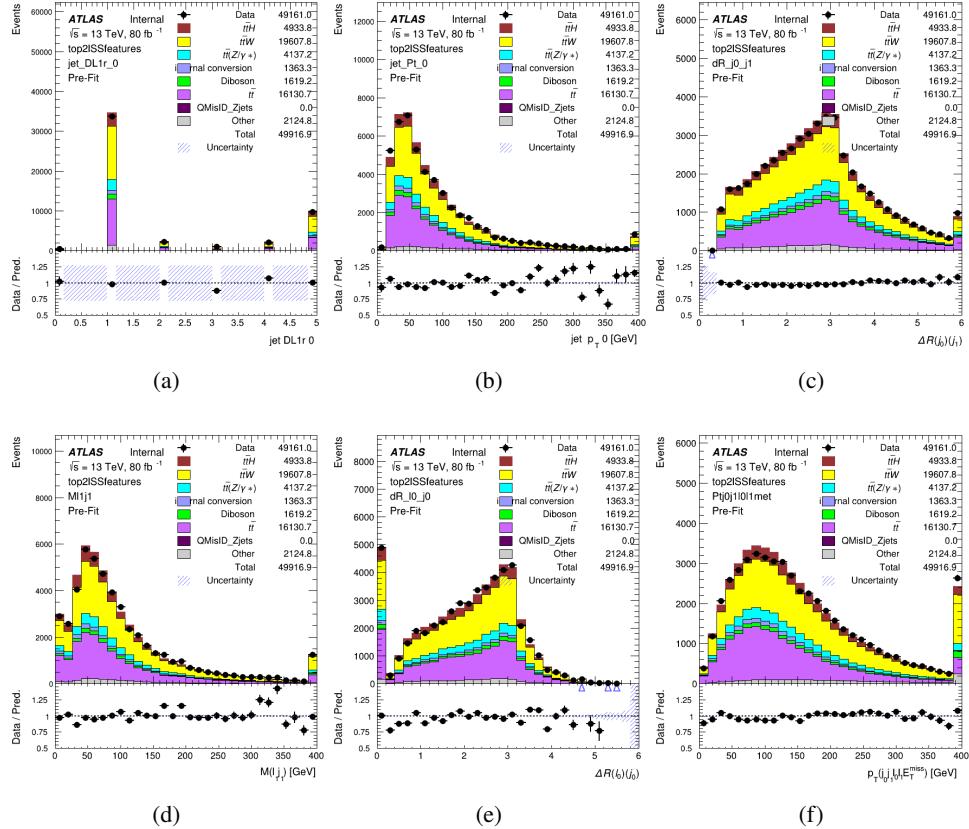


Figure 8.2: Data/MC comparisons of input features for top2ISS training for  $80 \text{ fb}^{-1}$  of data.

Table 4: Accuracy of the NN in identifying b-jets from tops in 2ISS events for, compared to the accuracy of taking the two highest b-tagged jets.

b-jet Selection	Neural Network	Naive
1 b-jet	58.6%	42.1%
2 b-jets	88.4%	87.1%
$\geq 3$ b-jets	61.7%	53.3%
Overall	73.9% %	67.2%

### 507 8.2.2 3l Channel

508 The input features used in the 3l channel are listed in table 5, with the same naming convention  
 509 as the 2ISS channel.

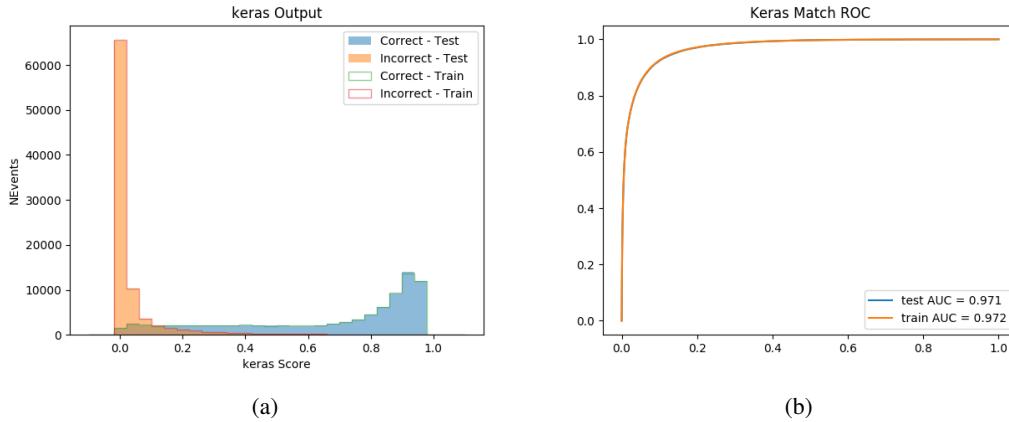


Figure 8.3: (a) the output score of the NN for correct and incorrect combinations of jets. (b) the ROC curve of the output, showing background rejection as a function of signal efficiency

jet $p_T$ 0	jet $p_T$ 1	jet $\eta$ 0
jet $\eta$ 1	Lepton $p_T$ 0	Lepton $p_T$ 1
Lepton $p_T$ 2	$\Delta R(j_0)(j_1)$	$M(j_0 j_1)$
$\Delta R(l_0)(j_0)$	$\Delta R(l_1)(j_0)$	$\Delta R(l_2)(j_0)$
$\Delta R(l_0)(j_1)$	$\Delta R(l_1)(j_1)$	$\Delta R(l_2)(j_1)$
$M(l_0 j_0)$	$M(l_1 j_0)$	$M(l_2 j_0)$
$M(l_0 j_1)$	$M(l_1 j_1)$	$M(l_2 j_1)$
$\Delta R(j_0 l_0)(j_1 l_1)$	$\Delta R(j_0 l_0)(j_1 l_2)$	$\Delta R(j_0 l_1)(j_1 l_0)$
$\Delta R(j_0 l_2)(j_1 l_0)$	jet DL1r 0	jet DL1r 1
$p_T(j_0 j_1 l_0 l_1 l_2 E_T^{\text{miss}})$	$M(t j_0 j_1 l_0 l_1 l_2 E_T^{\text{miss}})$	$\Delta\phi(j_0)(E_T^{\text{miss}})$
$\Delta\phi(j_1)(E_T^{\text{miss}})$	HT Lepton	HT jets
nJets	$E_T^{\text{miss}}$	nJets OR DL1r 85
nJets OR DL1r 60		

Table 5: Input features

510        A few of these features are shown in figure 8.4, comparing the distributions for correct and  
 511        incorrect combinations of jets.

512        The modeling of these inputs is validated against data, with figure 8.5 showing good  
 513        general agreement between data and MC. Plots for the complete list of features can be found in  
 514        section A.

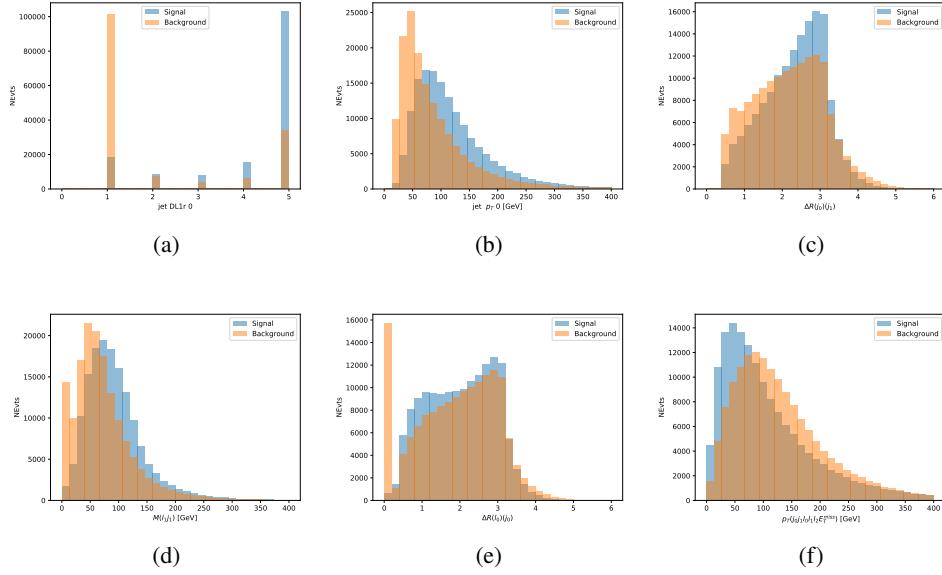


Figure 8.4: Input features for top3l training. The signal in blue represents events where both jet candidates are truth b-jets from top decays, and the orange is all other combinations. Scaled to the same number of events.

515 Again, the dataset is downsized to reduce the ratio of correct and incorrect combination  
 516 from 20:1, to 5:1. Around 7 million events are used for training, with 10% set aside for testing.  
 517 Based on the results of grid search evaluation, the optimal architecture is found to include 5  
 518 hidden layers with 60 nodes each. The output score distribution as well as the ROC curve for the  
 519 trained model are shown in figure 8.2.2.

520 This procedure is found to identify the correct pairing of jets for nearly 80% of 3l signal  
 521 events. The accuracy of the model is summarized in table 6.

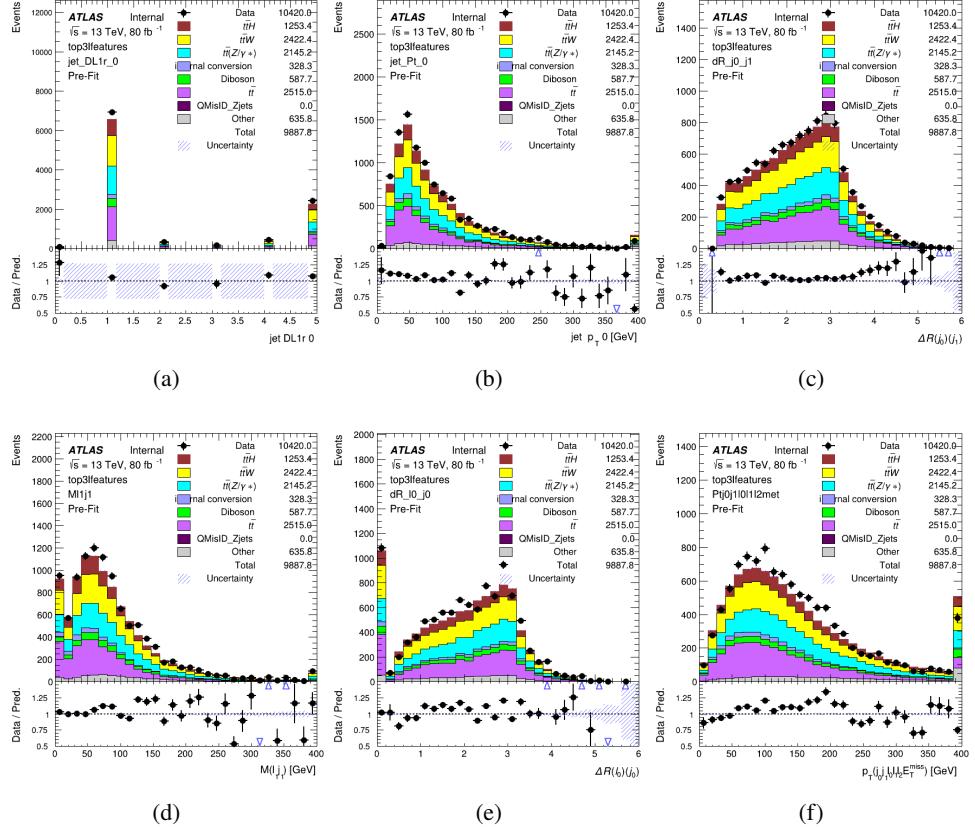


Figure 8.5: Data/MC comparisons of input features for top3l training for  $80 \text{ fb}^{-1}$  of data.

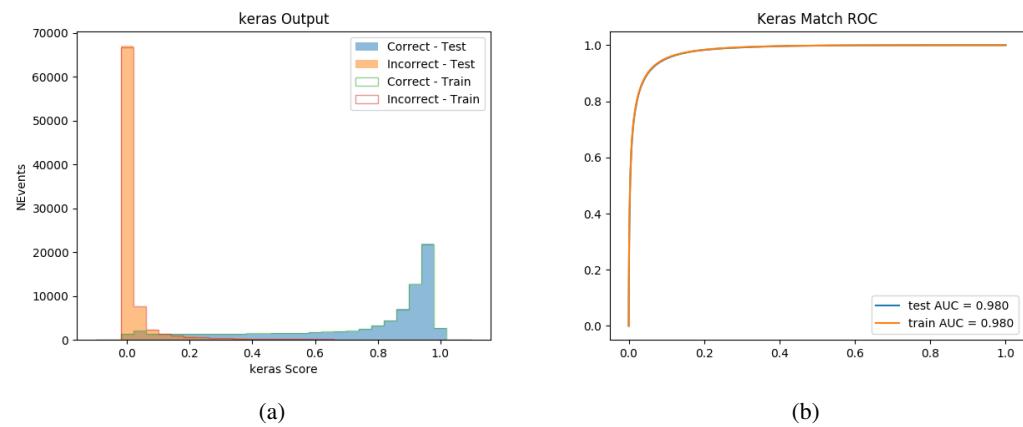


Figure 8.6: tmp

Table 6: Accuracy of the NN in identifying b-jets from tops, compared to the naive method of taking the highest b-tagged jets.

	NN	Naive
1 b-jet	69.0%	48.9%
2 b-jets	89.6%	88.3%
$\geq 3$ b-jets	55.7%	52.3%
Overall	79.8%	70.2%

### 522 8.3 Higgs Reconstruction

523 Techniques similar to the b-jet identification algorithms are employed to select the decay products  
 524 of the Higgs: kinematics of all possible combinations of reconstructed objects are fed into a neural  
 525 network to determine which of those is most mostly to be the decay products of the Higgs.

526 Again separate models are used for the 2lSS and 3l channels, while the 3l channel has now  
 527 been split into two:  $t\bar{t}H$  events with three leptons in the final state include both instances where  
 528 the Higgs decays into a lepton (and a neutrino) and a pair of jets, and instances where the Higgs  
 529 decays to two leptons.

530 3l events are therefore categorized as either semi-leptonic or fully-leptonic. In the semi-  
 531 leptonic case the reconstructed decay products consist of two jets and a single leptons. For  
 532 the fully-leptonic case, the decay products include 2 of the three leptons associated with the  
 533 event. For training the models, events are separated into these two categories using truth level  
 534 information. A separate MVA, described in section 8.5, is used to make this distinction at reco  
 535 level and determine which model to use.

536 For all channels, the models described in section 8.2 are used to identify b-jet candidates,

537 whose kinematics are used to identify the Higgs decay products. These jets are not considered  
538 as possible candidates for the Higgs decay, justified by the fact that these models are found to  
539 misidentify jets from the Higgs decay as jets from the top decay less than 1% of the time.

540 **8.3.1 2ISS Channel**

541 For the 2ISS channel, the Higgs decay products include one light lepton and two jets. The neural  
542 network is trained on the kinematics of different combinations of leptons and jets, as well as the  
543 b-jets identified in section 8.2, with the specific input features listed in table ??.

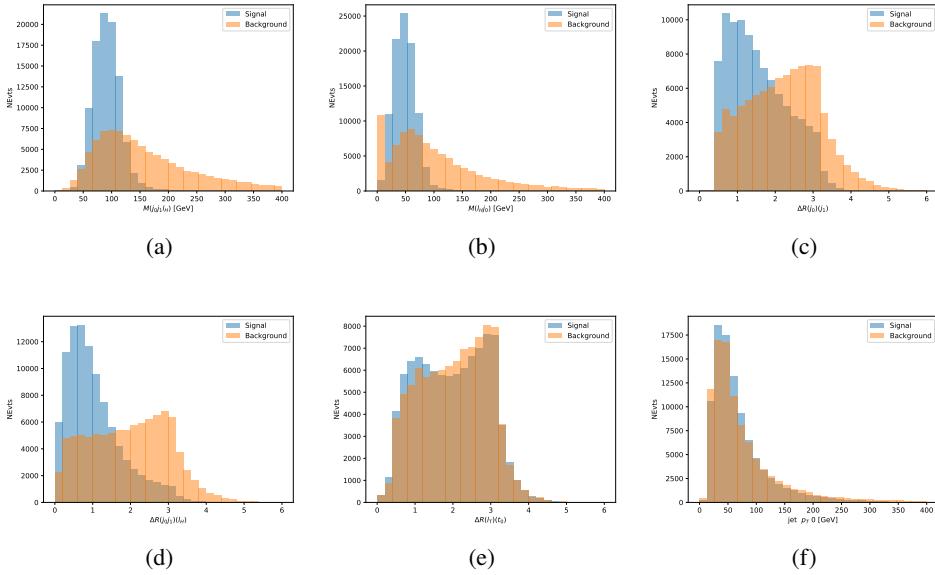


Figure 8.7: Input features for higgs2lSS training. The signal in blue represents events where both jet candidates are truth b-jets from top decays, and the orange is all other combinations. Scaled to the same number of events.

544        The modeling of these inputs is validated against data, with figure 8.2 showing good  
 545        general agreement between data and MC. Plots for the complete list of features can found in  
 546        section A.

547        The neural network identifies the correct combination 55% of the time. It identifies the  
 548        correct lepton 85% of the time, and selects the correct lepton and at least one of the correct jets  
 549        81% of the time.

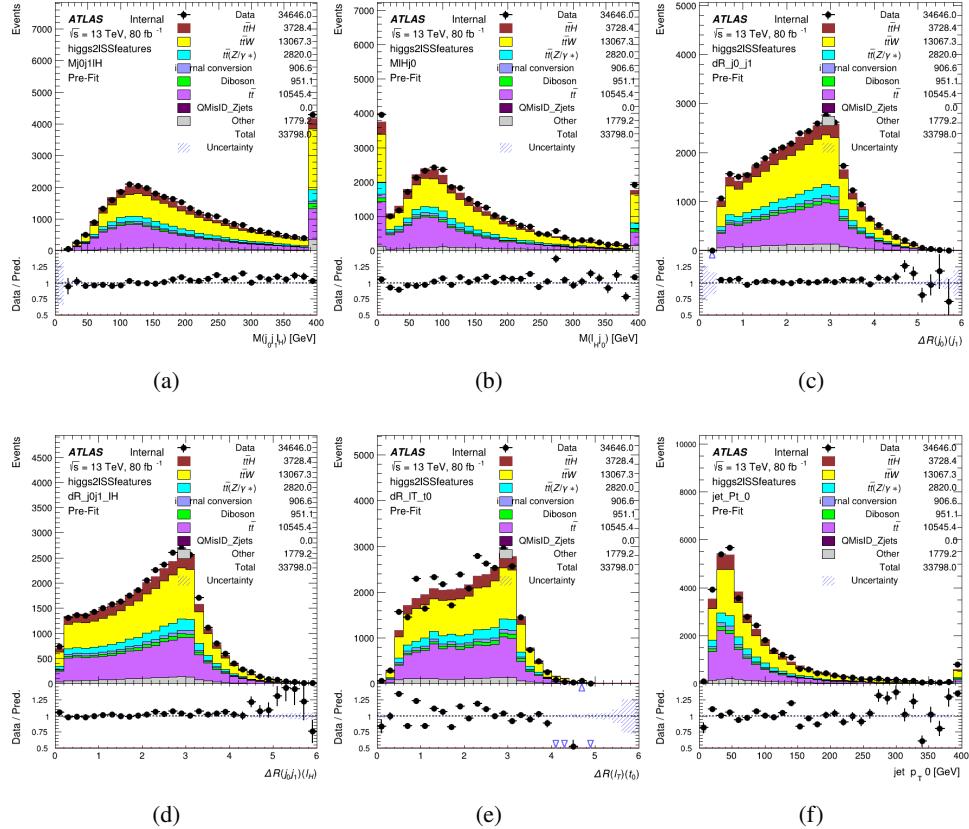


Figure 8.8: Data/MC comparisons of input features for higgs2lSS training for  $80 \text{ fb}^{-1}$  of data.

### 550 8.3.2 3l Semi-leptonic Channel

551 For 3l  $t\bar{t}H$  where the Higgs decay semi-leptonically, the decay products include one of the three  
 552 leptons and two jets. In this case, the other two leptons originated from the decay of the tops,  
 553 meaning the opposite-sign (OS) lepton cannot have come the Higgs. This leave only the two  
 554 same-sign (SS) leptons as possible Higgs decay products.

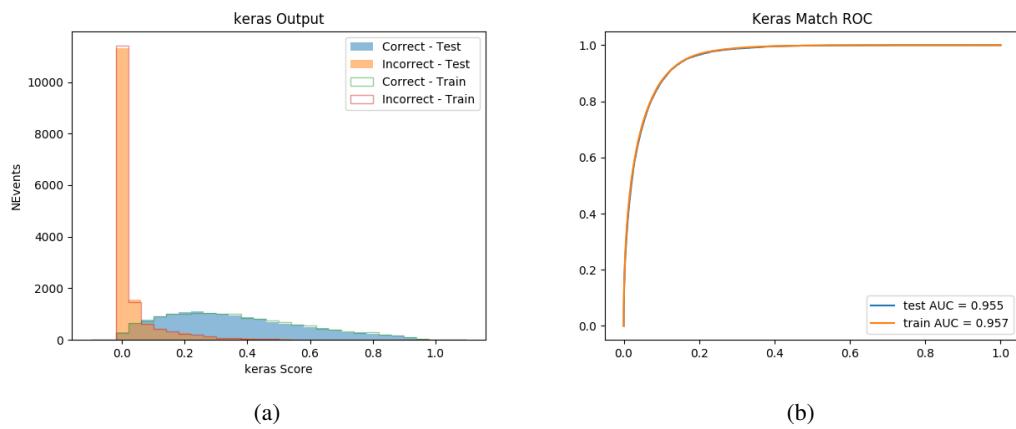


Figure 8.9: (a) the output score of the NN for correct and incorrect combinations of jets. (a) the ROC curve of the output, showing background rejection as a function of signal efficiency

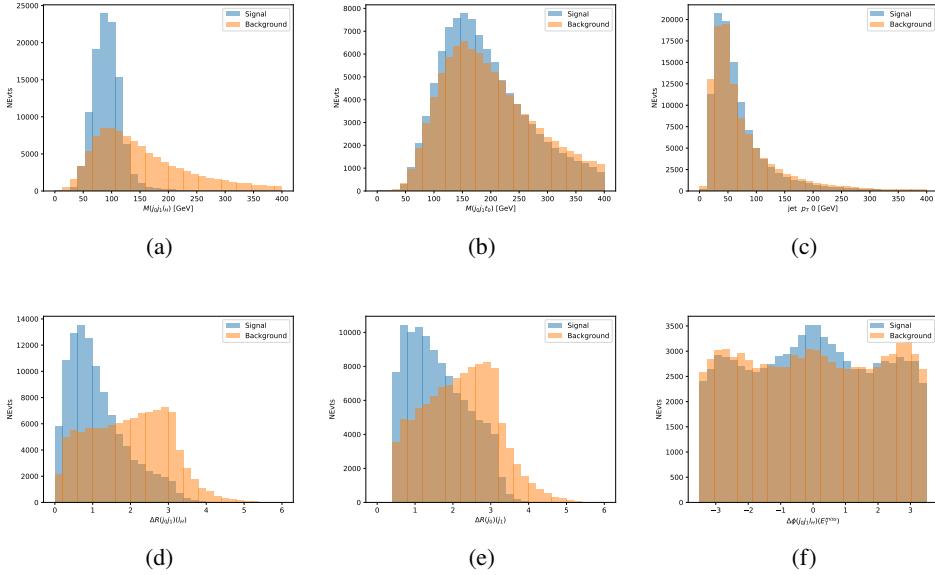


Figure 8.10: Input features for higgs3lS training. The signal in blue represents events where both jet candidates are truth b-jets from top decays, and the orange is all other combinations. Scaled to the same number of events.

555        The modeling of these inputs is validated against data, with figure 8.11 showing good  
 556        general agreement between data and MC. Plots for the complete list of features can found in  
 557        section A.

558        The neural network identifies the correct combination 65% of the time. It identifies the  
 559        correct lepton 85% of the time, anselects the correct lepton and at least one of the correct jets  
 560        83% of the time.

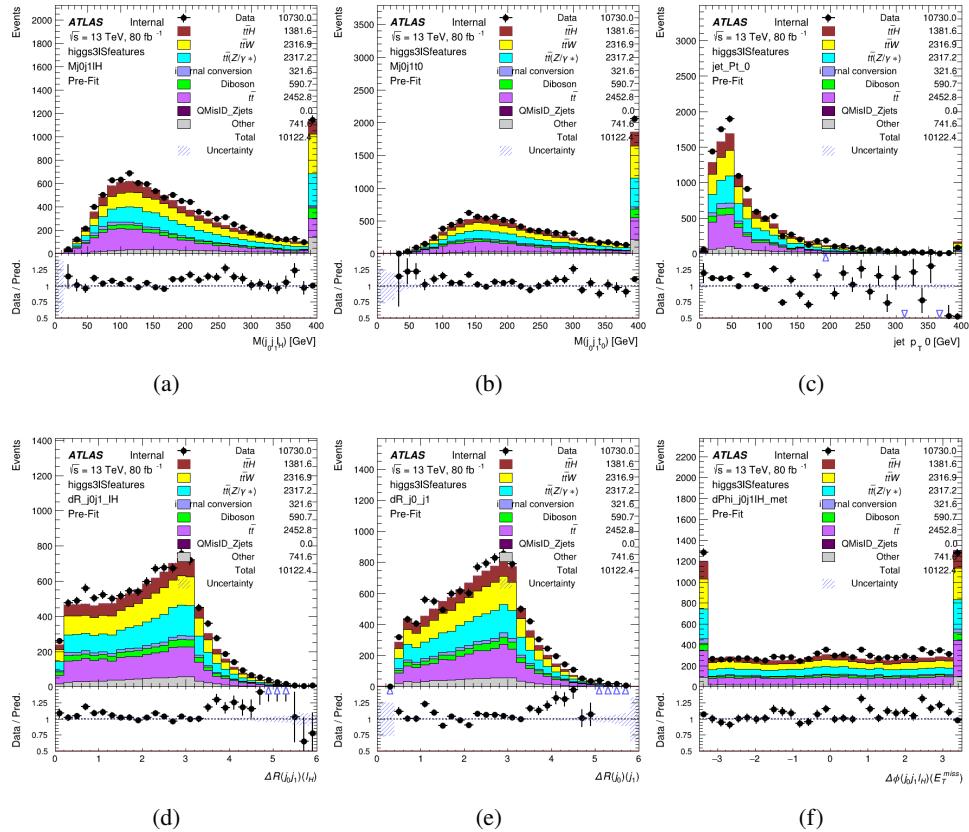


Figure 8.11: Data/MC comparisons of input features for higgs3lS training for  $80 \text{ fb}^{-1}$  of data.

### 8.3.3 3l Fully-leptonic Channel

562 In the fully-leptonic 3l case, the goal is identify which two of the three leptons originated from  
563 the Higgs decay. Since one of these two must be the OS lepton, this problem is reduced to  
564 determining which of the two SS leptons originated from the Higgs. The kinematics of both  
565 possibilities are used for training, one where the SS lepton from the Higgs is correctly labeled,  
566 and one where it is not.

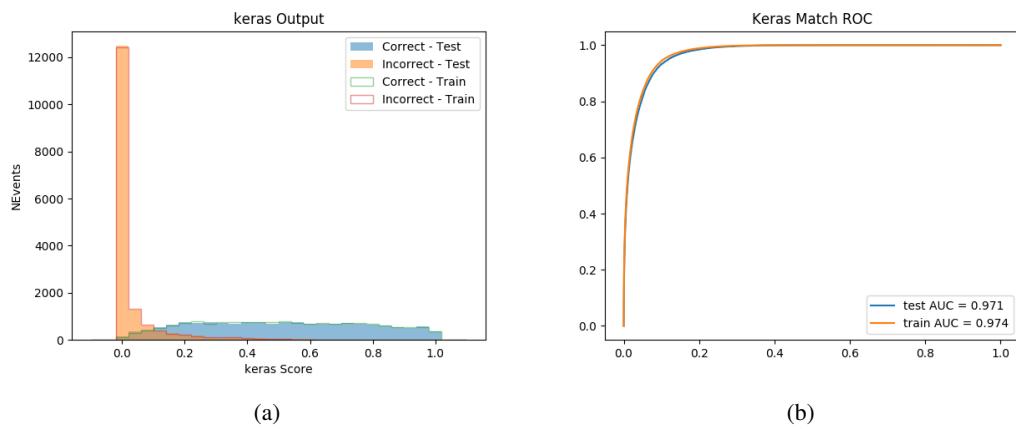


Figure 8.12: (a) the output score of the NN for correct and incorrect combinations of jets. (a) the ROC curve of the output, showing background rejection as a function of signal efficiency

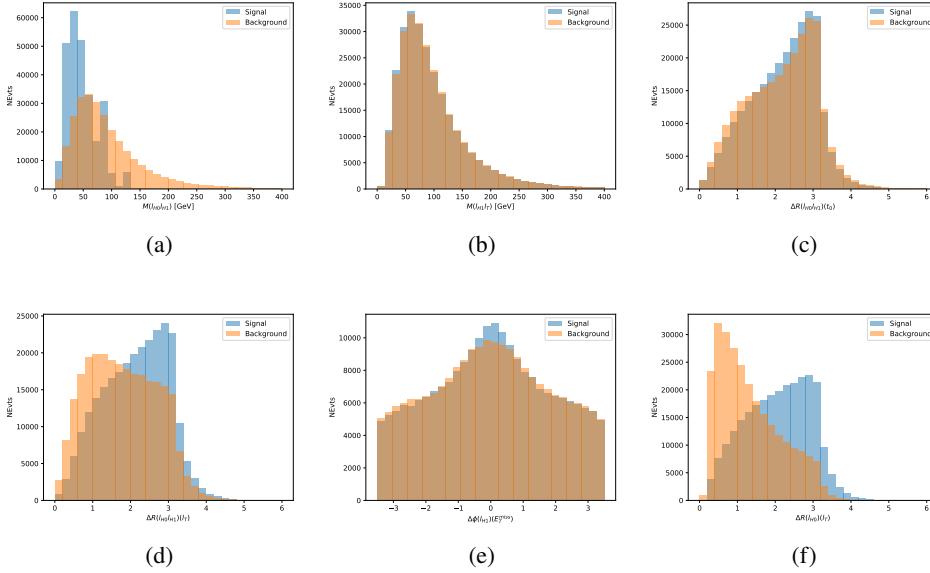


Figure 8.13: Input features for higgs3lF training. The signal in blue represents events where both jet candidates are truth b-jets from top decays, and the orange is all other combinations. Scaled to the same number of events.

567        The modeling of these inputs is validated against data, with figure 8.14 showing good  
 568        general agreement between data and MC. Plots for the complete list of features can found in  
 569        section A.

570        The correct lepton is identified 80% of the time.

## 571        8.4 $p_T$ Prediction

572        Once the most probable decay products have been identified, their kinematics are used as inputs  
 573        to a regression model which attempts to predict the momentum of the Higgs Boson. Once again,  
 574        a DNN is used. Input variables representing the b-jets and leptons not from the Higgs decay

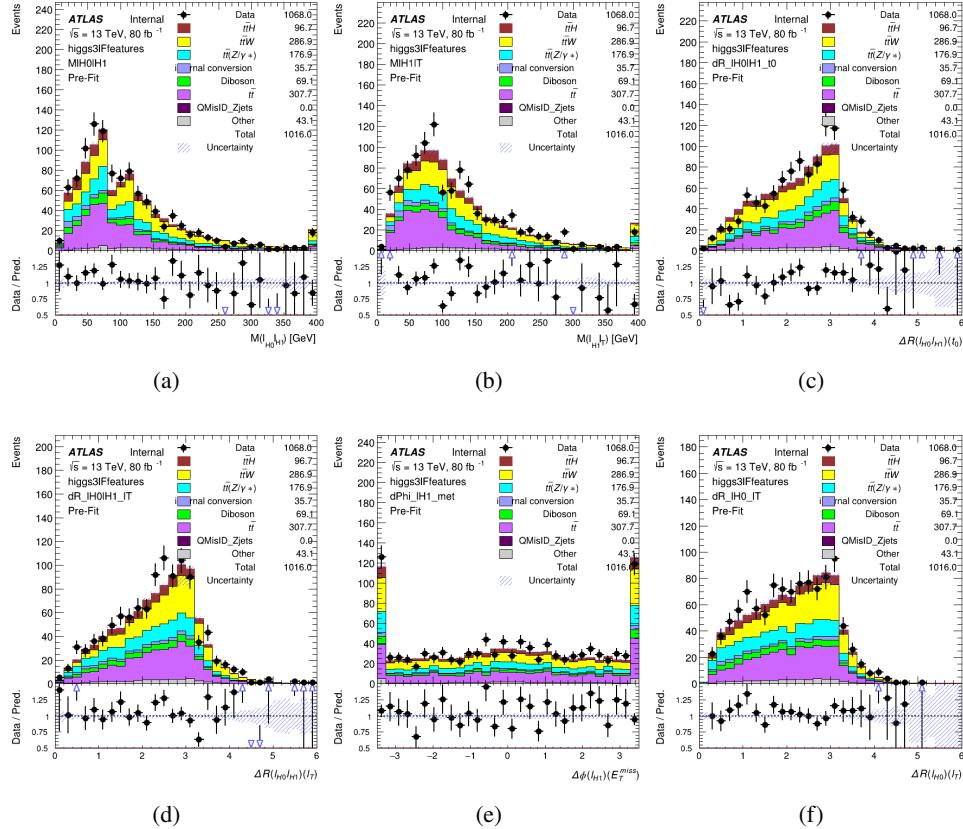


Figure 8.14: Data/MC comparisons of input features for higgs3IF training for  $80 \text{ fb}^{-1}$  of data.

575 are included as well, as these are found to improve performance. The truth  $p_T$  of the Higgs,  
 576 as predicted by MC, are used as labels. Separate models are built for each channel - 2lSS, 3l  
 577 Semi-leptonic and 3l Fully-leptonic.

578 As a two-bin fit is targeted for the final result, some metrics evaluating the performance  
 579 of the models aim to show how well it distinguished between "high  $p_T$ " and "low  $p_T$ " events. A  
 580 cutoff point of 150 GeV is used to define these two categories.

581 Because the analysis uses a two bin fit of the Higgs  $p_T$ , the momentum reconstruction

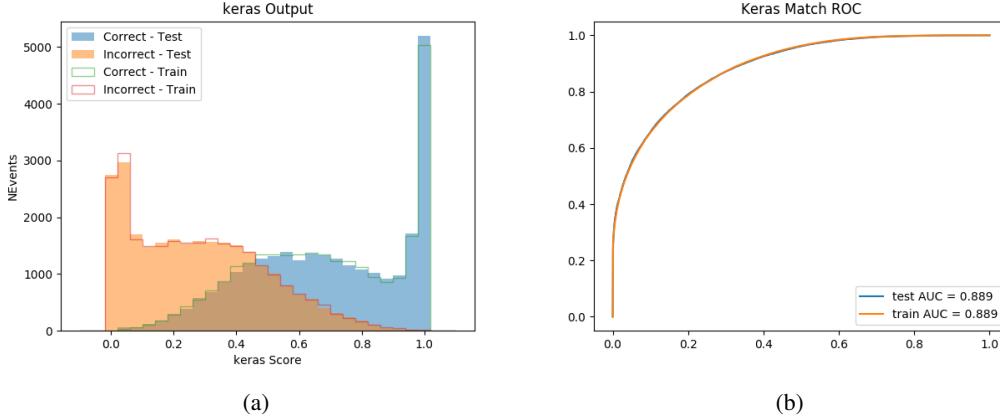


Figure 8.15: (a) the output score of the NN for correct and incorrect combinations of jets. (a) the ROC curve of the output, showing background rejection as a function of signal efficiency

582 could be treated as a binary classification problem, rather than a regression problem. This  
 583 approach is explored in detail in section A.4, and is found not to provide any significant increase  
 584 in sensitivity. The regression approach is used because it provides more flexibility for future  
 585 analyses, as it is independent of the cutoff between high and low  $p_T$ , as well as the number of  
 586 bins. Further, a regression allows the output of the neural network to be more clearly understood,  
 587 as it can be directly compared to a physics observable.

588 **8.4.1 2ISS Channel**

589 The input variables listed in table ?? are used to predict the Higgs  $p_T$  in the 2ISS channel. Here  
 590  $j_0$  and  $j_1$  are the two jets identified as Higgs decay products. The lepton identified as originating  
 591 from the Higgs is labeled  $l_H$ , while the other lepton is labeled  $l_T$ , as it most have come from the  
 592 decay of one of the top quarks. The Higgs Reco Score and b-jet Reco Score are the outputs of  
 593 the Higgs reconstruction algorithm, and the b-jet identification algorithm, respectively.

594      The optimal neural network architecture for this channel is found to consist of 5 hidden  
 595      layers with 40 nodes each. The input data set includes 1.2 million events, 10% of which is used  
 596      for testing, the other 90% for training. Training is found to converge after around 150 epochs.

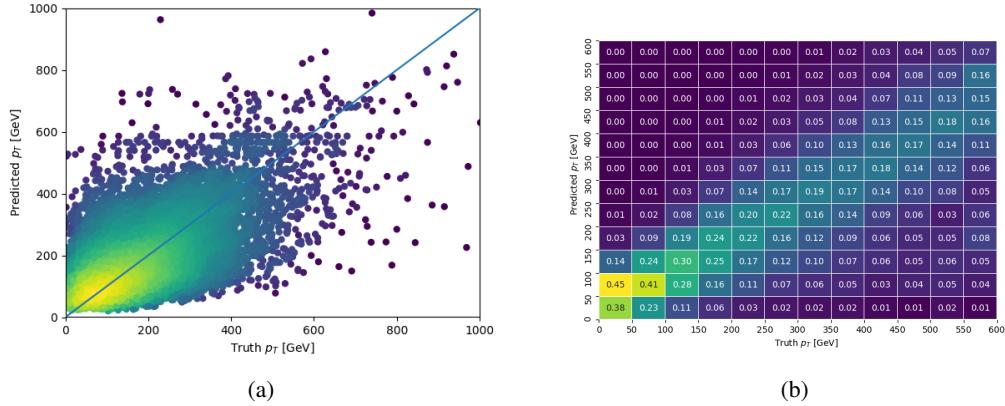


Figure 8.16:

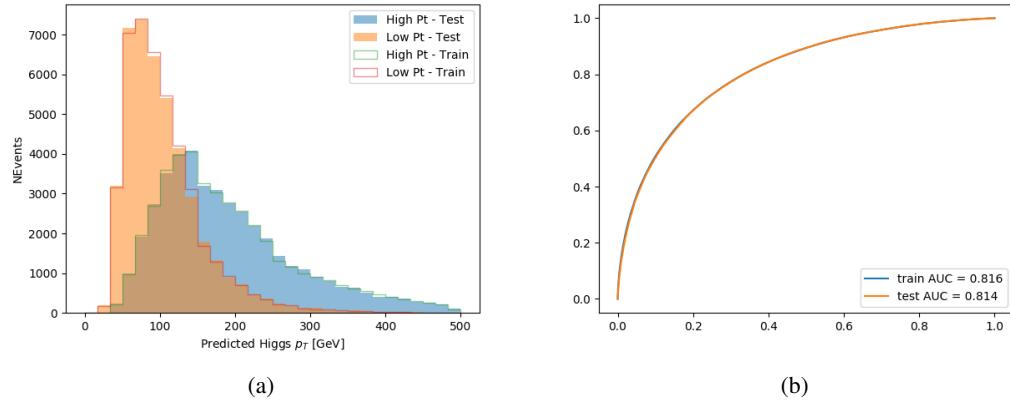


Figure 8.17:

#### 597 8.4.2 3l Semi-leptonic Channel

598        The optimal neural network architecture for this channel is found to consist of 5 hidden  
 599        layers with 40 nodes each. The input data set includes one million events, 10% of which is used  
 600        for testing, the other 90% for training. Training is found to converge after around 150 epochs.

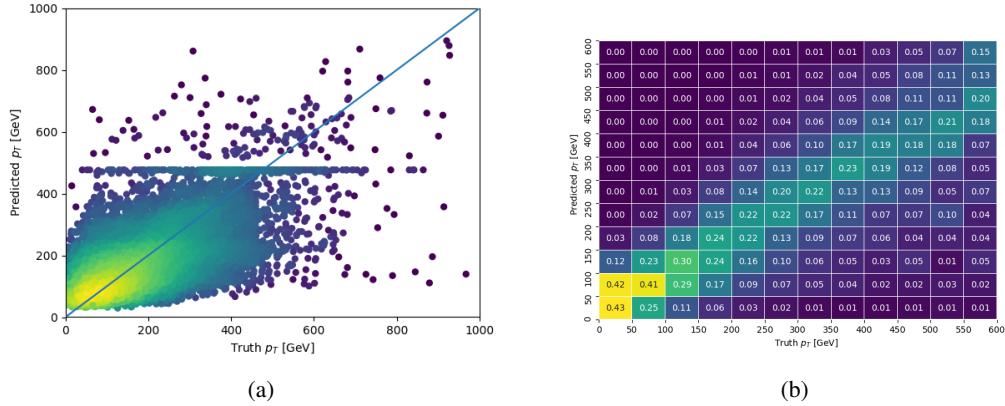


Figure 8.18:

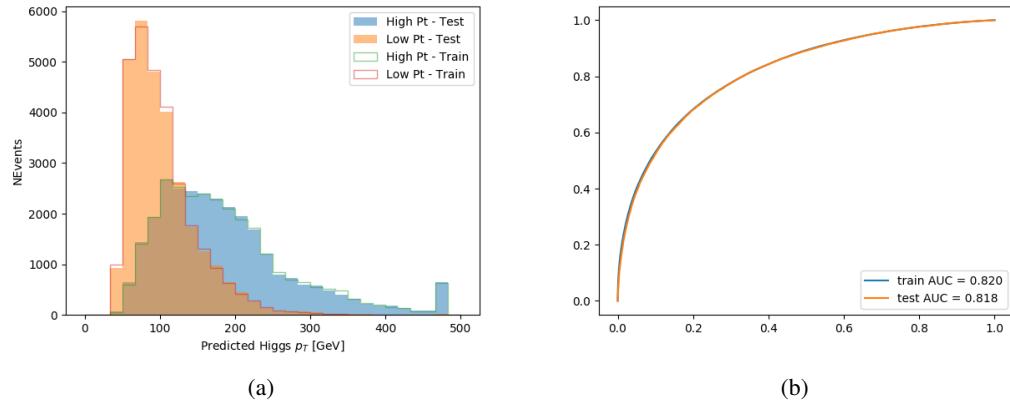


Figure 8.19:

#### 601        8.4.3 3l Fully-leptonic Channel

602        The optimal neural network architecture for this channel is found to consist of 5 hidden  
 603        layers with 40 nodes each. The input data set includes 400,000 events, 10% of which is used for  
 604        testing, the other 90% for training. Training is found to converge after around 150 epochs.

605        The predicted transverse momentum, as a function of the truth  $p_T$ , is shown in figure ??.

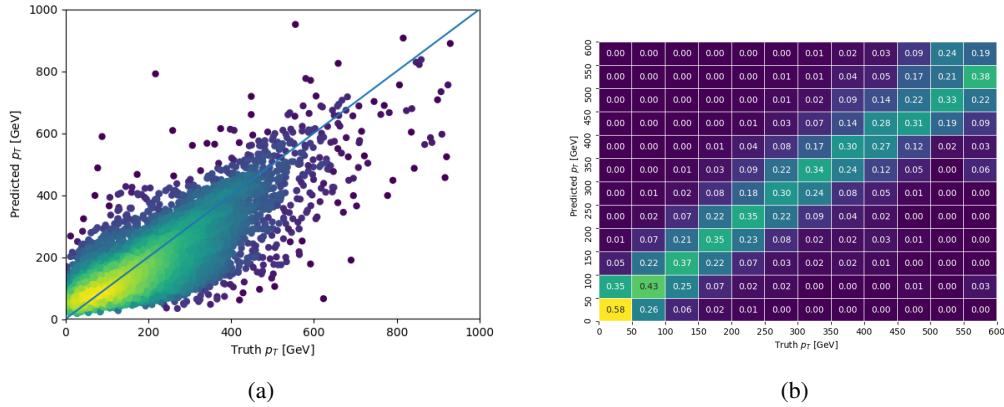


Figure 8.20:

606        When split into high and low  $p_T$ , based on a cutoff of 150 GeV, the

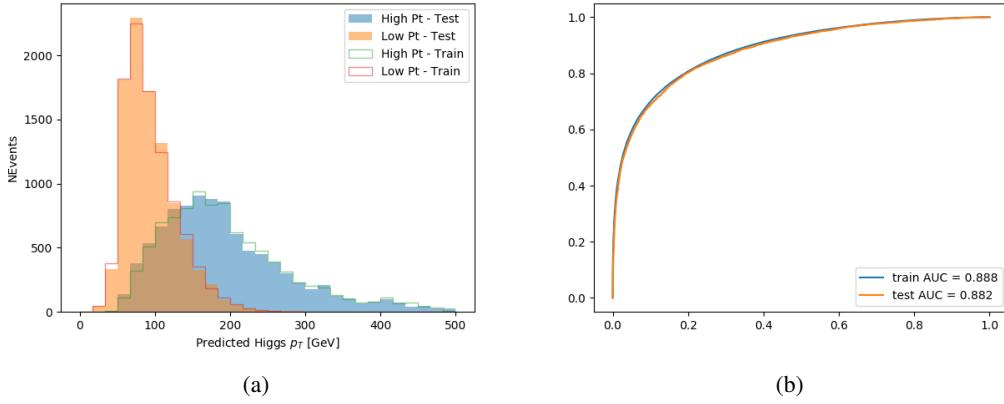


Figure 8.21:

607 **8.5 3l Decay Mode**

608 In the 3l channel, there are two possible ways for the Higgs to decay, both involving intermediate  
609 W boson pairs: Either both W bosons decay leptonically, in which case the reconstructed decay  
610 consists of two leptons (referred as the fully-leptonic 3l channel), or one W decays leptonically  
611 and the other hadronically, giving two jets and one lepton in the final state (referred to as the  
612 semi-leptonic 3l channel). In order to accurately reconstruct the Higgs, it is necessary to identify  
613 which of these decays took place for each 3l event.

614 The kinematics of each event, along with the output scores of the Higgs and top recon-  
615 struction algorithms, are used to distinguish these two possible decay modes. The particular  
616 inputs used are listed in table ??.

617 A neural network with 5 hidden layers, each with 50 nodes, is trained to distinguish these  
 618 two decay modes. The output of the model is summarized in figure 8.22.

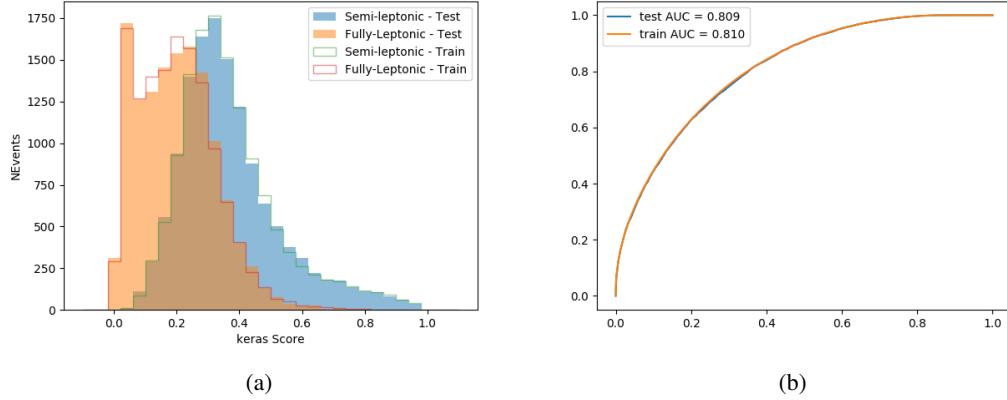


Figure 8.22:

## 619 9 Signal Region Definitions

620 Events are divided into two channels based on the number of leptons in the final state: one with  
 621 two same-sign leptons, the other with three leptons. The 3l channel includes events where both  
 622 leptons originated from the Higgs boson as well as events where only one of the leptons

### 623 9.1 Pre-MVA Event Selection

624 A preselection is applied to define orthogonal analysis channels based on the number of leptons  
 625 in each event. For the 2lSS channel, the following preselection is used:

- 626 • Two very tight, same-charge, light leptons with  $p_T > 20$  GeV

- 627 •  $>=4$  reconstructed jets,  $>=1$  b-tagged jets

- 628 • No reconstructed tau candidates

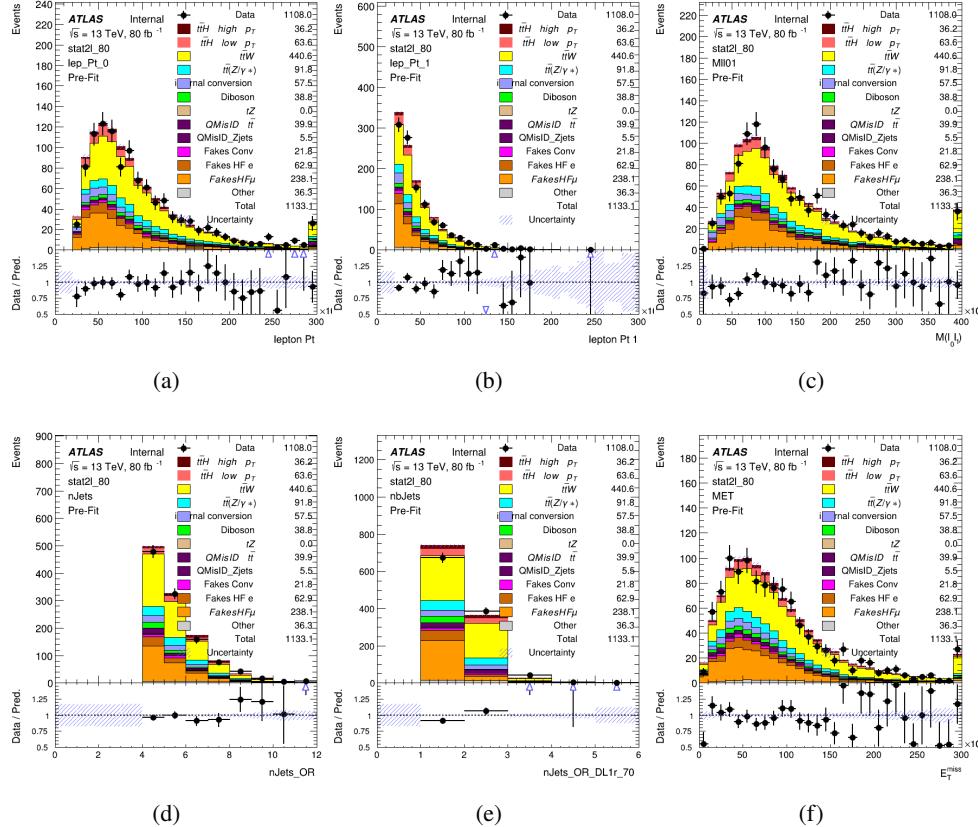


Figure 9.1:

629 For the 31 channel, the following selection is applied:

- 630 • Three light leptons with total charge  $\pm 1$
- 631 • Same charge leptons are required to be very tight, with  $p_T > 20$  GeV

- 632 • Opposite charge lepton must be loose, with  $p_T > 10 \text{ GeV}$

- 633 •  $>=2$  reconstructed jets,  $>=1$  b-tagged jets

- 634 • No reconstructed tau candidates

- 635 •  $|M(l^+l^-) - 91.2 \text{ GeV}| > 10 \text{ GeV}$  for all opposite-charge, same-flavor lepton pairs

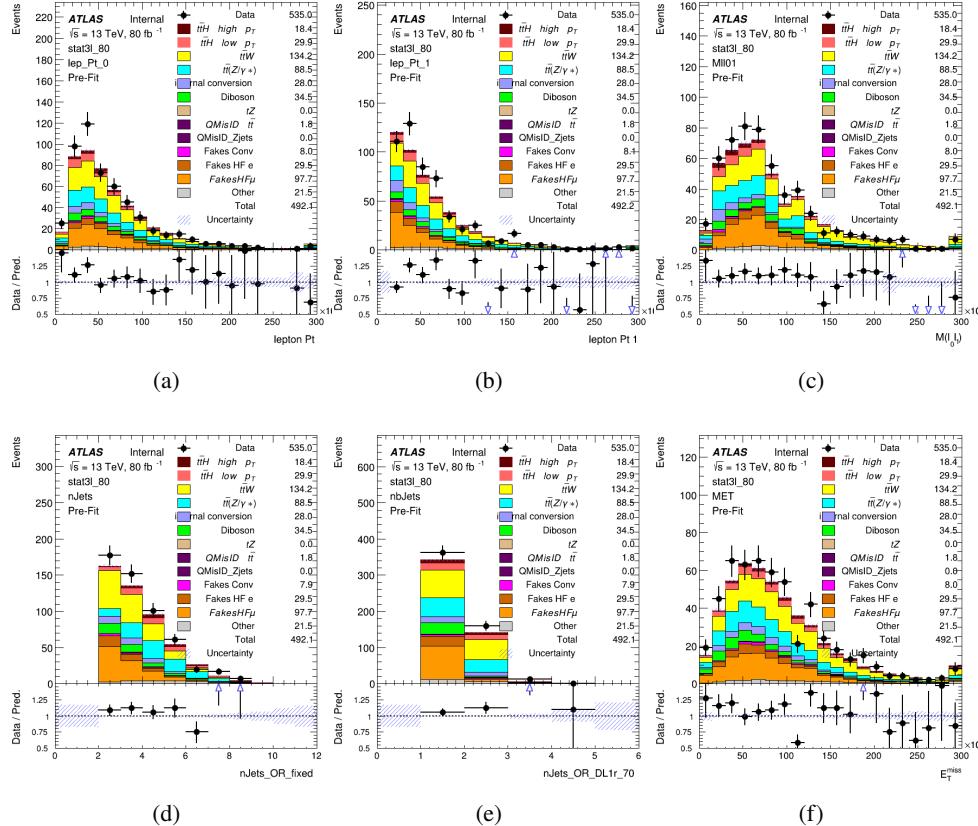


Figure 9.2:

---

**636 9.2 Event MVA**

637 Separate multi-variate analysis techniques (MVAs) are used in order to distinguish signal events  
638 from background for each analysis channel - 2lSS, 3l semi-leptonic (3lS), and 3l fully leptonic  
639 (3lF). In particular, Boosted Decision Tree (BDT) algorithms are produced with XGBoost  
640 [xgboost] are trained using the kinematics of signal and background events derived from Monte  
641 Carlo simulations. Events are weighted in the BDT training by the weight of each Monte Carlo  
642 event.

643 Because the background composition differs for events with a high reconstructed Higgs  $p_T$   
644 compared to events with low reconstructed Higgs  $p_T$ , separate MVAs are produced for high and  
645 low  $p_T$  regions. This is found to provide better significance than attempting to build an inclusive  
646 model, as demonstrated in appendix A.2. A cutoff of 150 GeV is used. This gives a total of 6  
647 background rejection MVAs - explicitly, 2lSS high  $p_T$ , 2lSS low  $p_T$ , 3lS high  $p_T$ , 3lS low  $p_T$ ,  
648 3lF high  $p_T$ , and 3lF low  $p_T$ .

649 The following features are used in both the high and low  $p_T$  2lSS BDTs:

---

HT	$M(\text{lep}, E_T^{\text{miss}})$	$M(l_0 l_1)$
binHiggs $p_T$ 2lSS	$\Delta R(l_0)(l_1)$	diLepton type
higgsRecoScore	jet $\eta$ 0	jet $\eta$ 1
jet $\phi$ 0	jet $\phi$ 1	jet $p_T$ 0
jet $p_T$ 1	Lepton $\eta$ 0	Lepton $\eta$ 1
Lepton $\phi$ 0	Lepton $\phi$ 1	Lepton $p_T$ 0
Lepton $p_T$ 1	$E_T^{\text{miss}}$	$\min \Delta R(l_0)(\text{jet})$
$\min \Delta R(l_1)(\text{jet})$	$\min \Delta R(\text{Lepton})(\text{bjet})$	mjjMax frwdJet
nJets	nJets OR DL1r 60	nJets OR DL1r 70
nJets OR DL1r 85	signal	topRecoScore
weight		

Table 7: Input features

650

While for each of the 31 BDTs, the features listed below are used for training:

$M(\text{lep}, E_T^{\text{miss}})$	$M(l_0 l_1)$	$M(l_0 l_1 l_2)$
$M(l_0 l_2)$	$M(l_1 l_2)$	$\text{binHiggs } p_T \text{ 3lF}$
$\Delta R(l_0)(l_2)$	$\Delta R(l_0)(l_1)$	$\Delta R(l_0)(l_2)$
$\Delta R(l_1)(l_2)$	$\text{decayScore}$	$\text{higgsRecoScore3lF}$
$\text{higgsRecoScore3lS}$	$\text{jet } \eta \ 0$	$\text{jet } \eta \ 1$
$\text{jet } \phi \ 0$	$\text{jet } \phi \ 1$	$\text{jet } p_T \ 0$
$\text{jet } p_T \ 1$	$\text{Lepton } \eta \ 0$	$\text{Lepton } \eta \ 1$
$\text{Lepton } \eta \ 2$	$\text{Lepton } \phi \ 0$	$\text{Lepton } \phi \ 1$
$\text{Lepton } \phi \ 2$	$\text{Lepton } p_T \ 0$	$\text{Lepton } p_T \ 1$
$\text{Lepton } p_T \ 2$	$E_T^{\text{miss}}$	$\min \Delta R(l_0)(\text{jet})$
$\min \Delta R(l_1)(\text{jet})$	$\min \Delta R(l_2)(\text{jet})$	$\min \Delta R(\text{Lepton})(\text{bjet})$
$mjj\text{Max frwdJet}$	$n\text{Jets}$	$n\text{Jets OR DL1r } 60$
$n\text{Jets OR DL1r } 70$	$n\text{Jets OR DL1r } 85$	$\text{signal}$
$\text{topScore}$	$\text{triLepton type}$	$\text{weight}$

Table 8: Input features

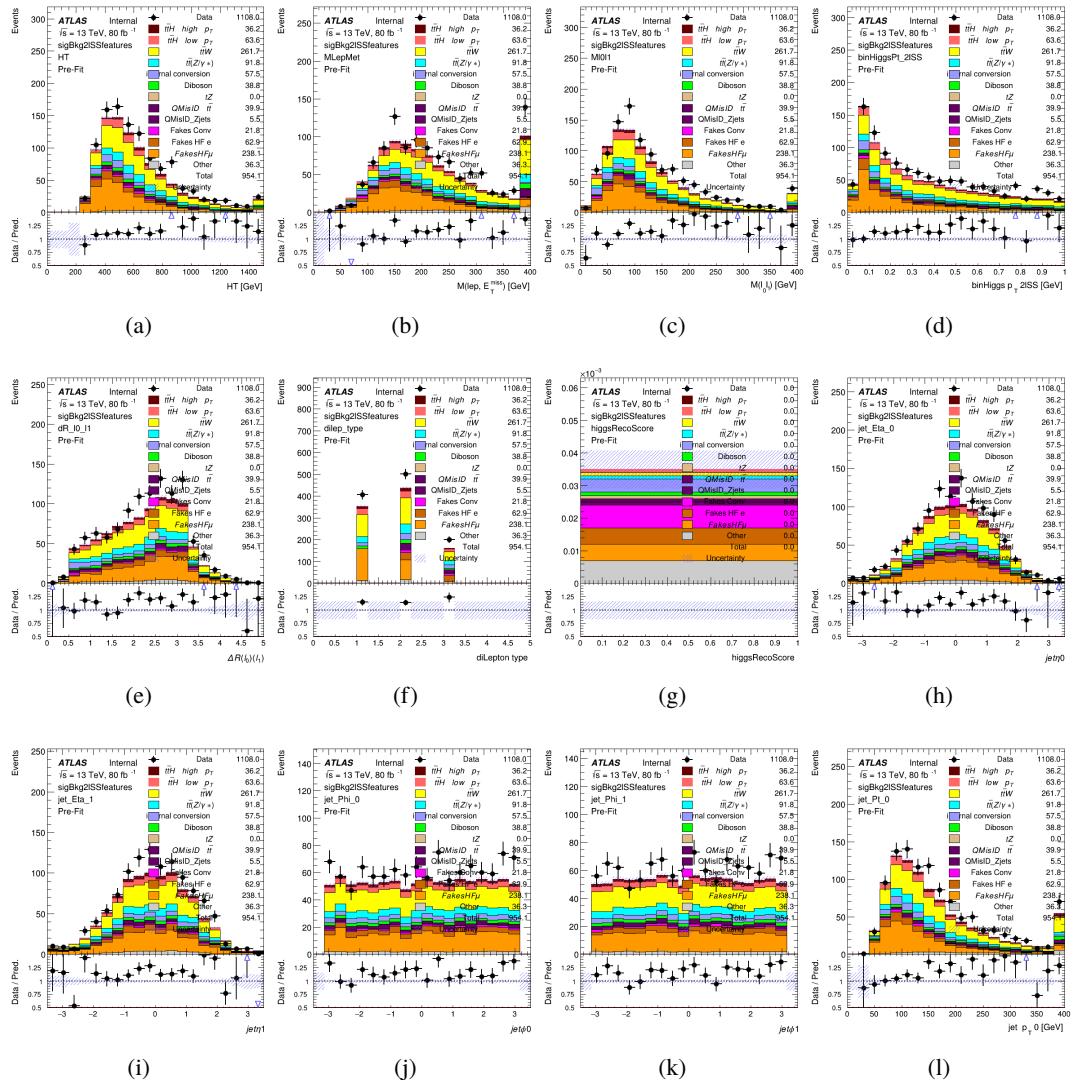


Figure 9.3:

651 The BDTs are produced with a maximum tree depth of 6, using AUC as the target loss  
 652 function.

653 Output distributions of each MVA are shown in figure 9.2.

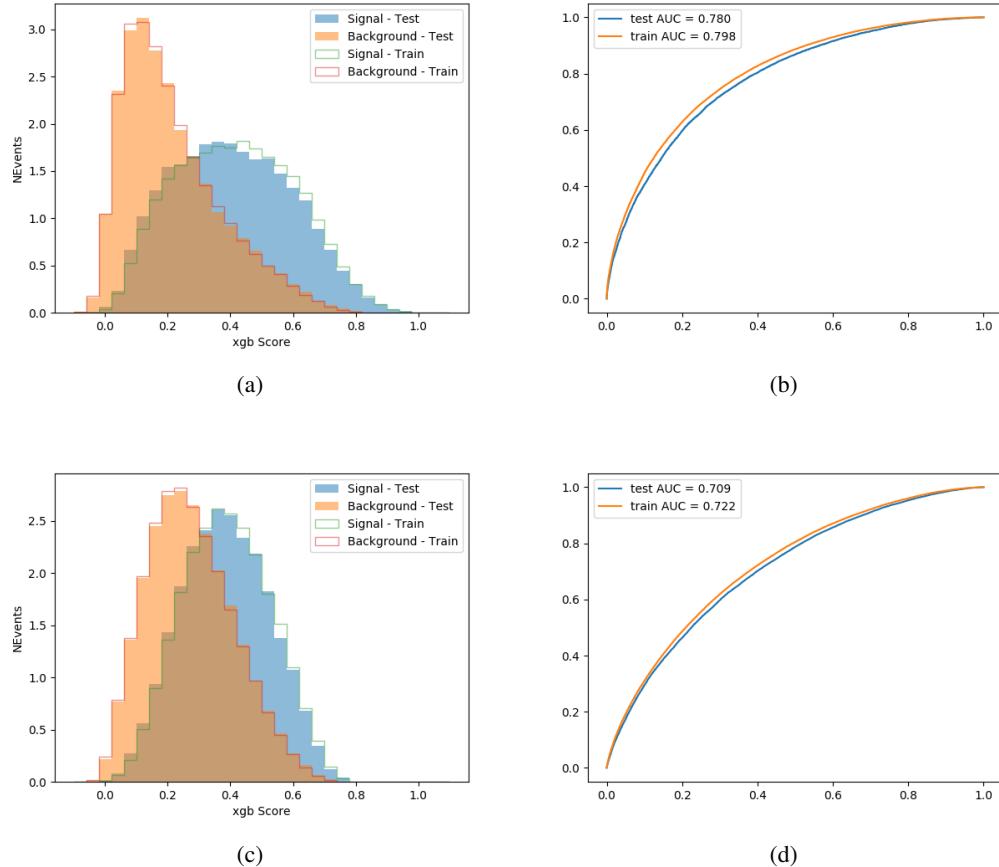


Figure 9.4:

### 654 9.3 Signal Region Definitions

655 Once pre-selection has been applied, channels are further refined based on the MVAs described  
 656 above. The output of the model described in section 8.5 is used to separate the three channel  
 657 into two - Semi-leptonic and Fully-leptonic - based on the predicted decay mode of the Higgs  
 658 boson.

659 For each event, depending on the channel as well as the predicted  $p_T$  of the Higgs derived

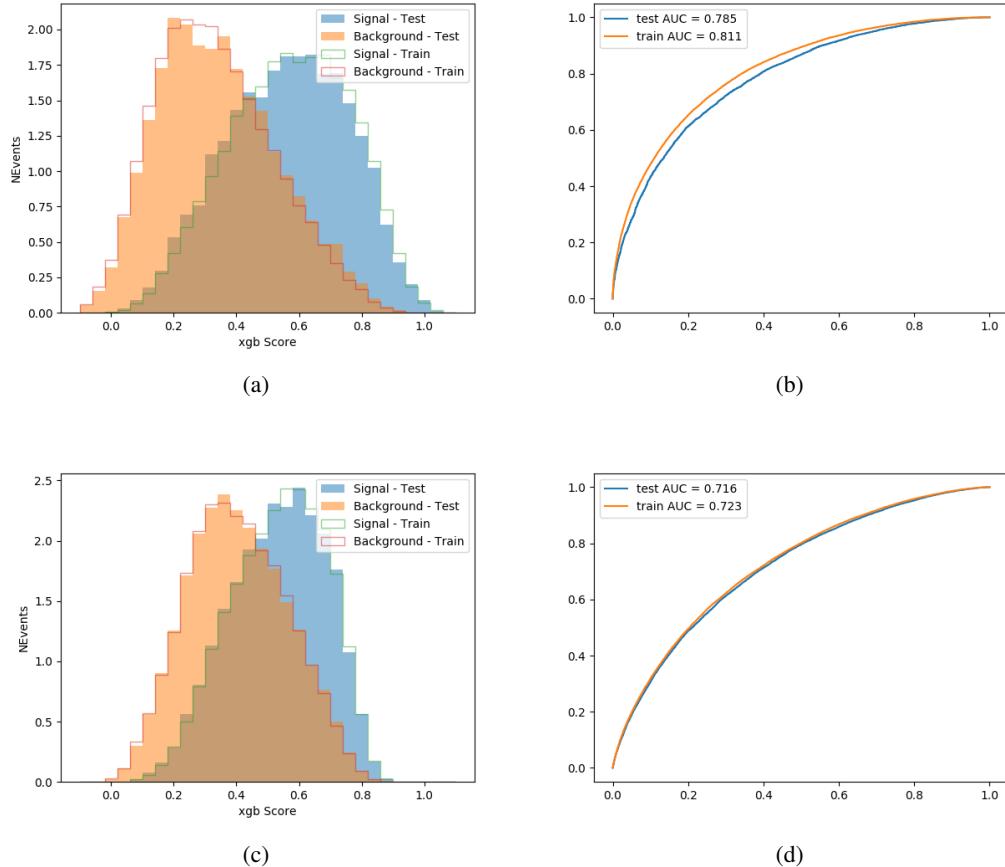


Figure 9.5:

from the algorithm described in section 8.4, a cut on the appropriate background rejection algorithm is applied. The specific selection used, and the event yield in each channel after this selection has been applied, is summarized below.

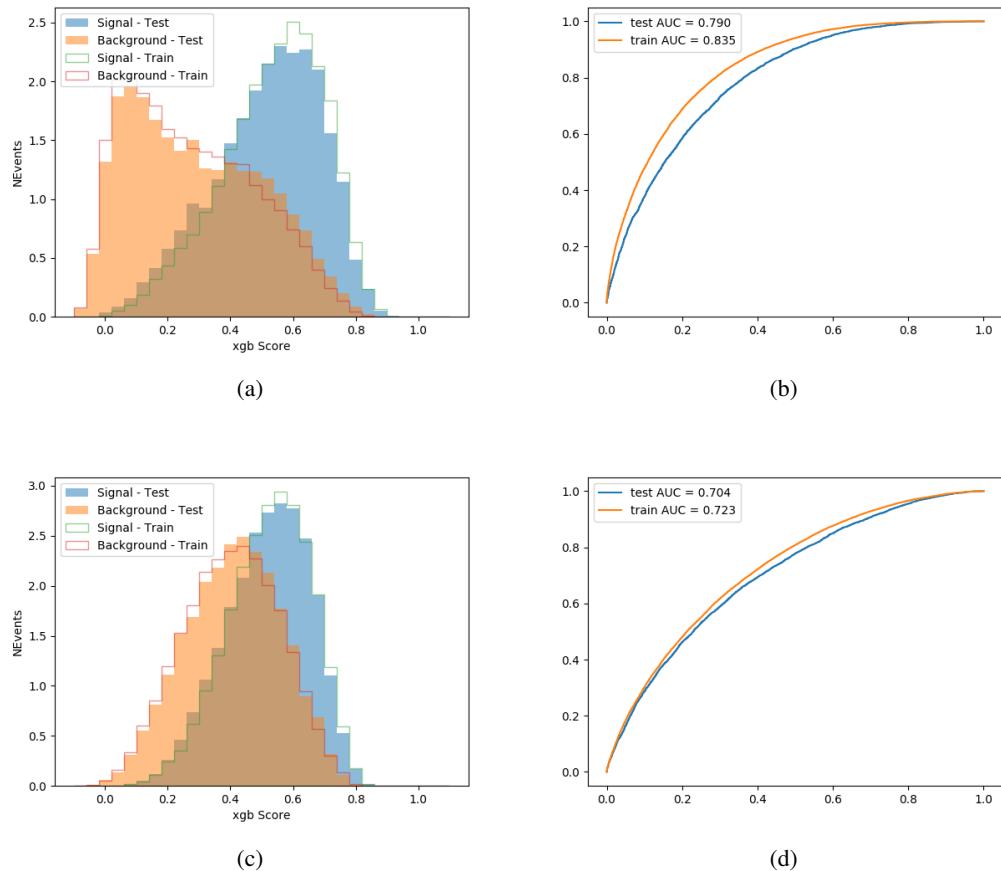


Figure 9.6:

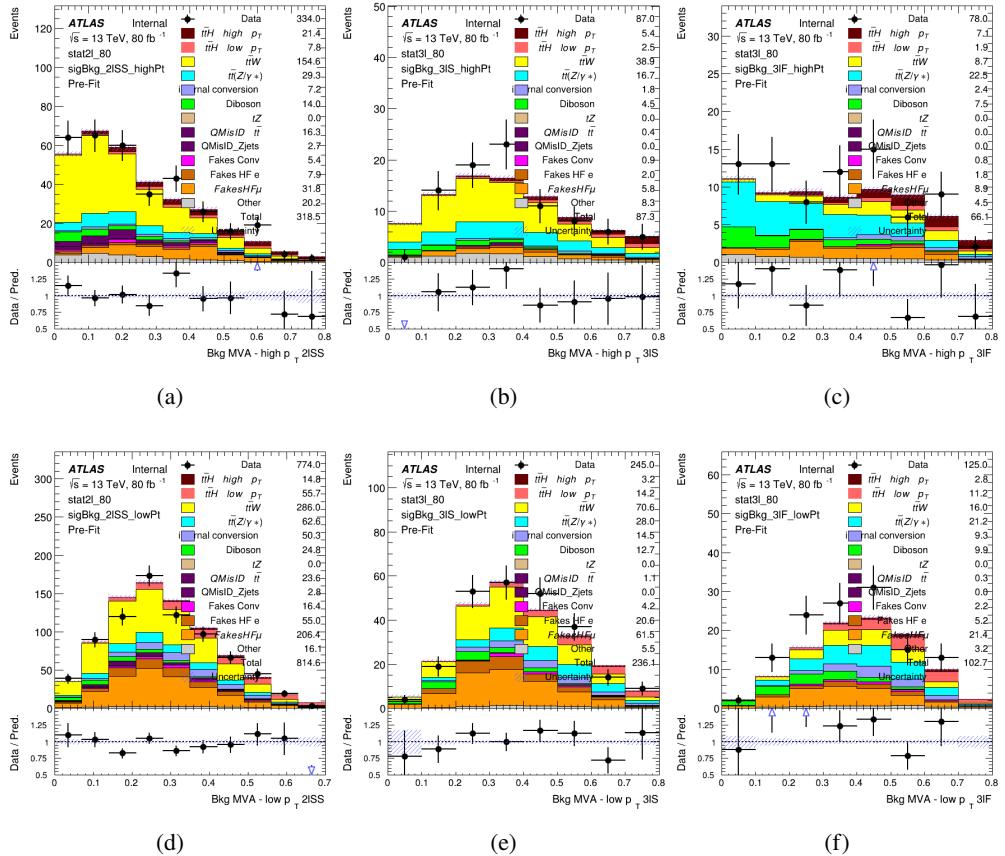


Figure 9.7: scores

### 663 9.3.1 2ISS

### 664 9.3.2 3l – Semi – leptonic

### 665 9.3.3 3l – Fully – leptonic

666 10 Background Rejection MVA

## 667 10.1 Background Rejection MVAs

668 Separate models are used in order to distinguish signal events from background for each analysis  
10th November 2020 – 08:46 67  
669 channel - 2lSS, 3l semi-leptonic, and 3l fully leptonic. In particular, Neural Networks produced

with Tensorflow are trained using the kinematics of signal and background events derived from Monte Carlo simulations. Further, because the background composition differs for events with a high reconstructed Higgs  $p_T$  compared to events with low reconstructed Higgs  $p_T$ , separate MVAs are produced for high and low  $p_T$  regions.

### 10.1.1 2lSS - High $p_T$

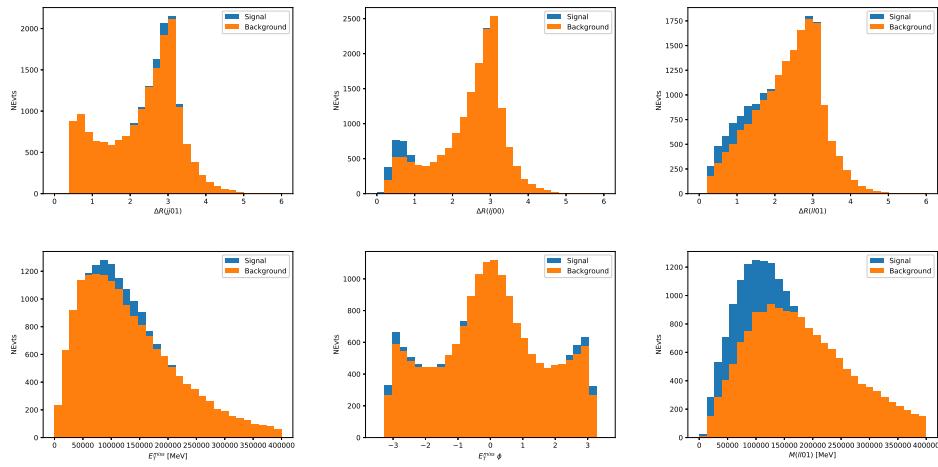


Figure 10.1:

675 **10.1.2 2lSS - Low  $p_T$**

676 **10.1.3 3l Semi-Leptonic - High  $p_T$**

677 **10.1.4 3l Semi-Leptonic - Low  $p_T$**

678 **10.1.5 3l Fully Leptonic - High  $p_T$**

679 **10.1.6 3l Fully Leptonic - Low  $p_T$**

## 680 **11 Systematic Uncertainties**

681 The systematic uncertainties that are considered are summarized in table ???. These are imple-  
682 mented in the fit either as a normalization factors or as a shape variation or both in the signal  
683 and background estimations. The numerical impact of each of these uncertainties is outlined in  
684 section 12.

685 The uncertainty in the combined 2015+2016 integrated luminosity is derived from a  
686 calibration of the luminosity scale using x-y beam-separation scans performed in August 2015  
687 and May 2016 [**lumi**].

688 The experimental uncertainties are related to the reconstruction and identification of light  
689 leptons and b-tagging of jets, and to the reconstruction of  $E_T^{\text{miss}}$ . The sources which contribute

Table 9: Sources of systematic uncertainty considered in the analysis. Some of the systematic uncertainties are split into several components, as indicated by the number in the rightmost column.

Systematic uncertainty	Components
Luminosity	1
Pileup reweighting	1
<b>Physics Objects</b>	
Electron	6
Muon	15
Jet energy scale and resolution	28
Jet vertex fraction	1
Jet flavor tagging	131
$E_T^{\text{miss}}$	3
Total (Experimental)	186
<b>Background Modeling</b>	
Cross section	24
Renormalization and factorization scales	10
Parton shower and hadronization model	2
Shower tune	4
Total (Signal and background modeling)	40
<b>Background Modeling</b>	
Cross section	24
Renormalization and factorization scales	10
Parton shower and hadronization model	2
Shower tune	4
Total (Signal and background modeling)	40
Total (Overall)	226

690 to the uncertainty in the jet energy scale [`jes`] are decomposed into uncorrelated components and  
 691 treated as independent sources in the analysis.

692 The uncertainties in the b-tagging efficiencies measured in dedicated calibration analyses  
 693 [`btag_cal`] are also decomposed into uncorrelated components. The large number of components  
 694 for b-tagging is due to the calibration of the distribution of the BDT discriminant.

695 The systematic uncertainties associated with the signal and background processes are

696 accounted for by varying the cross-section of each process within its uncertainty.

## 697 12 Results

698 Unblinded results are shown for the  $80 \text{ fb}^{-1}$  data set, as well as MC only projections of results  
 699 using the full Run-2,  $140 \text{ fb}^{-1}$  dataset.

### 700 12.1 Results - $80 \text{ fb}^{-1}$

701 A maximum likelihood fit is performed simultaneously over the regions shown in figure 12.1.

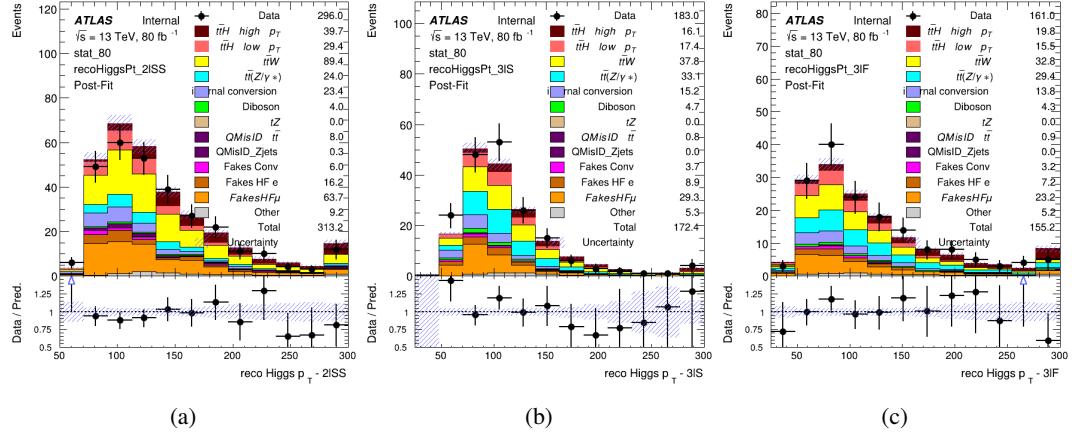


Figure 12.1:

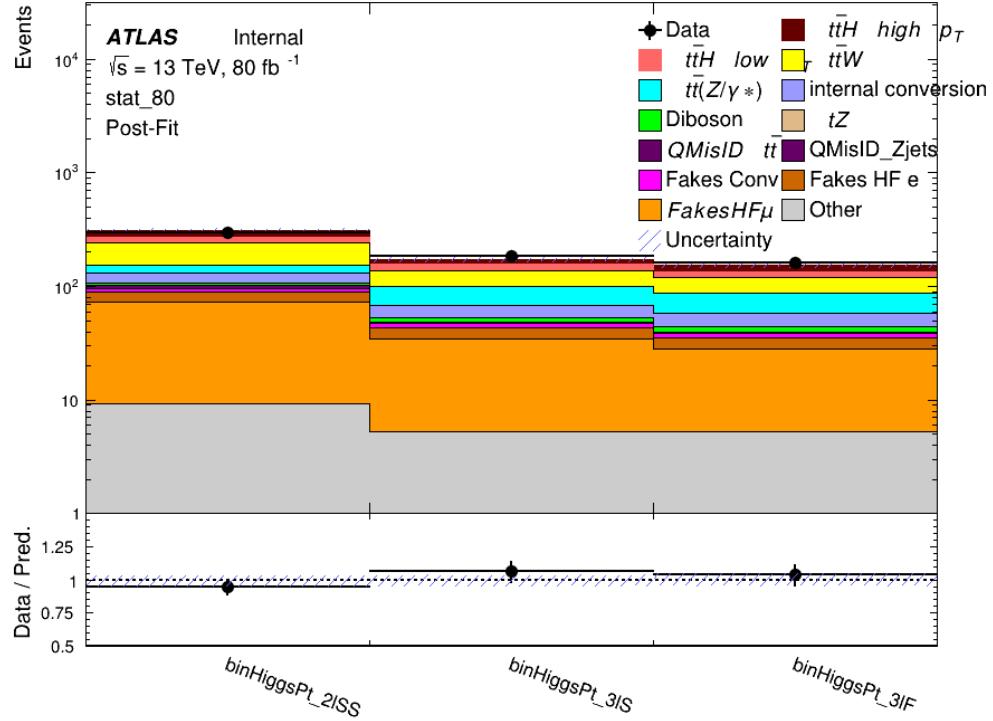


Figure 12.2: Post-fit summary of fit.

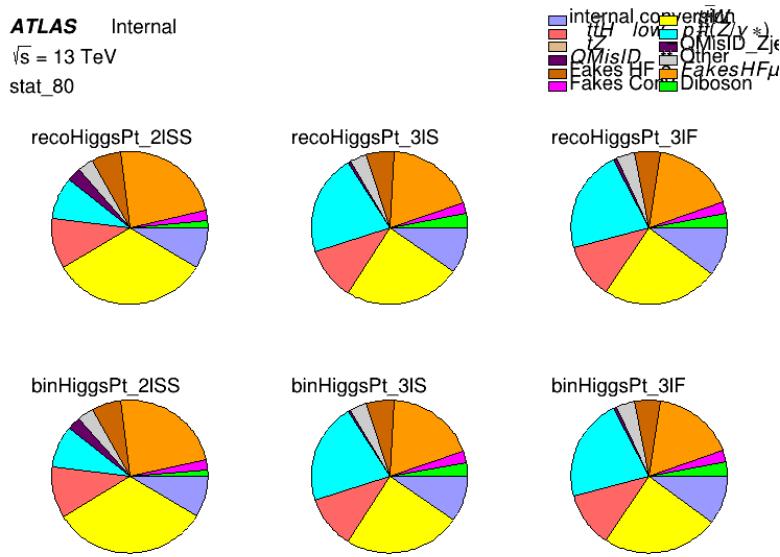


Figure 12.3: Background composition of the fit regions.

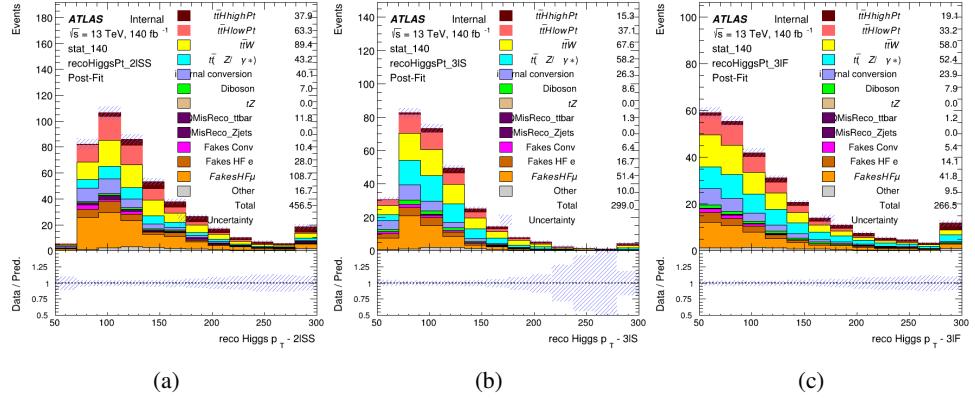


Figure 12.4:

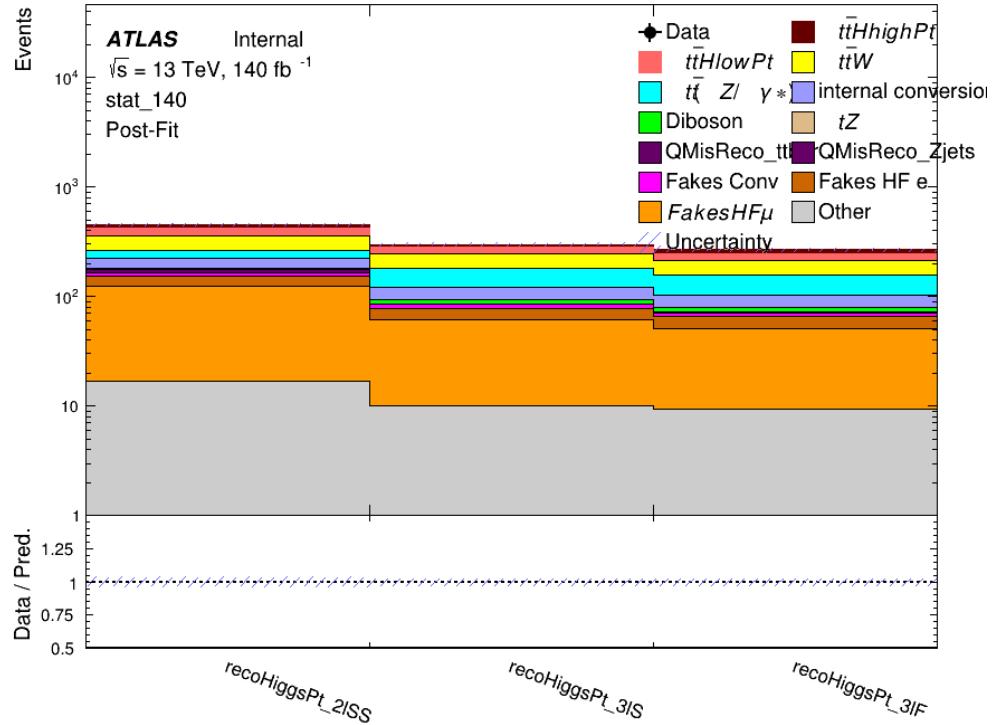


Figure 12.5: Post-fit summary of fit.

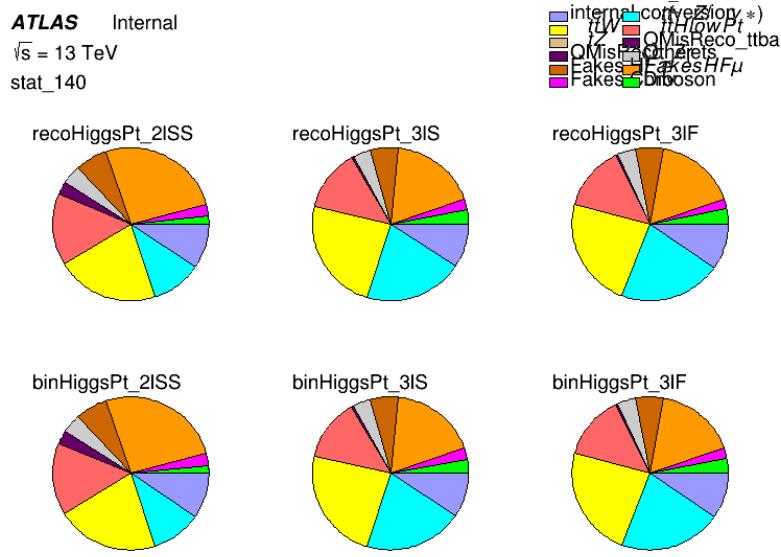


Figure 12.6: Background composition of the fit regions.

**702 12.2 Projected Results -  $140 \text{ fb}^{-1}$**

**703 Part V**

**704 Conclusion**

705 As search for the effects of dimension-six operators on  $t\bar{t}H$  production is performed. An effective  
 706 field theory approached is used to parametrize the effects of high energy physics on the Higgs  
 707 momentum spectrum. The momentum spectrum is reconstructed using various MVA techniques,  
 708 and the limits on dimension-six operators are limited to X.

<sup>709</sup> **List of contributions**

<sup>710</sup>

<sup>711</sup> **Appendices**

<sup>712</sup> **A Machine Learning Models**

<sup>713</sup> The following section provides details of the various MVAs as well as a few studies performed  
<sup>714</sup> in support of this analysis, exploring alternate decisions and strategies.

<sup>715</sup> **A.1 Higgs Reconstruction Models**

<sup>716</sup> **A.1.1 b-jet Identification Features - 2lSS**

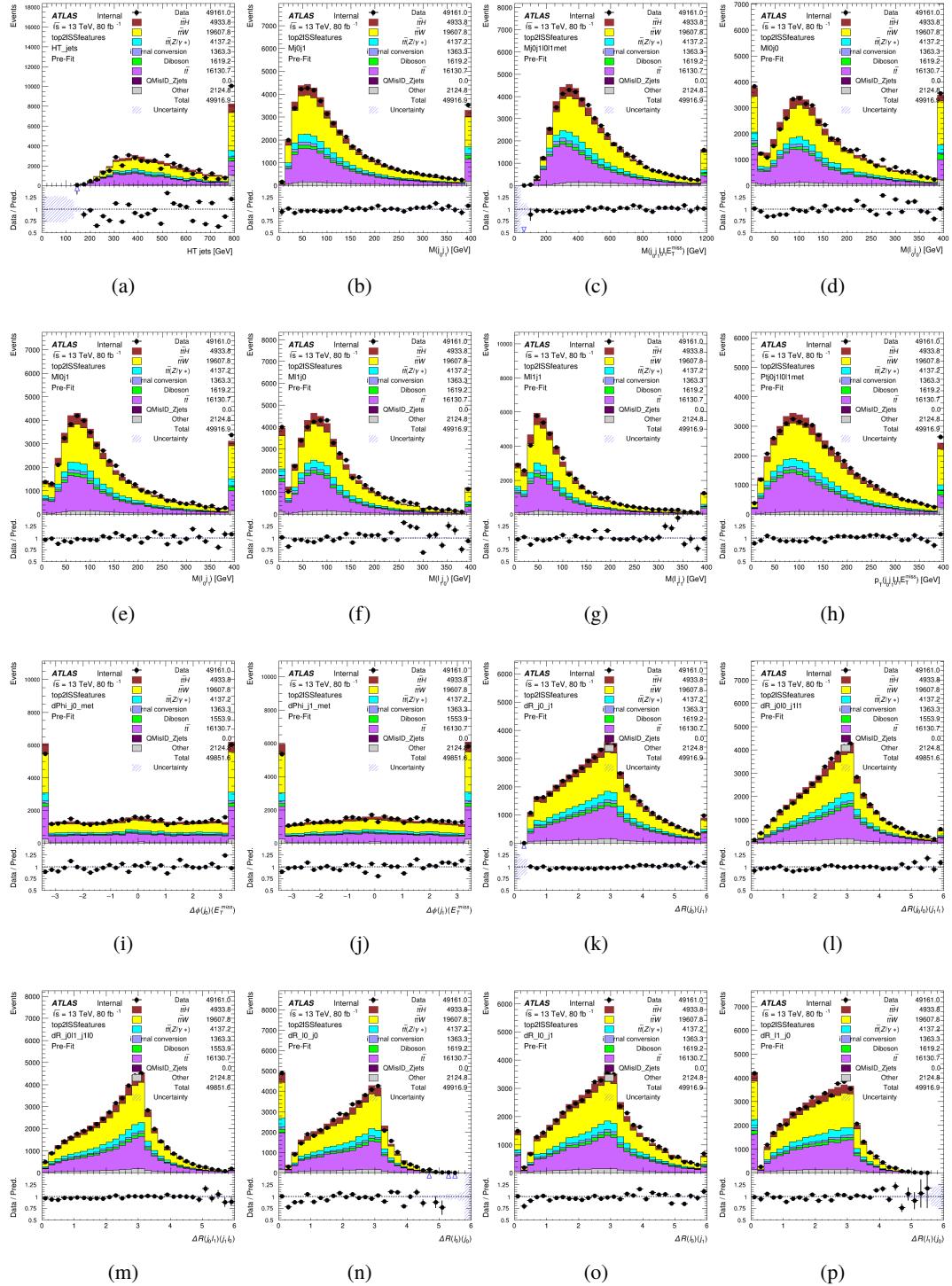


Figure A.1: Input features for top2lSS

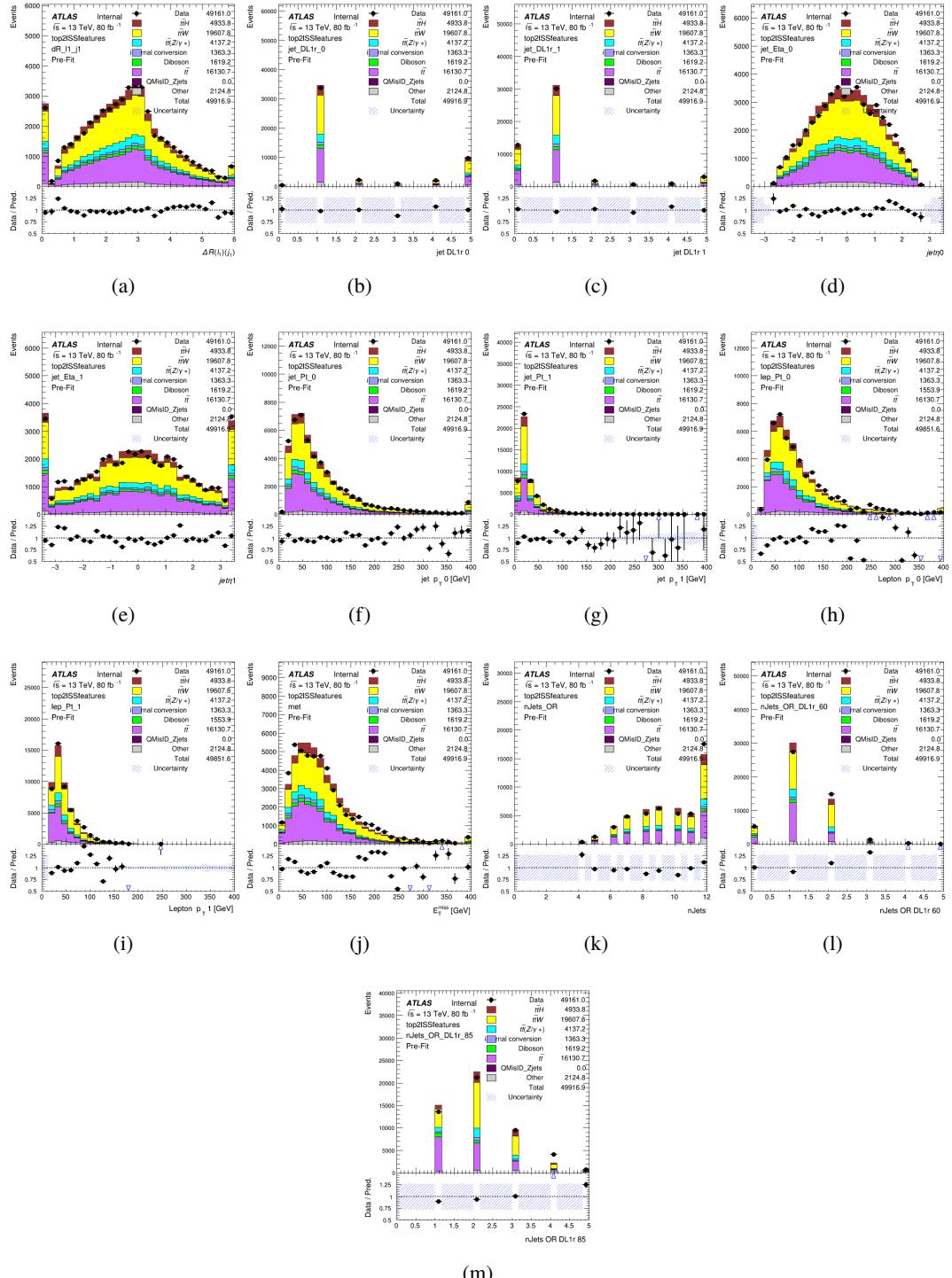


Figure A.2: Input features for top21SS

717 **A.1.2 b-jet Identification Features - 3l**

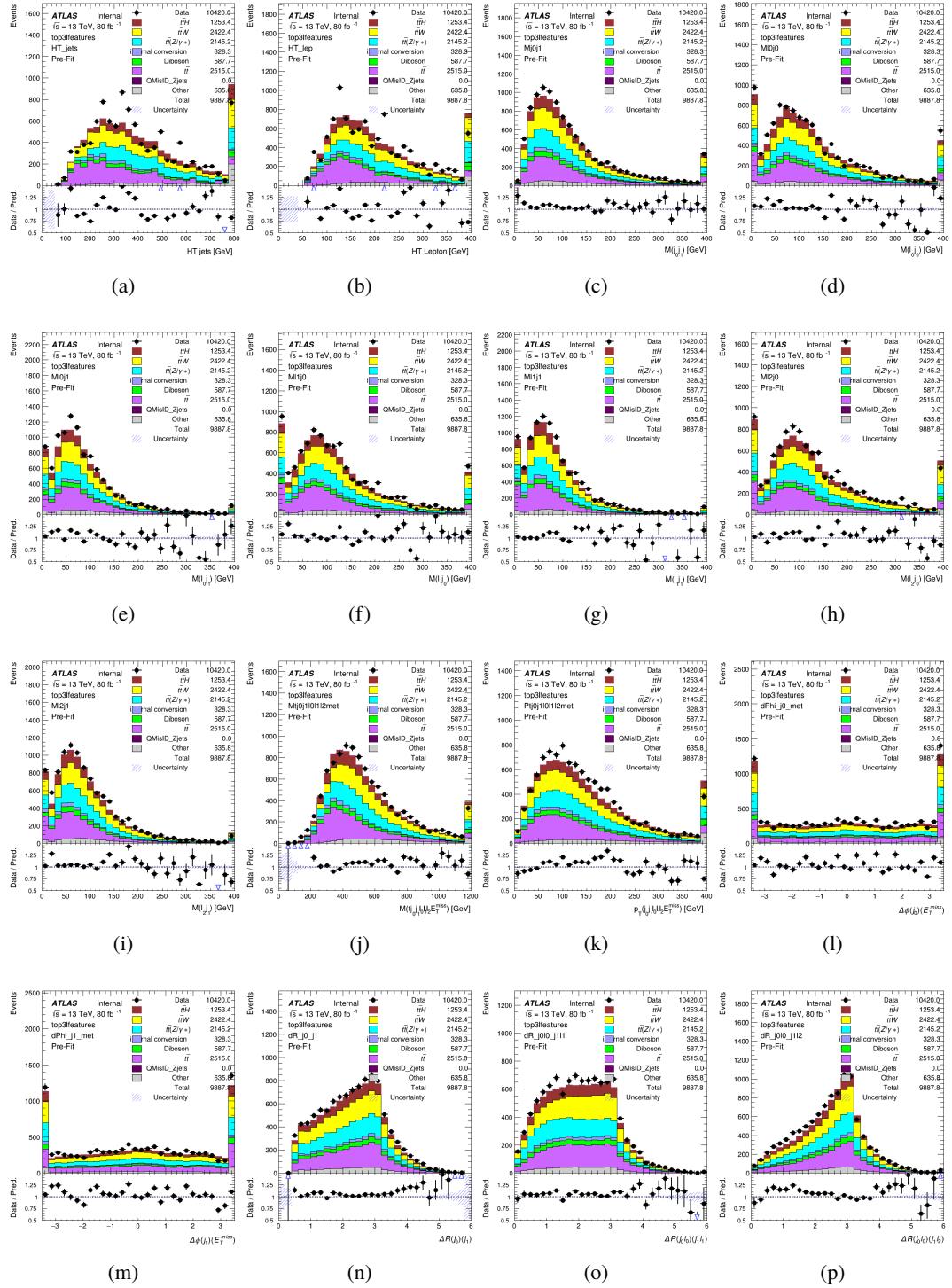


Figure A.3: Input features for top31

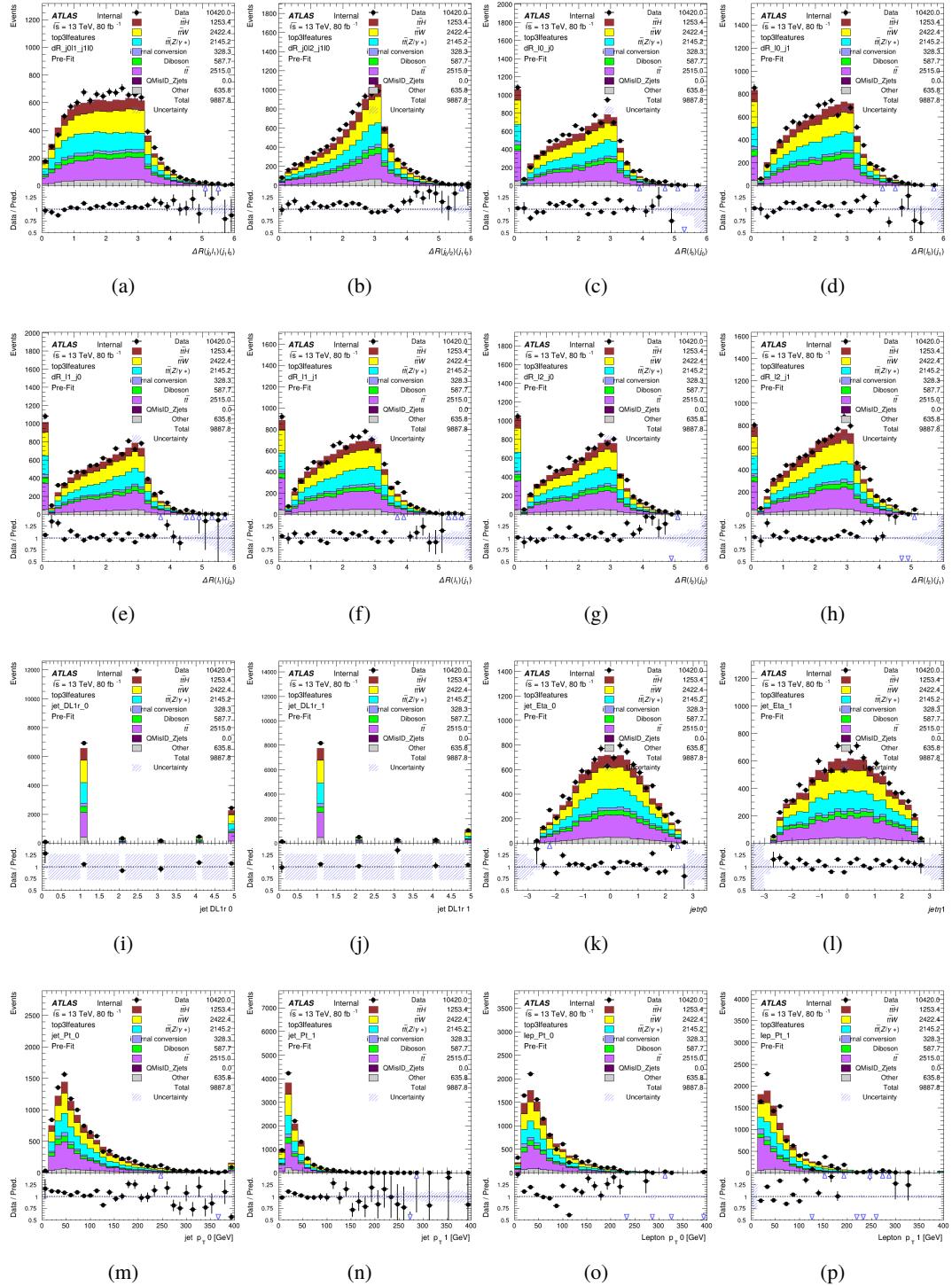


Figure A.4: Input features for top31

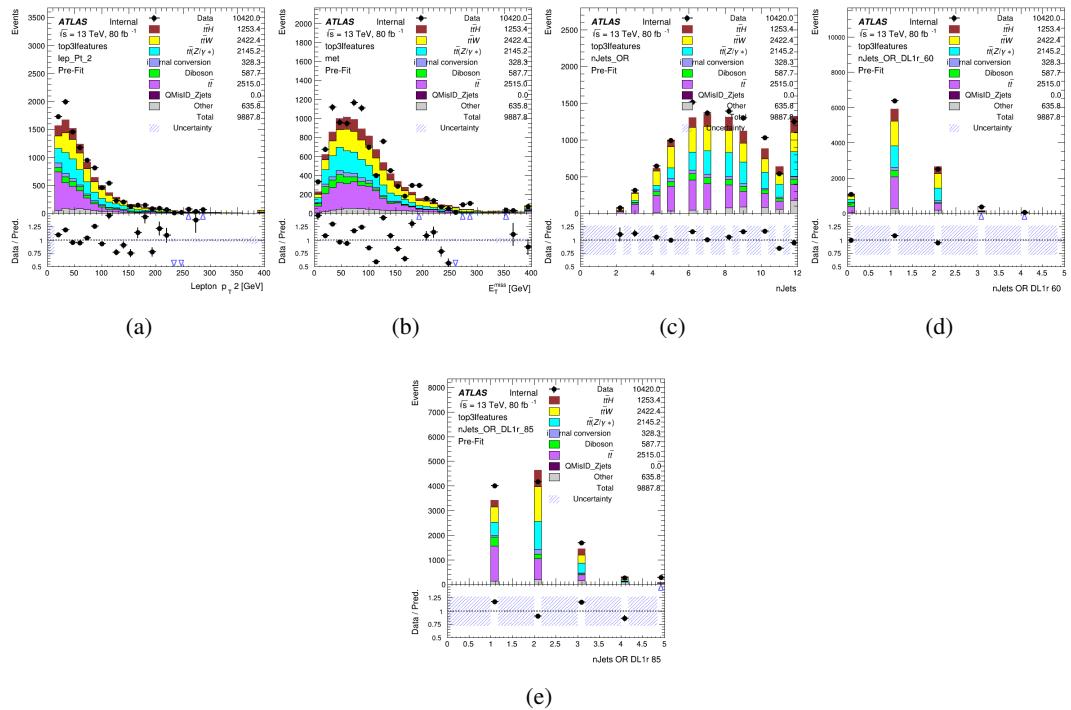


Figure A.5: Input features for top31

718 **A.1.3 Higgs Reconstruction Features - 2lSS**

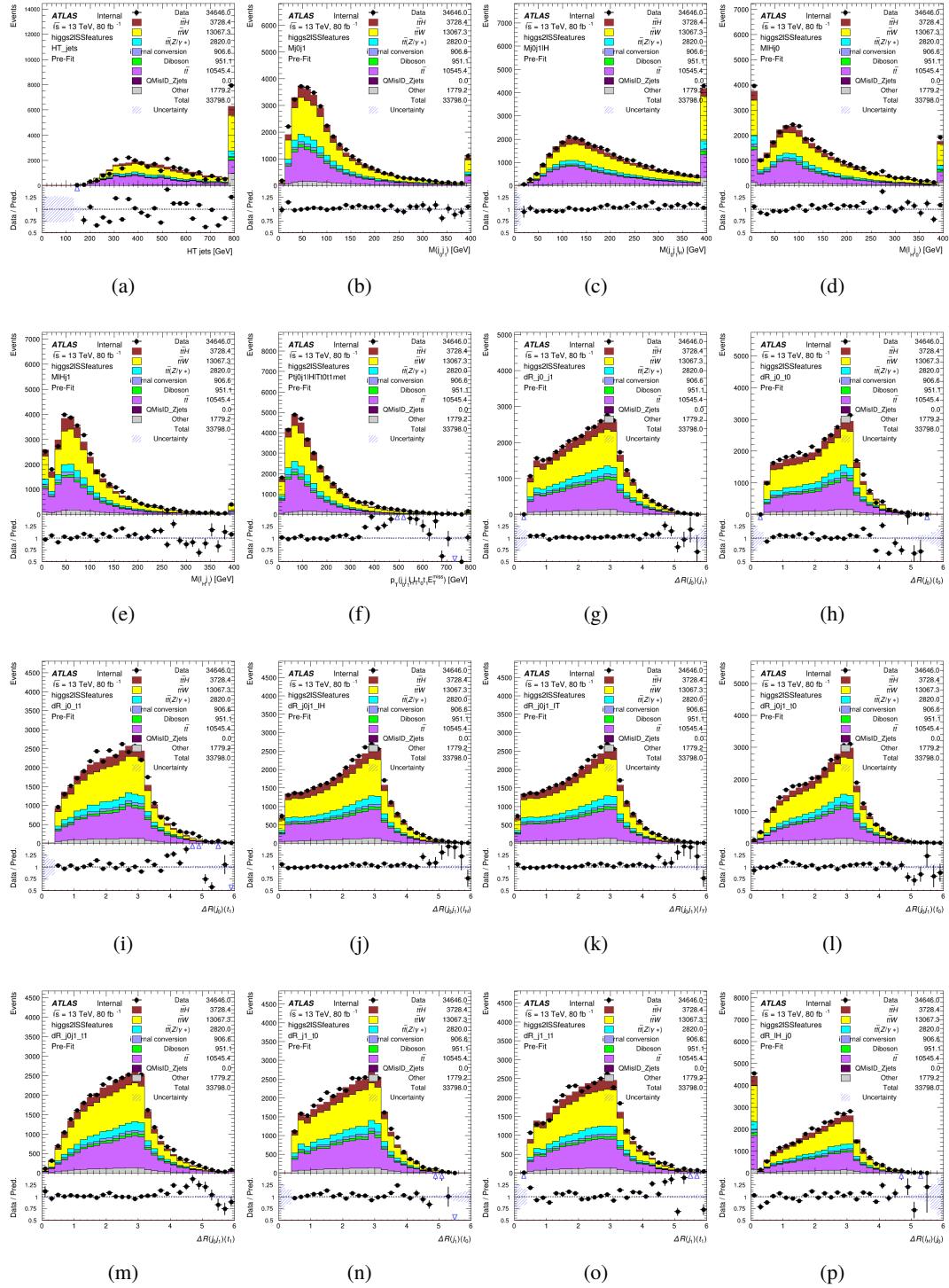


Figure A.6: Input features for higgs2IS

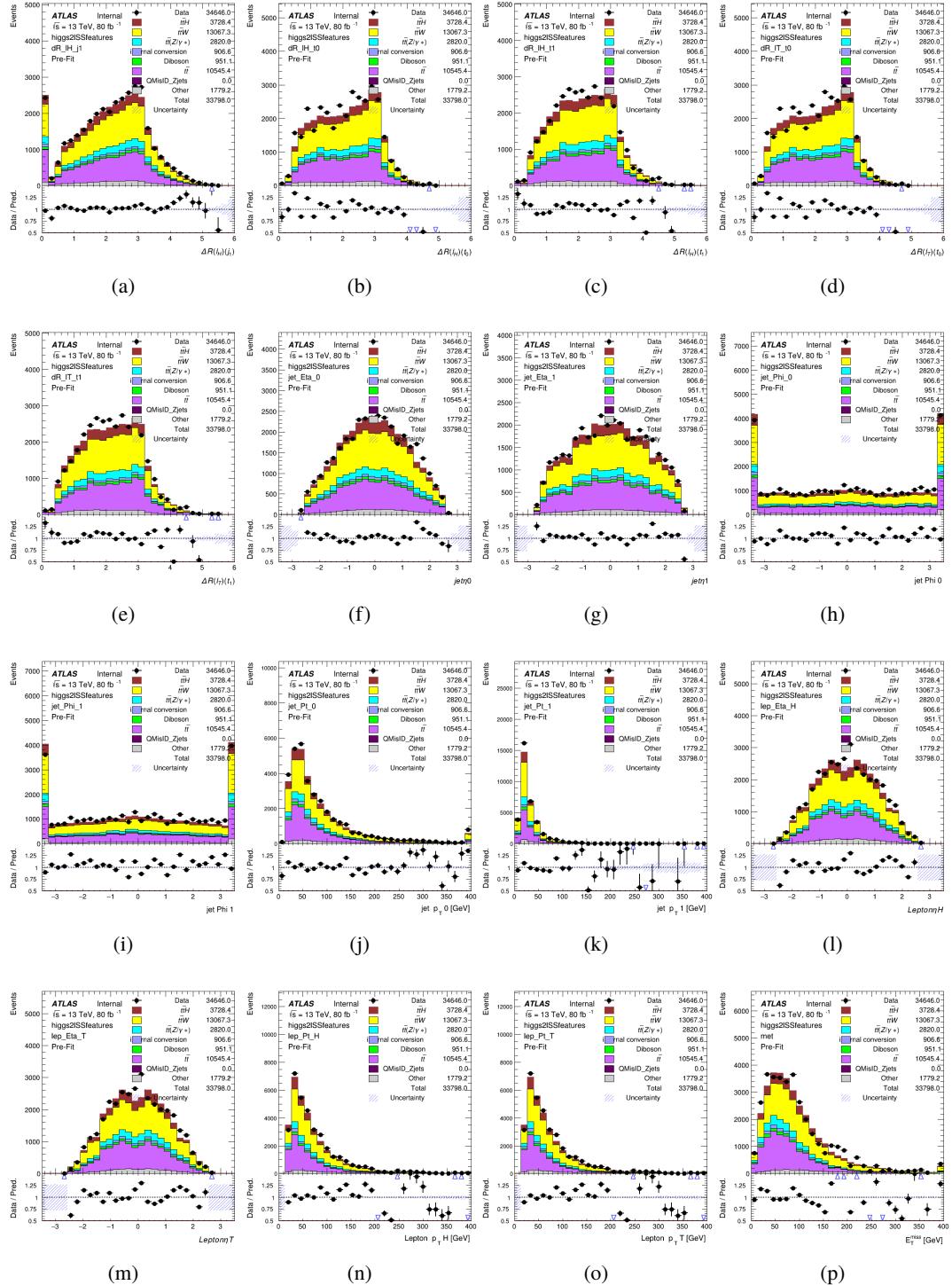


Figure A.7: Input features for higgs2IS

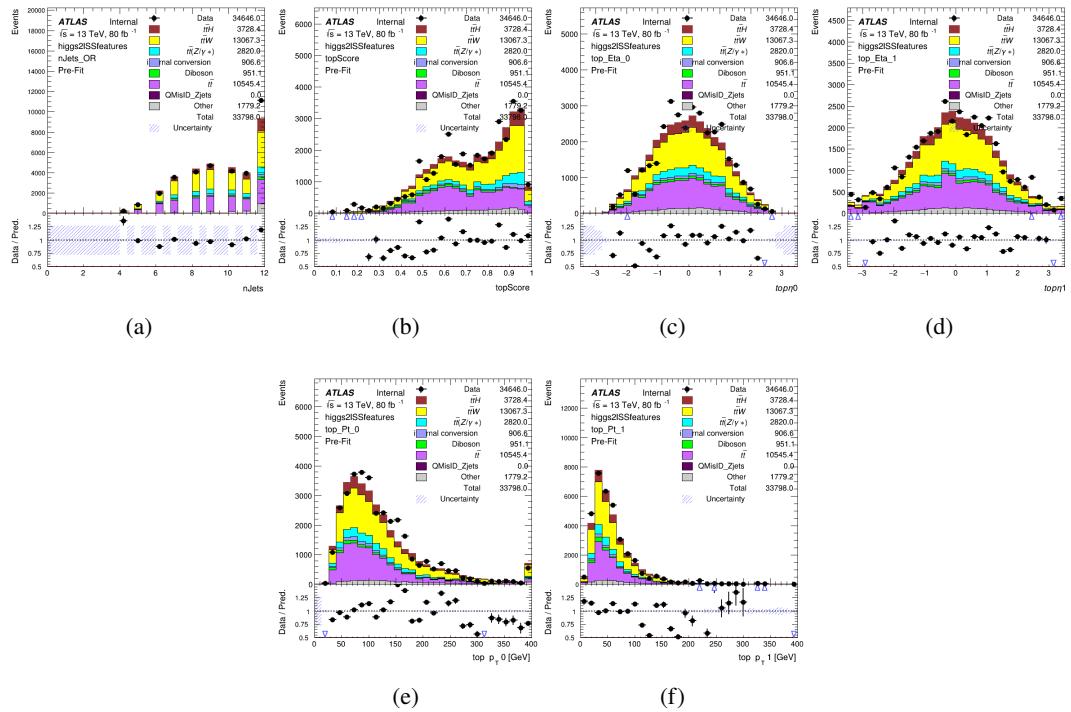


Figure A.8: Input features for higgs2lSS

<sup>719</sup> **A.1.4 Higgs Reconstruction Features - 3lS**

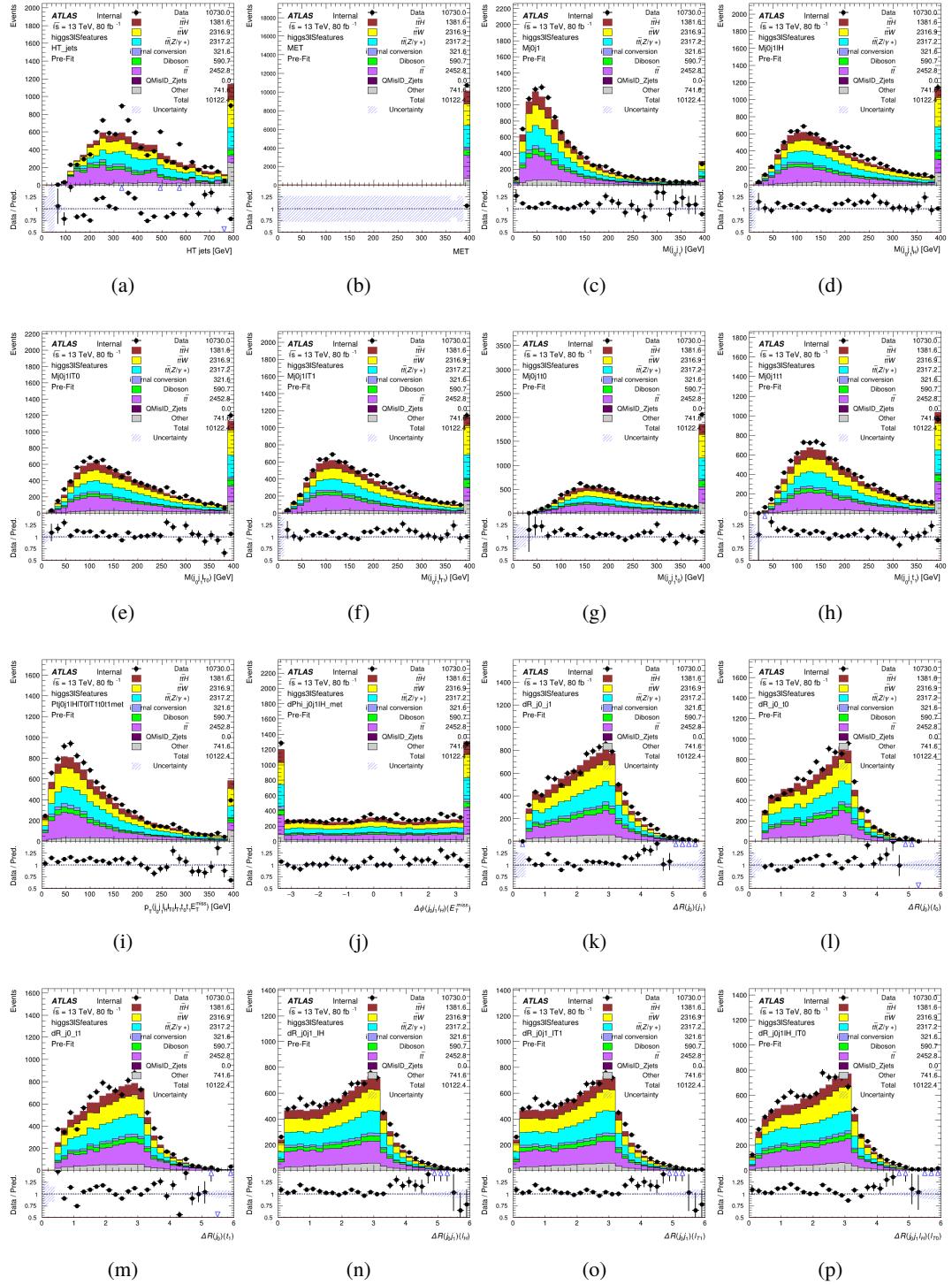


Figure A.9: Input features for higgs3IS

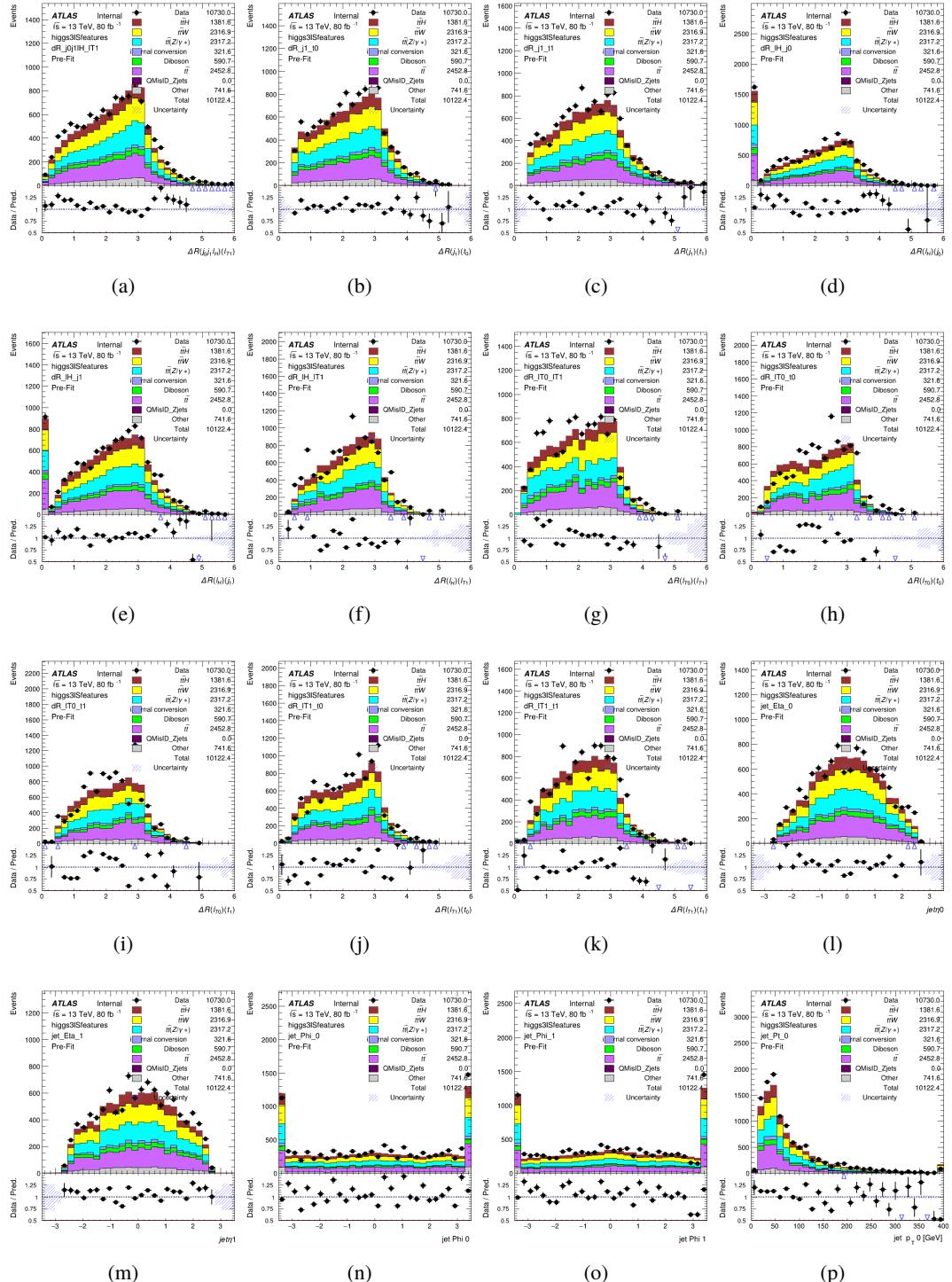


Figure A.10: Input features for higgs3l

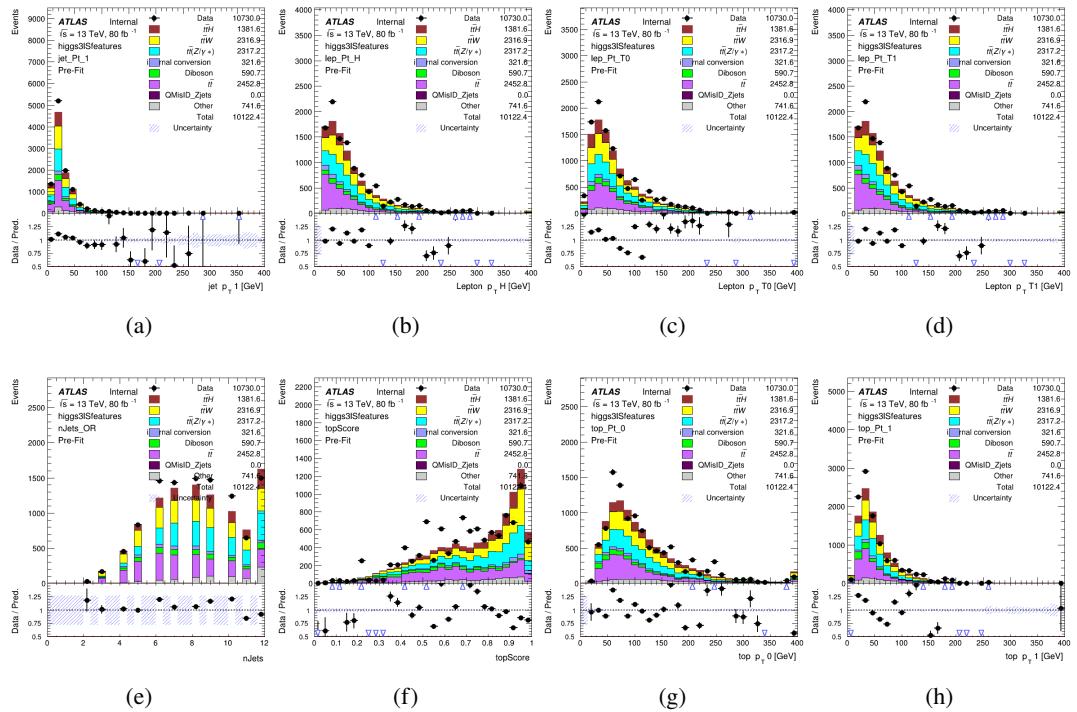


Figure A.11: Input features for higgs3lS

720 **A.1.5 Higgs Reconstruction Features - 3lF**

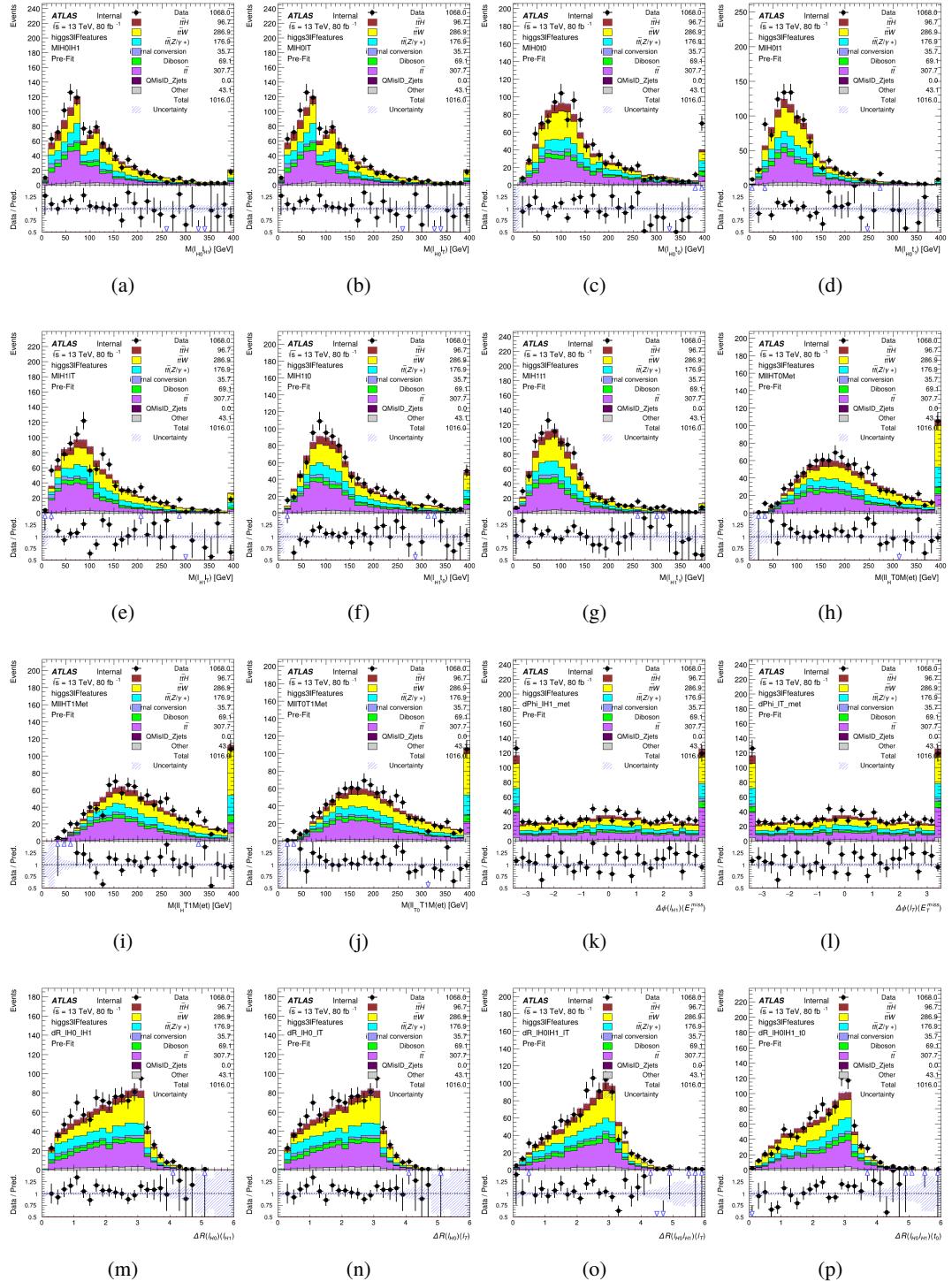


Figure A.12: Input features for higgs3lF

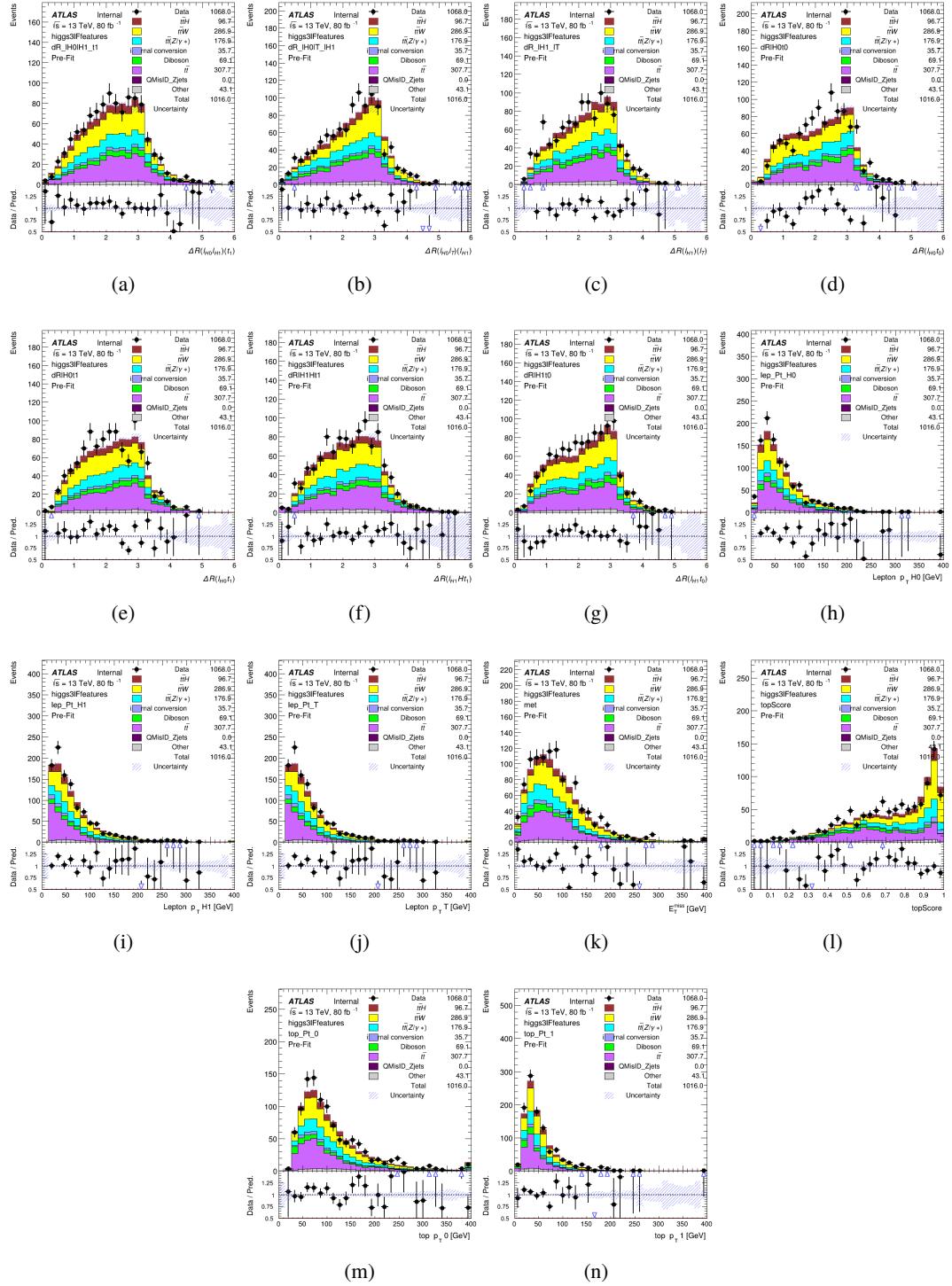
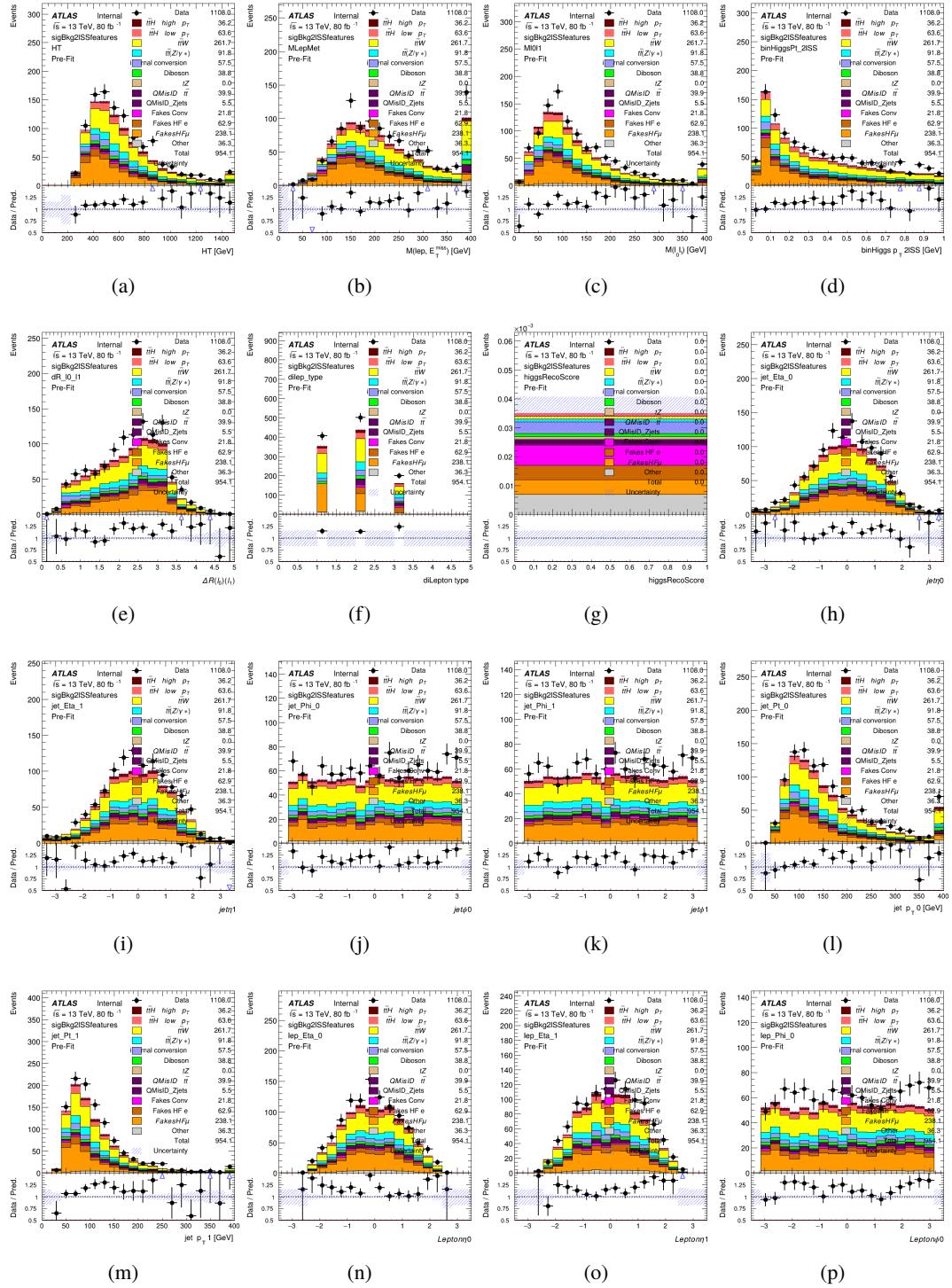


Figure A.13: Input features for higgs3lF

<sup>721</sup> **A.2 Background Rejection MVAs**

<sup>722</sup> **A.2.1 Background Rejection MVA Features - 2lSS**

Figure A.14: Input features for `sigBkg2IS`

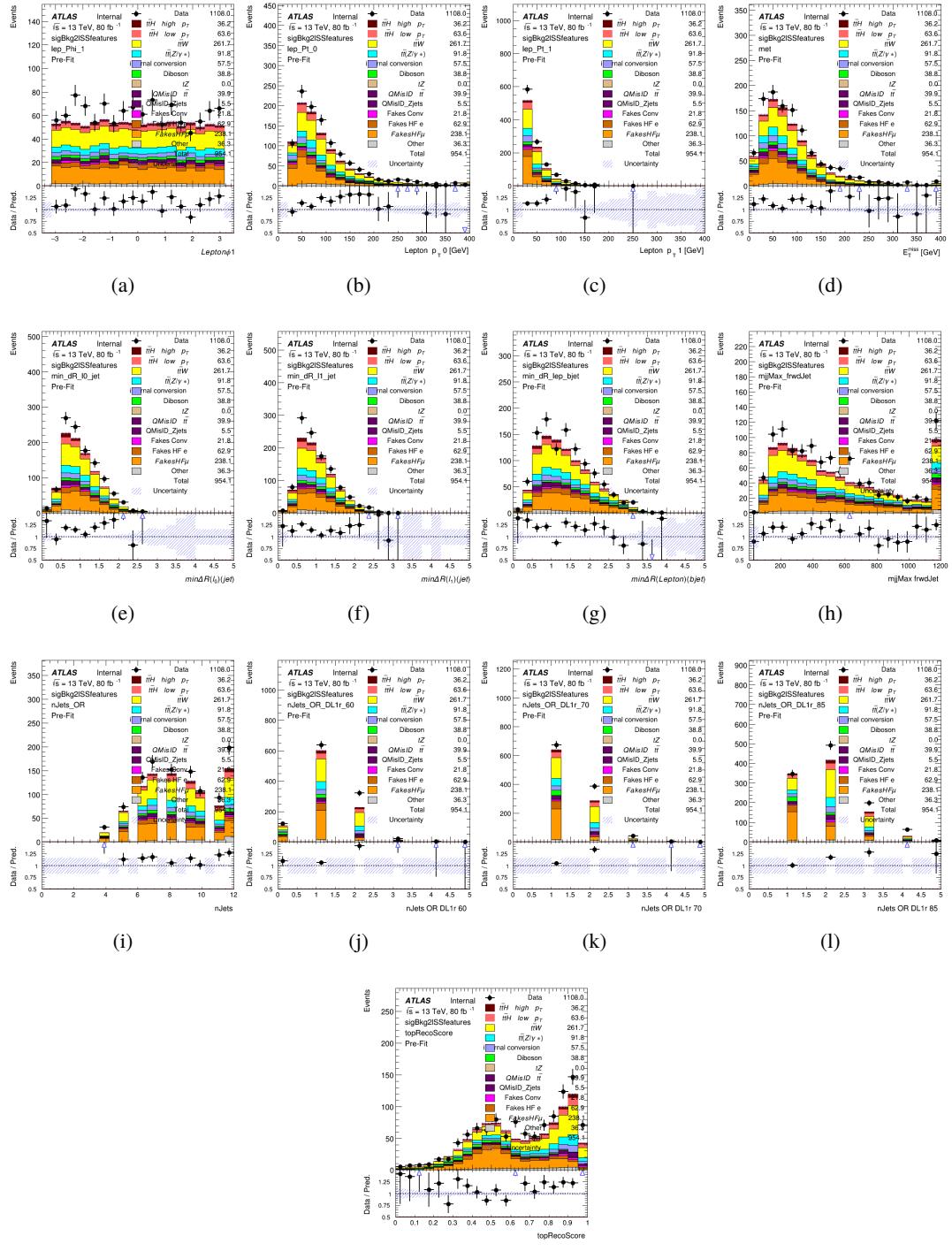


Figure A.15: Input features for sigBkg2lSS

<sup>723</sup> **A.2.2 Background Rejection MVA Features - 3l**

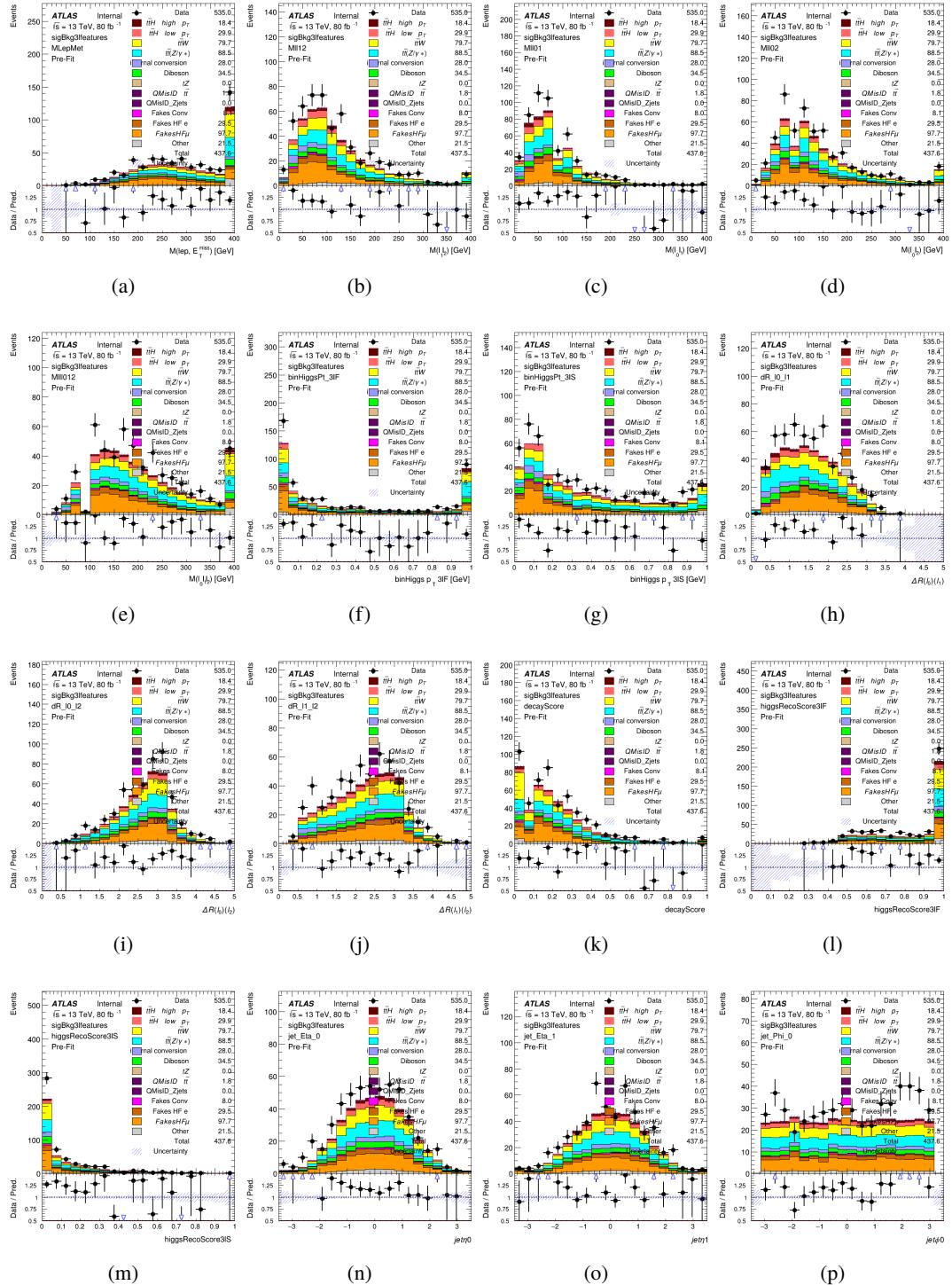
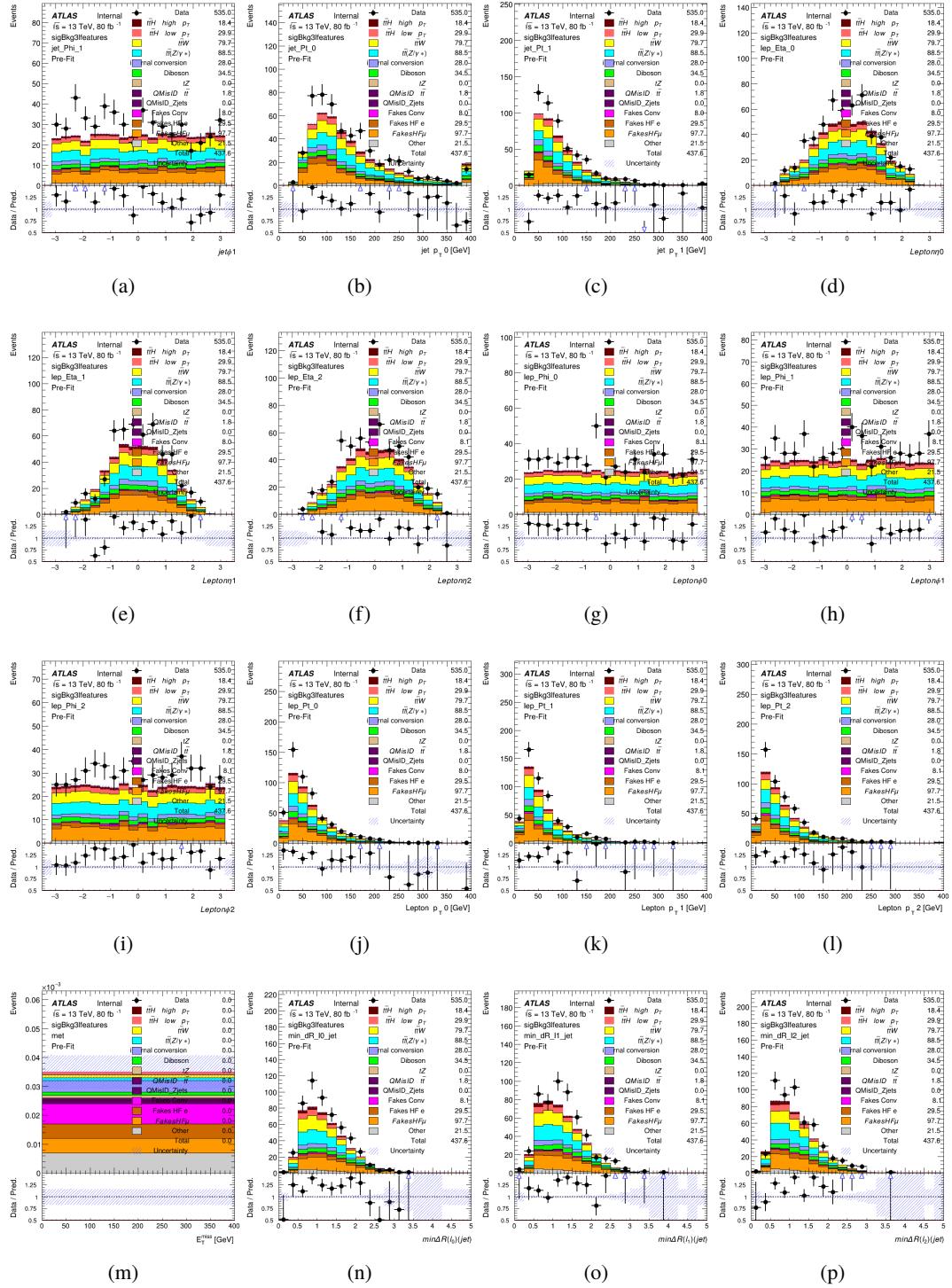


Figure A.16: Input features for sigBkg3l

Figure A.17: Input features for `sigBkg3l`

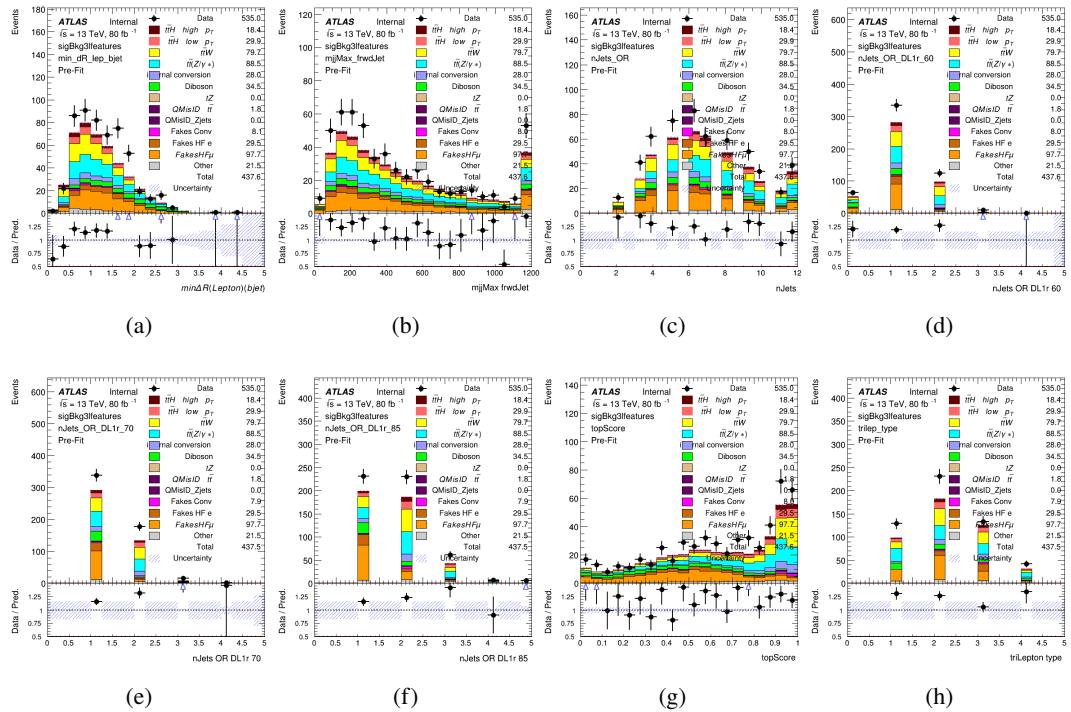


Figure A.18: Input features for sigBkg3l

724 **A.3 Alternate b-jet Identification Algorithm**

725 The nominal analysis reconstructs the b-jets by considering different combinations of jets, and  
 726 asking a neural network to determine whether each combination consists of b-jets from top quark  
 727 decays. An alternate approach would be to give the neural network about all of the jets in an event  
 728 at once, and train it to select which two are most likely to be the b-jets from top decay. It was  
 729 hypothesized that this could perform better than considering each combination independently, as  
 730 the neural network could consider the event as a whole. While this is not found to be the case,  
 731 these studies are documented here as a point of interest and comparison.

732 For these studies, the kinematics of the 10 highest  $p_T$  jets in each event are used for  
 733 training. This includes the vast majority of truth b-jets. Specifically the  $p_T$ ,  $\eta$ ,  $\phi$ ,  $E$ , and DL1r  
 734 score of each jet are used. For events with fewer than 10 jets, these values are substituted with 0.  
 735 The  $p_T$ ,  $\eta$ ,  $\phi$ , and  $E$  of the leptons and  $E_T^{\text{miss}}$  are included as well. Categorical cross entropy is  
 736 used as the loss function.

Table 10: Accuracy of the NN in identifying b-jets from tops in 2lSS events for the alternate categorical method compared to the nominal method.

Channel	Categorical	Nominal
2lSS	70.6%	73.9%
3l	76.1%	79.8%

737 **A.4 Binary Classification of the Higgs  $p_T$**

738 A two bin fit of the Higgs momentum is used because statistics are insufficient for any finer  
 739 resolution. This means separating high and low  $p_T$  events is sufficient for this analysis. As

740 such, rather than attempting the reconstruct the full Higgs  $p_T$  spectrum, a binary classification  
 741 approach is explored.

742 A model is built to determine whether  $t\bar{t}H$  events include a high  $p_T$  ( $>150$  GeV) or low  
 743  $p_T$  ( $<150$  GeV) Higgs Boson. While this is now a classification model, it uses the same input  
 744 features described in section 8.4. Binary crossentropy is used as the loss function.

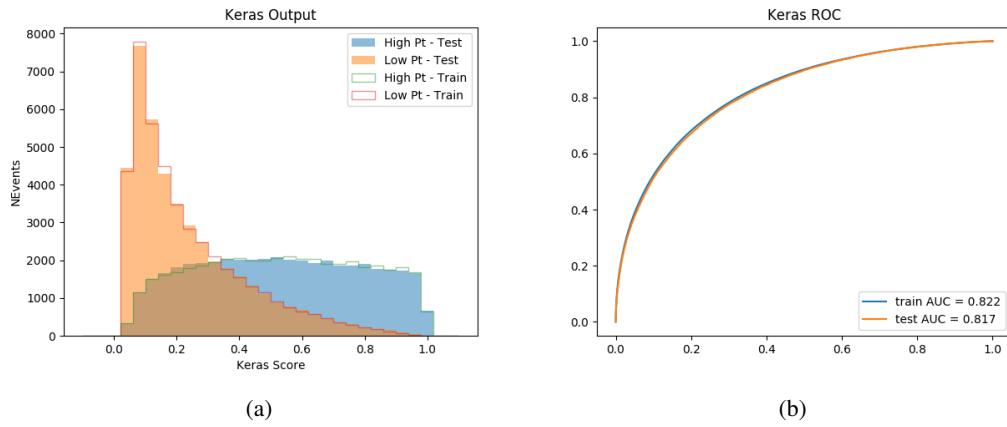


Figure A.19:

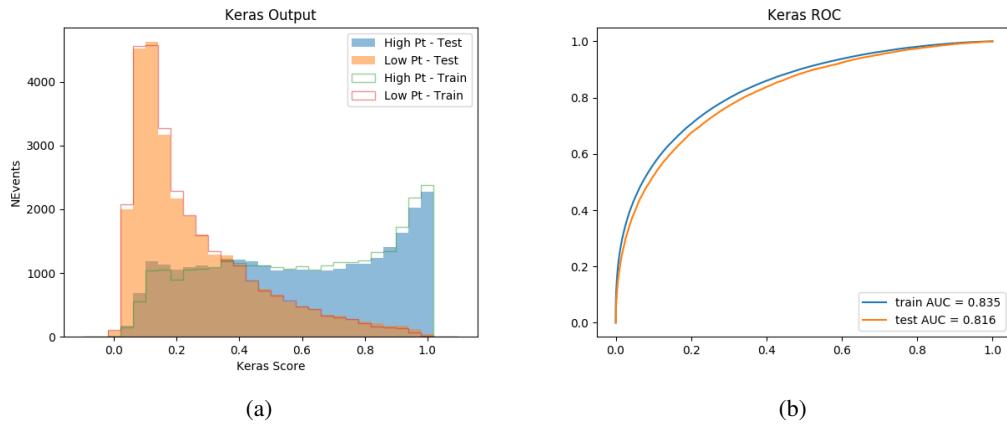


Figure A.20:

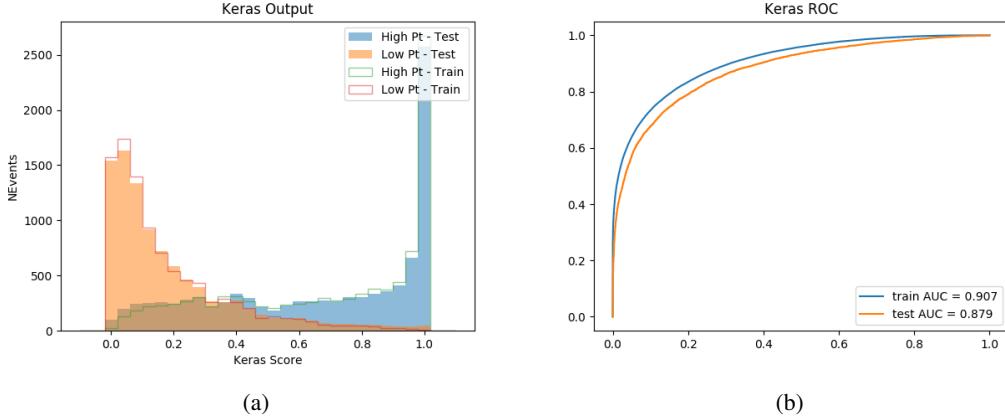


Figure A.21:

## 745 A.5 Impact of Alternative Jet Selection

746 A relatively low  $p_T$  threshold of 15 GeV is used to determine jet candidates, as the jets originating  
 747 from the Higgs decay are found to fall between 15 and 25 GeV a large fraction of the time. The  
 748 impact of different jet  $p_T$  cuts on our ability to reconstruct the Higgs  $p_T$  is explored here. The  
 749 performance of the Higgs  $p_T$  prediction models is evaluated for jet  $p_T$  cuts of 10, 15, 20, and 25  
 750 GeV.

751 **B**

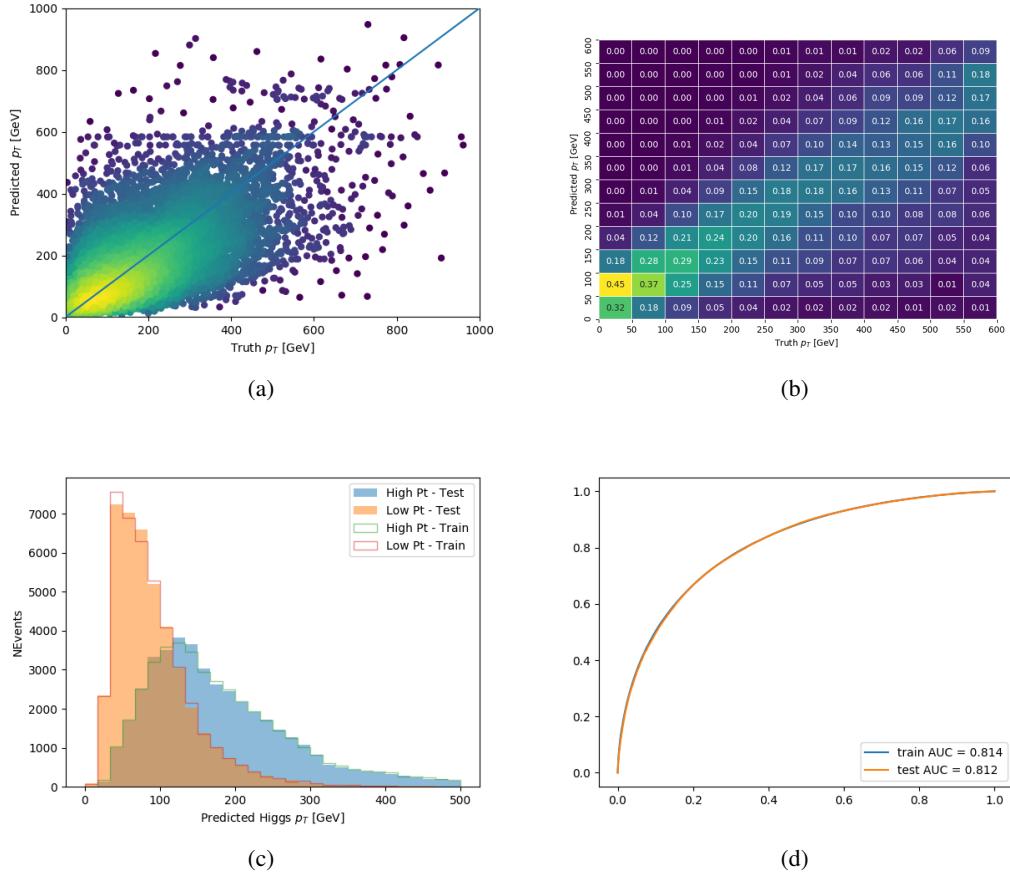


Figure A.22: