Semi-Dark Higgs Decay Analysis

CERN Summer Project Final Presentation 2024

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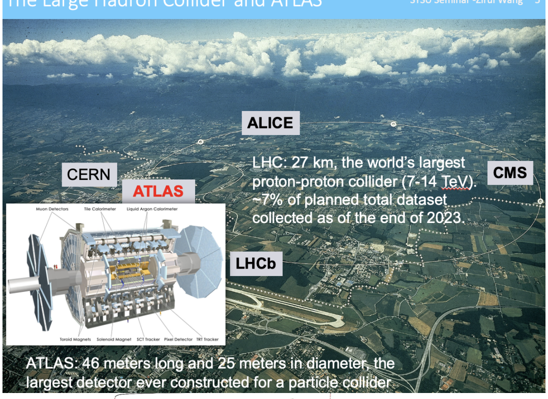
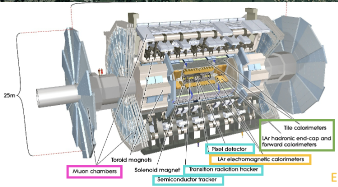
The ATLAS Experiment

- ATLAS (A Toroidal LHC ApperatuS) is comprised of an inner detector, calorimeters, muon spectrometer, and a magnet system.
  - The EM calorimeter measures the energy of electrons and photons.
  - There is a hadronic calorimeter which measures the energy of hadrons.
- The muon spectrometer measure the momentum of muons with the help of the magnet system which is comprised of both a toroidal and solenoid magnets.





Hadronic calorimeter
Trigger and measurement of jets and E_T^{miss}.

EM calorimeter
e/γ trigger, identification and measurement.

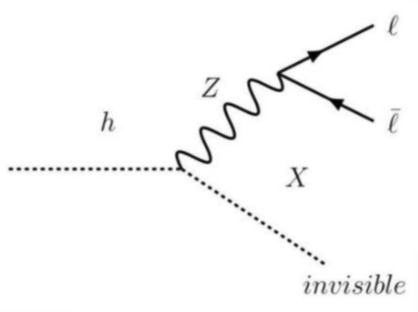
Muon Spectrometer:
Muon trigger and tracking.

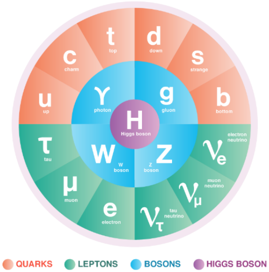
Inner detector
Precise tracking and vertexing, e/π separation.

- Solenoid Magnet: 2T
- Toroid Magnets: 0.5-1T

Semi-Dark Higgs Decay - Beyond the Standard Model

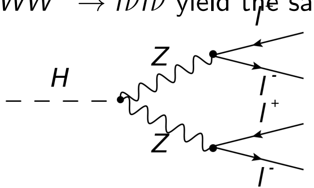
- With the discovery of the Higgs Boson a new area of study opened into Beyond the Standard Model theories with exotic Higgs decays
- **Exotic Higgs decay** searches have primarily focused on fully visible final states like $H \to 2f2f'$ or a completely invisible Higgs decay
- The Standard Model predicts the Higgs to decay invisibly only 0.1% of the time
  - ATLAS and CMS have put an upper bound on this measurement $\mathcal{O}(10\%)$
- **BSM theories** for partially visible decays of the Higgs (semi-dark) are much less explored and usually look at different areas of the parameter space for BSM theories





Semi-Dark Higgs Decay - $H \rightarrow ZX$

- Study the semi-visible decay $\mathbf{H} \rightarrow \mathbf{ZX}$ where X is a BSM particle invisible to LHC detectors
  - X manifests itself as missing transverse energy, $\not{E}_T$, and could be an axion like particle or dark photon for example
- My summer work primarily focused on the ZH production mode of the Higgs with a SM final state of $\mathbf{4l} + \not{E}_\mathbf{T}$, which mimics the BSM decay $\mathbf{H} \rightarrow \mathbf{ZX} \rightarrow \mathbf{ll} + \not{E}_\mathbf{T}$
- There are other production modes of the Higgs like gluon-fusion (Higgs is produced alone) and vector boson fusion (Higgs is produced along with jets)
  - **Gluon-fusion** - Higgs produced has low pT due to small phase space of $H \rightarrow ZX$
  - **Vector Boson Fusion** - Higgs is produced, alongside two high energy jets, through the interaction of two virtual bosons (W or Z) that are emitted by incoming quarks from the colliding protons
- It should be noted the SM decays $H \rightarrow ZZ^* \rightarrow ll\nu\bar{\nu}$ and $H \rightarrow WW^* \rightarrow l\nu l\bar{\nu}$ yield the same final state



Validation of Production Samples

- Validation is the process of studying a small sample of MC simulated data from an event generator (we are using Pyhtia8)
- Need to ensure the event generator accurately simulates the decay process of desired events, in our case we are interested in the $\mathbf{H} \rightarrow \mathbf{ZZ} \rightarrow \mathbf{ll}\nu\nu$ final state
- For our case the Pythia8 decay of $H \rightarrow ZZ$ is well studied so we don't expect anything wrong from the generator level, however we don't have older samples of $H \rightarrow ZZ \rightarrow llvv$ to validate against
- Validation needs to be done for a variety of production modes of the Higgs decay for the $2l + \not{E}_T$ signal study
  - Validation has been completed for the following production modes: ggH, VBF, $qqZ(\rightarrow ll)H$, $ggZ(\rightarrow ll)H$
  - Production modes I worked on for validation: $\mathbf{WH}$, $\mathbf{qqZ}(\rightarrow \nu\nu/\mathbf{qq})\mathbf{H}$, $\mathbf{ggZ}(\rightarrow \nu\nu)\mathbf{H}$

Sample Validation

- Validation is done at a particle level using Derived Analysis Object Data (DAOD) TRUTH converted from event-level (EVNT) information from MC simulations
- Despite not sending the MC simulated data through a detector simulation we do make some detector geometry sections on all channels:
  - e/μ from τ decay are vetoed using truth information

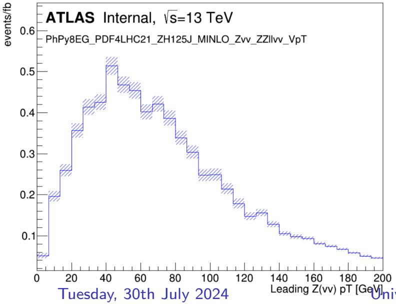
Object Selection

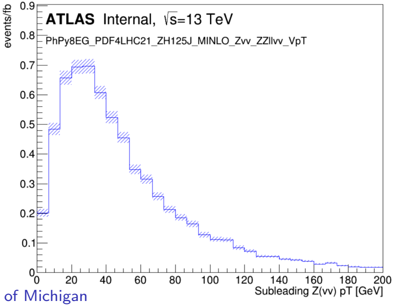
e	$p_T > 7\text{GeV}, \ |\eta| < 2.5$
μ	$p_T > 5\text{GeV}, \ |\eta| < 2.7$
τ/ν	$p_T > 5\text{GeV}, \ |\eta| < 4.5$

- Event Selection
  - Truth τ/ν are also used for Z boson reconstruction
  - Reconstruct Z with leptons ($l = e, \mu, \tau$) and neutrinos separately and select the one closest to Z mass from each group

Event Selection for $ggZ(\to \nu\nu)H$ and $qqZ(\to \nu\nu)H$

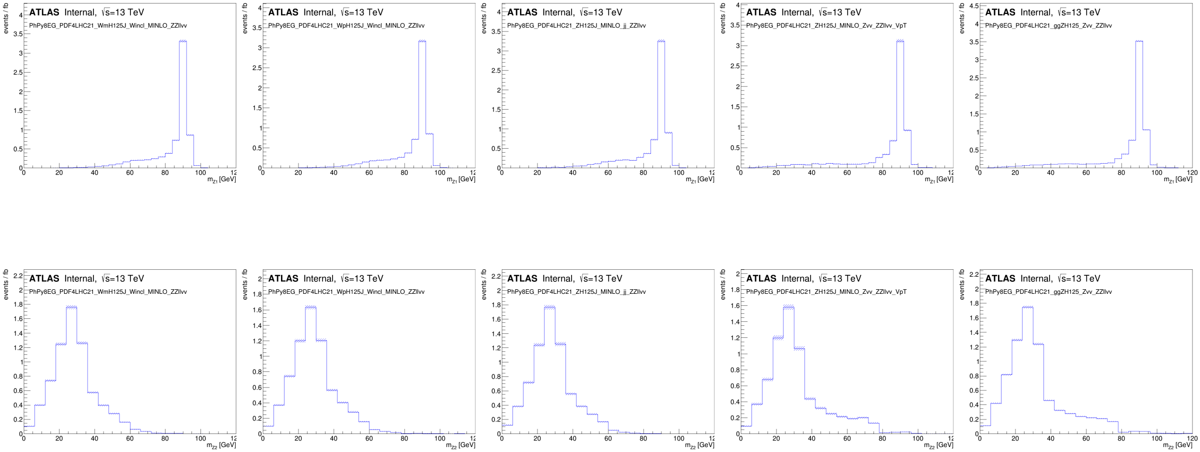
- Looking at decay $H \to ZZ \to ll\nu\nu$
- Need to decide which $Z \to \nu\nu$ belongs to associated ZH production or Higgs decay
- Two cases for $Z \to \nu\nu$
  - If only have one reconstructed Z with mass $\sim$ 91GeV (on-shell), then it belongs to production
  - If have two Z bosons each with reconstructed mass $\sim$ 91GeV (on-shell), need to determine which is from production
- To differentiate the two on-shells, compare transverse momentum of reconstructed Z bosons
- The $Z \to \nu\nu$ with higher transverse momentum likely comes from production process





Z mass from truth leptons, where the Z bosons are from Higgs decay

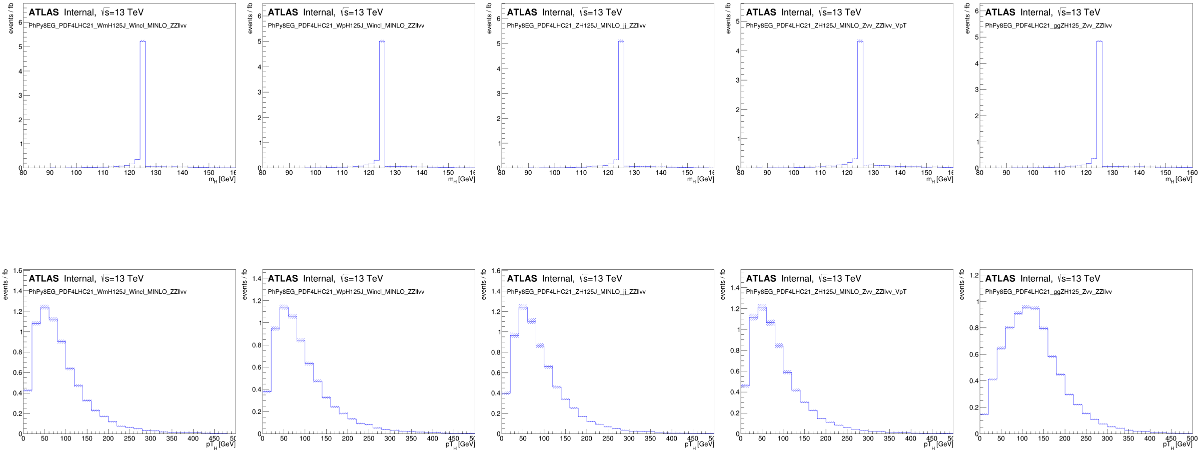
WmH | WpH | $qqZ(\to qq)H$ | $qqZ(\to \nu\nu)H$ | $ggZ(\to \nu\nu)H$



Top row: Z_1 mass; Bottom row: Z_2 mass

Higgs kinematics reconstructed from truth leptons

WmH | WpH | $qqZ(\to qq)H$ | $qqZ(\to \nu\nu)H$ | $ggZ(\to \nu\nu)H$



Top row: H mass; Bottom row H pT

Sample Request for Leptons+MET

- Now that we have validated out production channels we need to request a full simulation of the data
- First need to do a local production of the simulation using Job Options showering of $ZZ \to ll\nu\nu$, which will have a filter efficiency of $44\% = \frac{BR(ZZ \to ll\nu\nu)}{BR(ZZ \to llll) + BR(ZZ \to \nu\nu\nu\nu) + BR(ZZ \to ll\nu\nu)}$
- Along with the JO file and the .log file created with the local showering created a JIRA ticket for a full simulation of production modes

```
#--------------------------------------------------------------
# Pythia8 showering with the A14 NNPDF2.3 tune
#--------------------------------------------------------------
include("Pythia8_i/Pythia8_A14_NNPDF23LO_EvtGen_Common.py")
include("Pythia8_i/Pythia8_Powheg_Main31.py")


genSeq.Pythia8.Commands  += ['Powheg:NFinal = 2']


#--------------------------------------------------------------
# Higgs at Pythia8
#--------------------------------------------------------------
genSeq.Pythia8.Commands += [ '25:onMode = off',    # decay of Higgs
                             '25:onIfMatch = 23 23',
                             '23:onMode = off',#decay of Z
                             '23:mMin = 2.0',
                             '23:onIfAny = 11 12 13 14 15 16' ]



#--------------------------------------------------------------
# ZZ→llvv filter
#--------------------------------------------------------------
from GeneratorFilters.GeneratorFiltersConf import XtoVVDecayFilterExtended

filtSeq += XtoVVDecayFilterExtended()
filtSeq.XtoVVDecayFilterExtended.PDGGrandParent = 25
filtSeq.XtoVVDecayFilterExtended.PDGParent = 23
filtSeq.XtoVVDecayFilterExtended.StatusParent = 22
filtSeq.XtoVVDecayFilterExtended.PDGChild1 = [11,13,15]
filtSeq.XtoVVDecayFilterExtended.PDGChild2 = [12,14,16]
```

Production mode	**mc20a**	**mc20d**	**mc20e**	**total**
$ggZ(\to \nu\nu)$H	50k	70k	90k	210k
WmH	500k	620k	840k	1.96M
WpH	500k	620k	840k	1.96M
$qqZ(\to qq)H$	350k	440k	590k	1.38M
$qqZ(\to \nu\nu)H$	100k	130k	170k	400k

Cut-Based Analysis for $Z \rightarrow (ll)H \rightarrow ZX$

- Cut-based analysis is a process used to reduce background by removing events that mimic the signal, helps optimize the signal-to-noise ratio, to enhance the sensitivity of the experiment when looking for new signals
- Cuts made on MC and data from Run 2
  - **Momentum Cut**: Leading and subleading electrons needs to have a momentum of 27 GeV and 10 GeV respectively
  - **ΔR Cut**: Require a minimum angular separation of 0.05 for leptons
  - **JPsi Veto**: Used to reject events where the invariant mass of the charged lepton pairs is similar to that of the JPsi meson
  - **At least one quadruplet with 2 leptons pairs in an event**: We create a Z candidate using all combinations of muon and anti-muon pairs, same with electron-positron pairs, need at least two of these pairs
- Using our cut-based analysis code we can then process data from Run 2 and MC data that has been through a detector simulation and compare them

Data/Background Comparison Plots

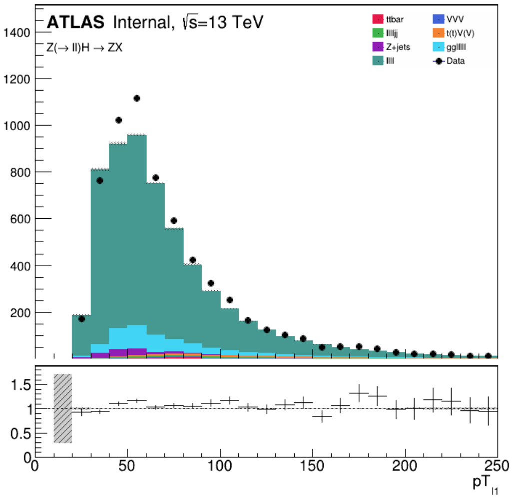


Figure: Leading Lepton pT

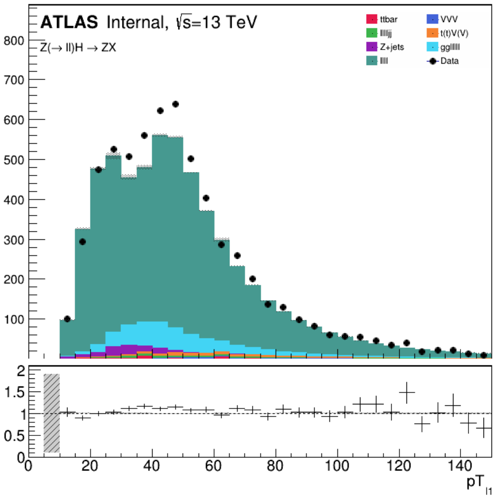


Figure: Subleading Lepton pT

Data/Background Comparison Plots

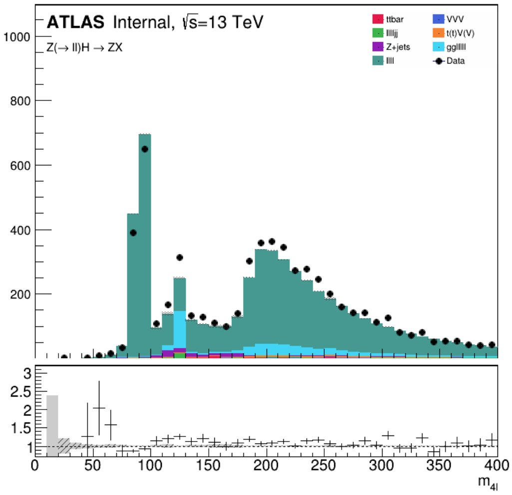


Figure: m4l

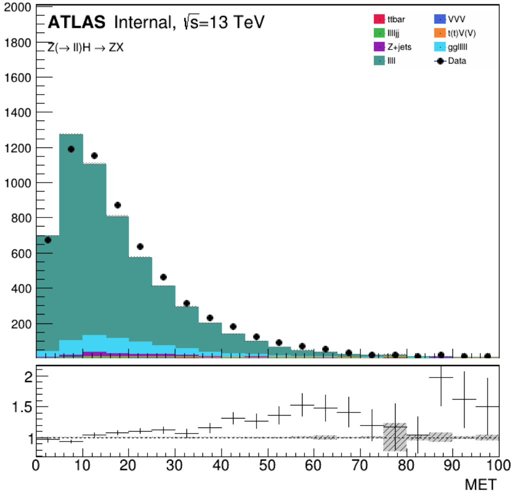


Figure: MET

Data/Background Comparison Plots

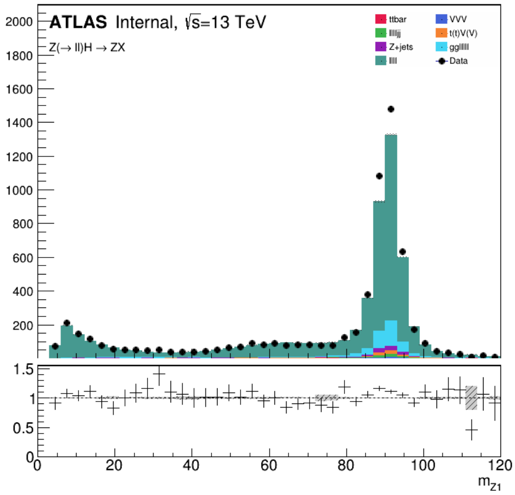


Figure: mZ1

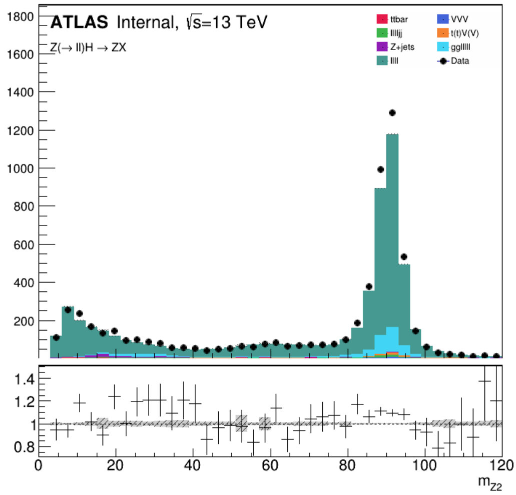


Figure: mZ2

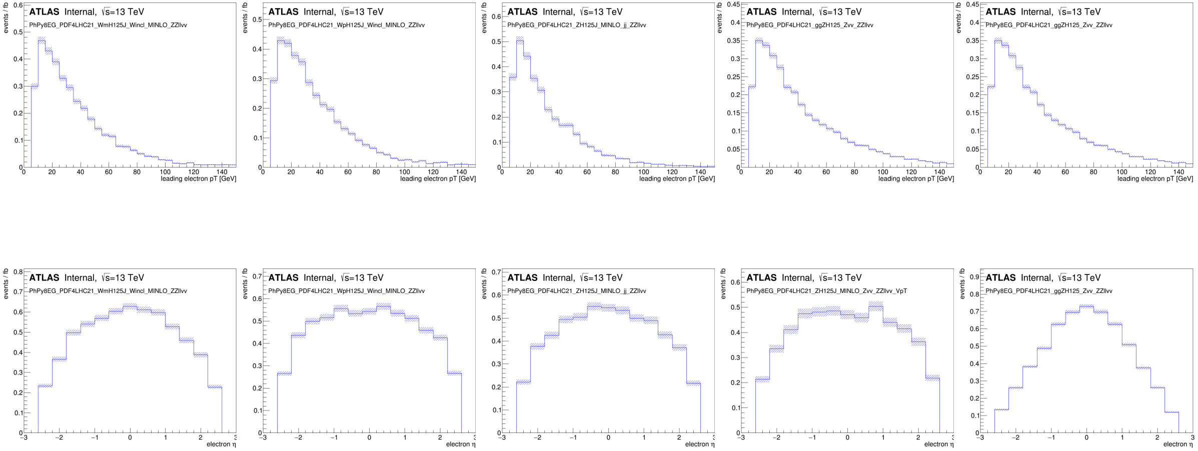
Conclusion

- Over the summer I have learned about the MC data validation process by creating and implementing code to reconstruct Z bosons in the SM decay $H \to ZZ \to ll\nu\nu$ while improving the misidentifaction problem of Z bosons from the production/decay. This problem can furhter be improved upon with the implementation of machine learning techniques
- I also learned about cut-based analysis and data/background comparison and how to use cuts to better showcase the signal region of the events of interest
- The next step and project that I started working on a few days ago is to use machine learning to optimize cuts and better classify the origin of reconstructed Z bosons. I will continue to work on this in the coming school year

I would like to thank Steve Goldfarb, Zirui Wang, and Xinmeng Ye for providing guidence and mentoring me throughout the summer

Backup Slides - Electron kinematics

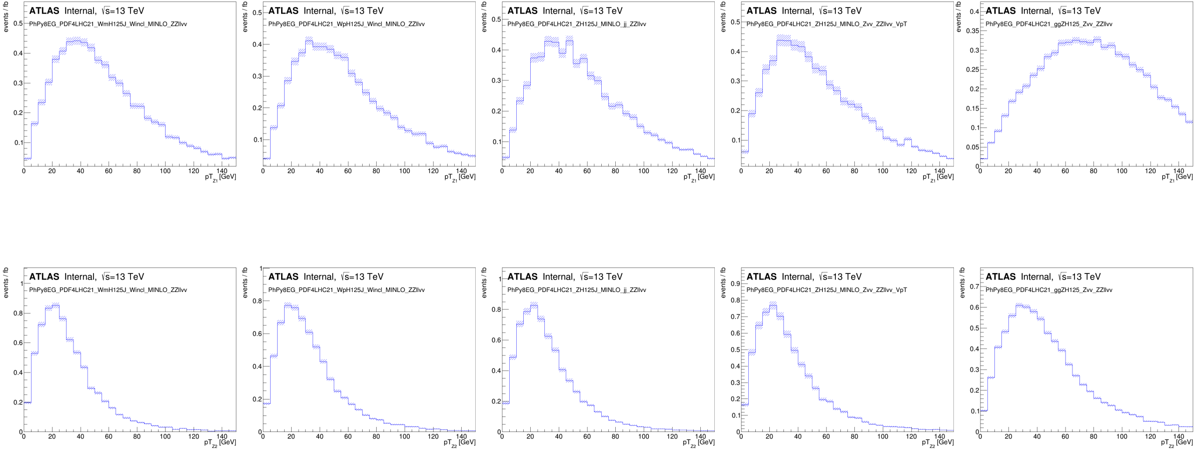
WmH | WpH | $qqZ(\to qq)H$ | $qqZ(\to \nu\nu)H$ | $ggZ(\to \nu\nu)H$



Top row: leading electron pT; Bottom row: electron η

Backup Slides - pT_Z from truth leptons, where the Z bosons are from Higgs decay

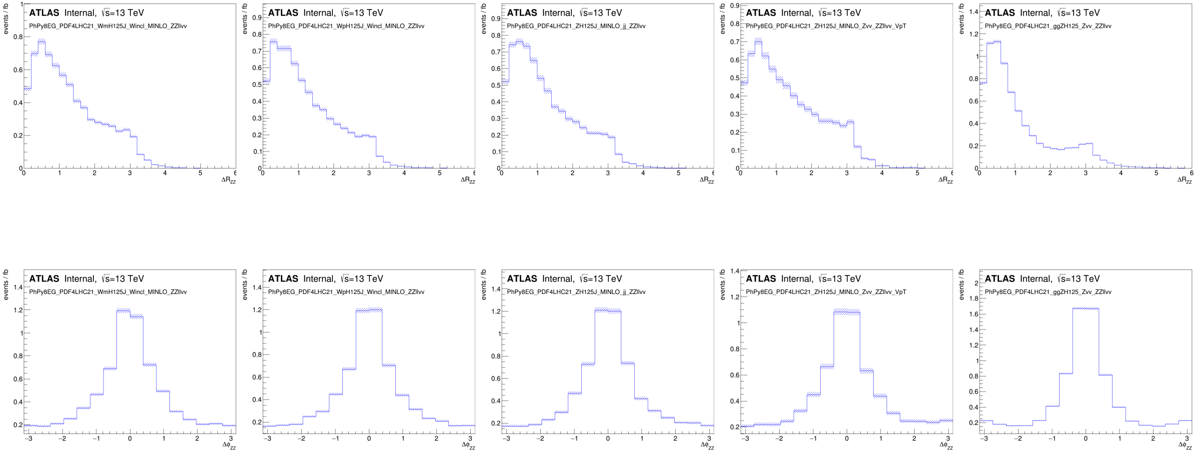
WmH	WpH	$qqZ(\rightarrow qq)H$	$qqZ(\rightarrow \nu\nu)H$	$ggZ(\rightarrow \nu\nu)H$



Top row: pT_{Z_1}; Bottom row: pT_{Z_2}

Backup Slides - Z angular distribution, where the Z bosons are from Higgs decay

WmH	WpH	$qqZ(\to qq)H$	$qqZ(\to \nu\nu)H$	$ggZ(\to \nu\nu)H$



Top row: ΔR_{ZZ}; Bottom row: $\Delta \phi_{ZZ}$

Backup Slides - Data/Background Comparison Plots

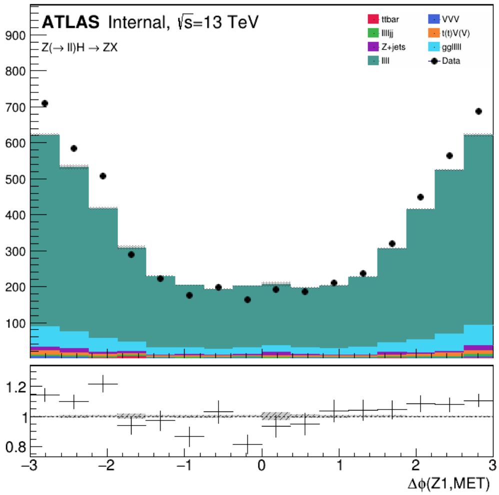


Figure: dphiZ1MET

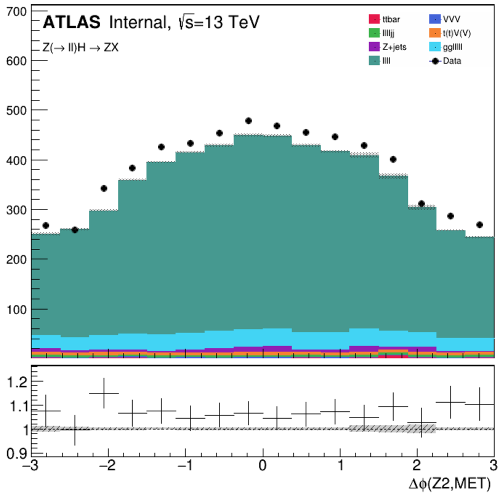


Figure: dphiZ2MET

Backup Slides - Data/Background Comparison Plots

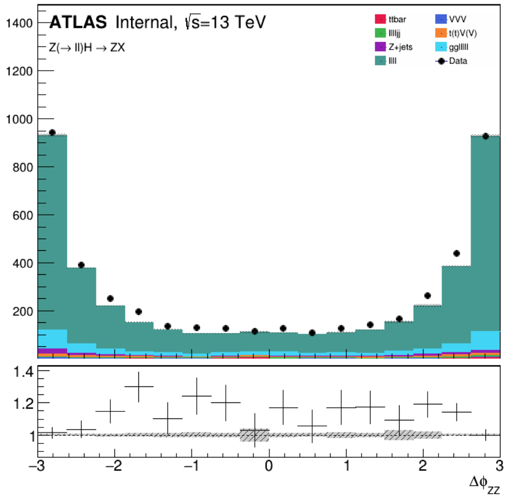


Figure: dphiZZ

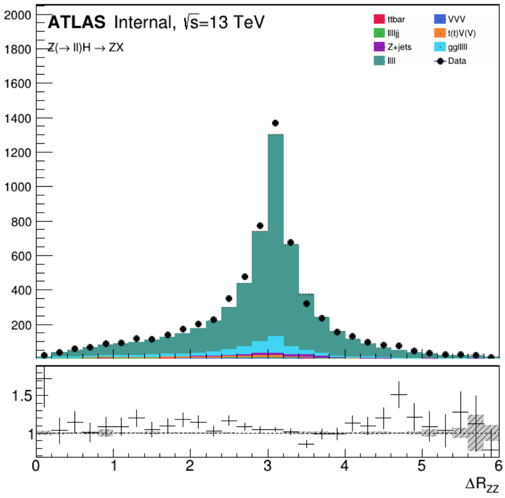


Figure: dRZZ

Backup Slides - Data/Background Comparison Plots

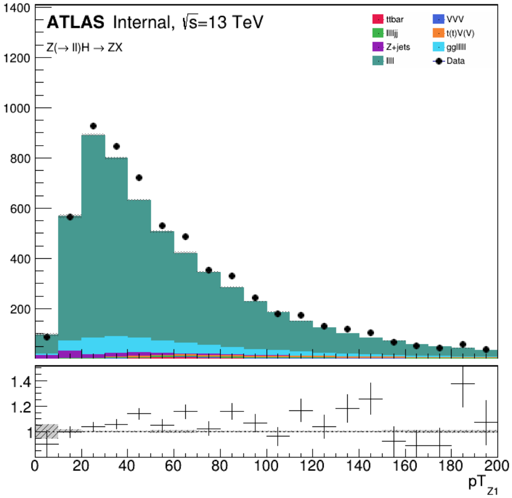


Figure: pTZ1

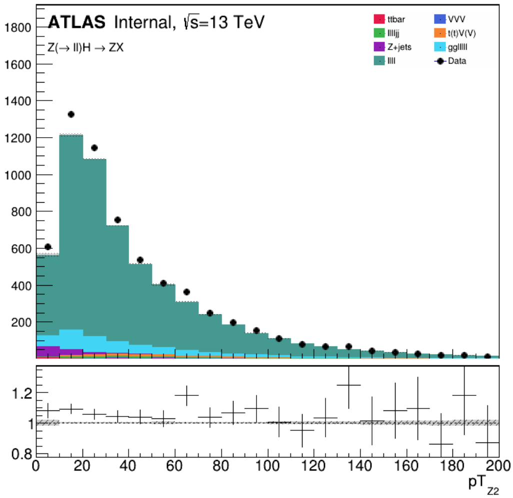


Figure: pTZ2

Backup Slides - Data/Background Comparison Plots

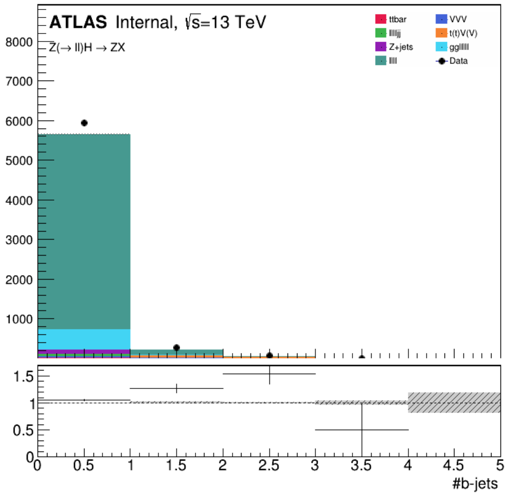


Figure: nbjets

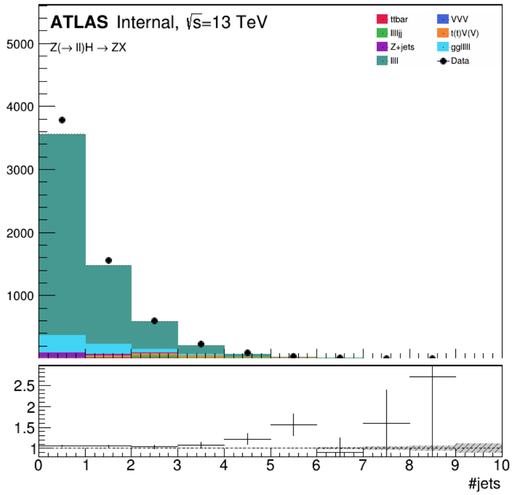


Figure: njets